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Tesis Doctoral

Concepción e Integración de Arquitecturas y Protocolos de Comunicación dentro de Sistemas de Supervisión y Control de Microrredes Inteligentes

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A los que quiero

“La ciencia más útil
es aquella cuyo fruto es el
más comunicable”

Leonardo Da Vinci

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RESUMEN

Las microrredes inteligentes se presentan como una solución para integrar las energías renovables así como para mejorar la eficiencia de la red por medio de la incorporación de las Tecnologías de Información y Comunicación (TIC). Sin embargo, la alta penetración de los recursos energéticos distribuidos (RED) en las microrredes, requiere una serie de cambios técnicos en los sistemas de comunicación caracterizados tradicionalmente por esquemas centralizados, donde un controlador central se comunica con todos los recursos energéticos distribuidos y toma decisiones, hacia esquemas descentralizados donde cada recurso energético distribuido tiene capacidad de comunicación y decisión de forma local.

En este sentido, el objetivo global de las estrategias de comunicación descentralizadas es dotar al sistema energético de una mayor escalabilidad, fiabilidad, robustez, y flexibilidad que la que presentan los sistemas centralizados. Además, las microrredes con esquemas descentralizados presentan una gran oportunidad para el advenimiento del futuro Internet de la Energía o Internet of Energy (IoE), ya que cada recurso energético distribuido desplegado en la microrred es susceptible de conectarse a la nube y enviar y recibir datos desde hacia la red en tiempo real, en cualquier momento y lugar.

Uno de los puntos críticos derivados de la incorporación de las TIC en las microrredes de gestión distribuida es garantizar la conectividad entre los recursos energéticos al tiempo que se satisfacen los requisitos técnicos de estos sistemas energéticos. Los distintos estándares y normas establecidas para el despliegue de microrredes destacan la necesidad de cumplir con algunos parámetros de calidad de servicio (Quality of Service, QoS) como ancho de banda, latencias, *throughput* (rendimiento), entre otros, ya que un ancho de banda bajo puede dar lugar a cuellos de botella, pérdida de paquetes de datos y distorsión. Por otra parte, si la comunicación no presenta una tasa positiva de promedio de éxito o sufre retardos y/o supera el tiempo requerido, la información no cumple su cometido y, en el peor de los casos, daños eléctricos se pueden producir en la microrred.

En la presente tesis se presenta el diseño, desarrollo e implementación de infraestructuras de comunicación distribuidas para la gestión, monitorización y control de microrredes que permitan administrar la potencia y energía eficientemente mediante comunicaciones síncronas y asíncronas. Además, este estudio describe las principales características de la Internet de la Energía, los principios en los que se basa, los elementos y tecnologías disponibles para lograr la comunicación entre los recursos distribuidos desplegados en la microrred y establece las principales diferencias de IoE con respecto a los sistemas tradicionales de monitoreo y gestión. Con toda esta información, se describe una propuesta de arquitectura de la Internet de la Energía aplicada a las microrredes y un prototipo de monitoreo y gestión.

Se han realizado ensayos experimentales para validar los estudios y propuestas realizadas. Para ello se ha desplegado una red Ethernet en la microrred experimental del Grupo de Sistemas Electrónicos Industriales (GSEI) y se ha dotado a cada recurso energético distribuido de capacidades de comunicación e inteligencia a través del acoplamiento de sistemas de placa única BeagleBone Black donde poder instaurar el software desarrollado. Los resultados han evidenciado que las arquitecturas de comunicación distribuida propuestas permiten comunicaciones robustas, eficientes, escalables y flexibles en el ámbito de las microrredes a la vez que se cumplen con los requerimientos técnicos demandados por éstas.

ABSTRACT

Smart microgrids are presented as a solution to integrate renewable energies as well as to improve the efficiency of the network through the incorporation of Information and Communication Technologies (ICT). However, the high penetration of distributed energy resources (DER) in microgrids requires several technical improvements on communication systems that are traditionally characterized by centralized schemes, where a central controller communicates with all distributed energy resources and makes decisions, towards decentralized schemes where each distributed energy resource has communication and decision capacities locally.

The main objective of decentralized communication strategies is provide to the energy system with better scalability, reliability, robustness, and flexibility that centralized systems do. Moreover, microgrids with decentralized schemes represent a great opportunity for the future Internet of Energy (IoE) due to each distributed energy resource could connect to the cloud and send and receive data in real time anywhere and anytime.

One of the major issues about the ICT integration on microgrids is to guarantee the connectivity among DERs at the same time that technical requirements are met. Different microgrid standards give specifications for these requirements and highlight the need to accomplish with quality of service parameters like bandwidth, delays, throughput, among others. The communication infrastructure in the microgrid must satisfy these timing requirements, because a low bandwidth can lead to bottlenecks, loss of data packets and distortion. Besides, if the communication delay exceeds the required time, the information does not fulfill its purpose and, in the worst case, electric damage in the microgrid could happen.

In this Ph.D. thesis the design, development and implementation of synchronous and asynchronous distributed communications infrastructures for the efficient microgrid monitoring and control are studied. In addition this study describe the main IoE characteristics, its foundation principles, available elements and technologies deployed into microgrid and the main differences between IoE and tradition systems are provided. Regarding these information, a proposal of architecture of the Internet of energy applied to the microgrid is described.

Experimental tests have been carried out in order to validate the theoretical studies and proposals presented in this thesis. It has been deployed an Ethernet network in the experimental GSEI microgrid. In addition, communications and intelligent capacities have been added to each distributed energy resource through the BeagleBone Black single board computers where the developed software has been deployed. The results showed that the proposed distributed communications architectures allow robust, efficient, scalable and flexible communications in the microgrids field at the same time that quality of service requirements are accomplished.

RESUM

Les micro-xarxes intel·ligents es presenten com una solució per integrar energies renovables així com per millorar l'eficiència de la xarxa mitjançant la incorporació de les Tecnologies de la Informació i la Comunicació (TIC). No obstant, l'alta penetració del recursos energètics distribuïts (RED) en les micro-xarxes requereix d'una sèrie de canvis tècnics en els sistemes de comunicació caracteritzats tradicionalment per esquemes centralitzats, el quals un controlador central es comunica amb tots el recursos energètics distribuïts i pren decisions, cap a esquemes descentralitzats on cada recurs energètic distribuït té capacitats de comunicació i decisió localment.

En aquest sentit, l'objectiu global de les estratègies de comunicació descentralitzades es dotar al sistema energètic de major escalabilitat, fiabilitat, robustesa i flexibilitat que els que presenten els sistemes centralitzats. A més, les micro-xarxes amb esquemes descentralitzats presenten una gran oportunitat per l'adveniment de la futura internet de la energia, ja que cada recurs energètic distribuït desplegat en la micro-xarxa es susceptible de connectar-se al núvol i enviar i rebre dades cap a la xarxa en temps real, en qualsevol lloc i moment.

Un dels punts crítics derivats de la incorporació de les TIC en les micro-xarxes de gestió distribuïda es garantir la connectivitat entre el recursos energètics distribuïts al temps que es satisfacen els requeriments tècnics de aquests sistemes energètics. Els diferents estàndards i normes establides per al desplegament de micro-xarxes destaquen la necessitat de complir amb alguns paràmetres de qualitat de servici com amplada de banda, latències i rendiment, entre d'altres, ja que una amplada de banda baixa resulta colls d'ampolla, pèrdues de paquets i distorsió. D'una altra banda, si la comunicació no presenta una taxa positiva de mitjana de èxit o sofreix retards o supera el temps requerit, la informació no acompleix la seua comesa i en el pitjor dels casos, danys elèctrics poden ocórrer en la micro-xarxa.

En la present tesi se presenta el disseny, desenvolupament i implementació d'infraestructures de comunicació distribuïdes per la gestió, monitorització i control de micro-xarxes que permeten administrar la potencia i energia eficientment mitjançant comunicacions síncrones i asíncrones. A més, aquest estudi es descriu les principals característiques de la internet de la energia, els principis en els quals es basa, elements i tecnologies disponibles per acomplir la comunicació entre els recursos energètics distribuïts desplegats en la micro-xarxa i estableix les principals diferencies de la internet de la energia respecte del sistemes tradicionals de monitorització i gestió. Amb aquesta informació, es descriu una proposta d’arquitectura de la internet de la energia aplicada a les micro-xarxes.

S’han realitzat assajos experimentals per validar els estudis i les propostes realitzades. Per a això, s’ha desplegat una xarxa d’ ethernet en la micro-xarxa experimental del grup de sistemes industrials i s’ha dotat a cada recurs energètic distribuït de capacitats de comunicació i intel·ligència mitjançant l’acoblament de sistemes de placa única BeagleBone Black on s’ha instaurat el software desenvolupat. Els resultats han evidenciat que les arquitectures de comunicació distribuïdes proposades permeten comunicacions robustes, escalables i flexibles en l’àmbit de les micro-xarxes al temps que es acompleixen els requeriments tècnics demandats per estes.

TABLA DE CONTENIDOS

0

INTRODUCCIÓN

Este capítulo introduce los antecedentes y los objetivos principales de la tesis, presenta la estructura del documento así como las principales publicaciones derivadas durante el desarrollo de la tesis.

Contenidos

0.1 Motivación y Objetivos

Las redes eléctricas son las encargadas de transportar y distribuir la electricidad generada en las centrales (ya sean las tradicionales nucleares, hidráulicas o de carbón) hasta los puntos de consumo final. La estructura básica de la red eléctrica actual se ha mantenido sin cambios, vertical en su operación (generación-transmisión-distribución) y con flujos de energía unidireccionales [40]. La demanda eléctrica mundial en el dominio de usuario va en aumento y de seguir así, se prevé un aumento de alrededor un 40% en el consumo final hasta el 2040 (Figura 0.1). Sin embargo, un crecimiento global del consumo conlleva una mayor necesidad de generación de electricidad, que en la mayoría de los casos es obtenida a partir de combustibles fósiles, que son los responsables de la emisión a la atmosfera de gases nocivos para el medio ambiente.

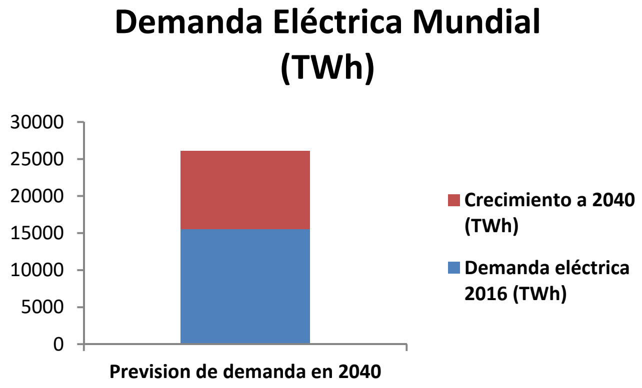

Figura 0.1. Demanda Eléctrica Mundial Actual y Previsiones a 2040. (Fuente: International Energy Agency. World Energy Outlook, 2017)

La escala de las futuras necesidades de electricidad y el desafío de descarbonizar el suministro de energía hacen necesario la búsqueda de fuentes energéticas alternativas, más limpias, que permitan, tanto la sustitución de las energías convencionales, manteniendo la calidad y fiabilidad del suministro de la actual red eléctrica, como la mejora de la eficiencia global de los sistemas actuales, ya que en el sistema eléctrico actual, la energía solamente fluye en una dirección y los problemas de almacenamiento de energía hacen necesaria una regulación constante entre la generación y el consumo, complicando el funcionamiento del mismo. Con objeto de dar solución a los retos presentados, surge un nuevo paradigma en el sistema eléctrico: Las Microrredes. Las microrredes son redes de distribución de bajo voltaje (ej. pequeña área urbana), pensadas para permitir el despliegue de generación distribuida (GD). La generación distribuida consiste en la generación de energía eléctrica por medio de pequeñas fuentes de generación de energía (micro generación) próximas al lugar de consumo. Mediante la generación distribuida se facilita la explotación de los recursos renovables (sol, viento, biocombustibles, entre otros) que supone beneficios como una reducción en cuanto a pérdidas en la distribución de la energía, reducción de los costes de suministro eléctrico al permitir el autoconsumo, una reducción de las emisiones de CO2 y un menor impacto paisajístico y ambiental. Es por ello que las fuentes de generación distribuida se establecen como una parte fundamental de las microrredes inteligentes o Smart Microgrids. Además de las fuentes de generación distribuida, las microrredes están compuestas por sistemas de almacenamiento de energía eléctrica (ESS), cargas controladas, y otros elementos incipientes como los vehículos eléctricos. Cada uno de estos elementos de la red es denominado recurso energético distribuido (RED). Las microrredes se integran con los sistemas clásicos de generación centralizados y por tanto pueden operar conectadas a la red de distribución principal (modo conectado), a través del punto de acoplamiento común (PAC), siendo capaces también de operar de forma autónoma (modo isla) en el caso de que se produzcan perturbaciones eléctricas o haya un corte de energía en la red de distribución de energía eléctrica [2].

La efectiva integración de las microrredes a la red eléctrica implica una transformación de la red, donde las Tecnologías de Información y Telecomunicación (TICs) formarán ahora el sistema nervioso del nuevo sistema eléctrico. En términos TIC, la futura microrred se enfrenta a requisitos de comunicación más exigentes y rigurosos que cualquier otra de red de comunicación, ya que debe ser capaz de coordinar gran cantidad de dispositivos a la vez que garantiza una conectividad completa, cumplir con las métricas de rendimiento para la integración de REDs en la red eléctrica y proporcionar una operación y gestión de los recursos en tiempo real y óptima para evitar posibles daños en la misma. La falta de estándares y la escasa información disponible sobre qué tecnologías de comunicación son las más adecuadas para este tipo de despliegues hace que este campo sea un tema abierto de investigación. Es por ello que, el objetivo principal de esta tesis y que resume el alcance de la misma consiste en el diseño y desarrollo de una infraestructura de comunicación, sus protocolos y arquitecturas de comunicación asociadas, para microrredes inteligentes residenciales que permita implementar, de manera segura y eficiente, los niveles de control de orden jerárquico más elevado para la optimización de los flujos de potencia dentro de la propia microrred, así como su posible interacción con el operador eléctrico, que proporciona el punto de conexión a la red o, en su caso, con el operador de otras microrredes cercanas con las que pueda estar interconectado. Además, la infraestructura de comunicación propuesta debe ser adaptable para la habilitación de la nueva generación de redes como la Internet de la Energía (Internet of Energy, IoE) con el fin de dar soporte a la futura gestión inteligente de nuevas aplicaciones de microrredes.

El motivo principal para la investigación sobre infraestructuras de comunicación para una microrred es que éstas son el punto clave para integrar los REDs, controlarlos y coordinarlos. Tradicionalmente, las tareas de control de los REDs en una microrred se llevan a cabo por medio de una estructura centralizada, controlador central de microrred (CCM), encargado tanto de la toma de decisiones como de proporcionar las comunicaciones entre todos los recursos de las microrred. Sin embargo, la penetración de recursos energéticos distribuidos a gran escala, hace que esta estructura de control no sea la adecuada ya que tiene dificultades para administrar en tiempo real una amplia gama de dispositivos [3,4] debido a que este tipo de arquitecturas no son escalables, no son confiables, una falla en el punto de control centralizado podría provocar varias fallas o incluso el apagado de todo el sistema, y no pueden manejar una red de nodos dinámica, ya que no soporta que los dispositivos puedan entrar y salir de la red formando diferentes topologías. Con el aumento de recursos energéticos distribuidos desplegados en las microrredes, el objetivo es que todos los objetos se controlen y monitoreen de manera eficiente sin perjuicio del tamaño de la red, dinamismo y topología. Por tanto, para que sea posible la óptima operación de la futura microrred con recursos energéticos distribuidos es necesario construir una arquitectura de comunicación descentralizada donde cada dispositivo energético opere de manera independiente. El diseño y desarrollo de una red de comunicación descentralizada es crucial para aumentar la autosuficiencia, capacidad de recuperación dinamismo, flexibilidad y escalabilidad de éstas. De hecho, las implicaciones de gran alcance y la complejidad de tales sistemas siguen siendo un gran desafío.

Otro de los motivos principales por el cual se ha focalizado el estudio en infraestructuras de comunicación es debido a que el desarrollo de la capa

TIC también debe tener en cuenta requisitos de internet de las cosas o Internet of Things (IoT). La computación en la nube se está volviendo omnipresente en la actualidad. Con el rápido desarrollo de las tecnologías de la información e internet, la microrred inteligente del futuro será un recurso de distribución bajo la acción combinada de Internet y la computación en la nube, concepto que muchos artículos científicos ya la están denominando como la internet de la energía o Internet of Energy (IoE) [5,6,7]. La internet de la energía proporciona un concepto innovador para mejorar la operación de la red eléctrica. La característica más buscada de IoE es que las unidades de energía se puedan acceder y gestionar de manera ubicua, es decir, cuando y donde se requiera de manera segura. Esto requiere monitoreo y gestión inteligente de la operación de la microrred en tiempo real. La IoE del futuro hará posible que los futuros sistemas de energía distribuida sean autogestionados, autosostenibles, y robustos a la vez que permitan la reorganización dinámica y la coordinación de servicios de mercado. Por tanto, la infraestructura de comunicaciones basada en Internet estará estrechamente unida al dominio de energía. Actualmente las arquitecturas físicas de capa TIC no responden a las características demandadas por las microrredes (escalabilidad, heterogeneidad, interoperabilidad y calidad de servicio (QoS)) junto con la perspectiva de IoE. Por tanto, para abordar los desafíos que emanan del advenimiento de IoE y la computación en la nube se requieren nuevas investigaciones.

En la presente tesis doctoral, con el fin de abordar el objetivo principal, el desarrollo de una infraestructura de comunicación totalmente descentralizada y habilitadora de IoE, se han definido los siguientes objetivos específicos:

- *Estudio y evaluación de la viabilidad de posibles tecnologías y protocolos de comunicación adecuadas para el entorno de microrredes residenciales. Identificación y caracterización de los requisitos que deben cumplir las comunicaciones para permitir esquemas de control óptimos.*

La evolución hacia sistemas descentralizados en escenarios como microrredes hace necesario el estudio de tecnologías y protocolos de comunicaciones, definiendo y seleccionando indicadores de mérito, a fin de determinar cuál o cuáles de ellos estarían mejor adaptados a las futuras necesidades de las microrredes residenciales. Además, la descentralización de la red complica el cumplimiento de requerimientos de red críticos de la microrred como el tiempo de retardo y la pérdida de datos, cuyo desempeño producen un gran impacto en los esquemas de control de la microrred, o el tráfico de datos y ancho de banda, que permiten evaluar el rendimiento de la red en términos de escalabilidad [8], y confiabilidad [9,10] al momento en que se enlazan nuevos dispositivos a la red. Esto es debido a que, generalmente, las redes descentralizadas a gran escala han sido desarrolladas para compartición de archivos o ciclos de procesador donde los requisitos de rendimiento son menos críticos. Además, cuando nos movemos hacia sistemas distribuidos altamente heterogéneos y dinámicos, los desafíos que IoE introduce al desarrollo de la capa de comunicación son significativos, derivado de la gran cantidad de objetos conectados, el volumen de datos producido, los patrones de comunicación requeridos, y la calidad de servicio a ofrecer. Todos estos retos y problemáticas son abordados en esta tesis.

- *Diseño y desarrollo de una arquitectura funcional y lógica para abordar la interconexión de los recursos energéticos distribuidos con los sistemas de comunicación que tenga en cuenta las perspectivas técnicas y de operación de las microrredes.*

La arquitectura de comunicación basada en redes Peer-to-Peer (P2P) es la que se ha empleado en este trabajo, siguiendo la tendencia en la mayoría de publicaciones existentes para el desarrollo de sistemas altamente distribuidos. Tradicionalmente las redes distribuidas de comunicación se han desarrollado en base al modelo Cliente-Servidor. En este modelo los nodos servidor son los encargados de proporcionar el servicio, es decir, otorgar capacidades de sistema distribuido, sin embargo, no son capaces de tomar cualquier iniciativa, ya que son reactivos y tienen que esperar a ser invocados por el cliente. Por el contrario, los nodos cliente concentran la iniciativa del sistema, acceden y utilizan los servicios. Así los clientes se comunican con los servidores pero no pueden comunicarse con otros clientes. Por otra parte, el servidor no puede comunicarse con los clientes hasta que los clientes hayan tomado la iniciativa y deciden comenzar una sesión de comunicación con el servidor. De este modo los sistemas basados en el modelo cliente-servidor lleva a ineficiencias del servicio, cuellos de botella o infrautilización de los recursos de la red. En las microrredes se requiere que los recursos energéticos distribuidos sean nodos tanto activos como reactivos, es decir, que sean capaces de comunicarse tanto para notificar eventos, conexiones y desconexiones a la red, alarmas, informar sobre parámetros críticos de la red, etc., así como para responder a señales de control, gestión y monitorización enviadas por el sistema. El modelo de comunicaciones P2P es un modelo de comunicación donde todos los nodos poseen los mismos roles, es decir, se trata de nodos pares que pueden actuar en el sistema tanto como clientes como servidores (en la terminología se le denomina servent palabra que deriva de la conjunción de los términos server-client). Este concepto se basa en la concepción de una red donde todos los nodos tienen capacidades y responsabilidades equivalentes (simétricas) lo que difiere del paradigma cliente-servidor tradicional. En el modelo P2P se crean redes virtuales a nivel de aplicación sobre la infraestructura de Internet. Los nodos en la red son llamados pares o peers, y cada nodo puede iniciar la comunicación, ser objeto o sujeto de ésta, es decir, ser proactivo. Sin embargo, los sistemas descentralizados P2P han sido principalmente desarrollados para aplicaciones donde los requerimientos de calidad de servicio, Quality of Service (QoS), no son tan críticos como en microrredes. Es por ello que uno de los objetivos específicos de la tesis es la identificación y caracterización de los requisitos que deben cumplir las comunicaciones P2P para permitir esquemas de control en microrredes. Posteriormente a esta caracterización, se diseña y desarrolla un protocolo P2P no solo que permita la transmisión de información entre REDs para producir un óptimo control de la red sino que cumpla con los requerimientos de calidad de servicio que impone las microrredes.

- *Diseño y desarrollo de un modelo de interoperabilidad middleware con el fin de dotar a los recursos energéticos distribuidos con inteligencia para percibir el mundo, tomar decisiones y actuar sobre el entorno de manera eficiente.*

Una vez desarrollada la arquitectura de comunicación que permitirá la comunicación entre recursos energéticos distribuidos es necesario dotar a los nodos de inteligencia para proveer de los servicios y aplicaciones demandados por las microrredes. Para ello es necesario el desarrollo de un software intermedio (“middleware”) que permita la interoperabilidad en tiempo real entre las diferentes unidades RED y los dote de razonamiento inteligente. El middleware es una capa de software adicional ubicada entre la red y las aplicaciones, que ofrece un espacio común para el intercambio de mensajes entre los distintos nodos del sistema distribuido y permite la inclusión de herramientas de análisis y gestión de datos para el efectivo control y monitorización de la microrred. El intercambio de mensajes mediante la capa middleware se consigue principalmente haciendo uso de paradigmas de comunicación solicitud-respuesta (Request-Response, RR) o publicación-suscripción (Publisher-Subscriber, PubSub). Por un lado, los esquemas de comunicación RR siguen un modelo síncrono basado en una interacción uno a uno, donde un emisor genera un mensaje de petición que el receptor recoge, procesa y devuelve el resultado. En este esquema, el emisor queda bloqueado hasta obtener la respuesta. Por otro lado, los esquemas de comunicación PubSub siguen un modelo asíncrono, basado en interacciones de uno a muchos, donde los proveedores de información (editores) publican eventos al sistema que los consumidores de información (suscriptores) se suscriben si están interesados en ellos. Las plataformas middleware convencionales se desarrollan soportando uno de los dos paradigmas de comunicación. Sin embargo, las soluciones middleware para microrredes deben adoptar y hacer uso simultaneo de ambos esquemas de comunicación, ya que, por ejemplo, en una microrred la información de control entre REDs requiere un sistema de comunicación basado en solicitud-respuesta, debido a que el control necesita una respuesta oportuna para llevar a cabo acciones inmediatas de manera que no se produzcan retardos en la comunicación que puedan dañar el sistema. Por otro lado, para tareas de monitorización, el paradigma de publicación-suscripción es necesario. Por ejemplo, si una carga (luz) cambia de encendido a apagado debe ser notificado como evento a los demás REDs de la red. Por tanto, el diseño y desarrollo de un middleware capaz de soportar ambos esquemas de comunicación junto con la implementación de las herramientas de gestión adecuadas que permitan el control y monitorización inteligente y eficiente de la microrred, es otro de los objetivos específicos del presente trabajo. Para ello, en esta tesis, se diseñan y desarrollan ambas tipologías de middleware de manera independiente. De esta forma, se realizará el análisis y evaluación del impacto que pueden tener ambos paradigmas de comunicación en el rendimiento de los esquemas de control de las microrredes antes de producir la integración para su uso simultáneo. Esto asegurará que se cumplan los requerimientos de calidad de servicio demandado por las diferentes aplicaciones de microrred siguiendo los estándares de calidad para microrredes como IEC61850, IEEE1646, etc.

- *Diseño y desarrollo de una plataforma habilitadora de IoE para la gestión de microrredes.*

El Internet de la energía o IoE es un paradigma emergente que aplica las tecnologías de internet de las cosas, Internet of Things (IoT), en los sistemas de control de energía. Hoy en día, IoE presenta nuevos desafíos significativos para el desarrollo de una infraestructura de comunicación óptima para microrredes inteligentes ya que debe proporcionar una alta disponibilidad para sistemas a gran escala que admitan comunicaciones P2P, plataformas de comunicaciones flexibles que permitan los paradigmas de comunicaciones RR y PubSub simultáneamente, atributos de rendimiento de calidad y enrutamiento eficiente y programación de alto nivel para integrar el software en los DER para conformar sistemas embebidos de computación ubicua a tiempo real. A fin de abordar estos retos, en esta tesis, se diseña y desarrolla una plataforma de comunicación que integra todas estas características para la habilitación de la futura IoE.

- *Validación en una microrred experimental de la infraestructura de comunicación desarrollada para la futura microrred inteligente.*

La infraestructura de comunicación propuesta se ha implementado en una microrred hibrida experimental para su evaluación en términos de calidad de servicio, uso de recursos computacionales y capacidad para la gestión y monitorización de la microrred. Primeramente, para la evaluación de la calidad de servicio de la red se medirán parámetros como ancho de banda, nivel de retardo o latencia, tráfico, pérdida de paquetes, etc. y se analizará si cumple con los estándares de microrredes establecidos. Seguidamente, un dispositivo IoE es un dispositivo restringido con recursos limitados de computación y almacenamiento, por ello se evaluará el uso de CPU y de memoria que hace el software de comunicación desarrollado con el objetivo de analizar si es óptimo para ser empotrado en sistemas de placa reducida o single board computers (SBC) donde es necesario bajos consumos de recursos computacionales debido a su reducido tamaño. Finalmente, para evaluar la capacidad de gestión y monitorización de la plataforma se ha desarrollado un algoritmo que permite la gestión de una microrred residencial teniendo en cuenta el perfil fotovoltaico y las tarifas eléctricas. Se analizará como mediante el envío y procesamiento de consignas de control y monitorización la microrred es capaz de gestionarse de manera inteligente.

0.2 Estructura de la Tesis

Esta tesis se presenta como compendio de cuatro publicaciones [1–4]. Las publicaciones se incluyen íntegramente en los Cap. 1-4. Dichas publicaciones concentran la parte más significativa de los estudios teórico-prácticos llevados a cabo durante la realización de la misma. Por otro lado, durante la elaboración de esta tesis se han realizado otras publicaciones no incluidas en este compendio.

La memoria de la tesis se divide en 3 grandes partes:

- Introducción (Cap. 0).
- Publicaciones (Cap. 1, 2, 3 y 4).
- Discusión de Resultados (Cap. 5) y, Conclusiones (Cap.6)

La primera parte de la tesis consiste en la introducción (Cap. 0). En esta parte de la tesis se introducen los aspectos fundamentales de la tesis, incluyendo las características principales de los sistemas de generación distribuida, las necesidades de actualizar la capa TIC de las microrredes con el fin de integrar eficientemente los recursos energéticos distribuidos, y los retos que presenta habilitar una internet de la energía. Además, las publicaciones obtenidas durante este trabajo se presentan.

La segunda parte de la tesis constituye el núcleo central de este trabajo, incluyendo los capítulos 1, 2, 3 y 4. En estos capítulos se presentan los artículos publicados en diferentes revistas donde se aborda la revisión de la literatura relacionada y se estudian las estrategias y el marco a considerar al diseñar soluciones de comunicaciones para el futuro manejo de las microrredes inteligentes.

Por último, la tercera parte de la tesis está dedicada a la discusión de los resultados obtenidos en la tesis (Cap. 5) y a las conclusiones y trabajos futuros derivados de estos trabajos (Cap. 6). El capítulo de discusión de los resultados describe cual ha sido la motivación, metodología y contribución para cada uno de los artículos publicados y discutir críticamente las ventajas, inconvenientes y aplicación de cada una de las estrategias abordadas en ellos.

0.3 Publicaciones

Esta sección presenta las publicaciones obtenidas durante el desarrollo de la tesis. Las cuatro primeras (i)-(iv) corresponden a los capítulos I, II, III y IV presentados en esta tesis como compendio de publicaciones.

(i) S. Marzal, R. Salas, R. González-Medina, G.Garcerá, E. Figueres, “Current challenges and future trends in the field of communication architectures for microgrids,” Renew. Sust. Energ. Rev., Vol. 82, no. 3, pp. 3610-3622, 2018.

(ii) S. Marzal, R. González-Medina, R. Salas-Puente, E. Figueres, G. Garcerá, "A Novel Locality Algorithm and Peer-to-Peer Communication Infrastructure for Optimizing Network Performance in Smart Microgrids," Energies, Vol. 10, no. 9, pp. 1275, 2017.

(iii) S. Marzal, R. Salas-Puente, R. González-Medina, G. Garcerá and E. Figueres, "Efficient Event Notification Middleware for Smart Microgrids over P2P Networks," in IEEE Transactions on Smart Grid.2018.

(iv) S. Marzal, R. González-Medina, R. Salas-Puente, G. Garcerá and E. Figueres, “ An Embedded Internet of Energy Communication Platform for the Future Smart Microgrids Management,” IEEE Internet of Things Journal, 2019.

(v) S. Marzal, E. Figueres, G. Garcerá y R. Salas, “Nodos P2P para el Control y Monitorización de Microrredes Inteligentes: Diseño, Desarrollo e Implementación”, Congreso Anual de Automática, electrónica Industrial e Instrumentación (SAAEI 2016).

(vi) S. Marzal, R Salas-Puente, R. Gonzalez-Medina, E. Figueres, G. Garcerá, “A New Content Location and Data Retrieval Algorithm for Peer to Peer in Smart Microgrids,” 17th Edition of the Mathematical Modelling Conference Series at the Institute for Multidisciplinary Mathematics.

(vii) S. Marzal, R Salas-Puente, R. González-Medina, E. Figueres, G. Garcerá, “A Peer-to-Peer (P2P) Overlay Communication Network Infrastructure for Smart Microgrids,” Congreso Anual de Automática, electrónica Industrial e Instrumentación (SAAEI 2017).

(viii) S. Marzal, R Salas-Puente, R. Gonzalez-Medina, E. Figueres, G. Garcerá, “Peer-to-Peer Decentralized Control Structure for Real Time Monitoring and Control of Microgrid,”, The 26th IEEE International Symposium on Industrial Electronics, 19-21 June 2017 Edinburgh, Scotland, UK. (ISIE2017).

(ix) I. Patrao, R. González-Medina, S. Marzal, G. Garcerá, E. Figueres, “Synchronization of power inverters in islanded microgrids using an FM-modulated signal,” IEEE Transactions on Smart Grid, 8(1), 503-510.2017.

(x) R. Salas-Puente, S. Marzal, R. González-Medina, E. Figueres, G. Garcerá, "Experimental Study of a Centralized Control Strategy of a DC Microgrid Working in Grid Connected Mode," Energies, vol. 10, no. 10, pp. 1627, 2017.

(xi) R. Salas-Puente, S. Marzal, R. González-Medina, E. Figueres, G. Garcerá, "Power Management of the DC Bus Connected Converters in a Hybrid AC/DC Microgrid Tied to the Main Grid." Energies , vol. 11, no. 4,pp. 794, 2018

(xii) R. Salas-Puente, S. Marzal, R. González-Medina, E. Figueres, G. Garcerá, "Practical Analysis and Design of a Battery Management System for a Grid-Connected DC Microgrid for the Reduction of the Tariff Cost and Battery Life Maximization." Energies vol. 11, no. 7,pp. 1889,2018.

(xiii) R. Salas-Puente, S. Marzal, R. González-Medina, E. Figueres, G. Garcerá, “An algorithm for the efficient management of the power converters connected to the DC bus of a hybrid microgrid operating in grid-connection mode”. Electric Power Components and Systems, 0(0), pp. 1–16, 2018.

(xiv) R. Salas-Puente, S. Marzal, R. González-Medina, E. Figueres and G. Garcerá, "Efficient management strategy of the power converters connected to the DC bus in a hybrid microgrid of Distributed Generation," 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe), Warsaw, 2017, pp. P.1-P.10.

En los siguientes capítulos se presentan estas cuatro primeras publicaciones. El orden de presentación de las publicaciones no es cronológico en base a la fecha de publicación sino conceptual según los objetivos perseguidos en la presente tesis. Los factores de impacto de las revistas donde se ha publicado la investigación pueden verse en la Tabla 0.1.

Tabla 0.1: Índices de impacto JCR.

Fuente: Web of Science

Revista	**2015**	**2016**	**2017**
Renew. Sust. Energ. Rev.	6.798 (Q1)	8.050 (Q1)	9.184 (Q1)
Energies	2.077 (Q2)	2.262 (Q2)	2.676 (Q2)
IEEE Trans. Smart Grids	3.190 (Q1)	6.945 (Q1)	7.365 (Q1)
IEEE Internet Things Journal	-	7.596 (Q1)	5.874 (Q1)

La primera publicación (i) aborda el estado del arte sobre las tecnologías de la comunicación e información utilizadas actualmente en los sistemas de microrredes. Se proporciona un estudio sobre los desafíos futuros para el despliegue y desarrollo de las microrredes con gestión y control distribuido. Una de las formas de comunicación y control de una microrred distribuida se modela en la literatura a través de sistemas multiagentes (multi-agent systems, MAS). En esta publicación, se subrayan las limitaciones de esta tecnología y se aboga por el uso de las comunicaciones P2P como una solución emergente para hacer frente a las necesidades de la futura microrred inteligente.

La segunda publicación (ii) presenta el diseño y desarrollo de una infraestructura de comunicación utilizando el paradigma de comunicación P2P para la implementación de servicios distribuidos en microrredes. Para adecuar los parámetros de calidad de servicio demandados por las microrredes, un algoritmo de localidad P2P se desarrolla en este trabajo. Los algoritmos de localidad reducen el tráfico de datos a través de la utilización de una ruta optimizada para la transmisión de datos mediante la creación de “clusters” (grupos de nodos) en base a criterios como la distancia, similitud entre nodos u otros elementos de asociación. Además, en este trabajo, se desarrolla un protocolo específico de monitoreo y control de microrredes utilizando el esquema solicitud-respuesta. Resultados experimentales de la infraestructura de comunicación propuesta se presentan.

La tercera publicación (iii) propone un middleware de comunicación distribuido basado en el esquema publicación-suscripción para el control y monitorización de microrredes, ya que permiten desacoplar el tiempo y espacio entre emisores y receptores, lo que resulta más eficiente para los servicios como la notificación de eventos en microrredes. Sin embargo, los esquemas pub-sub utilizan protocolos de enrutamiento multicast. Los protocolos multicast construyen árboles de nodos para el enrutamiento y transmisión de los datos que generan mucho tráfico en la red de comunicaciones, retransmisiones de información innecesaria y retardos importantes, lo que lleva a una sobrecarga del canal de comunicación. Esto se traduce en una utilización ineficiente y un rápido agotamiento de los recursos de red, que conduce a operaciones no fiables e inestabilidad en la operación de la microrred. En este trabajo, un nuevo middleware de publicación-suscripción de notificación de eventos sobre redes P2P es propuesto. En él, se implementa un nuevo algoritmo de enrutamiento basado en la curva de relleno de espacio de Hilbert (Hilbert Space Filling Curve, Hilbert SFC). Los resultados experimentales demuestran que el middleware propuesto mejora significativamente la eficiencia del sistema, rendimiento de la red y uso de los recursos computacionales.

Por último, la cuarta publicación (iv) propone el uso de la Web, Internet de la Energía, para administración de la información y computación de las microrredes. Para ello, este documento diseña y desarrolla una plataforma IoE para la gestión de la futura microrred inteligente. De esta forma, se define una estrategia para la integración de los diferentes esquemas de comunicación, RR y Pub-Sub; un algoritmo de gestión para una microrred residencial; sistemas de almacenamiento de datos e información y métodos de programación avanzado para el desarrollo de software para sistemas empotrados. Posteriormente, la plataforma se ha desplegado en una microrred experimental para la evaluación del desempeño. Los resultados muestran que la plataforma IoE propuesta cumple con los requisitos de microrred en términos de comunicación y operación del sistema.

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1

PUBLICACIÓN I

CURRENT CHALLENGES AND FUTURE TRENDS IN THE FIELD OF COMMUNICATION ARCHITECTURES FOR MICROGRIDS

Marzal, S., Salas-Puente, R., González-Medina, R., Garcerá, G., and Figueres, E. “Current challenges and future trends in the field of communication architectures for microgrids,” Renew. Sustain. Energy Rev., vol.81, no.3, pp.3610-3622, Feb. 2018.

Contenidos

Current Challenges and Future Trends in the Field of Communication Architectures for Microgrids

Abstract— **The concept of microgrid has emerged as a feasible answer to cope with the increasing number of distributed renewable energy sources which are being introduced into the electrical grid. The microgrid communication network should guarantee a complete and bidirectional connectivity among the microgrid resources, a high reliability and a feasible interoperability. This is in a contrast to the current electrical grid structure which is characterized by the lack of connectivity, being a centralized-unidirectional system. In this paper a review of the microgrids information and communication technologies (ICT) is shown. In addition, a guideline for the transition from the current communication systems to the future generation of microgrid communications is provided. This paper contains a systematic review of the most suitable communication network topologies, technologies and protocols for smart microgrids. It is concluded that a new generation of peer-to-peer communication systems is required towards a dynamic smart microgrid. Potential future research about communications of the next microgrid generation is also identified.**

Index Terms—**Microgrid, Communication Protocols, Multi-agent systems, Peer-to-Peer, Distributed architectures**

1.1. INTRODUCTION

The basic structure of the electrical grid has almost remained unchanged up to now. For decades the grid has delivered energy from remote power plants towards consumer loads in a unidirectional and centralized manner [1]. Currently, the generation, distribution and consumption of electricity is evolving at an impressive speed, driven by both the high penetration of distributed energy resources (DERs) that are being incorporated to the grid and the advances in information and communication (ICT) technologies. In this context the microgrid concept has emerged. A microgrid forms an autonomous power system that needs a ubiquitous information layer for coordination, monitoring and control of all the distributed energy resources deployed in it. Nowadays, most microgrids still rely on legacy communication networks. However, microgrid energy systems are transitioning from centralized systems towards distributed energy systems with more demanding reliability, security, and performance requirements. Therefore, a flexible and adaptive communication network architecture is required. To make effective decisions, power designers will need a basic understanding of communication network technologies that should be implemented on microgrids. Consequently, a description of the past, current and future trends as well as the fundamentals about communications for deploying intelligent microgrids is included in this paper. The basics of today’s communications in microgrids are also described. Next, the main challenges in the communication requirements of intelligent microgrids are defined, leading to the proposal of a new generation of smart microgrids. The most suitable communication architecture (network topologies, communication protocols and technologies) for the deployment of this proposal is discussed. Next, a new generation of peer-to-peer (P2P) communication systems for the future microgrids is proposed. Finally, new research topics for the transition to future microgrids are shown.

1.2. TODAY’S MICROGRID STATUS

A Microgrid (MG) (Figure 1) is a low voltage distributed network of individual consumers within a building, campus, or community that are interconnected with, at least, one shared distributed generation source (DG). A microgrid consists of a variety of loads, micro sources (MS) and energy storages systems (SS), called distributed energy resources (DERs), that acts as a single controllable entity with respect to the main grid [2], [3], [4]. Microgrid operates mostly connected to the main distribution network but they can be automatically disconnected from the main grid at the point of common coupling (PCC) in case of faults to provide a minimum level of service during a utility grid power outage. They can be reconnected once the fault has disappeared [5], [6]. Microgrids must have their own control to ensure the correct operation and coordination of the different DERs. A Microgrid Controller (MGC) is usually needed to manage the operation within the microgrid, the energy flows and the interconnection with the main grid. In addition, all microgrid devices need to communicate with the MGC.

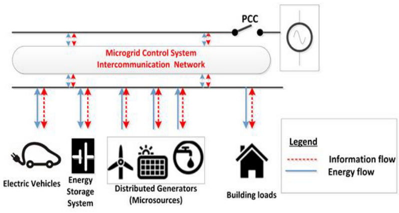


Fig.1. Simplified scheme of a microgrid with a Microgrid Controller

Traditionally, this control is carried out by means of a three level hierarchical scheme [7], [8]: (Figure 2): Distribution Management System or tertiary control (DMS), Microgrid Central Controller (MGCC) or secondary control and load control (LC) or primary control [5], [6], [9].

- Primary Control: This level of control operates in the time range of milliseconds to minutes, and reacts to the transient dynamics of the DER and the system to respond to any instantaneous deviation in the system’s voltage or frequency. This controller acts as local control for each DER unit and utilizes local measurements and responds to short-term events such as islanding detection, sudden real and reactive power mismatches, and power sharing.
- Secondary Control: This level of control operates in the time range of minutes to hours, and it

comprises the discrete dispatch of DER. This level is controlled by the MGCC. This controller is responsible for the optimal coordination and operation of the whole components connected in the same microgrid, assuring the overall maintenance of the grid parameters in both connected and island mode. The secondary control also incorporates control strategies and operations such as intentional islanding, resynchronization, and load shedding.

- Tertiary Control: This level of control operates in the time range of hours to days, and it involves the communication with the different microgrid central controllers (MGCCs), and management of the MG when it operates on the market. The main entities in this level are the Distribution Network Operator (DNO) and the Market Operator (MO) who are delegates of the main grid.

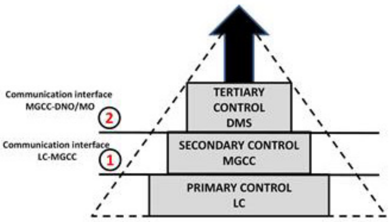


Fig.2.General Hierarchical Architecture of MG control. Communication interfaces for stablishing MG control.

Control strategies need communication networks or links between the different levels to achieve an optimal microgrid operation. Communication interfaces must be created to establish a bi-directional communication channels that allows information transfer between the different controllers [10] (Fig.2, ① and ②). Generally, data flows between nodes in both directions, i.e., each node are able of receiving and forwarding data over links with other nodes or endpoints. The nodes in microgrids are created by adding information and communication capabilities to the underlying distributed energy resource or component, giving rise to intelligent electronic devices (IEDs) [11]. In this way, the microgrid controller may communicate with IEDs and other components to provide them data or control commands.

For a successful information exchange between nodes within a microgrid system, predefined procedures or protocols for data transmission regulation are needed. A protocol suite consists of a layered architecture where each layer is assigned to a set of functions using one or more protocols [11]. Data communication networks commonly use multiple levels of protocols based on ISO-OSI (International Standards Organization/ Open Systems Interconnect reference) model [12] (seen Figure 3). This allows to convert the information in a form that can be transmitted. Thus, regarding communications, the effectiveness of the control and the communication microgrid infrastructure is linked with the microgrid control scheme and its communication architecture.

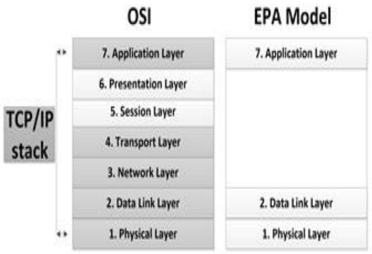


Fig.3. OSI Reference Model, EPA model and TCP/IP model

Today's microgrid installations use centralized architectures to implement the three level hierarchical scheme and achieve data transfers between entities. In these architectures power is delivered in a unidirectional way and consumers have a passive role characterized by non-controllable loads, lack of predictability and null contribution to the system management.

These centralized architectures where a central controller communicate with all microgrid resources and make decisions has been implemented, for many years, by Supervisory Control and Data Acquisition (SCADA) systems [13] which uses the Enhanced Performance Architecture (EPA) model [11] . EPA has three layers (1, 2 and 7) instead of the seven layers defined in the OSI model as depicted in Figure 3. This fact reduces the services offered by the EPA stack protocol. Otherwise, SCADA use direct communication links (i.e. no internet) [11] to send and receive commands and data through various protocols. Some of the most popular protocols in the electrical sector are MODBUS, PROFIBUS, CANBus or DNP3. All of them are generally based around Client-Server (Master-Slave) architectures with bus network topologies, [11], [14], [15].

Recently, there is growing a trend towards the use of new communication technologies based on internet or on Common Information Model (CIM). The Internet architecture is based on TCP/IP protocol. TCP/IP is an easy solution to the problem of achieving end-to-end communications [16]. TCP/IP protocol suite is used by Internet. The TCP/IP stack normally has four layers: Physical and Data Link layer (Link layer), Network, Transport and Application layers (Figure 3, TCP/IP stack). These protocols are now starting to be used in electrical control systems and it is evidenced by the evolution of the Industrial Protocols, that were previously cited, such as Modbus, DNP3 and Profibus towards Modbus/TCP, DNP3 over TCP and Profinet, respectively, for their integration on the traditional SCADA. These protocols exploit the benefits of TCP/IP to upgrade their capabilities. For instance, in the case of Modbus or Profibus over TCP/IP communication systems, they are reported undesirable events as incorrect address, packet failure, illegal function code received, etc. Besides the aforementioned properties, DNP3 over TCP/IP supports timestamps and data quality information that can be included in the messages [11]. However, despite these improvements, the centralized control based in client-server communication architectures cause inefficiencies in the communication microgrid system, provoked by several causes: On one hand, a failure in the centralized control point could lead on several faults or even shut down the entire system. On the other hand, the nodes (slaves) are not able to start a communication themselves with the master. In addition, there are difficulties to manage data in real time of a wide range of devices [17], [18]. As a result, these disadvantages can lead to provide poor services, bottlenecks or under-utilization of the network resources.

An alternative technology to be used in microgrids is Power Line Carrier (PLC). PLC technologies use the electric power lines as a medium that enable the bidirectional data exchange. It provides a vast coverage and in terms of infrastructure is the most cost-effective technology since the lines already exist. In recent years, microgrids activities have brought a lot of attention to PLC technologies. As an example, the microgrids installed in the University of Seville and NUAA in China, uses PLC as a communication medium for information management and transmitting data [19]. However, PLC technology has negative effects in the communication channel such as a noisy medium disturbed, distortion, frequency impedance alterations and the risk of signal attenuation [20].

The increasing introduction of distributed energy resources into the power grid changes the current scenario, because the incorporation of micro-generation allows bidirectional power flows and active consumers, i.e., the end users change their role of passive consumers to active prosumers. Consequently, immediate solutions about microgrid communication architectures that cope with these changes and enable high performance data delivery and real-time monitoring and control are needed, leading to reliable, resilient and sustainable microgrid control systems.

1.3. TOWARDS AN INTELLIGENT MICROGRIDS

It has been noted that communication system used in today's microgrid has important inefficiencies and it is also localized to support the integrated communications needed for the modern power grid (smart microgrid (SMG)). However, energy systems are increasingly distributed. The integration of DERs into the energy system cause many challenges into the communications field. To incorporate more renewable and alternative energy sources, the communication infrastructure must have the ability to easily handle an increasing amount of data traffic or services requests and must provide a real-time monitoring and control operation of all these nodes. Current serial communications deployed in SCADA systems refer to a set of legacy standards that are still used for low data rate applications and asynchronous bit transfer. Since microgrid operations need timely control actions, a Real-Time Measurement Parameters (RTMP) function is required [21]. To reach this goal, it´s mandatory to know which bandwidth and which latency (delay) can tolerate each microgrid application [22], [23], i.e., each microgrid function has its own latency and bandwidth requirement depending on the kind of system response it´s dealing with [12], [24], [25]. The IEC 61850 and IEEE 1646 standards [25], [26] give specifications for these requirements. The network performance requirements for each microgrid application have been summarized in Table I. Moreover, the expected communication delay of each kind of microgrid message was specified in [27], being summarized in Table II.

The communication infrastructure in the microgrid must satisfy these timing requirements, because a low bandwidth can lead to bottlenecks, loss of data packets and distortion. Besides, if the communication delay exceeds the required time, the information does not fulfill its purpose and, in the worst case, electric damage in the microgrid could happen [4]. In this regard, the underlying communication system needs to be designed with network performance requirements to meet the needs of time sensitive data streams, bandwidth and latency, among others. To satisfy this network performance requirements that smart microgrid traffic requires, Quality of Service (QoS) is needed. The Quality of Service concept is the network ability to provide priority treatment for communication packets of certain critical microgrid applications. QoS management is needed for distributed control and protection microgrid applications that have severe delay requirements and need to deliver information in an acceptable amount of time. For instance, the stability of the closed-loop while performing bilateral load following (with sampling rates typically in the range 100–1000 ms) is highly dependent upon the latency (delay), variability in latency (jitter), and packet losses that the control network induces [28]. Therefore, when networks exceed their capabilities to transfer, store and buffer data, packet loss and low delivery rates are experienced. As a result, when the network faces congestion due to dense data traffic, QoS allows a preferential delivery service for the most critical applications by ensuring sufficient bandwidth, latency and reducing data loss. QoS information is stored within the packet header in the form of a type of service (ToS) field to specify the class of service of each packet. Thus, based on the ToS byte, if there is a packet in a high priority queue, it´s served before the packets in low priority queues.

Besides, the increasing number of renewable energy sources and microgenerators as well as the integration of a large amount of DER units in the microgrid has an impact on the scalability of the communication system [8]. The main problem regarding the control of a wide number of DERs is that a failure of a device or a software error could bring down the entire system [29]. Furthermore, in networks with a high volume of devices is usual to add/remove devices to/from the network very frequently, therefore networks must be flexible enough, allowing the fluctuations of the number of devices and avoiding disturbances or instabilities. To cope with these potential failures, the system requires a certain level of redundancy, e.g., backup channels, software components and devices, etc. Critical functionalities in a smart microgrid demand more stringent availability requirements. It is worth pointing out that most network service providers (NSP) applications require less than 99.99% uptime, compared with 99.9999% for smart grids [20]. To achieve reliable and robust networks, the communication infrastructure must avoid link errors, routing problems, overloads, etc. Current SCADA systems cannot make these data available in a timely manner due to their limited bandwidth [30]. Thus, this capability requires the combination of advances in computational and analytical methodologies and self-healing protocols. In this context, Software Defined Networking (SDN) has emerged as a flexible, effective and reliable communication framework and as a power solution for the future communication network of the energy internet [31], [32]. This solution provides support for the dynamic, scalable computing and storage needs of complex digital networks by software and allows adaptive control and operations of networks in a cost-effective manner. These characteristics are favorable for developing hierarchical communication network architectures which allow to decouple control plane (which decides how to handle the traffic) from data plane (which forwards traffic). Moreover, SDN allows self-healing and self-organization [33] required features for the future smart microgrid developing.

TABLE I
MG APPLICATION AND NETWORK REQUIREMENT

Microgrid Messages	Bandwidth	Latency
Demand Response	14-100 Kbps	500 ms-several minutes
Distributed Energy Resources and Storage	9.6-56 Kbps	20 ms-15 s
Distributed Management	9.6-100 Kbps	100 ms-2s

TABLE II
MICROGRID MESSAGE TYPE DELAY REQUIREMENT FOR DIFFERENT MICROGRID FUNCTIONS (FROM [27]).

Microgrid Messages	Delay Requirements
Protection information	4 ms
Monitoring information	1s
Control information	16 ms-100ms
Operations and maintenance information	1s
Messages requiring immediate actions at receiving IEDs	1A:3 ms or 10ms;1B: 20 ms or 100 ms
Continuous data streams from IEDs	3ms or 10 ms
Synchronization messages	(Accuracy)

The integration of networking and communication technologies in microgrids may cause vulnerabilities of cyber attacks. In addition, due to the increase number of distributed energy resources in the grid, the attack targets are also rising, producing more access points to disrupt the grid [34]. Thus, a microgrid needs to be robust against security attacks. To guarantee a proper protection, it´s necessary to minimize the ‘attack surface’ and to decrease the security detection response time, increasing the amount of effort required to violate the network in order to guarantee a proper protection [35]. The security architecture for SMG communication networks should be divided into different levels and zones such as device level (e.g. recovery from attacks), system level (e.g. access control, authorization, encryption, authentication,…) and organization level (e.g. policies, mechanisms, …). As a result, protocols should be designed and adopted by the communication system in order to identify and correct weaknesses in their physical and cyber security parameters.

In conclusion, the implementation of smart microgrid concept and its optimal and efficient control architecture become a necessary for integration of a high volume of DER. For achieve that, the intelligent microgrid requires information and communication technologies. However, despite the urgent need to materialize the intelligent microgrid there are several challenges should face to ensure this new communication architecture addresses: i) Real-time operation and network performance requirements such as latency, bandwidth and QoS mechanisms, ii) Reliability: flexibility and availability to manage a large amount of DER, iii) Cybersecurity issues.

1.4. DECENTRALIZED GENERATION IN MGS

To evolve towards development of smart microgrids satisfy the requirements above mentioned in Section III is mandatory. For reaching these objectives, the grid should move from a centralized infrastructure to a decentralized one. The decentralized communication infrastructures remove the centralized controller as a single point of failure and therefore produce an improvement in the reliability of microgrids. In this structure all devices are able to control themselves independently as opposed to a “master” controller, i.e. each DER unit is considered as an agent. An agent is a computer system able to do tasks on an autonomous way and with capabilities to communicate with their neighbor nodes for solving problems through cooperation, coordination and negotiation [36]. As a result, the centralized hierarchical management scheme presented on Section II could be implemented employing a decentralized architecture. This section presents relevant distributed communication topologies, communication technologies and protocols to tackle the design of a communication distributed architecture for a microgrid.

1.4.1. Distributed communication network topologies for smart microgrids

Nodes or agents network topology in decentralized architectures is crucial in terms of developing an efficient and appropriate microgrid. According their logical topology and degree of decentralization, distributed networks can be broadly classified into the following architectures [36], [37], [38], [39] (Figure 4):

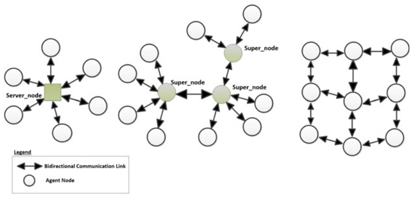


Fig.4. Decentralized architectures for microgrid control: Centralized, Hierarchical and Distributed

•**Centralized:** This topology uses a central server node to store nodes resources and information as well as act like an agent to coordinate actions among theirs. Nodes send messages to the central server to determinate the addresses of nodes that contain the required resources/data. However, like a decentralized system, once a node has the information, it can directly communicate with the searched node without help of the central server. In this structure, the agents have an increased intelligence (compared with typical nodes of the communication network) and improved communication capabilities. Additionally, some control tasks are distributed through agents, although they still have a lack of decision-making capabilities. Moreover, centralized distributed topologies still have a unique point of failure, scalability limits, performance degradation and lack of robustness.

•**Hierarchical:** This topology is characterized by having some agents (super nodes) that take authority over the actions of other agents. In this network exists various agents that carry out different hierarchical tasks. Most microgrid deployment in literature employs a three-level hierarchical architecture where, generally, top -level agents are responsible for critical decisions, middle-level agents make decisions about connected or disconnected grid tasks and the lower-level agents interact with sensors and devices. The choice and allocation of these super nodes is dynamic. This approach is still unreliable due to not all peers can act as super-nodes by a lack of resources.

•**Distributed:** In a distributed communication topology, each local agent is autonomous, has the same role in the network and is responsible for acquire knowledge about its own part of the network. A significant difference regarding the other architectures is that individual agents are allowed to discover other agent information through communication and coordination with their neighbors. This topology do not uses a central server to manage the network avoiding a single point of failure and allowing a very high scalable network.

The selection of the appropriate network topology has had an important impact on the information flow, on the performance and on the capability of the microgrid network to be expanded and updated. Fully decentralized topologies present several advantages among the others, as it´s been described above. Distributed centralized topologies are acceptable in microgrids where a pre-defined operator manages the microgrid and the generation and consumer sides of the power system have similar goals. The central server receives status information from all the units and can calculate an optimal global control strategy, providing a practical implementation of the control infrastructure and reducing the implementation costs. Nevertheless, decentralized control is the most suitable method when there are multiple energy devices on the generation and consumption sides to be managed, requiring real-time monitoring and adjustment. In this case, a centralized control could not meet the requirements. Although the installation costs of decentralized control topologies are higher than those of centralized control, the operation costs are greatly reduced and it can be amortized in a short time [40]. In addition, in decentralized networks it´s possible to install modular and scalable systems with a good precision.

1.4.2. Distributed communication technologies for smart microgrids

A distributed network is a collection of nodes placed at remote locations over a geographical area and connected through communication links for data transmission among the agents under operation. A link may be realized by means of different communication technologies supported by two main communication media, wired and wireless. The choice of the communication medium technology has its associated advantages and disadvantages that designers should evaluate. Therefore, one key aspect of smart microgrids communications design is to deploy suitable and future-proof wired/wireless technologies.

Traditionally, wired communications have been employed to transmit information through the electrical grid due to their better performance than wireless technologies regarding robustness, reliability, security and bandwidth properties. However, wired technology involves higher deployment cost. In addition the network expansion schemes become more complex. Some popular wired technologies used in microgrids are serial communication RS-232/422/485 for SCADA systems [23], Ethernet (IEEE 802.3 technology), bus based technologies (e.g. ModBus, ProfiBus) and Power-Line Communication (e.g. DLC, PLC, BPLC) [41]. However, except of Ethernet, these technologies cannot provide decentralized communications in a reliable manner. The possibility to implement Ethernet over microgrid systems were reviewed very recently by [42], [43]. These works demonstrates Ethernet's applicability for DER's data exchange allowing share bandwidth to all connected devices and it demonstrates that Ethernet can be used in a real time as well as a great scale.

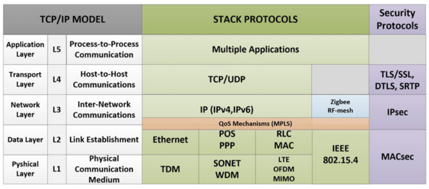
By other side, in spite of their (in general) lower performance in terms of robustness, the wireless technologies are increasing their security capabilities and could be an interesting solution for distributed microgrid communication links because of the cheaper installation costs. Depending on the network coverage, distinct groups of wireless network technologies can be identifies: WPAN (Wireless Personal Area Network), WLAN (Wireless Local Area Network), WMAN (Wireless Metropolitan Area Networks) and WWAN (Wireless Wide Area Network). The most popular solutions for wireless internet access in microgrids are [44]: Family standards IEEE 802.15 (Wireless Personal Area Network, WPANs), especially IEEE 802.15.4 standard (Low-Rate Wireless Personal Area Network, LR-WPAN) that defines the specification for low rate, low power, low complexity and short ranges or IEEE 802.11, Wi-Fi (WLANs). They are networks to cover small amounts of information over relatively small distances. Both technologies could be used to perform the links either between DERs at primary level and/or between DERs and MGCC at secondary level on the hierarchical microgrid control scheme. By other side, cellular networks (4G/3G/HSPA, LTE (Long-Term Evolution), LTE-A (Long-Term Evolution Advanced), and Evolution–Data Optimized) could be used for implementing links at tertiary level and/or between different microgrids [45].

The Wireless technologies listed above provide communication between nodes in a single hop. However, multi-hop technologies may be assumed a key function in microgrid network control research due to they allow to extending the coverage of a wireless network over multiple wireless hops. Mobile Ad-hoc Networks (MANETs) or Wireless Mesh Network (WMNs) are wireless multi-hop networks. An ad-hoc network is a collection of independent nodes that communicates without infrastructure support using wireless links. In this networks nodes operate as both host and routers, in other words, can act as a router to transmitting data of its nodes. Similar to the MANETs are WSNs that have been created to resolve limitations as well as improve the performance of WPANs, WLANs, WMANs, WWANs and MANETs in general [46]. These are networks composed with multiple Mesh Access Points (MAP), usually stationary points, that create mesh topologies whose aim is provide access to different infrastructure networks [47], for example clients in ad-hoc network operating in WI-FI network cannot access in a different radio technology network such as WPANs or other networks, while in case of WMNs both network access are possible through mesh routers. This characteristic is very important in order to achieve interoperability between microgrids. Examples of this kind of microgrids have been study in [48], [49], [50], [51]. This reviews determined that mesh networks offer higher levels of redundancy and robustness in terms of data communications in case of link degradation, failure or loss of node, either temporary or permanent very important characteristics for microgrids deployments. Multiple hops can be used to achieve a more balanced distribution of traffic over network [52], [53]. In fact, the wireless technologies presented before, are now including support for multiple-hop communications which is the case of the IEEE 802.15.4g (mesh network solution for smart metering) [54], IEEE 802.15.5 (mesh network for WPANs/ZigBee) [55] and 802.11s (networking capabilities to Wi-Fi) [56]. It is important to point out that exists the possibility to use this technique in cellular networks (4G or LTE) to achieve increasing the coverage or the capacity in the cell [57].

1.4.3. Main distributed smart microgrids networking protocols

To allow communications in a distributed network it´s essential to specify the set of protocols to be implemented in each node. The decentralized communication networks used in microgrids are focused on the implementation of suitable Transmission Control Protocol/Internet Protocol (TCP/IP) [58]. Current TCP/IP based communication systems provide a high enough bandwidth and real time monitoring and control of smart microgrids. Moreover, smart microgrids can deploy their “utility-Intranet” to obtain full control on communications with increased flexibility, security and reliability. The design of a client-server architecture for power grids using

TCP/IP for information transmission has been discussed in [59], [60]. For communication between two endpoints a protocol stack development is mandatory. In this section, the main layered protocols that could be used to deploy distributed smart microgrids are described. Figure 5 depicts both the main communication purpose at each layer in the TCP/IP protocol stack and the main networking protocols used in a Microgrid Control System.



TCP/IP MODEL			STACK PROTOCOLS				Security Protocols
Application Layer	L5	Process-to-Process Communication	Multiple Applications				
Transport Layer	L4	Host-to-Host Communications	TCP/UDP				TLS/SSL, DTLS, SRTP
Network Layer	L3	Inter-Network Communications	IP (IPv4,IPv6)			Zigbee RF-mesh	IPsec
			QoS Mechanisms (MPLS)				
Data Layer	L2	Link Establishment	Ethernet	POS PPP	RLC MAC	IEEE 802.15.4	MACsec
Pyshical Layer	L1	Physical Communication Medium	TDM	SONET WDM	LTE OFDM MIMO		

Fig.5. Communication and security common microgrid protocols stack in the TCP/IP model

1) Link Layer

This layer describes the operational physical and data link network functions. The Physical Layer (L1) is the medium used for the transfer of data. The Data Layer (L2) is used to establish a link between two nodes. As described before, distributed smart microgrids accept different communication technologies, wired and wireless. Regarding wired technologies, the control systems implemented in microgrids generally use the Ethernet protocol (IEEE 802.3) for fast and reliable operation, but the cost to develop this kind of network is expensive for long distance communications. Typically, the Ethernet protocol is coupled with the Medium Access Control (MAC) protocol, a sublayer of the L2 link layer. The MAC sublayer, in addition to the receive and transmit data frames, assigns addresses to each connected microgrid device. Commonly, these type of wired networks (coaxial cable or twisted pair) uses TDM (Time Division Multiplexing) as L1 protocol. TDM is a digital processing method that allows to share the total bandwidth among different connections. This is achieved through putting multiple data streams in a single signal by separating the signal into many segments, each one having a very short duration.

In smart microgrids over fiber optic networks, WDM (Wave Division Multiplexing) or SONET (Synchronous Optical NETwork) also called Synchronous Digital Hierarchy (SDH) are the protocols used in L1. WDM is a method which combines multiple signals on laser beams at various infrared (IR) wavelengths for their transmission along fiber optic media. Besides, SONET is a high data rate protocol (up to 40 Gbps) originally developed for voice communication over optical fiber networks. The L2 protocol for SONET is typically 'Packets over SONET'/SDH (POS). POS employs the Point-to-Point Protocol (PPP), a common L2 protocol used to establish a direct connection between two nodes that can simultaneously support multiple L3 network protocols including TCP/IP. The use of fiber optic technologies can multiply the effective bandwidth of a fiber optic communications system by a large factor, but its cost must be studied for its implementation in microgrids against the alternative of using Ethernet technologies into a cable [61], [62], [63]. Nowadays, the use of Ethernet in LAN is very common and has evolved to support high data rates over long distances, such as metropolitan area networks (MAN).

Recent advances in wireless communications with easy installation, low cost and acceptable transmission speed make this technology be viable for microgrid monitoring and control. For their implementation, two protocols can be used. L1 protocols, such as LTE, are used when they run on fourth generation cellular networks (4G). Protocol 802.14.5 is the common choice when ad hoc communication networks composed of radio nodes are used. LTE uses an L1 protocol called orthogonal frequency-division multiplexing (OFDM) to enable simultaneous two-way communications. LTE also employs multiple input and multiple output (MIMO) to multiply the capacity of individual radio links by using multiple transmit and receive antennas to exploit multi-path propagation of signals. L2 layer in cellular networks, LTE has a MAC sublayer that acts as interlinking with the RLC (Radio Link Control) sublayer that performs packet segmentation and flow control among entities. RLC also supports end-to-end IP connection. The L2 layer for ad-hoc networks support Radio Frequency Mesh (RF-mesh) such as IEEE 802.15.4g or IEEE 802.15.5. For smart microgrids applications the predominant RF-mesh standard is Zigbee (IEEE 802.15.5). Zigbee enhances the IEEE 802.15.4 standard by adding networking and security functions required for smart microgrid applications.

Additionally, in Section III it´s been pointed out that a communication infrastructure with Quality of Service (QoS) requirements is absolutely needed. Consequently, microgrids should adopt suitable mechanisms to guarantee QoS. In telecommunication networks, QoS differentiation is achieved through resource reservation and traffic prioritization [20]. These characteristics are implemented at a "layer 2.5" protocol, as it performs the functions of L1 and L2 while also including features that are typical of L3. For carrying out QoS implementation in communication networks, many families of standards define the medium access control (MAC) layer with the specification of different traffic categories. However, Internet by itself cannot assure QoS requirements, because the best-effort level of service for the delivery of data is the rule in today’s Internet [64], [65]. Therefore, traffic handling mechanisms must be implemented in microgrid networks at “2.5 layer”, using protocols such as Integrated Services (Intserv), Differentiated Services (Diffserv), Multiprotocol Label Switching (MPLS), IEEE 802.1p/q tags (QoS mechanism on Ethernet) and IP Precedence [66], [67]. These several QoS services allow a single network to satisfy different types of traffic by emulating many L1 and L2 protocols including T1, PPP, Frame Relay, and Ethernet.

2) Internet Layer

Internet Layer: The Internet Layer (L3) controls the operation of packet transmission by assigning addresses to nodes and routing frames along physical paths. The Internet Protocol (IP) is the most widely implemented networking layer protocol. Although the Internet is based on IP, the protocol is also used on networks unrelated to the Internet. IP enables end-to-end smart microgrids applications to communicate to any two endpoints that have at least one or more networks providing a data path between them by using various networking technologies, i.e., IP can operate independently of the underlying physical media, L1 and L2 layers. This characteristic provides interoperability among third-party non-compliant end devices and compliant communications networks. This allows much greater flexibility for interoperability as utilities implement their Smart Microgrid network. Therefore it plays a vital role in unifying the information while allowing utilities to select the communications technologies and end devices (meters, IEDs, etc.) that make the most sense for them. Network interoperability is indispensable in order to achieve an overall optimal system operation and connectivity, independent from the used physical medium, the type of devices and the manufactures [68].

IP is available with either of two versions (IPv4 and IPv6). In both versions, every system (node or endpoint) is identified by its unique network layer address, but the main difference between both IP versions is their respective host addressing systems: IPv4 uses 32-bit, whereas IPv6 uses 128-bit addresses. However, the version of IP currently deployed in most microgrid networks is IP version 4 (IPv4). Despite of this, microgrid network planning should consider future migration to IPv6, because the distributed energy resources (DERs) in the grid may need their own individual IP-address in the future. Currently, many investor-owned utilities have millions of electric meters installed. Other devices must be additionally considered, including an important amount of electric vehicles as potential roaming users in the future. That means that IPv4 might not have enough IP addresses for each of these large number of endpoints [69]. Additionally, multicasting is supported by IPv6 and introduces new features to QoS capabilities [70].

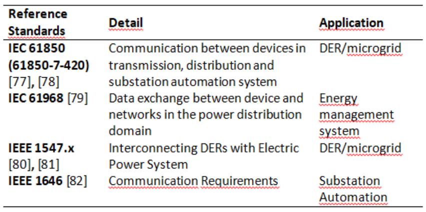
3) Transport Layer

Transport Layer: The transport protocols (L4) enable host-to-host communications. The two most common transport layer protocols are the Transmission Control Protocol (TCP) and the User Datagram Protocol (UDP). TCP is a connection-oriented protocol that provides reliable, sequenced, and error-checked delivery of a stream of packets between application endpoints. TCP is optimized for accurate and reliable delivery of packets rather than timely delivery, thus yielding relatively long delays. UDP is not connection-oriented, not providing any guarantee on packet delivery, but is highly time-sensitive [71]. The choice of the best suited protocol within a microgrid control system network depends mainly on design requirements based on the importance of speed versus reliability and on the need for error detection [11]. However, since the microgrid application requires reliable communications, TCP is the best option to be implemented [59]. On the contrary, shortcomings of TCP in performing congestion control for a large number of data sources and its inherently delayed acknowledgement could be ineffective for SMG control which can produce useless retransmissions of packets and throughput degradation [20], [60]. As a consequence, a large number of transport protocols and mechanisms have been proposed in order to improve the transport services offered to applications and to optimize the usage of the different technologies. For example, SCTP (Stream Control Transmission Protocol) and DCCP (Data Congestion Control Protocol) have been proposed to support the nodes mobility in the network [72] but these protocols are insufficient to address the transport characteristics of the nodes in the microgrid due to some intermediate nodes or Network Address Translation (NATs) may be not fully aware about these protocols (at the network level), which could lead to a blocking packets at the processing [73] and therefore a sub-optimal microgrid operation. These problems have motivated researches about development of novel protocols for their application in microgrids. Some of these are: SSTP (Scalable Secure Transport Protocol) and MPTCP (Multi-Path Transport Protocol) [74], [75], [76] that have been customized for grid data collection. By other side, for enhancing performance network mechanism, TCP-splitting is, nowadays, the most used approach in microgrids [60].

4) Application Layer

The application layer (L7) contains the protocols that support process-to-process communications, i.e. serves as the network interface for users and applications. It contains a variety of common functions such as resource sharing, remote file access, directory services, electronic messaging, etc. For microgrid network management, common application protocols like Dynamic Host Configuration Protocol (DHCP), Domain Name Service (DNS) or Network Time Protocol (NTP) can be used. Also specific protocols such Distributed Network Protocol (DNP3), Modbus, Profibus over TCP/IP or proprietary vendor specific protocols could be used [71]. However, for reliable and scalable communication architecture, interoperability is needed. In the field of the Microgrid, international standards have defined for achieve these interoperability at application layer. The most important of them are listed in table III.

The IEC 61850 is the most promising standard for design power communication networks [83], [84]. This standard has been proposed to increase the reliability and availability and to ensure interoperability. This standard use a communication model based on protocols such as Manufacturer Message Specification (MMS) for communication messaging, Simple Network Time Protocol (SNTP) for time synchronization and Generic Object Oriented Substation Events (GOOSE)- Sampled Measured Values (SMV) for fast messaging. It can operate over TCP based on implementing Ethernet [85]. The communication stack mapping the IEC 61850 services with the TCP/IP model layer is shown in Figure 6.



Reference Standards	**Detail**	**Application**
IEC 61850 (61850-7-420) [77], [78]	Communication between devices in transmission, distribution and substation automation system	DER/microgrid
IEC 61968 [79]	Data exchange between device and networks in the power distribution domain	Energy management system
IEEE 1547.x [80], [81]	Interconnecting DERs with Electric Power System	DER/microgrid
IEEE 1646 [82]	Communication Requirements	Substation Automation

5) *Security Protocols*

A microgrid control system network, apart from cyber-security mechanisms to prevent attacks, need protocols to provide network security (such as authentication and encryption). Security Protocols have to be end-to-end, lightweight, and scalable and prepared to be added at any layer to protect data transmitted between different microgrid applications and host. There are many end-to-end security protocols that can apply to microgrids networks and they can run over IP to ensure end-to-end security communications [35], [86], [87], [88]. Some security protocols are: Internet Protocol Security (IPsec), Transport Layer Security/Secure Sockets Layer (TLS/SSL), Datagram Transport Layer Security (DTLS), Secure Shell (SSH) Protocol or Secure Real-Time Transport Protocol (SRTP). These protocols have been used for microgrids security; however, for achieving a good level of security, the access of unauthorized nodes to the network information must be prohibited. A good option would be the use of MACsec [35]. A protocol that provides hop-by-hop security, so each node in the path has to verify the integrity and authenticity of the message in the reception block, and regenerate the MAC in the transmission block [35].

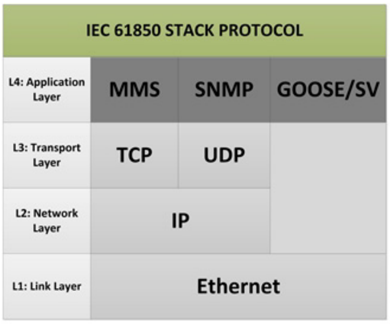


Fig.6. Typical IEC 61850 Ethernet-based communication TCP/IP stack.

This stack of protocols for deploying decentralized smart microgrids networks is most often implemented through a MAS technology (Multi-Agent System). In fact, the IEEE Power Engineering Society Intelligent Systems Subcommittee created the group the IEEE Power and Energy Society Multi-Agent Systems Working Group (MASWG) for defining the correct use of the MAS technology within the distributed power grid domain.

MAS consists of multiple intelligent agents that interact to solve problems through cooperation, coordination and negotiation. These agents can be structured forming fully decentralized topologies, where in each one of them the TCP/IP stack protocol is implemented to give them fully networking operation. Several papers have specially applied MASs to microgrids [39], [89], [90], [91]. However, the increasingly distributed and intelligent energy systems along with their multi-disciplinary nature yield such a big data volume that the management and control of microgrids is becoming a critical challenge. The latest research indicates that distributed MAS architectures have some limitations on the efficient and optimal management of these emerging microgrids [92], [93], [94], [95], [96], which are described below:

- MAS agents cannot simultaneously communicate with other agents, being only allowed one-on-one interactions among individual agents, i.e., the agents can only act as a client or as a server, which results in a lack of agent proactivity. In this way, if the agent detects a fault in its operation, it cannot communicate its fault to the network until another agent communicates with it. The absence of such functionality results in a poor microgrid critical resources management.
- Agents individual behavior is easily to know, whereas that cannot be extended to the behavior of the whole system. To get the overall operation information about the microgrid dynamic network, clusters of agents working in the same microgrid application or with the same needs should be formed. The absence of such functionality might result in the lack of knowledge about the global status of the microgrid and, thus, in the sub-optimal resources allocation.
- Agents have neither dynamic reorganization nor self-healing capabilities by themselves, which prevent to adapt to local-failures, microgrid blackouts, agents crashes or communication failures.

To overcome those limitations, a new generation of communication networks for microgrids is required. The new characteristics of those new networks are: i) Information exchange with neighboring DER management structures through virtual layers that allow dynamic reorganization, ii) Dynamic Reconfiguration and self-healing of DER management structures, iii) Better communication technologies for the proactive operation of devices and active consumers, and iv) New software layers at the TCP/IP protocol stack to meet the increasing microgrid service and complexity demands. These requirements are fulfilled by the new Peer-to-Peer (P2P) paradigm. Recent research suggests Peer-to-Peer (P2P) communication networks for microgrid environments which will give rise to the new dynamic distributed microgrids generation [97], [98], [99], [100], [101]. This argument is fully elaborated in the next section, as well as an implementation guideline.

1.5. FUTURE TRENDS FOR DYNAMIC MGS

In spite of the progress discussed in the above sections, continued efforts are needed to address some issues associated with MAS decentralized communications on microgrids. A dynamic and complex system like a microgrid needs to be designed to adapt autonomously. P2P-based technology for distributed self-management could change the future of power grids, because the P2P architecture has become a powerful control paradigm in a dynamic microgrid.

A P2P network is a communication architecture for decentralized systems. The agents, called peers, in contrast to MAS systems whose agents only can act as a server or a master, can act as both clients (masters) and servers simultaneously, which allows the agents to be proactive. Regarding P2P topology networks, the connectivity between nodes is essentially virtual, i.e. logical and structured topologies that are built on top of the physical networks [102] (Figure 7). Peer nodes do not suffer from the inflexibility of MAS physical network topologies, since they are logical in nature. Their increased flexibility allows for extensibility, self-healing and dynamic reconfiguration. This implies that peers communicate with each other to establish dynamic self-organizing structures on top of the underlying physical networks. The fact that P2P overlays can be built dynamically allows them to support a huge variety of application level services [103]. In addition, these structures can be deployed over wired or wireless communications technologies. Routing can be achieved with direct point-to-point LAN communications without sacrificing the self-configuration, scalability and fault tolerance properties of a P2P overlay [104]. However, P2P overlay networks are ad-hoc in nature [105]. The nodes are connected by multi-hop wireless paths using technologies such as Zigbee/IEEE 802.15.4, Bluetooth/IEEE 802.15.1 and IEEE 802.11.

Due to the virtual layer of the P2P architectures, peers disconnection from their underlying physical layer is allowed. This means that creation of a group of peers (clusters) for doing a particular task on a microgrid is possible [106]. Examples of clustering objectives include energy balancing, islanding and blackout prevention [37].

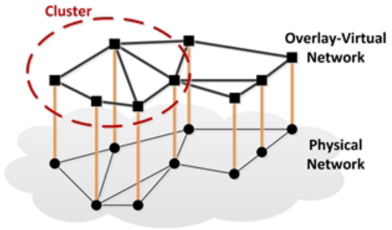


Fig.7. Overlay Network Architecture Scheme

Therefore, virtual self-management allows agents to make local adaptive decisions on the basis of the information they receive from the agents to which they are linked [107], i.e., global goals are achieved by local management on the basis of local goals and knowledge. In this context, the holonic system approach has emerged [37], [108], [109]. This concept balances the importance of global and local objectives through a hierarchy of collaborative holons. The word holon is composed by "holos" meaning whole and the suffix "on" which implies particle or part, so holon=whole & part. Thus, the term comes from a recognition that any peer is simultaneously a whole entity comprised of sub-entities which interact to form different types of holarchy (based in P2P). Besides peers can find one another based on peers-IDs or peers attributes among the peers multitude. Thus, the responses to objects cached in the local overlay contain pointers to nodes that are close to the node issuing the query, thus reducing congestion on the network as well as network latencies [110].

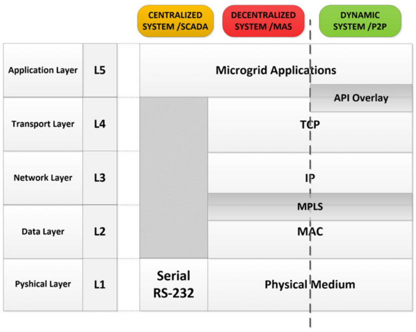


Fig.8. Protocol stack microgrid system evolution

Concerning mechanisms and protocols, the TCP/IP stack protocol is the most suitable standard for developing the peers. However, the overlays services need an additional software layer on the top of the TCP layer. Figure 8 presents a layered view about the different communication architectures for microgrids evolution.

The API Overlay layer is used to provide overlay-P2P services, being normally composed by two software layers: Overlay Routing and Messaging Layer and Overlay Management Layer (See Figure 9). Here, Software Defined Networking (SDN) is a need to virtualize networks.

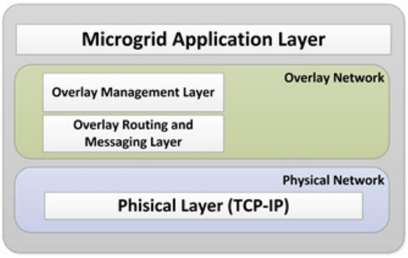


Fig.9. Stack Protocol of P2P Overlays

Overlay Routing and Messaging Layer provides networking P2P services to achieve the resource and network discovery, session establishment, routing, data transfer between nodes and entry/exit management of nodes (Plug and Play). The second application layer working on P2P service is responsible for the processing and data analysis, event management and status supervisory microgrid for stability maintenance.

As a result, it can conclude that this approach differs from conventional MAS in the dynamic and flexible cooperation, competition, supervision and part-whole. In addition, overlay structures combine the advantages of distributed control (such as scalability, adaptability and resiliency) and centralized control (reliability, optimally, practicability). Nevertheless, these P2P networks are still at the preliminary study stage for their implementation on the microgrid environment, being more research needed. Due to the growing complexity and unpredictability of the electrical systems, the study of microgrid dynamics becomes more complicated and new challenges arise which need to be addressed, such as:

- Peer-to-peer networks are mainly developed for file and processor cycle sharing, whose network performance requirements are less critical [111]. Thus, adapt this network technology to the performance networking smart microgrid requirements is essential. In this regard, it is needed to extend IEC 61850 standard in order to include this decentralized control and interoperability [83], [84].
- The current microgrid applications are not able to manage the uncertainty variability of distributed energy resources, among other factors that can change over time, because the methods used are often based on linear

models and deterministic forecasts that do not adequately manage the dynamic behavior of microgrids [112]. For this reason, advanced stochastic algorithms, predictive analytics and the use of nonlinear schemes should be applied into future microgrid applications to produce results with higher fidelity [113], [114], [115].

- The increasing number of renewable energy sources and microgeneration as well as the integration of a large amount of DER units in the microgrid requires advances in high performance computing and parallel processing. Due to get that, these methods require, on one side, greater quantities and greater speed in the data flow. On the other side, reduced processing data time and results in a more sensitive time scheme [116], [117]. Therefore data compatibility and exchange are likely to emerge as major challenges for implementation of dynamic microgrid capabilities.
- Currently, the data repository implemented in microgrid system use different forms of data; they can be structured and unstructured data. The development of a universally compatible communications protocol to handle these diverse data forms is another challenge to carry out [118].

Overall, the improvements in microgrid control systems for the future advanced microgrid generation are focused on leveraging fundamental advances in communications, mathematics and software computation as well as enable better technologies needed to increase the ranges and applications of energy-efficient advanced microgrids [118].

Figure 10 shows a possible evolution path towards dynamic microgrids. The comparison criteria and results can be found in table IV.

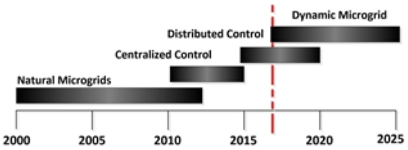


Fig.10. Roadmap to evolving to the dynamic microgrid.

1.6. CONCLUSION

This paper has reviewed the evolution of microgrid communication systems, from those in initial microgrids to the emerging distributed systems. Recent research trends have been also discussed. This paper highlights that network communications in microgrids have more critical performance requirements than other IT systems due to the need for higher reliability, scalability, robustness, QoS and cybersecurity. The constraints of current microgrid communication systems, produced by the penetration growth of distributed energy resources, have been identified.

The research conducted up to date has produced important advances in communications achieving a decentralized and adaptable microgrid, having established a significant basis for the future deployment of new microgrids. It has been shown that intelligent, autonomous and communicative entities can lead to the successfully control of an energy system. The adoption of the TCP/IP stack protocol allows end to end communications and network interoperability. Improvements of the network topology to best fit dynamic and flexible environments have been described. However, research is still required towards the next generation of dynamic microgrids, where DERs are widely coupled into the energy systems and should be dynamically interoperated by means of ICT technologies.

The technical studies reported in the literature indicate that a new peer-to-peer communication system approach is required to support the transition from the current decentralized communication systems to the next microgrid generation. This argument is reinforced by the concept of holonic systems, which combine global and local objectives. A hierarchy of clusters (or holons) based on P2P is proposed in order to optimize the overall microgrid system performance.

Summing up, there are challenges and important open research issues that have been identified and discussed, whose main purpose is to enhance the performance of peer-to-peer communication networks for their operation on microgrids. Adaptive logic and stochastic software approaches can be used for reaching the goals.

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TABLE IV

MICROGRID EVOLUTION SYSTEM COMPARISON

	CENTRALIZED (SCADA)	**DECENTRALIZED (MAS)**	**DYNAMIC DISTRIBUTED (P2P-Overlays)**
Access of information	Status microgrid information through the whole units	MAS provides each independent control with information about its neighbor	Control about neighbor or cluster knowledge
Data communication Structure	Global & synchronous communication	Local & asynchronous communication	Local & Global & asynchronous communication
Real-Time Functions	Difficult and expensive	Possible and inexpensive	Easy and inexpensive
Plug & Play Capacity	MGCC must be programmed	Can be achieved without any modification of the controller	Inherent to peers
Grid Model	Global grid model	Local grid model	Local and Global grid model
Fault Tolerance Ability	Poor fault tolerance ability	1 router failure → tolerated n routers failure → costly	n routers failure → tolerated self-healing
Flexibility &Modularity	Reconnection is required for additional DERs	MAS can install modular and scalable systems	Nodes can exit and enter without changes in the network
Scale	Few nodes	IPv4 →2^{32} nodes IPv6 →2^{128} nodes Hierarchical Domain	>2^{128} nodes Names Domain
Destination Nodes	Node identification not allowed	Unique IP identification → node	GUID (Global Unique Identifier) → several host nodes (Routing at nearest)
Interoperability	Not possible	Possible	Demanding
Network Performance	High Latencies and low bandwidth. QoS not allowed	Greater latencies and bandwidths. QoS is allowed	Low latencies and high bandwidth. Inherent QoS
Network	Physical (EPA)	Physical (TCP/IP)	Virtual (o TCP/IP)
Security	Poor	Only where all nodes are	Reachable, even in

NOMENCLATURE

CIM	Communication Information Model
DCCP	Data Congestion Control Protocol
DCHP	Dynamic Host Configuration Protocol
DER	Distributed Energy Resources
DG	Distributed Generation
Diffserv	Differentiation Services
DMS	Distribution Management System
DNO	Distribution Network Operator
DNP3	Distributed Network Protocol 3
DNS	Domain Name Service
DTLS	Datagram Transport Layer Security
EPA	Enhanced Performance Architecture
GOOSE	Generic Object Oriented Substations Events
GUID	Global Unique Identifier
HSPA	High Speed Packet Access
ICT	Information and Communication Technologies
IED	Intelligent Electronic Device
Intserv	Integrated Services
IPsec	Internet Protocol Security
ISO/OSI	International Standards Organization/ Open Systems Interconnect
LC	Load Control
LTE	Long Term Evolution
MAC	Media Access Control
MACsec	Media Access Control Security
MANET	Mobile Ad-hoc Network
MAP	Mesh Access Point
MAS	Multi Agent System
MG	Microgrid
MGCC	Microgrid Central Controller
MMS	Manufacture Message Specification
MO	Market Operator
MPTCP	Multi Path Transport Control Protocol
MS	Micro Source
NAT	Network Access Translation
NTP	Name Time Protocol
OFDM	Orthogonal Frequency Division Multiplexing
P2P	Peer-to-Peer
PCC	Point of Common Coupling
PLC	Power Line Carrier
PPP	Point-to-Point Protocol
QoS	Quality of Service
RFmesh	Radio Frequency mesh
RLC	Radio Link Control
RTMP	Real Time Measurement Parameters
SCTP	Stream Control Transport Protocol
SDH	Synchronous Digital Hierarchy
SDN	Software Defined Networking
SMG	Smart Microgrid
SMV	Sampled Measured Values
SNTP	Simple Network Time Protocol
SONET	Synchronous Optical Network
SS	Storage System
TCP	Transport Control Protocol
TDM	Time Division Multiplexing
TLS	Transport Layer Security
ToS	Type of Service
SSL	Security Socket Layer
SSTP	Scalable Secure Transport Protocol
UDP	User Datagram Protocol
WDM	Wave Division Multiplexing
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WMN	Wireless Mesh Network
WPAN	Wireless Personal Area Network
WWAN	Wireless Metropolitan Area Network

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2

PUBLICACIÓN II

A NOVEL LOCALITY ALGORITHM AND PEER-TO-PEER COMMUNICATION INFRASTRUCTURE FOR OPTIMIZING NETWORK PERFORMANCE IN SMART MICROGRIDS

Marzal S., R., González-Medina, R., Salas R, Figueres, E. and Garcerá, G., “A novel locality algorithm and peer to peer communication infrastructure for optimizing network performance in smart microgrids,” Energies, vol.10, no.9, pp.1009-1275, Aug. 2017.

Contenidos

A Novel Locality Algorithm and Peer-to-Peer Communication Infrastructure for Optimizing Network Performance in Smart

***Abstract*—** Peer-to-Peer (P2P) overlay communications networks have emerged as a new paradigm for implementing distributed services in microgrids due to their potential benefits: they are robust, scalable, fault-tolerant, and they can route messages even with a large number of nodes which are frequently entering or leaving from the network. However, current P2P systems have been mainly developed for file sharing or cycle sharing applications where the processes of searching and managing resources are not optimized. Locality algorithms have gained a lot of attention due to their potential to provide an optimized path to groups with similar interests for routing messages in order to get better network performance. This paper develops a fully functional decentralized communication architecture with a new P2P locality algorithm and a specific protocol for monitoring and control of microgrids. Experimental results show that the proposed locality algorithm reduces the number of lookup messages and the lookup delay time. Moreover, the proposed communication architecture heavily depends of the lookup used algorithm as well as the placement of the communication layers within the architecture. Experimental results will show that the proposed techniques meet the network requirements of smart microgrids even with a large number of nodes on stream.

***Index Terms*— smart microgrids; communication architecture; peer-to-peer overlay networks, decentralized systems, network performance parameters.**

2.1. INTRODUCTION

A microgrid (MG) is a low voltage distributed network formed by various distributed energy resources (DERs) consisting of a variety of loads, microsources (MS), energy storages systems (SS), and other incipient elements like electric vehicles (EVs) [1-3] (See Figure 1). Microgrids have emerged as a powerful, resilient and sustainable power grid that can integrate renewable energy systems for power generation [4-5], and manage in real time a large amount of distributed energy resources [6-7]. Microgrids can operate in grid-connected mode and islanded mode disconnected from the point of common coupling (PCC) with the main grid in case of faults [8-10]. In general, there are several kinds of faults that can originate the disconnection of a certain area in electrical grid, as it would be the case of short-circuit, line overloads, faults in substations, and so on. Once the fault has disappeared, they can be reconnected to the grid. In addition, a microgrid must have its own control architecture to ensure the correct operation and coordination of the different DERs.

In recent years, the introduction of Information and Communication Technology (ICT) in micrograms energy systems has led to the term “Smart Microgrid” (SMG) [11-12]. This concept has emerged to describe the way ICT transform micrograms operation and entail several applications like intelligent monitoring and control of distributed energy resources, automation, data networking and other tasks that can improve the efficiency of the system [12-14]. To realize these capabilities, distributed control systems have been proposed. Particularly, recent researches [13, 15-17] suggest Peer-to-Peer (P2P) overlay communication networks as a solution with great potential to provide high performance to decentralized microgrid control systems, including scalability, fault-tolerance and robustness.

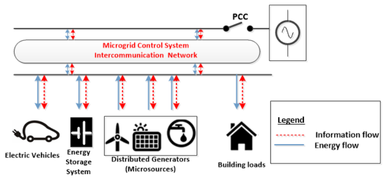


Fig.1. Simplified scheme of a microgrid.

Peer-to-Peer (P2P) overlay networks are virtual networks where the connectivity among the nodes is carried out through a physical IP network, while network topology is created in a virtual network, called overlay, which are built on top of the physical one. Overlays increase flexibility, extensibility and adaptive reconfiguration. This implies that each node communicates with each other to create self-organizing overlay structures on top of the subjacent physical networks [18, 19]

Distributed Hash Tables (DHTs) allow developing structured P2P systems due to its routing capabilities. DHTs support exact-match queries [20-21] i.e., given a query for a specific key, DHTs can efficiently locate the node which holds the keyword key. However, DHTs do not implement any mechanism of retrieval data application (Sit, 2008) and locality is not considered [21]. These facts are a serious drawback to implement communications in microgrids by means of DHTs due to, on one hand, data retrieval mechanism is essential to obtain and/or update data in this application [23]. On the other hand, locality allows creating a group of peers for a particular task [21]. Peers with close interests create “shortcuts” and use them to locate content. The underlying physical network path could be significantly different from the path on the overlay network if locality in DHTs is not considered. Therefore, the lookup latency in the overlay network could be quite higher and decrease the performance of the application layer [21, 24-25].

The control and the management of microgrids demand high efficiency in terms of network quality requirements (high bandwidth and low latency). However, peer-to-peer networks have been mainly developed for other applications such as file sharing and processor cycle sharing, whose network performance requirements are less-priority [26].

The main contributions of this work are, first, the proposal of a fully functional decentralized communication architecture, which includes a new clustering algorithm based in DHTs that adds locality capabilities for creating node clusters with close interests. The second contribution of the paper is the proposal of a specific application protocol, running on TCP/IP, for microgrids monitoring and control.

The paper is organized as follows. Section II gives some background on P2P networks and their application to microgrids. In addition, a specific DHT protocol (Chord) is described. Section III presents the network requirements in order to deploy efficient communication architectures for smart microgrids. In Section IV and V the proposed solutions are described. Concretely, the lookup algorithm is presented in section IV, while section V gives details about the communication architectures and a specific protocol for microgrids. Section VI reflects the results of the tests that have been carried out to evaluate the performance of the proposed solutions. Finally, Section VII provides some conclusions.

2.2. PEER-TO-PEER APPROACH FOR DECENTRALIZED MGS CONTROL

One of the key points for integrating DERs into microgrids is the design of a control architecture that coordinates each one of the DER units. Traditionally, the control tasks are carried out by means of a three level hierarchical structure [27-31], i.e., primary, secondary and tertiary control. The Field Level (Primary Control) is implemented in local DER. It is responsible for stable operation conditions in each DER. The Management Level (Secondary Control) is controlled by Microgrid Central Controller (MGCC), which ensures the synchronization between the MG and the main grid or the quality of the frequency and voltage of MG, among other tasks. Finally, Grid Level (Tertiary Control) carries out the management of MG when it operates in the market providing an economically optimal operation of microgrid.

Primary, Secondary and Tertiary levels can be combined or not with communication systems. However, to evolve towards the development of the intelligent microgrid, communication interfaces among the different control levels should be created. Thus, a bi-directional communication and channels are stablished in order to allow information transfer between the different controllers [32] for knowing the state of the whole system.

Today’s microgrid installations use centralized architectures to implement the three level hierarchical scheme and data transfers between entities. These centralized architectures where a central controller take decisions and provides communications between all microgrid resources have been implemented, for many years, by Supervisory Control and Data Acquisition (SCADA) systems [33]. In addition to the SCADA systems, other alternative technologies also used for control and management of centralized microgrids are Power Line Carrier (PLC) and Wireless Networks (WN). PLC technologies use the electric power lines as a medium that enable the bidirectional data exchange. It provides a vast coverage and in terms of infrastructure is the most cost-effective technology since the lines already exist. However, PLC technology has negative effects in the communication channel such as a noisy medium, distortion, frequency impedance alterations and the risk of signal attenuation [34].

Besides, wireless technologies have emerged as an alternative for centralized wired technologies due to their low cost, low power, flexibility and easy deployment [35]. Some studies about wireless networks in power systems for monitoring and control of segments in power transmission and delivery have been presented in [35-39]. However, the use of wireless technologies in power system environments present a number of challenges such as reliability concerns, wireless signal disruption due to electromagnetic interference (EMI), faded signals due to large distances of transmission or obstacles in the line-of-sight; overloading of bandwidth; quality or latencies degradation, among others [35, 40-41]

In Information and Communication Technology (ICT) terminology, these centralized structures (see Figure 2.a) are based on client-server communications architectures where every device of the network plays one of two roles: server or client. The server is the central point that receives status information from the whole units and it is able to calculate an optimal global control strategy. Besides, the client shares its resources via direct link to the server. This control structure causes inefficiencies in the communication system of the microgrid, which are provoked by several causes. On one hand, a failure in the centralized control point could lead to several faults or even shut down the entire system. In addition, there are difficulties for managing a wide range of devices in real time [42-43], because the system is hardly scalable. As a result, these disadvantages can lead to provide poor services, bottlenecks or under-utilization of the network resources. To address these shortcomings, the communications network should move from the conventional centralized infrastructure to a decentralized one. A decentralized communication infrastructure, removes the central controller as a single point of failure, providing a significant improvement in terms of reliability. Therefore, the hierarchical management scheme of microgrids should be implemented employing a decentralized architecture.

Decentralized architectures for power systems are usually implemented through a Multi-Agent Systems (MAS) technology [44-47]. In this structure each DER unit is considered as an agent. An agent is a computer system capable of performing tasks autonomously and with the ability to communicate with its neighboring agents to solve problems through cooperation, coordination and negotiation. Most MAS implement hierarchical topologies where some agents (super-agents) have authority over the actions of other agents [48] to form distributed decentralized systems (See Figure 2.b). However, these agents do not have the capacity to reorganize themselves [49]. In addition the individual behavior of the agents is easy to know while the whole system is unreachable [50]. The absence of such functionality might result in a lack of knowledge about the global status of the microgrid, as well as in a sub-optimal allocation and a poor management of the critical resources [49]. Therefore, a new paradigm based on peer-to-peer (P2P) communications could be a promising solution for improving the use of DERs and the network performance in microgrids [17, 51-53].

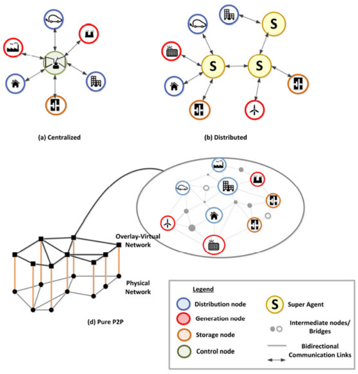


Fig.2.(a) Centralized, (b) Distributed and (c) Pure P2P Communication Architectures.

P2P systems are formed by peers. A peer is an agent [49] that can act both as server and client, characteristic that allows agents be proactive. P2P systems avoid a single point of failure and are much scalable because the available resources grow with the number of nodes joining the network. Nodes are capable to cooperate to achieve a common goal and they have self-organization capabilities. The connectivity between nodes, as Figure 2.c depicts, is carried out by creating virtual links, overlays, which are built on top of the IP network. Some advantages of these systems are the greater flexibility, their extensibility and their adaptive reconfiguration. This implies that each node communicates with each other to create self-organizing overlay structures on top of the subjacent physical networks [54].

It is worth pointing out that P2P networks have a high distributed nature, so they offer a scalability much larger than the one of other networks that are based on centralized or partially distributed systems, due to each peer could act as a server. Therefore, the typical bottlenecks of centralized and partially distributed systems are avoided because the number of servers increases linearly with the one of clients.

P2P architectures can be classified as Structured or as Unstructured according to their logical topology and degree of decentralization. On one side, an unstructured P2P network has a random and unstructured mesh network topology. There is not an algorithm for organization. The information and data resources are distributed among peers. A Broadcasting lookup technique is used to locate resources and data retrieval in unstructured P2P, in such a way that each peer propagates a request to its directly connected peers. The propagation remains until the message time to live (TTL) threshold (typically four) has been reached [55]. This broadcast creates a large amount of signal traffic and uses of a lot of network bandwidth [56]. These characteristics do not result in a scalable and efficient system.

On the other hand, structured P2P network has a dedicated network and a well-defined topology where peers are responsible for information and data resources. In structured overlays, a Distributed Hash Tables is used for routing in order to locate resources in the network. In this strategy each peer has a local table that is used as a lookup algorithm to route the request data according to node tables [57]. DHT allows the peers to find the addressed data using flat identifiers (IDs). This kind of P2P system improves the network communication usage, and it is showed in Figure 3.

Figure 3 compares the performance of broadcasting and DHT lookup algorithms for distributed peer to peer architectures. The complexity of each of these lookup algorithms can be evaluated by analytical metrics [58]. Analitycal metrics for structured DHTs and Broadcasting-unstructured P2P designs has been proposed in [59]. The computational behavior of these lookup algorithms is described by means of O, which describes the asymptotic behavior of the algorithms [58]. In a structured DHT overlay, each node maintains information about the O (logn) value of other nodes and solves lookup via O (logn) messages per lookup. In broadcasting, the metric is O (logn) messages per lookup. It is worth noting that O notation expresses the asymptotic upper bounds, since it bounds the growth of the messages exchange for a large enough number of input nodes. This means that the exchange messages grows no faster than a certain constant value (in the case of broadcasting) or a logarithmic one (in the case of DHTs). In fact, it grows slower. From a practical point of view, the value of O(n) agrees with n [58].

Message counts are considered as a metric value for communication overhead [60] and can give evidences about the network and the bandwidth usage, as well as about the end-to-end latencies. O(logn) and O(n) indicators depict the worst case scenario for n nodes in the network.

As Figure 3 shows, DHT lookup technique is more efficient than Broadcasting. Thus, it will be used in the proposed solution. In addition with DHT the resources discovery can be satisfied in a bounded number of steps even for large scale distributed systems

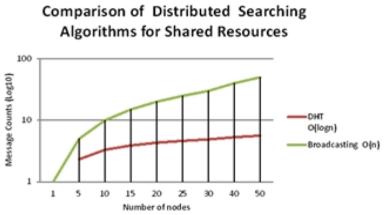


Fig.3. Numerical analysis for comparison of lookup P2P algorithms.

2.3. DESCRIPTION OF THE CHOSEN DHT ALGORITHM

There are in the literature a large amount of DHT routing infrastructures based on P2P systems, and a one possible taxonomy is done in [54] Examples of DHT protocols include Chord [61], CAN [62], Pastry [63], Tapestry [64] among others. They differ mainly in how peers maintain their routing tables to guarantee an efficient content location [65].

Among all of possible DHT routing protocols listed before, Chord protocol has been chosen as lookup algorithm. The reason is that Chord is the most popular structured routing protocol [54, 66] and it has several features that distinguish it from the others DHT lookups algorithms. These characteristics are [67]: i) Chord is completely distributed system, meaning that all nodes have the same role in the system; ii) Chord properly scales a large number of nodes; iii) Chord nodes can always be found even if they are continuously entering and leaving the network.

Although DHT-Chord protocol has been chosen to build up the proposed lookup algorithm, it is worth noting that the proposed concepts are independent of the chosen DHT protocol and they can be easily extended to others. Chord DHT-overlay organizes peers on a virtual ring topology ranged from 0 to 2^m-1 (Figure 4.a), where m is the number of bits in the identifiers. In this protocol each node is responsible for a collection of keys between its predecessor and itself for resource lookup (key-space). In this way, the resource ID is stored in the first peer, whose ID>= Resource ID (see Figure 4.b). Each node in the ring upholds a routing DHT table, called the finger table, which is used by the lookup algorithm (Figure 4.c).

The lookup algorithm is started by one node in the ring in order to find a particular key in the space-keys or by an external request and follows two steps [54, 66, 68]

- Firstly it checks if the node that started the search is in charge of that key. If this is true the search is over and the algorithm ends.
- Otherwise the node will employ its finger table to localize the closest successor of the target node's key and request the search of the key to the target node.

Let us consider an example. When peer #6 is searching the resource whose ID is 16, i.e. the target node will be peer #3, which is the node that stores ID=16 (see Figure 4). The peer #6 verifies if is in charge of that key. As it is not responsible for this resource, it will be check its finger table records. The finger table of peer #6 stablish that the nearest peer to the destination is peer #15 (See finger table of N6 in Figure 4.c), and it sends the request to this successor. As the peer #15 is also not liable for this resource, it would also check its own finger table, searching the closest peer of the target's node. The finger table of peer #15 stablish in this case that the closest node to reach the request is peer#3 (See finger table of N15 in Figure 4.c), thus it forward the message to this successor. Peer #3 has the resource and it is the destination, so the process ends.

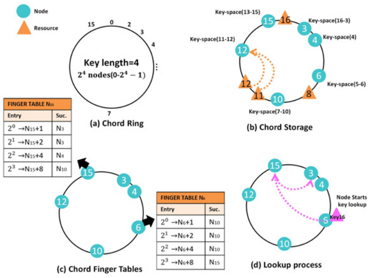


Fig.4. Chord Protocol Operation.

In a P2P system, each peer joins and leaves the system at any arbitrary time. Chord adapts efficiently as nodes join and leave the system, and can answer queries even if the system is continuously changing [24]. This means that the finger table is dynamically built through a stabilization mechanism.

2.4. NETWORK REQUIREMENTS FOR SMART MICROGRIDS

To control and monitor the intelligent microgrid, a Real-Time Measurement Parameters (RTMP) function is required [69-70]. To reaching this objective, is mandatory to know what bandwidth (used to signify the data rate in bits/second) and what latency (delay) may have the transmitted data among the microgrid components (DERs) for each microgrid function [71-73]. Each microgrid function has its own latency and bandwidth requirements depending upon the kind of system response is dealing with. The IEC 61850 and IEEE 1646 standards give specifications for these requirements as [Table 1] summarizes [74-76].

The communication system of the microgrid must satisfy these timing requirements because a low bandwidth can lead to bottlenecks, loss data packets and distortion. Besides, if the communication delay exceeds the required time, the information does not fulfill its purpose and, in the worst case, damage might be occurred [34]. In this regard, the underlying communication system needs to be designed with well-defined network performance requirements to meet the needs of time sensitive data streams, bandwidth and latency, among others [77-78].

TABLE I

MG APPLICATION AND NETWORK REQUIREMENT AS STATED BY IEC 61850 AND IEEE 1646 STANDARDS

Application	Network Requirements	
	Bandwidth	**Latency**
Demand response	14-100 *Kbps*	500*ms*–several minutes
Distributed energy resources and storage	9.6-56 *Kbps*	20*ms*-15*s*
Distributed management	9.6-100 *Kbps*	100*ms*-2*s*

Table I shows the needed performance requirements as states by IEC 61850 and IEEE 1646 standards. Besides these requirements, microgrids are evolving towards distributed and intelligent systems, needing to process a high volume of data. Thus, the management and control of microgrids is becoming a critical challenge. The latest research indicates that current distributed MAS have some limitations about the efficient and optimal management of microgrids [49, 79-82]. On one hand, to get the overall information about the microgrid dynamic network, the agents should be grouped in clusters, following a certain criterion (for instance, the kind of resource). The absence of such functionality might result in a lack of knowledge about the global status of the microgrid and, therefore, in sub-optimal resources allocation. On the other hand, agents have neither dynamic reorganization nor self-healing capabilities by themselves, which would result in better response to local-failures, microgrid blackouts, agents' crashes or communication failures.

According to the general needs that have been described above, P2P communication systems offers some interesting features to meet the desired requirements. First, P2P protocols have a high degree of flexibility and can be easily adapted to new applications by means of overlays. Second, the communication system must be highly scalable while maintaining the capability to process the growing volume of data. These characteristics are inherent to P2P systems. However, P2P networks were mainly developed for file sharing and processor cycle sharing. In these applications, the network performance requirements are less critical than the ones of microgrids (see Table I). Thus, they should be adapted to provide:

1) An application layer to retrieve data from the system. In conventional DHTs, the nodes store the keys to locate information of the key it is responsible for. Thus, each node should stablish its own methods to retrieve this information. To achieve this objective a communication infrastructure based on a stack protocol with an application layer has to be developed according to the goals of the microgrid.

2) A communication system able to achieve efficient and scalable routing for enhancing network performance, resulting in a highly distributed communication system, with low network traffic and latencies. Conventional DHTs not consider locality issues. However, locality lets to create clusters with similar interests, reducing the network overhead and latencies.

Therefore, conventional DHTs need to be adapted to the specific case of microgrids. The proposed solutions are widely explained in Section IV and Section V.

2.5. PROPOSED LOCALITY-ROUTING ALGORITHM

A missing feature in conventional DHTs is the ability to perform complex queries, such as a lookup operation containing regular expressions. One solution to the above problem is to perform the broadcasting in all the nodes (Full Flooding) or only in some of them, which are a part of the DHT (Limited Flooding). These solutions are currently used to many peer to peer applications.

In [78] a structured flooding algorithm is applied to the Chord architecture. In this flooding scheme, Full-Flooding (Full_F), when a node receives a lookup query, it forwards it to all the nodes of its finger table and recursively these nodes retransmit the lookup query to all their respective nodes. The flooding stops after TTL=4 hops. In this scheme the lookup message will visit each node at least one time to obtain data retrieval. However, in this model locality is not considered.

Typically, different criteria can be adopted to provide locality by creating logical groups that form communities in order to achieve common objectives and goals [83]. This approach is usual in limited flooding solutions. With the objective to compare the performance of the flooding algorithms with the one of the proposed solutions, we have adapted the conventional flooding algorithms, by adding the application layer and some specific features of microgrids.

In the case of microgrids, these logical groups are often categorized based on their nodes functionality (loads, generators, storage system, etc.) so that the exchange of messages outside a certain community is not taken into account and then don’t consume communication resources [19]. Therefore, the basic idea of the proposed algorithm is to add network locality to DHTs based on the type of DERs connected to the microgrid and also enabling data retrieval. In this way, to provide locality aware in DHTs systems, node’s finger table of traditional Chord model has been modified in order to embed DER functionality and keep the neighborhood of locality in the ID space (Chord space-key is not considered). In this scheme, when a node joins the network, it first identifies the kind of DER that has been associated to it, which may be a critical load (CL), a semi-critical load (SCL), a non-critical load (NCL), a distributed generator (DG) or a storage system (SS). After that, Limited Flooding (Limited_F) is applied. In Limited Flooding a node initiates the search for a specific functionality of the DER node by sending the query to all its neighbors that have the searched prefix. When a node receives the query message, it continues the flooding search until the message time to live (TTL) threshold (in this case TTL=4). Therefore the lookup message will visit each searched kind of node at least one time to obtain data retrieval.

However, with the main idea of reducing network latencies and unnecessary network traffic, besides the proposed locality finger table, a new Locality-Routing Algorithm (Proposed_LRA) has been developed. The locality-routing algorithm helps know the number of devices and their type (the searched prefix depends on the kind of device: CL, SS, DG, etc.) that are connected to the microgrid to provide an efficient management of the microgrid resources.

Figure 5 shows the flowchart of the LRA algorithm. When the lookup process of the peer-to-peer nodes starts, two threads are generated, either for ingoing or outgoing lookups petitions. The outgoing lookup process is started by a node of the network in order to find the searched prefix or kind of device. For that, a lookup message must be created. The searching message has three main fields: i) IP_node_source that contains the IP of the node which starts the lookup process; ii) DER prefix that contains the searched prefix nodes and iii) Match_Node_List, which is generated as the message progresses in the network and contains a list with the matched nodes. To conform the Match_Node_List field the Match_Search_Node Process starts and therefore the neighboring LRA finger table is going scrolled down. When the prefixes of the nodes in the LRA table match with the searched prefix, the node is added to the Node_Match_List and its IP is added to the Nodes_to_Send_List (only if the node number and its IP were not before in these lists). In addition, it is possible that the node does not content any neighbor containing the searched prefix in its LRA finger table. Therefore, the successor node must be verified to avoid a break in the searching process.

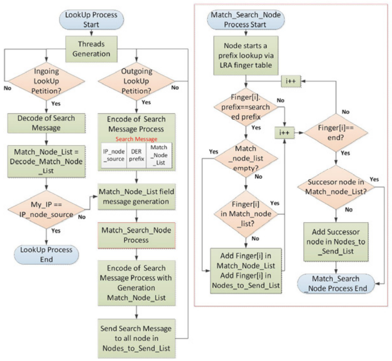


Fig.5. Flowchart of proposed LRA algorithm.

Once all the searched nodes are

found, the searching message is encoded and it will be sent to all the matched nodes. In this way, when an ingoing lookup process is started at the receiving node, it will be able to check the node match list and add its own new matched nodes (from the data stored in the received Match_Node_List) before to send a new query, to avoid sending redundant searching messages. The searching process continues until the source's node is reached.

2.6. Proposal of a Layered Communication Architecture and an application protocol for MG’s.

The efficient integration of DERs in microgrids needs the ability to monitor all units and provide real time control. According to that, the P2P control architecture introduced in section 2 seems to be a good infrastructure for the exchange of data and control actions among the DERs of microgrids. To create an operational peer able to run in the communication network of a smart microgrid, several software layers need to be built [57, 84-85]. The proposed communication architecture is based on a structured decentralized peer-to-peer overlay network and it is depicted in Figure 6.

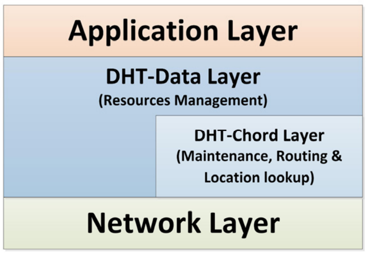


Fig.6. Proposed stack protocol of an operational peer for a generic DHT peer communication architecture

This solution applies the P2P overlay principles to the field of energy control and monitoring of DERs. Therefore, the proposed communication architecture should be implemented on each one of the nodes where an electric module (such as inverters, transformers, switches and so on) is connected. So, each node is interconnected with their electric modules and with the communications network.

The development of the different layers for implementing the proposed overlay P2P service is described below.

2.6.1. Network Layer

The network protocols used for this architecture are based on TCP/IP suite model. To improve the smart capacities of a microgrid, it is mandatory the ability to connect a large number of devices and handle a large volume of data in real time, which must be quickly updated to make decisions in the least possible time. Therefore, for the transfer of data it is needed: i) a large bandwidth, ii) high data rate and iii) a network layer with fast channel response. To accomplish these requirements, TCP/IP is preferred for interconnecting power systems devices, because it provides high connectivity, high bandwidth and quick response [86]. The interconnection network ensures reliable and secure communication between components by employing an internet protocol (IP) and data traffic remains secure and safe because the transport communications protocol (TCP) is connection-oriented. In addition the IEC 61850 via Ethernet standard suggests the use of TCP/IP for efficient communications among microgrid components [87-88].

2.6.2. P2P Layer

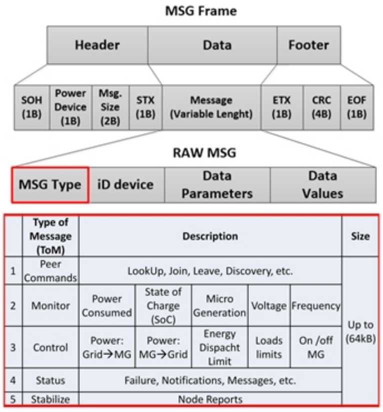
The proposed P2P layer defines two levels or software layers for implementing overlay-P2P services (See Figure 6): On one hand, DHT-Chord layer provides P2P networking services to achieve the following tasks: i) resource and network discovery, ii) session establishment, iii) routing, iv) data transfer among nodes and v) entry/exit management of nodes. To evaluate the network performance, the different algorithms previously developed will be implemented in this level. On the other hand, the second P2P layer is responsible for handling the peer resources information.

In the P2P overlay networking layer, an Application Programing Interface (API) has been developed to run the node functions i) to iv) that have been listed in the previous paragraph. In this layer, each peer maintains the connection with their neighbor peers. Moreover, this layer includes neighbor discovery and it has a bootstrap engine for session establishment. For joining and leaving the network there is a join/leave protocol. The overlay networking layer also provides the mechanisms for routing data packets across a large network. In addition, Chord runs a special stabilization algorithm, called stabilize, which is periodically executed by each node every 60 milliseconds to keep the list of predecessors and successors and to confirm that the ring integrity has not been corrupted. Therefore, if a certain node n fails, the nodes whose finger table includes n are responsible for finding the n's successor. It must be avoided that the failure of n provokes a disruption of the queries that are in process while the system is re-stabilizing. To achieve that, each peer maintains a successor list of its r nearest successor's node. In this way, when a certain node m notices that its successor has failed, it replaces the failed node by the first alive entry from its successor list. The queries will continue while the algorithm is correcting the finger table entries and the successor list. This allows not significantly increasing the end to end latencies if a node fails.

Besides, the DHT-Data layer stablishes how the peers self-organize its resources and also the data management. It is worth noting that the DHT-data layer comprehends data bases and uses the DHT-Chord one for storage of data. The Data layer for each node is defined as described below. On one side, peers should be able to react by sending messages in certain situations, for instance, in faulty conditions, when the operative power limits are reached, etc. On the other side, peers should be continuously providing information about its actual status and also the one of its neighbors. Thus, the data base of each node is composed by two parts, named static and dynamic sides. The static side provides the description of the node itself (kind of DER: CL, SCL, NCL, DG…), the IP address, the GUID (Global Unique Identifier) and the definition of its power limits. The dynamic side periodically collects, from itself and from its neighbor peers, the main power parameters for knowing the global status of the microgrid.

2.6.3. Application Layer

The application layer is responsible for the processing and data analysis, as well as event management and supervision of the microgrid status. In addition, a specific microgrid communication protocol has been developed and implemented at the application layer for transmitting data among peers. Figure 7 shows an overview of the implemented Microgrid communication packet structure. The message header contains the type of message (ToM), the id device address, and data parameters and values. As Figure 7 shows, there are five ToMs that each peer of the network can send to the others. The function and the size of each ToM are also described.



	Type of Message (ToM)	Description					Size
1	Peer Commands	LookUp, Join, Leave, Discovery, etc.					Up to (64kB)
2	Monitor	Power Consumed	State of Charge (SoC)	Micro Generation	Voltage	Frequency	
3	Control	Power: Grid→MG	Power: MG→Grid	Energy Dispacht Limit	Loads limits	On /off MG	
4	Status	Failure, Notifications, Messages, etc.					
5	Stabilize	Node Reports					

Fig.7. Developed Packet Frame Structure.

Fig. 8 shows four different architectures that can be used to implement the proposed algorithms. Depending on the used architecture, the performance of the network varies. The four evaluated architectures are: i) Full-flooding-Architecture (Full_F*), ii) Limited-flooding-Architecture (Limited_F*), iii) Simple Query-Response (simple QR) and iv) Embedded Query-Response (Embedded QR). In a), b) and c) approaches, any peer of the network can launch the primitive QUERY about a specific kind of device to know their operational parameters. The difference between a normal QUERY and a primitive QUERY is that the second one is directly and only sent to the matched nodes. These nodes reply to the source node without transmitting the query through the ring. When the query is launched, the lookup process starts (according to the algorithm executed) and find the nodes of the network that are of the queried type. Then, the resources management is performed. Once the node receives the responses from the different peers, the data exchanges using periodic request-responses queries are executed. These queries occur between queried nodes through the application layer. In d) the application layer is embedded into the P2P layer, so that both data exchanges and lookup process are simultaneously launched.

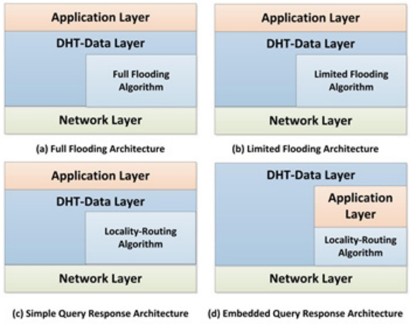


Fig.8. Different approaches with a specific DHT peer algorithm over of the proposed communication architecture.

To better understand the differences between simple and embedded query response architectures, Fig. 9 illustrates the sequence diagram of both architectures. Flooding architectures have not been considered because they are not based on the chosen DHT protocol.

As it can be seen in Fig.9.a, a peer sends out a lookup message to the LRA finger table neighbors that match with the searched prefix. Thus the neighbor peers propagate the lookup message among the matched nodes that are listed in its LRA finger table. The lookup message is passed around the ring following this procedure. When the lookup message reaches the source node, it has the information about all the matched nodes. Once it has this information, it is able to send the primitive query directly to the matched nodes without passing through other peers. Fig.9.b, shows that the primitive query message is embedded in the lookup message. As a result, both the number of messages that need to be sent and the latency of the system are significantly reduced. Figure 10 shows the used pseudo-code to embed the application layer into the DHT-P2P one.

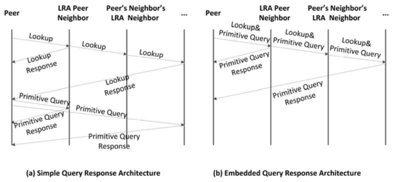


Fig.9. Time-space diagram showing the lookup and query-response processes for the (a) simple and the (b) embedded communication architectures

Fig. 10 shows how the application layer has been implemented in the P2P layer. The Manager module manages the overall operations of each node in the P2P network. The peer is initialized by providing a port to listen for incoming connections (serverport), a host address (serverhost) and a node identifier (node). The handlers is a class that contains the different peers' functions. Using threads the mainloop of a peer begins up a socket that listens for incoming connections from other peers. When an incoming connection is accepted, the server will have a new socket object used to send and receive data on the connection. Then, the main loop calls a separate method to handle communication with this connection in a new thread. When the peer wants to lookup matched nodes, it set the parameters for query (params) and conform the message through invoking the application layer module. The message is passing by reference to the lookup function which allow for embedding the application layer into the DHT layer. The lookup function method uses the LRA routing function to decide where to send the message.

```
def DHT_Layer():

    node = Node.Node()
    Data_Base=bd_conex.BDConn()

    ## ---------node parameters------

    node.ipAddr = 'XXX.XXX.X.X'
    node.Port=10000
    codeHash = hashlib.sha1()
    codeHash.update(node.ipAddr)
    code=node.code = int(struct.unpack('16xI',codeHash.digest())[0]&(2**8)-1)
    Host=node.ipAddr
    myDER='CL'
    tables=Data_Base.tablesg()
    Data_Base.tables_generation(tables,Host,myDER)
    serverport=PORT
    node=node
    serverhost=Host
    btpeer=Manager.handlers(serverport,node,serverhost)
    btpeer.buildpeers(node)

    #----Threads generation-------

    t=threading.Thread(target=btpeer.mainloop,args=[])
    t.start()
    #----Application layer embedded into DHT_layer-------
     params=application_layer.params_to_monitor
     application_message=application_layer.frame_generation(params)
     btpeer.lookup(key,application_message)
```

Fig.10. DHT layer pseudo-code. Detail of embedded application layer.

It is worth noting that the proposed communication architecture should be implemented in each one of the nodes where an electric module (such as inverters, transformers, switches and so on) is connected. Therefore, each node is interconnected with the electric modules and also with the communication infrastructure through embedded single board computers (SBC). Moreover, the proposed communication system is adaptable to any kind of microgrid with Ethernet connectivity. In this case, the experimental evaluation by means of virtual machines (VM) has been performed by taking into account that the proposed solutions will be applied in the future to a Hybrid AC-DC [89-90] microgrid that is in course of deployment in our laboratory, as Figure 11 shows. The nomenclature used in this figure has been detailed in Table II.

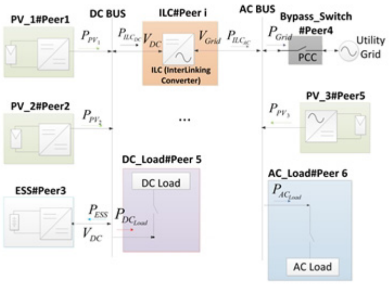


Fig.11. Conceptual scheme of the experimental hybrid microgrid with 8 nodes.

TABLE II
NOMENCLATURE

P_{PVn}	Power supplied by the PV arrays
P_{PV}	PV power generated by the DC MG
P_{DCLoad}	Overall power consumed by the DC loads
P_{Grid}	Power injected from the HY MG to the grid
P_{ILC_AC}	Power injected from the DC bus to the AC bus by the ILC, measured at the AC side of the ILC
P_{ILC_DC}	Power injected from the DC bus to the AC bus by the ILC, measured at the DC side of the ILC
P_{ESS}	Battery bank charge power seen from the DC bus
P_{ACLoad}	Overall power consumed by the AC loads
P_{AC_DGs}	Power supplied by the AC DGs
V_{Grid}	RMS value of the grid voltage
V_{DC}	DC bus voltage

2.7. EXPERIMENTAL RESULTS

An experimental setup has been built to evaluate both the performance and behavior of the different lookup algorithms and the communication architecture for control purposes. To achieve this objective, a server with a hypervisor (VMware ESXi) has been used to run 25 virtual machines. Each VM run Ubuntu 14.04. The VMs are connected to the LAN through a virtual switch limited to 100Mbps.

The resources of each VM have been limited to 512MB of RAM and 200 MHz of CPU. This configuration agrees with the one of the embedded system that we will use to migrate from virtual to physical machines, so the experimental results that are presented are realistic and valuable to preliminary validate the proposed solutions.

2.7.1. *Algorithms Comparison*

The performance of the different lookup algorithms has been studied by measuring the number of lookup messages and the lookup latency. Figure 12 represents the total number of lookup messages that have been sent from a source node (which initiates the search) and retransmitted by the intermediate nodes. It may be seen that the number of messages that are required to perform the query process increases as the number of nodes does. However the rate of increase with the flooding algorithms is more abrupt than with LRA. The reason is that flooding algorithms do not use a method to know if the queried peer has been visited before. The proposed Locality-Routing Algorithm uses a routing algorithm that allows knowing what target peers have been previously visited and avoid to send redundant messages, so that the number of messages required is significantly reduced

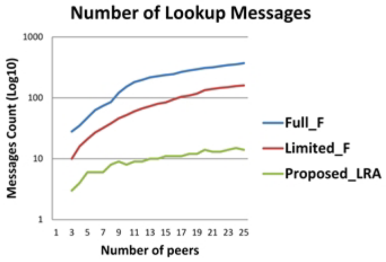


Fig.12. Comparison of the number of lookup messages sent by the different algorithms

Figure 13 shows the evolution of the lookup latency as the number of peers increases. It has been verified that flooding algorithms need much more time to perform lookups than the proposed algorithm. Two reasons justify this result; on one hand, only the target's peers are visited with the proposed algorithm, so that the number of peers to perform the lookup process is lower. On the other hand, each peer is visited only one time, avoiding redundant visits.

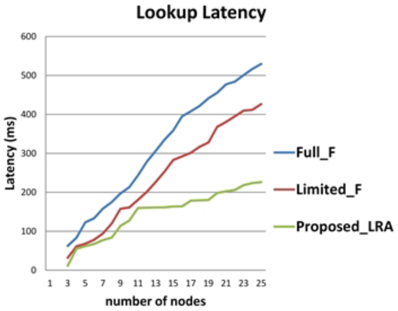


Fig.13. Comparison of lookup latency by the different algorithms

2.7.2. *Communication Architectures Comparison*

The performance of the proposed communications architectures has been studied. The evaluated scenario reproduces data exchanges between matched peers using request-response at 100% of the communications load, i.e., the transmitted messages have the Maximum TCP Segment Size (1500 bytes). The criteria for performance evaluation are the following:

- Total number of messages exchange: it is referred to the total number of messages that have to be exchanged among all peers both for lookup the match peers as for sharing information among them.

- End-to-end Latency: it contains the information obtained from the total nodes in the network regarding the lookup latency and the processing latency.

In both cases, the number of matched nodes has been taken to be equal to 60% of the total nodes in the network, i.e. for 25 peers, the number of matched nodes will be 15.

Figure 14 shows that the number of total messages exchanged with the embedded QR approach is lower than with simple QR even if the same locality-routing algorithm is used. It is worth to point out that simple QR needs an additional application layer to recollect data from the match nodes, while embedded QR doesn't need because the nodes respond by sending its operational parameters in the same lookup process.

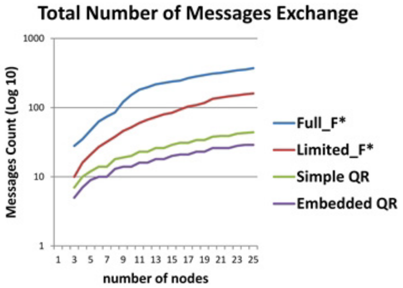


Fig.14. Comparison of total number of messages exchange by different communication architectures

Figure 15 shows that end-to-end delay in embedded QR architecture is lower than the query-response approach because the total delay is mainly produced by the processing delay. The lookup delay can be considered not significant when the application layer is embedded in the P2P routing layer. The total end to end delay for 25 nodes with embedded QR is around 500 milliseconds while for simple QR is around 650ms because its lookup latency is around 200 milliseconds (see Figure 13). Thus, the average processing delay per node in embedded QR architecture can be estimated around 20 milliseconds. This means that the average latency to process a TCP packet with maximum segment size in an embedded query-response design (round-trip time delay) is around 20 milliseconds, which meet the network microgrid requirements that were outlined in Table I.

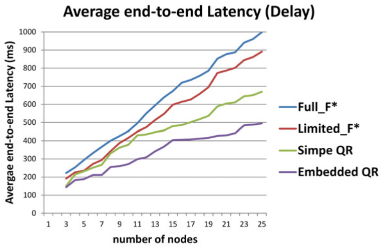


Fig.15. Comparison of end-to-end packet network delay by different communication architectures.

2.7.3. Network Performance Analysis

In the previous sections it has been demonstrated that the embedded query-respond is the most efficient communication architecture for control and monitoring of smart microgrids, as well as the latency network requirements are fulfilled. In this section, the network usage and the bandwidth requirements are evaluated. With this goal, periodic query-response queries tests have been carried out, where information is transmitted from each peer at a frequency of 1Hz and 100% of TCP load.

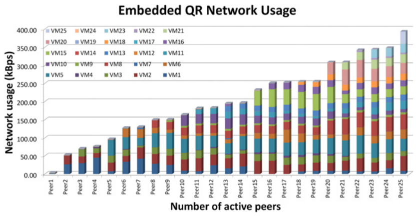


Fig.16. Network usage (in Kbps) per peer on a network of N=25 peers

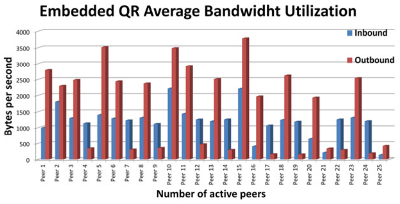


Fig.17. Average bandwidth utilization (inbound and outbound) per peer on a network of N=25 peers

Figure 16 and Figure 17 show the network usage generated by peers in the network and the bandwidth utilization (per peer), respectively. The total traffic generated by 25 peers in Figure 16 is around 400 kBps. The traffic is much lower than the bandwidth provided by the Ethernet installation (Ethernet's 100BaseT twisted pair cable (UTP)), which would possibility the execution of a large number of nodes. Otherwise, the average bandwidth per peer (Figure 17) is around 1200 bytes/sec inbound and 1600 bytes/sec outbound. These results show that both network usage and average bandwidth meets the distributed control microgrid requirements (Table I).

2.8. DISCUSSION OF RESULTS, CONCLUSIONS AND FUTURE WORK

In this paper a decentralized communications infrastructure based on peer-to-peer overlay technology for control and monitoring of smart microgrids has been proposed. It has been shown that the peer-to-peer paradigm can be applied to build up the communications layer of microgrids, with a set of potential improvements in terms of robustness, efficiency, scalability and flexibility. A novel scheme of locality-routing algorithm (LRA) based on DHT-Chord overlay has been developed. The presented experimental results show that the number of lookup messages and, consequently, the lookup latency network, are lower with the proposed LRA scheme than with other DHT-flooding techniques. The network overhead is reduced by reducing the amount of lookup messages. Besides, both DHT-flooding lookups algorithms and LRA algorithm have been integrated into a fully decentralized communication architecture to provide optimal control and monitoring of smarts microgrids. The architecture design has been optimized by embedding the additional application layer with the P2P layer. The results show that the performance of each one of architectures depends strongly of the used lookup algorithm as well as the placement of the communication layers in the architecture. Finally, the embedded model has been tested by using relevant network performance parameters such as latency, network usage and bandwidth. The experimental evaluation shows that the proposed P2P architecture are useful for demanding environments where strict network specifications are required, and also that the communication performance meets the network requirements of smart microgrids.

In spite of the advantages of the proposed solutions, there are some limitations that can be pointed out and will guide our future research work:

- The clusters in the proposed algorithm have been organized around a specific type of DER, such as critical loads, distributed generators, etc. In order to add flexibility to the algorithm, it could be interesting to study the clusters' classification from other features different that the nature of the DER.
- The proposed algorithm creates one overlay layer on top of the physical network. However multiple overlays layers could be created to provide other microgrid services. For example, in a second layer, multicast services could be provided. These services could very useful in the microgrid context. For example, when a set of real-time control signal needs to be distributed to a large set of participants. This issue could be carried out by means of tunnels [91] which can give multicast services access to the end peers. Overlay multicast can also be perceived as topic-based publish/subscribe [92].
- The proposed solutions have a certain security degree due to redundant link and self-reconfiguration [19] have been implemented. However, the system is sensitive to malicious attacks such as Sybil or Eclipse [93-94]. Thus additional security procedures should be studied and implemented to reduce the sensitivity to malicious attacks.
- The IEC 61850 standard has been widely used in smart substations and it has been also proposed to smart microgrids. It defines priority GOOSE (Generic Object Oriented Substation Events) messages and switching Ethernet for fast and reliable transmissions among DERs. The objective is to improve the transmission efficiency and guarantee that the transmission time of each message is lower than 4 ms [95-97]. The protocol stack should implement this communication mechanism.
- The proposed solutions have been validated by means of experimental results that have been carried out by means of virtual machines. The achieved results take into account most of the system physical limitations. Therefore, it can be concluded that the proposed solutions are an interesting approach to the problem of communications in smart microgrids. However, additional experiments should be carried out by means of a real microgrid to completely validate the concept. This is one of the future works that should be performed.

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3

PUBLICACIÓN III

EFFICIENT EVENT NOTIFICATION MIDDLEWARE FOR SMART MICROGRIDS OVER P2P NETWORKS

Marzal, S., Salas-Puente, R., González-Medina, R., Garcerá, G., and Figueres, E. “Efficient Event Notification Middleware for Smart Microgrids over P2P Networks,” IEEE Trans. On Smart Grids, 2018.

Contenidos

Efficient Event Notification Middleware for Smart Microgrids over P2P Networks

Abstract**—** Microgrids are moving towards large-scale smart distributed networks which demand an efficient and reliable communication infrastructure to manage, control and monitor energy resources. With regard to this, publisher/subscriber event-based middleware has become relevant for large-scale distributed time applications because it allows decouple time and space between senders and receivers. Particularly the content publish/subscribe systems over structured peer-to-peer (P2P) networks has emerged to enhance scalability and dynamism of notification middleware systems. However, this type of systems use multicast routing schemes that still generate much network traffic and as a consequence an overload of the communication channel is produced. This results in inefficient network utilization and rapid depletion of network resources leading to unreliable operations, degradation of system performance and even instability of the microgrid. In this paper, a new content-based publish/subscribe notification middleware over structured P2P systems is proposed, such that smart microgrid communication requirements are met. This proposed system organizes the publications and subscriptions in a one dimensional representation using the Hilbert space filling curve. Through this representation, an innovative routing and matching algorithms are developed. Experimental results demonstrate that the proposed publisher/subscribe system significantly enhance efficiency of the system, network performance and the use of computational resources.

Index Terms**—Notification middleware, P2P systems, microgrids.**

3.1. INTRODUCTION

Microgrids (MGs) are defined as groups of distributed energy resources (DERs) formed by distributed generation (DG), both renewable and/or conventional, energy storage system (ESSs) and loads. Microgrids can operate connected to the main grid via the point of common coupling (PCC) (grid connected mode) or completely separated from the main grid (island mode) [1]. The data transmissions among microgrid components are implemented via communication networks. Thus, the management and control of the microgrid by the Microgrid Control System, MCS, rely on a robust communication infrastructure [2]. One of the key points for integrating DERs into microgrids is the design of a control architecture that coordinates each one of the DER units. Traditionally, this control architecture is categorized into three major groups: centralized, decentralized and distributed control methods [3]. In this study a distributed architecture is considered (Figure 1), in which the local nodes have its own MCS and are able to take decisions. In addition, nodes can share their information through two-way communication links [4].

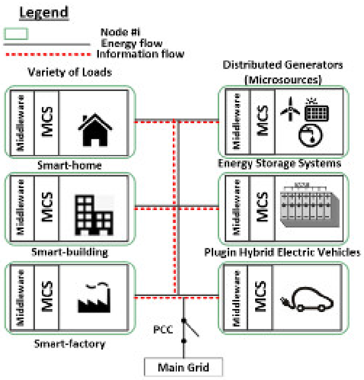


Fig.1. Overview of the distributed microgrid scenario

Nowadays, smart microgrids communications have to deal with large-scale distributed energy resources and manage them in real-time and dynamically. To cope with this, middleware architectures are one of the technologies adopted and they are a critical element in adapting to the challenges of smart microgrids [5]. In particular, microgrids require agile, flexible, real-time communication solutions, which have driven the growth of event-based middleware architectures. In an event-driven communication scheme, the signal transmission is triggered only in response to an event when a significant change of controlled or monitored physical variables occurs. A convenient way to construct microgrid services that use event infrastructures is through the implementation of communication middleware that works under a publish/subscribe (pub/sub) paradigm [6]. Pub/sub paradigm allows non-blocking asynchronous communications and one-to-many messages distribution for event notification.

In this regard, structured P2P networks have become popular as a platform to develop event-driven pub/sub middleware for large-scale distributed systems. These networks have many advantages such as decentralization (central points are not needed), self-organization (nodes can dynamically arrive or depart) and scalability (available resources grow with the number of nodes in the network) [7],[8]. In fact, recent researches [9],[10] suggest the extension of the IEC 61850 communication standard for microgrids to include P2P communication systems aiming to better adapt to the new large-scale distributed scenario of microgrids.

Existing pub/sub systems based on structured P2P networks, traditionally use topic-based systems for publishing event notifications and multicast protocols for routing this event notification [11]. However, the use of these techniques is not optimal for microgrids because its network requirements are more demanding [12]. The reasons for that are the following: on one hand, in topic-based pub/sub systems each event is labeled with a topic (predefined subjects). The main disadvantages of the topic-based model are the limited flexibility and accuracy it offers to subscribers. As a result, a subscriber has to receive all the notifications relative to a topic though the subscriber might be interested in only a subset of the events. In addition, topic-based systems give limited choices of subscriptions while in microgrids applications, the subscribers must be able to specify their interests more accurately using a set of predicates, leading to a more optimal and efficient control [13]. On the other hand, multicast routing generates a large network traffic which can produce congestion, increased delays and poor bandwidth utilization. Moreover, with multicasting a high amount of false positives could take place, due to an event could be transmitted to nodes that are not interested in it or not need to route it to other destinations [11]. The pub/sub systems that work in environments where vital information is transmitted, false positives are not acceptable because the efficiency of the whole system could be significantly reduced [14].

Furthermore, communications between DERs is carried out through IEDs (Intelligent Electronic Devices). IEDs are devices equipped with operating systems that make two-way communication possible to monitor and manage the power grid. However, the main problem to their use is the limited computational capabilities. Given the event-driven middleware should be embed in each node of microgrid, the computational resources used for the middleware operation should be minimized [15].

Summarizing, conventional pub/sub notification-based middlewares are not properly adapted for microgrid environments due to the following reasons: they not offer subscription flexibility, they produce a high amount of network traffic as well as high network latencies; finally, they need high rates of computational resources. Therefore, the development of an event notification middleware specifically designed for microgrids is needed, which should be adapted to the quality performance requirements of this kind of applications.

In this paper a new and efficient event notification middleware architecture based on pub/sub content-based system over structured P2P networks particularly built for smart microgrids is proposed. The main contributions of this work are: (i) a Hilbert mapping system which allows subscribers defining multiple dimensions of the contents in a single dimensional space by using a set of ranges (this allows for greater subscriptions flexibility and robustness in contrast with topic-based systems that are restricted to predefined topics), ii) an efficient content matching algorithm to reduce false positives rates and speed-up routing decisions and iii) a routing protocol based on ranges representation, ranged based routing protocol (RBR) instead of multicast routing. The proposed protocol reduces the network traffic, as the pub/sub system can transmit an event only to the subscribers that are concerned in.

These contributions allow a greater network performance and also save computational resources. The reduction of the network traffic involves a low number of messages transmitted so the CPU utilization decreases while the subscriptions optimization reduces the communication overhead, which reduces the memory usage.

The paper is organized as follows. In Section 2, the challenges of event notification middleware for MGs are provided. In section 3, the proposed solution is described. In Section 4, experimental results are presented and analyzed. Finally, Section 5 provides some conclusions.

3.2. CHALLENGES OF EVENT NOTIFICATION-BASED MIDDLEWARE FOR MICROGRIDS

To avoid unnecessary information request, an event notification service (ENS) that use event-based communication model can be used in microgrids. This service will be able to monitor and control the power network in an efficient manner as this communication architecture reduces the communication and computation load [16], [17]. In this technique, the pub/sub communication paradigm is mainly used to notify system changes to a set of interested receivers. In a pub/sub system, the providers of information (publishers) disseminate events to the system and the information consumers (subscribers) subscribe to the event that are interested on. All data are published or subscribed to/from the middleware service domain (Figure 2). When the middleware receives a publication it searches for matching subscriptions and notify them, and then the required data communication is achieved [18]. Relative to subscription models, the data distributed through the middleware service can be topic-based or content-based. On the one hand, in topic-based systems, the subscribers define its interest for a specific topic and will receive messages regarding to that topic. For instance, in the case of microgrids topics could be critical loads, photovoltaic generators, storage devices, island mode, etc. On the other hand, in content-based system, subscribers can define conditions over the content of the topic. For example, under the topic “Photovoltaics generator” it may be defined a certain number of attributes. A set of three attributes of interest could be Power (supplied to the grid), DC voltage (at the PV field) and State (connected or disconnected). As it can be deduced, content-based pub/sub is a more robust architecture, as subscribers can select its filtering criteria through the definition of multiple dimensions of the message contents [19]. Note that topic-based systems are restricted to pre-defined subject fields.

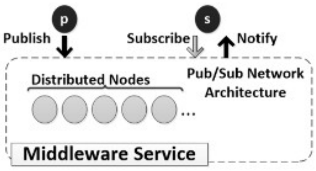


Fig.2. Communication architecture of a publish/subscribe system. (p and s indicate a generic publisher and subscriber respectively)

Event driven data exchange is an essential requirement for future self-manageable microgrid implementations [20]. In fact, the IEC61850 standard promotes the development of pub/sub services. However, microgrids are growing and managing a great amount of DERS. Therefore, some IEC 61850 components could be inadequate for Smart Microgrid (SMGs) development. In this sense, IEC 61850 standard should be extended to include large distributed control architectures implementing P2P systems [9]. This goal is indispensable for a system that can be continuously changing, such as a smart microgrid. Regarding to that, a general overview of middleware platforms for smart grids is presented in [5], [15], [21], [22], [23], [24].These works analyzes the key challenges associated with implementing services in the middleware layer. It is concluded that event notification middleware architectures for SMGs have various challenges:

1. *Real-time distributed pub/sub protocols which enable P2P communications [25], [26]:* P2P communication architecture provides a more reliability and suitable environment for distributed devices as it permits self-discovery of new nodes/devices and self-organization. Due to this, the dynamic participation of the nodes/devices in the network is allowed and it is especially important for microgrids, in which a large number of devices (electric vehicles, loads, etc.) can be continuously joining and leaving the microgrid.
2. *Flexible subscription system:* Moving the subscription model from topic-based to content-based improve the system flexibility and accuracy [18], [27].
3. *Reduced computational resources consumption:* To make feasible the Smart Microgrid, power devices deployed in it are equipped with IEDs. They are usually embedded systems with limited computing resources. The limited nature of the embedded system resources, especially memory size and CPU, complicates meeting the real-time constraints [28]. Since event-driven middleware must be embedded in each node of the microgrid, the computational resources used for the middleware operation should be minimized.
4. *Network quality requirements:* To guarantee the network stability face to certain events, the microgrid control system should monitor all the network elements and act accordingly when a parameter exceeds the specified thresholds. To achieve that, data must be delivered promptly. In microgrids, latency and bandwidth are essential to meet the microgrid requirements [29] following IEC 61850 and IEEE 1646 standards (See Table I) [30], [31].

Based on the described above, some solutions have been proposed in [32], [33] to address some of these challenges. In [32] a pub/sub middleware for microgrids is developed. Similarly, in [33] the authors present a novel middleware framework (GridStat) for the power grid operation. As performance indicators, they use the latency and load scalability parameters. Both studies propose a pub/sub communication architecture for event notification middleware. However, they use agents instead of P2P nodes. Although agents can be structured forming decentralized topologies, they cannot act simultaneously as servers and clients, which results in a lack of agent proactivity. The connectivity between them is not carried out by creating virtual links (overlays), which cause lack of self-discovery and self-healing capabilities [34]. To overcome these limitations, [25], [26] propose a Data Distribution Service (DDS) middleware. This kind of middleware uses Pub/Sub communications over P2P networks. Furthermore, [26] performs a comparative analysis of the latencies and bandwidth measurements of the DDS middleware. However, in both studies, the pub/sub system is topic-based and the routing of events is carried out by multicast. In general, the existing P2P pub/sub systems are usually created by using any kind of structured overlay networks. These structured systems are called DHT's (Distributed Hash Table) because their use tables for routing. Examples of DHT networks include Chord, CAN, Tapestry, etc. Using a DHT-P2P solution, the information can be sent by multicasting. The use of a multicast routing protocol for the pub/sub system has been the natural choice in topic-based DHT systems, as each published topic is identical to one multicast group. However, multicasting cannot be directly used in content-based systems because subscribers cannot be directly mapped to multicast groups [35], [36]. Moreover, when a multicast routing is used the data is replicated and sent to all the nodes in the list. The multicast process and data replication introduce high latencies and also high traffic that can be not suitable for microgrids.

TABLE I

NETWORK REQUIREMENTS FOR MGS APPLICATIONS

Communication Requirement	**Latency**	**Bandwidth**
Distribution Management	100ms-2s	9.6-100kbps
Demand Response	500ms-several minutes	14-100kbps per node
Monitoring Information	15ms-200ms	9.6-56kbps
Control Information	16ms-100ms	9.6-56kbps
Messages requiring immediate actions	1A:3 ms or 10ms;1B: 20 ms or 100 ms	9.6kbps
Outage Management	2s	56kbps

The multicast routing problem has been studied in some research works [11], [17], [27] looking for clusters of nodes configuration for multicast groups in order to reduce the network traffic. In these solutions, the routing system allows each node to create a routing table that associates the subscription of interest. Thus, each node is incorporated to the clusters that contain its subscription information and each publisher transmits a notification through the group of clusters. Upon publishing an event, the node transmits a notification to the nodes that are in its routing table and simultaneously are interested in that topic, as well as those nodes that operate as a relay node for the topic. The matching system of these solutions works as follows: once the node receives the notification, it extracts the information, filters the content and subscribes if the content matches.

However, refs [11] and [27] are topic-based and they are solutions that have not been specifically developed for energy environments. Therefore, the network performance and the optimization of computational resources have not been taken into account. In addition, although [17] is developed for energy environments, the pub/sub system is also topic-based and is not as efficient as content-based, due to there is not guarantees that subscribers receive accurate information about the topics they are interested in. As a consequence, the routing system still generates an excessive traffic as an event can be sent to not interested nodes and they do not need to route it [9]. In addition, the topic-based system also influences in the matching system that could produce too much false positives.

To overcome this limitation, in [14], an indexing system to provide content-based pub/sub systems over P2P networks is presented. A one dimensional representation using Hilbert space filling curve for pub/sub system is created. The results indicate that with Hilbert indexation, subscription forwarding load and speed up content matching is reduced. However, this system is neither a solution for microgrids nor routing mechanisms are proposed. In fact, this solution has been developed for file sharing applications in P2P environments. However, in such applications, the network performance requirements are less critical than the ones of microgrids. For that, this system is not a suitable solution for microgrids.

In summary, the previously proposed solutions that develop pub/sub middlewares for energy networks have some common limitations: (i) their focus is on the theoretical background of middleware architectures without any performance analysis; (ii) their studies are constrained to topic-based systems which use multicast routing mechanisms, with no attention to the network performance cost or the wasted computational resources; and (iii) neither the content pub/sub system over P2P networks nor their routing mechanism have been evaluated for MGs. Table II summarizes these conclusions. Therefore, the best pub/sub communication system to develop an optimal event notification middleware for microgrids seems to be a P2P content-based pub/sub system. For this reason, this paper is focused on developing such kind of middleware architecture for microgrids.

TABLE II
Review on Pub/Sub middleware architectures for Energy Network

Ref.	**Pub/Sub middleware over P2P networks**	**Content Based**	**Routing Aware**	**Performance Network Analysis**	**Computer Resource Analysis**	**Energy Networks**
[32], [33]	–	–	–	●	–	●
[25],[26]	●	–	●	●	–	●
[11],[27]	●	–	●	–	–	–
[17]	●	–	●	●	–	●
[14]	●	●	–	●	–	–
This study	●	●	●	●	●	●

Legend: ● Indicates that the characteristic is available in the category specified in the column heading. – Indicates that it does not

3.3. Proposed Event Notification Middleware

The proposed system is a content-based pub/sub event notification middleware over a P2P Chord overlay protocol. It is composed by the following components:

(A) An indexing scheme to implement a content-based pub/sub over P2P networks to improve the system flexibility and accuracy.

(B) A content matching subscription mechanism for reducing the number of false positives.

(C) An optimized routing engine (RPL protocol) for event dissemination system, to accomplish microgrid network performance requirements.

(D) An event notification service application for achieving a fully distributed system.

Figure 3 presents the architecture of the proposed system.

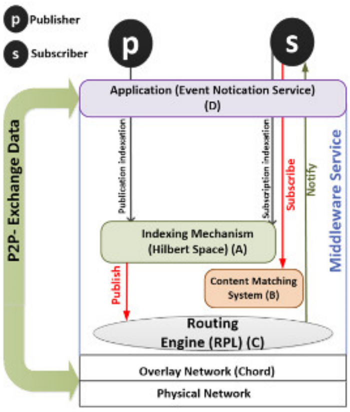
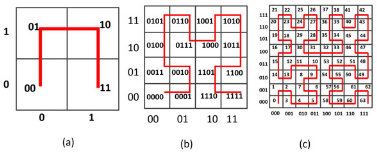


Fig.3. Overview of the proposed architecture

3.3.1. (A) The indexing mechanism construction

For content-based communication in a pub/sub system, a crucial component is the index space, as it is responsible for mapping the data elements to this index space. To be able to effectively support the subscription management, the multidimensional content space has been associated to a single dimensional space by means of the Hilbert Space Filling Curve (Hilbert-SFC) [37]. The $d-$dimensional space can be seen as a $d-$dimensional cube and the SFC is recursively constructed. For that, the $d-$dimensional cube is first partitioned into 2^k intervals and these intervals are numbered from 0 to 2^k-1. As a result of the cube partitioning, $(2^k)^d$ cubes of $d-$dimensional are obtained. Each one of the cubes is called cell [14].The partitioned d-dimensional space is represented by H_k^d. The index of each cell has been produced by using the Hilbert space filling curve and it is represented as $C=(x_1,x_2,\dots.x_d)$ where x_i is an integer of the Hilbert key in the partitioning space [38]. To illustrate this, the drawings of the first, second and third order approximation of the Hilbert curve have been depicted in Figure 4, corresponding to: H_1^2,H_2^2 ,H_3^2, respectively. In Figure 4 (a) and 4 (b), the Hilbert cells have been indexed in binary, while in Figure 4 (c) they have been indexed in its corresponding integer Hilbert key in the partitioning space.

By applying the Hilbert mapping to this multidimensional space, the proposed system maps each one of the d-dimensional attributes to a point of the SFC. This feature achieves high expressiveness in subscriptions as well as the reduction of the average message size for event publication and subscriptions. In this way, a reduction of both communication overload and latencies is achieved. The publication and subscription indexing are detailed below.



(a) (b) (c)

Fig.4. (a) H_1^2, (b) H_2^2 , (c) H_3^2 . The assignment of keys to cells in a Hilbert Space: first, second and third order.

1) Events Publication

In the proposed solution, every event publication ‘p’ belongs to the event space H and has an event type ‘τ’. It is defined as follows:

$$(p:\ \tau)\epsilon\, H$$

An event type τ has the following definition; $\tau=(n_\tau,\{a_0,a_1,\dots a_{d-1}\})$ where n_τ represents the event type name and $\{a_0, a_1, \dots a_{d-1}\}$ is a collection of event attribute types. Each attribute has its own value, v_i, in such way that every publication (event), p, symbolize a point in the content space and can be defined as:

$$p: \tau\{(a_0, v_0), (a_1, v_1), \dots (a_{d-1}, v_{d-1})\} \quad (2)$$

2) *Events Subscription*

A variant of content-based publish/subscribe is proposed. Through this modification, the subscribers specify their interest in two steps. Firstly, the event type is designated and secondly a collection of predicates regarding this event are defined. Thus, an event subscription ‘s’ has an event type ‘τ’, which is a collection of predicates with its attributes.

$$s: \tau = \{r_1, r_2, \dots, r_k\} \quad (3)$$

The set $\{r_1, r_2, \dots, r_k\}$ represents a conjunction of predicates. A predicate $'r'$ is a tuple, $r = (a_r, v_r)$ where a_r is the attribute name and v_r is the attribute value. Thus, each predicate represents the subset of the corresponding attribute domain in which the subscriber is interested in. The bounds of the subscription for i_{th} attribute are defined by each predicate. Therefore, a subscription is represented by a rectangle that is composed by cells in the partitioned space.

Figure 5 illustrates an example of the proposed indexing pub/sub system in the two dimensional Hilbert space. Let us consider that three publications p_1, p_2, p_3 are generated and represented as 4, 57 and 55 respectively. Let us also consider that a certain subscription ‘s’ is given by the set of cells {4, 5, 6, 7, 56, 57, 58, and 59} (the blue rectangle in Figure 5). As it can be seen p_1 and p_2 are events of interest for such subscription while p_3 will be ignored.

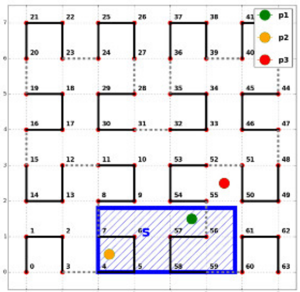


Fig.5. Example of publications and subscription indexing in a two dimensional space, H_3^2

3.3.2. *(B) Content Matching System*

A subscriber can have multiple subscriptions of interest. However, the management of large amount of information regarding subscriptions could lead to a big size of the subscriptions table. Big size of subscription tables results in a waste of processing resources and memory requirements as well as a large amount of redundant traffic. In order to avoid the unessential subscriptions dissemination and to reduce the size of the subscription tables, a subscription merging technique based on [14] has been implemented. Merging is a method that gives the minimum filter that represents a collection of subscriptions defined in the content space. Formally, a subscription S is a merger of set of subscriptions:

$$S_1, S_2 \dots S_n \; if \; S \supseteq \bigcup_{i=1}^{n} S_i.$$

Finding the minimum-bounding rectangle that comprises a set of subscriptions is the simplest way to achieve the subscription merging [14]. Since each subscription is represented by the boundaries of each attribute, a subscription can be represented as a d-dimensional rectangle in the content space. The result of merging is a new rectangle, $S_{\_aug}$, that includes all the original subscriptions, $S_{\_or}$, that are being merged. Figure 6 shows the result of merging applied to three subscriptions in a H_3^2 Hilbert space by means of minimum bounding rectangle. The merging rectangle is the minimum-bounding rectangle ($S_{\_aug}$) that contain those cells that intersect with the original subscriptions and it is defined as follows:

$$S_{\_aug} = \{\mathrm{C}(x_1, x_2, \ldots, x_d) \in H_k^d \; where \; C(x_1, x_2, \ldots, x_d) \cap \mathrm{S} \neq \emptyset\} \quad (4)$$

In this sample, the resulting augmented subscription $\mathrm{S}_{\mathrm{aug}}$ is the rectangle that has intersection with the original subscriptions. Therefore, the set off cells that form the augmented subscription, $\mathrm{S}_{\mathrm{aug}}$, is {4,5,58,59,7,6,57,56,8,9,54,55,11,10,53,52}.

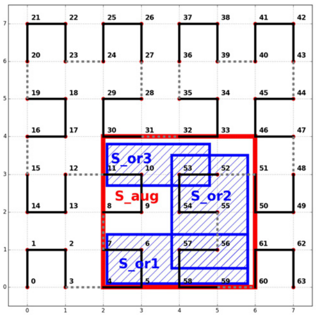


Fig.6. Merging of three original subscriptions $\mathrm{S}_{\_\mathrm{or}}$ in the augmented subscription $\mathrm{S}_{\_\mathrm{aug}}$ indexed in the partitioned space, H_3^2

Once the indexing cells of the augmented subscription are identified, the intervals that represent these cells must to be found. These set of intervals (ranges) are based on the Hilbert indexing space that compose the augmented subscription. As an example, the set of cells that form the augmented subscription considered in Figure 6 results in the following two intervals for representing the subscription: {[4, 11], [52, 59]}. In this way, after receiving a publication, the system verifies the augmented subscription ranges. As it can be seen, the area of the augmentation subscription comprises some fragments of the content space that are not included in the original subscription. As a consequence, false positives may be generated when a publication is disseminated. This number of false positives is considerably small, due to the minimum surface area of the augmented subscription is taken.

3.3.3. *(C) RBR Protocol (Ranged-Based Routing Protocol)*

As explained in section I, P2P generates high network traffic rates, so the conventional events dissemination-routing engines are not useful in the case of microgrids. For this reason, a Ranged-Based Routing (RBR) Protocol has been developed. The process of event routing is necessary for achieving an efficient event notification middleware. The main goal of the proposed routing engine is to meet the microgrid network performance requirements. For that, it is essential to find the cluster of nodes whose subscription matches with the given event. This avoids unnecessary retransmissions and reduces the network traffic.

The middleware has been developed over structured (DHT) P2P networks. The DHT protocol preferred for this work has been the Chord protocol, whose features are shown in Table III [39]. The basic idea of Chord is the following. The Chord DHT overlay arranges peers on a circle topology ranging from 0 to $2^{\mathrm{m}}-1$, where m is the number of bits of the identifiers. The peers are ordered following their identifiers. A key is stored in each node. The key identifier space assigns the keys between each one of the nodes and their predecessors. Each node in the circle also upholds a routing table, called finger table, which contains information about other neighbors (predecessor and successor) in the identifier space. The neighbor nodes that comprise the routing table have been selected deterministically, using an overlay-specific metric. The routing table is used by the lookup algorithm for efficient routing. Figure 7 shows an example of Chord overlay network.

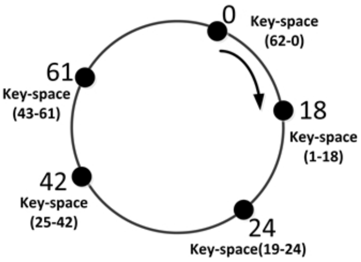


Fig.7. Example of DHT Chord overlay network with an identifier space $[0,2^{6})$.

TABLE III
CHORD ROUTING PROTOCOL FEATURES

Properties	
Popularity	Chord is the most popular DHT routing protocol
Design	Reduce the complexity in designing P2P systems.
Large-distributed system	Allows developing completely distributed systems. Nodes have the same responsibility in the system
Scalability	Is able to scale a large number of nodes
Self-discovery	Allows nodes be located even if the network is highly dynamism and nodes enter and leave continuously
Self-organization	Nodes failures and disconnections are detected

Once the P2P layer is defined, the routing mechanism can be executed. On one hand, subscriptions nodes must to be initialized and the subscriptions must to be mapped to each Chord peer identifier. For that, the node's finger table of the traditional Chord algorithm has been modified in order to embed the augmented subscription ranges and keep the neighbor in the identifier space. Thus, in this scheme, when a subscriber node joins the network, it generates its identifier, type of events which it is interested in and the ranges of each event. After that, it sends the data to its neighbors. Hence, the subscriptions of the peers are mapped to each Chord peer identifier. On the other hand, when the publisher node is initialized, it creates two threads, one for ingoing and other for outgoing routing petitions, and remains waiting for an event. When an event is generated, the outgoing process is started and the event can be disseminated through the entire ring. The major challenge is how the event can be routed to the nodes whose content space overlaps the range of subscription. The proposed routing procedure developed for this system is shown in Figure 8.

This process is started when a publisher publishes an event in order to find subscriber nodes whose subscription matches with the given event. To achieve that, firstly, the event is indexed by using the Hilbert content space. Secondly, the event message must to be created. The event message has three main fields: i) The IP address of the node that sends the event, ii) the indexed event information, and iii) the list (Match_Node_List) with the matched subscribers nodes, which is generated as the event message progresses among the nodes of the ring. To build up this list, the Match_Search_Node process starts (Figure 9). For that, the node consults its finger table, which has been modified with regard to conventional Chord, to contain information about: i) the event type of each subscription (τ_i), ii) the ranges of this subscription (R_i), and the link ($\mathrm{L_i}$) that contains the IP address and identifier (id) of the node $\mathrm{n_i}$. Therefore the routing table has the entries $(\tau_i, R_i, \mathrm{L_i})$. To determine the nodes subscription match, the node searches in its routing table and it verifies the type of event. If the event type matches to the one that the node is looking for, then it checks if it's subscripted to the subscription ranges of that node. If both of these conditions are met, the event message will be encoded and it will be sent to all matched nodes. Through sending the node match list, the receiver nodes is able to verify if the message has already been sent to the destination before to send it again, avoiding redundant searched messages.

Upon receiving an event, if the node is one of the subscribers, it decodes the message and then the matching process starts. In this process, the event is matched against all the subscriptions ranges stored in it and, if the event is not a false positive, it will subscribe to it. The searching process continues until the source's node is reached. On the contrary, if the event message reaches a publisher node (ingoing routing petition), before decoding the message, it verifies if is the source node. If not, it decodes the message and continues delivering it among the nodes of the ring until the node source is reached. The process finish when the source node is reached.

The scalability of the system is achieved using the node match list that is stored in the nodes, avoiding unnecessary traffic in the network. The objective is to identify the clusters; in this way, each node that contains matching subscribers receives one message per event, minimizing both communication and computational costs.

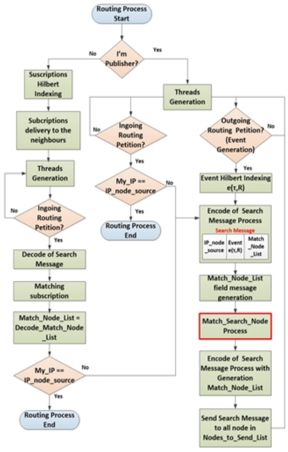


Fig.8. Flowchart of proposed Ranged-Based Routing (RBR) Protocol

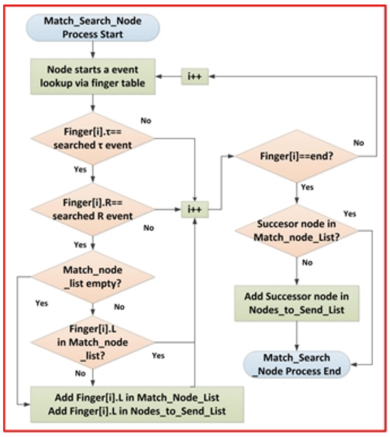


Fig.9. Detail of Match_Search_Node Process

3.3.4. (D) Application Layer

Since microgrids are inherent distributed systems, the event notification middleware have been designed following a distributed architecture. To achieve that, each peer in the system acts as a Notification Broker (NB), in other words, each peer implements a notification interface and the whole system acts as a single NB. As a result, the interface will not be a bottleneck, and the system will not have a single point of failure. Moreover, a P2P design avoids the need for centralized control and gives the flexibility to join or leave the system at any time. When a new node joins the pub/sub network, it contacts with its predecessor and successor and send its event types and subscription ranges that are interested in. When an event in the microgrid occurs, a node in the network publishes this event to the matching nodes in the ring. Upon receiving a publication, the node looks for the matched subscribers and forwards the publication according to the RBR protocol. It also sends the node list that has been received to avoid redundant search messages. An event matches a subscription if and only if the event type is matched and the Hilbert index of the cell for the publication is included in one of the intervals representing the subscription. For unsubscribing, the procedure is exactly the opposite of the subscribing process. The leaving node notify the leaving event to its predecessor and successor and the remaining nodes update its finger table. Besides, the protocol has self-organization capabilities. For this, Chord runs a stabilize algorithm in each node every 60 milliseconds to keep the list of predecessors and successors and to confirm that the ring integrity has not been corrupted. The subscriptions are actualized every 60 milliseconds in order to add or remove subscriptions. In this case, if a new subscription is merged by an existing subscription without changes in augmented subscription, it is not forwarded. Moreover, the proposed event notification middleware has a certain security degree in terms of integrity of data. This feature is achieved by implemented redundant links and self-reconfiguration methods. However, the system could be damaged by cyber-attacks such as Sybil or Eclipse [40], [41]. Thus, additional security procedures such as tapping should be studied and implemented to reduce the sensitivity to malicious attacks. These aspects are out of the scope of this paper, which is focused on improving the efficiency of the microgrids middleware.

To illustrate the interest of the proposed middleware in microgrid environments, let us see an example of application. Let us assume that the event type “island mode” in microgrids is defined by two attributes: AC voltage and frequency. This is because in island mode, the grid voltage and frequency must be controlled to keep these variables in a desirable area. In accordance with European Standard EN50160 [42], the normal operating conditions for systems with no synchronous connection to an interconnected system (island mode) are described in table IV.

TABLE IV

VOLTAGE AND FREQUENCY VALUES FOR ISLAND MODE STABLISHED BY EN50160 STANDARD

	Voltage	**Frequency**
Range#1	230 Volts ± 10% (i.e. 207<V(volts)<253) during 95% of a week	50 Hz ± 2% (i.e. 49<f(Hz)<51) during 95% of a week
Range#2	230Volts +10%/-15% (i.e.195.5<V(volts)<253) during 100% of the time	50 Hz ±15% (i.e. 42.5<f(Hz)<57.5) during 100% of the time

Figure 10 shows the operation zones that are defined as normal by the standard. Note that they are three zones clearly delimited. In the first one (zone #1) the microgrid is always operating in normal conditions. The zone #3 corresponds to abnormal conditions. Finally, in zone #2 the operating conditions are classified as normal or abnormal depending on the conditions that table V specifies, so the time that the system is into zone#2 shall be monitored. Therefore, it is interesting to define as an event and create a subscription when the system is operating in zone #2.

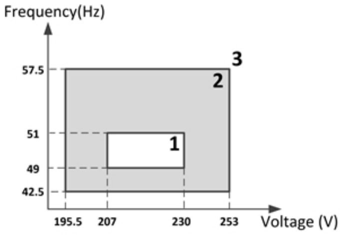


Fig.10. Operation zones in island mode defined by EN50160 standard

Thus the system for this example could be made as follows. On one hand, table V defines the four original subscriptions, $s_1, s_2, s_3 \text{ and } s_4$, with its event type and its corresponding predicates. Note that the predicates associated to these subscriptions correspond to the operating conditions of interest (zone #2). The subscription to the other zones could be carried by following a similar procedure.

TABLE V

SUBSCRIPTION EXAMPLE

Subscription and predicates **τ=Island Mode**	
Subscription s_1: τ(195.5≤voltage≤207 U 42.5≤current≤57.5)	Subscription s_2: τ(195.5≤voltage≤253 U 42.5≤current≤49)
Subscription s_3: τ(230≤voltage≤253 U 42.5≤current≤57.5)	Subscription s_4: τ(195.5≤voltage≤253 U 51≤current≤57.5)

Figure 11 illustrates the proposed example in addition with three possible publications $\mathrm{p}_1, \mathrm{p}_2, \mathrm{p}_3$ each one corresponding to the described operation zones. The resulting augmented subscription $\mathrm{S}_{\mathrm{aug}}$ is the rectangle that has intersection with the original subscriptions.

Therefore, the set off cells that form the augmented subscription, S_aug, is {0,1,14,15,16,19,3,2,13,12,17,18,4,7,8,11,30,29,5,6,9,10,31,28,58,57,54,53,32,35,59,56,55,52,33,34,60,61,50,51,46,45}. It is worth to point out that p3 will be detected as a false positive, but the system knows that it corresponds to the zone#1 so it can be easily eliminated from the list of interest.

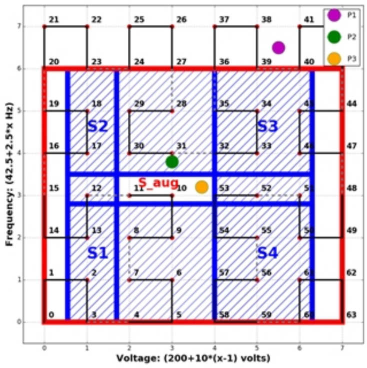


Fig.11. Sample publication and subscription

3.4. EXPERIMENTAL RESULTS

The proposed routing engine and matching system using Hilbert space have been evaluated and compared with the routing and matching methods based on multicast, which are used traditionally in microgrids. To carry out this evaluation, an experimental setup (shown in Figure 12) has been built up to measure the main performance indicators of the network that where defined in section II: subscriptions flexibility, latency, bandwidth consumption, routing performance, efficiency and computational resources saving. Conceptually, there is not a limitation on the number of nodes that can be interconnected by means of the proposed distributed techniques. However, some physical limitations will appear in a practical implementation, which are mainly associated to the limits of the communication channel (bandwidth, baud rate, noise, etc...). The experimental setup is able to manage up to 20 nodes.

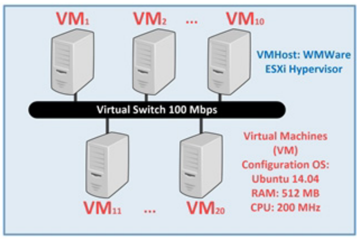


Fig.12. Schematic drawing of the experimental setup

This configuration agrees with the one of the embedded systems that we have initially chosen to migrate from virtual to physical machines, so the experimental results that are presented are realistic and valuable to preliminarily validate the proposed solution. All tests were run for 15 minutes with publishers publishing an event every 10 seconds. The Hilbert matrix used for experimental evaluation has been H_3^2.

It is worth noting that the proposed middleware should be implemented on each one of the nodes. Therefore, each node is interconnected with its corresponding electric devices of the microgrid and also with the communication infrastructure. In this way, the proposed communication system is adaptable to any kind of microgrid configuration and network topologies.

3.4.1. Subscriptions Flexibility

As it has been explained before, there are two major classes of publisher/subscriber systems: topic-based and content-based.

On the one hand, in topic-based systems, subscribers join a group containing a topic of interest. Publications are identified by specific topics. Therefore, all publications related to that topic are broadcasted to all nodes of the specific group.

On the other hand, in content-based systems, the subscribers can accurately specify their interest using a set of predicates. In other words, a subscription is a request formed by a set of constraints. Therefore, in the proposed system, the Hilbert filling curve is used to map a multi-dimensional space to a compact Hilbert key, which specifies the pair (attribute, value) that defines the constrains. Whit both the Hilbert dimension and order, the attributes and the values are specified, respectively. In this way, two pairs of (attribute, value) can be represented with a Hilbert key by using 2D-n order Hilbert curve. Similarly, three pairs of (attribute, value) by using 3D-n order, and so on (see Figure 13).

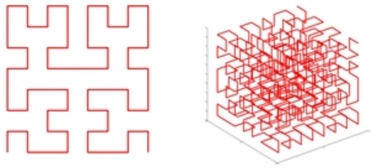


Fig.13. Hilbert space-filling curve (2D- 3rd order and 3D-3rd order from left to right)

By using Hilbert space filling curve a subscription with N constraints can be encode as a unique Hilbert key. Once the Hilbert key is package, the RPL protocol will be able to send the message only to those nodes whose subscription matches with all the publication constraints. In other words, all nodes that are subscribed to that Hilbert key.

To compare the performance of both techniques, the topic-based approach has been emulate as content-based one as follows:

i) Firstly, the publication with the specified topic is broadcasted to all nodes that are subscribed to the specific topic group.

ii) Once the nodes are subscribed, they inform to the publishers about their subscription. Therefore, the first constraint will be sent only to those nodes that have been subscribed to that topic.

iii) The nodes that match with the topic and with the first constraint also inform to the publishers. In this way, the publishers send the second constraint only to those nodes that match these conditions. This process continues by sending publications for the N constraints.

Figure 14 shows a comparative study of the number of the interchanged messages that are needed to send a set of publications. The results obtained with Hilbert content-based are compared to the ones achieved by topic-based in three cases: no constraints, with one constraint and with two constraints.

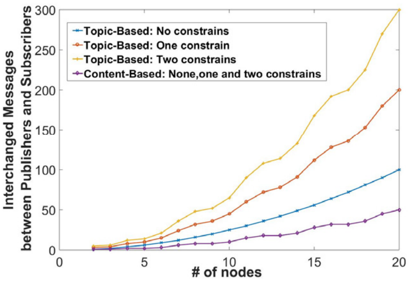


Fig.14. Costs of publishing messages in relation with the publications constraints by using topic and content based approaches.

As it can be seen in Figure 14, the number of interchanged messages by using the filtered topic-based approach depends on both, the number of nodes in the network and on the number of constraints in the publication. Indeed, for sending N constraints the publishers need to know the nodes that are subscribed to the first N-1 constraints to verify that the subscription match to all the publication constraints. This fact generates more network traffic. On the contrary, with the filtered Hilbert content-based approach, N constraints can be defined in a unique Hilbert key. Therefore, the number of interchanged messages only depends on the number of nodes in the system and it does not depend on the number of publication constraints. The higher expressiveness and flexibility of content-based approach reduce the need for network resources. The network robustness and scalability improve due to the notifications are only sent to the actual subscribers.

3.4.2. Network Performance

This section focuses on the two most critical components that dictate the performance of network in microgrids: delays and bandwidth. Regarding network delay, Figure 15 shows the overall End-to-End (ETE) delay, that is the time elapsed from the publication source to the last subscriber, in average value for pub/sub solutions based on multicast vs. Hilbert. This figure shows that ETE delay for the proposed system is lower than the one that offers the pub/sub system based on multicast. Note that the proposed system reduces the subscription-forwarding load at each node. Therefore, the ETE delay is lower than the achieved one by using traditionally pub/sub based on multicast methods. As it is shown, the proposed pub/sub middleware improves the ETE delay between 35% and 48%, and the improvement increases as more nodes connect to the network. The total ETE delay for 20 nodes achieved by means of the proposed pub/sub middleware is around 270 ms, while with pub/sub based on multicast it is around 530 ms. Thus, the average ETE delay per node in the proposed system can be estimated around 14 ms. This means that the average latency to process a publication in a pub/sub based on Hilbert middleware is around 14 ms, which meet the network microgrid requirements that were outlined in Table I.

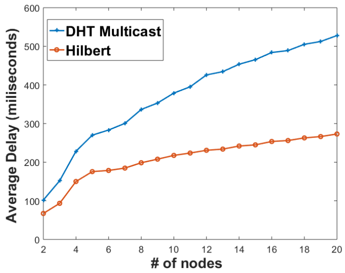


Fig.15. Comparison of average ETE delay vs increasing number of nodes for pub/sub based on multicast and Hilbert

Related to bandwidth measurements, Figure 16 shows the average bandwidth consumption in the network for different scales. For that three different scales are considered with testbeds of 5, 10 and 20 nodes connected to the network, and the bandwidth consumption of the proposed pub/sub system against that of pub/sub based on multicast routing method has been compared.

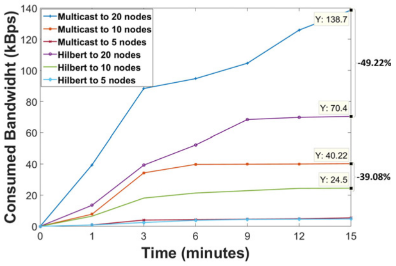


Fig.16. Average total bandwidth consumption in time for different scale

As it can be seen in Figure 16, the bandwidth consumption with the proposed pub/sub method increases less rapidly that with pub/sub methods based on multicast. Overall, the average total bandwidth consumption over 15 minutes decreases by up to 39.08% for 10 nodes and 49.2% for 20 nodes where using the proposed pub/sub middleware. These results could justify the use of the proposed pub/sub system based on Hilbert at the application layer as better use of available bandwidth is produced due to the traffic is reduced by eliminating redundant transmission. This redundant transmission has been reduced by applying subscription merged which can greatly reduce the subscription dissemination traffic. In addition, the bandwidth savings increase with the size of the network, ensuring more scalable communications.

3.4.3. *Routing Performance*

The main benefits of the proposed RPL protocol are a reduction in both the network traffic (Figure 17) and the routing time (Figure 18). The traffic in the network has been measured by averaging the total bandwidth consumption in kilobytes per second. Figure 17 shows the average total network traffic (in consumed bandwidth) for 20 nodes at 15 minutes.

As Figure 17 shows, the RPL-Hilbert technique consumes near two times less traffic that multicasting. The reason is that, by using RPL protocol, the neighbor routing tables of each node have information about their subscriptions. In this way, each publication is delivered only to the subscribed nodes and not to the subscribed clusters as multicast routing does. Consequently, a network traffic reduction is achieved. In addition, RPL protocol has self-organization capability due to the overlay Chord infrastructure. With this feature, each node knows the disposition of their neighbors, which produces an effective method for publication and subscription propagation and allows a reduction in the routing time. Figure 18 shows the average matching time of publications against subscriptions. The average matching time is the average time to route the publications to the matched subscriber. They have been generated 3000 subscriptions (50 random subscriptions for each subscriber node) to evaluate the publication matching time.

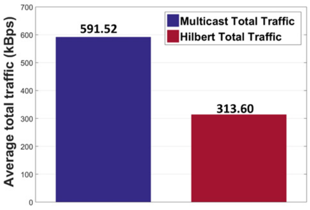


Fig.17. Consumed bandwidth on 20 nodes network for pub/sub system based on multicast and Hilbert routing.

As it can be seen in Figure 18, it takes around 13 milliseconds to route a publication against 3000 subscriptions by using the proposed RPL-Hilbert algorithm. With DHT Multicast this time is around 29 milliseconds. The matching time does not significantly increase as the number of subscriptions grows. This indicates that the proposed approach is suitable for large scale publish/subscribe systems and can efficiently process a large number of messages (publications and subscriptions).

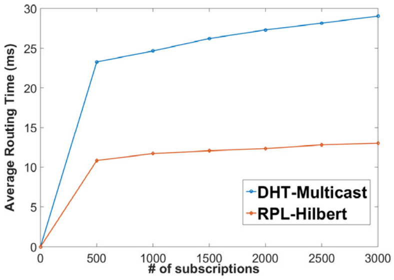


Fig.18. Average Publication Matching Time

3.4.4. *Efficiency: False Positives*

Figure 19 is the result of one of the most important performance metric for efficiency, false positives. A false positive is defined as a message received by the node that is not interested in the message. This figure shows the total average number of received messages per node. This refers to the total publication messages that receive the nodes. Moreover, the figure also shows the percentage of false positive for this quantity of received messages. As it can be seen, both average received message and false positives with the proposed method results in considerable reduction regarding pub/sub based on multicast routing approaches. The percentage of false positive decreases as network grows, which ensure more efficient communications. This is due to the use of Hilbert mapping for routing and merging matching that allows the proposed pub/sub system having more chance to forward an event to a better neighbor. Note that the event is embedded in the routing table and the event matching has more probability of success. Moreover, by using the minimum-bounding rectangle as merging technique, the area for false positives is reduced and the number of the unwanted publications is small.

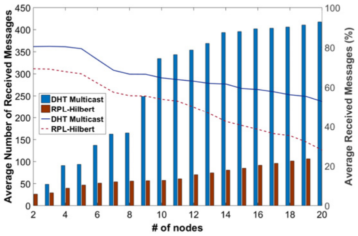


Fig.19. Percentage of false positive according to the average number of received publications per node

3.4.5. *Computational Resources Savings*

System memory and CPU are critical resources for the operation and performance of any software system. The use of the merging technique allows reducing the routing subscription tables' size. Thus the processing and storage memory requirements that are used by the nodes are also reduced. Figures 20 and 21 show the average amount of active memory and CPU load, respectively, on a network of 20 peers over 15 minutes, with both the proposed pub/sub system and the one based on multicast.

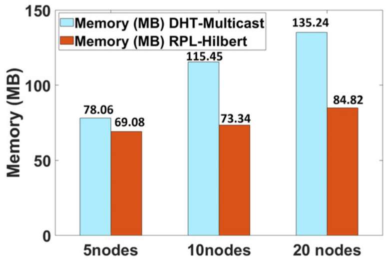


Fig.20. Average Active Memory used (in MB). Measurements have been taken for three different scales for pub/sub solutions based on multicast and Hilbert over 15 minutes.

Multicast needs more memory as the scale increases, up to 130 MB of memory for 20 nodes over 15 minutes, while pub/sub based on Hilbert requires 85 MB in the same conditions. Similar to the memory analysis, the CPU savings increases with the size of the network. Multicast solutions use around 74 MHz of CPU for 20 nodes over 15 minutes while Hilbert solution uses around 56 MHz.

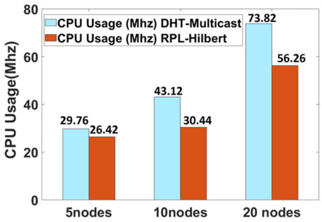


Fig.21. Average CPU usage (in MHz). Measurements have been taken for three different scales for pub/sub solutions based on multicast and Hilbert over 15 minutes.

The showed results confirm that the proposed system can be implemented with a reasonable computational resources usage which allows its implementation in embedded systems

3.5. CONCLUSIONS

In this paper a new event notification middleware for content-based pub/sub over peer-to-peer network suitable for large-scale microgrids has been presented. The proposed middleware uses multidimensional indexing to represent publications and subscriptions in one-dimensional space through the Hilbert space-filing curve. Based on this representation, routing, merging and matching algorithms have been developed. On one hand, the ranged based routing protocol (RBR) developed can construct and efficient event dissemination while it has desirable properties such as self-organization and scalability. On the other hand, the proposed merging and content matching algorithms improve the traffic performance and reduce the false positives rate due to the minimization of the space of participation nodes that have no interest in the event, providing a higher level of reliability guarantee. Experimental results have shown that middleware based on the Hilbert space improves efficiency, reduces the overall network traffic and latencies and achieves better computer resources savings. Those improvements are needed to meet the demanding communications requirements for microgrids. The tests have been carried out by means of virtual machines by taking into account most of the system physical limitations. Therefore, it can be concluded that the proposed solutions are an interesting approach to the problem of communications in smart microgrids.

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4

PUBLICACIÓN IV

AN EMBEDDED INTERNET OF ENERGY COMMUNICATION PLATFORM FOR THE FUTURE SMART MICROGRID MANAGEMENT

Marzal, S., González-Medina, R., Salas-Puente, R., Garcerá, G., and Figueres, E. “An Embedded Internet of Energy Communication Platform for the Future Smart Microgrid Management,” IEEE Internet of Things Journal

Contenidos

An Embedded Internet of Energy Communication Platform for the Future Smart Microgrid

***Abstract*—**Microgrids are moving toward electric power systems in a sort of an internet of energy (IoE) where a large number of generators can be connected anywhere. In this regard, to realize the envisioned IoE, information and communication technologies (ICT) are crucial for developing innovative applications and services as well as achieving high levels of efficiency in microgrids. However, due to the variety of ICT, there is not a de facto standard solution to implement IoE platforms. Moreover, standards for the current Internet of Things (IoT) platforms are not optimal for developing IoE platforms, which present more demanding challenges. In such context, this paper presents an embedded IoE platform for management of smart microgrids. The performance of this platform has been tested in an experimental microgrid. Results show that the proposed platform fulfills the microgrids requirements and it is able to manage the energy flows, the safety issues, etc. in microgrids.

Index Terms—Microgrids, Internet of Energy, ICT, embedded technology

4.1. INTRODUCTION

The current and expected future needs of energy demand along with the challenge of gradual electric power supply decarbonization, demand the search for alternative, cleaner and renewable energy sources. From this point of view, Microgrids (MGs) have been raised as a potential solution for the integration of these renewable and distributed energy resources in the energy system. A microgrid can be defined as a low-voltage distributed network composed by Distributed Generators (DG), Energy Storage Systems (ESSs), local loads and power electronic interfaces, which can operate in either grid connected and island modes [1].

The integration of Distributed Energy Resources (DERs) into MGs is traditionally carried out by means of centralized control systems, in which a central controller communicates with all the microgrid resources, receiving information about its state and taking the control decisions. However, the recent increase in the number of DERs that are deployed into microgrids provokes that centralized communication topologies are not the optimal solution for monitoring and controlling the microgrid resources. In effect, these topologies could lead to inefficiencies in the communication network, even the fault or the shutdown of the global system if the central control point fails [2]. To overcome this limitation, decentralized communication topologies have been proposed for microgrids. In these topologies, an improvement of the microgrid reliability is achieved by removing the central controller as a single point of failure. Following the decentralized approach, the local nodes have their own Microgrid Control System (MCS) and, therefore, have the ability to take decisions. This is the key issue that features Smart Microgrids (SMGs), i.e., the added intelligence including bidirectional communications, sensing and management capabilities. In addition to in time detecting and reacting to events, these features allow the ability to maintain high levels of efficiency, reliability, and Quality of Service (QoS). Is in this scenario where the concept of Internet of Energy (IoE) can be interesting (Figure 1). Compared with the traditional microgrid, the IoE allows connected devices (DERs) become globally accessible and real-time controllable, anytime, anywhere [2], [3], [4].

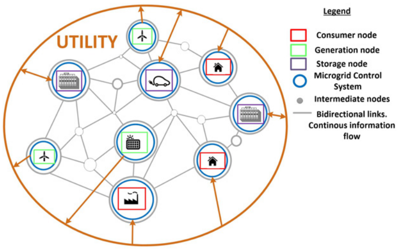


Fig.1.Overview of the future IoE Smart Microgrid Scenario

The Internet of Things (IoT) can integrate objects to the Internet. To achieve that, the IoT infrastructure is composed by embedded smart devices, with limited computational resources, which are able to provide certain real time services, such as monitoring, communications, controlling, among others [5],[6]. This idea can be extended to IoE which deals to interconnect distributed energy resources by means of the Internet [7].The structure of the Internet of Things is mainly based on Peer-to Peer (P2P) networks composed by autonomous nodes [8]. It is worth to point out that P2P communications networks have been mainly developed for applications such file and processor cycle sharing, whose network performance requirements are less critical (in the order of seconds) than microgrid functions (in the order of milliseconds). Moreover, normally IoT networks have an excessive dependence on the existing Internet data center service [9],[10]. This fact could produce delays in dispatching services, provoking undesirable effects in the microgrid. Therefore, the current IoT software and related communication platforms are not properly adapted for microgrids environments due to QoS requirements for microgrids are particularly demanding [11]. Moreover, although the IoE concept can be applied to SMGs, there is not a standard solution for its implementation [12]. In fact, the current microgrids development does not use the IoE approach [13].

To overcome these limitations, this paper proposes a novel IoE platform and distributed embedded systems that implement real-time interfaces between the microgrid and the cloud. The platform is oriented to monitoring and control purposes and is able to fulfill the demanding performance requirements of microgrids.

The main scientific contributions of the paper are summarized as follows:

1) The design and development of a flexible, distributed and embedded

IoE communication platform based on P2P communications which can effectively collect, process and analyze the microgrid data, from anywhere and anytime, for monitoring and control purposes.
2) An innovative IoE-P2P middleware which is able to work in both synchronous and asynchronous mode, to guarantee the choice of the proper and optimal type of communication for each task or communication messages that are interchanged into the microgrid. To our knowledge, currently there is not any communication IoE platform that involves synchronous and asynchronous P2P distributed communications.
3) An IoE protocol and a routing algorithm specifically designed for monitoring and control of SMGs, which is able to fulfill the demanding SMGs requirements.
4) To implement a real IoE platform the DERs have been embedded into devices with limited computational resources. The efficient use of the computational resources in order to guarantee the required SMGs performance is experimentally proved.
5) To evaluate the proposed IoE infrastructure in terms of QoS, it has been deployed in an experimental microgrid becoming, at least to our knowledge, the first experimental IoE communication platform for managing SMGs.

The rest of this paper is organized as follows; Section 4.2 describes the challenges for developing IoE communication platforms. In Section 4.3 the proposed communication platform is described. In Section 4.4 some experimental results are presented and discussed. Finally, Section 4.5 provides the conclusions of this study.

4.2. CHALLENGES OF THE INTERNET OF ENERGY

The Internet of Energy is an emerging paradigm that applies IoT technologies to energy control systems [14]. Today, IoE introduces significant new challenges for developing advanced communication infrastructure for SMGs [13],[15]. To better understanding of the challenges that face the IoE, the main differences between Internet of Energy and traditional microgrids are described as follows [8],[16],[17]:

1. The architecture: In contrast with traditional microgrids, the IoE architecture is highly integrated with an information network. In today's microgrids, the information system and the physical system are independent. In contrast to this, the information system is vital for the IoE due to it allows the interaction with the physical system. By combining both physical and information networks, the IoE aims to optimize the energy utilization on the basis of safe and stable operation.

2. The access of Information: A microgrid is formed of locally distributed energy resources in order to improve reliability. In contrast, Internet of Energy aims at comprehensive energy optimization, which consists on the autonomous access to multiple DERs. In the Internet of Energy there is not a centralized hardware or administrative nodes in the network, thus the nodes have the same hierarchy and roles.

3.The information and energy exchange: The IoE demands equal, free and real-time energy and information sharing, which can be achieved by using address and routing capabilities, avoiding faults in case of nodes failures. This is not limited to the primary path and backup paths as traditional microgrids do.

4. The embedded capabilities: Unlike traditional microgrid, the distributed energy resources deployed on the microgrid become controllable anytime and anywhere. Each node has embedded and "plug and play" capabilities, so if damage or fault is caused at any node, this event will not affect to the operation of the whole system.

Related to the architecture, the IoE, as any Internet of Thing (IoT) platform, has a structure based on four layers: Things, Network, Service and Cloud. With this architecture, networking, data transfer and applications are highly integrated.

The access of information is another challenge in IoE. Traditionally, communication architectures for microgrids use a client-server based communication topology for information accesses. In this approach the data center plays a central role to process the petitions and manage the information, which means that the DERs have little autonomy. Differently, in the IoE, each distributed energy resource should act as both clients (master) and server simultaneously [18]. The kind of networks that allow this functionality are called P2P networks. In these networks, the connectivity between the nodes is carried out by creating virtual links, overlays, which are built on top of the physical network which allow more flexibility than physical networks, extensibility, self-healing and dynamic reconfiguration. Therefore, create virtual links that allow nodes self-management in order to make local adaptive decisions on the basis of the information they receive from the agents to which they are linked is a big challenge to achieve the IoE.

One of the major challenges to realize the envisioned IoE is the information and energy exchanges in real-time. One of the features of the IoE is its massive scale. In particular, a large number of devices can be connected to the microgrid producing continuous flows of data that must be processed in real-time [19]. Since microgrids are complex distributed systems, the IoE infrastructure needs a direct, efficient and in time communication to meet the demanding microgrid network performance requirements (in the order of few milliseconds). According to the IEC 61850 and IEEE 1646/1647 standards the typical response time for different SMG functions should follow the values in Table I [20],[21],[22].

TABLE I
NETWORK REQUIREMENTS FOR MGS

Function	**Response Time**
Monitoring Information	15ms-200ms
Control Information	16ms-100ms
Messages requiring immediate actions	3ms- 100ms
Distribution Management	100ms-2s
Demand Response	500ms-several minutes

Besides, energy systems are becoming increasingly complex, so it is vital to build flexible architectures with a high capacity to exchange information in a networking environment that is in continuous evolution. In such an environment some quality properties, like efficiency, mobility support, adaptability, reliability, and timeliness, are required [23]. The fulfilment of these requirements is achieved by middleware solutions, located in the service layer, mainly based on the Request/Response (RR) or the Publish/Subscribe (PubSub) paradigms. In the first case, RR is a communication scheme based on one-to-one communication interaction. Senders deliver request messages to specific receivers that process and reply the request. This message exchange follows a synchronous method invocation, i.e., to guarantee the message delivery, the connection remains open until the responses arrive. However, the difficulties for decoupling time and space make that the RR paradigm is not well suited for mobility support, since the requester can be indefinitely blocked while waiting for a response. In the second case, PubSub is a non-blocking asynchronous communication scheme where the distribution of events is one-to-many. The providers of information (publishers) disseminate events to the system and the information consumers (subscribers) are subscribed to the events in which they are interested. Nevertheless, this method has difficulty guarantying a reliable delivery due to the decoupling between subscribers and publishers. It is worth pointing out that conventional middleware platforms have been developed by implementing only one of the two communication paradigms [23]. However, middleware solutions for microgrids need simultaneously using RR and PubSub-based communication mechanisms [12],[23],[24].

The reasons for that are, on the one hand, that in a microgrid the control information among DERs require a communication system based on query-response. In this regard, a timely response is needed for carrying out immediate actions, due to if the communication delay exceeds the required time, the information does not fulfill its purpose and, in the worst case, damage might occur. On the other hand, for microgrid monitoring tasks, PubSub paradigm is needed. For example, when a load is switched from off to on, an event could be notified to other DERs to evaluate the global status of the microgrid. Another challenge related to middleware is that IoE devices can be shared by several IoE services or applications. This fact may lead to resource conflicts and transient overloads that should be solved by the middleware. Therefore, the interaction management between devices that is carried out by the middleware should involve new forms of routing based on logical criteria, such as: the type of DERs device, the subscriptions or communities of interest, the geographical proximity, etc. Summarizing, middlewares for microgrids need to support both RR and Pub-Sub communications paradigms due to each communication paradigm provides orthogonal functionalities and different quality properties. Table II defines the contribution of each communication paradigm to the proposed IoE platform.

TABLE II

PROPERTIES PROMOTED BY EACH COMMUNICATION PARADIGM

Property	RR	PubSub
Efficiency	Partial	Partial
Adaptability	–	●
Security	●	Partial
Reliable delivery	●	–
Timeliness	●	–
Mobility	–	●

Legend: ● Indicates that the characteristic is available in the category specified in the column heading. – Indicates that it does not

By definition, in the IoE, any network-connected device is an embedded system. Hence, an IoE device has limited computing and storage resources. In conventional IoT, devices often operate in a single-thread context without parallel processing support [12]. This means that tasks are sequentially processed. However, in microgrids this is not optimal due to a critical task might not be in time because the resources are busy by performing other tasks. So, a crucial challenge for The IoE-platform is to develop embedded software in each node, which should be able to manage multiple thread and parallel processing with minimum waste of computational resources. Moreover, due to the virtual layer of the P2P architectures, Plug and Play (P&P) capabilities are allowed and when the peers join the network, peers communicate with each other to establish dynamic self-organizing structures on top of the underlying physical networks.

To transform traditional systems into IoE, all these challenges must to be faced. The working line for developing IoT-based energy systems are outlined below.

With regard to the challenges that have been described above, several studies can be found in the literature. In [14],[25] the requirements of IoE are provided. However, the infrastructures have not been developed and neither simulation analysis nor experimental results about the performance of the IoE platforms have been carried out. In [13], [26], [27], [28], [29], [30], [31], [32], [33] several IoT software infrastructures that enable energy management are presented. In these studies, only simulation results have been carried out so the main practical issues related to the deployment of a real platform are not treated.

Moreover, they neither involve P2P distributed networks nor the integration of the different communications paradigms. A major issue related to the application of the IoE concept to microgrids is the development of hardware allowing the practical deployment of this kind of networks. In this sense, special attention should be paid, among other aspects, to the use of embedded devices, the influence of the electromagnetic noise on the communication quality and the practical verification of performance requirements.

In summary, a practical IoE platform should provide:

1) High availability for large-scale systems that support P2P communications,

2) Flexible communications platforms which allow RR and PubSub communications paradigms,

3) Provide quality performance attributes and efficient routing

3) High level programming to embed the software into the DERs.

4.3. The Proposed IoE Communication Platform

Building a distributed IoE platform for energy management is a challenging task. The tasks that must been executed by the platform are: (i) the integration of the MG devices in the communication network, and (ii) the interconnection of the devices among them and with the IoE cloud for monitoring and control purposes. To carry out these tasks the proposed IoE communication platform is composed by 4 layers, as shown in Figure 2. A description of each layer is provided below.

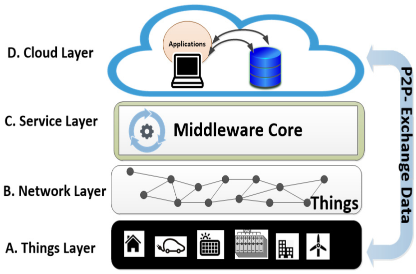


Fig.2. Overview of the proposed IoE platform

A sample schema of this platform is depicted in Figure 3. It is composed by the following components:

(A) The things layer which integrates the available microgrid hardware to control/sense the status of the things

(B) The network layer which defines the protocols and networks used for connect the things

(C) The service layer which creates and manages services according to the things needs. This layer relies on the middleware technology which provides messaging and routing layer which support run-time switching between RR and PubSub communications paradigms to integrate microgrid services and functionalities in IoE.

(D) The cloud layer which includes the IoE application. This layer is at the top of the architecture and is responsible to data store and data analysis. Application layer comprise of the custom Microgrid applications that is making use of the things data.

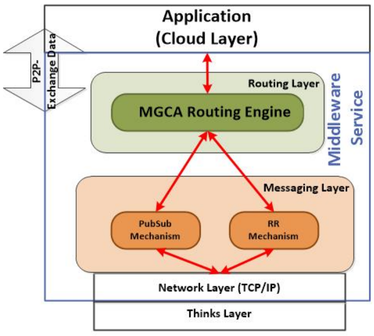


Fig.3. Simplified schema of the proposed IoE platform architecture

4.3.1. A. Things Layer

Following the IoT/IoE terminology, each DER of the microgrid is tagged like a thing. Therefore, DERs must incorporate an Intelligent and Communicative Electronic Device (IED). There are two communication interfaces in this layer. The first interface communicates each DER with the power network and it is carried out by means of UART serial communications. Modbus is the chosen serial protocol to implement this interface, due to it is an open protocol that requires low computer resources; in addition, it defines a message structure that DERs can recognize and use. The second interface links each DER with the distributed communication network. In this case, a

P2P communication network over Ethernet is the chosen technology due to the advantages described in Section 4.2.

4.3.2. B. Network Layer

The network layer is the infrastructure that allows things to manage the communication in the distributed network and transmit messages between things and the service layer. In this layer, TCP/IP are the chosen protocols due to these protocols are the standard for the Internet. They enable end-to-end communications independently of the underlying physical media, things and network layer. This characteristic provides interoperability among third-party non-compliant end devices and compliant communications networks. This characteristic provides interoperability among third-party non-compliant end devices and compliant communications networks, improving flexibility. Network interoperability is indispensable to achieve an overall optimal system operation and connectivity, independently from the chosen physical medium, the type of devices and manufacturers.

4.3.3. C. Service Layer

In this layer, the middleware is considered a key technology for developing efficient IoE applications [3], since this layer provides the interconnection between things and the cloud layer. An essential issue is the accomplishment of the network requirements for MGs and the appropriate and reliable message delivery. It is therefore vital to develop a middleware able to provide QoS in terms of latency, delivery rates and bandwidth, among other factors. In order to fulfill these requirements, the proposed middleware is formed by two layers: Messaging layer and Routing layer.

Messaging Layer

As it has been outlined in Section II, the integration of RR and PubSub communication mechanisms in microgrids is needed. Each communication paradigm provides orthogonal functionalities and different quality properties. With Request/Response communication pattern, quality properties as reliability, timeliness and security are achieved. In addition, efficiency, mobility support and adaptability are quality properties achieved by PubSub architecture. Both communication systems have been developed by the authors in [34] and [35] respectively. Therefore, this subsection is only focused on the integration of RR and PubSub. It is worth pointing out that both systems are integrated in the middleware but they are not simultaneously working.The proposed mechanism to automatically select RR or PubSub as communication system is based on the type of exchanged message. Table III shows the type of messages and their associated communication system that have been defined for the proposed IoE platform.

TABLE III
INTERCHANGED MESSAGES ON THE PROPOSED IOE PLATFORM

Type of message	Description	Comm. Type
Peers Commands	Lookup, Join, Leave, Discovery	PubSub
Monitoring Information	Power Consumed, State of Charge (SoC), Micro Generation, Voltage, Frequency, etc.	RR/ PubSub
Control Information	Flows of energy: Grid to MG, MG to Grid, Energy Dispatch Limit, Load Limits, MG On/Off, etc.	RR
Critical Messages	Messages that require immediate actions	RR
Distribution Management	Peers coordination actions	RR/PubSub
Demand Response	Non priority data (energy market, peers data, etc.)	PubSub
Status	Failure, Notifications Messages	PubSub
Stabilize	Node Reports	PubSub

In this regard, a specific microgrid communication protocol has been developed for transmitting data among *things.* In the proposed protocol, a set of attributes associated with each delivered message are defined. These attributes are: (i) type of message, which identifies the communication mechanism (RR or PubSub), (ii) iD Device, which identifies the type of DER (Critical Load (CL), Non Critical Load (NCL), Photovoltaic Generator (PVG), Energy Storage System (ESS), etc.), (iii) subscription code, only in case of PubSub messages, which identifies the events in which subscribers are interested and (iv) data parameters and values, which are transmitted into the P2P network. Figure 4 shows an overview of the implemented microgrid communication packet structure. The developed message packet frame (MSG Packet Frame) follows a fairly uniform overall structure which contains a header, data, and footer. The header and the footer fields contain several bytes of control information, which is used to communicate important facts about the data that the message contains and how it is to be interpreted and used. The data that should be transmitted (payload of message) is composed by the attributed listed above

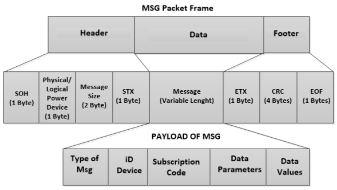


Fig.4. Overview of Packet Frame Structure

When a packet is sent, the proper method (RR or PubSub) is selected. Then, the packet is transmitted to the target things, accordingly to the routing algorithm that is explained below. The target things process the packet based on the communication type.

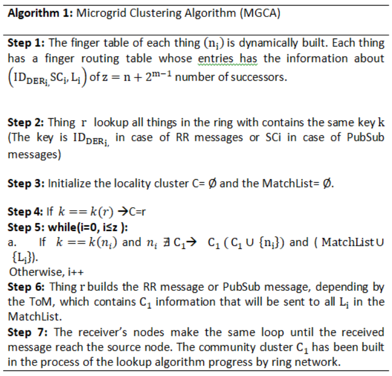
Routing Layer

P2P networks generates high rates of network traffic which can lead to high delays, poor bandwidth utilization, packet loss, wasted computer resources, among other inefficiencies. This is due to, traditionally, flooding techniques are used in P2P networks for routing. In flooding routing schemes, when a node receives a query, it forwards it to all the nodes of its routing table and the nodes recursively retransmit the query. The flooding stops after TTL = 4 hops. The lookup message will visit each node at least one time to obtain data retrieval.

To avoid unnecessary retransmissions and reduce the network traffic to meet the microgrid network performance requirements, a microgrid clustering algorithm (MGCA) has been developed to carry out the messages routing. Clusters are logical groups of things in form of communities to achieve common objectives [36].Thus, in this work, the routing is based on transmitting the information only to the selected clusters instead of broadcasting the information to all the things.

The proposed MGCA is a content-based algorithm. In this approach, the logical clustering is formed depending on the active communication type (RR or PubSub). For RR routing, the clusters are formed following the DER functionality (i.e. its iD Device). In the case of PubSub routing, the things are grouped in clusters according to the subscription code. The chosen protocol to create the clusters has been a modified Chord Distributed Hash Table (DHT). The Chord DHT protocol is a well-known protocol for P2P networks [37] in which peers find other peers, and have access to their respective data, through a ring topology. Each peer in the ring upholds a finger table, which is a distributed hash table that stores the peer identifiers that are used by the lookup algorithm for routing. The finger table of the conventional Chord DHT has been modified in order to establish the communication only with the cluster of interest. To achieve this, the finger table needs to discriminate among the categories of clusters. Therefore, it embeds both the DER functionality and the subscriptions code. When a thing joins the peer network, it sends this information to the things neighbors. Thus, each thing has a modified routing table whose entries follow the form $\left(\mathrm{ToM}, \mathrm{ID}_{\mathrm{DER}_{\mathrm{i},}} \mathrm{SC}_{\mathrm{i}}, \mathrm{L}_{\mathrm{i}}\right)$, where ToM identifies the type of message (RR or PubSub), $\mathrm{ID}_{\mathrm{DER}_{\mathrm{i}}}$ identifies the DER functionality, SC_{i} stands for a subscription code, and L_{i} is a link that contains the IP address. With this modification of the finger tables, the clustering process can be done by means of the MGCA algorithm. This algorithm searches the things that are inside of the cluster of interest accordingly to the DER functionality (with RR) or the subscription codes (with PubSub). When the matched things are identified, a message with the things match list will be sent to the thing that has started the request.

Based on the described above, the Microgrid Cluster Algorithm is presented in Algorithm 1. The algorithm uses an overlay Chord-graph ranged from ranged from 0 to $2^{\mathrm{m}}-1$, where m is the number of bits in the identifiers.



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Algorithm 1: Microgrid Clustering Algorithm (MGCA)

Step 1: The finger table of each thing $(\mathrm{n_j})$ is dynamically built. Each thing has a finger routing table whose entries has the information about $\left(\mathrm{ID}_{\mathrm{DER}_{\mathrm{j},}} \mathrm{SC_j}, \mathrm{L_i}\right)$ of $\mathrm{z} = \mathrm{n} + 2^{\mathrm{m}-1}$ number of successors.

Step 2: Thing $\mathrm{r}$ lookup all things in the ring with contains the same key $\mathrm{k}$ (The key is $\mathrm{ID}_{\mathrm{DER}_{\mathrm{j},}}$ in case of RR messages or SCi in case of PubSub messages)

Step 3: Initialize the locality cluster C= Ø and the MatchList= Ø.

Step 4: If $k == k(r)$ → C=r
Step 5: while(i=0, i≤z ):
    a.  If $k == k(n_i)$ and $n_i$ ∄ $\mathrm{C_1}$ → $\mathrm{C_1}$ ( $\mathrm{C_1} \cup \{\mathrm{n_j}\}$) and ( MatchList ∪ $\{\mathrm{L_j}\}$).
    Otherwise, i++
Step 6: Thing r builds the RR message or PubSub message, depending by the ToM, which contains $\mathrm{C_1}$ information that will be sent to all $\mathrm{L_j}$ in the MatchList.
Step 7: The receiver's nodes make the same loop until the received message reach the source node. The community duster $\mathrm{C_1}$ has been built in the process of the lookup algorithm progress by ring network.
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It should be note that Cluster C_1 has all locality nodes of searched key type ($\mathrm{ID}_{\mathrm{DER}_{\mathrm{i},}}$ in case of RR messages or SC_{i} in case of PubSub messages). The MatchList is composed by all IPs of nodes which the message will be sent. In this way, this thing can establish the communication only with the things that are included in that list, avoiding sending unnecessary messages and reducing the latencies and the used bandwidth.

4.3.4. D. Cloud Layer

The cloud layer stores the historical data that has been obtained from the DERs for global supervision purposes. Storing historical data is one of the required features for IoE applications and services [38]. The cloud layer of the IoE platform contains virtualized servers. Moreover, an application interface with stored historical data for each DER has been implemented. The historical database is able to store and manage a huge amount of data, which is provided to the cloud infrastructure by the application interface.

4.4. APPLICATION TO THE MICROGRIDS MANAGEMENT: A CASE EXAMPLE

To illustrate the above concepts, it has been considered a residential microgrid composed by loads, photovoltaic generation and storage devices (ESS). The microgrid under consideration is managed following the photovoltaic generation profile and the so-called Time of Use (ToU) tariffs. The possibility of connecting both critical (CL) and non-critical loads (NCL) has been taking into account in this example. From the management point of view, the main difference between CL and NCL is the higher priority of CL if the available energy is low. NCL will be considered as constant load that will be connected or fully disconnected if there is not enough energy to supply it. Instead, CL is not disconnected but the supplied power is limited according to the available energy and the applicable tariff. This is a general approach that is compatible with the particular case of having the need of fully supplying CL independently from the tariff (i.e. if there is not enough PV generation, the needed energy would be demanded to the grid assuming the corresponding costs).

TOU tariffs are a new concept designed to incentivize costumers to use more energy at off-peak times. Normally these tariffs are classified in Peak, Shoulder and Off-Peak periods, being the peak tariff the most expensive and the off-peak the cheapest. Only for illustrating purposes, Figure 5 shows the considered tariffs along the day.

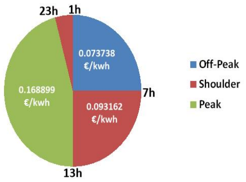

Fig.5. Applied TOU periods

A ToU-algorithm has been developed to dynamically manage the flows of energy into the microgrid according the load profile, the State of Charge (SoC) of EES, the available PV generation and the applicable tariff. Figure 6 shows the flowchart of the algorithm with the set of rules that has been taken into account. The main guidelines are described below:

1) The hired power (HP) is the maximum power that can be consumed from the main grid. The maximum power that can be supplied to the loads (PLim) is the sum of the photovoltaic generation (PV), the hired power (HP) and the power that can be extracted from the batteries (PBat). Therefore, the power consumed by the loads can be greater than HP only if photovoltaic

production is available or there is enough energy stored in the batteries.

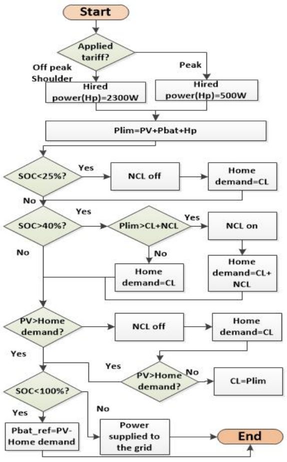

Fig.6. Flowchart of the TOU-Algorithm

2) It has been considered a tariff with time discrimination (peak and off-peak stretches). Therefore two values have been established for HP, corresponding to each one of the stretches. The energy supplied by the main grid in the peak stretch is much more expensive, so HP is significantly reduced in this stretch.

3) Two types of loads have been considered: a constant power non-critical load (NCL) and critical loads (CL), whose consumption varies according to a typical consumption profile. NCL is activated only if there is enough available power and the battery charge (SOC) is greater than 40%. NCL is deactivated as long as the battery charge is below 25%. Finally, CL is always connected but Plim limits the supplied power.

4) The battery is only charged if there is surplus photovoltaic production. If the battery is fully charged, the surplus is injected into the grid.

5) Note that these set of rules are just an example of power management in the microgrid. These rules are the context to apply the proposed communication architecture, which is the main objective of this paper. In this way, the proposed IoE middleware is used for efficiently routing the interchanged messages. PubSub is used to notify the applicable ToU tariff to all DERs (or things) in the network and RR transmits the microgrid commands according to the restrictions that were outlined in Table I. The historical data is stored in the cloud layer to supervise the global status of the microgrid.

4.5. EXPERIMENTAL RESULTS

To evaluate the performance of the proposed IoE platform, it has been applied to an experimental hybrid microgrids (HY-MG) in which there are two interconnected AC and DC buses [39]. As Figure 7 shows, the microgrid has six connection nodes, each one of them having a connected DER following table IV, (i.e. there is only a thing connected to each one of the nodes, so the terms nodes and things are equally used in the following). In this table, it has been described the kind of DER and the physical laboratory equipment that has been used to emulate it. Note that the performance of NCL and ILC has not been emulated. A 750 W resistor and 10 kVA three phase inverter have been used to implement NCL and ILC, respectively.

A 400V DC bus and a three-phase 230V AC bus compose the power network. As it can be seen in Figure 8, each thing interacts with the power network and with the virtual distributed communication network through embedded single board computers (SBCs). The chosen SBC has been the Beagle Bone Black (BBB), which is a low-cost, small size and powerful SBC that is considered the best option for developing real-time IoT applications [26]. This board features an ARM-Cortex-A8 running at 1 GHz. Regarding the memory capacities, it integrates 512MB RAM and 2GHz onboard flash eMMC, which hosts a Debian 9 operating system. Moreover, it also includes GPIO ports, USB port, 10/100 Ethernet port and a HDMI connection port, among others functionalities. For these reasons, BBB has been used in this work as communication gateway to Ethernet-P2P network, as well as running platform to host the proposed IoE middleware.

Figure 7 shows a picture of the experimental setup, following the scheme that Figure 6 shows.

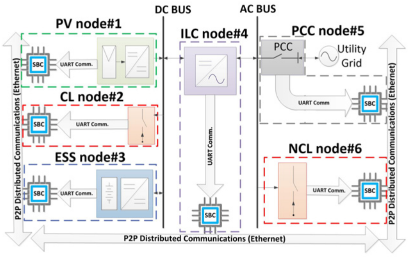

Fig.7. Conceptual hybrid microgrid diagram with six nodes and their communication interfaces.

It is worth noting that each node has an additional electronic board (EB) that works together with the corresponding SBC. The SBC provides connection to the virtual network via Ethernet, while the EB is only used for controlling the lab equipment to emulate the desired behavior of the connected DER, following Table IV. Obviously, there is not necessary an EB controller for the nodes in which the DER is not emulated (in this case, CL and ILC)

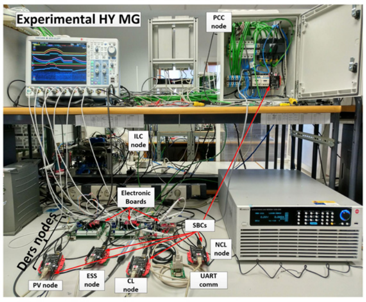

Fig.8. Picture of the experimental setup

In order to evaluate the proposed IoE communication platform, three tests have been carried out: A) IoE platform Response Time evaluation, B) IoE platform performance evaluation, C) Routing performance Evaluation, and D) IoE platform computational resources usage (on the embedded system) evaluation.

TABLE IV

CHARACTERISTICS OF THE LAB EQUIPMENT

Nodes	Lab Equipment
#1	PV Generator, emulated by means of a DC programmable power supply (AMREL SPS 800-12 DO13)
#2	CL node, emulated by means a high power programmable DC electronic load (Chroma 63205A-1200-200)
#3	EES node, emulated by means a programmable bidirectional DC power supply (REGATRON TC.GSS.20.600.400.S.HMI)
#4	ILC node, a three phase inverter(10kVA)
#5	PCC node, emulated by means an AC three phase power source (Pacific, 360AMX).
#6	NCL node, a resistive load (750W)

4.5.1. IoE Platform Time-Response Evaluation

To evaluate the response time of the communication system, it has been analyzed the transmission of an activation event for NCL. The experiment has been carried out by using both RR and PubSub paradigms. However, the response time of RR communications has a large impact on the overall message exchange, so the experiment has been focused on RR. With PubSub communications, the message exchange contains mostly unidirectional notification messages.

A.1 Time Response of Request-Response Communications

Figure 9 shows the communications exchange between two nodes during the NCL activation event using RR communication.

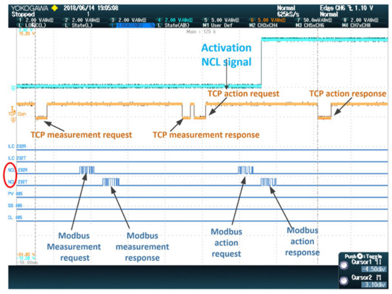

Fig.9. Communication exchanges to produce the NCL event activation

It is worth pointing out that, to carry out the different time measurements, the GPIO pins on Single Board Computers (SBC) and Electronic Boards (EBs) have been activated. Particularly, TLS pin (Transport Layer Security) for SBCs and the two pairs DTR/DSR (Data Terminal Ready/ Data Set Ready) RTS/CTS (Request to Send/Clear to Send) for EBs. Figure 10 shows the diagram with the signals activation related with the different communication exchanges.

Note that DTR/DSR-RTS/CTS pins have been used for data flow control to the devices (Modbus protocol activation). However TTL pin are mostly used for data flow control between the host and device (TCP protocol activation).

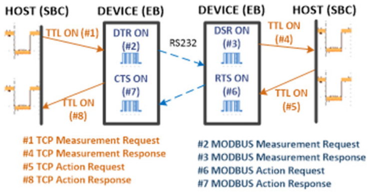

Fig.10. Diagram with the different GPIO signals activation for time request measurements

The communications exchanged during the NCL activation are the following: the source node of the P2P network request the state of the NCL node (TCP measurement request); when the NCL node in the network is reached (see the red circle in Figure 9), it reads its state through Modbus communication (Modbus measurement request) and responds (Modbus measurement response) by following TCP/IP protocol. When the source node is reached (TCP measurement response) it sends an ON action request (TCP action request); when this message arrives to the NCL (Modbus action request) it sends the ON signal and the NCL is activated (See NCL signal activation in blue). Finally, NCL sends an acknowledgement message (Modbus action response) through TCP/IP, which reaches the source node (TCP action response).

In this example the responses time of the different MG functions has been determined (See Figure 11)

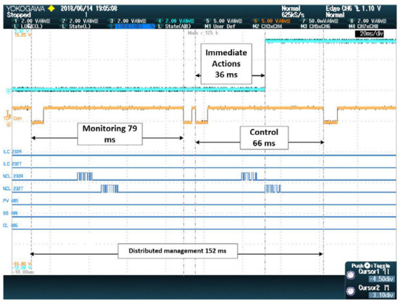

Fig.11. Response times of the exchanged messages by using RR communication

Table V defines the functions associated with the measured times. Table VI resumes the measured time-responses of each microgrid function with the proposed IoE platform, by comparing them to those required by microgrids. As it can be seen, the response time of the proposed IoE platform meets the network microgrid requirements.

TABLE V

DEFINITION OF CONSIDERED RESPONSES TIMES

Function	Definition
Monitoring	Time difference between the time instant when an information request is send by the source node until the response reaches the source node
Control	Time difference between the time instants when a control request is send by the source until the control ACK message is reached by node source
Immediate actions	Time difference between the time instants when an action request is sent by the source node until the action is executed.
Distributed Management	Time difference between the time instants when information and an action request is sent by the source node until the responses reach the source node.

TABLE VI

RESPONSE TIMES OBTAINED BY THE PROPOSED IOE PLATFORM

	Time Response	Time Response
Monitoring Information	79 ms	15ms-200ms
Control Information	66 ms	16ms-100ms
Messages requiring immediate actions	36 ms	3ms-100ms
Distribution Management	152 ms	100ms-2s

Since in RR protocol, the requesting node keeps waiting for the response, a critical scenario (overload) has been considered to evaluate the platform's response time. For that, three hosts in broadcast have been requesting at once over the NCL node periodically every second during 10 minutes. The Response time between a minimum delay (best case), a medium delay (regular case) and a maximum delay (worst case) has been measured. Figure 12 shows the platform's response time under overload considering the delay time in the best, regular and worst case.

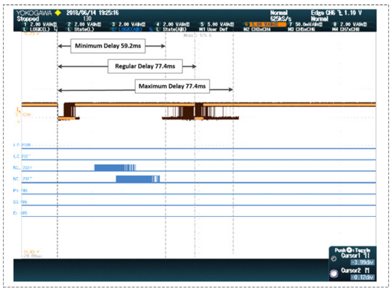

Fig.12. Response times under overload by using RR communication

As it can be seen, even in the worst case the response time of the proposed IoE platform meets the network microgrid requirements.

However, if a node failure occurs and the requester node does not receive the response of the destination node after three message retransmission, the node assumes that these nodes have left the network, and then update the list of its neighbors. It is worth to point out that, in normal conditions, the nodes communicate that they are leaving the network. Thus, in the case of node failure, it will not previously warn that leaves the network and the system will have proof that a failure has occurred. The subsequent management of failures is beyond the scope of this paper.

A.2 Time Response of Publisher-Subscribe Communications

The delays associated to the Pub-Sub communications have been evaluated by means of the Demand Response function. The Demand Response is a function that allows customers, voluntarily, to participate in load management. In table I, the required Demand Response Time (DRT) is in the range from 500 ms to several minutes. Since it is a specification relatively relaxed (several minutes without specifying a concrete superior limit), it has been implemented by means of a PubSub communication pattern. Figure 13 shows an example of the Demand Response function implemented through PubSub communication. In the example, the nodes CL (pink) and NCL (blue) are subscribed to a publication related to the loads activation/deactivation. The measurement of the DRT starts when the TCP/IP connection is stablished (t0). As it can be seen in the figure, DRT=1575ms for CL disconnection and DRT=1800 ms for activation of NCL. The measured times are clearly into the specified range.

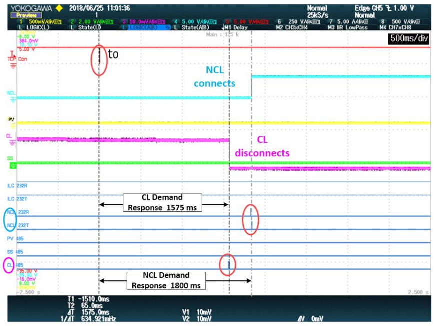

Fig.13. Demand response time by using PubSub communication

4.5.2. IoE Platform Performance Evaluation

The goal of the proposed IoE platform is to support vertical applications that process the information from the things layer to the cloud layer. To evaluate the performance of the proposed IoE platform, the application example that was described in Section IV has been implemented on the experimental microgrid. The ToU-Algorithm that was introduced in that section (see Figure 6) has been deployed in each DER of the microgrid, running on top of the proposed IoE middleware. Figure 14 shows the behavior of each DER according to the programmed ToU-Algorithm and the set of communications that is taking place among the nodes of the microgrid.

Fig.14. Set of IoE communications (down), control sígnals and flows of Energy (up) in the application example under consideration

The experiment emulates the behavior of the microgrid under study along a day (from 00 h to 24h). In the figure, it can be seen the reference signals for each node (i.e., the control signals to emulate the performance of the desired DER, which are labeled with the suffix “ref”) as well as the power that is actually delivered or absorbed by the corresponding DER: PV generator (orange), NCL (light blue), CL (dark blue), ESS (red) and ILC (violet). It is worth noting that power is positive in loads when it is absorbed, but in the case of the PV generator and the ESS, it is assumed as positive when delivered. In the case of the ILC, the power is positive when the energy is flowing from the DC bus to the AC bus. It should be also noted that the reference signals are sent through the proposed IoE platform. As Figure 14 shows, the power that is being supplied/absorbed by each DER agrees perfectly with the corresponding reference signal. Therefore, the proposed IoE platform is efficiently working and all the commands are sent in a timely and reliable manner (see the communication packets at the bottom of the figure), verifying that the proposed IoE platform is adequate for the microgrids management.

4.5.3. Evaluation of Routing Performance

The main benefits of the proposed MGCA protocol are a reduction in both the network traffic (See Figure 15.a) and the routing time (See Figure 15.b). The performance of the proposed routing protocol has been compared with the one of flooding routing technique.

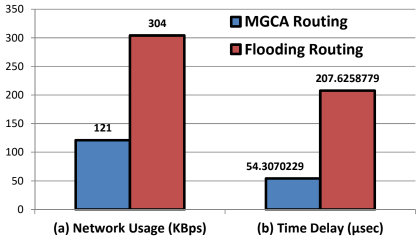

Fig.15. Comparison of network usage in KBps (15.a) and time delay in microseconds (15.b) between MGCA and Flooding routing

The traffic in the network has been measured by averaging the network usage in kilobytes per second (KBps). In the same way, the average time delay is the average time to route the query to the matched nodes in microseconds. Both measurements have been evaluated for 6 nodes during 15 minutes.

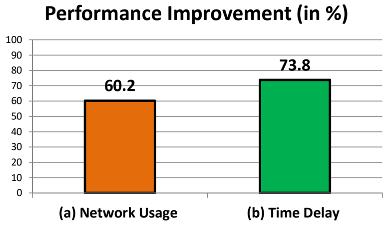

Fig.16. Improvement (in %) of MGCA routing protocol over Flooding protocol

As Figure 16.a shows, the MGCA routing protocol improves near 60% the network usage. In other words, the proposed routing protocol consumes near three times less traffic that flooding techniques. The reason is that the routing tables of MGCA protocol have information about neighbors and clustering can be formed. In this way, each query is delivered only to the matched nodes in the cluster and not to the all nodes in the routing table as flooding routing does. Consequently, a network traffic reduction is achieved. In addition, MGCA protocol has self-organization capability due to the overlay Chord infrastructure. With this feature, each node knows the disposition of their neighbors, which produces an effective method for queries propagation. Figure 16.b shows a reduction around 73.8 % in the routing time with MGCA with regard to the flooding protocol.

4.5.4. Evaluation of Computational Resources Usage

Embedded systems work under several resources constraints as size, weight and consumed energy, among other limitations. As a consequence, they have limited memory and CPU capacities. Therefore, an efficient resource management is an essential aspect to integrate SBCs in real-time applications. In order to demonstrate that the proposed IoE middleware accomplish with the constraints of the chosen embedded hardware, it has been measured the usage of memory, as well as the percentage of CPU, for processing of the proposed algorithms. To evaluate these parameters, they have been both measured with (IoE mode) and without (Idle mode) running the proposed IoE middleware. Obviously, the differences between the values that have been measured in both operation modes are the additional resources that the proposed IoE algorithm needs. As Figure 17 shows, the additional average CPU usage when the IoE algorithm is running is 4.35%. Similarly, the additional average active memory usage is 10.6%. It is worth noting that the needed computational resources are really far of the limits of the chosen SBC, so that other functionalities as storage of historical events, security protocols, etc. could be implemented. The implementation of such functionalities is out of the scope of this paper.

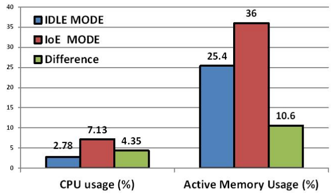

Fig.17. Comparison of CPU and memory average use (in % with regard to the full capacity of devices) between Idle and IoE modes

4.6. CONCLUSIONS

In this paper a new IoE communication platform for the management of microgrids has been presented. The proposed platform is based on a flexible IoT layered infrastructure that has highly scalability and integrates distributed energy resources (*things* layer). The platform is composed by four layers: *things,* IoE middleware, MG services and cloud.

The platform has been physically implemented on an experimental hybrid-microgrid by means of Beagle Bone Black devices.

The achieved experimental results have shown that: 1) the IoE platform provides timely responses to events within precise timing constraints in order to guarantee a desired level of performance, 2) The proposed IoE platform operates efficiently for power management of residential applications and 3) The IoE platform is able to work properly under the restrictions of physical embedded systems.

Therefore, it can be concluded that the proposed solution is an interesting approach to the envisioned IoE in the context of microgrids. In addition, it may be easily extended to the Smart Grid concept.

ACKNOWLEDGEMENTS

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5

DISCUSIÓN DE RESULTADOS

Este capítulo analiza los resultados obtenidos en las cuatro publicaciones presentadas. Describe las herramientas y equipos de laboratorio utilizados. Describe la motivación, contribuciones de cada una de las publicaciones obtenidas así como un análisis de los resultados y conclusiones. Además se complementan las publicaciones presentadas con nuevos resultados relevantes que fueron obtenidos y que no fueron incluidos por motivos de espacio.

Contenidos

5.1 Herramientas

Antes de comenzar el análisis de los resultados de cada una de las publicaciones obtenidos a lo largo de esta tesis, se presentarán las diferentes herramientas que han sido empleadas en el desarrollo de estos trabajos, con especial interés en aquellos elementos que no han sido descritos en las publicaciones. Por una parte se describe la metodología utilizada y las herramientas de desarrollo, simulación y experimentación que han sido clave durante todo el trabajo.

5.1.1 Metodología

La presente Tesis Doctoral trata sobre el diseño y desarrollo de arquitecturas y plataformas de comunicación para la gestión eficiente de energía en microrredes inteligentes. Los sistemas de comunicación propuestos estarán preparados para su óptimo funcionamiento en entornos residenciales, consiguiendo altos estándares de calidad. En concreto, se propone el desarrollo de protocolos y arquitecturas de comunicación para microrredes residenciales que permitan implementar, de manera segura y fiable, los niveles de control de orden jerárquico más elevado para la optimización de los flujos de potencia dentro de la propia microrred, así como su posible interacción con el operador eléctrico que proporciona el punto de conexión a la red, o, en su caso, con el operador de otras microrredes cercanas con las que pueda estar interconectado.

Para lograr estos objetivos, en esta tesis se ha empleado una metodología convencional, basada en cinco fases (Ver Figura 5.1.1.1):

Durante la primera fase se hará una revisión bibliográfica de los distintos esquemas de control e infraestructuras de comunicación asociadas (protocolos, tecnologías, topologías,…) para su aplicación a la gestión y operación de microrredes residenciales, analizando en detalle las ventajas e inconvenientes que presenta cada modelo, así como las necesidades existentes dentro del área de interés sobre las que investigar. Se pretende proponer arquitecturas de comunicación que se adapten a las necesidades de comunicación dentro de la propia microrred que presente características destacables sobre el resto.

Figura 5.1.1.1 Diagrama de la metodología de trabajo.

Una vez analizadas las soluciones existentes y las necesidades actuales, y con un extenso conocimiento del estado del arte, de las bondades y carencias de las soluciones existentes en la literatura, se definen los objetivos de trabajo. Con los objetivos establecidos, se procederá a desarrollar propuestas de la arquitectura o plataformas de comunicación que se adapte de manera específica a las necesidades de la transmisión de datos dentro de la propia microrred y de ésta al exterior para implementar los niveles jerárquicos de control más elevados.

Una vez las distintas propuestas tienen una formulación adecuada, se comienza el trabajo de investigación propiamente dicho, compuesto por tres partes bien diferenciadas pero íntimamente ligadas entre sí:

Desarrollo → Simulación → Implementación

Por tanto, la tercera fase corresponderá al desarrollo software de las arquitecturas y plataformas de comunicación propuestas. Este proceso abarca el diseño y codificación de la estructura del software. En esta fase se crea el sistema, es decir, se redactan los programas, se generan los ficheros de datos, se desarrollan bases de datos y las capas de aplicación.

La cuarta fase corresponde a la simulación de los desarrollos software obtenidos. Mediante herramientas de simulación se valida la aptitud de las arquitecturas y plataformas de comunicaciones propuestas. Se simularán todos los parámetros del modelo que se consideren especialmente relevantes, para su posterior validación en las pruebas experimentales.

En la quinta y última fase se procederá a la validación de la arquitectura propuesta en la microrred implementada en las dependencias del departamento de Ingeniería Electrónica de la UPV. El prototipo construido servirá para validar los datos de simulación, así como para una evaluación más realista de los resultados obtenidos. Se analizarán los resultados obtenidos con el fin de formular conclusiones y futuras líneas de investigación.

5.1.2 Desarrollo

Cabe resaltar en este punto que todas las arquitecturas y plataformas de comunicación propuestas en esta Tesis han sido desarrolladas enteramente por la doctorando.

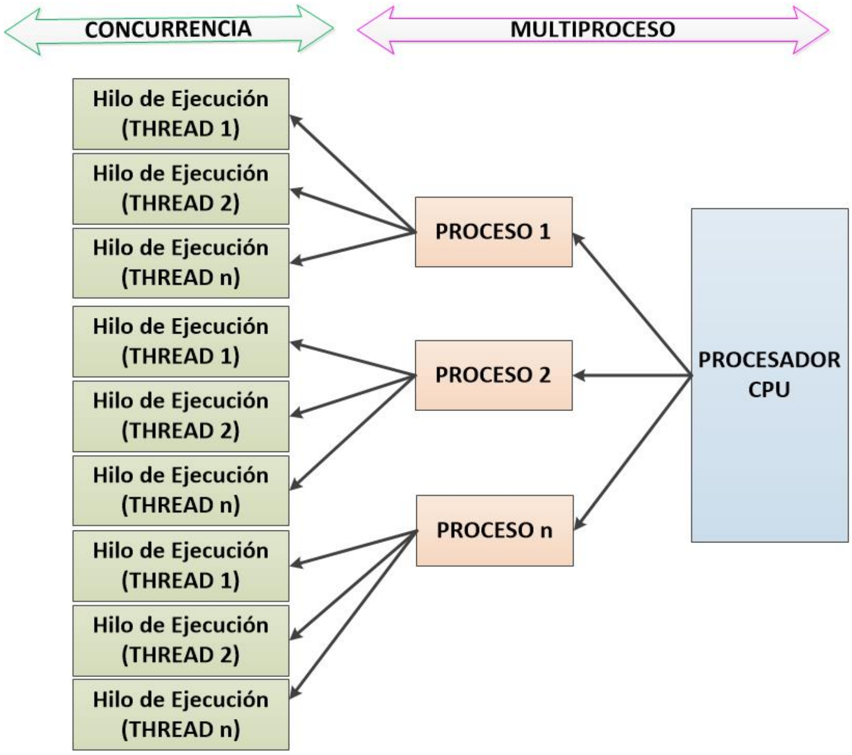
La plataforma de comunicación y arquitecturas propuestas han sido desarrolladas utilizando el entorno de desarrollo integrado (*Integrated Development Environment,* IDE) de software libre y multiplataforma Pycharm que permite la creación de programas con el lenguaje de programación Python.

Python es un lenguaje orientado a objetos (Programación Orientado a Objetos, POO). Un objeto es una unidad que engloba en sí mismo características y comportamiento necesarios para procesar información. Cada objeto contiene datos y funciones. Un programa se construye como un conjunto de objetos, o como un único objeto. La programación orientada a objetos es un paradigma de programación que busca representar entidades u objetos agrupando datos y métodos que puedan describir sus características y comportamiento.

Tal y como se ha descrito en profundidad en el capítulo I, el desarrollo de las plataformas de comunicación para microrredes requieren de una naturaleza distribuida, embebida y en tiempo real:

- Aplicaciones Distribuidas: Se ejecuta en múltiples máquinas, teniendo cada máquina su propio procesador, su propia memoria y corriendo su propio sistema operativo. Requiere intercomunicación a través de la red.
- Aplicaciones Embebidas: Se ejecuta en un entorno computarizado especial. Requiere codiseño hardware/software.
- Aplicaciones de Tiempo Real: Tiene entre sus especificaciones requerimientos temporales.

Para conseguir una aplicación distribuida, cada nodo de la microrred requiere de un despliegue hardware/software. Por tanto el software a desarrollar debe poder embeberse en un ordenador de placa reducida con limitación de recursos computacionales (CPU y memoria) y debe poder realizar las tareas en tiempo real y conforme a unos requisitos de calidad. Para lograr estas características, se ha utilizado programación multiproceso y concurrente. La programación multiproceso permite la ejecución de varios procesos al mismo tiempo corriendo en un único procesador. La programación concurrente es la simultaneidad de múltiples tareas (Figura 5.1.2.1). Con la programación concurrente se consigue la correcta secuencia de interacciones o comunicaciones entre los procesos así como el acceso coordinado de recursos que se comparten entre todos los procesos. Por tanto, en cada proceso puede haber más de un contexto de ejecución activo simultáneamente. Con la programación multiproceso podemos producir un ahorro de los recursos computacionales del sistema mientras que con la programación concurrente hace posible la ejecución de varias actividades produciendo beneficios en la eficiencia de procesamiento, sincronización entre procesos en tiempo real.



5.1.2.1 Esquemático programación multiproceso y concurrente.

Para modelar la comunicación entre nodos se ha utilizado programación concurrente y en particular sockets de comunicación para el intercambio de datos. El socket designa un concepto abstracto del canal de comunicación por el cual dos procesos pueden intercambiar cualquier flujo de datos. La particularidad que tienen frente a otros mecanismos de comunicación entre procesos (IPC-Inter Process Communication) es que posibilitan la comunicación aun cuando ambos procesos corren en distintos sistemas unidos mediante una red. De hecho, el API (*Application Programming Interface*) de sockets es la base de cualquier aplicación que funcione en red puesto que ofrece una librería de funciones básicas que el programador puede usar para desarrollar aplicaciones en red.

El lenguaje de programación Python proporciona dos clases para la implementación de sockets o Threads (hilos de ejecución); Socket Stream y

Socket Datagrama. La principal diferencia entre estas dos clases está en el uso de protocolo de transporte, mientras socket stream hace uso del protocolo TCP (Transportation Control Protocol), Socket Datagrama hace uso del protocolo UDP (User Datagram Protocol). El protocolo TCP proporciona mayor cantidad de servicios que UDP, por ser un protocolo orientado a conexión. Además principalmente garantiza: control de flujo, detección y corrección de errores así como reconocimiento del paquete recibido. Por ello, se ha implementado la comunicación haciendo uso de la clase Socket Stream. Un socket se identifica unívocamente por la dupla dirección IP + número de puerto. Una comunicación entre dos procesos se identifica mediante la asociación de los sockets que estos emplean para enviar y recibir información hacia y desde la red: identificador de socket origen + identificador de socket destino.

Como ya se ha adelantado las comunicaciones diseñadas en esta Tesis son comunicaciones basadas en pares, comunicaciones P2P. A diferencia de una arquitectura cliente/servidor en la que se desarrolla estas dos aplicaciones en dos partes asimétricas: el servidor, que proporciona servicios y que está disponible de manera confiable en una dirección conocida de internet conocida, y el cliente que se conecta al servidor para solicitar información. Las aplicaciones P2P son más difíciles de desarrollar ya que en un sistema P2P, todas las máquinas (nodos) ejecutan el mismo programa que funciona simultáneamente como servidor y como cliente. La siguiente figura ilustra cómo suceden los intercambios de mensajes entre pares en una red. Cada aplicación que se ejecuta en un nodo proporciona una interfaz cliente para la ejecución de consultas y ejecuta simultáneamente un "bucle principal" que escucha las conexiones entrantes de otros pares (parte servidor).

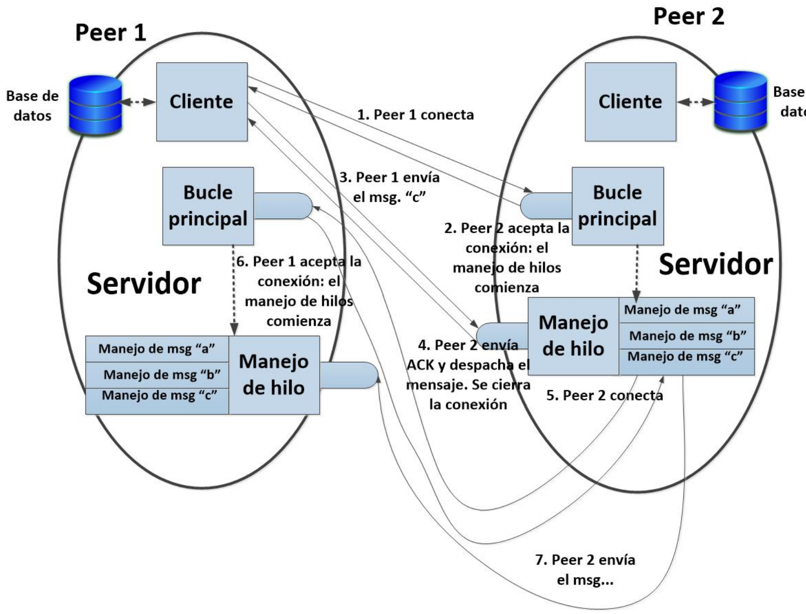


Figura 5.1.2.2.Diagrama comunicación P2P.

En la figura 5.1.2.2, se muestra un diagrama de una escena donde el cliente del Peer 1 envía una solicitud de conexión al Peer 2 (paso 1). El bucle principal del Peer 2 detecta la solicitud de conexión entrante y comienza un hilo separado para manejar los datos reales de la solicitud (paso 2). Tras el establecimiento de la conexión, el Peer 1 envía un mensaje de consulta (mensaje “c”) al Peer 2 (paso 3). En el paso 4, la tarea de "manejo de hilo" del Peer 2 recibe el mensaje, envía un acuse de recibo al Peer 1, cierra la conexión y luego llama a una función / método apropiado para manejar el mensaje según su tipo. Después de procesar el mensaje, la función "Manejo de msg. “c”" necesita enviar un mensaje de respuesta de consulta al Peer 1, por lo que intenta conectarse (paso 5). El bucle principal de Peer 1, al escuchar estas conexiones, acepta la conexión e inicia su manejador de hilo (paso 6) para recibir los datos del mensaje de Peer 2 (paso 7). Una vez recibido el mensaje, Peer 1 hace lo que hizo Peer 2 en el paso 5, y el proceso continúa.

El componente servidor, se trata de una aplicación concurrente, donde el servidor puede atender múltiples peticiones simultáneas. Para ello, se ha desarrollado un esquema de comunicación asíncrona o no bloqueante mediante un modelo multihilo (multithreading model), donde el servidor en este caso tiene una organización interna de hilos concurrentes y cooperantes. Entre las ventajas de realizar la comunicación de manera no bloqueante y asíncrona se encuentran:

- *Las que permiten el desarrollo de técnicas de aprovechamiento de recursos de cómputo:*

Normalmente en un modelo cliente-servidor, mientras el servidor está esperando para recibir datos de un cliente, si el “stream” o chorro de datos esta vació, el hilo principal o “main thread” se bloqueará hasta que el pedido de datos sea satisfecho. Por lo tanto, el servidor no podrá hacer nada hasta que reciba los datos del cliente. Si otro cliente tratara de conectarse al servidor al mismo tiempo, el servidor no podrá procesar el pedido de conexión porque estará bloqueado por el primer cliente. Esto es debido a que la planificación de la CPU sigue un modelo FIFO lo que se conoce como “primero en llegar primero en ser servido, First In Fist Out”. Sin embargo, para sistemas distribuidos, como el planteado, donde necesitamos soportar múltiples clientes al mismo tiempo, esta situación no es aceptable por lo que el diseño del servidor se convierte en una cuestión crítica. Por ello, mediante el uso de múltiples threads, la CPU se reparte par cada proceso y se permite que las tareas se ejecuten paralelamente. Recuperando los resultados conforme las operaciones vayan terminando.

- *Las que permiten el desarrollo de técnicas de aprovechamiento de recursos de comunicación:*

Favoreciendo el rendimiento (aumento del througput de la aplicación, solapamiento de E/S con cómputo) y escalabilidad del canal de comunicaciones al reducirse los tiempos de espera por contención de acceso al canal y mejorando la estabilidad y tolerancia a fallo del sistema, de tal forma que si una comunicación falla no se cae todo el sistema. Por tanto, la parte servidora de la aplicación está dedicada a escuchar posibles conexiones de dispositivos que quieran establecer comunicación. El diseño de la aplicación servidor crea un hilo principal *class Myhilosup (threading.Thread)* que al iniciarlo arranca múltiples hilos *class Multihilos Server (threading.Thread)* capaces de atender a múltiples dispositivos. Es decir, cada vez que se conecte un dispositivo se ejecutará un thread que atenderá las peticiones de ese dispositivo. Además, para cada conexión entrante de dispositivo, cada hilo particular será capaz de guardar el ID del dispositivo según su tipología (A: Almacenamiento, C: Carga, G: Generador) basado en su dirección IP y el puerto de origen cada uno de ellos en la base de datos.

La componente cliente de la aplicación, la primera acción que lleva a cabo es la invocación a la BBDD para descubrir qué dispositivos se encuentran conectados a la microrred. Una vez conoce los dispositivos puede conectarse a cualquiera de ellos para realizar el control y monitorización mediante el envío de señales de control con petición de lectura o escritura a los parámetros del dispositivo DER, que serán actualizados en la base de datos. Decir, que el cliente tiene la capacidad de conectar simultáneamente con tantos dispositivos como desee. Para ello, se han implementado diferentes métodos para producir la interacción de grupos de dispositivos que soportan la replicación de datos y la replicación de cómputo para mejorar la disponibilidad y mejorar las prestaciones. En estos modelos de interacción de grupos se han desarrollado los siguientes patrones de comunicación: *Multicast(),* para realizar envíos de datos desde un miembro a un determinado subgrupo de receptores (dispositivos); *Broadcast()*, para realizar envíos de datos a todos los dispositivos y Unicast o punto a punto() para comunicaciones desde un participante emisor a otro receptor.

Además de estos métodos también se han desarrollado los métodos *genera_conex(), envio_ mensaje() y recibir_respuesta()*. La aplicación cliente por tanto está diseñada como una aplicación paralela donde el cliente es capaz de lanzar múltiples peticiones simultaneas de forma asíncrona. Para ello, la metodología empleada es la realización de llamadas asíncronas a delegados. Un delegado es un tipo de dato, por lo que se puede instanciar, y a través de estas variables llamar a funciones que tienen la misma estructura (tipo de datos de retorno y parámetros) que el delegado, es decir, los delegados permiten básicamente realizar llamadas a métodos de forma dinámica. Cuando creamos un delegado a un método y lo utilizamos para realizar llamadas asíncronas lo que se hace es llamar a ese método en un hilo de ejecución diferente; por lo que inmediatamente después de realizar la llamada el programa continúa su ejecución y en paralelo con el método, de esta forma se permite realizar múltiples peticiones simultaneas a los distintos dispositivos cuyas respuestas se irán recuperando conforme las operaciones vayan terminando.

Entre las ventajas de realizar la comunicación mediante llamadas asíncronas a delegados se encuentran el aumento de rendimiento de cómputo, de esta forma se permite realizar otra operaciones (hacer trabajo productivo) mientras se espera el resultado de la operación, y la garantía de escalabilidad del sistema porque las siguientes peticiones que se produzcan no serán encoladas y podrán ser atendidas enseguida por threads libres del pool.

A continuación se presentan trozos de código referente a la componente servidor y cliente.

Clases de la aplicación concurrente definida para el servidor

```
class Myhilosup(threading.Thread):

    def __init__(self):
        threading.Thread.__init__(self)

    def run (self):
        global clients
        # logging setup
        logging.basicConfig(level=logging.INFO,
                        format='[%(asctime)s] %(levelname)s:
%(message)s',
                        datefmt='%d/%m/%Y %I:%M:%S %p')
        # initialize global vars
        clients = set()

        # set up socket //
        sock = socket.socket(socket.AF_INET,
socket.SOCK_STREAM)
        sock.setsockopt(socket.SOL_SOCKET,
socket.SO_REUSEADDR, 1)
        sock.bind((host, port))
        sock.listen(5)
        print '-= Microrred Server =-'
        print '>> Listening on:',port

        while 1:
            try:
                conn, addr = sock.accept()
                server = Multihilos_Server(conn, addr)
                server.start()
                print("hilo principal")

             except Exception, e:
                      print e
```

Funciones de los métodos de la aplicación cliente

```
def run(self):

[…]

    # --------------------------Definición de delegados-------
----------------

        if (self.flag_crear_lista_grupos_com==1):
            self.crear_lista_grupos_com(self.iden,self.ip)
            self.flag_crear_lista_grupos_com=0
            last_time=time.time()


        if (self.flag_generar_conexiones==1):
            self.generar_conexiones(self.lista_conectados)
            self.flag_generar_conexiones=0
            last_time=time.time()


        if (self.flag_envio_mens == 1):
            self.envio_mens(self.lista_conectados,
self.mensaje)
            self.flag_envio_mens = 0
            last_time=time.time()

        if (self.flag_recibir == 1):
            self.recibe_respuesta(self.lista_conectados)
            self.flag_recibir = 0
            last_time=time.time()


#------Codigo reservado a realizar las llamadas asincronas a
los métodos------

def Peticion_crear_lista_grupos_com(self,iden,ip):
    self.iden = iden
    self.ip=ip
    self.flag_crear_lista_grupos_com=1


def Peticion_generar_conexiones(self, listaconex):
    self.lista_conectados=listaconex
    self.flag_generar_conexiones=1

def Peticion_envio_mens(self, listaconex, mensaje):
    self.lista_conectados = listaconex
    self.mensaje = mensaje
    self.flag_envio_mens = 1
```

```
def Peticion_recibe_respuesta(self, listaconex):
    self.lista_conectados = listaconex
    self.flag_recibir = 1
```

En referencia a la base de datos, se trata de una base de datos con un modelo relacional, la cual permite establecer interconexiones (relaciones), entre los datos que están guardados en las tablas y a través de dichas conexiones relacionar los datos de las tablas interconectadas. Además, para administrar y desarrollar la aplicación de la base de datos creada es necesario un SGBD (Sistema Gestor de Bases de Datos). Se trata de utilizar herramientas computacionales para acceder a los datos de forma que se puedan almacenar, recuperar y gestionar la información de forma práctica y eficiente. En consecuencia el SGBD de la microrred ha sido desarrollado en lenguaje Python. Para la conexión con la BBDD se ha importado la biblioteca MySQLdb que permitirá una conexión remota o local con los servidores de MySQL. En el SGBD también se han desarrollado funciones para conformar la aplicación de la BBDD tales como; *ejecutar_consulta(), insertar_datos(), leer_datos(), borrar_datos(), cambiar_datos(), reiniciar_tablas()* o *eliminar_tablas(),* entre otras.

Por otra parte, para poder habilitar los servicios necesarios para ofrecer sitios web dinámicos y aplicaciones web se ha instalado el conjunto de aplicaciones software LAMP (Linux, Apache, MySQL y PHP), siendo Linux el sistema operativo, Apache el servidor web, MySQL la base de datos donde se almacenan los datos y PHP para dar soporte al contenido dinámico.

5.1.3 Simulación

Para lograr un sistema de comunicación distribuido para el control, gestión y monitorización de microrredes, el software desarrollado debe implementarse en cada nodo de la microrred (inversores, transformadores, interruptores, etc.). Para simular este comportamiento se ha implementado una plataforma con máquinas virtuales (Figura 5.1.3.1).

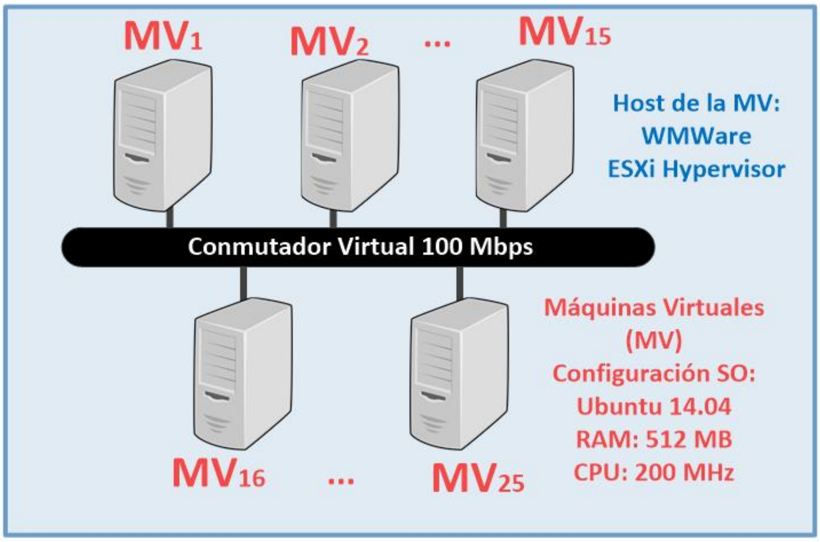


Figura 5.1.3.1. Dibujo esquemático de la configuración utilizada para la simulación.

Se han configurado 25 máquinas virtuales que emulan el comportamiento de una microrred de 25 nodos en un entorno real, teniendo en cuenta que las soluciones propuestas se aplicarán en el futuro a una microrred híbrida AC-DC. Se ha creado esta configuración de simulación para evaluar el rendimiento y el comportamiento del software desarrollado en términos de rendimiento de la red de comunicación (latencia, paquetes enviados, ancho de banda, etc.) y en términos de rendimiento de recursos computacionales (CPU y memoria).

Para lograr este objetivo, se ha utilizado un servidor con un hipervisor (VMware ESXi) (VMware Inc, Palo Alto, CA, EE. UU.) para ejecutar 25 máquinas virtuales. Cada máquina virtual ejecuta Ubuntu 14.04. Las máquinas virtuales están conectadas a la LAN a través de un conmutador virtual limitado a 100 Mbps. Los recursos de cada máquina virtual se han limitado a 512 MB de RAM y 200 MHz de CPU. Esta configuración ha sido adecuada para que coincida con los sistemas integrados que elegimos inicialmente para migrar de máquinas virtuales a máquinas físicas, por lo que los resultados experimentales que se presentan son realistas y valiosos para validar preliminarmente la solución propuesta.

Para la toma de resultados se ha utilizado CACTI para medir el rendimiento de la red y VMWare para medir el rendimiento computacional.

CACTI es una herramienta de monitoreo de red a tiempo real del uso de recursos de red por parte de los dispositivos. Es una herramienta que permite graficar series de datos con bases de tiempo del estado de la red de comunicación. Por su parte, VMWare dispone de un subsistema de recopilación de datos de rendimiento computacional de los dispositivos virtuales que también se muestran en gráficos.

5.1.4 Experimentación: Descripción de la Microrred

La experimentación de la presente tesis doctoral se ha realizado en la microrred experimental del Grupo de Sistemas Electrónicos Industriales del Departamento de Ingeniería Electrónica de la UPV, que se muestra en la Figura 5.1.4.1.

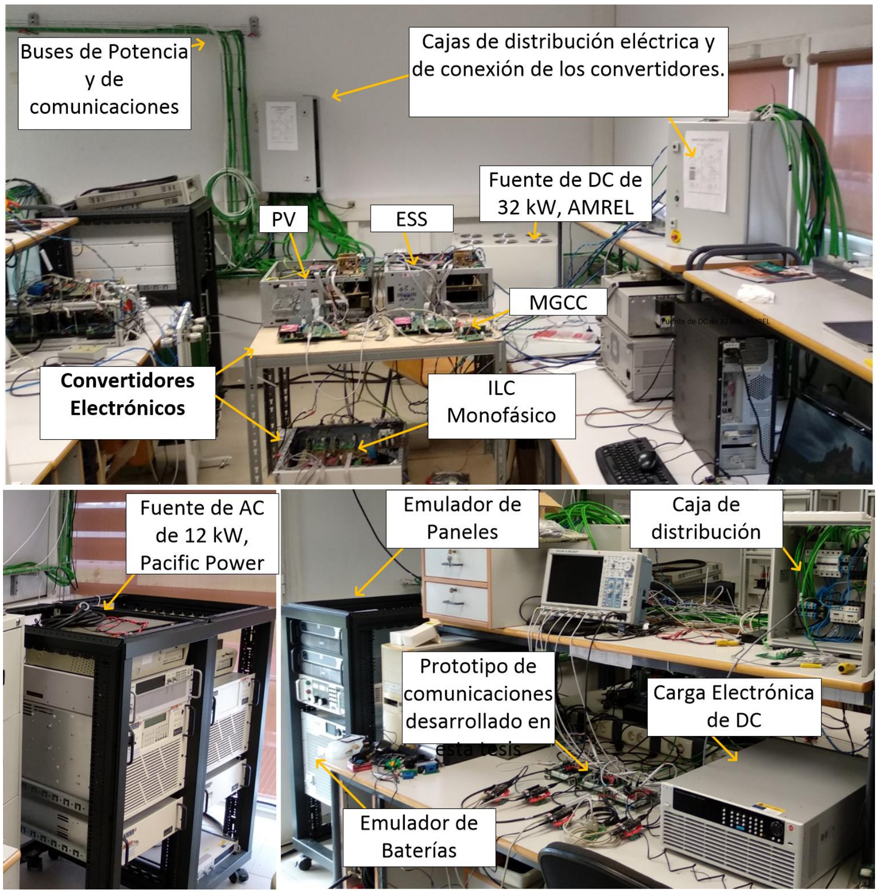


Figura 5.1.4.1. Fotografía de la microrred experimental del Grupo de Sistemas Electrónicos Industriales del Departamento de Ingeniería Electrónica de la UPV.

La figura muestra el esquema eléctrico de la microrred AC/DC híbrida implementada. La microrred se basa en un bus de DC y un bus de AC, este último conectado al punto de conexión común de la red pública de distribución mediante un interruptor estático. La interconexión entre los buses de DC y AC es realizada por un inversor de interconexión *(Interlinked Converter, ILC)* monofásico de 10 kW con topología en puente completo, lo que permite un flujo de potencia bidireccional. En el modo conectado a red, el ILC funciona como una fuente de corriente que inyecta potencia al bus de AC de manera sincronizada y regula la tensión en el bus de DC. Cuando la red pública es monofásica, el voltaje nominal del bus de DC es VDC = 400 V ± 20 V, la tensión de la red vale VGrid = 230 Vrms y su frecuencia es FGrid = 50 Hz ± 1. Para evaluar el rendimiento de las plataformas de comunicación propuestas en esta tesis de manera experimental se han considerado seis nodos de la microrred tal y como se observa en el esquema de la Figura 5.1.4.2

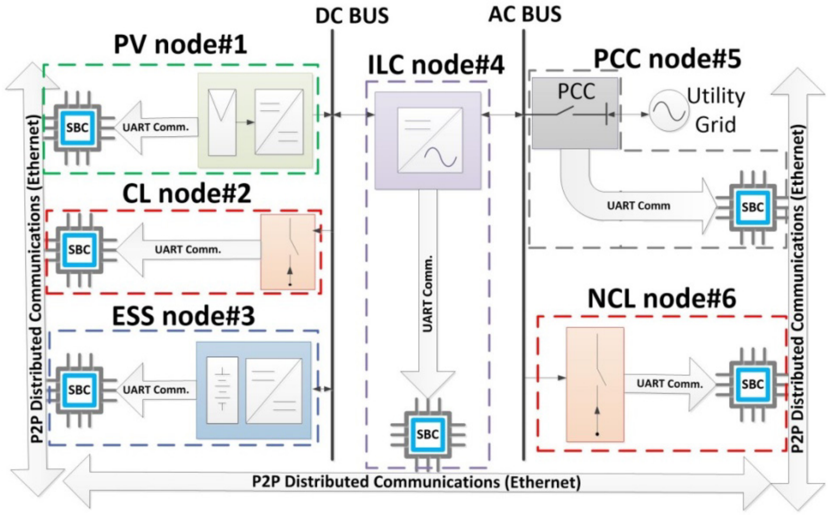


Figura 5.1.4.2. Esquemático de la microrred híbrida con seis nodos y sus interfaces de comunicación.

Como se muestra en la Figura 5.1.4.2, la microrred está compuesta por seis nodos de conexión, cada uno de ellos con un recurso energético distribuido (RED) conectado siguiendo la tabla 5.1.4.1. En esta tabla, se ha descrito el tipo de RED y el equipo de laboratorio físico que se ha utilizado para emularlo. Hay que tener en en cuenta que el rendimiento del ILC y de la carga no critica, *Non Critical Load, NCL,* no se ha emulado. Se han utilizado una resistencia de 750 W y un inversor trifásico de 10 kVA para implementar NCL e ILC, respectivamente.

Tabla 5.1.4.1: Características del equipamiento de Laboratorio.

Nodo	**Equipo de Laboratorio**
#1	Generador Fotovoltaico *(Photovoltaic, PV)*, emulado por una fuente programable DC de 32 kW, (AMREL SPS 800-12 DO13)
#2	Carga Crítica (*Critical Load, CL*) emulado por una carga electrónica de DC de 5 kW. (Chroma 63205A-1200-200)
#3	Almacenamiento de energía *(Energy management System, ESS)* emulado por una fuente DC/DC bidireccional de 20 kW (REGATRON TC.GSS.20.600.400.S.HMI).
#4	ILC, inversor trifásico de 10KVA
#5	Punto de Conexión Común (Point Common Couple, PCC) emulado por una fuente de AC de 12 kW de tipo monofásica/trifásica (Pacific, 360AMX).
#6	Carga No Critica, *(Non Critical Load, NCL)*. Carga resistiva de 750W

Como se puede ver en la Figura 5.1.4.3, cada nodo interactúa con la red eléctrica y con la red de comunicación virtual distribuida a través de computadoras integradas de una sola placa (SBC). El SBC elegido ha sido el Beagle Bone Black (BBB), que es un SBC de bajo costo, tamaño pequeño y potente que se considera la mejor opción para desarrollar aplicaciones de IoT en tiempo real. Esta placa cuenta con un ARM-Cortex-A8 que funciona a 1 GHz. En cuanto a las capacidades de memoria, integra 512 MB de RAM y 2GHz de memoria flash eMMC integrada, que aloja un sistema operativo Debian 9. Además, también incluye puertos GPIO, puerto USB, puerto Ethernet 10/100 y un puerto de conexión HDMI, entre otras funcionalidades. Por estos motivos, BBB se ha utilizado en este trabajo como puerta de enlace de comunicación a la red Ethernet-P2P, así como como plataforma de ejecución para alojar el middleware IoE propuesto.

Vale la pena señalar que la arquitectura de comunicación propuesta debe implementarse en cada uno de los nodos donde se conecta un módulo eléctrico (como inversores, transformadores, interruptores, etc.).

Por lo tanto, cada nodo está interconectado con los módulos eléctricos y también con la infraestructura de comunicación a través de computadoras integradas de placa única (SBC), como muestra la figura. Además, el sistema de comunicación propuesto es adaptable a cualquier tipo de microrred con conectividad Ethernet.

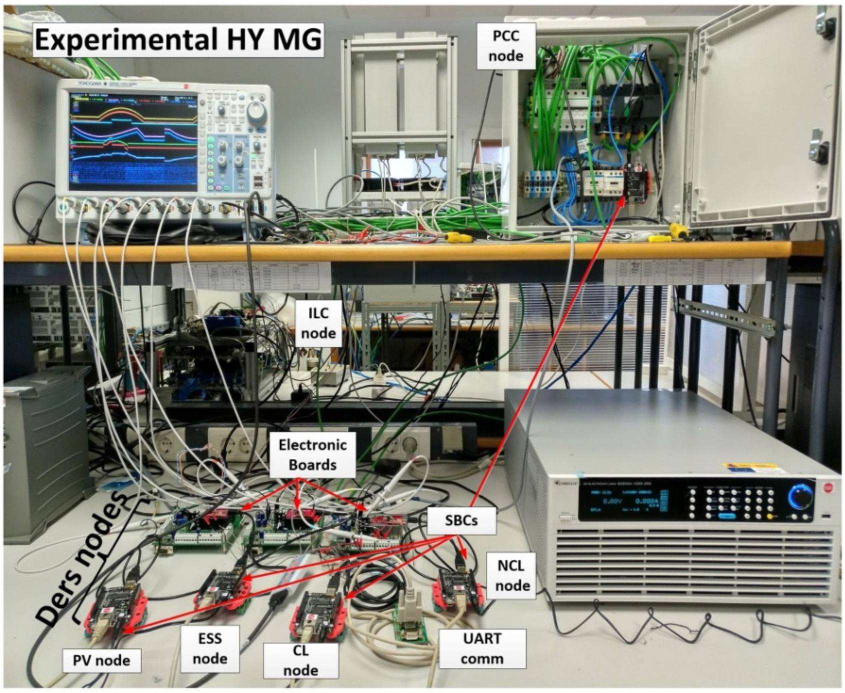


Figura 5.1.4.3. Detalle de las conexiones para crear el nodo inteligente (emuladores y BeagleBone Black).

5.2 Publicación I

En el Capítulo 1 se incluye la primera publicación.

S. Marzal, R. Salas, R. González-Medina, G. Garcerá, E. Figueres, *"Current challenges and future trends in the field of communication architectures for microgrids,"* Renewable and Sustainable Energy Reviews, Vol. 82, no. 3, pp. 3610-3622, 2018.

Motivación

Tal y como se ha descrito anteriormente en la introducción, las tecnologías de la información y la comunicación (TIC) son un requisito indispensable en la futura microrred inteligente para proporcionar operaciones técnicas y de mercado avanzadas. El movimiento hacia las futuras necesidades de las microrredes requiere desarrollar una infraestructura de comunicación distribuida que permita la integración de los recursos de energía distribuidos (RED) para su monitoreo y control que dé respuesta a estas complejidades. Debido al creciente aumento de los REDs en las microrredes, la infraestructura de comunicación debe tener la capacidad de manejar una gran cantidad de dispositivos, datos y tráfico de información en tiempo real de manera eficiente y fiable. En base a esto, el estándar IEEE 1547 para microrredes *"Standard for Interconnecting Distributed Resources with Electric Power Systems"* en su punto IEEE1547.3-2007 define la funcionalidad, parámetros, metodología y métricas de rendimiento para la monitorización, intercambio de información y control para las fuentes distribuidas interconectadas con el sistema eléctrico, y en él se propone o se sugiere el uso de las redes de comunicación P2P para llevar a cabo tales tareas. Sin embargo, en el estándar no se estudia su idoneidad, los requisitos técnicos necesarios y retos que supone la transición hacia la futura microrred inteligente, cuestiones que motivan la publicación del presente artículo.

Contribución

El trabajo propuesto muestra una revisión completa de los fundamentos de las comunicaciones en la evolución pasada, presente y futura de las microrredes. Las principales contribuciones de este artículo son: (i) Descripción de los principales desafíos en los requisitos de comunicación de las futuras microrredes inteligentes, (ii) Descripción de las principales limitaciones de las tecnologías implementadas actualmente en la generación de las microrredes distribuidas, (iii) Discusión de la infraestructura de comunicación más adecuada para el desarrollo de microrredes distribuidos, (iv) Descripción de la idoneidad de los sistemas de comunicación P2P para la monitorización y gestión de microrredes distribuidas, (v) Definición de las tecnologías P2P y futuros retos para su implementación y despliegue en microrredes.

Análisis de los Resultados

Las microrredes deben tener su propio sistema de control para asegurar la operación y coordinación de los diferentes REDs. Este sistema de control necesita de una infraestructura de comunicación para así lograr una óptima operación de la microrred. Tras la revisión de la literatura realizada en este artículo, se ha podido comprobar que la evolución de las microrredes (Figura 5.2.1), y por tanto, el sistema de control de éstas, está intimidante relacionado con la infraestructura de comunicación desarrollada e implementada que incluye aspectos como la topología de red, la arquitectura de protocolos y la tecnología implementada. La topología de red se refiere a la disposición de la red y líneas de conexión (geometría de la red); de la misma manera, la arquitectura de protocolos se define como una pila de protocolos por capas donde cada capa tiene una función e implementa un protocolo o tecnología.

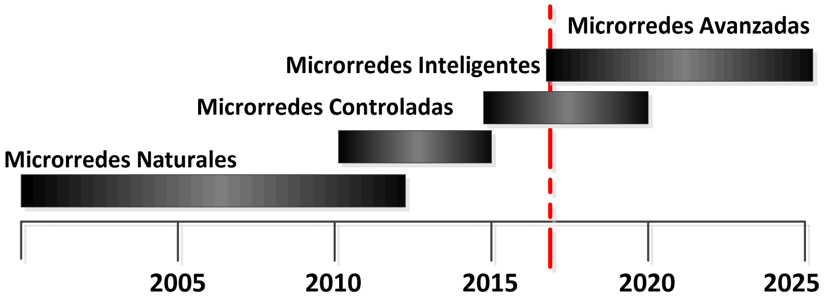


Figura 5.2.1. Hoja de ruta hacia las microrredes avanzadas.

Generalmente las distintas arquitecturas de protocolos se basan en el modelo de interconexión de sistemas abierto, también llamado **OSI** (en inglés *open system interconnection*). Se trata de un modelo de protocolos descriptivo creado por la Organización Internacional para la

Estandarización. Es decir, es un marco de referencia para la definición de arquitecturas de interconexión de sistemas de comunicaciones. La figura 5.2.2 muestra el modelo de referencia OSI y la función que realiza cada capa. A medida que se evoluciona hacia las microrredes avanzadas, la pila de protocolos implementada cambia. El artículo discute ampliamente estos aspectos.

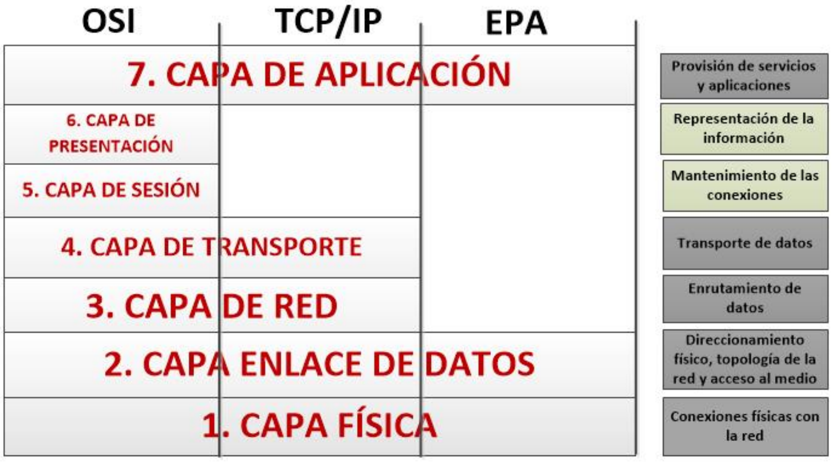


Figura 5.2.2. Pilas de comunicación OSI,TCP/IP y EPA

Tras el nacimiento de las primeras microrredes, denominadas microrredes naturales, que surgen al utilizar generación próxima a los puntos de consumo, aparece la necesidad de incorporar un sistema de control para coordinar estos recursos, por lo que pasan a denominarse microrredes controladas. Las instalaciones de microrredes controladas de hoy en día utilizan el modelo de referencia EPA (Enhanced Protocol Arquitecture) como pila de protocolo. EPA en comparación con el modelo OSI, que tiene siete capas, tiene tres capas (1, 2 y 7), ver Figura 5.2.2. Tradicionalmente, la tecnología alámbrica es la empleada por estos sistemas en la capa física (Capa 1) y en particular los estándares de conexión física RS232/RS422/RS485. Las tecnologías RS232/422/485 sobre cable no permiten proporcionar comunicaciones descentralizadas, y definen una topología de red centralizada en la capa 2 para implementar las estrategias de control y lograr la transferencia de información entre entidades. Mediante esta topología un controlador central, el controlador central de microrredes (CCM), se comunica con todos los recursos de la microrred y toma decisiones. Sin embargo, esta tipología presenta ineficiencias debido a que una falla en el punto de control centralizado podría provocar varias fallas o incluso la caída de todo el sistema. Además, los recursos energéticos distribuidos tienen un rol pasivo debido a que generalmente implementan en la capa 7 protocolos basados en arquitecturas cliente-servidor (maestro-esclavo) soportados por enlaces físicos del tipo RS-X tales como MODBUS, PROFIBUS, CANBus o DNP3, los cuales son protocolos de capa de aplicación para instalaciones industriales. En el modelo cliente-servidor existe una distinción rígida entre las funcionalidades del nodo cliente y el nodo servidor. De hecho, los nodo servidor son los encargados de proporcionar el servicio, sin embargo, no son capaces de tomar cualquier iniciativa, ya que son reactivos y tienen que esperar a ser invocados por el cliente. Por el contrario, los nodo cliente concentran la iniciativa del sistema, acceden y utilizan los servicios. Así los clientes se comunican con los servidores pero no pueden comunicarse con otros clientes. Por otra parte, el servidor no puede comunicarse con los clientes hasta que los clientes hayan tomado la iniciativa y deciden comenzar una sesión de comunicación con el servidor. De este modo los sistemas basados en el modelo cliente-servidor lleva a ineficiencias del servicio, cuellos de botella o infrautilización de los recursos de la red. Además de las deficiencias presentadas, las microrredes controladas con una pila de protocolos EPA, al no tener capa de red y transporte, presentan dificultades para gestionar los datos en tiempo real.

En la última década, las limitaciones de las arquitecturas de comunicación centralizadas junto con la introducción cada vez mayor de recursos energéticos distribuidos en la red eléctrica y la tendencia creciente hacia el uso de tecnologías basadas en internet cambian el escenario actual de las microrredes que evolucionan desde una topología centralizada offline a una descentralizada con acceso a internet que permita la gestión de una red de comunicación a tiempo real.

Debido al crecimiento de recursos energéticos distribuidos en una red distribuida y dado que las operaciones de microrred requieren acciones de control en tiempo real, el sistema necesita ser diseñado con requisitos de rendimiento de red y calidad de servicio (Quality of Service, QoS) para satisfacer las necesidades de flujos de datos sensibles al tiempo, ancho de banda y latencia, entre otros. Por tanto, resulta obligatorio conocer qué ancho de banda y qué latencia (retardo) puede tolerar cada aplicación de microrred. Es decir, cada función de microrred tiene su propio requisito de latencia y ancho de banda, dependiendo del tipo de respuesta del sistema que se trata. Las normas IEC 61850, IEEE 1647-1646 dan especificaciones para estos requisitos. Los requisitos de rendimiento de la red, en base a estos estándares, para cada aplicación de microrred se han resumido en Tabla 5.2.1. Por otra parte, el retardo de comunicación para cada tipo de mensaje de microrred se ha resumido en la Tabla 5.2.2.

Tabla 5.2.1. Requerimientos de red en microrredes

Aplicación de Microrred	Ancho de Banda	Latencia
Respuesta de la demanda	14-100 Kbps	500 ms-varios minutes
Recursos energéticos distribuidos y Almacenamiento	9.6-56 Kbps	20 ms-15 s
Gestión distribuida	9.6-100 Kbps	100 ms-2s

Tabla 5.2.2. Requerimientos de retardo para diferentes funciones de la microrred

Mensajes de Microgrid	Requerimientos de retardo
Información de protección	4 ms
Información de monitorización	1s
Información de control	16 ms-100ms
Información de operaciones y mantenimiento	1s
Mensajes de acción inmediata	1A:3 ms or 10ms;1B: 20 ms or 100 ms
Mensajes entre REDs	3ms or 10 ms
Mensajes de sincronización	(Precisión)

Por su parte, las infraestructuras de comunicación descentralizadas eliminan el controlador centralizado como un único punto de falla y, por lo tanto, producen una mejora en la confiabilidad de la operación en microrredes. En esta estructura, todos los dispositivos pueden controlarse de manera independiente en lugar de con un controlador central. Además, la arquitectura implementada se basa en la pila de protocolos TCP/IP. El conjunto de protocolos TCP / IP es el estándar de facto de Internet. La pila TCP / IP normalmente tiene cuatro capas: física y capa de enlace de datos (Capa de enlace), Capas de red, Transporte y Aplicación [Fig. 5.2.2]. Los sistemas de comunicación basados en TCP / IP proporcionan un óptimo ancho de banda para el manejo de grandes cantidades de dispositivos y control en tiempo real. En la capa física TCP/IP soporta tanto tecnologías alámbricas como inalámbricas. En tecnologías alámbricas Ethernet permite topologías descentralizadas y enrutamiento a través de TCP/IP, lo que permite una mejora de los retardos. Por otro lado, las soluciones más populares en el ámbito de las microrredes para el acceso inalámbrico a Internet son las WPAN (redes inalámbricas de área personal-familia IEEE 802.15) y Wi-Fi (familia IEEE 802.11). Para la capa de red, el protocolo de internet IP (Internet Protocol) permite comunicaciones extremo a extremo independientemente de los medios físicos subyacentes lo que proporciona interoperabilidad, característica que es indispensable para lograr una operación y conectividad óptima del sistema en general, independientemente del medio físico utilizado y el tipo de dispositivos. En la capa de transporte, el protocolo TCP (Transmission Control Protocol) permite transmisión de los datos de manera confiable, secuenciada y control de errores. Finalmente, como protocolo de aplicación se pueden utilizar protocolos propietarios especialmente desarrollados para la gestión de microrredes o protocolos estándar como IEC 61850.

La evolución hacia microrredes inteligentes se materializa a través de la tecnología de Sistemas MultiAgentes (SMA). Un SMA es un sistema compuesto por múltiples agentes inteligentes capaces de realizar acciones de manera autónoma y que interactúan entre ellos con el propósito de alcanzar una serie de objetivos que tienen delegados, a través de la cooperación, coordinación y negociación. Estos agentes pueden estructurarse formando topologías totalmente descentralizadas, donde en cada uno de ellos implementa el protocolo de pila TCP / IP, lo que atribuye a cada agente de capacidades de comunicación y gestión. Sin embargo, los sistemas energéticos son cada vez más distribuidos e inteligentes y tienen un carácter más multi-disciplinar lo que se traduce en nuevos desafíos para lograr una gestión y operación óptima de las microrredes ya que son necesarios, entre otros requerimientos: (i) nuevas tecnologías para el funcionamiento proactivo de los nodos, (ii) nuevas capas de software en la pila de protocolos TCP/IP para satisfacer las necesidades crecientes de servicio, e (iii) intercambios de información entre dispositivos en capas virtuales que permita la reorganización dinámica de los nodos que permita capacidades plug and play así como la auto-reconfiguración y sanación de la red.

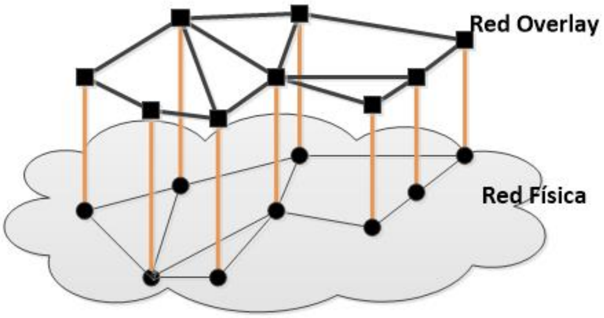
Las últimas investigaciones indican que los SMA presentan algunas limitaciones para ajustarse a estos nuevos requerimientos debido a:

- Los agentes de los SMA no pueden comunicarse simultáneamente con otros agentes, sólo se permiten interacciones uno a uno entre agentes, es decir, los agentes solo pueden actuar como un cliente o como un servidor, lo que resulta en una falta de proactividad del agente. De esta forma, si el agente detecta un fallo en su funcionamiento, éste no podrá comunicar su fallo a la red hasta que otro agente se comunique con él. La ausencia de tal funcionalidad podría resultar en una mala gestión de los recursos críticos de la microrred.

- En un SMA se conoce el comportamiento individual de cada uno de los agentes. Sin embargo el comportamiento global del sistema es difícilmente entregado. Para obtener el estado global del sistema de agentes, se deben formar clusters de agentes o agrupamiento de agentes. Los cluster son grupos de agentes que se forman para realizar acciones comunes. La ausencia de dicha funcionalidad podría resultar en la falta de conocimiento sobre el estado global de la microred y, por lo tanto, en la asignación sub-óptima de recursos.

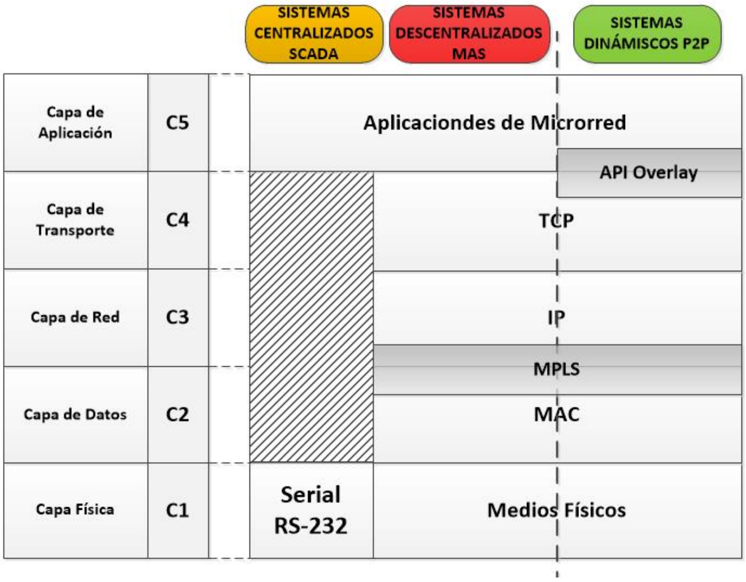
- Las interacciones entre los agentes se llevan a cabo en la capa física y no virtual lo que impide una reorganización dinámica de la red ni capacidades de auto-sanación para adaptarse a fallas locales, apagones de microrred, fallos de agentes o fallos de comunicación.

Para superar esas limitaciones, recientes investigaciones perfilan a la tecnología entre pares, (en inglés, peer-to-peer P2P) como un potente paradigma para el control de la futura generación de microrred, las microrredes dinámicas o avanzadas. Una red P2P es una arquitectura de comunicación descentralizada donde los agentes, ahora llamados pares, pueden actuar tanto como clientes (maestros) como servidores (esclavos) simultáneamente, lo que permite a los pares un carácter proactivo, en comparación con los agentes que sólo actuar como servidor o maestro. Respecto a la topología de las redes P2P, la conectividad entre los pares es esencialmente virtuales, es decir, topologías lógicas y estructuradas (llamadas overlays) que están construidas sobre las redes físicas [Ver Figura 5.2.3]. Debido a la implementación de esta capa virtual los pares no sufren de la inflexibilidad de las topologías físicas, en las que se basan los SMA, y se permite extensibilidad, autocuración y reconfiguración dinámica. Además, el hecho de que las estructuras son de naturaleza lógica, se construyen por encima de las redes físicas subyacentes, ofrecen una gran variedad de servicios de nivel de aplicación así como la creación de clusters para una determinada actividad. Además, las redes P2P se pueden implementar a través de tecnologías por cable o inalámbricas sobre la pila de protocolos TCP/IP, y el desarrollo de una capa de software en la parte superior de la capa TCP, bien propietario o estándar, para la provisión de servicios y aplicación de microrredes.



5.2.3. Esquema de arquitectura de red de superposición u overlay.

La figura 5.2.4 presenta la evolución de la arquitectura de capas de las microrredes. Las diferenciaciones y propiedades de cada una de las microrredes consideradas se pueden encontrar en la Tabla 5.2.3.



5.2.4. Pila de protocolos de la evolución de la microrred

Tabla 5.2.3. Comparación de la evolución de microrredes.

	MICRORREDES CONTROLADAS (CONTROLADOR CENTRAL)	**MICRORREDES INTELIGENTES (SMA)**	**MICRORREDES AVANZADAS (P2P)**
Acceso a la información	Centralizado desde el controlador central	Descentralizado	Distribuido y dinámico
Estructura de comunicación de datos	Global y síncrona	Local y asíncrona	Local, global y asincrona
Funciones de tiempo real	Difícil y caro	Posible y barato	Fácil y barato
Capacidad Plug&Play	El Controlador Central debe ser programado	Puede ser obtenida	Inherente a los peers
Costes	Alto	Bajo	Bajo
Tolerancia a fallos	Poca tolerancia a fallos	Fallo 1 router → tolerado Fallo n routers → costoso	Fallo n routers failure → tolerado (auto-sanación)
Flexibilidad y modularidad	La reconexión es requerida para adición de RED	SMA pueden instalar módulos y sistemas escalables	Los nodos pueden entrar y salir de la red sin modificaciones de la red
Escalabilidad	Pocos nodos	IPv4 →2^{32} nodos IPv6 →2^{128} nodos Dominios jerarquicos	>2^{128} nodos Dominio de nombres
Nodos destino	Identificación de nodos no permitidos	Identificación única de un nodo por IP	Identificación por
Interoperabilidad	No es posible	Posible	Demandado
Rendimiento de la red	Altas Latencias y bajos anchos de banda. QoS no permitido	Mejores rendimientos en relación de latencias y ancho de banda. QoS esta permitido	Bajas latencias y altos anchos de banda. QoS inherente
Red	Physical (EPA)	Physical (TCP/IP)	Virtual (o TCP/IP)
Seguridad	Pobre	Solo cuando los nodos son seguros	Conseguible, incluso en entornos nos seguros

Como se observa en la tabla 5.2.3, con la implementación de la tecnología P2P en microrredes, se combinan las ventajas del control distribuido (como la escalabilidad, adaptabilidad resiliencia) y el control centralizado (confiabilidad, óptimización, globalidad). Sin embargo, estas redes presentan desafíos que deben ser abordados para su implementación en entornos de microrred, tales como:

- Las redes P2P se han desarrollado principalmente para la compartición de archivos y ciclos de procesadores, cuyos requisitos de rendimiento de red son menos críticos. Así, adaptar esta tecnología a los requisitos de red de las microrredes es esencial para un realizar un control y monitoreo óptimo. En este sentido, es necesario extender la norma IEC 61850 para incluir descentralización e interoperabilidad.
- Las aplicaciones actuales de microrred no son capaces de gestionar la incertidumbre y variabilidad de los recursos energéticos distribuidos, entre otros factores que pueden cambiar con el tiempo, ya que generalmente los métodos utilizados son modelos lineales y pronósticos deterministas que no son capaces de gestionar adecuadamente el comportamiento dinámico de las microrredes. Por esta razón, algoritmos estocásticos avanzados, análisis predictivo y el uso de esquemas no lineales debe aplicarse en las futuras microrredes para producir resultados con mayor fidelidad.
- El creciente número de fuentes de energía renovables y microgeneración, así como la integración de una gran cantidad de unidades DER, requiere avances en la computación de alto rendimiento y procesamiento paralelo, de manera que se proporcione, por un lado, mayores velocidades en el flujo de datos y, por otra, reducción en el tiempo de procesamiento.
- Actualmente, el repositorio de datos implementado en las microrredes hace uso de diferentes formas de datos. Éstos pueden ser estructurados y desestructurados. El desarrollo de un protocolo de comunicaciones universal y compatible capaz de manejar diferentes formatos de datos es otro desafío a llevar a cabo.

Conclusiones

Los actuales sistemas de control centralizados para microrredes presentan limitaciones provocados principalmente por la creciente penetración de los recursos energéticos distribuidos y la necesidad de realizar un control en tiempo real que demanda comunicaciones de red con requisitos de rendimiento más críticos que otros sistemas de TIC debido a la necesidad de mayor confiabilidad, escalabilidad, robustez y QoS. La investigación realizada hasta la fecha ha producido importantes avances en las comunicaciones logrando esquemas descentralizados con protocolos de acceso a internet en tiempo real, estableciendo una base importante para el futuro despliegue de la las microrredes avanzadas. Éstas han demostrado que agentes inteligentes, autónomos y comunicativos pueden conducir al control exitoso de una microrred descentralizada. Además, la adopción de la pila de protocolos TCP/IP permite comunicaciones finales entre agentes e interoperabilidad. Sin embargo, el futuro de las comunicaciones en las microrredes eléctricas se centra en la implementación de estrategias de control dinámicas y comunicación entre pares, P2P, que doten a la microrred de características avanzadas tales como flexibilidad, auto-sanación, auto-reconfiguración y servicios mejorados. Estas mejores en el sistema de control de microrredes para la futura generación de microrredes se centra en el aprovechamiento de los avances en comunicaciones, matemáticas y software de computación.

5.3 Publicación II

En el Capítulo 2 se incluye la segunda publicación de este compendio.

S. Marzal, R. González-Medina, R. Salas, E. Figueres, G. Garcerá, , *"A Novel Locality Algorithm and Peer-to-Peer Communication Infrastructure for Optimizing Network Performance in Smart Microgrids,"* Energies, Vol. 10, no. 9, pp. 1275, 2017.

Motivación

Las redes de comunicación Peer-to-Peer (P2P) han surgido como un nuevo paradigma para implementar servicios distribuidos en microrredes debido a sus beneficios potenciales: son robustas, escalables, tolerantes a fallos, y pueden enrutar mensajes incluso cuando una gran cantidad de nodos están frecuentemente entrando y saliendo de la red. Las mayores barreras técnicas para la implementación de redes de comunicaciones P2P en microrredes son, hoy en día, que éstas han sido principalmente desarrolladas para otras aplicaciones como la compartición de archivos o ciclos de procesador donde los requerimientos de red son menos exigentes que los demandados para las microrredes. Los distintos estándares y normas establecidas para el despliegue de microrredes destacan la necesidad de cumplir con algunos parámetros de calidad de servicio (QoS) como latencia, ancho de banda, *throughput* (rendimiento), entre otros, que garanticen la correcta interconexión de los recursos energéticos distribuidos a la microrred para su óptimo monitoreo y control. Con la motivación de desarrollar una arquitectura de comunicación P2P que cumpla con los requerimientos de red demandados por las microrredes, en este artículo se diseña y desarrolla un algoritmo de localidad para redes P2P que garantice el cumplimiento de éstos. A su vez, con el objetivo global de proveer servicios distribuidos de microrred, se desarrolla un protocolo específico basado en solicitud-respuesta (Request-Response, RR) para el monitoreo y control de microrredes.

Contribución

El trabajo propuesto muestra una arquitectura de comunicación P2P totalmente distribuida y funcional basada en el paradigma de comunicación solicitud-respuesta para el monitoreo y control de microrredes. La arquitectura de comunicación desarrollada cumple con los diferentes parámetros de calidad de servicio especificados en los distintos estándares para la interconexión eléctrica y gestión de fuentes de energía distribuida tales como IEC 61850, IEEE 1646 e IEEE 1547. Este trabajo muestra los resultados experimentales obtenidos de realizar la comparativa de las arquitecturas de comunicación P2P convencionales con la propuesta.

Análisis de los Resultados

Las redes P2P son redes de área extensa donde los nodos pueden actuar simultáneamente como clientes y servidores, lo que permite realizar tareas de forma distribuida, escalable y eficiente. La conectividad entre peers (nodos) se lleva a cabo mediante la creación de enlaces virtuales, capa de superposición u *overlay* en inglés, que se construyen en la parte superior de la red IP. Esta característica permite que los nodos puedan reorganizarse y reconfigurase por sí mismos.

Las arquitecturas de P2P pueden clasificarse en no estructuradas y estructuradas, según su topología lógica y grado de descentralización. Por un lado, en las redes P2P no estructuradas los enlaces de red se establecen de forma arbitraria formando una topología de red de malla aleatoria, es decir no hay un algoritmo para la organización de los nodos. En ellas, los recursos de información y datos se distribuyen entre los peers de la red por lo que el servicio de búsqueda de recursos en estas redes se basa en una técnica de difusión *(Broadcasting)* para su localización. Mediante la difusión o *broadcast* cada petición de búsqueda tiene que recorrer todo o parte de la red de nodos para encontrar el nodo que contiene la información buscada. La desventaja principal de estas redes es que la transmisión de mensajes de búsqueda genera una gran cantidad de tráfico de datos y utiliza una gran cantidad de ancho de banda de red lo que desemboca en cuellos de botella y altas latencias, características que resultan ineficientes para un sistema escalable y eficiente. Por otro lado, las redes P2P estructuradas tienen una red dedicada y una topología bien definida donde los pares son responsables de la información y los recursos de datos. En las superposiciones estructuradas, una tabla de hash distribuida (Distributed Hash table, DHT) se utiliza para enrutar y ubicar los recursos en la red. En esta estrategia, cada par tiene una tabla local que se utiliza como un algoritmo de búsqueda para enrutar los datos de solicitud según las tablas de nodos. Este tipo de sistema P2P mejora el uso de la comunicación de red, tal y como muestra la Figura 5.3.1.

Figura 5.3.1. Sobrecarga de comunicación vs estado del nodo para las distintas estructuras P2P

La Figura 5.3.1 compara el rendimiento de los algoritmos P2P no estructurados y estructurados. En teoría, la complejidad de búsqueda de cada uno de estos algoritmos puede ser evaluada por métricas analíticas por medio del orden (O), que describe el comportamiento asintótico de los algoritmos. De hecho la notación O expresa los límites superiores asintóticos, ya que limita el crecimiento del intercambio de mensajes para un número suficientemente grande de nodos de entrada. Esto significa que los sistemas P2P estructurados basados en DHTs garantizan que cualquier nodo puede ser localizado con un intercambio de mensajes de orden O(logn) de media, siendo n el número de nodos que forman el sistema; mientras que los sistemas P2P no estructurados basados en broadcasting lo hacen con un orden O(n). El intercambio de mensajes se considera un valor métrico para dar información de la sobrecarga de comunicación y pueden proporcionar evidencias sobre el uso de la red y ancho de banda, así como sobre las latencias experimentadas de extremo a extremo. Tal y como muestra la figura, los sistemas P2P estructurados necesitan de un intercambio de mensajes menor para la localización de un nodo dado, para un número n de nodos en la red. Es por ello, que se ha decido la implementación de una red de comunicación P2P estructurada DHT en la solución propuesta.

A pesar de que los sistemas DHT P2P estructurados presentan mejor rendimiento de la red de comunicación que los no estructurados, todavía presentan deficiencias para su implementación en microrredes por lo que deben ser adaptados. Estas deficiencias son:

(1) Los sistemas DHT convencionales no consideran localidad. La localidad permite crear grupos de nodos con intereses similares para lograr una tarea particular. De esta manera, aplicando técnicas de localidad a los protocolos de enrutamiento, se permite crear accesos directos y usarlos para localizar contenido de manera eficiente. El sistema DHT está basado en un espacio de claves y mapea dicho espacio de claves en los nodos que forman la red P2P. De esta forma, cada nodo de la red tiene asignado una clave que representa un contenido. Esto permite crear una red de información que asocia claves con valores en la forma de pares {clave, valor} y de esta forma cualquier nodo participante puede recuperar el valor asociado con una clave dada utilizando un protocolo de enrutamiento. Aunque, como se ha comentado anteriormente, los distintos sistemas P2P garantizan enrutar un mensaje en un tiempo de orden O(logn), en condiciones normales, recientemente se han publicado estudios donde se ha demostrado que las distintas topologías de nodos creadas para el enrutamiento influyen en la eficiencia y la latencia de red.

(2) Los sistemas DHT convencionales no consideran mecanismos para la recuperación de los datos. Para recuperar los datos es necesario una capa de aplicación. La capa de aplicación es responsable del procesamiento y análisis de los datos.

Con el fin de superar estos inconvenientes en el presente trabajo de investigación se ha propuesto:

(1) Diseño y desarrollado de un algoritmo de localidad (Locality Routing Algorithm, LRA) basado en la formación de clusters (grupos) en función de la tipología del recurso energético distribuido (RED) que permite enrutar los mensajes de manera más eficiente, reduciendo sobrecarga en la red y disminuyendo las latencias de comunicación. Esto permite una mejora en el rendimiento de la red de

comunicaciones de las microrredes, permitiendo el cumplimiento de los estándares.

(2) Diseño y desarrollo de una arquitectura de comunicación basada en la pila de protocolos TCP/IP con capa de aplicación. En la capa de aplicación, un protocolo específico basado en solicitud-respuesta (Request-Response, RR) para comunicaciones P2P se ha desarrollado. Esto permite la recuperación y análisis de los datos para llevar a cabo tareas de gestión y supervisión de los sistemas, las microrredes en este caso.

Una configuración experimental se ha implementado para evaluar el rendimiento y comportamiento de los desarrollados presentados tanto del algoritmo de búsqueda, LRA, como de la arquitectura de comunicación para fines de control y supervisión.

Por una parte, el rendimiento del algoritmo LRA propuesto se estudia en comparación con los algoritmos de inundación (flooding) e inundación limitada. En el esquema de inundación, cuando un nodo recibe una consulta de búsqueda, éste la reenvía a todos los nodos de su tabla DHT y estos nodos retransmiten recursivamente la búsqueda a todos los nodos de sus respectivas tablas, hasta ubicar el recurso solicitado. En el caso de inundación limitada, la propagación de la búsqueda permanece hasta alcanzar el umbral del tiempo de vida del mensaje (Time To Live, TTL) (generalmente cuatro). Con el algoritmo LRA propuesto, se crean grupos de localidad en función del RED buscado. Con esta arquitectura sólo se envían mensajes a aquellos nodos cuyo recurso energético distribuido (RED) coincide con el RED solicitado. A continuación, se presentan el número de mensajes de búsqueda enviados y la latencia de búsqueda para cada uno de los algoritmos.

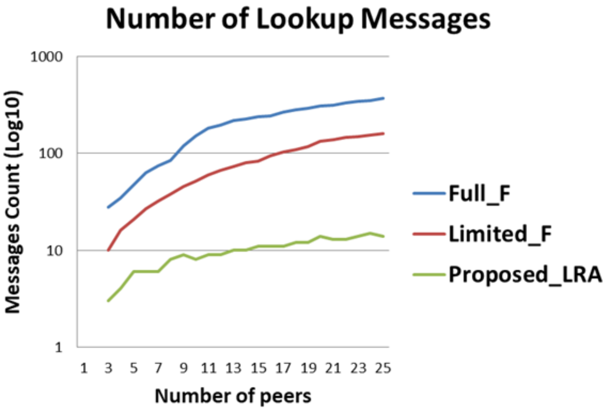


Figura 5.3.2. Comparación de la cantidad de mensajes de búsqueda enviados por los diferentes algoritmos.

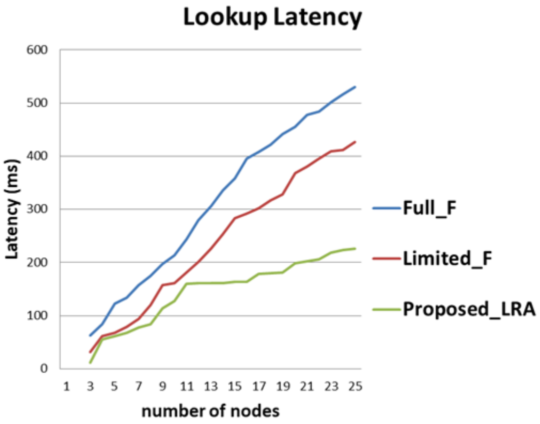


Figura 5.3.3. Comparación de la latencia de búsqueda con los diferentes algoritmos.

Tal y como se muestra en las figuras 5.2.2 y 5.2.3, tanto el número de mensajes como la latencia de búsqueda se reduce considerablemente para el algoritmo LRA. Por una parte, referente al número de mensajes de búsqueda requeridos, los algoritmos de inundación o flooding no usan un método para saber si el par (o nodo) consultado ha sido visitado antes. Sin embargo, el algoritmo de enrutamiento de localidad propuesto utiliza un enrutamiento que permite saber qué pares han sido visitados previamente de manera que se evita el envío de mensajes redundantes, por lo que la cantidad de mensajes de búsqueda se reduce significativamente. De esta manera, al necesitar menos mensajes de búsqueda, las latencias de búsqueda también se ven reducidas.

Por otra parte, se ha desarrollado una capa de aplicación para cada uno de los algoritmos de búsqueda de manera que se permita la recuperación de los datos. Los diferentes escenarios reproducen intercambios de datos en la capa de aplicación utilizando el método de solicitud-respuesta (request-response, RR). Mediante el mecanismo de comunicación RR el nodo origen (nodo solicitante) envía los mensajes de búsqueda a los nodos coincidentes. Los nodos coincidentes responden al nodo origen con un ack y seguidamente el nodo solicitante envía a aquellos nodos que han respondido con una ack, un mensaje de petición de información. Para mejorar el rendimiento de la red de comunicación, la petición de búsqueda e información se ha embebido de manera que aquellos nodos que coincidan con los nodos buscados responderán directamente a la solicitud de información sin necesidad de enviar ACks. Como resultado, tanto el número de los mensajes como la latencia del sistema se reducen significativamente. El rendimiento de las diferentes arquitecturas se presenta en las figuras 5.3.4 y 5.3.5. Los criterios para la evaluación del desempeño son: (i) el número total de intercambio de mensajes (Figura 5.3.4), que se refiere al número total de mensajes que se intercambian entre los nodos tanto los mensajes de búsqueda como para los mensajes de transmisión de la información, (ii) la latencia de extremo a extremo (Figura 5.3.5), considerada como el retardo referido a la latencia de búsqueda y la latencia de procesamiento de la información.

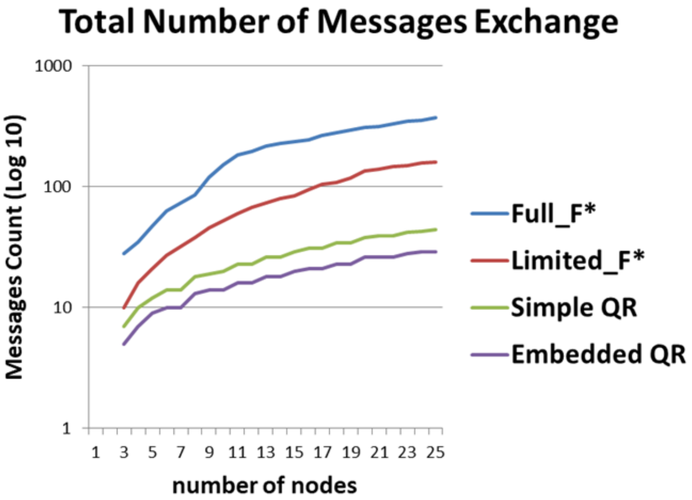
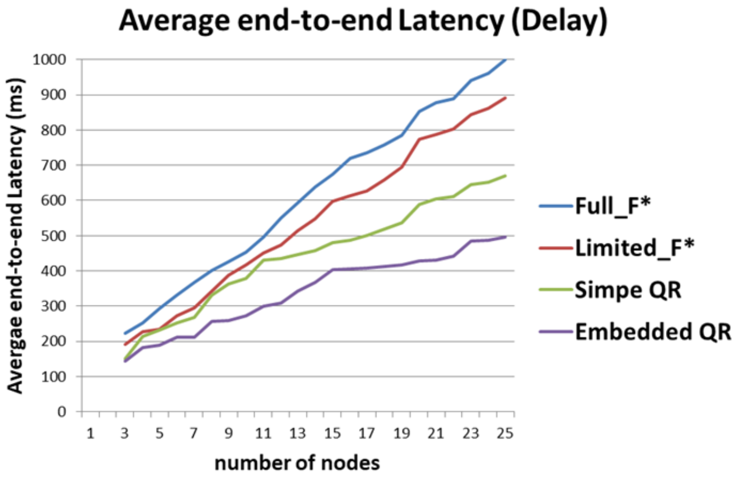


Figura 5.3.4. Comparación del número total de mensajes intercambiados entre las diferentes arquitecturas de comunicación.

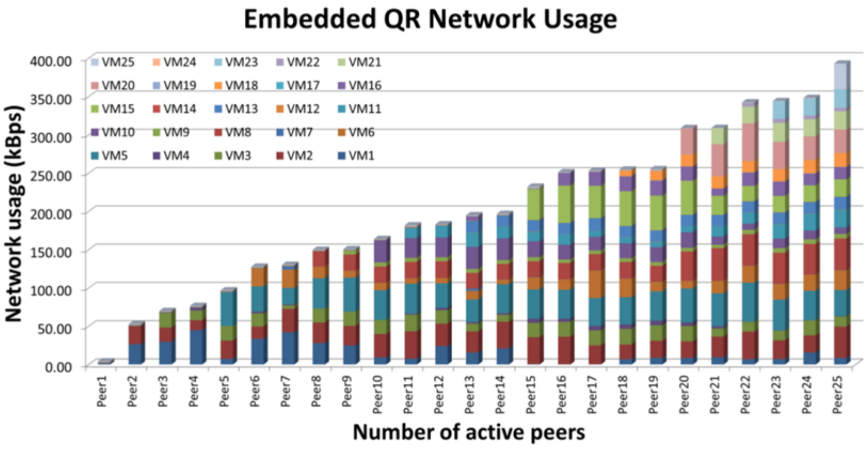


5.3.5. Comparación del retardo de red de extremo a extremo experimentado por las diferentes arquitecturas de comunicación

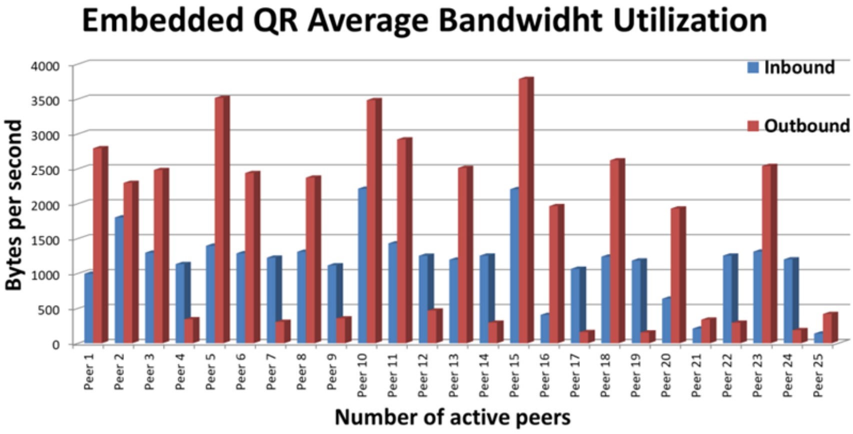
Las Figuras 5.3.4 y 5.3.5 demuestran que la arquitectura de comunicación basada en LRA embebida, es la arquitectura más eficiente para el control y monitoreo de microrredes inteligentes, y que cumple con los requisitos de latencia especificados en la norma (Tabla 5.3.1). Además, con el fin de evaluar la idoneidad de la arquitectura propuesta para las microrredes, medidas sobre el uso de red y el ancho de banda se han realizado (Figuras 5.3.6 y 5.3.7, respectivamente).

Tabla 5.3.1. Requerimientos de red en microrredes

Aplicación de Microrred	Ancho de Banda	Latencia
Respuesta de la demanda	14-100 Kbps	500 ms-varios minutes
Recursos energéticos distribuidos y Almacenamiento	9.6-56 Kbps	20 ms-15 s
Gestión distribuida	9.6-100 Kbps	100 ms-2s



5.3.6. Uso de la red (en Kbps) por par en una red con N = 25 pares



5.3.7. Utilización del ancho de banda promedio (entrante y saliente) por nodo par en una red con N = 25 pares

Conclusiones

Se ha propuesto una arquitectura de comunicación descentralizada basada en tecnología P2P para el control y monitorización de microgrids inteligentes. Se ha demostrado que el paradigma de comunicación P2P se puede aplicar para construir la capa de comunicación para microrredes ya que permiten comunicaciones robustas, eficientes, escalables y flexibles.

La arquitectura propuesta ha sido específicamente desarrollada para cumplir con los requerimientos de comunicación demandados por las microrredes. El diseño de la arquitectura se ha optimizado incorporando la capa de aplicación en la capa de red P2P donde un nuevo esquema de algoritmo de enrutamiento de localidad (LRA) basado en DHT ha sido desarrollado. Los resultados experimentales presentados muestran que el número de mensajes de búsqueda y, en consecuencia, la latencia de búsqueda en la red, son más bajos con el esquema de LRA propuesto que con otras técnicas de inundación de DHT. Además, el rendimiento de la arquitectura depende tanto del algoritmo de búsqueda utilizado como de la colocación de las capas en la pila de protocolos. En este caso, con la incorporación de la capa de aplicación en la capa de red, tanto los mensajes intercambiados como las latencias de extremo a extremo también se reducen.

Finalmente, el modelo incorporado se ha probado utilizando parámetros de rendimiento de red relevantes, como el uso de la red y el ancho de banda. La evaluación experimental muestra que la arquitectura P2P propuesta es útil para entornos exigentes en los que se requieren especificaciones de red estrictas, y también que el rendimiento de la comunicación cumple con los requisitos de red de las microrredes inteligentes.

5.4 Publicación III

En el Capítulo 3 se incluye la tercera publicación de este compendio

S. Marzal, R. Salas-Puente, R. González-Medina, G. Garcerá, E. Figueres, "Efficient Event Notification Middleware for Smart Microgrids over P2P Networks," IEEE Transactions on Smart Grid.

Motivación

La motivación principal del desarrollo de este trabajo científico ha sido la presentación de un middleware basado en el paradigma de comunicación publicación-suscripción (en inglés, Publisher-Subscriber, PubSub) capaz de notificar eventos sobre el funcionamiento de la microrred a tiempo real y de manera eficiente. A partir del middleware propuesto es posible el intercambio de datos impulsado por eventos entre los recursos energéticos distribuidos, desplegados a gran escala sobre sistemas P2P estructurados, de modo que se cumplen con los requisitos de comunicación de la microrred inteligente. El intercambio de datos impulsado por eventos es un requisito esencial para futuras implementaciones de microrredes auto gestionables. De hecho, el estándar IEC61850 promueve el desarrollo de servicios de publicación / suscripción. Sin embargo, las microrredes están creciendo y manejando una gran cantidad de DERS, por lo que los actuales middlewares de notificación de eventos PubSub presentan ineficiencias para los actuales desafíos de las microrredes inteligentes. Por tanto, la idea principal de este artículo consiste en la adecuación de los middleware de notificación de eventos para el desarrollo de Smart Microgrid con arquitecturas de control distribuido que implementan sistemas P2P con una mejora evidente de las prestaciones.

Contribución

Los actuales middlewares convencionales basados en la notificación / publicación no se adaptan adecuadamente a los entornos de microrredes debido a las siguientes razones: no ofrecen flexibilidad de suscripción, producen una gran cantidad de tráfico de red así como altas latencias de red, y necesitan altas tasas de recursos computacionales. Por lo tanto, es necesario el desarrollo de un middleware de notificación de eventos específicamente diseñado para microrredes, que debe adaptarse a los requisitos de calidad de rendimiento de este tipo de aplicaciones.

En este documento se propone una nueva y eficiente arquitectura de middleware de notificación de eventos basada en un sistema de publicación-suscripción de contenido sobre redes P2P para microgrids inteligentes. Las principales contribuciones de este trabajo son: (i) un sistema de mapeo de Hilbert que permite a los suscriptores definir múltiples dimensiones de los contenidos en un único espacio dimensional mediante el uso de un conjunto de rangos. Esto permite una mayor flexibilidad y solidez de las suscripciones, ii) un algoritmo de coincidencia de contenido eficiente para reducir las tasas de falsos positivos y acelerar las decisiones de enrutamiento y iii) un protocolo de enrutamiento basado en la representación de rangos, protocolo de enrutamiento basado en rangos (en inglés, ranged based routing protocol (RBR)), en lugar de enrutamiento de multidifusión. El protocolo propuesto reduce el tráfico de la red, al permitir la transmisión del evento solo a los suscriptores interesados.

Estas contribuciones permiten un mayor rendimiento de la red y también un ahorro de los recursos computacionales. La reducción del tráfico de la red implica un bajo número de mensajes transmitidos, por lo que la utilización de la CPU disminuye, mientras que la optimización de las suscripciones reduce la sobrecarga de comunicación, lo que reduce el uso de la memoria.

Análisis de los Resultados

En un esquema de comunicación impulsado por eventos, la transmisión de la señal se dispara solo en respuesta a un evento, es decir, cuando ocurre un cambio significativo dentro de su domino o de las variables físicas que se controlan. Una forma conveniente de construir servicios de microrredes que usan infraestructuras de eventos, es a través de la implementación de middleware de comunicación que funciona bajo un paradigma de publicación / suscripción (Pub-Sub). En el paradigma de publicación / suscripción los proveedores de información (editores) difunden eventos al sistema y los consumidores de información (suscriptores) se suscriben al evento en el que están interesados. En él, todos los datos se publican o se suscriben a / desde el dominio del servicio de middleware (Figura 5.4.1). Además, este paradigma de comunicación permite comunicaciones asíncronas (los proveedores de información asumen que la respuesta por parte de los subscriptores no se recibirá inmediatamente o incluso puede que no se reciba) y que la distribución de mensajes sea de uno a muchos para la notificación de eventos.

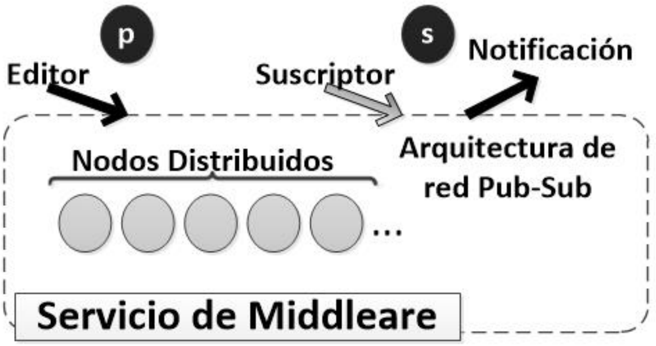


Figura 5.4.1. Arquitectura de comunicación de un sistema de publicación / suscripción. (p y s indican un editor suscriptor genérico respectivamente)

Con el objetivo de adaptarse mejor a los nuevos escenarios distribuidos de gran escala, las redes P2P estructuradas se han vuelto populares como plataforma para desarrollar middlewares basados en comunicaciones publicación/suscripción dirigida a eventos. Los sistemas de publicación / suscripción existentes basados en redes P2P estructuradas, tradicionalmente utilizan sistemas basados en temas como modelos de suscripción y protocolos de multidifusión para enrutar la notificación de eventos. Sin embargo, el uso de estas técnicas no es óptimo para microrredes por estos motivos:

En relación con *los modelos de suscripción*, los datos distribuidos a través del servicio de middleware pueden estar basados en temas o en contenido. Por un lado, en los sistemas basados en temas, los suscriptores definen su interés por un tema específico y recibirán mensajes relacionados con ese tema. Por ejemplo, en el caso de las microrredes, los temas pueden ser cargas críticas, generadores fotovoltaicos, dispositivos de almacenamiento, modo isla, etc. Por otro lado, en el sistema basado en contenido, los suscriptores pueden definir condiciones sobre el contenido del tema. Por ejemplo, en el tema "Generador fotovoltaico" se puede definir un cierto número de atributos. Un conjunto de tres atributos de interés podría ser: Potencia (suministrada a la red), voltaje de corriente continua (para generadores fotovoltaicos) y estado (conectado o desconectado). Como se puede deducir, el pub / sub basado en contenido es una arquitectura más robusta, ya que los suscriptores pueden seleccionar sus criterios de filtrado a través de la definición de múltiples dimensiones del contenido del mensaje. Tenga en cuenta que los sistemas basados en temas están restringidos a campos predefinidos.

El uso de un *protocolo de enrutamiento de multidifusión* para el sistema publicación/ suscripción ha sido la elección natural en los sistemas P2P estructurados basados en temas, ya que cada tema publicado es idéntico a un grupo de multidifusión. Sin embargo, la multidifusión no se puede usar directamente en sistemas basados en contenido porque los suscriptores no se pueden asignar directamente a grupos de multidifusión. Además, cuando se utiliza un enrutamiento de multidifusión, los datos se replican y se envían a todos los nodos de la lista. El proceso de multidifusión y la replicación de datos introducen altas latencias, una pobre utilización del ancho de banda y también un alto tráfico que no es adecuado para los requerimientos de las microrredes. Además, con la multidifusión, podría producirse una gran cantidad de falsos positivos, ya que un evento podría transmitirse a los nodos que no están interesados en él o que no necesitan enrutarlo a otros destinos. Los sistemas de publicación / suscripción que trabajan en entornos donde se transmite información de vital importancia, los falsos positivos no son aceptables porque la eficiencia de todo el sistema podría reducirse significativamente.

Por tanto, los desafíos clave para la implementación de arquitecturas de middleware de notificación de eventos para microrredes inteligentes son los siguientes:

1. ***Comunicaciones P2P***: La arquitectura de comunicación P2P proporciona un entorno más confiable y adecuado para los dispositivos distribuidos, ya que permite el autodescubrimiento de nuevos nodos (dispositivos) así como la auto organización. Debido a esto, la participación dinámica de los nodos (dispositivos) en la red está permitida y es especialmente importante para las microrredes, en las que una gran cantidad de dispositivos (vehículos eléctricos, cargas, etc.) pueden unirse o salir de la microrred.

2. ***Sistema de suscripción flexible***: Mover el modelo de suscripción basado en temas a un modelo de suscripción basado en contenido mejora la flexibilidad y precisión del sistema.

3. ***Reducción del consumo de recursos computacionales***: para hacer factible el *Smart Microgrid* (o las microrredes inteligentes), las comunicaciones entre los dispositivos de potencia deben llevarse a cabo mediante IEDs (Dispositivos electrónicos inteligentes). Los IED son dispositivos equipados con sistemas operativos integrados que hacen posible la comunicación bidireccional para monitorear y administrar la red eléctrica. Por lo general, los sistemas integrados tienen recursos informáticos limitados. La naturaleza limitada de los recursos del sistema integrado, especialmente el tamaño de la memoria y la CPU, complica el cumplimiento de las restricciones en tiempo real. Dado que el middleware controlado por eventos debe estar integrado en cada nodo de la microrred, los recursos computacionales utilizados para la operación del middleware deben minimizarse.

4. ***Requisitos de calidad de la red***: para garantizar la estabilidad de la red frente a ciertos eventos, el sistema de control de la microrred debe monitorear todos los elementos de la red y actuar en consecuencia cuando un parámetro excede los umbrales especificados. Para lograrlo, los datos deben ser entregados con prontitud. En microrredes, la latencia y el ancho de banda son esenciales para cumplir con los requisitos de la microrred según las normas IEC 61850 e IEEE 1646 (consulte la Tabla 5.4.1).

Tabla 5.4.1. Requerimientos de red para las aplicaciones de Microrred

Requerimiento de Comunicación	Latencia	Ancho de Banda
Gestión de la distribución	**100ms-2s**	**9.6-100kbps**
Respuesta a la demanda	**500ms-varios minutos**	**14-100kbps por nodo**
Información de Monitoreo	**15ms-200ms**	**9.6-56kbps**
Información de Control	**16ms-100ms**	**9.6-56kbps**
Mensajes que requieren acciones inmediatas	**1A:3 ms or 10ms;1B: 20 ms or 100 ms**	**9.6kbps**
Gestión de cortes	**2s**	**56kbps**

Con el objetivo de cumplir con los desafíos propuestos descritos anteriormente, una arquitectura eficiente de middleware P2P de notificación de eventos basado en un sistema de pub / sub con modelo de suscripción basado en contenido especialmente diseñado para microrredes inteligentes se propone. La arquitectura propuesta se compone de los siguientes módulos:

(A) Un esquema de indexación para implementar un sistema de comunicación de publicación/ suscripción basado en contenido sobre redes P2P para mejorar la flexibilidad y precisión del sistema.
(B) Un mecanismo de suscripción de contenido coincidente para reducir el número de falsos positivos.
(C) Un motor de enrutamiento optimizado basado en rangos (protocolo Ranged Based Routing protocol, RBR) para el sistema de difusión de eventos, de manera que se pueda cumplir con los requisitos de rendimiento de la red de microrred.
(D) Una aplicación de servicio de notificación de eventos para lograr un sistema completamente distribuido.

La figura 5.4.2., presenta la arquitectura del sistema propuesto.

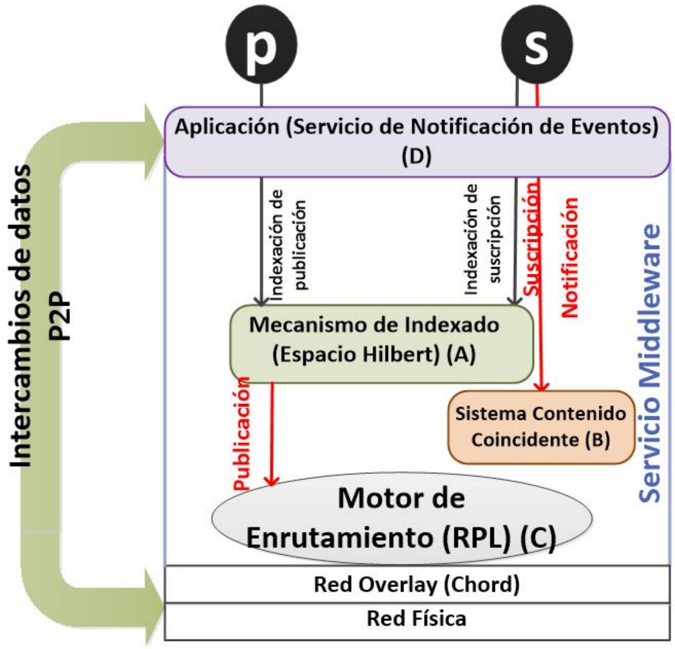


Figura 5.4.2. Esquema de la arquitectura de comunicación propuesta

(A) Esquema de Indexación de Hilbert.

Para poder soportar de forma flexible la gestión de suscripciones se utiliza la curva de relleno de espacio de Hilbert (en inglés, Hilbert Space Filling Curve (Hilbert-SFC)). La matriz de Hilbert permite asociar contenido multidimensional a un espacio de una sola dimensión. Al aplicar el mapeo de Hilbert, el sistema propuesto mapea cada uno de los atributos d-dimensionales a un punto de la SFC. Esta característica logra una alta expresividad en las suscripciones, así como la reducción del tamaño promedio de los mensajes para la publicación de eventos y suscripciones. De esta manera, se logra una reducción tanto de la sobrecarga de comunicación como de las latencias.

(B) Mecanismo de suscripción de contenido

Un suscriptor puede tener múltiples suscripciones de interés. Sin embargo, la administración de una gran cantidad de información con respecto a las suscripciones podría llevar a un gran tamaño de la tabla de suscripciones. El gran tamaño de las tablas de suscripción genera una pérdida de recursos de procesamiento y requisitos de memoria, así como una gran cantidad de tráfico redundante. Para evitar la diseminación de las suscripciones no esenciales y para reducir el tamaño de las tablas de suscripciones, se ha implementado una técnica de fusión de suscripciones. La fusión es un método que proporciona el filtro mínimo que representa una colección de suscripciones definidas en el espacio de contenido. El filtro mínimo se define como el rectángulo mínimo que comprende un conjunto de suscripciones.

(C) Motor de enrutamiento basado en rangos

El objetivo principal del motor de enrutamiento propuesto es cumplir con los requisitos de rendimiento de la microrred. Para ello, el protocolo trata de encontrar el grupo de nodos cuya suscripción coincida con el evento dado. Esto evita retransmisiones innecesarias y reduce el tráfico de red.

El funcionamiento del protocolo propuesto se basa en modificar las tablas de enrutamiento incluyendo parámetros de los nodos vecinos con el fin de determinar la coincidencia de suscripción de nodos. Por tanto, las tablas de los nodos han sido modificadas de forma que contienen información sobre el tipo de eventos a los que están suscritos los nodos, los rangos de suscripción de cada evento al que están suscritos e información del enlace de ese nodo (dirección ip e identificador (id) del nodo). Por tanto, cada tabla de enrutamiento de los nodos tienen las siguientes entradas $(E_i, R_i, \mathrm{L_i})$ siendo E_i e tipo de eventos a los que están suscritos, R_i rangos de suscripción de los eventos, y $\mathrm{L_i}$ datos del enlace del nodo (ip e id).

Con esta información, un nodo editor ya puede encontrar aquellos nodos que están suscritos. Para determinar la coincidencia de suscripción de nodos, el nodo busca en su tabla de enrutamiento y verifica el tipo de evento. Si el tipo de evento coincide con el que está buscando el nodo, comprueba si está suscrito a los rangos de suscripción de ese nodo. Si se cumplen estas dos condiciones, el mensaje del evento se codificará y se enviará a todos los nodos coincidentes. Además en este mensaje, se manda la lista de coincidencias de nodos. Con esta lista, los nodos receptores pueden verificar si el mensaje ya se ha enviado al destino antes de enviarlo nuevamente, evitando los mensajes de búsqueda redundantes. Por su parte, los nodos receptores, al recibir un mensaje, si el nodo es uno de los suscriptores, descodifica el mensaje y luego comienza el proceso de coincidencia. En este proceso, el evento se compara con todos los rangos de suscripciones almacenados en él y, si el evento no es un falso positivo, se suscribirá a él.

La escalabilidad del sistema se logra utilizando la lista de coincidencias de nodos que se almacena en los nodos, evitando el tráfico innecesario en la red. El objetivo es identificar los grupos, de esta manera, cada nodo que contiene suscriptores coincidentes recibe un mensaje por evento, lo que minimiza los costos de comunicación y computacionales.

(D) Aplicación de servicio de notificación de eventos

Dado que las microrredes son sistemas distribuidos inherentes, el middleware de notificación de eventos se ha diseñado siguiendo una arquitectura distribuida. Para lograrlo, cada peer en el sistema actúa como un intermediario de notificaciones, en inglés Notification Broker (NB), en otras palabras, cada par implementa una interfaz de notificación y todo el sistema actúa como un solo NB. Como resultado, la interfaz no será un cuello de botella y el sistema no tendrá un solo punto de falla.

Además, un diseño P2P evita la necesidad de un control centralizado y brinda la flexibilidad de unirse o salir del sistema en cualquier momento. De esta manera, cuando un nuevo nodo se une a la microrred, se pone en contacto con el nodo predecesor y sucesor al que se va a unir y envía toda la información ($E_i, R_i, \mathrm{L_i}$) para que éstos actualicen sus tablas de enrutamiento. De manera contraria, para cancelar la suscripción, el procedimiento es exactamente el opuesto al proceso de suscripción. El nodo saliente notifica el evento saliente a su predecesor y sucesor y los nodos restantes actualizan su tabla de enrutamiento eliminando la información de los nodos salientes. Además, el protocolo tiene capacidades de auto organización. Para esto, el algoritmo de enrutamiento ejecuta un algoritmo de estabilización en cada nodo cada 60 milisegundos para mantener la lista de predecesores y sucesores y para confirmar que la integridad de la topología de la red no se ha dañado. Las suscripciones se actualizan cada 60 milisegundos para agregar o eliminar suscripciones. Además, el middleware de notificación de eventos propuesto tiene un cierto grado de seguridad en términos de integridad de los datos. Esta característica se logra mediante la implementación de enlaces redundantes y métodos de auto-reconfiguración.

La arquitectura del sistema propuesto se ha evaluado y comparado con los métodos de enrutamiento e indexación basados en multidifusión, que se utilizan tradicionalmente en microgrids. Para llevar a cabo esta evaluación, se ha creado una configuración de simulación definida en el apartado 5.1.3. Mediante la configuración del citado setup se miden los principales indicadores de rendimiento de la red que se definieron anteriormente: flexibilidad de suscripciones, latencia, consumo de ancho de banda, rendimiento de enrutamiento, eficiencia y ahorro de recursos computacionales. La configuración experimental es capaz de gestionar hasta 20 nodos. A continuación de describen los resultados de la simulación.

A. Flexibilidad de suscripción

Como se ha explicado anteriormente, hay dos clases principales de sistemas de Publicación-Suscripción: basados en temas y basados en contenido. Por un lado, en los sistemas basados en temas, los suscriptores se unen a un grupo que contiene un tema de interés. Las publicaciones se identifican por temas específicos. Por lo tanto, todas las publicaciones relacionadas con ese tema se difunden a todos los nodos del grupo específico. Por otro lado, en los sistemas basados en contenido, los suscriptores pueden especificar con precisión su interés utilizando un conjunto de predicados. En otras palabras, una suscripción es una solicitud formada por un conjunto de restricciones. Por lo tanto, en el sistema propuesto, la curva de relleno de Hilbert se utiliza para asignar un espacio multidimensional a una clave compacta de Hilbert, que especifica el par (atributo, valor) que define las restricciones. Con la dimensión y el orden de Hilbert, se especifican los atributos y los valores, respectivamente. De esta manera, dos pares de (atributo, valor) se pueden representar con una clave de Hilbert utilizando la curva de Hilbert de orden 2D-n. De manera similar, tres pares de (atributo, valor) utilizando el orden 3D-n, y así sucesivamente (Ver Figura 5.4.3). Por tanto, al utilizar la curva de relleno de espacio de Hilbert, una suscripción con N restricciones puede codificarse como una clave única de Hilbert.

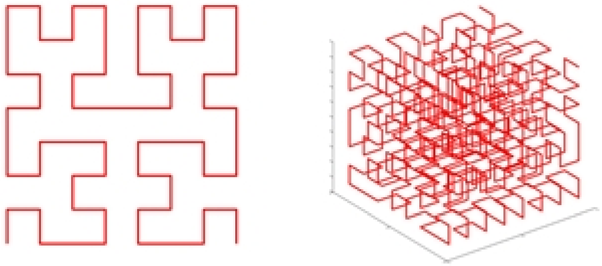


Figura 5.4.3. Curva de relleno de espacio de Hilbert (2D-3er orden y 3D-3er orden de izquierda a derecha)

La Figura 5.4.4 muestra un estudio comparativo del número de mensajes intercambiados que se necesitan para enviar un conjunto de publicaciones por ambas técnicas (Publicación-Suscripción basado en temas y basado en contenido). Los resultados obtenidos con el contenido de Hilbert se comparan con los obtenidos por tema en tres casos: sin restricciones, con una restricción y con dos restricciones.

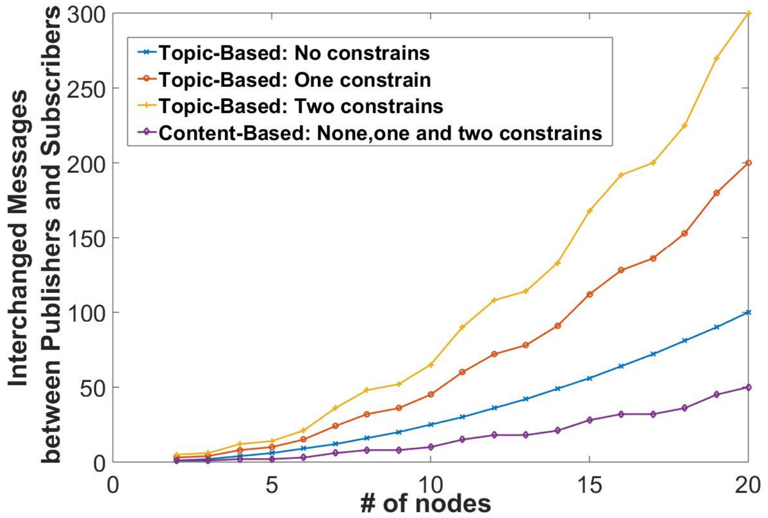


Figura 5.4.4. Mensajes Intercambiados entre Editores y Suscriptores en relación con las restricciones de publicaciones (Sin restricción, con una y dos restricciones) mediante el uso de enfoques basados en temas y contenidos

Como puede verse en la figura, la cantidad de mensajes intercambiados utilizando el enfoque basado en temas depende tanto de la cantidad de nodos en la red como de la cantidad de restricciones en la publicación. De hecho, para enviar N restricciones, los editores necesitan conocer los nodos que están suscritos a las primeras restricciones N-1 para verificar que la suscripción coincida con todas las restricciones de publicación. Este hecho genera más tráfico de red. Por el contrario, con el enfoque basado en el contenido de Hilbert, N restricciones se pueden definir en una clave única de Hilbert. Por lo tanto, la cantidad de mensajes intercambiados solo depende de la cantidad de nodos en el sistema y no depende de la cantidad de restricciones de publicación. La mayor expresividad y flexibilidad del enfoque basado en contenido reducen la necesidad de recursos de red. La robustez y la escalabilidad de la red mejoran debido a que las notificaciones solo se envían a los suscriptores reales.

B. Rendimiento de la Red

Esta sección se centra en el análisis de los dos parámetros más críticos que dictan el rendimiento de la red en microrredes: el retardo y el ancho de banda. Con respecto al retardo de la red, la Figura 5.4.5 muestra el retardo global de extremo a extremo (En inglés, *End-to-End Delay, ETE Delay*), es decir, el tiempo transcurrido desde la publicación de un evento del nodo fuente hasta que se alcanza el último suscriptor dado en valor promedio para soluciones de publicación / suscripción basadas en multidifusión frente a Hilbert. Esta figura muestra que el retardo ETE para el sistema propuesto es inferior al que ofrece el sistema de publicación / subsistema basado en multidifusión. Es importante tener en cuenta que el sistema propuesto reduce la carga de reenvío de suscripción en cada nodo. Por lo tanto, el retardo ETE es menor que el alcanzado al utilizar los métodos pub / sub basados en métodos de multidifusión. Como se muestra, middleware propuesto mejora el retardo ETE entre 35% y 48%, y la mejora aumenta a medida que más nodos se conectan a la red. El retardo total de ETE para 20 nodos logrado mediante middleware pub-sub propuesto es de alrededor de 270 ms, mientras que con los métodos pub / sub basados en multidifusión es de alrededor de 530 ms. Por lo tanto, el retardo promedio de ETE por nodo en el sistema propuesto puede estimarse en alrededor de 14 ms. Esto significa que la latencia promedio para procesar una publicación en un sistema pub / sub basado en el método de Hilbert es de alrededor de 14 ms, lo que cumple con los requisitos de microrred describen en la Tabla 5.4.1.

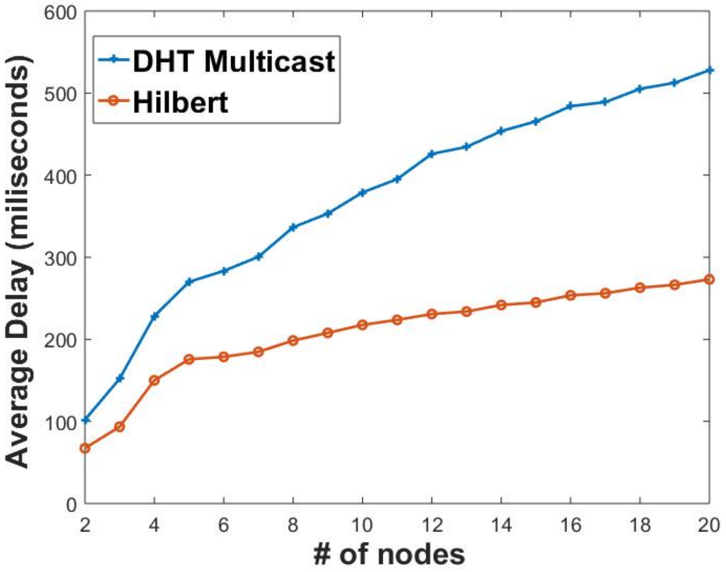


Figura 5.4.5. Comparación del retardo promedio de extremo a extremo frente al número de nodos
para pub / sub basado en multidifusión y Hilbert

En relación con las mediciones de ancho de banda, la Figura 5.4.6 muestra el consumo promedio de ancho de banda en la red para diferentes escalas. Para ello, se consideran tres escalas diferentes con bancos de pruebas de 5, 10 y 20 nodos conectados a la red, y se comparó el consumo de ancho de banda del sistema PubSub propuesto con el del PubSub basado en el método de enrutamiento de multidifusión

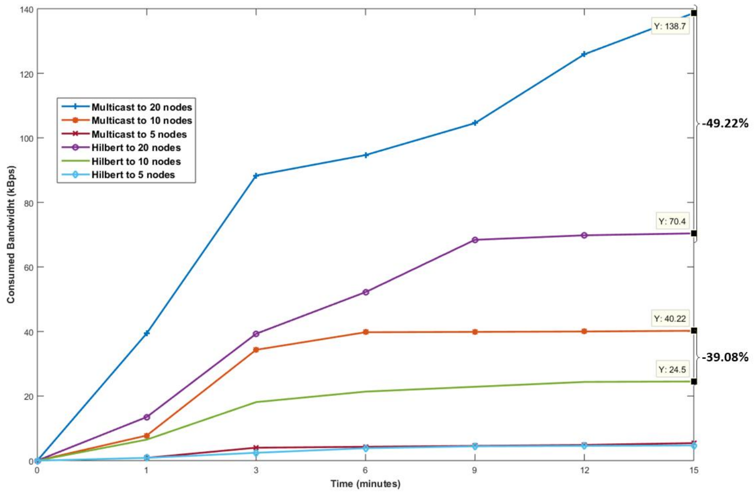


Figura 5.4.6. Promedio del consumo total de ancho de banda en el tiempo para diferentes escalas

Como se puede ver en la figura el consumo de ancho de banda con el método de publicación / suscripción propuesto aumenta menos rápidamente que con los métodos de publicación / suscripción basados en multidifusión. En general, el consumo promedio de ancho de banda total en 15 minutos disminuye hasta en un 39,08% para 10 nodos y en 49,22% para 20 nodos en los que se utiliza el middleware de PubSub propuesto. Estos resultados podrían justificar el uso sistema propuesto basado en Hilbert en la capa de aplicación, ya que se produce un mejor uso del ancho de banda disponible debido a que el tráfico se reduce al eliminar la transmisión redundante. Además, tal y como se deduce de la figura, los ahorros de ancho de banda aumentan con el tamaño de la red, lo que garantiza comunicaciones más escalables.

C. Rendimiento de Enrutamiento

Los principales beneficios del protocolo propuesto son una reducción tanto del tráfico de red (Figura 5.4.7) como del tiempo de enrutamiento

(Figura 5.4.8). El tráfico en la red se ha medido promediando el consumo de ancho de banda total en kilobytes por segundo. La Figura 5.4.7 muestra el promedio del tráfico total de la red (en ancho de banda consumido) para 20 nodos a los 15 minutos.

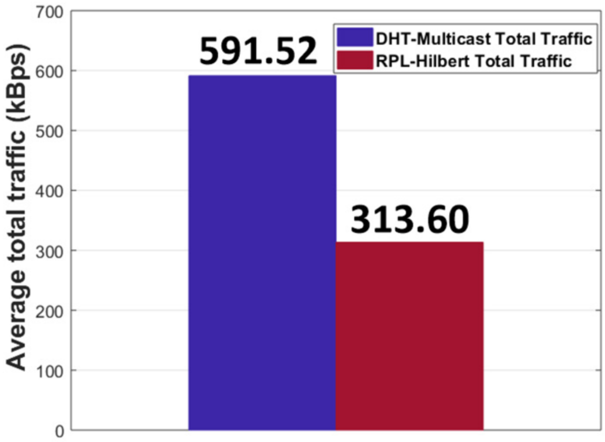


Figura 5.4.7. Ancho de banda consumido en la red de 20 nodos para el sistema pub / sub basado en multicast y el sistema propuesto basado en enrutamiento de Hilbert.

Como muestra la Figura 5.4.7, la técnica propuesta RBR-Hilbert consume casi dos veces menos tráfico de red que las basadas en multidifusión. El motivo es que, mediante el uso del protocolo propuesto, las tablas de enrutamiento de vecinos de cada nodo tienen información sobre sus suscripciones. De esta manera, cada publicación se entrega solo a los nodos suscritos y no a los clústeres suscritos como lo hace el enrutamiento de multidifusión. En consecuencia, se logra una reducción de tráfico de red. Además, el protocolo RBR tiene capacidad de autoorganización debido a la infraestructura de red superpuesta *(overlay)*. Con esta característica, cada nodo conoce la disposición de sus vecinos, lo que produce un método eficaz para la publicación y la propagación de suscripciones y permite una reducción en el tiempo de enrutamiento. La Figura 5.4.8 muestra el tiempo promedio de coincidencia de las publicaciones con las suscripciones. El tiempo promedio de coincidencia es el tiempo promedio para enrutar las publicaciones al suscriptor coincidente. Se han generado 3000 suscripciones (50 suscripciones aleatorias para cada nodo de suscriptor) para evaluar el tiempo de coincidencia de publicación.

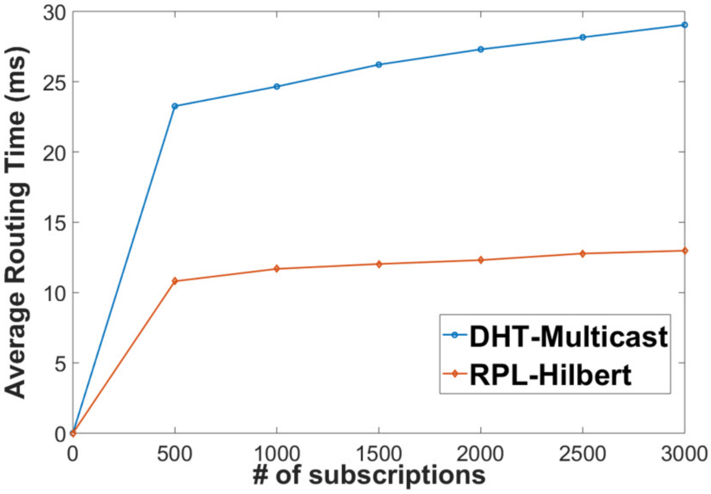


Figura 5.4.8. Tiempo promedio de coincidencia de publicaciones frente a las suscripciones

Como se puede ver en la Figura 5.4.8, el tiempo utilizado para enrutar una publicación contra 3000 suscripciones mediante el uso del algoritmo RBR-Hilbert propuesto es de alrededor 13 milisegundos. Con DHT-Multicast este tiempo es de alrededor de 29 milisegundos. Además, con el sistema propuesto el tiempo de coincidencia no aumenta significativamente a medida que aumenta el número de suscripciones. Esto indica que el enfoque propuesto es adecuado para sistemas de publicación / suscripción a gran escala y puede procesar eficientemente una gran cantidad de mensajes (publicaciones y suscripciones)

D. Eficiencia: Falsos Positivos

La Figura 5.4.9 con los falsos positivos, es el resultado de una de las métricas de rendimiento más importantes para la eficiencia. Un falso positivo se define como un mensaje recibido por el nodo que no está interesado en el mensaje. Esta figura muestra el número promedio total de mensajes recibidos por nodo. Esto se refiere al total de mensajes de publicación que reciben los nodos. Además, la figura también muestra el porcentaje de falsos positivos para esta cantidad de mensajes recibidos. Como puede verse, tanto los mensajes recibidos como los falsos positivos con el método propuesto dan como resultado una reducción considerable con respecto a la publicación / suscripción basada en los enfoques de enrutamiento de multidifusión.

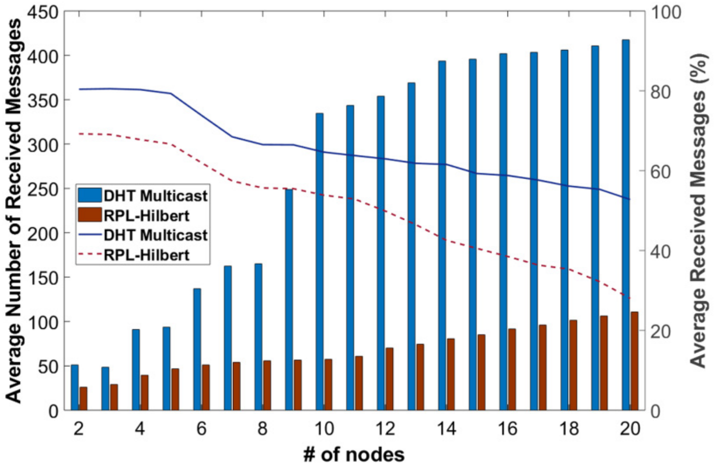
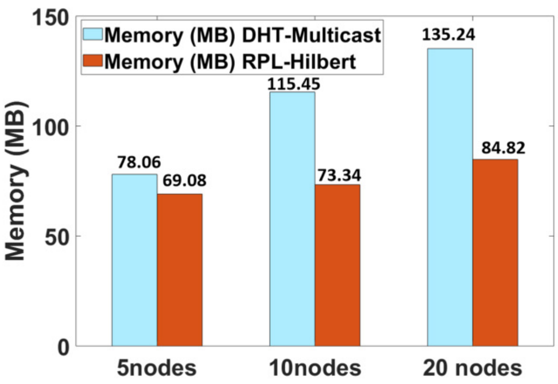


Figura 5.4.9. Porcentaje de falsos positivos según el número promedio de publicaciones recibidas por nodo

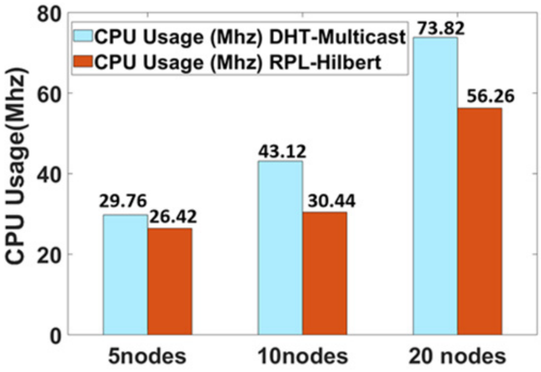
El porcentaje de falsos positivos disminuye a medida que crece la red, lo que garantiza comunicaciones más eficientes. Esto se debe al uso del mapeo de Hilbert para enrutar en combinación con el método de coincidencia permite al sistema propuesto tener más posibilidades de reenviar un evento a mejores candidatos vecino. Hay que tener en cuenta que el evento está incluido en la tabla de enrutamiento y que la coincidencia del evento tiene más probabilidades de éxito. Además, al utilizar el rectángulo de delimitación mínimo como técnica de fusión, reduce el área de falsos positivos y el número de publicaciones no deseadas es pequeño.

E. Recursos Computacionales

La memoria del sistema y la CPU son recursos críticos para la operación y el rendimiento de cualquier sistema de software. El uso de la técnica de fusión permite reducir el tamaño de las tablas de suscripción de enrutamiento. Por lo tanto, los requisitos de memoria de procesamiento y almacenamiento que utilizan los nodos también se reducen. Las Figuras 5.4.10 a y 5.4.10 b muestran la cantidad promedio de memoria activa y carga de CPU, respectivamente, en una red de 20 pares durante 15 minutos, con el sistema de publicación/suscripción propuesto y el basado en multidifusión.



(a)



(b)

Figura 5.4.10. (a) Memoria activa promedio utilizada (en MB). Se han tomado medidas para tres escalas diferentes para soluciones de pub- subs, basadas en multidifusión y Hilbert durante 15 minutos. (b) Uso promedio de la CPU (en MHz). Se han tomado medidas para tres escalas diferentes para soluciones de pub-subn, basadas en multidifusión y Hilbert durante 15 minutos.

Como se observa, la multidifusión necesita más memoria a medida que aumenta la escala, hasta 130 MB de memoria por 20 nodos en 15 minutos, mientras que el sistema propuesto basado en Hilbert requiere 85 MB en las mismas condiciones. Al igual que en el análisis de memoria, el ahorro de CPU aumenta con el tamaño de la red. Las soluciones de multidifusión utilizan alrededor de 74 MHz de CPU para 20 nodos en 15 minutos, mientras que la solución de Hilbert usa alrededor de 56 MHz. Los resultados mostrados confirman que el sistema propuesto puede implementarse con un uso razonable de recursos computacionales que permita su implementación en sistemas integrados.

Conclusiones

En este documento, un nuevo middleware de notificación de eventos para una red de publicación /suscripción sobre contenido basada en peers, adecuado para microrredes a gran escala se ha presentado. El middleware propuesto utiliza la indexación multidimensional para representar publicaciones y suscripciones en un espacio unidimensional a través de la curva de relleno de espacio de Hilbert. Sobre la base de esta representación, se han desarrollado algoritmos de enrutamiento, mapeo y coincidencia. Por un lado, el protocolo de enrutamiento basado en rangos (RBR) desarrollado puede construir y diseminar eventos de manera eficiente, mientras que tiene propiedades deseables, como la auto organización y la escalabilidad. Por otro lado, los algoritmos de mapeo y coincidencia de contenido propuestos mejoran el rendimiento del tráfico y reducen la tasa de falsos positivos debido a la minimización del espacio de nodos de participación que no tienen interés en el evento, lo que proporciona un mayor nivel de garantía de confiabilidad. Los resultados experimentales han demostrado que el middleware basado en el espacio de Hilbert mejora la eficiencia, reduce el tráfico y las latencias de la red en general y logra un mejor ahorro de recursos informáticos. Esas mejoras son necesarias para cumplir con los exigentes requisitos de comunicaciones para microrredes. Las pruebas se han realizado mediante máquinas virtuales teniendo en cuenta la mayoría de las limitaciones físicas del sistema. Por lo tanto, se puede concluir que las soluciones propuestas son un enfoque interesante para el problema de las comunicaciones en microrredes inteligentes.

5.5 Publicación IV

En el Capítulo 4 se incluye la tercera publicación de este compendio

S. Marzal, R. Salas, R. González-Medina, G. Garcerá, E. Figueres, *“An Embedded Internet of Energy Communication Platform for the Future Smart Microgrids Management,”* IEEE Internet of Things Journal, 2019

Motivación

Las microrredes se están moviendo hacia sistemas de energía eléctrica en una especie de Internet de energía (IoE) donde se puede conectar una gran cantidad de generadores en cualquier lugar. En este sentido, para materializar el IoE previsto, las tecnologías de la información y la comunicación (TIC) son cruciales para el desarrollo de aplicaciones y servicios innovadores, así como para lograr altos niveles de eficiencia en las microrredes. Sin embargo, debido a la variedad de las TIC, no existe una solución estándar de facto para implementar plataformas IoE. Además, los estándares para las plataformas actuales de Internet de las cosas (IoT) no son óptimos para desarrollar plataformas IoE, que presentan desafíos más exigentes. Además, las plataformas middleware convencionales desarrolladas para llevar a cabo la IoT se basan en un único paradigma de comunicación, RR o PubSub. Sin embargo, las soluciones IoE requieren del desarrollo de middleware que utilicen simultáneamente mecanismos de comunicación basados en RR y PubSub. Las razones de esto son, por un lado, que en una microrred la información de control entre los RED requiere un sistema de comunicación basado en la consulta-respuesta. En este sentido, se necesita una respuesta oportuna para llevar a cabo acciones inmediatas, ya que si el retraso de la comunicación excede el tiempo requerido, la información no cumple con su propósito y, en el peor de los casos, podrían producirse daños. Por otro lado, para las tareas de monitoreo de microrred, se necesita el paradigma de PubSub. Por ejemplo, cuando una carga se apaga, se puede notificar un evento a otros RED para evaluar el estado global de la microrred. En tal contexto, la motivación principal de la realización de este artículo científico es triple: En primer lugar, desarrollar una plataforma IoE incorporada para la gestión de microrredes inteligentes con grandes cantidades de recursos energéticos distribuidos. En segundo lugar, que esa plataforma IoE admita los paradigmas de comunicación RR y PubSub desarrollados en las dos publicaciones anteriores. En sendas publicaciones, se presentaba cada uno de los sistemas de manera independiente, el reto es incorporar estos mecanismos de comunicación para que funcionen indistintamente según las necesidades de transmisión de los datos debido a que cada paradigma de comunicación proporciona funcionalidades ortogonales y diferentes propiedades de calidad necesarios para la gestión y monitorización de microrredes. Por último, la tercera motivación ha sido, desplegar esta arquitectura de IoE en una microrred experimental para comprobar y demostrar que la plataforma propuesta es válida para microrredes y que además cumple con los estándares de calidad demandados por éstas.

Contribución

Las principales contribuciones científicas del artículo se resumen a continuación:

1) El diseño y desarrollo de una plataforma de comunicación IoE flexible, distribuida e integrada, basada en las comunicaciones P2P, que puede recopilar, procesar y analizar los datos de la microrred de manera efectiva, desde cualquier lugar y en cualquier momento, para fines de monitoreo y control.

2) Un middleware IoE-P2P innovador que puede funcionar en modo síncrono y asíncrono, para garantizar la elección del tipo de comunicación adecuado y óptimo para cada tarea o mensajes de comunicación que se intercambian en la microrred. Por lo que sabemos, actualmente no hay ninguna plataforma de IoE de comunicación que implique comunicaciones distribuidas P2P síncronas y asíncronas.

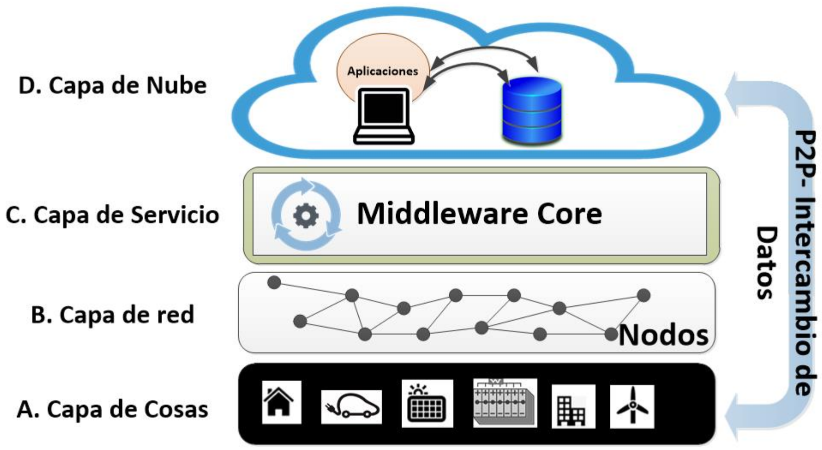
3) Un protocolo IoE y un algoritmo de enrutamiento específicamente diseñado para el monitoreo y control de microrredes inteligentes, que puede cumplir con los exigentes requisitos de éstas.

4) Para implementar una plataforma IoE real, los DER se han integrado en dispositivos con recursos computacionales limitados. El uso eficiente de los recursos computacionales para garantizar el rendimiento de las microrredes inteligentes requerido se prueba experimentalmente.

5) Para evaluar la infraestructura de IoE propuesta en términos de QoS, se ha implementado en una microrred experimental, convirtiéndose, al menos en nuestro conocimiento, en la primera plataforma de comunicación experimental de IoE para administrar microrredes inteligentes.

Análisis de los Resultados

El Internet de las cosas (IoT) puede integrar objetos a Internet. Para lograr eso, la infraestructura de IoT está compuesta por dispositivos inteligentes integrados, con recursos computacionales limitados, que pueden proporcionar ciertos servicios en tiempo real, como monitoreo, comunicaciones, control, entre otros. Esta idea puede extenderse a IoE, que trata de interconectar recursos energéticos distribuidos a través de Internet. La estructura de la Internet de las cosas se basa principalmente en redes punto a punto (P2P) compuestas por nodos autónomos. Cabe señalar que las redes de comunicaciones P2P se han desarrollado principalmente para aplicaciones como el uso compartido de ciclos de archivos y procesadores, cuyos requisitos de rendimiento de red son menos críticos (en el orden de segundos) que las funciones de la microrred (en el orden de milisegundos). Además, normalmente las redes IoT tienen una excesiva dependencia del servicio de centro de datos de Internet existente. Este hecho podría producir retrasos en los servicios de despacho, provocando efectos indeseables en la microrred. Por lo tanto, el software actual de IoT y las plataformas de comunicación relacionadas no se adaptan adecuadamente a los entornos de microrredes debido a que los requisitos de QoS para microrredes son particularmente exigentes. Además, aunque el concepto de IoE se puede aplicar a las microrredes inteligentes, no existe una solución estándar para su implementación. De hecho, el desarrollo actual de las microrredes no utiliza el enfoque IoE. Para superar estas limitaciones, este documento propone una plataforma IoE novedosa y sistemas integrados distribuidos que implementan interfaces en tiempo real entre la microrred y la nube. La plataforma está orientada a propósitos de monitoreo y control y es capaz de cumplir con los exigentes requisitos de rendimiento de las microrredes. La plataforma de comunicación IoE propuesta está compuesta por 4 capas, como se muestra en la Figura 5.5.1.



5.5.1. Esquema de la plataforma IoE propuesta

En la Figura 5.5.1 se muestra el esquema de la plataforma IoE propuesta, la cual está compuesta por los siguientes componentes:

(A) La capa de cosas que integra el hardware de microrred disponible para controlar / detectar el estado de las cosas.

(B) La capa de red que define los protocolos y las redes utilizadas para conectar las cosas.

(C) La capa de servicio que crea y administra los servicios de acuerdo con las necesidades de las cosas. Esta capa se basa en la tecnología de middleware que proporciona la capa de enrutamiento y mensajería que admite el cambio en el tiempo de ejecución entre los paradigmas de comunicaciones RR y PubSub para integrar servicios y funcionalidades de microrredes en IoE.

(D) La capa de la nube que incluye la aplicación de IoE. Esta capa se encuentra en la parte superior de la arquitectura y es responsable del almacenamiento de datos y el análisis de datos. La capa de aplicación comprende las aplicaciones de microrred personalizadas que utilizan los datos de las cosas.

A continuación se proporciona una descripción de cada capa.

A. Capa de cosas

Siguiendo la terminología de IoT / IoE, cada recurso energético distribuido, RED, de la microrred es etiquetado como una *cosa*. Por lo tanto, los RED deben incorporar un dispositivo electrónico inteligente y comunicativo (en inglés, *Intelligent Electronic Device, IED*). Hay dos interfaces de comunicación en esta capa. La primera interfaz comunica cada RED con la red eléctrica y se realiza mediante comunicaciones serie UART. Modbus es el protocolo en serie elegido para implementar esta interfaz, ya que es un protocolo abierto que requiere bajos recursos informáticos; Además, define una estructura de mensajes que los RED pueden reconocer y usar. La segunda interfaz enlaza cada RED con la red de comunicación distribuida. En este caso, una red de comunicación P2P a través de Ethernet es la tecnología elegida.

B. Capa de red

La capa de red es la infraestructura que permite que las *cosas* administren la comunicación en la red distribuida y transmitan mensajes entre las *cosas* y la capa de servicio. En esta capa, TCP / IP son los protocolos elegidos debido a que estos protocolos son el estándar para Internet. Permiten las comunicaciones de extremo a extremo independientemente de los medios físicos subyacentes, las *cosas* y la capa de red. Esta característica proporciona interoperabilidad entre dispositivos finales no compatibles de terceros y redes de comunicaciones compatibles. La interoperabilidad de la red es indispensable para lograr una operación y conectividad óptima del sistema en general, independientemente del medio físico elegido, el tipo de dispositivos y fabricantes.

C. Capa de servicio

En esta capa, el middleware se considera una tecnología clave para desarrollar aplicaciones eficientes de IoE, ya que esta capa proporciona la interconexión entre las *cosas* y la capa de la nube. Un problema esencial es el cumplimiento de los requisitos de red para las MG y la entrega de mensajes adecuada y confiable. Por lo tanto, es vital desarrollar un middleware capaz de proporcionar QoS en términos de latencia, tasas de entrega y ancho de banda, entre otros factores. Para cumplir estos requisitos, el middleware propuesto está formado por dos capas: capa de mensajería y capa de enrutamiento.

1) Capa de mensajería

Como se ha descrito anteriormente, se necesita la integración de los mecanismos de comunicación RR y PubSub en microrredes. Cada paradigma de comunicación proporciona funcionalidades ortogonales y diferentes propiedades de calidad. Con el patrón de comunicación de Solicitud / Respuesta (RR), se logran propiedades de calidad como confiabilidad, oportunidad y seguridad. Además, la eficiencia, el soporte de movilidad y la adaptabilidad son propiedades de calidad logradas por la arquitectura de Publicación/Suscripción (PubSub). Ambos sistemas de comunicación han sido desarrollados en las anteriores publicaciones (Publicación II y Publicación III). Por lo tanto, en este artículo, solo se enfoca en la integración de RR y PubSub. Vale la pena señalar que ambos sistemas están integrados en el middleware, pero no funcionan simultáneamente. El mecanismo propuesto para seleccionar automáticamente RR o PubSub como sistema de comunicación se basa en el tipo de mensaje intercambiado.

En este sentido, se ha desarrollado un protocolo de comunicación específico de microrred para transmitir datos entre las *cosas*, de manera que cuando se envía un paquete, se selecciona el método adecuado (RR o PubSub). Luego, el paquete se transmite a las *cosas* de destino, de acuerdo con el algoritmo de enrutamiento que se explica a continuación. Las *cosas* de destino procesan el paquete según el tipo de comunicación

2) Capa de enrutamiento

Las redes P2P generan altas tasas de tráfico en la red, lo que puede provocar grandes retrasos, una mala utilización del ancho de banda, pérdida de paquetes, recursos informáticos desperdiciados, entre otras ineficiencias. Esto se debe a que, tradicionalmente, las técnicas de inundación (floading) se utilizan en las redes P2P para el enrutamiento. En los esquemas de enrutamiento de inundación, cuando un nodo recibe una consulta, la reenvía a todos los nodos de su tabla de enrutamiento y los nodos retransmiten recursivamente la consulta. La inundación se detiene después de un tiempo de vida *(Time to Live, TTL)* TTL = 4 saltos. De esta manera, el mensaje de búsqueda visitará cada nodo al menos una vez para obtener la recuperación de datos.

Para evitar retransmisiones innecesarias y reducir el tráfico de red y cumplir con los requisitos de rendimiento de la red de la microrred, se ha desarrollado un algoritmo de agrupamiento o de clustering de microrred (*Microgrid Clustering Algorithm*, MGCA) para llevar a cabo el enrutamiento de mensajes. Los clústeres son grupos lógicos de *cosas* en forma de comunidades para lograr objetivos comunes. Por lo tanto, en este trabajo, el enrutamiento se basa en transmitir la información solo a los clústeres seleccionados en lugar de transmitir la información a todas las cosas. En la sección publicación IV, el funcionamiento de este algoritmo está ampliamente desarrollado.

D. capa de nube

La capa de nube almacena los datos históricos que se han obtenido de los RED con fines de supervisión global. El almacenamiento de datos históricos es una de las características requeridas para las aplicaciones y servicios IoE. La capa de la nube de la plataforma IoE contiene servidores virtualizados. Además, se ha implementado una interfaz de aplicación con datos históricos almacenados para cada RED. La base de datos histórica puede almacenar y administrar una gran cantidad de datos, que la interfaz de la aplicación proporciona a la infraestructura de la nube.

Para ilustrar los conceptos anteriores, se ha considerado una microrred residencial compuesta por dispositivos de carga, generación fotovoltaica y almacenamiento (ESS). La microrred en cuestión se gestiona siguiendo el perfil de generación fotovoltaica y las llamadas tarifas de tiempo de uso (*Tariff of Use, ToU*). La posibilidad de conectar cargas críticas (*Critical Loads, CL*) y no críticas (*Non Critical Loads, NCL*) se ha tenido en cuenta en este ejemplo. Desde el punto de vista de gestión, la principal diferencia entre CL y NCL es la prioridad más alta de CL si la energía disponible es baja. NCL se considerará como una carga constante que se conectará o desconectará completamente si no hay suficiente energía para suministrarla. En este sentido, la CL no se desconecta, pero la potencia suministrada está limitada de acuerdo con la energía disponible y la tarifa aplicable. Se trata de un enfoque general que es compatible con el caso particular de tener la necesidad de suministrar totalmente a CL independientemente de la tarifa (es decir, si no hay suficiente generación fotovoltaica, la energía necesaria se exigirá a la red asumiendo los costos correspondientes).

Las tarifas TOU son un nuevo concepto diseñado para incentivar a los clientes a usar más energía en las horas de menor actividad. Normalmente, estas tarifas se clasifican en los períodos de Punta, LLano y Valle (en inglés, *Peak, Shoulder and Off-Peak periods*, respectivamente); siendo la tarifa de

Punta la más cara y la Valle la más barata. Solo con fines ilustrativos, la Figura 5.5.2 muestra las tarifas consideradas a lo largo del día.

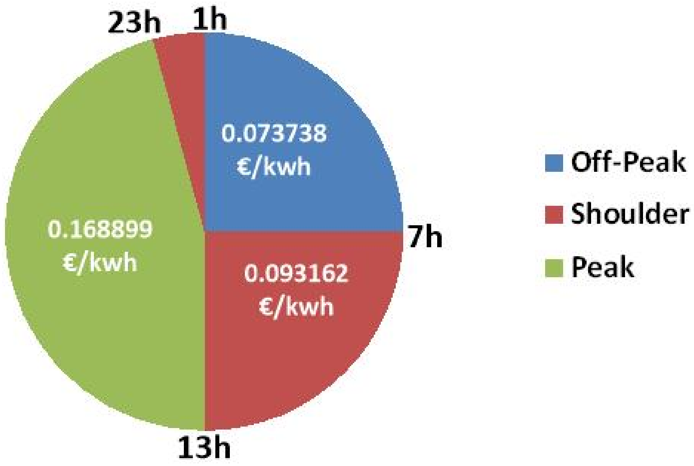


Figura 5.5.2. Tarifas TOU aplicadas.

Se ha desarrollado un algoritmo ToU para gestionar dinámicamente los flujos de energía hacia la microrred según el perfil de carga, el estado de carga (*State of Charge, SoC*) de EES, la generación fotovoltaica disponible y la tarifa aplicable. El algoritmo se ha diseñado para que se produzcan eventos en todos los sistemas conectados a la red inteligente. El objetivo es aprovechar la producción fotovoltaica y la batería para alimentar las cargas del sistema sin superar la potencia contratada (*Hired Power, HP*) con la red eléctrica. Las principales directrices llevadas a cabo por el algoritmo se describen a continuación:

1) La potencia contratada (HP) es la potencia máxima que se puede consumir de la red principal. La potencia máxima que se puede suministrar a las cargas (PLim) es la suma de la generación fotovoltaica (PV), la potencia contratada (HP) y la potencia que se puede extraer de las baterías (PBat). Por lo tanto, la potencia consumida por las cargas puede ser mayor que HP solo si la producción fotovoltaica está disponible o hay suficiente energía almacenada en las baterías.

2) Se ha considerado una tarifa con discriminación horaria (tramos Punta y Valle). Por lo tanto, se han establecido dos valores para la potencia contratada, correspondientes a cada uno de los tramos. La energía

suministrada por la red principal en el tramo máximo es mucho más cara, por lo que la potencia contratada se reduce significativamente en este tramo.

3) Se han considerado dos tipos de cargas: una carga no crítica (NCL) de potencia constante y cargas críticas (CL), cuyo consumo varía según un perfil de consumo doméstico. NCL se activa solo si hay suficiente energía disponible y la carga de la batería (SOC) es superior al 40%. NCL se desactiva siempre que la carga de la batería sea inferior al 25%. Finalmente, CL siempre está conectado pero Plim limita la potencia suministrada.

4) La batería solo se carga si hay excedente de producción fotovoltaica. Si la batería está completamente cargada, el excedente se inyecta en la red.

Es importante resaltar que este conjunto de reglas es solo un ejemplo de la gestión de energía en la microrred. Estas reglas son el contexto para aplicar la arquitectura de comunicación propuesta, que es el objetivo principal de este artículo. De esta manera, el middleware IoE propuesto se utiliza para enrutar de manera eficiente los mensajes intercambiados. PubSub se usa para notificar la tarifa de ToU aplicable a todos los RED (o *cosas*) en la red y RR transmite los comandos de microrred de acuerdo con las restricciones que se detallan en la Tabla 5.5.1. Los datos históricos se almacenan en la capa de la nube para supervisar el estado global de la microrred.

Tabla 5.5.1. Requerimientos de red de las microrredes

Función	**Tiempo de Respuesta**
Monitoreo de Información	15ms-200ms
Control de Información	16ms-100ms
Mensajes que requieren acciones inmediatas	3ms- 100ms
Gestión Distribuida	100ms-2s
Respuesta a la demanda	500ms-varios minutos

Para evaluar el rendimiento de la plataforma IoE propuesta, se ha aplicado esta arquitectura de comunicación en la microrred experimental desplegada en el Laboratorio del Grupo de Sistemas Electrónicos Industriales de la UPV siguiendo el despliegue experimental descrito en el punto 5.1.4.

Para evaluar la plataforma de comunicación de IoE propuesta, se han realizado tres pruebas: A) Evaluación de tiempo de respuesta de la plataforma de IoE, B) Evaluación de rendimiento de la plataforma de IoE, C) Evaluación de rendimiento de enrutamiento y D) Evaluación del uso de recursos computacionales de la plataforma de IoE propuesta.

A. Evaluación de tiempo de respuesta de la plataforma IoE

Para evaluar el tiempo de respuesta del sistema de comunicación, se ha analizado la transmisión de un evento de activación para NCL. El experimento se ha llevado a cabo utilizando los paradigmas RR y PubSub. Sin embargo, el tiempo de respuesta de las comunicaciones RR tiene un gran impacto en el intercambio de mensajes, por lo que el experimento se ha centrado en RR. Con las comunicaciones de PubSub, el intercambio de mensajes contiene principalmente mensajes de notificación.

A.1 Tiempo de respuesta de las comunicaciones de solicitud-respuesta

La Figura 5.5.3 muestra el intercambio de mensajes de comunicación entre dos nodos durante el evento de activación de NCL utilizando la comunicación RR.

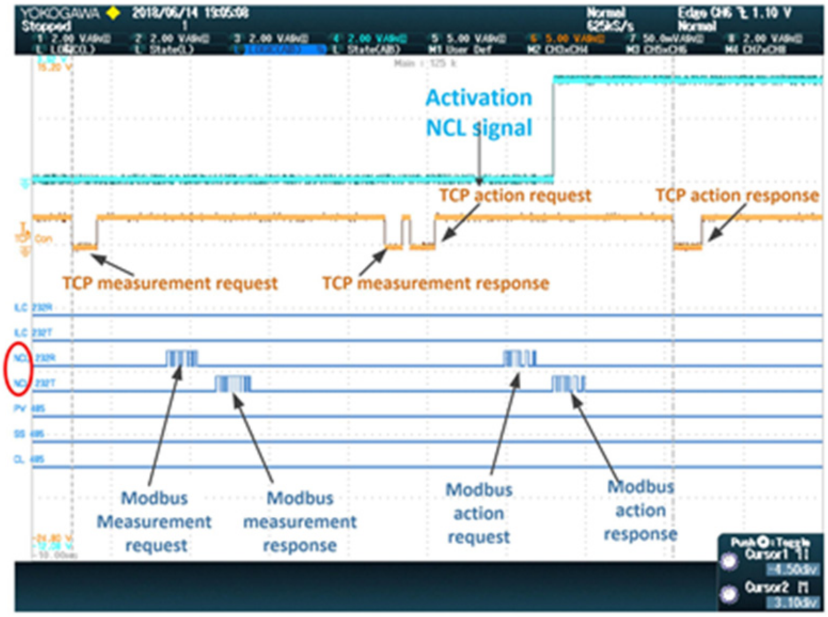


Figura 5.5.3. Intercambios de comunicación para producir la activación del evento NCL.

Cabe señalar que, para realizar diferentes mediciones de tiempo, se han activado los pines GPIO en las computadoras de placa única (SBC) y las tarjetas electrónicas (EBs). En particular, el pin TLS (*Transport Layer Security*) para los SBC y los pines DTR / DSR (*Data Terminal Ready/ Data Set Ready*) y RTS / CTS (*Request to Send/Clear to Send*) para EBs. La Figura 5.5.4 muestra el diagrama con las señales de activación relacionadas con los diferentes intercambios de comunicación.

Señalar en cuenta que los pines DTR / DSR-RTS / CTS se han utilizado para el control del flujo de datos a los dispositivos (activación del protocolo Modbus). Sin embargo, los pines TTL se utilizan principalmente para el control del flujo de datos entre el host y el dispositivo (activación del protocolo TCP).

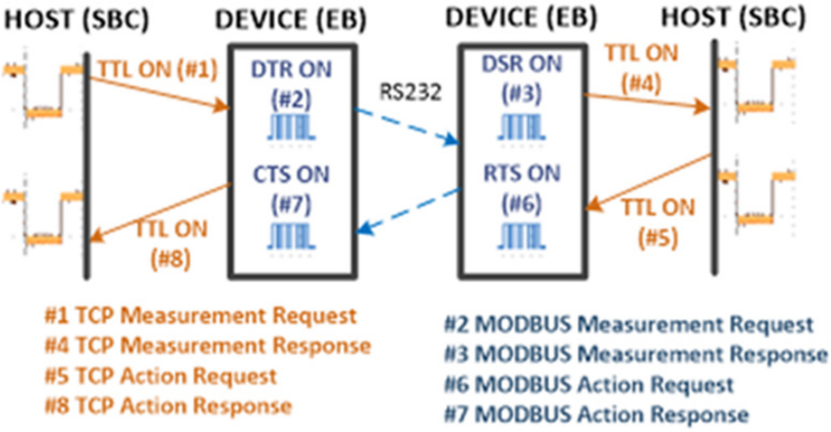


Figura 5.5.4. Diagrama con las diferentes señales de activación de GPIO Para realizar las mediciones de solicitud de tiempo de respuesta

Las comunicaciones intercambiadas durante la activación de NCL son las siguientes: el nodo fuente de la red P2P solicita el estado del nodo NCL (Figura 5.5.3, *TCP measurement request*); cuando se alcanza el nodo NCL en la red (círculo rojo destacado en la Figura 5.5.3), lee su estado a través de la comunicación Modbus (Figura5.5.3*, Modbus measurement request*) y responde (Figura 5.5.3*, Modbus measurement response*) siguiendo el protocolo TCP / IP. Cuando se alcanza el nodo de origen (Figura 5.5.3*, TCP measurement response*), envía una solicitud de acción ON (Figura 5.5.3*, TCP action request*); Cuando este mensaje llega a la NCL (Figura 5.5.3*, Modbus action request*), envía la señal ON y la NCL se activa (Ver Figura 5.5.3, señal de activación de NCL en azul). Finalmente, NCL envía un mensaje de confirmación (*Modbus action response*) a través de TCP / IP, que llega al nodo de origen (Figura 5.5.3, TCP action response). En este ejemplo, se ha determinado el tiempo de respuesta de las diferentes funciones de Microrred (Figura 5.5.5)

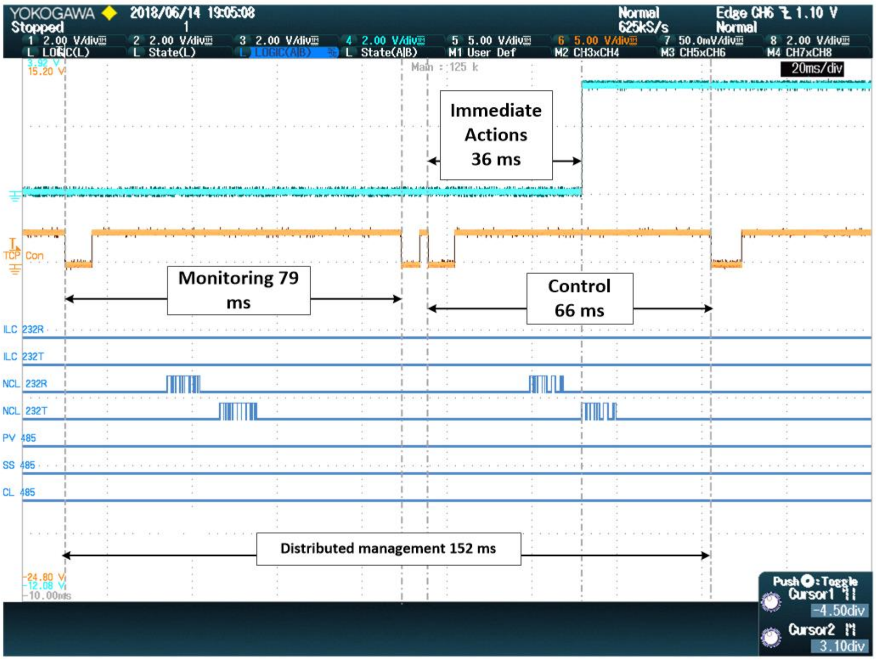


Figura 5.5.5. Tiempos de respuesta de los mensajes intercambiados utilizando la comunicación RR.

La Tabla 5.5.2 muestra las mediciones de las respuestas de cada función de la microrred con la plataforma IoE propuesta comparadas con las requeridas por las microrredes. Como puede verse, el tiempo de respuesta de la plataforma de IoE propuesta cumple con los requisitos de la red de microrred.

Tabla 5.5.2. Tiempos de respuesta obtenidos por la plataforma IoE propuesta

Función	Tiempo de Respuesta de la Plataforma IoE propuesta	Tiempo de Respuesta demandado por las Microrreds
Monitoreo de Información	79ms	15ms-200ms
Control de Información	66ms	16ms-100ms
Mensajes que requieren acciones inmediatas	36ms	3ms- 100ms
Gestión Distribuida	152ms	100ms-2s

Como en el protocolo RR, el nodo solicitante se queda esperando la respuesta del nodo solicitado, se ha considerado un escenario crítico (sobrecarga de comunicación) para evaluar el tiempo de respuesta de la plataforma. Para eso, tres hosts en transmisión han estado solicitando a la vez sobre el nodo NCL periódicamente cada segundo durante 10 minutos. Se ha medido el tiempo de respuesta entre un retraso mínimo (el mejor caso), un retraso medio (caso tipico) y un retraso máximo (el peor caso). La Figura 5.5.6 muestra el tiempo de respuesta de la plataforma bajo sobrecarga de comunicación considerando el tiempo de retardo en el mejor, típico y el caso peor.

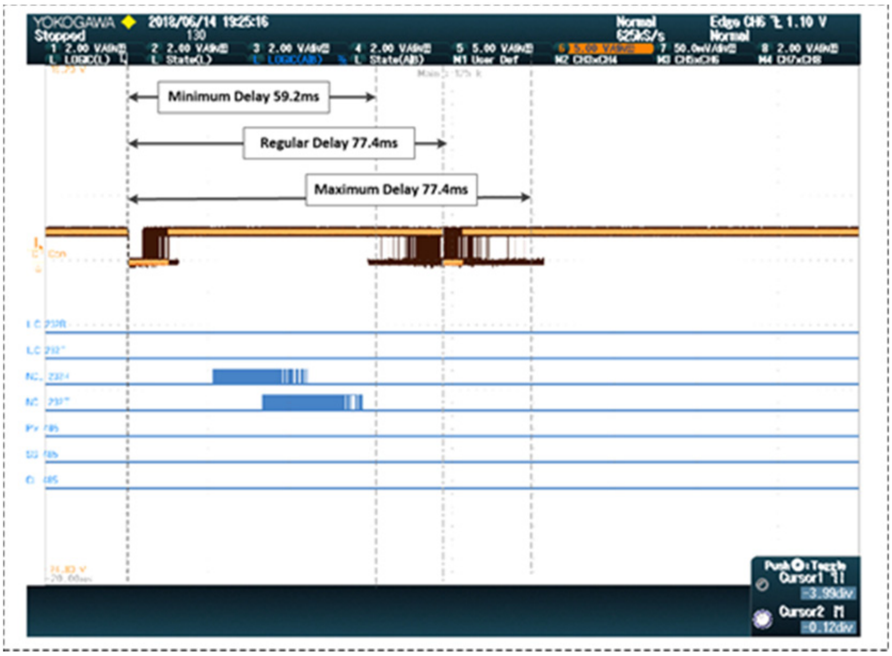


Figura 5.5.6. Tiempos de respuesta bajo sobrecarga usando comunicación RR.

Como se puede observar, incluso en el caso peor, el tiempo de respuesta de la plataforma IoE propuesta cumple con los requisitos de la red de microrred.

Sin embargo, si ocurre una falla en el nodo y el nodo solicitante no recibe la respuesta del nodo de destino después de la retransmisión de tres mensajes, el nodo asume que estos nodos han salido de la red y luego actualizan la lista de sus nodos vecinos. Vale la pena señalar que, en condiciones normales, los nodos comunican que están abandonando la red. Por lo tanto, en el caso de fallo de nodo, no advertirá previamente que abandona la red y el sistema tendrá pruebas de que se ha producido un fallo. La gestión posterior de las fallas está fuera del alcance de esta tesis.

A.2 Respuesta en el tiempo de comunicaciones de publicación-suscripción

Los retrasos asociados a las comunicaciones PubSub se han evaluado mediante la función de respuesta de demanda de la microrred. La respuesta a la demanda es una función que permite a los clientes, voluntariamente, participar en la administración de la carga. En la tabla

5.5.1, el tiempo requerido de respuesta a la demanda está en el rango de 500 ms a varios minutos. Dado que es una especificación relativamente relajada (varios minutos sin especificar un límite superior concreto), se ha implementado mediante un patrón de comunicación PubSub. La Figura 5.5.7 muestra un ejemplo de la función de respuesta a la demanda implementada a través de la comunicación PubSub. En el ejemplo, los nodos CL (marcado en rosa) y NCL (marcado en azul) están suscritos a una publicación relacionada con la activación / desactivación de cargas. La medición de la función de la respuesta a la demanda se inicia cuando se establece la conexión TCP / IP (t0). Como se puede ver en la figura, la respuesta a la demanda para la desconexión de CL es igual a 1575ms y para la activación de NCL el tiempo de respuesta a la demanda es igual a 1800 ms. Los tiempos medidos están claramente en el rango especificado.

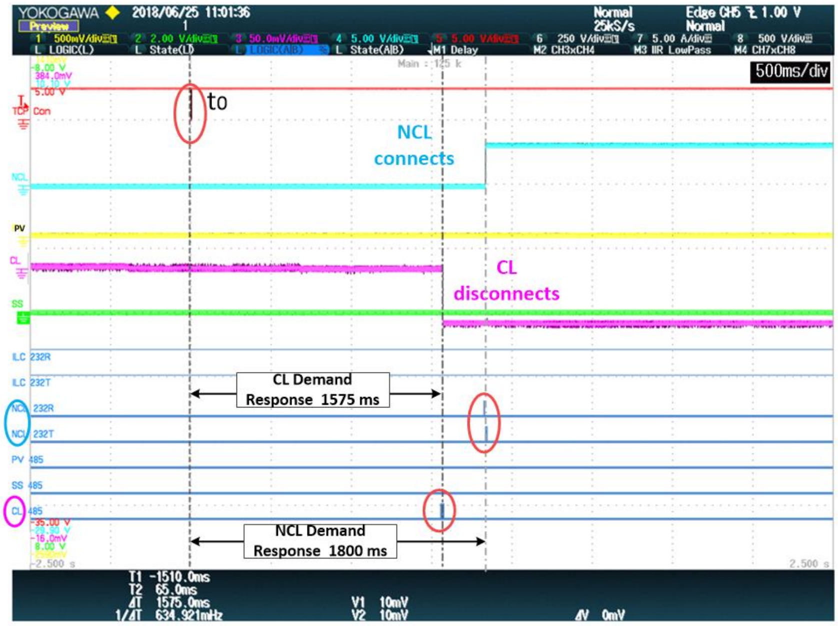


Figura 5.5.7. Tiempo de respuesta a la demanda mediante el uso de la comunicación PubSub.

B. Evaluación del rendimiento de la plataforma IoE

El objetivo de la plataforma IoE propuesta es admitir aplicaciones verticales que procesan la información de la capa de *cosas* a la capa de la nube. Para evaluar el rendimiento de la plataforma de IoE propuesta, el algoritmo de ToU descrito anteriormente se ha implementado en cada RED de la microrred, ejecutándose sobre el middleware IoE propuesto. La Figura 5.5.8 muestra el comportamiento de cada RED de acuerdo con el algoritmo de ToU programado y el conjunto de comunicaciones que tiene lugar entre los nodos de la microrred.

El experimento emula el comportamiento de la microrred en estudio a lo largo de un día (de 00 h a 24h). En la figura, se pueden ver las señales de referencia para cada nodo (es decir, las señales de control para emular el desempeño del RED deseado, que están etiquetadas con el sufijo "ref"), así como la potencia que realmente se entrega o se absorbe por el RED correspondiente: generador fotovoltaico (naranja), NCL (azul claro), CL (azul oscuro), ESS (rojo) y ILC (violeta). Vale la pena señalar que la potencia es positiva en cargas cuando se absorbe, pero en el caso del generador fotovoltaico y el ESS, se asume como positiva cuando se entrega. En el caso del ILC, la potencia es positiva cuando la energía fluye desde el bus de CC al bus de CA. También se debe tener en cuenta que las señales de referencia se envían a través de la plataforma IoE propuesta. Como muestra la Figura 5.5.8, la potencia que suministra / absorbe cada RED coincide perfectamente con la señal de referencia correspondiente. Por lo tanto, la plataforma de IoE propuesta funciona de manera eficiente y todos los comandos se envían de manera oportuna y confiable (vea los paquetes de comunicación en la parte inferior de la figura), verificando que la plataforma de IoE propuesta es adecuada para la gestión de microrredes.

Figura 5.5.8. Ejemplo de aplicación bajo consideración. Muestra del conjunto de señales de comunicación IoE (mostrados en la parte inferior), señales de control y flujos de energía (mostrados en la parte superior).

C. Evaluación del rendimiento del algoritmo de enrutamiento

Los principales beneficios del protocolo MGCA propuesto son una reducción tanto del tráfico de red (Ver Figura 5.5.9.a) como del tiempo de enrutamiento (Ver Figura 5.5.9.b). El rendimiento del protocolo de enrutamiento propuesto se ha comparado con el algoritmo de enrutamiento por inundación.

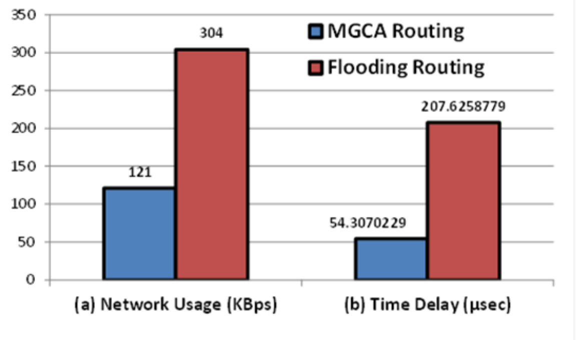


Figura 5.5.9. Comparación del uso de la red en KBps (5.5.9.a) y el tiempo de retardo en microsegundos (5.5.9.b) entre MGCA y el enrutamiento de inundación.

El tráfico en la red se ha medido promediando el uso de la red en kilobytes por segundo (KBps). De la misma manera, el tiempo promedio de retardo es el tiempo promedio para enrutar la consulta a los nodos coincidentes en microsegundos. Ambas mediciones han sido evaluadas para 6 nodos durante 15 minutos. Como muestra la Figura 5.5.10.a, el protocolo de enrutamiento MGCA mejora cerca del 60% del uso de la red. En otras palabras, el protocolo de enrutamiento propuesto consume casi tres veces menos tráfico que las técnicas de inundación. La razón es que las tablas de enrutamiento del protocolo MGCA tienen información sobre los vecinos y se pueden formar agrupaciones. De esta manera, cada consulta se entrega solo a los nodos coincidentes en el clúster y no a todos los nodos en la tabla de enrutamiento como lo hace el enrutamiento de inundación. En consecuencia, se logra una reducción de tráfico de red. Además, el protocolo MGCA tiene capacidad de autoorganización debido a la infraestructura de Chord superpuesta. Con esta característica, cada nodo conoce la disposición de sus vecinos, lo que produce un método eficaz para la propagación de consultas. La Figura 5.5.10.b muestra una reducción de alrededor del 73.8% en el tiempo de enrutamiento con MGCA con respecto al protocolo de inundación.

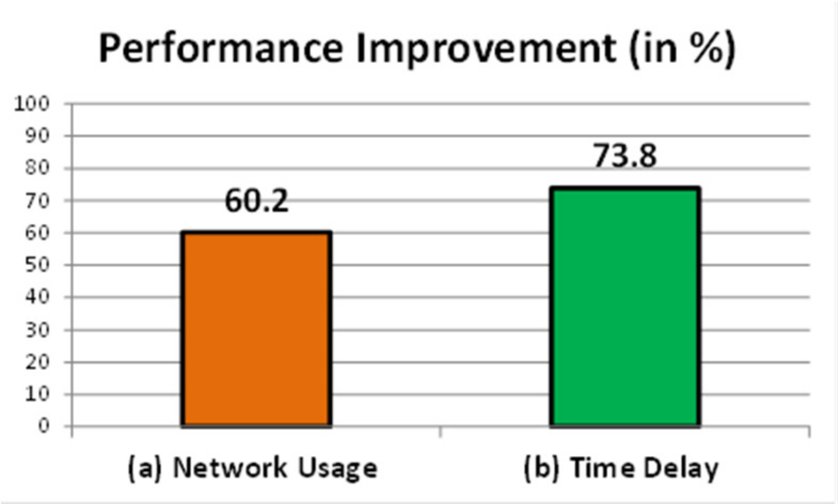


Figura 5.5.10. Mejora (en%) del protocolo de enrutamiento MGCA sobre el protocolo de Inundación

D. Evaluación del uso de recursos computacionales.

Los sistemas integrados funcionan bajo varias restricciones de recursos como tamaño, peso y energía consumida, entre otras limitaciones. Como consecuencia, tienen capacidades limitadas de memoria y CPU. Por lo tanto, una gestión eficiente de recursos es un aspecto esencial para integrar los SBC en aplicaciones en tiempo real. Para demostrar que el middleware IoE propuesto cumple con las restricciones del hardware integrado elegido, se ha medido el uso de la memoria, así como el porcentaje de CPU, para procesar los algoritmos propuestos. Para evaluar estos parámetros, se han realizado medidas ejecutando el middleware IoE propuesto (modo IoE) y sin ejecutarlo (modo iddle). Obviamente, las diferencias entre los valores que se han medido en ambos modos de operación son los recursos adicionales que necesita el algoritmo IoE propuesto. Como muestra la Figura 5.5.11, el uso promedio adicional de la CPU cuando se ejecuta el algoritmo IoE es de 4.35%. Del mismo modo, el uso de memoria activa promedio adicional es del 10,6%. Vale la pena señalar que los recursos computacionales necesarios están realmente muy lejos de los límites del SBC elegido, de modo que se pueden implementar otras funcionalidades como el almacenamiento de eventos históricos, protocolos de seguridad, etc. La implementación de tales funcionalidades está fuera del alcance de esta tesis.

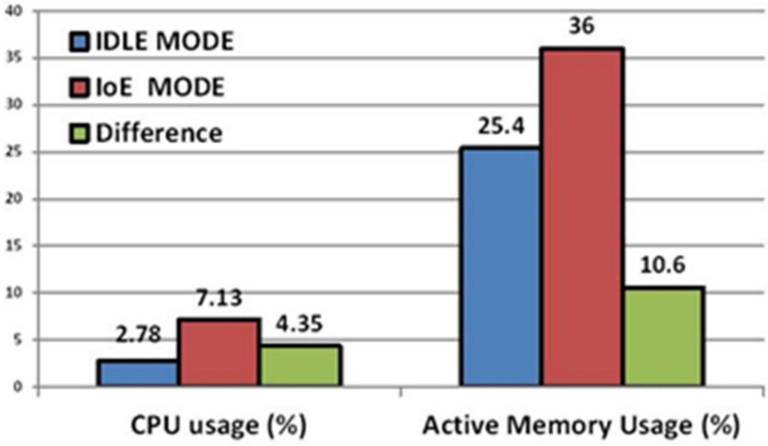


Figura 5.5.11. Comparación del uso promedio de la CPU y la memoria (en% con respecto a la capacidad total de los dispositivos) entre los modos IoE e iddle.

Conclusiones

Este artículo ha presentado una nueva plataforma de comunicación IoE para la gestión de microrredes inteligentes. La plataforma propuesta se basa en una infraestructura flexible desplegada en capas de IoT que tiene una gran escalabilidad e integra recursos de energía distribuidos (capa de cosas). La plataforma está compuesta por cuatro capas: cosas, middleware IoE, servicios de microrred y nube. La plataforma se ha implementado físicamente en una microrred híbrida experimental mediante dispositivos BeagleBone Black.

Los resultados experimentales logrados han demostrado que: 1) la plataforma IoE proporciona respuestas oportunas a eventos dentro de restricciones de tiempo precisas para garantizar un nivel de rendimiento deseado, 2) La plataforma IoE propuesta funciona de manera eficiente para la administración de energía de aplicaciones residenciales y 3) La plataforma IoE puede funcionar correctamente bajo las restricciones de los sistemas embebidos físicos.

Por lo tanto, se puede concluir que la solución propuesta es un enfoque interesante para el IoE previsto en el contexto de las microrredes. Además, puede extenderse fácilmente al concepto de Smart Grid.

6

CONCLUSIONES Y TRABAJOS FUTUROS

Este capítulo reúne las conclusiones más relevantes obtenidas durante el desarrollo de la tesis, así como también presenta algunas líneas de investigación que pueden ser derivadas de este trabajo.

Contenidos

6.1. Conclusiones

Una de las conclusiones más interesantes derivadas del trabajo desarrollado en las publicaciones anteriormente presentadas, es la creciente penetración de los sistemas de generación distribuida y la introducción de las tecnologías de la información y la comunicación (TIC) en las microrredes eléctricas, dando lugar a un cambio de paradigma hacia las microrredes inteligentes. Sin embargo, el movimiento hacia la futura microrred inteligente requiere desarrollar infraestructuras de comunicación distribuidas que incluyan arquitecturas, tecnologías y protocolos que permitan la coordinación de una gran cantidad de recursos energéticos distribuidos de manera que se mantenga la integridad del sistema y un funcionamiento sin problemas al tiempo que satisfacen requisitos de red y calidad de servicio.

El trabajo presentado en esta tesis se centra en este ámbito y buscó aportar contribuciones relevantes en el desarrollo de infraestructuras de comunicación distribuidas para contribuir a la materialización de microrredes inteligentes. En consecuencia, las principales aportaciones son:

1. Diseño y desarrollo de una red Peer-to-Peer (P2P) que consta de pares distribuidos independientes cooperando para compartir información y recursos entre los recursos energéticos distribuidos desplegados en la microrred. Con redes P2P se permite crear enlaces virtuales sobre la red de capa física, utilizando el protocolo de comunicación TCP/IP. En las redes P2P cada peer o nodo actúa simultáneamente como cliente y servidor lo que evita nodos centrales y otorga propiedades de flexibilidad, fiabilidad, auto sanación, auto.reconfiguración y plug-play.

2. Diseño y desarrollo de una infraestructura de comunicación descentralizada basada en el paradigma de comunicación *Request-Response (RR)* que integra los recursos energéticos distribuidos para el control y monitorización de microrredes inteligentes de forma síncrona.

3. Diseño y desarrollo de un protocolo de enrutamiento basado en algoritmos de localidad que se integra en la arquitectura de comunicaciones RR para cumplir con los requisitos de red que demandan las microrredes inteligentes en términos de calidad de

servicio (Quality of Service, QoS) tales como ancha de banda, latencia y uso de red.

4. Diseño y desarrollo de una infraestructura de comunicación descentralizada basada en el paradigma de comunicación Publisher-Subscriber (PubSub) que integra los recursos energéticos distribuidos para el control y monitorización de microrredes inteligentes de forma asíncrona.

5. Diseño y desarrollo de un protocolo de enrutamiento basado en algoritmos de rangos del espacio de indexación de Hilbert que se integra en la arquitectura de comunicaciones PubSub para cumplir con los requisitos de red que demandan las microrredes inteligentes en términos de calidad de servicio (Quality of Service, QoS) tales como de ancha de banda, latencia, uso de red y tasa de falsos positivos del sistema PubSub.

6. Diseño y desarrollo de una Internet de la Energía (Internet of Energy, IoE) que incorpora los paradigmas de comunicación RR y PubSub desarrollados anteriormente para su uso simultaneo. Utilización de técnicas de programación multiproceso y concurrente que permite la reducción del uso de recursos computacionales para la integración del código del sistema en sistemas embebidos que permita convertir los recursos energéticos distribuidos en inteligentes.

7. Implementación de la plataforma de comunicaciones de la Internet de la Energía desarrollada en la microrred experimental desplegada en el laboratorio del Grupo de Sistemas Electrónicos Industriales que fue parte implementada en el alcance de esta tesis. Se estudia los tiempos de respuesta y uso de recursos de red y cómputo de la plataforma IoE. Para ello se ha desarrollado un algoritmo que gestiona dinámicamente los flujos de energía hacia la microrred según el perfil de carga, el estado de carga (SoC) de los sistemas de almacenamiento de energía, la generación fotovoltaica disponible y la tarifa aplicable. Con esta información se realiza la planificación del intercambio de potencia en la microrred diariamente, estableciendo en determinados momentos del día el estado de carga deseado en las baterías y la potencia en los convertidores.

A partir del estudio realizado en la presente tesis doctoral, hay algunos aspectos con el trabajo desarrollado y presentado en esta tesis que no fueron abordados ni contemplados en esta tesis y, en consecuencia, surgen futuras líneas de investigación, que se pasa a describir en el punto siguiente.

6.2 Trabajos Futuros

Las líneas de trabajo futuras derivadas de esta tesis son varias. A continuación se procede a su enumeración para posteriormente ser explicadas con cierto grado de detalle. Las líneas para futuros trabajos son:

1. Adición de capas virtuales para la creación de distintos servicios de microrred

2. Asegurar la ciber-seguridad de la microrredes y su interacción con el exterior

3. Integración de la tecnología Blockchain en las microrredes inteligentes

El contexto en el que se ha enmarcado esta tesis es el de la presentación de arquitecturas de comunicación distribuidas en microrredes con recursos energéticos distribuidos a gran escala. De este marco genérico surgen nuevas líneas de investigación para trabajos futuros, en particular debe destacarse la posibilidad de desarrollar capas virtuales adicionales para la creación de nuevos servicios de microrred. Las redes P2P propuestas crean una única capa virtual llamada *overlay o* superposición que se construye sobre la capa física y permite un aumento de la flexibilidad, la extensibilidad y la reconfiguración adaptiva. Esto implica que cada nodo se comunica entre sí para crear estructuras de superposición auto-organizadas en la parte superior de las redes físicas subyacentes pudiendo otorgar un servicio para la microrred. Sin embargo, podrían crearse múltiples capas de superposición para proporcionar diversas funcionalidades a la microrred. Por ejemplo, ubicar en distintos planos distintos conjuntos de datos [1] como datos de video, metadatos, datos de información, etc. Esto permitiría mejorar el rendimiento del enrutamiento, ancho de banda y tiempos de retardo del sistema [2] a la vez que puede proporcionar distintos servicios como video streaming, monitorización y control sin sacrificar el rendimiento de cada capa individual [3]

Otro trabajo futuro a desarrollar viene derivado de la conexión de los recursos energéticos distribuidos a la red de internet y la vulnerabilidad en materia de seguridad que esto supone. La digitalización de la infraestructura energética tiene como consecuencia una mayor exposición a incidentes y ataques cibernéticos, es por ello, que el riesgo de ataques a infraestructuras críticas es uno de los más probables y con mayor impacto

[4], por lo que evitar una brecha de seguridad en estos sistemas es fundamental. Asimismo, según el organismo gubernamental norteamericano ICS-CERT el sector que más ataques cibernéticos recibe es el de la energía. Por tanto, es fundamental la investigación tanto para producir la minimización como la eliminación de riesgos cibernéticos de la infraestructura energética, un proceso necesario para garantizar la seguridad de todos los actores que forman parte de este mercado. Las soluciones propuestas en esta tesis, tienen cierto grado de seguridad debido a la utilización de enlaces redundantes y la auto-reconfiguración [5]. Sin embargo, el sistema es sensitivo a ataques maliciosos como Sysbil o Eclipse [6,7]. Es por ello que deben estudiarse procedimientos de seguridad adicionales así como su implementación para reducir la sensibilidad a los ataques maliciosos.

Por último, otra línea de investigación que se considera en esta tesis, no sólo por su innovación sino también por la revolución que supone para el futuro del sistema energético, es la incorporación de la tecnología Blockchain en las transacciones energéticas. Blockchain o cadena de bloque, es una tecnología que permite realizar cualquier tipo de transacción sin intermediarios y se caracteriza por ser inmutable, transparente, seudónima, trazable, segura y pública [8,9,10]. Además, no es posible falsificarla ya que posee criptografía y se puede integrar con web o smartphones. Todas estas características posicionan al blockchain como una tecnología revolucionaría para el sector energético. Actualmente los contratos de compra de electricidad se refieren a un emplazamiento físico determinado por un contador y no a un usuario. Con la incorporación de la tecnología blockchain se podría asociar a un usuario consumos específicos en cualquier lugar y en cualquier momento, y cobrarle por tales consumos, sin importancia del momento o lugar donde se realice ese consumo. De esta forma, un usuario podría cargar su teléfono móvil o coche eléctrico en un centro comercial, en un hotel o incluso en transporte público e imputar esos consumos a la persona y no al emplazamiento donde se realice éste. Además, el registro de estos consumos podría hacerse de forma automática. Tal y como se deduce, blockchain es una herramienta con grandes posibilidades, sin embargo, la comunidad científica advierte, de que la tecnología blockchain deberá abordar varios desafíos importantes antes de conseguir una adopción global. Algunos de los desafíos que se destacan son desafíos en materia legal y regulatoria, seguridad, escalabilidad, entre otros.

7

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