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Deploy&Forget wireless sensor networks for itinerant applications

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A R T I C L E I N F O

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A B S T R A C T

Industrial Internet of Things (IIoT) is a disruptive paradigm which will bring new ways of monitoring, control and management for Industry 4.0 and Smart Cities. It relies on smart and connected sensors enabled by a new generation of communication technologies such as Wireless Sensor Networks (WSN). Although various solutions are becoming available, the reality is most of the end users of these systems won't be communications experts, so the complexity and deployment difficulties are strong barriers for adopting this technology. This article briefly summarizes the state of art of current industrial wireless sensor networks technology, and presents the concept of Deploy&Forget network: a solution to enable the rapid deployment of WSN by assisting users onsite, reducing time and complexity of deployment, and includes a designed protocol stack to ensure unattended and long lasting operation. This technology emerges as an evolution of previous WSN works where these problems where clearly identified, and has been deployed and validated in water management tasks for Valencia, energy measurement in offices, and contextual monitoring for "Zero-Defect Manufacturing" for Industry 4.0.

1. Introduction

The concept of applying sensors to elements such as machines, robots, motors or vehicles is not new in industrial sector. Modern industry depends on a wide range of sensors and communication networks which have led to a high level of automation, efficiency in processes and quality of products. The more recent introduction of M2M (machine-to-machine) systems has allowed direct connection between machines without the need for human intervention, which is one more step towards more autonomous systems. Historically, these operational technologies have worked in independent networks, with robust protocols that provide dependability and security that has never been achieved with consumer technology.

However, the industrial sector is becoming ever more digital, in a society that is more involved than ever in technology. This new world values solutions with greater connectivity and more added value. There are now emerging needs for which the classic solutions in terms of architectures and automation are clearly limited: greater quantities of data in real time, better scalability, flexibility and connectivity. This means breaking with the rigid, closed character of traditional industrial architectures, and it is here that the IoT (Internet of Things) appears as a candidate solution. IoT is a collection of concepts and technologies, a paradigm with diverse points of view and multi-disciplinary activities, which introduces the ubiquitous presence of sensors in digital environments (Smart Sensors). This is done using cabled or wireless connections and unique addressing schemes that allow interaction between each other, as well as cooperating with other systems to create new applications and services.

The arrival of IoT into the consumer world has led to greater connectivity with a minimum of barriers, where low cost is one of the most relevant characteristics. However, industry presents a completely different scenario from that of the consumer world, a scenario where security, dependability and low latency are the principal objectives, and where stopping industrial processes because of failure or for maintenance is not an option. In industry these factors may directly affect the quality and efficiency of processes and products, company profits, safety of personnel and the care of materials. These strong business and technical requirements act as a sort of filter for new technologies. The technologies that pass the filter are able to offer functional guarantees in critical business environments are now known Industrial-IoT (IIoT) [1]. IIoT can be applied in a range of sectors, such as manufacturing, energy, Smart cities, eHealth or building management. It offers a new dimension of applications and services directed at improvements in efficiency and quality of processes, agility and flexibility in decision-making, simple transparent connectivity between locations, businesses and countries and the generation of new value added services.

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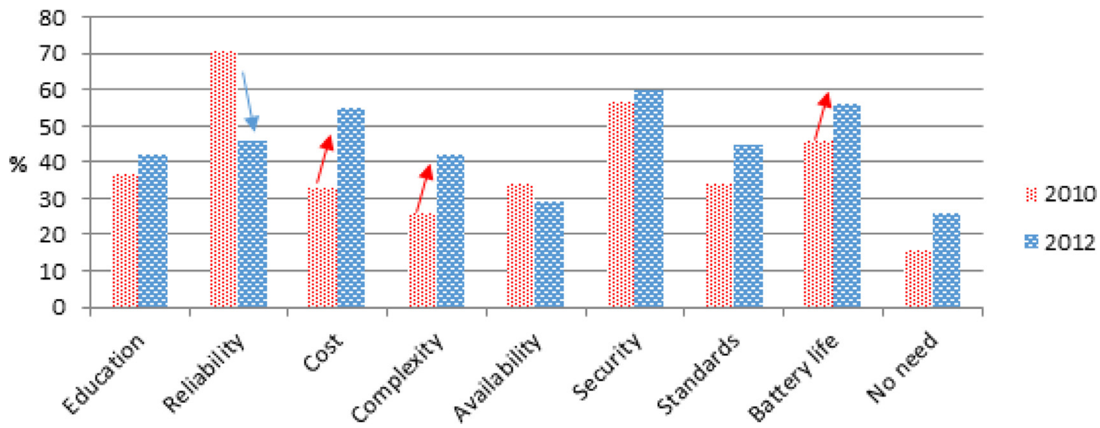


Fig. 1. Main inhibitors for using WSN in Industry. Source On World [6].

Access technologies for Smart Sensors can be based on cabled or wireless systems [2]. Wireless systems have the most potential for future research in the field of IIoT, with Wireless Sensor Networks (WSN) technologies being the main focus of attention. Using WSNs, it is possible to use a large number of sensors located at any point of the area in question (not only in areas with communication infrastructure and energy supply) in a simple, economical manner. In wireless networks the cabled part is eliminated, thus expensive problems such as cost of installation and maintenance are removed, allowing installation in mobile elements (vehicles, robots, Smart tools, etc.) and also use for specific tasks which requires a fast network deployment such as diagnostics and audits. The increase in knowledge of these technologies, the maturity of solutions based on mesh topologies, and the spread of industry standards such WirelessHART [3] and ISA100.11a [4], have placed WSNs as a disruptive technology in industrial automation.

Their popularity and expected growth has been steadily increasing but considering the benefits they offer there are still many challenges to give the final impulse for massive adoption in industry [5]. WirelessHART and ISA100a are long established technologies, which is the reason WSNs are considered widespread adopted, but the motivation to overcome arisen concerns and obstacles is redirecting the trend towards solutions based on IP addressable sensors and open IEEE standards, envisaged to better support Industrial IoT and Industry 4.0 use cases, and not only factory automation. These trends can be derived from the last survey carried out by ON World in industry, where results also demonstrated that dependability is no longer a problematic area. This is logical given that communication protocols are becoming even more robust. However, security and the lack of standards still present growing worries for the end-user. Costs, complexity, system integration and battery life are the most commonly perceived obstacles against (see Fig. 1) using this technology at present, responsible for its slow adoption in production. Updated values with respect to Fig. 1 can be found in [7].

Concerning complexity, it is important to consider that WSN solutions are not generally deployed by communications experts. The deployment phase is usually a complex task that requires prior planning, coverage studies, connectivity tests, all of which becomes more complicated when the system is being continuously installed and then uninstalled, as is often the case for inspection tasks or audits. WSN solutions must be capable of forming autonomous, automated networks, such that the installer can leave the factory with a stable functioning network. While in operation, the system must be able to self-repair, and evaluate weak connections or channels with high interference in order to re-plan. The system must also carry out self-diagnostics when the service is interrupted or there are problems with a node, etc., so that visits by technicians and down time of machinery can be avoided. Battery life is also a crucial aspect in these types of networks, as this will limit processing and communication capacities and thus affect network lifetime. Both complexity and battery life have an important impact on the total cost of deploying these types of systems. In this article a diverse range of novel technologies for Deploy&Forget WSNs which offer partial solutions to these problems are presented. These solutions are to be used by operators during the deployment phase, and are designed to enable reliable, unassisted working that maximizes the network lifetime. This article is structured as follows: Section 2 shows related work and existing solutions; Section 3 introduces the proposed solutions for implementing a Deploy&Forget network, analysing the techniques, mechanisms and technologies proposed for both stages (deployment and steady operation); Section 4 describes experiments and tests results; finalizing with Section 5's conclusion and future work.

2. Related work

The complexity of WSNs and the difficulties associated with deployment is a recurring problem in the literature. This problem has worried researchers and held back the adoption of these systems in industry. In spite of the work carried out to generate guides for deploying WSNs for personnel with little experience [8,9] , or factsheets that summarize real experiences to be used as a reference [10], the reality is that time and specialized staff are still necessary for these tasks. The capacity to self-monitor and self-configure have been identified as the key characteristics when dealing with deployment problems [11], but this has not translated to the commercial systems. This problem has even generated work that shows automated deployment of WSNs, removing the human factor in this phase and replacing them with robotic elements [12], or enabling automatic movement of the nodes in order to maintain connectivity to the network [13].

The proposed solutions have come from different perspectives and can be classified in three categories: pre-deployment, during-deployment, and post-deployment (see Table 1).

The **pre-deployment** solutions are focused on planning tools for the installation and prior checks. In general, these are based on algorithms for 2–3 dimensional spaces that seek to optimize one or more objectives [14], such as maximizing the area covered by sensors [15], improve the range of detecting and sensing [16], radio coverage [17,18], cost and useful lifetime [19], control of topology [20], energy saving [21,22], probability of detection of [23], or scalability [24]. Some algorithms are specifically designed to optimize the reliability of the network in industrial scenarios, such as the Hybrid Binary Differential Evolution Harmony Search Algorithm [25]. From these algorithms, a range of software applications allow WSN deployment design [26,27], finding the optimum locations for sensors and their transmission powers in relation to the points of interest in the installation, the location of the sink, and the physical and structural characteristics of the scenario. This type of

Table 1
WSN deployment stages.

Stage	Tools	Results
Pre-deployment	Planning tools for the installation	Radio Coverage, Cost, Lifetime, link quality prediction
During-deployment	Monitoring and configuration tools	Check connectivity and configuration, Measure signal strength, Localize nodes introducing problems in the network. Network topology Discovery
Post-deployment	Monitoring and control tools	Deploy and connectivity test, Faults localization, required reconfiguration

planning is the standard methodology for deploying sensor networks but it only provides a theoretical reference. A number of authors agree that real deployments differ considerably from these prior simulations [28,29], due to the fact that the complexity of the real environment lies in the variability of conditions, and that the deployment must be done by trained technicians in order to correct any errors that may arise.

The **post-deployment** solutions cover the processes carried out after the initial deployment of the network to check if it working correctly and make any necessary final configurations. Onur et al.[30] proposed a series of quality parameters which evaluate whether the network coverage is sufficient or if the system needs to be reconfigured again. It is also possible to find in the literature a range of monitoring and control tools designed to be used after deployment of the system [31,32]. POWER [33] is a platform that, through the introduction of deployment checks and a range of connectivity tests, finds any faults in the network and proposes ways of improving performance. MoteView [34] is a Crossbow monitoring software that works as a client interface between users and remote sensors. Among its functions, it has the capacity to allow the user to visualize the list of live nodes in the system and to know their condition. Moreover, it shows a map of the topology of the network, with information on placements and connection with neighbours. There are a number of similar tools available, such as SpyGlass [35], TinyViz [36], Surge Network Viewer, MonSense [37], Octopus [38], SNAMP [39], MeshNetics WSN Monitor, Mica Graph Viewer [40], and Marwis [41]. Honeywell [42] uses a technology that, after obtaining data from a multihop network such as routing tables, connection quality, etc., simulates the functioning network including node failure in order to verify its robustness and to detect weak points and bottle-necks. In the case that one of these methods detects nodes without connectivity or problem points in the network, there are algorithms that propose the locations of nodes that can act as additional relays [17,23]. The main problem with these tools is that the rectification process becomes quite iterative; basically trial and error, until the network is free of errors or improves its quality parameters, requiring lots of time and deployment of the whole network in each iteration.

During-deployment solutions cover the tools that help during the deployment of the system, such as checking connectivity and configuration of each node. In an ideal situation, a system that is easy to set up, this would be the principal approach at this stage, thus avoiding, as far as possible, the two previously mentioned solutions. The current solutions are centred on Deployment Time Validation tools (DTV), which are instruments for technical diagnostics and network validation, but which do not form part of the final network. TASK [43] is a joint project between the University of Berkeley and MIT, who, in an early phase of the development of WSNs detected the difficulties involved in the deployment phase, and designed a collection of monitoring and configuration tools to ensure that the network was completely functional before abandoning the installation. For the deployment phase, these tools include software that can be installed in a laptop and which allows access to each node, and to check whether the nodes within reach are alive and functioning correctly, but without checking the network as a whole. In SeeDTV [44], an embedded device is presented which verifies the connectivity of the nodes with an end server in star topologies, the RSSI and node battery values. Barrenetxea et al [9] presented a device based on TASK and LUSTER, but for multi-hop networks with passive functioning based on "sniffing" the data transmitted between stations. In [8] a suite of tools was presented which can be used from any hand-held device and which consists of three tests: connectivity with the parent node, to check node by node whether the tree topology is correctly formed; network coverage, to check if all nodes can exchange messages; and device coverage, to check the quality of the link and the loss rate with the destination. MoteFinder [45] is a tool designed for use with a PC which allows the user to communicate with specific nodes in the network, measure signal strength, y localize nodes that are functioning incorrectly or even generating problems in the network. These solutions are aimed at technical personnel, and thus often the problems lie in use of the tools by untrained staff, specifically in interpretation of results, and carrying out modifications to correct any problems which may exist. Moreover, validation tools are required, which consist of equipment that is external or additional to the network.

The previously industrial wireless standards mentioned, WirelessHART and ISA100.11a, don't address directly this problems, although manufacturers do provide their own solutions to help users make the deployment of their products easier. Since WirelessHART was the first standard to be used by the industry, the number of manufacturers using this solution is higher. Members such as Emerson, Pepper + Fuchs, Phoenix Contact have their own coverage planning and simulation tools that help in the pre-deployment stage of networks using WirelessHART. There are also tools that help in the stage during the deployment and commissioning of the network (like Phoenix Contact's WirelessHART Network Commissioning Tool), as well as deployment guides that help operators to locate different types of devices. The manufacturers also have tools that allow monitoring the network in the post-deployment stage, and some studies have been done on possible passive monitoring tools, which are based on the use of sniffers. The number of ISA100.11a device manufacturers is somewhat smaller, so there are fewer tools specifically targeted to ISA100 devices. Some manufacturers have roofing planning tools, such as HoneyWell and its RF-Lite tool. Another IEEE 802.15.4 MAC layer based solution, the Zigbee protocol was not taken into account for industrial applications until later evolutions of its specifications (although it is extended in domestic IoT applications), with the specification ZigBee Pro [46] which, with the aim of reaching industrial market, included the ability to dynamically change the transmission channel of the entire network. A summary of available solutions for deployment and unassisted operation for these relevant technologies in the market is shown in Table 2. WIA-PA [47], which has also adopted the IEEE 802.15.4 physical layer, has not been included in the table as it is a very recent standard and mainly supported by Chinese companies, so there is not information available regarding deployment tools.

As can be seen in Table 2, network deployment assistants in other relevant standards such as WirelessHART also require external tools or devices, often proprietary of each vendor, and require technical skills to learn their operation and follow the guidelines and instructions.

The work presented in this article shows a new solution for the during-deployment phase, aimed specifically at non-technical personnel and without the need for external equipment. It should be noticed that in every deployment there are steps that cannot be avoided, for instance placing nodes and test their connectivity, but these steps, which can be quite iterative and repetitive can be reduced in number and time. Nevertheless, the presented solution offers considerable advantages during the WSN deployment process as it allows set-up and continuous data collection tasks, such as audits, to be carried out easily. In other circumstances these tasks would be particularly complex for untrained or non-technical personnel. Once installed, the network manages itself au-

Table 2
Deployment tools in relevant industrial WSN technologies.

	Pre-deployment
WirelessHART	WirelessHART network planning tool,WiNC, WirelessHART network Planner tool, $AMS^{TM} wirelessSNAP-ON^{TM}$, Emerson estimators, SoftDEL wireless network Planner
ISA100.11a	RF-Lite
ZigBee	ZEIN
	During-deployment
WirelessHART	WirelessHART network commissioning tool, Planning and deployment networks, guide system Engineering, Guidelines IEC 62591
ISA100.11a	OneWireless Network Planning and Installation Guide, Guidelines for Layout and Installation of Field Wireless Devices
	Post-deployment
WirelessHART	$AMSTMWirelessSNAP-ONTM$, SoftDEL Wireless Network Monitor, Passive Monitoring Software Tool for Deployed WirelessHART Networks, Autonomous Diagnostic Tool
ISA100.11a	SoftDEL Wireless Network Monitor
ZigBee	XCTU, SoftDEL Wireless Network Monitor
	Unassisted operation
WirelessHART	Setting routing and planning Information using the Network Manager
ISA100.11a	Setting routing and planning Information using System Manager
ZigBee	Updating routes based on the cost of the links

tonomously and maximizes the node lifetime through intelligent routing based on energy conservation.

3. Deploy&Forget proposed solution

3.1. Assisting in the deployment stage

For an easy, rapid and more efficient network deployment, it is necessary to avoid the need of pre-deployment studies/tools and additional management devices, increasing the complexity of the wireless sensor nodes. This means adding in each node mechanisms and tools that enable triggering a connectivity and quality test, performing that test and showing the results in a user friendly manner. Although this involves the introduction of some extra hardware in nodes, such as buttons and led indicators, and additional software responsible for the network analysis test, the final impact in cost per node is barely affected. The process of deployment is depicted in Table 3.

The novelty of this solution is the management of the quality along all the nodes involved in the communication to the gateway, what is called "path quality", instead the common approximation of measuring the one-hope quality (usually the RSSI for node on deployment). This is really relevant in mesh scenarios, where the reliability of the communications depends not only on the radio link with the next node, but on all nodes involved in the communication. The mechanism behind the quality test is based on the exchange of control messages during the deployment stage, that gather the link and path related information needed by the node to calculate and show the path quality through its user interface in the form of led indicators. The message exchange and states machines for the process running on the nodes can be seen in Figs. 2–4.

In Fig. 2, the diagram shows the exchange of messages during test operation. Node 0, which wants to join the network, sends the request for information, which travels through the assigned path up to the gateway. In each hop, nodes add the data needed to calculate the quality. The gateway then responds, with a control message which includes QDSN (quick deployment sensor network) headers to identify the test and the destination node, and a payload which integrates the quality of previous hops and the current link, updated at each hop (i.e.: node 1 sends back a QDSN message with the integrated quality of link B and C and the data about A link). This way, a control message can transmit information about a path with several hops with a fixed limited packet size (does not introduce extra headers for each hop). The content can be summarized as the quality of the path of the parent candidate, plus the information required to calculate the quality of the link to that parent. It also carries a header to identify the packet as quality test, so receiving nodes can react accordingly.

The variables included in the data processed during the test quality are:

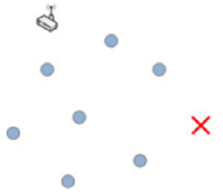
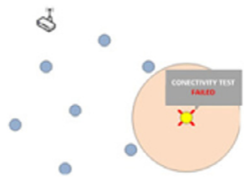
- ETX (expected transmission count) [48] as link quality through packet loss estimation, as more needed retransmissions indicate that packets are getting lost in the selected links.
- LQI (link quality indicator) for link quality [49], and signal estimation. Occasionally RSSI (signal strength indicator) can be also checked for link information although LQI is a better indicator regarding quality of the signal. Nevertheless, LQI alone can present issues for representing the real quality of the connection: a weak signal in the presence of noise may give a high LQI, strong noise (from a nearby interferer) may give high RSSI and high LQI, or a very strong signal that causes the receiver to saturate can also give high LQI. All this are false positives that can affect the quality estimation. Therefore, the other parameters are introduced to contribute to a more final quality result that ensures the robustness of the communication.
- Number of neighbours for each node for resiliency in case a node goes down, and palliate other interferences. By introducing number of neighbours, we give a bonus to locations where more paths can be available if the selected parent fails.
- RTT (round trip time) for delay calculation: longer delays can mean poor connectivity and long routes with too many hops, and in some situations affect the application with stricter time requirements.

The described test gives the quality at the time of deployment, which means the situation during operation can change due to the nature of the channel, and hence change the quality achieved in the first stage. Nevertheless, the selected factors included aim to give a result that will not change significantly over time, except by major changes in the network, and this is addressed during steady operation.

Fig. 3 shows the state machine of the node triggering the test. It indicates that the quality test request is performed with a timer and a retry counter. The test is launched, and first looks for previous information on delay of the path, as an initial check of connectivity. Then it sends the quality test request, and if it fails to receive response after 3 s, it retries up to 3 times. Fig. 4 shows a similar state machine belonging to an intermediate or relay node. This node receives messages and decides, based on its type (request, response or other), how to proceed by updating the payload with requested data and relaying towards next hop.

Once the nodes are deployed in an optimal or acceptable location, the underlying network mechanism described in next section handle the operation in steady mode. This method of deployment, with quality assessment and the software/hardware tools required have been recently patented [50]. Fig. 5 illustrates the hardware proof of concept of the mentioned patent.

Table 3
Deployment process example.

	1. The user is deploying the network. The next location to sensorize is marked in red.
	2. The user decides to deploy the node in the centre of the sensing area. With the quality test, the user checks the connectivity and quality of the connection with the WSN Gateway. After triggering the connectivity test, the user knows there is no connectivity in that spot.
	3. The user then moves to a near spot and performs the test again. Connection is successful but the quality is too low. This could depend on several factors such as number of hops, latency, packet loss or signal to noise ratio, resulting in a unreliable spot. The information about quality is kept as simple as possible to reduce complexity on hardware and Human-Machine Interface (HMI) side, and avoid non-experts' confusion.
	4. The user decides to perform another test inside the selected area, but in another possible spot. The result of the test shows better quality than in the previous spot, so the user deploys the node and continues to next sensor designated area

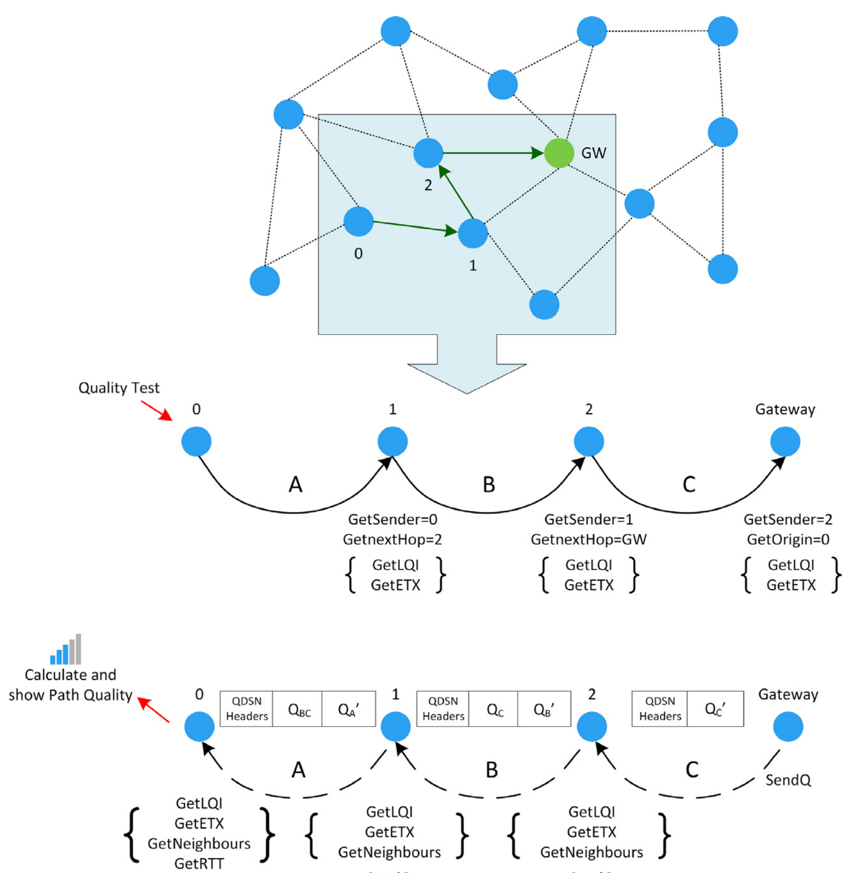


Fig. 2. Quality Test Message exchange diagram.

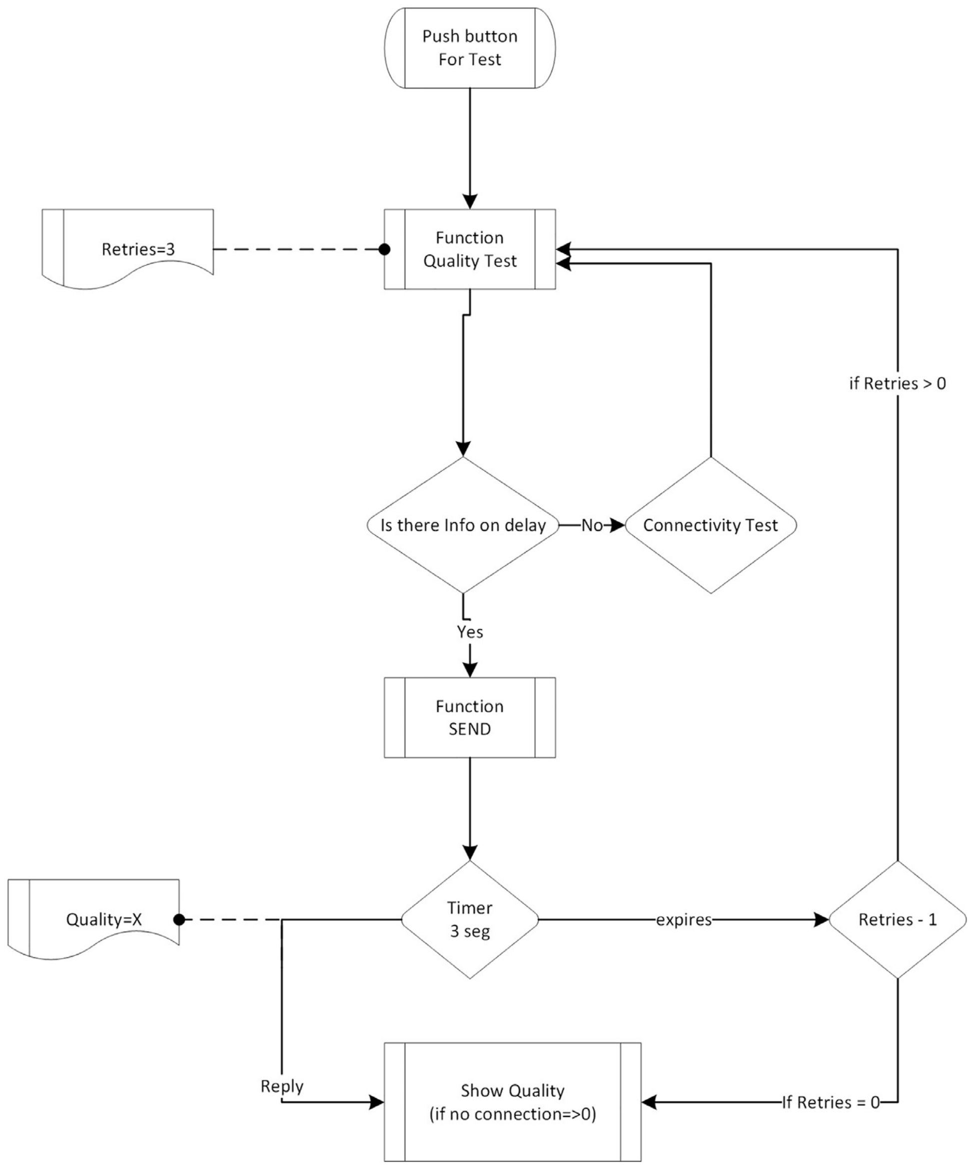


Fig. 3. State machine of quality test at node under deployment.

3.2. Operation in steady state

Once the WSN is deployed, the designed communications protocol stack (see Fig. 6) must ensure unattended operation with the best performance available. To do this, the WSN implements different state of the art open protocols, from physical link to application layer, in order to optimize robustness and interoperability and achieve the typical requirements of industrial use cases.

To maximize reliability and ease of use, the best topology candidate for a Deploy&Forget WSN is the mesh topology. This requires a more complex protocol stack and additional management protocols, but abstracts the end user from architecture and topology issues. In a reliable mesh network, every node has at least two other nodes to communicate with, and a routing protocol to solve routes and forward messages to the network gateway. Mesh networks are potentially more reliable than classic star topologies: the path redundancy and the routing protocol enable dynamic management of the network to face interferences, blocked routes, nodes failures or moving nodes, dealing with the different routing possibilities the network is bringing.

The use of an efficient Medium Access Control (MAC) protocol is of vital importance for Wireless Sensor Networks (WSN). The MAC layer is responsible for channel access policies, scheduling, buffer management and error control. In a Deploy&Forget WSN, we need a MAC protocol to provide energy efficiency, reliability, low access delay and high throughput as major priorities, while ensuring a basic level of auto-management and self-healing.

Research on this field has been active for more than a decade [51], when the first protocols and techniques such as preamble sampling (which is a method still in use in many protocols) were introduced. Depending on the medium access strategies, researchers have classified MAC protocols as we can see in Fig. 7.

The different techniques and approaches serve the purpose of adapting the MAC layer to fit the application, as the final goal of the WSN, network topology, node distribution and location, and even node capabilities (batteries, processing power, etc.).

Contention/random based access protocols address a duty cycle mechanism for energy efficiency, with the aim of keeping transmission and reception time to the minimum, providing reliability and low delay to some extent, but collisions and interferences still make these solutions far from robust for harsh industrial environments requiring strict timing and QoS features. Static/scheduled access (access during defined time slots and on defined channels) ensures a first level of reliability and

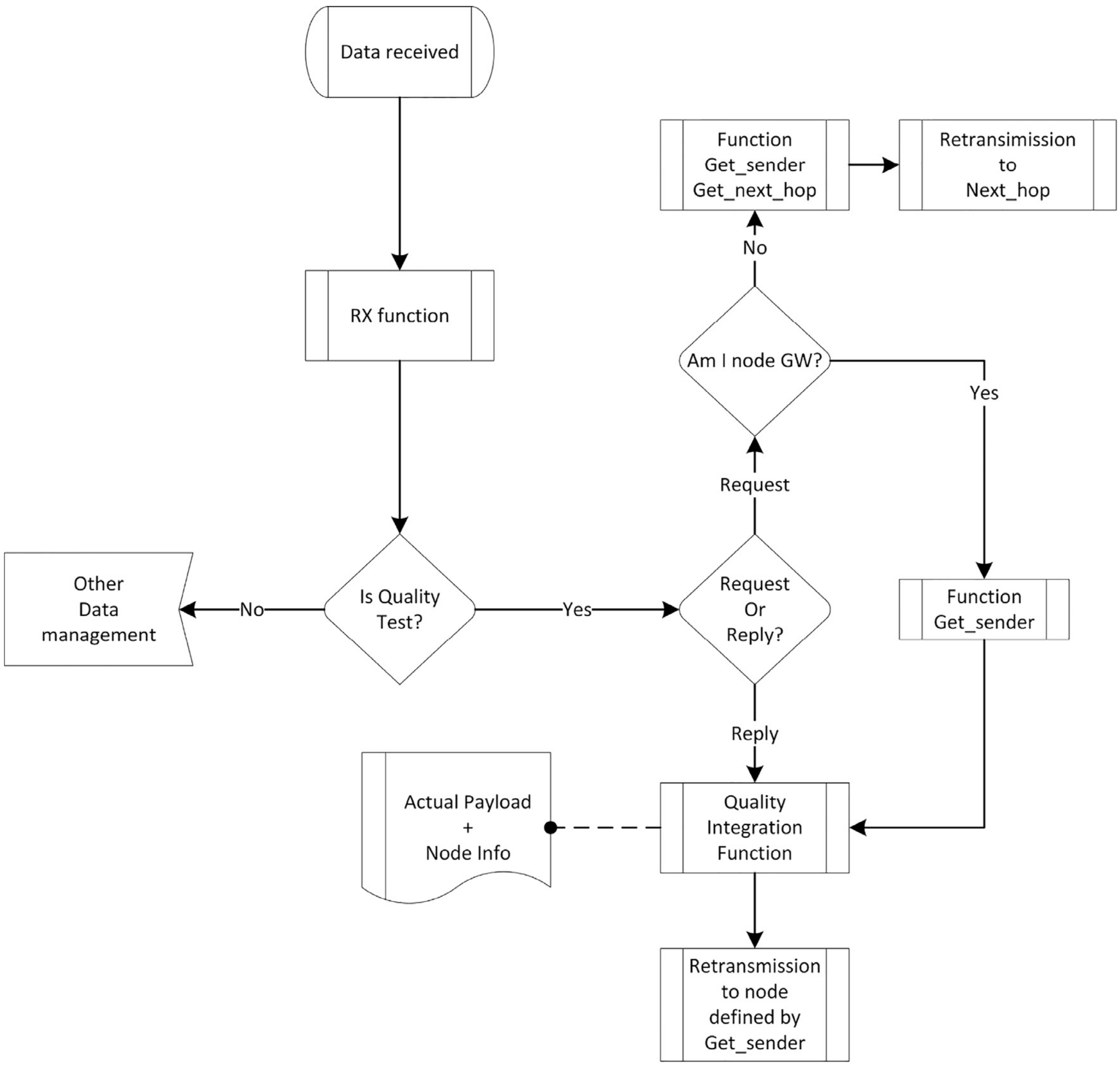


Fig. 4. State machine of nodes along path to network gateway.

Fig. 5. Hardware nodes with implemented QDSN mechanism.

determinism, but becomes more complex for multi-hop networks. Channel utilization is low when only few nodes have data to transmit (time slots are wasted on idle nodes). This can be a problem for network scalability, but on the other hand these protocols provide collision free and high throughput communications, with guaranteed bounded delays and robustness against interferences.

The IEEE802.15.4e protocol, with its Time Slotted Channel Hopping (TSCH) behaviour mode is a recent amendment to the medium access control (MAC) portion of the IEEE802.15.4 standard [52], focused on industry, with a direct inheritance from WirelessHART [3] and ISA100.11a [4]. The time-slotted operation allows for a more closely engineered network operation for deterministic properties and reduction in collisions. It can also reduce the amount of time the nodes need to actively participate in the communication and thus can save potentially a significant amount of energy in the nodes. The channel hopping aspect of TSCH is an easy and efficient technique to combat multipath fading and external interference (for example by Wi-Fi transceivers).

Furthermore, the IPv6 protocol will be mandatory for the development of new network architectures, as the protocol has many desirable features like scalability, enhanced security, good mobility support, stateless address auto-configuration, and many more. The standardization of IPv6 transport over the TSCH mode of IEEE 802.15.4e is driven from the IETF working group 6TiSCH [53]. On top of that, 6TiSCH uses IPv6 Neighbour Discovery to find the addresses of reachable neighbours and RPL (routing protocol for low power lossy networks) to implement packet processing and forwarding along with multipoint-to-point and point-to-multipoint routing and optimization of the routes according to multiple constraints such as energy or latency.

The routing protocol for low power lossy networks, or RPL, defines an IPv6 Distance Vector generic protocol which specifies how to build a "Destination Oriented Directed Acyclic Graph" or DODAG by applying different objective functions (O.F. onwards) and metric constraints, so it is able to adapt to a variety of networks. A network using RPL can have several graphs or different network topologies (DAG from now on), called instances, which meet specific requirements depending on the O.F. used as criteria to create the paths between nodes and the DAG Root. In the Deploy&Forget philosophy, this can be used as a tool for

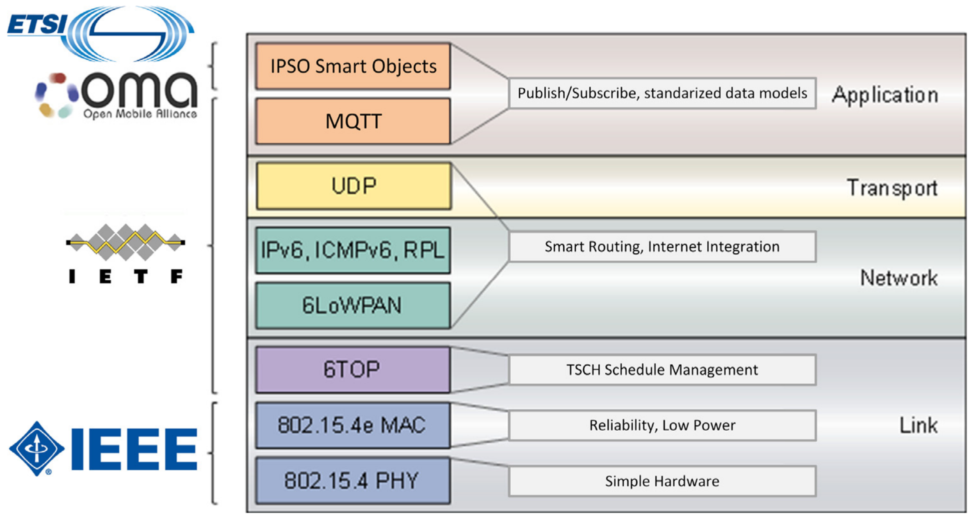


Fig. 6. Full protocol stack used for Deploy&Forget WNS.

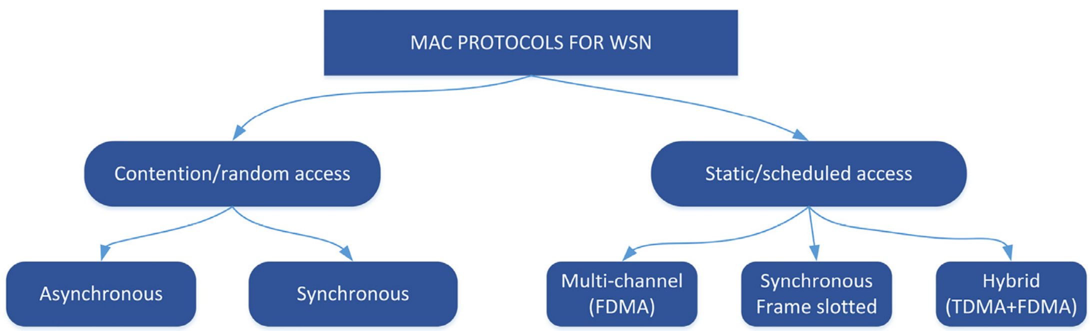


Fig. 7. MAC protocols classification.

enabling a longer unattended operation time, ensuring all the sensors are getting data as long as possible, and there are available routes to deliver this data. With our implementation, a specific set of services allow to configure RPL O.F.s to be aware of neighbour node's remaining energy in order to dynamically build a topology that optimizes battery lifetime (similar services and functions can be used for different optimizations). The process follows this scheme:

- Get the current remaining energy of the node, at the given rate of consumption (when requested to inform its neighbours to construct the topology).
- Set a remaining energy threshold, to force routing through different paths (applies hysteresis)
- Request the remaining energy of neighbours, at the given rate of consumption:

The RPL routing protocol implements the control message exchange (DIO or DAG Information Object, and DIS or DAG Information Solicitation, broadcast control messages) for supporting this path selection mechanism (see Fig. 8).

Algorithms 3.1, 3.2 and Eq. (1) shown the presudo code of the algorithms involved in the construction of a network topology for the energy optimization nodes.

$$p\!-\!> energy\_estimation = \frac{Energy\_est\_value_i \times Current_i \times Voltage}{RTIMER_{second} \times Runtime} \quad (1)$$

$i = (TX, RX, CPU, LPM, \ldots)$

$RTIMER_{second} \approx 32768 ticsk/second$

Algorithm 3.1 wsn_nm_best_parent(NM_node p1, NM_node p2.

metric1 = wsn_nm_path_cost(p1)
metric2 = wsn_nm_path_cost(p2)
/* A higher metric value is worse */
minimum_diff = ENER_SWITCH_THRESHOLD
if p1 is best_parent **then**
  if $metric2 > metric1 + minimum\_diff$ **then**
    return $best\_parent = p1$
    else return $best\_parent = p2$
  endif
endif
if p2 is best_parent **then**
  if $metric1 > metric2 + minimum\_diff$ **then**
    return $best\_parent = p2$
    else return $best\_parent = p1$
  endif
endif

The energy estimation function establishes a counter that registers the amount of processor ticks that a certain element has been actively consuming energy, for instance the radio circuit in transmission or receive mode (each mode has a different consumption value), the CPU, the board in Low Power Mode, and any other present consumers (LEDS, I/O, etc.).

By knowing the amount of time active and what current consumption and voltage supply specifications the mote has, we can estimate the total energy consumed and therefore the energy remaining. The

Algorithm 3.2 wsn_nm_path_cost(NM_node p).

```
/* If energy is 0,this means battery is depleted or node is sink */
/* If sink, the metric equals 0 (mains powered), always be lowest
   rank */
energy_metric = wsn_energy_value()
if energy_metric == 0 and
  p−>rank > sink−>rank then
  return cost = WSN_NM_MAX_PATH_COST
/* infinite cost when battery is depleted */
  else
/* take cost from parent to sink (rate use of battery of corresponding
   parents)
and studied node own behavior */
    link_cost = energy_metric
    return cost = p−>energy_estimation + link_cost
  endif
```

implementation takes care of transforming the time magnitude from ticks to seconds, a sensor present in the boards allows to get the real voltage value provided by the battery, and derives a value that can transform into a significant metric without burdening memory, and fit into standard RPL control messages. The result from Eq. (1) gives in this case mW per second, indication of how fast nodes are consuming their battery. The logic behind this mode of operation for choosing routes is to obtain a metric that does not only take into account the remaining battery in terms of mWh, but also how fast it is depleting. At a given time, a node with less remaining battery but a slower draining rate can last longer in the long term. In the end, the routes are optimized to choose the slowest battery draining rate possible.

The selection of a new parent (path) is triggered reacting to two different causes: a node has detected some change or irregularity in the network (i.e. a node losses connectivity with parent, a new node joins the network, etc.), or a specified exponential timer expires (this timer's period is short after network changes, and increments as times passes by without changes, for avoiding unnecessary traffic, but still has a top limit to be able to react to undetected changes). Additionally, the implemented O.F. includes a hysteresis mechanism (see Algorithm 3.2), which instructs a mote only to change its parent if the metric difference between current and candidate is high enough, in order to maintain certain network stability. In this case, the configuration used establishes a difference of 1% of battery.

On the other hand, traditionally the metric ETX (expected transmissions) is used to implement an O.F. that achieves paths with best quality, minimizing packet loss. Being N_x the number of packets received by node x, the ETX metric between nodes i and j is calculated as:

$$ETX_{ij} = \frac{N_i}{N_j} \tag{2}$$

In this case, the RFC6719 (The Minimum Rank with Hysteresis Objective Function, or MRHOF) is used, also enabling the recommended option of squaring the ETX value used as metric, which basically will favour good links over short paths (recommended when reliability is the top priority).

Depending on the final application or use case, this ETX metric may still be valid and of interest, so our network can be also configured easily to use an ETX as O.F.

During the experimentation, we compared both options to extract strengths and weaknesses of both configurations, and best practices for their use. The experiments are designed implementing only one O.F at a time in order to compare and validate the expected results.

As application protocol for message exchange we have selected [54]. This protocol allows the implementation of a publish/subscribe paradigm within the architecture, in which the typical client/server schema is changed by a philosophy in which there are components that generate information, and others consume such information. Consumers can indicate which are the contents they want to receive automatically every time a message of this type is generated. This means producers (sensors) and consumers (applications) are all connected to a virtual bus where all the data is shared in live. To achieve this the information contained in a message is catalogued based on a topic. MQTT is agnostic to the content, which means that it does not define the payload, being able to carry any content of interest. For telemetry purposes we've selected the IPSO Smart Objects standard, which defines a common data model for the exchanged data. MQTT + IPSO is a lightweight and simple to implement solution for restrained devices, while offering basic QoS configurations and the best results for real time and telemetry applications, for networks with low number of devices [55].

3.3. Scalability

In every network deployment, scalability is one of the issues to be concerned about. This is even more important when dealing with wireless communications due to the channel characteristics. In this type of networks, end to end delay and packet losses due to collisions are the most critical parameters affected by a growing number of nodes. The MAC protocol and mode, TSCH, uses slotted access in time and frequency domains. This reflects in the possibility of scheduling each node's access to the channel to transmit and receive information: on one hand, collisions are greatly reduced as not all the nodes contest for the channel at the same time, like in CSMA, and on the other hand, by introducing the frequency domain in the scheduling, different nodes can talk at the same time by using different channels, which multiplies the possible connections without interferences with respect to a classic TDMA, and the end to end delay can be bounded, according to application requirements. Scheduling algorithms for TSCH multi-hop networks are not defined by the standard, and only a minimal configuration recommendation for the network to work is proposed. In this sense, the scheduling may need fine tuning to adapt to different scenarios, and they can have direct impact on the operation of the devices, by introducing more control traffic or consume too much of the restricted memory available, so the Deploy&Forget network proposed uses a static scheduling that allows one active slot per network hop (parent nodes in receive mode, child node in transmit), plus one active slot for synchronization and retransmissions, which obtained good results regarding PDR (packet delivery ratio) and avoided desynchronizations of the network. Also, the routing protocol controls dynamically the routes and paths to the sink node, and given that the Energy O.F used balances the battery draining rate, networks with higher number of nodes usually mean more neighbours and parent candidates to optimize the routes. Hence in this sense, the routing is not affected by scalability issues. Nevertheless, the aim or application of the proposed Deploy&Forget network is not oriented to very huge scale deployments, and a limited number of nodes (10 30) are often enough to cover a wide area.

4. Experiment and results

The tests of this Deploy&Forget WSN has been conducted on a real scenario in an open space, but defining an area of deployment that enables forcing meaningful topologies to analyse the energy saving mechanisms during routing, and to prove the stability and robustness that can be achieved in a multi-hop network, to support the "forget" features in steady state operation. The hardware used (see Fig. 5) is a modified Zolertia Re-mote and its CC2538 ARM®Cortex®-M3 with a 2.4Ghz IEEE 802.15.4 radio interface (this hardware also includes a CC1200 868/915Mhz RF transceiver which is not used at this point), programmed with Contiki OS 3.0.

The deployment of the test network benefits from the tools and steps described in Section 3.1 or deployment operation, but this deployment stage is difficult to quantify due to the close relation to human factors involved. The deployment itself will vary depending on the skills of the

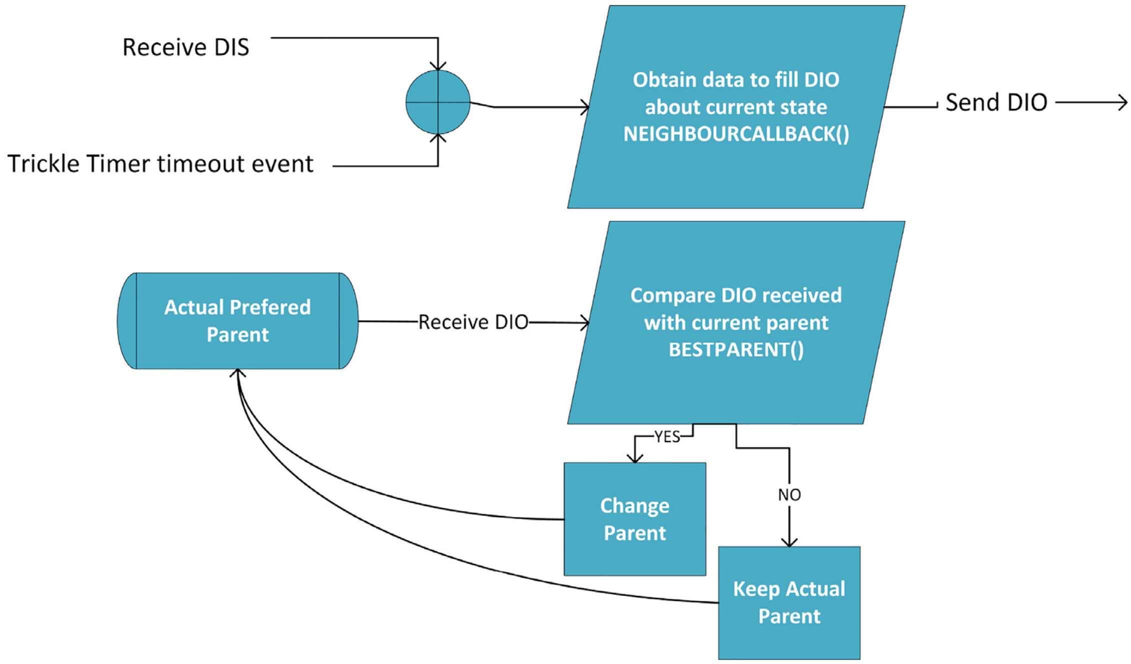


Fig. 8. Flow chart showing routing behaviour according to the energy algorithms involved in the construction of a network topology for the energy optimization on nodes.

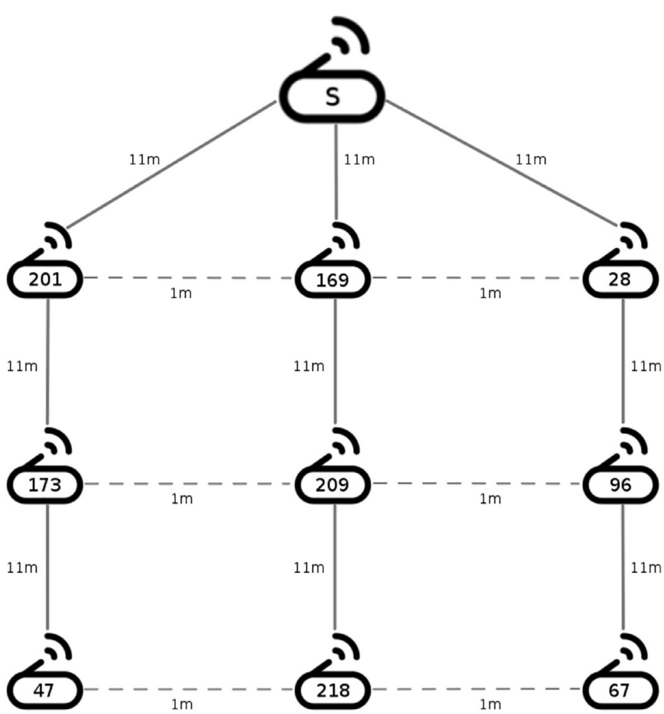


Fig. 9. Network deployment during test.

Table 4
Quality values obtained on set-up the network.

Parameter	1st level	2nd level	3rd level
ETX	[1.0,1.3]	[1.0,1.3]	[1.0,1.3]
RSSI	[−67, −74]	[−67, −74]	[−67, −74]
Neighbors	[2,4]	[2,4]	[2,4]
RTT	10	20	30

person attending the deployment and the scenario characteristics at a given time. The deployment test could be twofold: testing the time it takes an expert to deploy the WSN with the proposed solution or other solutions, and testing the times it takes an expert versus an untrained operator.

As a reference for the reader, after several experiments, average value of 6 minutes has been obtained. This period of time includes the task of power-on of the nodes and location/relocation in points where the optimum were obtained. Others solutions such as those mentioned in the related work require coverage simulations, location planning and using different tools before the deployment. These additional activities suppose extra deployment time before the sensors placement on the test area, and can vary greatly due to several external factors included, making the assessment very case/experiment iteration specific, even for an expert, obtaining too random results, but always higher than those obtained for our solution.

Bearing in mind that the objective is that a person without any technical skills can deploy the network in the same time as an experienced user, comparing the time it would take for a non-expert to deploy the network without any tools, or with some planification tools as proposed in related work, is not possible regarding the experience and skills needed. Trained personnel may be able to react when informed quality is low due to a specific metric, but given that the quality assessment is balanced with different metrics and that changing one may influence the other, prone to confuse other non-experts using the WSN, the deployment tool under study keeps a basic interface.

Therefore, the experimental results section focus on the steady operation and the application of technologies described in Section 3.2. Once the deployment is completely set, the quality of the links remains above a threshold that allows us to assume that the metrics involved in the quality function do not fluctuate enough to require a relocation of any node. Therefore, the quality of all links will remain in a steady state as long as there is no change in the physical topology. The Table 4 shows the values of the different quality metrics for each level during the first moments of operation of the network.

Fig. 9 shows the deployed network, comprising a 10 node mesh network (9 nodes plus the gateway of the WSN). The physical topology is chosen in order to force multi-hop logical topologies, this is, further nodes cannot communicate directly to the sink. Specifically, our test network features 3 hops, validated before launching the experiments after

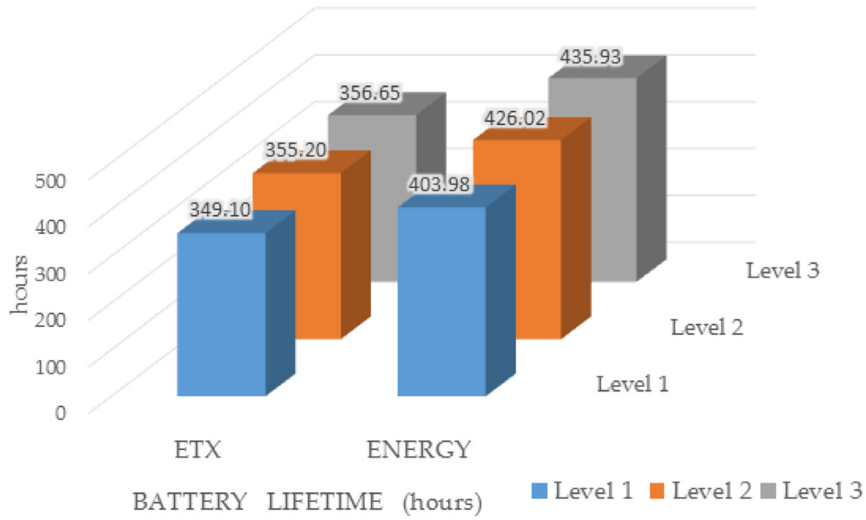


Fig. 10. Battery lifetime achieved during experiments.

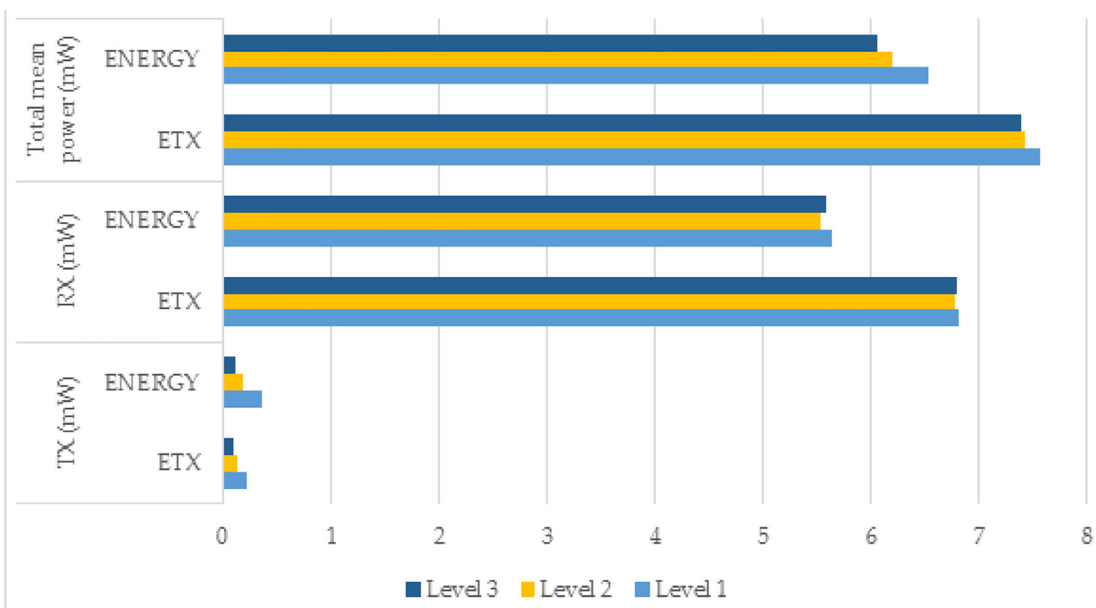


Fig. 11. Relevant power consumption profiles achieved during test.

Table 5
TSCH and communication configuration parameters.

Parameter	Value
TSCH slotframe size	11 slots
Number of Channels	4
Active slots	4 slots
Channels used	15, 20, 25, 26
Data generation period	5 s
Transmission power	0 dBm
ETX (squared) threshold	1.25
Energy threshold	1% faster consumption

Table 6
Hardware elements different power consumption values, defined by current draw.

Hardware element	Current consumption
Radio RX	24 mA
Radio TX	20 mA
CPU idle LPM	7 mA
CPU	1.3 mA

testing different distances and transmission power configurations. Other configurations and hardware related data can be seen in Tables 5 and 6 are selected for achieving the best performance of the network and minimizing packet loss and synchronization issues.

For testing the behaviour of the energy optimization routing policies implemented, a simple application of power consumption data telemetry transmission is used, in order to obtain statistics for the proposed Energy O.F versus the commonly used ETX O.F, and all hardware not involved purely in communication has been disabled (buttons and LEDs).

Fig. 10 shows results in terms of battery life achieved for nodes of each level during the experiments. It can be seen that Energy O.F achieves longer node lifetime. During several experiments, this O.F accomplished up to 15% longer lifetime in first level nodes, and up to 22% longer lifetime for last level nodes. Also, as expected, nodes closer to the gateway consume the battery faster, because they are relaying

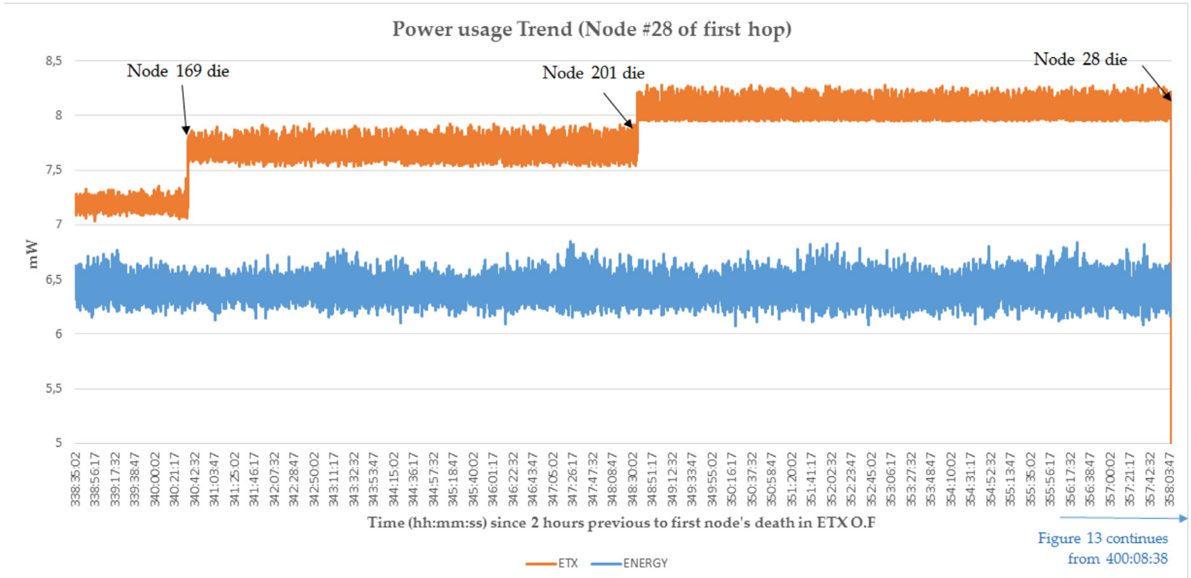


Fig. 12. Power consumption trend for the oldest node of first hop, detailed since 2 h before the first neighbour's battery exhaustion happens, up to the time of death of all first hop nodes in ETX O.F. Experiment.

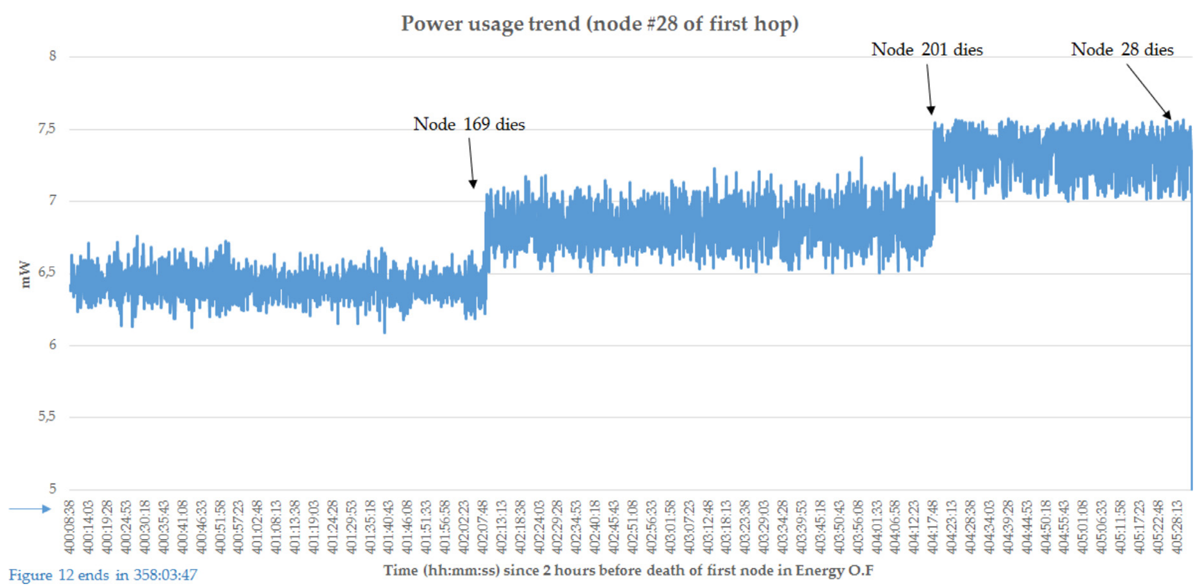


Fig. 13. Power consumption trend for the oldest node of first hop, detailed since 2 h before the first neighbour's battery exhaustion happens, in the case of Energy O.F. Experiment, which happens several hours later than previous figure.

more packets than the other nodes. Following figures show further results that help analyse the operation of the network.

Fig. 13 Power consumption trend for the oldest node of first hop, detailed since 2 h before the first neighbour's battery exhaustion happens, in the case of Energy O.F, which happens several hours later than previous figure.

Looking at Fig. 11, the relevant power consumption actors (transmission, listening and total in mW), for nodes grouped by the level (number of hops to sink), are detailed and it can be derived that even if the Energy O.F. shows higher consumption due to active radio transmissions, it reduces the active radio reception consumption. With the Energy O.F, the traffic is balanced between nodes to try to make them discharge evenly, while with ETX some nodes hold higher traffic load until they die. This behaviour can be observed in Fig. 12 and Fig. 13. This figures show the power usage trend of the last first level node alive, which means the behaviour of nodes when neighbours disconnect can be observed. This reflects in the rising steps in power usage, because when one node dies, the remaining have to relay the traffic load the exhausted one was serving.

Nodes featuring ETX O.F. start failing several hours before than with Energy O.F. On the other hand, the Energy O.F. makes the first node to die much later (around 61 h of difference between first node down in both O.F.) by balancing the power consumption between neighbours, but this means that once one of them dies, the others have a similar low battery left and die shortly after. In fact, for ETX O.F. there is a difference in level 1 nodes death times of around 17 h, while for Energy O.F. this difference reduces to around 3–5 h.

Balancing the battery of nodes adds another complimentary benefit, because maintaining a higher number of neighbour nodes available at all time increases the resiliency of the network, allowing more optional paths for the data to be routed.

5. Conclusions

The technology and solutions proposed are aim to provide an effortless but productive use of Wireless Sensor Networks, encouraging the adoption of WSN based solutions in industrial use cases by overcoming the traditional barriers of low reliability in that type of harsh scenarios. To do this, the solution proposed is two folded. On one hand, facilitates the deployment of the WSN in order to shorten deploy time and avoid the necessity of pre-deployment studies and qualified personnel, which translates in a more time and cost-effective network deployment. On the other hand, use the last state of the art communication protocols and mechanisms, based on deterministic schedules to access the medium, multi-channel support, and smart routing to achieve an optimized, resilient, energy efficient working network that can operate unattended during longer periods of time.

As a future work, the information about energy consumption and quality of a path will be combined to determine the calculation of the routes in an optimal way for the steady operation, choosing paths with more reliability and reduced data loss without compromising the energy autonomy of the nodes and hence the lifetime of the entire network. Experiments and tests with the proposed implementation of the Deploy&Forget WSN show promising results and can help motivate developments to further enhance WSNs adoption and application in industrial and IIoT scenarios.

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