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METIS research advances towards the 5G mobile and wireless system definition

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Abstract

The Mobile and wireless communications Enablers for the Twenty-twenty Information Society (METIS) project is laying the foundations of Fifth Generation (5G) mobile and wireless communication system putting together the point of view of vendors, operators, vertical players, and academia. METIS envisions a 5G system concept that efficiently integrates new applications developed in the METIS horizontal topics and evolved versions of existing services and systems. This article provides a first view on the METIS system concept, highlights the main features including architecture, and addresses the challenges while discussing perspectives for the further research work.

Keywords: 5G; Beyond 2020; METIS; System concept

1 Introduction

In the decade beyond 2020, it will be necessary to support 1,000 times [a] higher mobile data volume per area [1] together with new wireless broadband communication services coming from a plethora of different market segments. These requirements will go beyond the natural evolution of IMT-Advanced technologies, which show the need for a new mobile generation, with certain disruptive features with respect to legacy technologies. Although there is no unanimous agreement so far, this seems to be the birth of the Fifth Generation (5G) technologies.

Mobile and wireless communications Enablers for the Twenty-twenty Information Society (METIS) is an integrated research project partly funded by the European Commission under the Framework Programme 7 (FP7) research framework [2]. METIS aims at laying the foundation for the beyond 2020 wireless communication systems by providing the technical enablers needed to address the very challenging requirements foreseen for this time frame. Such a system has to (1) be significantly more efficient in terms of energy, cost, and resource utilization than today's systems, (2) more versatile to support a significant diversity of requirements (e.g., payload size, availability, mobility, and Quality-of-Service (QoS)) and new scenario use cases, and (3) provide better scalability in terms of number of connected devices, densely deployed access points, spectrum usage, energy, and cost. The technical goals derived from these main objectives for METIS [3] are:

- 1,000 times higher mobile data volume per area,
- 10 to 100 times higher typical user data rate,
- 10 to 100 times higher number of connected devices,
- 10 times longer battery life for low-power devices,
- 5 times reduced end-to-end (E2E) latency, reaching a target of 5 ms for road safety applications.

The key challenge is to meet these goals at a similar cost and energy consumption as today's networks.

From the point of view of METIS, a complete redesign of the Internet is discarded. Since the current Internet has become so large, the implementation of new architectural principles is impractical due to the commercial and operational difficulties it poses. Some concepts such as information-centric networking (ICN) [4] are considered unrealistic, although some of its fundamentals, as the universal caching, have to be taken into account in order to efficiently distribute the traffic load in the network. If 5G includes a revolution, it will come from the radio interface design, where some new paradigms under discussion represent a radical change in the current view we have on mobile networks in addition to some fundamental

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changes in the mobile core functionalities, e.g., driven by new concepts of mobility.

In this challenging task, the METIS project has defined a set of five essential Horizontal Topics (HTs) to be consolidated into a single 5G system concept. These HTs are direct device-to-device communications (D2D), massive machine communications (MMC), moving networks (MN), ultra-dense networks (UDN), and ultra-reliable communications (URC) [5].

The present paper discusses a number of design choices and features that change the way we understand mobile networks. It is worth noting that this article represents the common vision of the set of network operators, industrial, and academic partners that work together in the METIS project. It does not provide the final solution, but highlights the most promising research lines, which combine efforts in common directions in the project.

In the next section, we present the METIS view on the key functional and technical features of the next generation mobile system, detailing the network architecture in Section 3. Section 4 highlights the technical enablers and research challenges that address the technical goals of the project for 5G. We finally draw the main conclusions of the paper in Section 5.

2 Main features of the 5G system

All mobile generation changes so far have been based on a new radio link concept and have provided an increase of the peak data rate of approximately two orders of magnitude. The 5G system must meet the requirements of increased rate and capacity needed beyond 2020 and requirements on reduced latency. However, the integration of new services and application areas is as important as increasing rate and reducing latency. The 5G system will be the wireless enabler of the Internet of things and, in addition to human users, must cater to different machine-type communications with widely different requirements. All together, the range of requirements will increase as compared with current mobile broadband (MBB) technologies. For instance, the data rates will range from very low for sensor data to very high rates for high-definition video. Latencies will range from extremely low for safety-critical applications to applications where latency is not really a constraint. Packet sizes will vary from small for, e.g., smartphone applications to large for, e.g., file transfers.

By using a system architecture that supports also D2D communication and UDN deployments, METIS foresees a multi-Radio Access Technologies (RAT) system that efficiently integrates fundamental building blocks as:

- *Evolved mobile broadband (eMBB)* will provide high data rates and low latency communications improving quality of experience (QoE) for the users. As depicted in Figure 1, eMBB will go much beyond current MBB solutions.
- *Massive machine communications (MMC)* will provide up- and down-scalable connectivity solutions for tens of billions of network-enabled devices, where scalable connectivity is vital to the future mobile and wireless communications systems.
- *Vehicle to Vehicle, Device and Infrastructure (V2X) and driver assistance services* require cooperation between vehicles and between vehicles and their environment (e.g., between vehicles and vulnerable road users over smartphones) in order to improve road safety and traffic efficiency in the future. Such V2X services for MNs require reliable communication links that enable the transmission of data packets with guaranteed maximum latencies even at high vehicle speeds.
- *Ultra-reliable communications (URC)* will enable high degrees of availability. It is required to provide scalable and cost-efficient solutions for networks supporting services with extreme requirements on availability and reliability. Reliable service decomposition provides mechanisms for graceful degradation of rate and increase of latency, instead of dropped connections, as the number of users increases.

To address these challenges, new flexible air interfaces, new possible waveforms, and new multiple access schemes, medium access control (MAC), and radio resource management (RRM) solutions (e.g., [6,7]), and signaling protocols must be investigated to discard the idea that physical layer improvements are already close to their upper limit. However, the foreseen steps towards the ubiquitous high bit-rate services pass mainly by managing multi-cell and multi-user

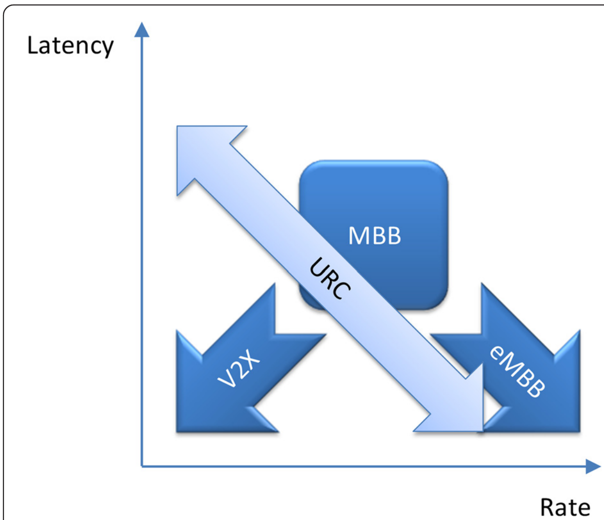

Figure 1 Extension of requirements as compared with current MBB technologies.

MIMO together with new paradigms of network deployment with multiple RATs and multilayer networks.

The key supporting enablers include:

- *Dense and dynamic RAN* providing a new generation of dynamic radio access networks (RANs). The term RAN 2.0 could be also used referring to this flexibility of the RAN.
- *The spectrum toolbox* contains a set of enablers (tools) to allow 5G systems to operate under different regulatory and spectrum sharing scenarios.
- *Flexible air interface* incorporating several radio interface technologies operating as a function of the user needs.
- *Massive MIMO*, in which the number of transmit and receive antennas increase over an order of magnitude.
- *New lean signaling/control information* is necessary to guarantee latency and reliability, support spectrum flexibility, allow separation of data and control information, support large variety of devices with very different capabilities, and ensure energy efficiency.
- *Localized contents/traffic flows* allow offloading, aggregation, and distribution of real-time and cached content.

2.1 Dense and dynamic RAN

There is a consensus that future traffic demand will require a high density of a variety of access nodes [8,9]. UDN refers to this new paradigm of wireless communication network, which includes network cooperation and ultra-dense availability of access points. Nomadic and moving nodes, mounted on a car, bus, or train, can provide connectivity to users in their proximity and increase data rates by reducing the radio distance to the nearest access node. D2D communications will guarantee the ubiquity of high-quality services and offload the infrastructure transport network [10].

Network densification has been used for wireless evolution during last years and will continue this trend in the next decade [11]. Even some authors have speculated about a 10 year-out situation in which the number of access points could surpass that of active users [12]. UDNs present serious challenges in terms of mobility support, interference management, and operation (cost, maintenance, and backhaul).

In the context of mobility in UDNs, the classical approach of user-initiated mobility management based on measurement reports poses a severe problem, provided the increased signaling and device measurement overhead. Therefore, current trends of self-configuration of handover parameters [13] must be revisited to adapt to the 5G scenarios with random layout and a variety of cell ranges. Moreover, mobility prediction will be fundamental to initiate the handover with enough time in advance.

On the other hand, from a radio planning point of view, the disparity in transmission powers in heterogeneous deployments invalidates traditional DL-based cell association mechanisms. Cell range expansion (RE) seems to be the solution to overcome this problem. An additional benefit is a more effective offloading from the macro layer to the small cells [14]. Whereas RE partially compensates UL interference issues, DL interference is increased at the new small-cell edge due to the DL transmissions from the macro cell to other users. For this reason, 3GPP has already introduced improvements in the inter-cell interference coordination mechanisms of LTE-A [15,16]. To sum up, higher densification is nowadays being pursued by applying patches to the old ideas, and this has reached its limit with the current densification values. Given this, it is clear that new system designs are needed for 5G networks to tackle the root of the problem, that is, the huge imbalance between the nature of mobile devices and cell infrastructure. This leads to the idea of asymmetric user association and the fact that UL and DL should be treated as independent networks. This way, the unity of the cell is broken, and UL and DL are totally decoupled and served by different access points [17].

This decoupling philosophy is also being proposed in the 3GPP for the splitting of control and user planes (C/U-plane) [18]. Given this, it is possible to transmit the C-plane, and consequently HO messages, from a stable macro cells whereas the U-plane is transmitted from the closest small cell (see Figure 2). The recent work by Li Yan et al. argues about the suitability of this approach for future 5G networks and provides interesting insights on practical aspects [19].

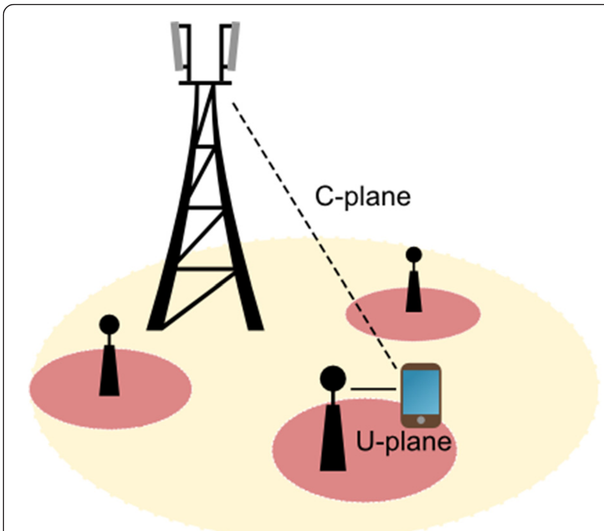

Figure 2 Decoupling of control and user plane in UDN.

Another important problem is the provision of high-quality services within vehicles on the move. One possible solution to address the problem in the future will be the deployment of a relay within the vehicle. The relay can be connected to the vehicular rooftop antenna, in order to establish a robust (relay/backhaul) link to the cellular network. On the other hand, relays allow for optimum coverage conditions inside the vehicle and a certain control of the consumed resources through the usage of closed subscriber groups. Since the use of a relay eliminates the vehicle penetration loss (VPL) and provides additional antenna gains due to better characteristics of the rooftop antenna, this solution improves significantly the link budget [20] and allows for a more efficient resource utilization of the cellular network. However, in current LTE networks, an additional overhead burden due to signaling exists (around 10%), and therefore, the benefit from the use of those relays is to be demonstrated.

Concerning the research on mobile relaying, most studies focus on network architecture aspects [21-23], mostly on the basis of its usage in LTE/LTE-Advanced (see Figure 3). In this case, the mobile Relay Node (RN) is connected as a regular user to a base station, known as donor e-Node B (DeNB). Moreover, regarding the system performance assessment, the expected gain derived from the usage of moving relays is investigated, for instance in [23]. Other studies evaluate the impact of deploying mobile femtocells from the point of view of spectral efficiency and signaling overhead considering opportunistic use of spectrum and scheduling [24,25]. Current research on the integration of moving networks into 5G focuses on improved procedures, channel prediction, reduced signaling, and optimum backhauling [26].

In order to reduce the link distance, the 3GPP initiated in Release 12 the study item on the use of device-to-device (D2D) communications under the name of proximity services (ProSe) [27]. The 3GPP defines D2D communication as a type of communication between two nearby UEs in which there is not any routing through the core network. ProSe in LTE-Advanced is also aimed at critical situations and must be functional when cellular networks are not operational.

In 3GPP, ProSe studies focus on two aspects, namely D2D discovery, also known as proximity detection, and D2D communication. D2D discovery aims at identifying other neighbor UEs for possible D2D communication, whereas D2D communication is the actual direct link for data transfer. For both operations, it is of paramount importance to design and efficient control plane to synchronize terminals, ensure radio link security, and keep track on the mobility during the communication phase. Figure 4 shows the current approach for this functional split in 3GPP. More details on this control plane design for D2D communications can be found in [28] and references therein.

D2D discovery is usually localized in static resources while D2D communications should use resources in an opportunistic manner, only when necessary. However, this communication mode may introduce severe interferences into the overlaying cellular network, which results in the need for dynamic and network-controlled radio resource allocation to the D2D link [29]. Several methods have been proposed to deal with this coexistence [30]. Feng et al. [31] proposed a resource allocation scheme for D2D communications operating in opportunistic manner focusing on the guarantee of QoS requirements in the heterogeneous network. On the other hand, Xu et al. in [32] designed an iterative auction for resource allocation whereas Lingyang et al. proposed a game for this resource allocation [33].

Beyond these concepts, METIS foresees a new generation of dynamic RAN, referred to as RAN 2.0. Following an analogy with the Web 2.0 concept, in RAN 2.0, the user devices can become active entities of the RAN, in addition to existing network nodes (see Figure 5). This user-centric network (UCN) is a new paradigm of wireless networking in which user devices will temporarily take over the role of access nodes for other users, e.g., to guarantee the ubiquity of high-quality services. This multi-hop cellular solution

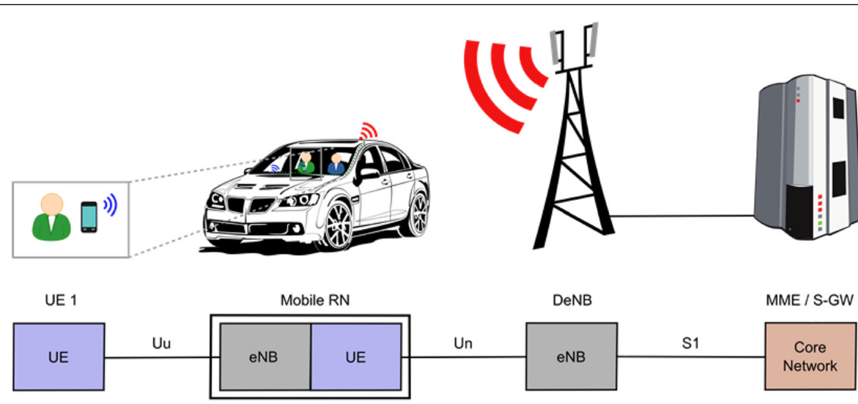

Figure 3 Current LTE-A architecture for moving networks.

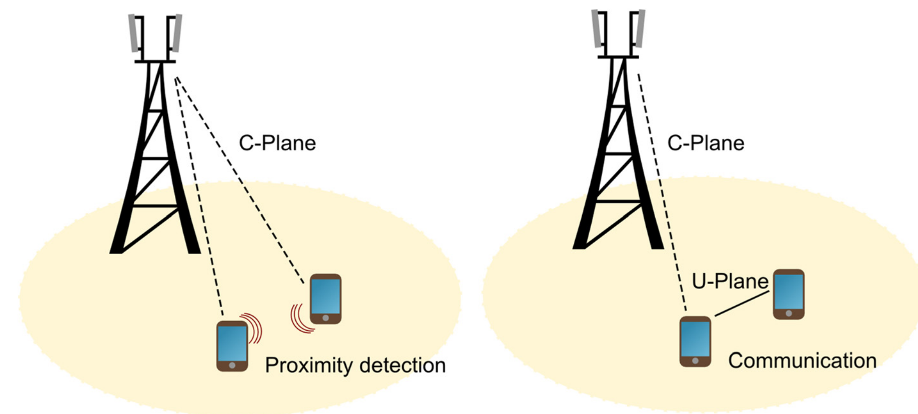

Figure 4 D2D approach in 3GPP.

opens the door for an interconnection of devices that collaborates within a group of users they trust searching for mutual benefit, similar to a social network. RAN 2.0 implies a flat architecture from service point of view resulting in low latency. It is also accompanied by an agile infrastructure support, since *ad hoc* and smart coordinated setup of networks is expected under this service/user-centric model. Finally, RAN 2.0 also entails a different distribution of intrinsic functions that can be executed in any node depending on its hardware and software capabilities.

This concept has been also discussed under the name of Spontaneous Smartphone Network (SSN) [34], since it depends heavily on the network functionalities provided by the smartphone operating system. All current operating systems have tethering capabilities to route packets from the cellular link to another short-range wireless interface like Wi-Fi, but operating at IP layer. However, this tethering characteristic is not working transparently to the end user, lacks adequate security control procedures for the pairing and ciphering of the information, cannot make use of cooperation and does not support self-organizing principles to manage the links, and ensures minimum interference and dynamic configuration to face unexpected changes in the channel conditions. Current research is focusing mainly on the dynamic configuration of the network [34] and on security [35], likely the main showstopper of this 5G enabler.

2.2 The spectrum toolbox

Of course, new spectrum bands must be identified in the International Telecommunication Union-Radio-communication (ITU-R) Radio Regulations to support the increase of traffic demand. In this direction, the worldwide allocation of a number of bands to International Mobile Telecommunications (IMT) technologies is on the agenda for the next World Radio Conference 2015 (WRC-15). Figure 6 shows

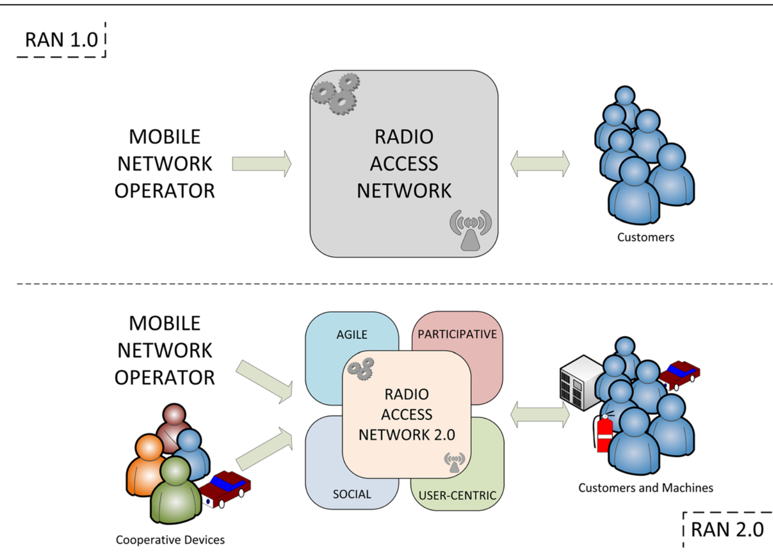

Figure 5 RAN 2.0 concept.

the possible candidate bands for IMT under WRC-15 agenda [36]. Despite the fact that the current practice of predominantly using dedicated licensed spectrum will remain the main stream, new regulatory tools and approaches of sharing the spectrum and optimizing its use must be devised [37]. On the other hand, the coverage of higher frequency bands may be limited, for example, to hot spots or dense areas. MMC and low latency on the other hand are required in wide area coverage.

For its special relevance, we need to mention here the use of millimeter wave (mmW) communications (30 to 300 GHz). Although conventionally beyond 6 GHz spectrum has been discarded due to its high attenuation, recent research points towards its potential use for backhaul, D2D and even cellular communications [38]. Moreover, semiconductor technologies are getting mature enough to reduce cost and power consumption of wireless communications in these new bands [9]. On the other hand, propagation problems can be tackled thanks to the use of massive MIMO and the resulting huge antenna array gains. Recent measurements at 28 and 73 GHz in New York University [39] have revealed that, with an accurate beam-selection, signals can be detected at a distance between 100 to 200 m even in the absence of line of sight (LoS). This result has motivated an increased interest of the wireless community on cellular mmW communications. This proposal still requires intense research to overcome its main challenges, that is, the support of mobility for the optimum beam selection and the design of transmission techniques that alleviate the need for feedback on channel state information (CSI) to the transmitter [40].

2.3 Flexible air interface

The variety of spectrum options leads to a system concept incorporating a number of air interfaces, each optimized for a specific set of use cases. The air interfaces including their protocol stacks will be configurable to a great extent in order to meet the diverging traffic demands of different applications. They will be integrated in smart and dynamic wireless software-defined networks (SDNs), [41], which means a generalization of the software-defined radio (SDR) concept [42]. In contrast to existing cellular systems, sophisticated technologies such as ultra-dense access node deployments and multi-node coordination will be supported to achieve optimum performance [43]. Frequency division duplex (FDD) and time division duplex (TDD) systems are expected to further coexist, while TDD-only operation is expected to become more widely used in higher frequency bands. Full duplex is under investigation, but its use will probably be restricted to low-power radio nodes, e.g., for indoor and outdoor small cell applications (including in-band wireless backhaul). Evolved versions of existing communication systems need to be efficiently integrated.

2.4 Massive MIMO

In massive MIMO, we see a very large antenna array at each base station and in general an order of magnitude more antenna elements as compared with conventional systems. Massive MIMO can be used for a more efficient backhaul wireless link or even for the access link, in which a large number of users are served simultaneously. Here, massive MIMO is interpreted as multiuser MIMO with lots of base station antennas. Although massive MIMO has been historically associated with the use of beamforming, new trends are arising towards the use of spatial multiplexing techniques in conjunction with beamforming to make the most of the richness of the channel [44]. With the incorporation of nomadic and moving nodes, sophisticated MIMO solutions can be implemented in a vehicle node, making advanced multi-user MIMO feasible.

Massive MIMO can increase system capacity by a factor of 10 and, at the same time, increase the energy efficiency on the order of 100 times [45]. This boost in capacity comes from the use of aggressive schemes of spatial multiplexing whereas the improvement in energy consumption is due to the concentration of power in very concrete space regions.

The main concern when the concept of massive MIMO comes to real deployments relies on the factor form of an antenna of hundreds of element. In this sense, the concept of massive MIMO is intrinsically related to its use in high frequencies, e.g., in the centimeter wave (cmW) and mmW bands, which will reduce the size of each of these elements [46]. Many different configurations for the real antenna arrays can be used, as depicted in Figure 7, ranging from distributed antenna systems, to planar and cylindrical arrays.

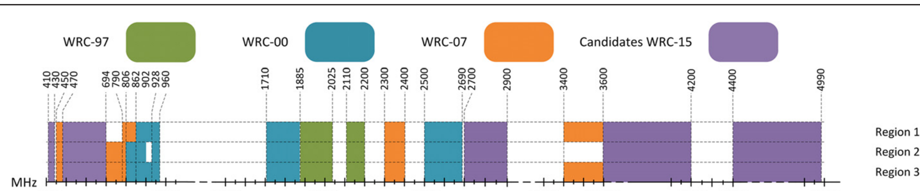

Figure 6 Possible candidate bands for IMT under WRC-15 Agenda Item 1.1.

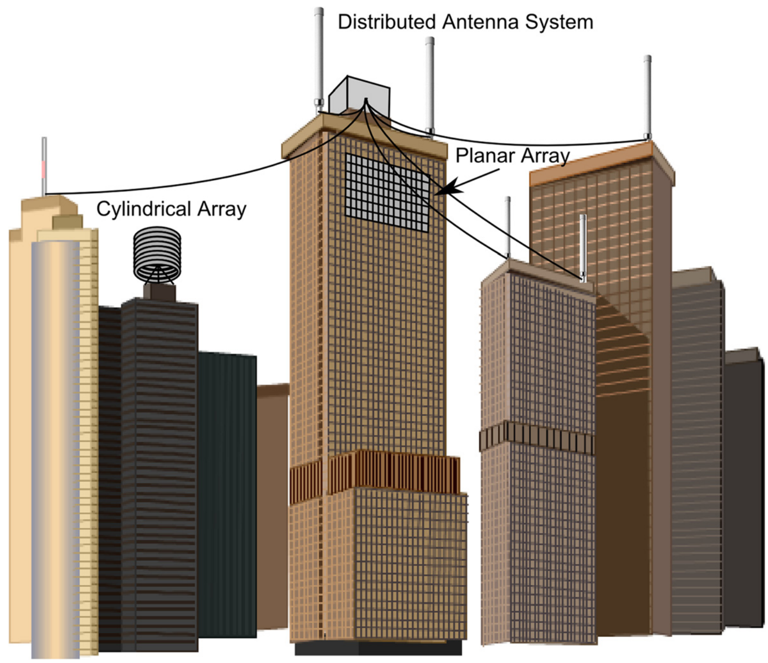

Figure 7 Different alternatives for the deployment of massive MIMO, including distributed antennas, planar arrays and cylindrical arrays.

Extensive use of beamforming will be an essential tool to improve link budgets. In addition, spatial multiplexing using massive MIMO techniques at mmW along with small cell geometries seems to be a symbiotic convergence for throughput boost [47]. The success of these techniques might be threatened by impairments in the transmission and reception chain, such as hardware limitations and lack of appropriate channel knowledge. This will be a matter of exhaustive research in the coming years. Another important problem with massive MIMO is pilot contamination. The number of orthogonal uplink pilot sequences is limited and depends on the coherence interval, which is very small at higher frequency bands. When reusing the same pilot from two transmitters, the negative consequences derived from interferences are referred to as pilot contamination. A beamforming scheme based on the channel estimates obtained from contaminated pilots results in interferences directed to those transmitters using the same pilot [48]. Therefore, new transmission schemes based on blind channel estimation are to be designed for the next generation mobile [49].

2.5 New signaling/control information

The control information/signaling needs to be fundamentally readdressed in 5G systems to accommodate the different needs of different services. In order to facilitate the spectrum-flexible multi-layer connectivity for eMBB services, a separation of control and data plane can be used. One example is mmW communication, where the control channel can be established at lower frequencies. Another example is network-controlled communication of content via D2D connection, offloading the cellular network. More generally, the user centricity of 5G systems shown in Figure 5 induces separation of control and data planes.

MMC, on the other hand, benefits from a closer coupling between the control and data plane, even integration of the control and data planes. MMC also requires optimized sleep mode solutions for battery-operated devices and mobility procedures with a minimum of signaling and measurements.

URC requires guaranteed latency and reliability. Here, it should be noted that the successful reception of control information is a prerequisite for communication of the data part. For very reliable, low-latency V2X connection, the device discovery can be assisted by the wide-area network. The increasing number of network nodes requires lean signaling for energy performance boost.

Another aspect that requires further attention is security. In the sensible case of D2D communications, the wide-area system shall provide security parameters to both communications links based on the internal credentials of the users. This network-assisted security establishment is a challenging issue in the development of D2D communications.

2.6 Localized contents and traffic flows

One of the main goals of METIS is to reduce current E2E latency performance to less than 5 ms. However, the delay budget analysis of legacy technologies reveals that most of the delay comes from the Internet and the core network parts of the E2E connection. Therefore, localized traffic flows, including data traffic offloading, aggregation, caching, and local routing, contribute to meeting this target.

The network operator improves the user experience by providing, e.g., authentication and security features while reducing the load on the data transport. In this framework, context information and network assistance for D2D discovery are of paramount importance to enable such direct communication.

In MMC, the use of concentrators acting as local gateways could allow direct communication among sensors located in capillary networks without the need to reach the core network gateway. For MMC, the localized traffic flows allow low-power access to the network. The network edge nodes can provide aggregation and information fusion of sensor data reducing the transport load and provide local added information value. Further, the necessary context information for MMC operations can be stored locally.

For delay-sensitive services, e.g., road safety applications, it is necessary to turnaround the traffic flow and perform critical computations close to the user to meet the latency constraints of less than 5 ms.

Moreover, the concept of caching could be shifted to the network edges, reaching access nodes or even the own devices that could act as proxies in case of having the requested content in the memory [50].

3 Flexible network architecture for 5G

The 5G architecture development is driven by three key aspects, namely, flexibility, scalability, and service-oriented management. All of these three aspects are complementary to each other such that the diverse set of 5G technologies which aim to fulfill broad range of service requirements can be efficiently supported. Flexibility is the core aspect to enable dynamic configuration of the necessary network functionalities for the efficient realization of a target service and use case. Furthermore, the future-proof architecture shall be flexible enough to handle diverse requirements of the use cases and services that we foresee today and the ones that may emerge in the future and cannot be anticipated now. On this basis, scalability will be assisted by flexibility to fulfill the requirements of extremely contradicting services, e.g., MMC verses multi-user ultra high definition (UHD) tele-presence.

As addressed above, the new generation of RAN networks envisaged for 5G needs to efficiently handle multiple layers and a variety of air interfaces in the access and the backhaul domains. They have to control and cope with the dynamics of traffic, user behavior, and active nodes involved and need to be able to differentiate a larger variety of QoS characteristics, such as ultra-low latency traffic, ultra-reliable communications, and broadcast traffic. SDN, Network Function Virtualization (NFV) [51], and advanced self-organizing network (SON) technologies will play an important role in the implementation and control of the network functionalities, in particular, to improve scalability and reliability as shown later in this paper with respect to achievement of METIS goals.

The generic METIS 5G network architecture, as sketched in Figure 8 from the topological point of view, must accommodate a number of technical enablers and communication paradigms while taking into account existing and emerging evolutionary and revolutionary architectural trends. The network topology will comprise various flavors of Cloud-RAN (C-RAN) [52], traditional access nodes as well as new virtual access nodes where the fixed-cell concept disappears in favor of device-centric communications. Traditional access nodes are the ones that we have today with the hardware and software components existing together, e.g., dedicated hardware implementations of base stations. The virtual

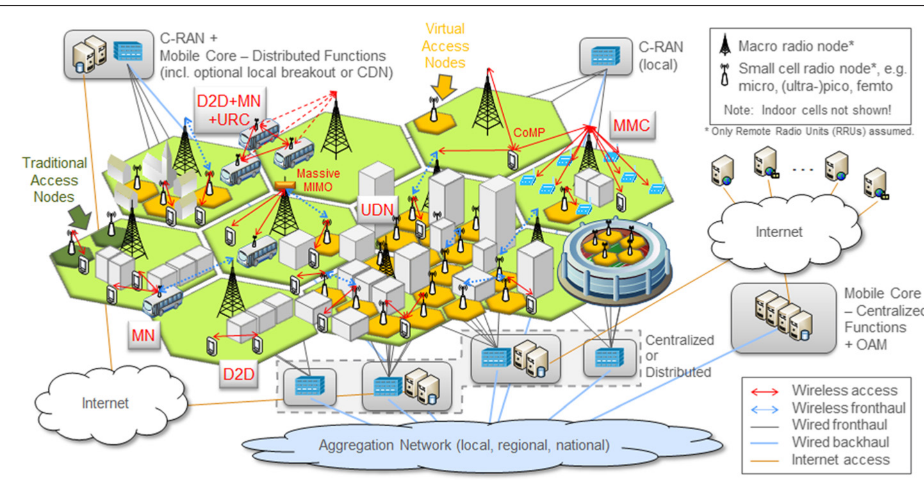

Figure 8 Generic 5G network architecture (high-level topological view).

access node is a new notion anticipated for 5G mobile and wireless communications networks, where the functionalities at an access node will be run by various virtual machines that can be modified or extended based on a need basis of the services and/or use cases to be supported.

Moreover, 5G network architecture will also be scenario and use-case specific, e.g., it may be different in areas with low user density compared to deployments in ultra-dense areas, such as Mega-Cities.

Implementation of radio network and service functions in C-RAN environments will simplify the mapping of SDN and NFV features (known from core function virtualization in data centers) to the RAN. It also increases flexibility with respect to integration of decentralized core functions in C-RAN processing units like local mobility management, local breakouts, and content delivery networks (CDNs) with caching capabilities [50]. Due to centralized processing and minimum delay among baseband processing units (BBUs), C-RAN environments allow simplified clustering of cells for joint RRM and interference coordination (including coordinated multipoint transmission/reception (CoMP)). Dependent on network infrastructure availability of the mobile network operator and delay limitations set on back-/fronthaul links [b], e.g., by CoMP schemes, C-RANs can be deployed in a distributed or more centralized way, which differentiate especially in terms of the number of contained BBUs (realizable via virtual machines on general purpose processors, possibly with support of hardware accelerators for dedicated physical layer computing tasks). Nevertheless, the BBU number of a local C-RAN can be also high in case of UDN, e.g., for a stadium scenario.

A first consideration of the main functional building blocks to appear in the METIS 5G RAN architecture from the logical point of view is shown in Figure 9. Flexibility shall enable a dynamic configuration of the necessary network functionalities in order to fulfill the requirements of a target service. This can necessitate new or tailored functionalities that will be made available on-demand based on the capabilities, such as processing and memory, of the network elements. On this basis, the functions may be updated or enabled on different time scales and spatial dimension. For example, a machine may be updated by cluster-head functionality when there are at least a minimum number of other machines in the proximity, and the candidate cluster-head machine has the capabilities of running that functionality. The Service Flow Management, as depicted in the logical view of architecture, has the task of analyzing the services and outlining the requirements for data flows through network, which will be orchestrated by the Function Coordinator. We note that to realize such flexibility end-user devices, e.g., nomadic nodes, D2D relays, and MMC gateways, are to be integrated as network elements. Function Coordinator has an interface with Function Agents by which it can configure the Base-Band Elements (BBEs) and core network elements (CNEs) based on the service requirements, also known as service orchestration, and forms the service chain. For example, addition of new functions and updates of the existing functions at BBEs and CNEs are performed by the Function Agent considering the configurations received from the Function Coordinator. Here, service requirements are determined by the Service Flow Management. Wireless SDN (WSDN) Controller sets up the service chain on the physical network infrastructure taking into account the configurations orchestrated by the Function Coordinator. WSDN Controller then constructs the data plane processing for the

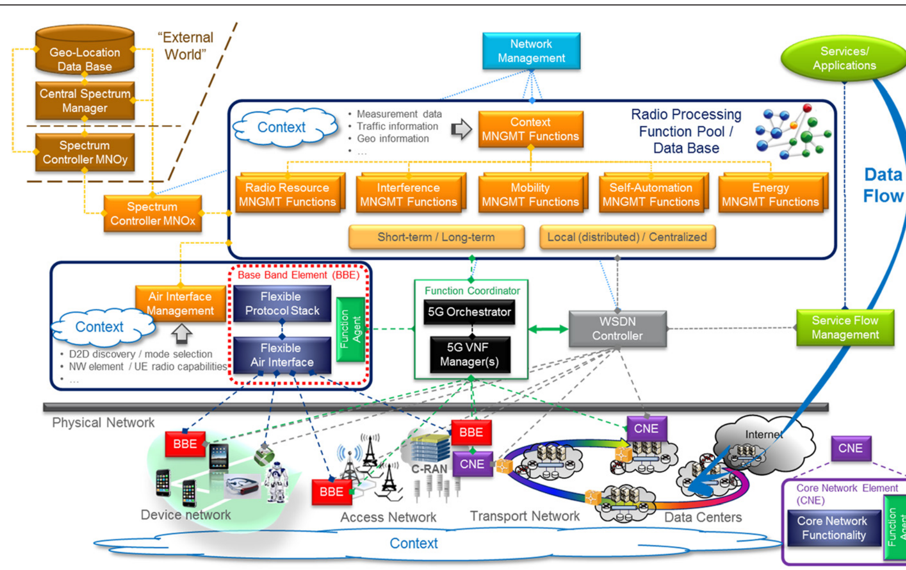

Figure 9 Generic 5G network architecture (high-level functional/logical view).

data flow, i.e., it builds up the connections for the service chain of CNEs and BBEs in the physical network through which the data flow passes. Accordingly, WSDN Controller configures the routers/switches (i.e., has interfaces to routers/switchers) also by factoring in radio-specific functionalities like resource scheduling and mobility management. It is worth noting that conventionally C-RAN infrastructure comprises BBUs. This corresponds to BBEs in the envisioned logical architecture. Nevertheless, thanks to the flexibility, which is anticipated for 5G, some core functionalities can also be moved to C-RAN. Therefore, C-RAN can compromise multiple BBEs as well as CNEs as depicted in Figure 5.

The envisioned architecture will provide the necessary flexibility to realize efficient integration and cooperation of functional blocks according to the individual service and network function needs of the HTs as well as functions for future evolution of existing cellular and wireless networks. The functions can be flexibly modified, tailored, and created by the Function Coordinator (consisting of 5G NFV Orchestrator and 5G virtual network function (VNF) Managers) according to the data flows and can be moved to the relevant network elements on-demand. In this regard, the context information, which is collected from the whole network, will be efficiently utilized by management functions. The architecture is based on WSDN approach to enable on-demand creation of customized virtual networks using shared resource pools and allowing effective service-adaptive decoupling of control and data plane in order to optimize routing and mobility management across the whole service transport chain. From the perspective of the end-to-end flow, even protocol stacks will be optimized and customized via software according to the required services and the network topology, i.e., the protocol stack becomes more and more a set of functional building blocks flexibly/dynamically combined on-demand to fulfill the very specific tasks for a certain service. On this basis, BBEs comprise flexible protocol stack, flexible air interface, and Function Agent. Moreover, it is worth noting that WSDN Controller can also be virtualized running as a VNF with its Element Management System (EMS) & VNF Manager [53].

In contrast to present 4G, certain functionalities of the user equipments (UEs) may be partially controlled by the operator, e.g., for D2D relaying. Furthermore, not only do the UEs connect to the network, but also a wide range of devices, such as, sensors and robots, will co-exist, and the operator may have further degrees of freedom to coordinate the functionalities of these devices. It has to be noted that flexibility may be limited by capabilities of the network elements involved, such as sensors, which may not be updated with all new functionalities, e.g., due to hardware limitations.

Especially for operators with both fixed and mobile network infrastructure, cost reduction in future deployment stages is of great importance. For reuse of common network infrastructure on transport and access layer (Fixed-Mobile Convergence (FMC)), WSDN and NFV are, as well, seen as the key enablers [54] allowing multi-operator network infrastructure and resource sharing in a cost-optimized way. The integration of joint core functionalities belongs to the next steps towards FMC.

An exemplary use case is described in the following. The motivation is to enhance the user experience of an extremely high density of active users and machines in an area where normally the mobile access network nodes are sparsely deployed. The challenge is then to fulfill the requirements of such a massive connectivity of a mixture of eMBB and MMC devices for a certain time period by the network that is highly under-dimensioned for such a use case. Within the framework of the envisioned flexible architecture, service flow management determines that there is an over-flow of mixture of services to be provisioned to massive number of devices and triggers the Function Coordinator regarding this situation. The Function Coordinator (here 5G Orchestrator) in turn updates the service chain to handle these requirements. One solution to tackle the signaling congestion is to perform clustering mechanisms where a cluster head coordinates the scheduling of a group of devices. In this regard, Function Coordinator (here VNF Manager) commands the Function Agents of the selected cluster heads (selection can be performed by the Context Management Entity according to the collected context, e.g., device capabilities reported by Function Agents) in the target region to install the cluster-head functionality in the BBEs of those selected cluster heads. The functionality definition is taken from the Radio Processing Function Pool via Function Coordinator (here 5G Orchestrator) and Function Agents. It is worth noting that the cluster head functionality is only utilized for a given time period when the service is required. Due to limited machine capabilities, e.g., small memory, such cluster head functionality, may be removed depending on the service and energy efficiency requirements. Based on the input from Function Coordinator (here 5G Orchestrator), the WSDN Controller can now perform the re-routing of the data flows according to service chain in line with the updated network topology.

Although in the envisioned flexible architecture, there are additional logical entities introduced, which are needed to enable the anticipated flexibility, compared to today's network architecture, there is a general consensus that adopting these architectural trends has various advantages in terms of cost savings (see, e.g., [51]). For instance, a virtualized network enables faster service provisioning, i.e., increased speed of time to market, and extension of the "classical" service portfolio to new offerings for, e.g., 3rd party connectivity providers (XaaS incl. network sharing), which implies revenue increase for the operators as the impact on the hardware deployments is minimized. As instead of dedicated hardware implementations, commercial-off-the-shelf hardware can be utilized, a better capital efficiency can be reached. Along with the cost savings, better optimization of the network resources can contribute to the energy savings in the network, which is in turn coupled with the cost savings, as well. It is worth noting that this trend is already ongoing on the fixed network side [55], and this vision for 5G mobile network environment can create synergy among fixed and mobile networks.

4 Meeting the METIS goals for 5G - Research challenges

In this section, we briefly discuss the primary methods envisaged for the main features of the 5G system concept that can contribute most beneficially to achieve the METIS goals stated at the beginning of this paper.

4.1 1,000 times higher mobile data volume per area

The primary methods to address this goal are to use more frequency spectrum, to use more network nodes, and to enhance network performance and spectral efficiency.

4.1.1 Use more frequency spectrum

Both higher data rates and higher data volume require access to more frequency spectrum for mobile communications. As stated before, in WRC-15, it is expected that clearly more spectrum will be released for mobile communications. This new spectrum lies in the frequency range between 300 MHz and 6 GHz. However, for the future 5G system, these new spectrum opportunities will not be sufficient. Additionally, the release of new spectrum in the mmW bands was postponed to WRC-18.

Moreover, new spectrum access schemes are being considered such as Licensed Shared Access (LSA) [56], which would allow using further spectrum for mobile communications especially in higher frequency bands in a more flexible way. Accordingly, research is conducted on further novel spectrum access schemes, e.g., for coordinated spectrum sharing between different UDNs, supporting network densification as addressed below.

Also, wireless local area network (WLAN)-type systems [57] operating in the unlicensed bands, such as the ISM and U-NII bands at 2.4 and 5 GHz, as well as the 60 GHz band, can be more tightly integrated.

4.1.2 Use more network nodes

Densification of networks by deploying more nodes is already applied today with femto or pico cells providing local connectivity for increased capacity in addition to the macro cells in the wide-area. This trend is expected to continue, where the small cells can make use of higher frequency bands, such as the 3.5 GHz bands or the mmW bands. The use of TDD with higher frequencies can become more prominent as compared with 3G/LTE today. The different network layers/cell hierarchies and RATs are to be integrated by means of smarter networks. Dedicated implementation solutions such as distributed RRUs can be developed for specific deployments such as for providing coverage of very crowded places, e.g., stadiums and events. To this end, intensive research is conducted to support MN and UDN, e.g., solutions for in-band backhaul, where the access and backhaul share the same spectrum, specific distributed RRM schemes, or dynamic nomadic node selection for backhaul optimization.

4.1.3 Enhance network performance and spectral efficiency

Enhanced network performance and spectral efficiency are to be achieved by applying more sophisticated protocol and air interface technologies as compared to LTE-A [58]. The primary air interface technologies in this regard are the use of multiple antennas, possibly involving massive antenna constellations, multi-stream transmission such as spatial multiplexing or non-orthogonal multiple access, and cooperation techniques such as coordinated multi-node transmission or solutions based on interference alignment.

4.2 10 times to 100 times higher typical user data rate

The primary methods to address this goal are to use spectrum aggregation and more dynamic spectrum access, usage of higher frequencies up to mmW frequencies and short-range communications.

4.2.1 Spectrum aggregation and more dynamic spectrum access

Spectrum aggregation is already defined by 3GPP LTE-A and enables peak data rates up to about 1 Gbps. This may evolve further to take into account the new bands released during WRC-15. Aggregation of multiple bands over a wide range of frequencies poses challenges concerning the cost and efficiency of radio frequency filter and transceiver solutions, in particular for the UEs. Global research must be conducted to propose new schemes for spectrum opportunity detection and assessment and spectrum management concept for LSA. Based on the need for spectrum, these technical enablers shall help to obtain spectrum by negotiating access to it with other entities and also assessing the use of spectrum.

4.2.2 Usage of higher frequencies

Usage of higher frequencies up to mmW frequencies will further increase the achievable data rates to 10 Gbps or beyond. To compensate for the path loss at such high frequencies, high antenna directivity is required if transmission range shall be beyond a few meters. Accordingly, flexible air interfaces for mmW frequencies must be developed. The identification of suitable frequency bands and the characterization of the propagation channel demand new investigations.

4.2.3 Short-range communications
Finally, reducing the transmission distance, approaching short-range communications, e.g., D2D or UDN, is also an efficient means to increase user data rate. Indeed, node densification and dynamic RAN (cf. RAN 2.0 described previously) can allow confining interference to very specific areas of use while reducing the signal attenuation. Both effects shall boost the signal to interference plus noise ratio (SINR) thus increasing the user data rate by a logarithmic law.

4.3 10 times to 100 times higher number of connected devices
The primary methods to address this goal are to reduce signaling overhead, to use dynamic profiles of users, and to implement traffic concentration, in particular for MMC applications.

4.3.1 Reduce signaling overhead
Signaling overhead can be reduced by designing more efficient protocols and by thinning out some protocol layers, e.g., for the simplification of end-to-end procedures. On the air interface, the signaling for random access, time adjustment, and/or resource assignment can be reduced, for example, by using contention-based access, waveforms that are more tolerant to timing mismatch as compared to orthogonal frequency division multiplexing (OFDM), and/or by resource reservation, making the air interface more flexible and suitable for small payload traffic. For instance, methods dedicated to contention-based access for massive number of devices without scheduled access and multi-user detection facilitated by compressive sensing are good candidates to reduce signaling.

4.3.2 Use dynamic profiles of users
NFV technologies can play a role to overcome current limitations of a rigid protocol stack by allowing flexible configuration of the network functionalities. The future air interface shall support this flexibility by using dynamic profiles of users, of which entries are configurable to pre-defined use cases. In this sense, some radio functions will be activated/deactivated on demand depending on the specific needs of the service and the status of the network. Again, the user-centric paradigm applies, since the network shall adapt its topology and operation mode according to the needs of each user.

4.3.3 Traffic concentration
Finally, traffic concentration can be achieved by means of gateways, for example, by linking a capillary MMC network to a wide area cellular network. In this framework, the RAN might configure one specific device to act as such concentrator (cluster head) by using D2D communications to collect all data from the surrounding machines. It is expected that this last hop link should work on a different radio interface to host a large number of mesh devices with severe energy constraints. For instance, techniques are developed to reduce the amount of traffic in gateway-based MMC solutions by context-based device grouping and signaling.

4.4 10 times longer battery life for low power MMC devices
The primary methods to address this goal are to improve air interface, procedures, and signaling and to reduce the distance between the MMC devices and the access node. Techniques to improve the air interface include the use of sleep modes, energy-efficient modulation, coding and multiple access schemes, for example, use of constrained modulation techniques such as Gaussian Minimum Shift Keying (GMSK), very robust coding and/or spreading allowing very low transmission powers, and simplified procedures such as those introduced for the previous goal.

The MMC devices can, in some scenarios, be brought closer to the access node, for example, by gateways connecting a capillary network to a wide area network or by denser deployment of small cells.

4.5 Times reduced End-to-End (E2E) latency
The primary methods to address this goal are to use more efficient network architectures, more efficient air interface designs, signaling and procedures, better QoS differentiation, and direct D2D communication.

4.5.1 Efficient network architectures
Low-latency network architectures are concerned with shortening the distances and number of hops between the user and the content, for example, by distributing some network functions that are centralized today or by applying local and universal caching as well as local breakouts to external networks like Internet, service provider, or enterprise networks.

4.5.2 Efficient air interface designs
The air interface may adapt the frame structures in order to reduce the Transmission Time Interval (TTI) and/or Hybrid Automatic Repeat reQuest (HARQ) round trip times. While this can efficiently be implemented at the higher frequencies where more bandwidth is available, this can become very inefficient for wide area coverage. Signaling and procedures can be thinned out, by simplifying their components.

Table 1 Main enablers for the 5G design

Technique	Impact	Pros	Cons
D2D communications	System capacity can be increased by a factor of 2 using the same bandwidth when some RRM mechanisms are used for opportunistic access and there exists full cooperation among devices. Latency is also reduced to the order of the TTI length (e.g., 1–2 ms).	With properly selected safety distance, D2D communication can use the spectrum allocated to small cells (mostly uplink band) without affecting the small cell performance.	How to motivate cooperation of users is still one open issue. Battery consumption is something critical in current systems and D2D communication model is only accepted by the end user for him/her own benefit. Specification is far from being ready for D2D integration. Opposition from some mobile network operators is also an important barrier to overcome.
New air interfaces	Access time can be reduced down to 1.5 ms if new air interfaces are coupled with efficient access procedures (as shown by FBMC evaluations [60]). Due to the very good frequency localization, the transmit power can be concentrated on only very few subcarriers to eventually enhance significantly the expected coverage or to reduce battery consumption. This is of special relevance for machine-type communications, in which payload is very small.	The well-localized signal energy in frequency domain of the multi-carrier signal also allows for efficient access to fragmented spectrum and efficient spectrum sharing, as a minimum amount of guard bands are needed for the signal separation in frequency.	Changing the waveform impacts the signal structures, implying a revolutionary step towards a new radio generation. Backward compatibility thus cannot be guaranteed, however, for a new radio generation this should not be crucial requirement.
Ultra-dense network	Capacity is directly proportional with the number of nodes, provided centralized interference coordination. For indoor cases, the coefficient of proportionality could be as high as 0.73 with ISD of 10 m.	Together with increasing the bandwidth, the use of more nodes is an easy means to achieve desired levels of capacity.	Cost is the main issue of this approach, together with the need for interference coordination. In case of certain isolation between cells, this need for coordination is relaxed.
Traffic concentration	The use of accumulators or concentrators for machine-type communications improves range of coverage and sensors' throughput. The improvement factor is between two and three thanks to those relays. For the same throughput and coverage needs, traffic concentration reduces battery consumption.	Concentrators also reduce signaling overhead thanks to the coupling of parallel signaling flows.	Performance heavily depends upon the appropriate relay selection.
Moving networks	In vehicles equipped with two access points, one for outside transmission/ reception and another for inside users, their best reception chain improves the link budget for the end user up to 9 dB, in cases where the user is outside the car, and up to 24 dB, when the user is within the car. This results in better coverage or higher user throughput, mostly in the cell-edge.	Battery is not a big issue for vehicles, which opens the door for more active collaboration between cars and end-users. Moreover, the number of antennas integrated in vehicles can be much higher than in the handheld devices. This allows for massive-MIMO solutions.	Mobility of access points increase management complexity mostly due to the higher dynamicity of the network.
Localized traffic flows	With a dedicated bandwidth of 80 MHz, end-to-end latency is reduced to 60%, as compared with current LTE-A system. Moreover, half of the traffic can be off-loaded from the cellular system.	Use of localized traffic flows is simple to implement and can be easily integrated into current networks.	Universal caching requires storage resources as well as the design of specific signaling mechanisms.
Massive MIMO	Spectral efficiency can be increased by a factor of 20 when using 256 antennas in the transmitter and receiver side as compared with four antenna systems. For the same spatial multiplexing capability as legacy systems (8 streams), beamforming gain reaches 15 dB.	Simple way of increasing cell efficiency mostly for small cell deployments. Fits together with the use of higher frequencies above 6 GHz due to the reduced antenna size.	Pilot contamination is one of the main showstoppers of the use of massive MIMO. Moreover, TDD mode seems to be a must to reduce signaling overhead thanks to the use of channel reciprocity principle. Form factor forces the use of centimeter wave or mmW to compact massive antennas. Finally, performance is very sensitive to mobility and computation burden could make multi-user solutions unaffordable.

Table 1 Main enablers for the 5G design *(Continued)*

Spectrum above 6 GHz	Meeting the 5G user expectations will require much larger bandwidths as today, in the order of 2 GHz, which can only be available at frequencies above 27 GHz (e.g., 27.5 to 29.5 GHz; 40.5 to 42.5 GHz; 47.2 to 50.2 GHz; 57 to 76 GHz; or 81to 86 GHz).	No restrictions on previous allocations of paired FDD spectrum allows for the use of TDD mode, which is much more efficient for channel estimation. Higher frequencies also reduce antenna size, thus permitting massive MIMO implementations.	Path losses are much higher at such high frequencies, which reduces the coverage to small distances or relies on the use of higher order beamforming to overcome such high attenuations.

4.5.3 Better QoS differentiation
Better QoS differentiation is important in this context. As the low-latency transmission may become inefficient, it should only be applied with the services that require such low latencies and should be avoided with delay-insensitive services.

4.5.4 D2D
D2D can be used between devices within transmission range of each other which saves a radio hop and the routing of traffic through the network. In some case, it can be applied also for local broadcasting, for example, where vehicles broadcast position/velocity information to enhance traffic safety.

5 Conclusions
This paper has presented the current view on the 5G system concept from the METIS project. Within the 5G system concept and its main features, a generic overview for the envisioned flexible 5G network architecture is provided. More details on this architecture proposal can be found in [59]. In contrast to current 3GPP work, D2D communications must be a cornerstone of the new 5G technology going towards the new RAN 2.0 paradigm. Flexible radio air interface can offer the best solutions targeted to different use cases. Moreover, the ultra density of access nodes, including vehicles, devices, and base stations, requires further research into the definition of more efficient mobility procedures and signaling simplification. On the other hand, a crucial difference of the future 5G networks in comparison to existing 4G networks is that the system must be from-start designed not only for human-centric, but also for machine-centric traffic in MMC with different service demands. Intensive research is required in the fields of overlaying multiple transmissions, new air interfaces, smart pre-allocation of resources, reduction of the synchronization requirements, and context/service-aware configuration of the radio access. Finally, special attention must be paid to the development of URC techniques, capable of supporting new services like tactile Internet or V2X communications for traffic safety.

Simulation results in METIS have proven the potential of some of the techniques discussed along this paper. Table 1 summarizes the impact of most significant techniques together with some comments concerning the pros and cons of their use in 5G systems. Note that the quantitative analysis provided in Table 1 is derived from several simulations in up to 12 different test cases. For the sake of simplicity, we are not going to include in this paper the details of all these test cases. Please refer to METIS deliverables for additional information [2,60].

Of significant relevance is the use of D2D communications, which could increase average system capacity by a factor of 2 (with high density of users and common interests in the consumed contents), and moving networks, in which cars can operate in relaying mode for other users, e.g., out-car users in case of nomadic node operation [61,62]. Thanks to relaying, vehicle penetration losses are avoided and the reception chain improves, due to the better characteristics of the antenna and the receptor in the vehicle. The mobile relay operates in a separate band in full duplex mode, that is, is totally transparent for the network point of view that treats the vehicle cell like a regular user. Moreover, the collaboration of cars allows for a feasible implementation of universal caching, by which cars forward cached content directly to interested user. Results have proven two positive effects of this universal caching. First, caching reduces end-to-end latencies of cached users. This reduction increases with smaller packets, that is, when the non-radio-transmission delay is more relevant over the whole end-to-end latency. The second positive effect of universal caching is the offloading of traffic. According to current shape of cellular network contents, one fourth of the users may be offloaded from the classical network. With the current traffic type distribution, about one half of the traffic load might be offloaded.

5.1 Endnotes
[a]In comparison with data traffic in 2010.

[b]Backhaul is denoted as the link between aggregation (alternatively core) network and BBU of the radio node. The fronthaul is denoted as the link between BBU and Radio Remote Unit (RRU). This denotation is valid also for the C-RAN case [52].

Competing interests
The authors declare that they have no competing interests.

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