WHITE PAPER ON CRITICAL AND MASSIVE MACHINE TYPE COMMUNICATION TOWARDS 6G

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Editors:
Nurul H. Mahmood[1] · Onel López · Ok-Sun Park · Ingrid Moerman · Konstantin Mikhaylov · Eric Mercier · Andrea Munari · Federico Clazzer · Stefan Böcker · Hannes Bartz

Contributors:
Nurul H. Mahmood · Stefan Böcker · Andrea Munari · Federico Clazzer · Ingrid Moerman · Konstantin Mikhaylov · Onel López · Ok-Sun Park · Eric Mercier · Hannes Bartz · Riku Jäntti · Ravikumar Pragada · Yihua Ma · Elina Annanperä · Christian Wietfeld · Martin Andraud · Gianluigi Liva · Yan Chen · Eduardo Garro · Frank Burkhardt · Hirley Alves · Chen-Feng Liu · Yalcin Sadi · Jean-Baptiste Dore · Eunah Kim · JaeSheung Shin · Gi-Yoon Park · Seok-Ki Kim · Chanho Yoon · Khoirul Anwar · Pertti Seppänen

Affiliations:
- N. H. Mahmood, O. López, K. Mikhaylov, C.-F. Liu, E. Annanperä, H. Alves and P. Seppänen are with University of Oulu, Finland.
- O.-S. Park, E. Kim, J. Shin, G.-Y. Park, S.-K. Kim and C. Yoon are with ETRI, South Korea.
- I. Moerman is with imec - Ghent University, Belgium.
- E. Mercier and J.-B. Dore are with CEA-Leti, France.
- A. Munari, F. Clazzer, H. Bartz and G. Liva are with German Aerospace Center (DLR), Germany.
- S. Böcker and C. Wietfeld are with TU Dortmund University, Germany.
- R. Jäntti and M. Andraud are with Aalto University, Finland.
- R. Pragada is with InterDigital, USA.
- Y. Ma is with ZTE, China.
- Y. Chen is with Huawei Technologies, Canada.
- E. Garro is with Universitat Politècnica de València, Spain.
- Y. Sadi is with Kadir Has University, Turkey.
- F. Burkhardt is with Fraunhofer IIS, Germany.
- K. Anwar is with Telkom University, Indonesia.

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[1] Corresponding editor, email: nurulhuda.mahmood@oulu.fi

Executive Summary

By 2030, our societies will become digitalized and data-driven, enabled through the key verticals like connected industries, intelligent transport systems and smart cities. Machine Type Communication (MTC) encompassing its massive and critical aspects, and near instant unlimited wireless connectivity are among the main enablers of such digitalization at large.

The recently introduced 5G New Radio is natively designed to support both aspects of MTC to promote the digital transformation of the society and particularly improve the overall efficiency of different vertical sectors. However, it is evident that some of the more demanding requirements of MTC cannot be fully supported by 5G networks. Alongside, further development of the society towards 2030 will give rise to new and more stringent requirements on wireless connectivity in general, and MTC in particular.

Driven by the societal trends towards 2030, the next generation (6G) will be an agile and efficient convergent network serving a set of diverse service classes and a wide range of key performance indicators (KPI).

This white paper explores the main drivers and requirements of an MTC-optimized 6G network, and presents a set of research directions for different aspects of MTC that can be synthesized through the following six key research questions:

- Will the main KPIs of 5G, namely reliability-latency-scalability, continue to be the dominant KPIs in 6G; or will emerging metrics such as energy-efficiency, end-to-end (E2E) performance measures and sensing become more important?
- How can different E2E service mandates with different KPI requirements be delivered through a multi-disciplinary approach jointly considering optimization at the physical up to the application layer?
- What are the key enablers towards designing ultra-low power receivers and highly efficient sleep modes to support ultra-low-cost ultra-low-power or even passive MTC devices?
- How can a disruptive rather than incremental joint design of a massively scalable waveform and medium access policy be tackled to efficiently support global connectivity for MTC?
- How can new service classes characterizing mission-critical and dependable MTC in 6G be supported through multifaceted connectivity and non-cellular centric wireless solutions?
- What are the potential enablers of long-term secure schemes considering the heterogeneous requirements and capabilities of MTC devices? How can lightweight and flexible usable ways of handling privacy and trust be designed in MTC by combining the user perspective with the technical perspective?

Introduction

1

Background and Objectives

The year 2020 is expected to witness large scale global deployment of fifth generation (5G) wireless network. While 5G is being deployed across the globe, the research community has already started posing the question: What will the sixth generation (6G) be? This was the main theme of the first 6G Wireless Summit held in Levi, Finland in March 2019, which led to the world's first 6G white paper published in September 2019 [1].

To delve further into this question, 6G Flagship[2] has developed a set of 12 new white papers exploring selected thematic topics[3] in depth in conjunction with the second 6G Wireless Summit held virtually in March 2020[4]. The objective is to investigate key research questions and potential enabling technologies for 6G with respect to the different thematic topics.

This white paper addresses the evolution of critical and massive machine type communication (MTC) towards 6G. In particular, the white paper will explore the societal development and use cases pertinent to MTC towards 2030; identify key performance indicators (KPI) and requirements; and discuss a number of potential technical enablers for MTC in future 6G networks. The main takeaway points are highlighted through the six key research questions presented in the executive summary.

State of the Art

Wireless connectivity is now a ubiquitous utility, much like water and electricity. Wireless networks were initially designed to connect people. However, they have now evolved to enable MTC allowing applications residing in different machine type devices (MTD) to interconnect wirelessly without the need for human intervention.

A network formed by different connected MTDs is known as the Internet of Things (IoT). IoT enables a wide range of applications with diverse requirements in many different verticals. This ranges from best-effort connectivity for simple sensors to high data-rate, extremely reliable real-time connectivity, e.g. for vehicles. IoT use cases in 5G New Radio (NR) can be classified into two broad service classes, namely ultra-reliable low latency communication (URLLC) and massive MTC (mMTC).

5G NR network aims to optimize the resource utilization for high connection density (e.g., 1 million connections per square kilometer) mMTC use cases, and also support a timely, efficient, and reliable mechanism to deliver the target information to one or multiple devices for URLLC use cases with 99.999% reliability at 1 millisecond (ms) user plane latency [2].

The basic NR framework defined in 3GPP Release 15 provides a scalable and configurable air interface design to support ultra-low latency transmission using configurable numerology and frame structures, and very short mini slots down to two symbols in duration. Similarly, grant-free (GF) transmission has been specified in NR to reduce the signaling overhead and latency, which is suitable for both URLLC and mMTC, especially in the uplink.

[2] *www.6gflagship.com*
[3] The white papers are available online at *https://www.6gchannel.com/6g-white-papers/*
[4] *http://www.6gsummit.com/*

Future releases of 5G NR (Release 16 in mid-2020 and Release 17 later) will include further enhancements for URLLC and mMTC services. In addition to connectivity through the cellular infrastructure, sidelink connectivity with another IoT device or smartphone will be introduced. Moreover, GF transmission will be extended to support sidelink transmissions and be enhanced with non-orthogonal multiple access (NOMA). Finally, narrow band IoT (NB-IoT) and Long Term Evolution - MTC (LTE-M) will be integrated with 5G NR to provide dedicated MTC services. Please refer to [3] and the references therein for a detailed discussion.

Though cellular networks offer access to diverse services and rates through larger bandwidths and a more extensive network, the supported devices and the network itself are usually too power-hungry and costly for many MTC applications. To alleviate these limitations, low power wide area networks (LPWAN) such as SigFox, LoRA/LoRAWAN and Ingenu, have been specifically designed for MTC. These are usually extremely power efficient and are able to provide connectivity over a long range (up to tens of kilometers), though the data rates and the supported use cases are rather limited. Alongside these, there exist a number of proprietary industrial communication networks (ICN) designed to serve the needs of factory and process automation in industries.

While 5G NR and other wireless systems have enabled mMTC and URLLC services under certain scenarios, the true vision of IoT connectivity as required by the diverse range of MTC applications is yet to be realized. In particular, MTC is fundamentally different from conventional human type communication (HTC). The current approach of modifying the existing wireless systems primarily designed for HTC to meet connectivity needs of IoT is proven to be rather inefficient and unscalable.

There are also some lack in considering end-to-end (E2E) aspects as part of the design, that is, a full protocol stack from the physical layer (PHY) to the application layer (APP), and a full connection path from APP to APP. Moreover, different MTC scenarios and applications may have divergent requirements. Hence, connectivity solutions need to be application-aware and may need multiple radio access technologies (RAT) to ensure their robustness.

The number of IoT connected devices is expected to grow three-fold in the next decade (from about 11 billion in 2019[5] to 30 billion by 2030[6]), serving a wide variety of use cases with highly diverse requirements. As 5G NR and other MTC systems continue to evolve in the near future, there is a need to design a robust, scalable, and efficient 6G wireless network that can address the limitations of the existing systems and meet the emerging requirements of 2030 society and beyond.

Although 6G research is still in the exploration phase, there are already a good number of publications exploring what 6G will be. An initial vision of what 6G might be is presented in [1, 4], which is further elaborated in [5–10]. A comprehensive vision of 6G as a human-centric mobile communications network, along with issues beyond communication technologies that could hamper research and deployment of 6G are discussed in [11]. Considering a more specific perspective, potential key enablers for MTC in 6G are discussed in [12].

This white paper intends to further contribute to the ongoing discussion shaping 6G design by presenting a unified and holistic picture of an intelligent and E2E-optimized wireless network capable of supporting MTC evolution towards the 6G era.

[5] *https://www.ericsson.com/en/mobility-report/reports/november-2019/iot-connections-outlook*
[6] *https://www.statista.com/statistics/802690/worldwide-connected-devices-by-access-technology/*

MTC Megatrends Towards 2030

2

Our society is developing fast with many transformative changes taking place within a short span of time, for which MTC is a key technology enabler. The main drivers, some representative use cases, key requirements and service classes of MTC towards 2030 are schematically presented in Figure 1 and further detailed next.

2.1 Drivers

Frost & Sullivan's Visionary Innovation Group[7] has identified 12 global megatrends futurecasting key themes that will shape the society at large by 2030. Out of these megatrends, those that we believe will strongly drive the evolution of MTC in the next decade are listed below. It is worth mentioning that most of the following societal and technological trends are also aligned towards United Nations' 2030 Sustainable Development Goals (SDG) for an inclusive, trustworthy and self-sustainable society. Please refer to [13] for a detailed discussion on 6G drivers and UN SDGs.

Autonomous mobility

MTC will be a key driver in the growing trend towards making anything that moves autonomous and intelligent. For instance, intelligent transport systems (ITS) will require the provision of reliable connectivity between multiple actors. Improving the level of driving automation (from level 3 to level 4 or level 5) is expected to increase the number of sensors and edge processing systems integrated within the vehicles. To be most efficient, these systems will utilize real-time wireless connectivity to their sensor/actuator nodes and external processing units. The increasing role of artificial intelligence (AI) in both the vehicle and the infrastructure also imposes stricter requirements on the information transfer process. Additionally, the recent advances in unmanned vehicles and related applications will require a three-dimensional (3D) connectivity landscape.

Connected living

Ubiquitous connectivity anytime and anywhere will facilitate new possibilities at home, in entertainment, health and work, and in providing citizen services. 6G will drive our cities to be super smart and fully connected with a plethora of autonomous services, which will be enabled by a forecasted 30 billion connected IoT devices by 2030.

Factories of the future

Transformational shifts in production and industries and novel human-machine interactions are enabled by MTC. By supporting diverse needs and requirements, it will provide the groundwork towards Industry 5.0. Industry 5.0 targets producing customized and personalized products in mixed sensing/actuation/haptics scenarios instead of the dominant data collection and analytics scenarios of Industry 4.0. Industry 5.0 will involve much more interactivity, both local and remote, with even more diverse and stringent demands regarding wireless connectivity compared to Industry 4.0 [14].

Digital reality as frontier technology

Augmented/virtual/mixed reality (XR) will evolve from a niche market application to widespread adoption resulting in new use cases and applications. MTC will play a fundamental role in facilitating the user experience and enabling novel and efficient man-machine interfaces to present the data coming from machines in a more natural way. Rapid advances in wireless brain-computer in-

[7] *https://ww2.frost.com/research/visionary-innovation/*

teractions and multisensory XR requirements will drive a massive proliferation of cost-effective miniaturized smart wearable and implant sensors with quality of service (QoS) guarantees.

Towards a 'zero' world

The proliferating vision of the zero-world concept is shifting focus towards technologies that innovate to zero, for example, 'zero-energy' technologies and 'zero-touch' systems. Innovation to 'zero' will require MTC to deliver higher performance at zero or very low energy consumption; or to provide zero-latency and zero-error capabilities for enabling real-time control and emergency IoT use cases.

Data as the new oil

Towards 6G, data markets will emerge connecting data suppliers and customers. The data generated by the widely distributed MTDs will have enormous business and societal value. The value-added services of data marketplaces will be empowered by emerging technologies like AI and DLT, while adding new data-centric KPIs such as the age of information (AoI), privacy and localization accuracy.

2.2 Use Cases

Considering the foreseen economic, societal, technological, and environmental context of the 2030 era, future network demands must be jointly met in a holistic fashion. It is therefore not straightforward to forecast use cases of MTC towards 6G. However, in the following, we list a number of plausible use cases, which by their generality and complementarity, we believe depict a representative picture of the different possible MTC use cases in 6G.

Connected industries

Industry 4.0 converges advanced manufacturing techniques with data-driven technologies and AI tools to improve the operational and performance efficiency of enterprises. Further evolution towards Industry 5.0 and the emerging trend of personalization and customization will require future factories to be even more agile and adaptable, supported by massive mobile connectivity and versatile production assets. This requires the evolution of existing KPIs of reliability, latency and throughput, while also supporting new ones such as localization accuracy and those measuring man-machine interface performance.

Swarm networking

Autonomous vehicles like self-driving cars, automated guided vehicles (AGV) and unmanned aerial vehicles (UAV) have started finding application in a myriad of use cases. A swarm is a group of such devices collectively performing tasks in a distributed fashion to achieve an overall mission objective. Towards 2030 such swarms will be commonplace in shop floors, connected logistics and transport, emergency response, etc., requiring robust connectivity solutions for such complex but localized MTC networks.

Personalized body area network

Wearable devices like smart watches and ear-buds are a part-and-parcel of our everyday life today. By 6G era, such MTDs will radically evolve, thanks to advances in man-machine interface that will render the devices seamlessly integrated, for example in our clothing or even implanted as skin-patches and bio-implants, while being effortless to operate [10]. While 6G MTC networks will play a significant role as enabler of such personalized body area network, different aspects of it will also impose different requirements on the network.

Zero-energy IoT

MTDs at the extreme end of the IoT ecosystems are mostly low-power sensors. Such MTDs are powered by batteries or energy harvesters and are very limited in computing and storage capabilities to reduce costs and enlarge lifetime. Circuit technology advances towards 2030 aim at reducing their power consumption up to the point of keeping them perpetually alive [15].

Wireless Energy Transfer (WET) and backscatter technology are fundamental enablers. Lifetime requirements would demand more than 40 years of continuous operation, for which stand-by and active power consumption may require to be below 1 nanowatt and 1 microwatt, respectively.

Internet of Senses

Internet of Senses will allow all human senses to interact with machines by enabling haptic interaction with sensory or perceptive feedback. This will revolutionize the way we manipulate and interact with our surroundings and will enable truly immersive steering and control in remote environments. Ultrareliable, ultra broadband and ultra-responsive near real-time network connectivity may be mandatory, demanding massive, specialized and adaptive sensor deployments and interactions.

Smart contracts

Distributed Ledger Technologies (DLT) allow value transactions between parties through decentralized trust. Towards 2030, MTC networks will expand DLT's application horizons because of the increasing need to transfer valuable, authenticated sensor data, services, or micro-

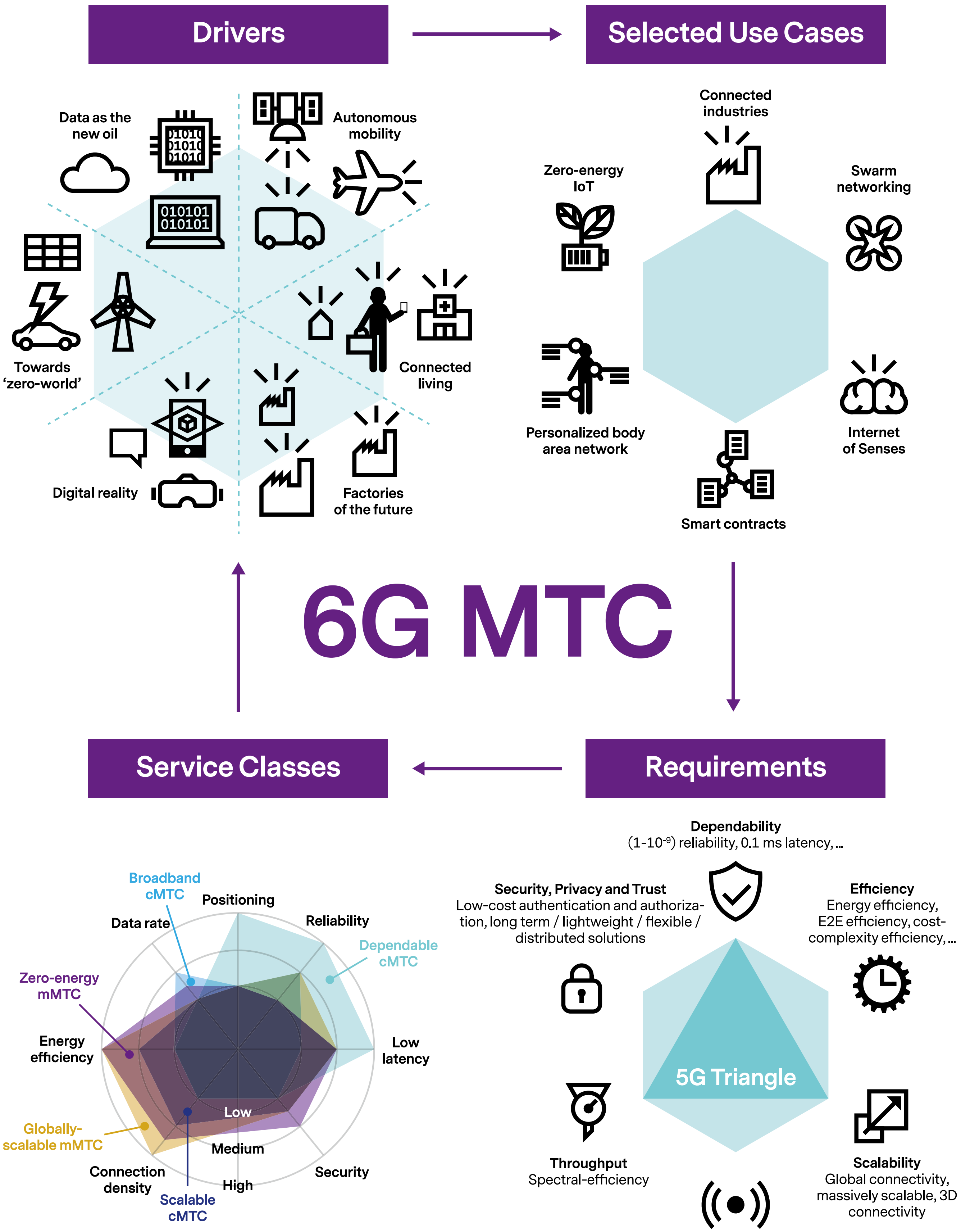


Figure 1: Drivers, use cases, requirements and service classes of 6G MTC towards 2030.

payments between the IoT devices and other parties. For instance, two cars meeting on the road may want to buy data from each another about the road conditions ahead [16]. These distributed sensing services demand connectivity with a synergistic mix of URLLC and mMTC to guarantee low-latency, reliable connectivity, and scalability.

2.3 Requirements

As evidenced by the above use cases, 6G KPIs and requirements will be diverse and include novel metrics alongside the existing ones considered in 5G.

International Telecommunication Union – Radiocommunication Sector (ITU-R) has defined the minimum technical performance requirements for International Mobile Telecommunications for 2020 (IMT-2020) including a number of KPIs, such as reliability, latency, connection density, and energy efficiency (EE) [2]. In 6G, more stringent requirements will be inevitable for these KPIs, while the QoS demands will evolve to be E2E. For example, in industrial scenarios, closed-loop control applications will require E2E reliability of up to $1\text{-}10^{-7}$ to maintain close synchronization at E2E latencies as low as 1 ms [17], for which a per-link reliability of around $1\text{-}10^{-9}$ and user plane latency around 0.1 ms may be required. This would allow instant optimization based on real-time monitoring of sensors and the performance of components, collaboration between a new generation of robots, and the introduction of wirelessly connected wearables and augmented reality on the shop floor.

Similarly, the emerging need for the ultra-dense deployment of industrial IoT devices will require 3D connectivity supporting up to 100 connections per m^3. In terms of EE, the ultimate 6G vision is to achieve zero-energy MTDs through a combination of efficient hardware design and energy harvesting techniques [5].

Alongside the existing ones, new KPIs are becoming increasingly relevant for 6G. The main focus here is on AoI, interoperability, dependability, positioning, sustainability and E2E EE. AoI characterizes the freshness of information and answers how frequently the information status at a sink node needs to be updated through status update transmissions from a source node. Hence, it is crucial for networked monitoring and control systems such as cyber-physical systems.

Considering the heterogeneity of access technologies (wired and wireless) and deployment scenarios, 6G technologies are expected to facilitate seamless integration and interoperability across the heterogeneous networks. Meanwhile, reliability will evolve towards dependability, which is an umbrella QoS term characterizing the attributes of availability, reliability, security and system integrity used to characterize system lifecycles and failures. Localization accuracy will be relevant for emerging applications using positioning as a service, such as controlling AGVs on factory floors [18].

Finally, while 5G mostly addresses device EE, the EE vision towards 6G will be wider and more stringent, encompassing sustainability, cost (production, installation, maintenance and operational costs) and E2E EE (including energy consumption of the infrastructure). For instance, the total cost and energy consumption per successfully delivered bit at APP between end devices including its environmental impact, will be of utmost importance towards the 6G era.

2.4 MTC Service Classes

MTC in 5G is split into URLLC, or critical MTC (cMTC), in controlled environments with small-payloads and low-data rates, and mMTC for large/dense deployments with sporadic traffic patterns. In the coming decade, owing to emerging industrial use cases and the verticalization of the service provision, these two domains will develop into several specialized subclasses, hence demanding multi-dimensional optimization and scalable designs. So 6G will need to serve highly diverse applications ranging from data-rate hungry holographic images and connected 360 XR to massive access for various types of IoT devices. MTC service classes for 6G are proposed to be classified in this white paper as follows:

Dependable cMTC: which refers to supporting extreme ultra-reliability and low latency along with other measures of dependability (e.g., security) as well as precise positioning, and can be seen as the direct evolution of 5G URLLC, e.g. for autonomous driving.

Broadband cMTC: which refers to supporting mobile broadband (MBB) data with high reliability and low latency, e.g. XR, cloud gaming, robotic aided surgery.

Scalable cMTC: which refers to supporting massive connectivity with high reliability and low latency, e.g. critical medical monitoring and factory automation.

Globally-scalable mMTC: which refers to supporting ultra-wide network coverage throughout all space dimensions, including volumetric density of devices. The role of UAV swarms and non-terrestrial networks (NTN) is fundamental for enabling global mMTC connectivity.

Zero-energy mMTC: which covers massive deployments of EE radios with exceptionally long battery life and network lifetimes, e.g. soil monitoring and precision agriculture. This aims to cover techniques for zero-energy radios, energy harvesting (EH), backscatter communication and extreme EE resource allocation.


C1115
R348
C418
C417
C1080
C1076
C439
C217
C381
R267


C1099
C491

Potential Enabling Technologies 3

Novel approaches in designing the enabling technology components for MTC towards 6G will be necessary to successfully meet the 6G visions and requirements laid out in Section 2. In this section, we pinpoint a number of illustrative solutions spanning different layers of the protocol stack, ranging from efficient hardware design to the considerations at the applications layer itself.

The holistic MTC network architecture presented in Section 3.1 provides a bird's eye view of the solution landscape and frames the forthcoming discussion. Energy efficient hardware considerations such as the zero-energy air interface are presented next in Section 3.2, followed by a discussion on enablers for globally available and massively scalable MTC services in Section 3.3.

Finally, mission-critical MTC serving the needs of industrial sectors and related verticals, and privacy and security aspects considering the heterogeneity of MTC devices and applications are discussed in Sections 3.4 and 3.5, respectively.

3.1 Holistic MTC Network Architecture

3.1.1 Introduction to MTC Networks

Owing to the sheer variety of scenarios, services and requirements, today's portfolio of the MTC RATs and the architectural options underlying the different MTC networks is excessively multitudinous and diverse. However, today there is no single killer MTC RAT—a "Jack of all trades"—which can address the needs of a decently significant share of the envisaged MTC applications and use cases. It is also unlikely that such a RAT will appear in the near future.

Likewise, not a single MTC RAT is omnipresent and, vice versa, in many environments, multiple RATs and networks do coexist, thus forming a heterogeneous multi-connectivity-enabled environment. However, such an environment is typically disjoint—the networks often belong to different administrative domains—i.e., run by various stakeholders, each of which manages its network independently of the others. Moreover, in the case of the RATs operating in the unlicensed bands (Bluetooth, WiFi, IEEE 802.15.4 or LoRaWAN to give an example), the different RATs and even multiple networks employing the same RAT may compete for the same radio resources.

The further development of the new MTC network architecture has to take off from this starting point to harmonize the connectivity landscape and make it sustainable, whilst maximizing the performance of (i) individual machines, (ii) the network as a whole, and, at the end of the day, (iii) the plethora of services and applications served by the machines and the network(s).

3.1.2. Key Trends in MTC Network Architecture

A number of the current key trends affecting the MTC network architecture has to be accommodated in the new MTC network architecture towards 6G. These can be summarized as:

- The evolution of networks is moving from being cell-based towards becoming cell-free. Cell-free networks imply no explicit connection established between an MTD and a base station (BS) of a network cell, thus reducing the signaling overhead while improving the reliability by enabling multiple BSs to demodulate the incoming transmissions, either separately or jointly.
- Further increases of the network heterogeneity due to (i) the appearance of local micro-operators deploying new private or public networks (with a

"crowd-driven networking" paradigm representing one of the extremes), (ii) the introduction of the new RATs and the evolution of the existing RATs, and (iii) the shrinking of the cell sizes due to moving to higher frequency bands and/or applying more advance modulation and coding schemes leading to very geographically concentrated specialized deployments serving specific end goals.

- The enabling of the infrastructure-less and dynamically formed networks for critical missions, servicing out of cellular coverage and use cases implying high mobility (e.g., drone platooning or the mobile BS case).
- The need to support an ever growing number of vastly different traffic patterns and service classes (e.g., priorities, including emergency traffic) for individual and/or groups of MTDs.
- Wireless energy transfer holds vast potential for replacing batteries or increasing MTD's lifespans, which is crucial for sustainability since battery waste processing is already a critical problem. RF-WET, which refers to the use of radio frequency (RF) signals for intentionally powering EH MTDs, has been identified as a key component of future wireless systems. Seamless network-wide integration of WET in future 6G MTC networks calls for a new approach in network design under which spectrum resources for separate WET carriers, efficient channel state information (CSI)-limited strategies for serving energy-exhausted devices, and distributed approaches for supporting ubiquitous energy accessibility within the network coverage area, may be required.

3.1.3. Holistic MTC Networks

The envisaged holistic MTC network architecture (see Figure 2) of the future should be highly efficient to fully utilize resources. Furthermore it should be intelligent at the edge for dynamic requirements and be software-defined with an iterable design. To increase the efficiency, the network requires native support for dynamic and collaborative orchestration between E2E applications communicating across multiple heterogeneous network domains (wired/wireless/optical), operated by different stakeholders (cellular, public, private) and involving different RATs. To facilitate interoperability, the interfaces, through which this should be handled, must be technology agnostic, meaning that E2E applications should not be aware of the underlying technologies and RATs, but should still be able to express their requirements to the network.

The selection of the RAT(s) and the possible configuration parameters need to be handled through open algorithms based on the E2E QoS requirements of applications and the fairness considerations between them, which in some cases will have to be made known to the network orchestrator(s), and mindful of the possible alternatives and the effects on the performance of the network as whole. Machine learning (ML) methods represent a promising mechanism to help address this challenge.

Importantly, the set of the possible RAT alternatives, as well as the number and distribution of machine-clients,

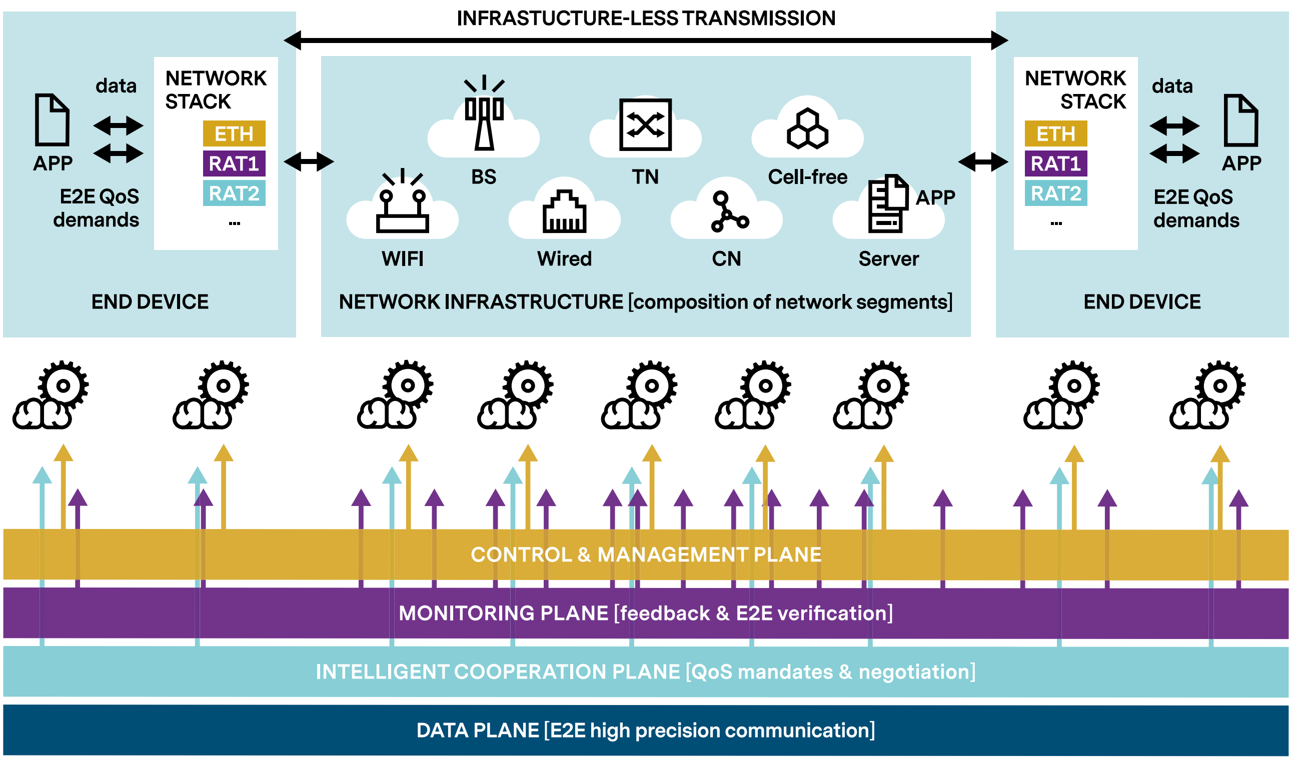


Figure 2: Holistic MTC architecture driven by end-to-end QoS demands.

their traffic patterns and communication needs are not static and can change drastically both in space and in time. This postulates the need for equipping the network with efficient real-time localization and optimization mechanisms both of centralized and distributed nature, which can be deployed at the edge and even moved to the individual devices (e.g., as a mobile agent).

The introduction of effectively manageable control and emergency traffic channels is also highly desirable. Importantly, the holistic MTC architecture should simultaneously be future proof and backward compatible not only within a single network operator domain but also across domains, supporting the interoperability between new and old generations and releases within one generation. In this context, the softwarization of the network and radio functions, allowing for the time- and cost-efficient update of the network and radio elements and new functionality introduction will be especially crucial.

3.1.4. Ultra-Low Power MTC Networks

Zero-energy devices will require a new air-interface which in turn has impact on the network architecture (cf. Section 3.2). These devices will require the network to illuminate them with relatively large amounts of power. The powering could be provided by using a dedicated carrier. Alternatively, information transmission of the base station or neighboring users could be utilized for this purpose. In the latter case, the backscatter devices could form an underlay network within the MTC network consisting of active transmitters. Such an underlay operation is sometimes referred to as ambient backscatter communication (AmBC) and is further discussed in Section 3.3.

3.1.5. Open Standards

It is obvious that the design of a holistic post-5G MTC network architecture and development of the underlying optimization mechanisms and technical solutions introduces a major research challenge and requires the investment of substantial resources both by academia and industry. However, what we consider to be the most crucial challenge and the first step to be addressed is reaching the agreement and developing the specifications for the common interfaces and procedures allowing different networks and even their elements to talk to each other.

The next and even more arduous step, requiring consolidation of efforts and goodwill of the whole community as well as that of the political and regulatory authorities, would be the development of these interface specifications into universal cross-disciplinary standards spanning beyond the borders of individual regions and application domains. This would open the path to the development of an efficient, ubiquitous unplugged MTC in the context of 6G or, possibly, a later release.

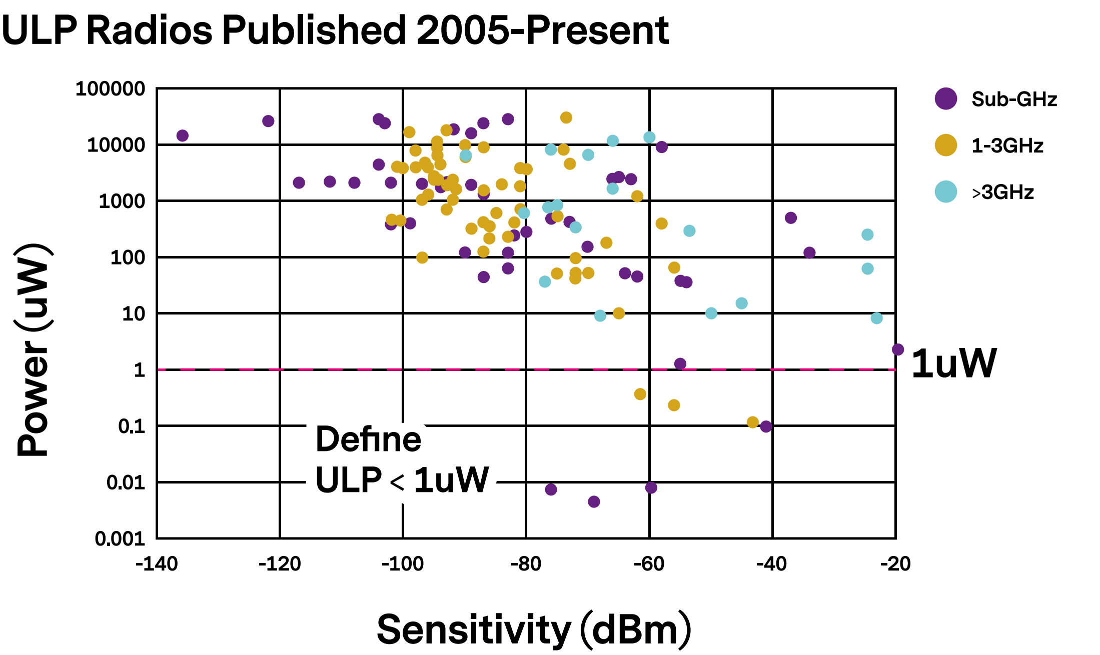
This section presented a holistic network architecture focusing on MTC in future 6G networks as a particular use case. A broader vision for 6G Edge Intelligence envisioning a transition from IoT to Intelligent Internet of Intelligent Things utilizing data-driven machine learning and artificial intelligence is presented in [19].

3.2 Energy Efficient MTC Devices

This section discusses the design of energy efficient MTDs considering both, mMTC and cMTC use cases. In order to support a scalable deployment of massive MTDs in 6G, energy efficiency will be among the most important KPIs. The efficient design of MTDs will be enabled through a combination of ultra-low power (ULP) receiver architecture, enhanced EH techniques and zero energy communication schemes. On the other hand, collaborative and distributed intelligence at the device and the network are foreseen as a key enabler for cMTC. The first step in such an 'intelligence-focused' design would be the optimization of the device hardware itself through the development of 'on device intelligence' blocks.

3.2.1 Ultra-Low Power Receiver Architecture

ULP transceivers are essential to support the billions of expected MTDs in a sustainable way. While other as-



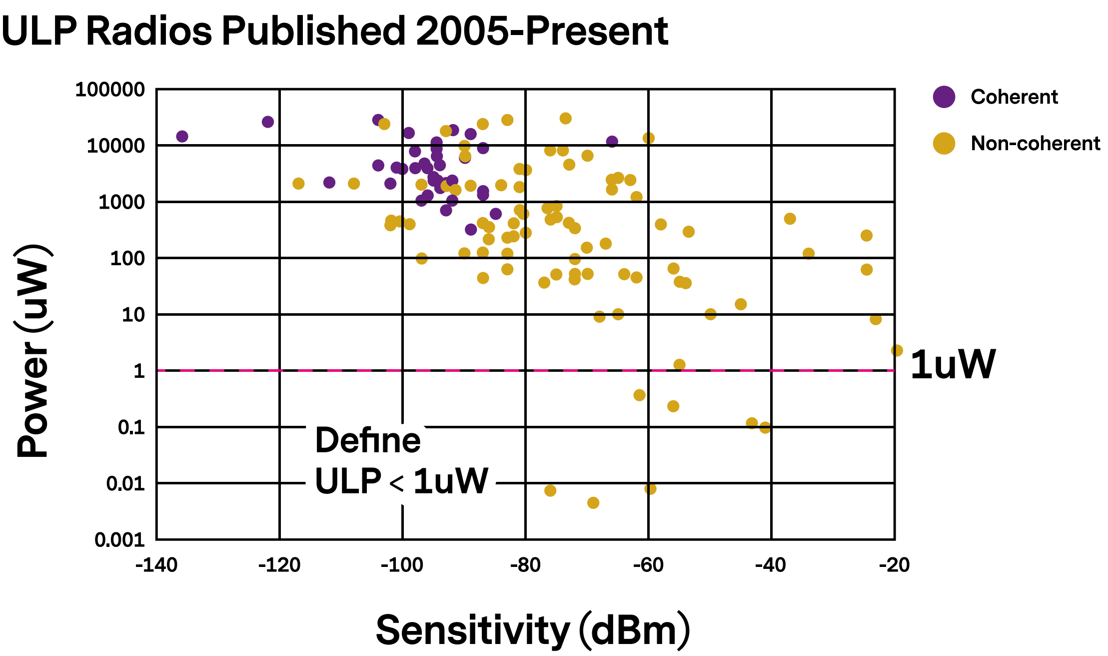


Figure 3: State of art ULP receiver design power consumption versus sensitivity per frequency band and type of design [20].

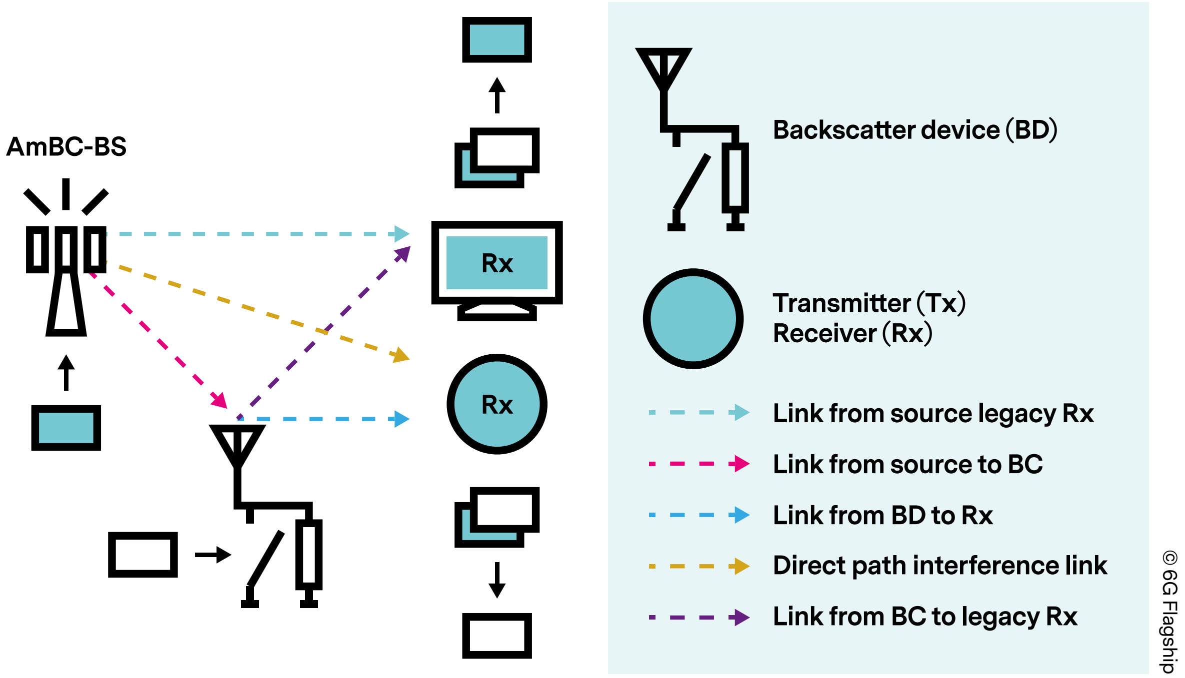


Figure 4: Deployment option for AmBC-BS.

pects of MTD design have developed significantly over the years, EH state of the art shows that the available energy remains low and that no revolutionary technology has appeared in the past decade. Hence sustainable mMTC operation cannot be solely powered through EH, including wireless power transfer; and further MTD development must still target ULP.

Significant power reductions can be achieved by considering the energy consumption of the MTD as a whole, instead of treating the individual elements, such as the antennas and RF transceivers, separately. The antennas should be part of the device package, and the interface with the RF transceiver must be considered, not only as conventional impedance matching, but as an optimized intimate connection. Indeed, smaller radiating elements, thereby with narrower bandwidths and better selectivity and stronger robustness to blocking signals, can be beneficial with a band filtering split along the whole chain from the antenna to the embedded digital intelligence.

The transceiver power consumption can also benefit from better power schemes of the various building blocks. Duty cycling or event-driven architectures are to be favored as they may directly impact the power consumption by the usage factor of the transceiver itself. It nevertheless necessitates the power-up settling time to be very short with high flexibility to enable swift changes of state from sleep to on.

Specifically considering the transmitter, the generated waveform and its amplification before emission has to comply with high linearity specifications and energy efficiency, provided that the final power amplifier can handle flexible biasing mechanisms, such as very efficient envelope tracking features to make the supply voltage fit the power amplifier requirements.

Robustness in a wide-spectrum operation remains of high importance and the performance of the whole receiver chain has to optimized. A graphical representation in Figure 3 shows the power consumption versus sensitivity [20]. It clearly demonstrates that the sub-GHz band with simple non-coherent modulation schemes (on-off keying) represents a promising direction towards achieving below 100 nW power consumption at less than -80 dBm sensitivity.

3.2.2 Ambient Backscatter Communications for 6G mMTC

Ambient backscatter communications is a promising new technology to alleviate cost, power consumption and spectrum occupancy. In AmBC, backscatter devices can communicate with each other by modulating and reflecting received RF signals from ambient sources such as cellular BSs [21]. This method consumes significantly less power than typical active transmitters as no voltage-controlled oscillator and power amplifier are required. The key technical challenges in using AmBC for MTC are:

Direct path interference

The direct path signal power from the ambient source to the receiver is typically several orders of magnitude stronger than the scattered path containing the information of interest. Interference cancellation (IC) can be applied but receivers with a high dynamic range (a high number of bits in the analog-to-digital converter) would be needed. Thus, a more efficient solution would be to cancel the signal in the spatial domain using null steering.

Unknown and fast changes of the amplitude and phase of the ambient signal

The AmBC receiver sees the amplitude and phase variations of the ambient signal as fast fading. For instance, legacy systems using OFDM signal, appear as Rayleigh fading to the AmBC receiver. From the AmBC system perspective, the ideal ambient source signal would have a constant amplitude. Multi-antenna receivers could use beamforming to receive multiple copies of the direct path signal separately and compensate for the phase variations as in passive radar receivers.

Backscatter propagation

In the backscatter case, the pathloss is inversely proportional to the fourth power of the utilized carrier frequency which severely limits the range of the system at higher frequencies. Moreover, in the AmBC bi-static (AmBC-BS) case, where both backscatter transceivers are powered by ambient signals (as shown in Figure 4), the pathloss is inversely proportional to the product of the square distances between the transmitter (energy source) and the device, and the device and the receiver. If one of the distances is short, the other can be long as discussed in [22].

Energy harvesting

Even though the energy consumption of AmBC devices is much less than that of the active transmitters, it still needs some power to operate. The device could use a battery, but a better design would be to utilize EH to make battery-free active devices [23].

Co-existence with the legacy receiver

Interference from AmBC devices to legacy receivers depends on the utilized waveforms. In the case of the OFDM-based legacy system, AmBC causes interference only if its symbol duration is short compared to the OFDM symbol duration. Otherwise the AmBC modulated signal path appears as an additional multi-path component that can be tracked by the receiver [24]. AmBC device can also avoid interfering with the legacy receiver by shifting the scattered signal to the guard or adjacent band.

3.2.3 Energy Optimized Communication

Zero-energy and wake up radios

MTC devices significantly benefit when the battery-life matches the useful lifetime (up to ~40 years) of the device. To accomplish this, the RF front-ends may operate in two different modes, in the conventional low power

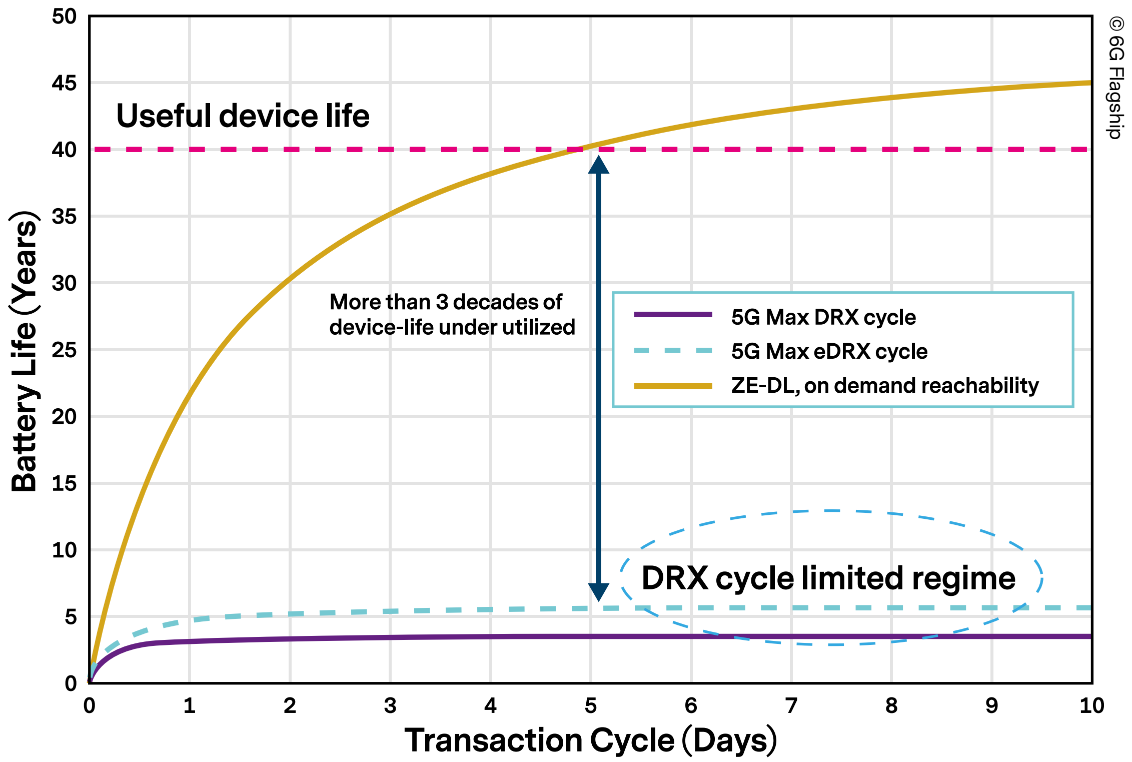


Figure 5: Battery life of a mobile IoT device using DRX-PSM and ZE-DL.

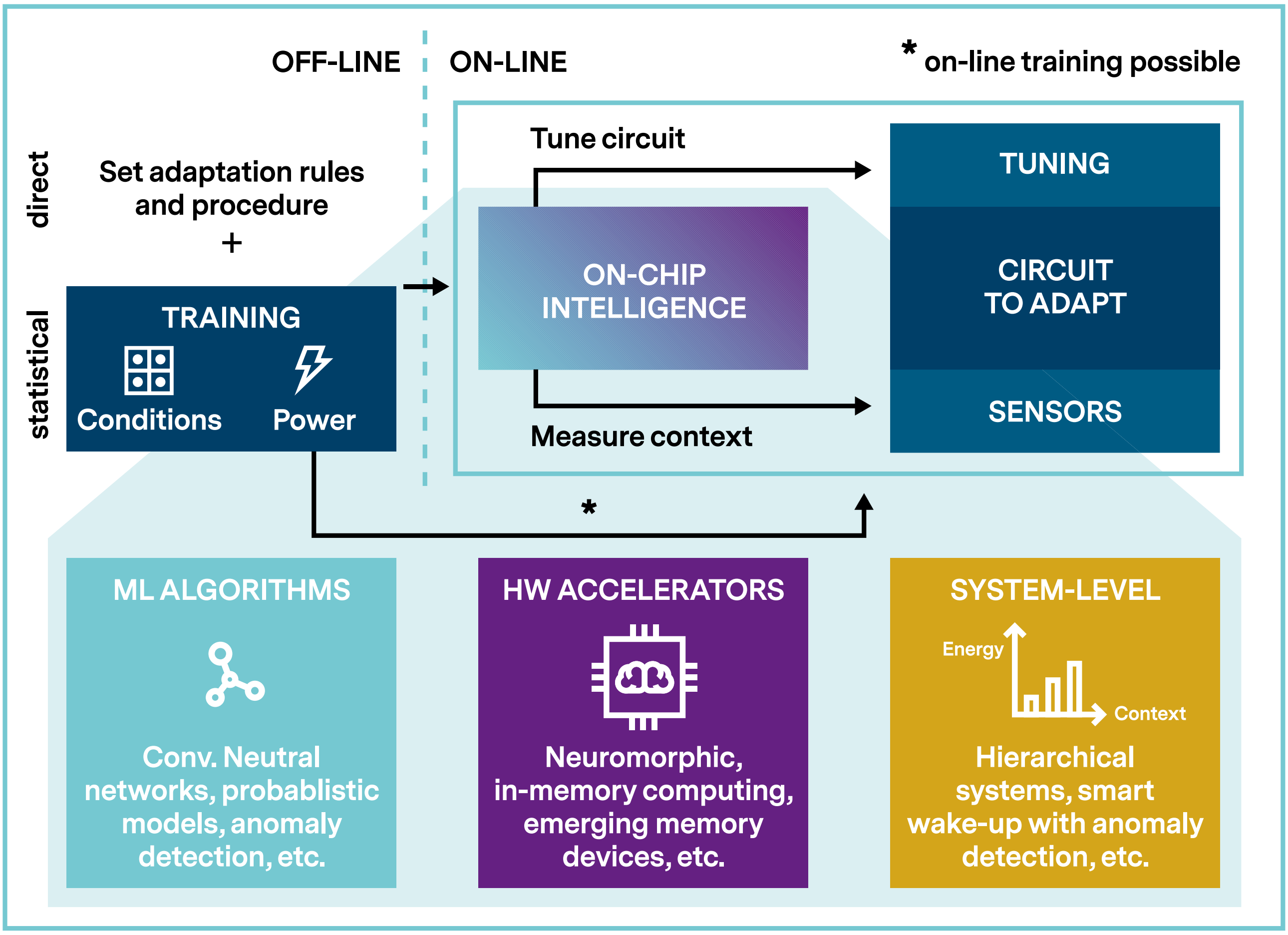


Figure 6: Illustration of possible strategies for on-chip device intelligence.

active mode, and an always-on (even during sleep) very low power consumption power saving mode (PSM) running specific processes to capture, sense and classify the available signals, including wake up signals (WUS).

A true zero-energy wake up radio (WUR) architecture consists of a specific ULP receiver path used to decode the information contained in the WUS frame and supplemented by an EH front-end path for remote powering capabilities. Its adoption must consider supplementing the legacy air interface and its PHY layer (waveform and signaling) and system-level operational paradigms required by both the ULP receiver and EH.

The power is carried by the optimized preamble of the frame which can be as simple as a single unmodulated RF carrier or a multi-tone power optimized waveform. Energy harvested from the preamble should be sufficient to decode and operate the information contained in the WUS control and body fields.

A self-powered always-on feature can also be considered, for which EH from the incoming frame is not used. Thanks to adequate frame decoding, the reachability of the MTC via paging with a negligible delay can be achieved by downlink signaling recognition. This could also make use of short duty cycling to further save power.

Whether it is true zero-energy or self-powered always-on, the WUS capture, initially introduced in 3GPP release 15 for NB-IoT and MTC devices and further enhanced in release 16 [25], necessitate a receiver with embedding adaptive blocks that can adapt themselves to the current context. Requirements for sensing quite wide frequency bands to catch the current-in-use channels while maintaining correct decoding in the presence of strong signals are expected [26]. Indeed, the power consumption may benefit from event-driven blocks, coupled with digital supervising hardware designed with wake-up capabilities.

Discriminating signaling and information spread is supported from BSs side. It can also send individually– or group–addressed WUS frames, eventually with power optimized preambles within coverage for ZE MTCs.

As an example, Figure 5 shows an MTD's battery life corresponding to the legacy maximum DRX cycles of {10.24 s, 43.69 min}, as well as to a measurement cycle of 2.56 s, and PSM on duty cycle of 25%. The figure further plots the MTD's battery life under the utilization of a ZE WUR.

With the considered parameters, a ZE WUR operating over a new ZE air interface is capable of supporting ~40 years battery life—more than three decades of device life improvement over 5G.

In the long-term, zero energy air interface is expected to support the battery-less operation of IoT/MTDs by eliminating the device batteries by further enabling limited payload data reception in the downlink direction as well as backscattering-based limited payload data transmission in the UL direction as discussed in the previous section.

Efficient hardware for on-device intelligence

One of the key enablers for the next generation of MTDs, especially in the context of cMTC use cases, is the development of on-device intelligence blocks. The term intelligence here covers a plethora of applications, usually based on AI or ML algorithms. These applications range from device adaptation regarding the operating context to save battery life, to smart compressed sensing schemes, event-driven sensor interfaces or adaptive communication protocols to optimize data transfer [27].

Embedding the required algorithmic functionalities on-chip while limiting the device's power consumption remains a challenge. Without PSM, dedicated processors are too power hungry for most embedded applications. Thus, an increased EE means designing an integrated strategy, as illustrated in Figure 6. This includes (i) the ML algorithm with training (performed on-chip or off-chip), and (ii) hardware accelerators with their associated circuitry (sensors, tuning mechanisms, etc.).

For instance, small-scale tasks (e.g. smart-wake up) would use low-power algorithms, such as probabilistic classifiers or decision trees. Meanwhile, large-scale tasks (e.g. on-device processing) would use advanced algorithms, such as deep learning. On the other hand, hierarchical systems can be designed, adapting their performance and energy with the context (e.g. cascaded classifiers) [28].

Besides, hardware accelerators are becoming neuromorphic, i.e. inspired by the energy-efficiency of the human brain. This means typically using analog processing blocks, event-driven circuits, and/or distributed memories [29].

3.3 Global Massively Scalable MTC

The success of MTC within the 6G ecosystem is tightly bound to the capability of offering globally available and massively scalable service for IoT solutions targeting a vast landscape of requirements. In this section, a number of fundamental technology enablers required to achieve this goal are highlighted.

We start with some considerations concerning global coverage, focusing on the impact of frequency regulations and on the role of NTNs, and later to span the design implications along the protocol stack. The design of efficient non-orthogonal solutions capable of handling massive traffic over GF channels, possibly without CSI is required at PHY, together with a tailored channel code design. At the medium access control (MAC) layer, the peculiar traffic characteristics of MTC applications call for both novel random access schemes and advanced (persistent) scheduling approaches. Finally, we review the implications for the higher layers.

3.3.1 Global Coverage

Frequency regulations

The principal challenge obstructing the implementation of global roaming for machines today is the discrepancy of regulations specifying the use of radio frequency spectrum in different countries. The frequency bands, the maximum transmit power, duty cycle and permitted media access mechanism(s), and even the allowed applications, may differ substantially from one region to another. This problem is especially vital for the unlicensed bands between 30 MHz and 2.4 GHz, but it also affects cellular technologies, including 5G[8]. As a part of the evolution towards 6G, moving to even higher frequency bands, which are today still mostly unregulated in many countries, provides a unique opportunity to harmonize the spectrum worldwide and thus enable global roaming. However, a strong political effort will be needed to harmonize the spectrum in the sub-GHz bands to support machine applications requiring long-range connectivity.

Non-terrestrial networks

A key enabler of true global connectivity for MTC is represented by NTN, leveraging the use of low-Earth orbit (LEO) satellites, drones, high-altitude platforms and UAVs to dynamically offload traffic from the terrestrial

[8] *https://www.everythingrf.com/community/5g-frequency-bands*
[9] *https://www.astrocast.com/*
[10] *https://www.oneweb.world*
[11] Under this general class we collect all schemes in which nodes transmit their messages without any type of pre-assignment or coordination.

system component and to reach otherwise unserved areas. First steps in this direction are already being taken within the 5G standardization, with a work- and study-item to support enhanced MBB (eMBB) and IoT services, respectively, starting from Release 17. In parallel, the market is witnessing the growth of commercial solutions providing global MTC connectivity via LEO constellations (e.g., the very low power provider Astrocast[9], high speed reliable Internet provider OneWeb[10] and Amazon's project Kuiper), prompting NTN as a fundamental component in the future of 6G [30]. From this standpoint, new engineering challenges arise, e.g. to cope with the high Doppler spread or to route information via inter-satellite or inter-drone links, calling for novel waveform and network designs. On a broader perspective, the special requirements and challenges likely to be faced by 6G to become the first mobile radio generation truly aimed at closing the digital divide and provide rural and remote connectivity are discussed in [31].

3.3.2 Physical Layer

Non-orthogonal PHY solutions

State-of-the-art solutions for efficient GF access allow multiple devices to share the same physical time and frequency resources, relying on distinguishable pilots. In the presence of mMTC, though, reliability may be jeopardized, and NOMA is one of the key solutions to solve the resource collision issue. The success of this approach depends on both user detection and data decoding on the shared resources.

With the periodic or sporadic traffic pattern of mMTC, only a small portion of devices are simultaneously active. Pilot detection can be stated as a compressed sensing problem, for which advanced algorithms like approximate message passing detection can be applied [32].

On the other hand, advanced NOMA receivers call for a careful design of the multi-user detection (MUD) algorithm as well as iterative IC structure between MUD and channel decoders. Low complexity MUD algorithms and an efficient IC structure to approach near maximum-likelihood performance while keeping the implementation cost acceptable is the key design philosophy. Examples such as expectation propagation algorithms with hybrid soft and hard IC structures have been proved to be efficient [33] in such cases. Joint user activity detection and decoding can also be further considered to optimize the performance.

While advanced NOMA has been well-researched in configured GF schemes, in other GF approaches[11], the global power control, resource allocation and configuration cannot be accomplished efficiently, calling for advancements towards uncoordinated access policies. This poses the further challenge of multi-user interference, for which the one-dimensional randomness of the power domain yielded thanks to the near-far effect may not be enough. Instead, higher-dimensional randomness including also, e.g. code- and spatial-domains should be introduced.

In code domain schemes, prior knowledge of the statistical properties of the data (e.g., constellation shape), codebook, and cyclic redundancy code (CRC) should be fully utilized for advanced blind detection [34]. Although spatial domain NOMA is quite effective in improving the spectral efficiency, the use of conventional pilots to acquire CSI causes severe pilot contamination. Possible solutions include blind (pilot-free) data-driven methods [35], channel predictions using non-RF data [36] and the enhancement of pilot design. The use of multi-pilots along with the application of strategies similar to modern random access to decode them is an example of the latter [37]. Using the theory of modern random access, a number of users approaching the pilot length can be accommodated while resolving possible pilot collision via IC.

CSI-free/limited schemes

CSI-based schemes allow compensating for the channel impairments and consequently improve the communication performance. This holds when CSI acquisition costs are negligible, as in traditional broadband-orientated services. However, that may no longer be the case under strict constraints on latency, energy, and/or when serving a huge number of devices. In such cases, new and intelligent CSI-limited approaches are required. For instance, as network densification grows towards the 6G era, the chances of operating under stronger line of sight (LoS) conditions increase, and beamforming schemes relying just on the channel statistics tend to reach near-optimum performance. Such statistical beamforming would allow valuable resources to be saved in terms of energy and time since real-time CSI acquisition can be avoided.

Coding for short packets

Error correcting codes employed in 5G NR include low-density parity-check (LDPC) codes and polar codes. The former have been tailored for the eMBB service class, whereas the latter are optimized for the transmission of control information. Both schemes require substantial adaptations to serve mMTC systems. In particular, bearing in mind the typical design choices of modern MAC protocols for mMTC, the following challenges can be identified: (i) the construction of close-to-optimal codes for intermediate block lengths (approx. from 100 bits to a few thousand bits); (ii) a strong error detection capability, possibly achieved without the overhead of an outer CRC code [38]; (iii) the design of decoding algorithms capable of handling limited or no CSI at the receiver [39]. The three identified challenges may lead to a modification of 5G coding schemes, by including profiles that specifically address the mMTC setting.

3.3.3 Medium Access

Modern random access schemes

In the presence of a massive population of transmitters with intermittent and possibly unpredictable traffic patterns, classical scheduling approaches become rapidly inefficient, due to the explosion of the required overhead. Random access solutions appear as natural alternatives, providing the demanded flexibility. Unfortunately, classical ALOHA-based medium access schemes suffer from highly limited efficiency and are thus impractical for the stringent demands of MTC in 6G.

In recent years, modern random access schemes have been proposed as an answer to such challenging questions [40, 41]. While the first schemes have focused on simple repetition of the transmitted messages and the use of IC at the receiver, more recently advanced multi-user code constructions and multi-user joint decoding have been investigated under the common umbrella of unsourced random access [42]. A thorough investigation of the practical implications of using these highly efficient schemes as a fundamental enabler for 6G MTC scenarios is still under study. How enabling user activity detection, as well as user time-synchronization, and keeping receiver complexity under control, are among the open problem in the research community.

The presence of small cells and the rising interest in mega-constellation also opens the way for exploiting the possible presence of many receivers to design efficient random access schemes [43].

Persistent grant-free scheduling and resource allocation design

The heterogeneous traffic and QoS characteristics of mMTC require tailored approaches to address different applications. While modern random access solutions are promising for IoT devices with sporadic/unpredictable traffic, periodic data and strict time-dependent QoS characteristics such as jitter and latency of various MTC applications can be satisfied by persistent GF scheduling schemes. These solutions significantly reduce the control signaling burden and provide greater QoS-provisioning efficiency and may be a strong candidate for achieving GF access for periodic, data generating, QoS-constrained, mMTC applications [44].

An architecture in which sporadic, periodic and event-driven traffic are sliced into different bands, each supported by random-, persistent- or hybrid-access schemes can be envisioned for mMTC towards 6G. Persistent scheduled access schemes could be jointly optimized exploiting PHY flexibility and multiple numerologies in order to satisfy diverse traffic and QoS requirements while achieving greater scalability [45]. Such cross layer optimization would also need to consider coexistence among multiple numerologies, orthogonal/non-orthogonal waveforms etc., and can be efficiently addressed using AI inspired solutions.

3.3.4 Impact on Higher Layers

Impact of grant-free transmission on higher layers

When GF transmission without any type of pre-assignment is employed, higher layers can be simplified without any connection state transition. How to effectively merge the multiple interactive procedures requires careful consideration. An example is shown in Figure 7 where connection-free transmission can be achieved enabling instant MTC transmissions at any time without the delay of establishing a connection.

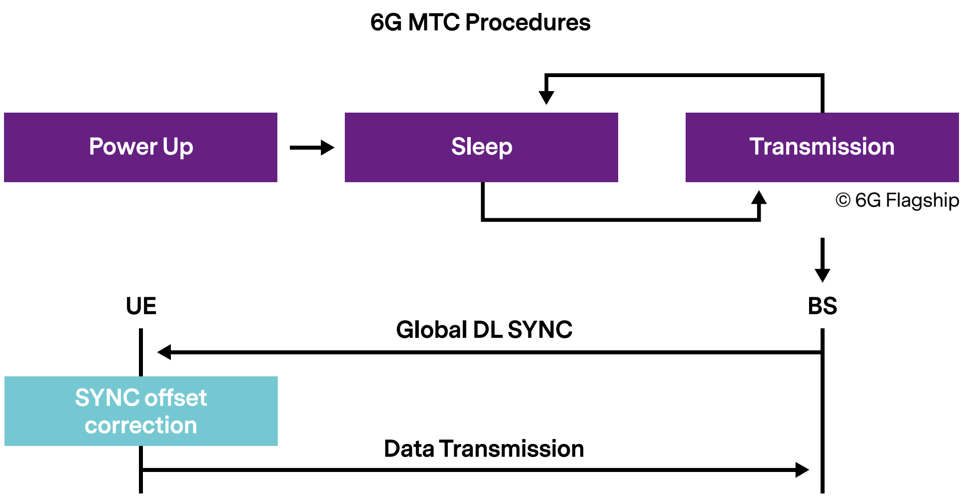
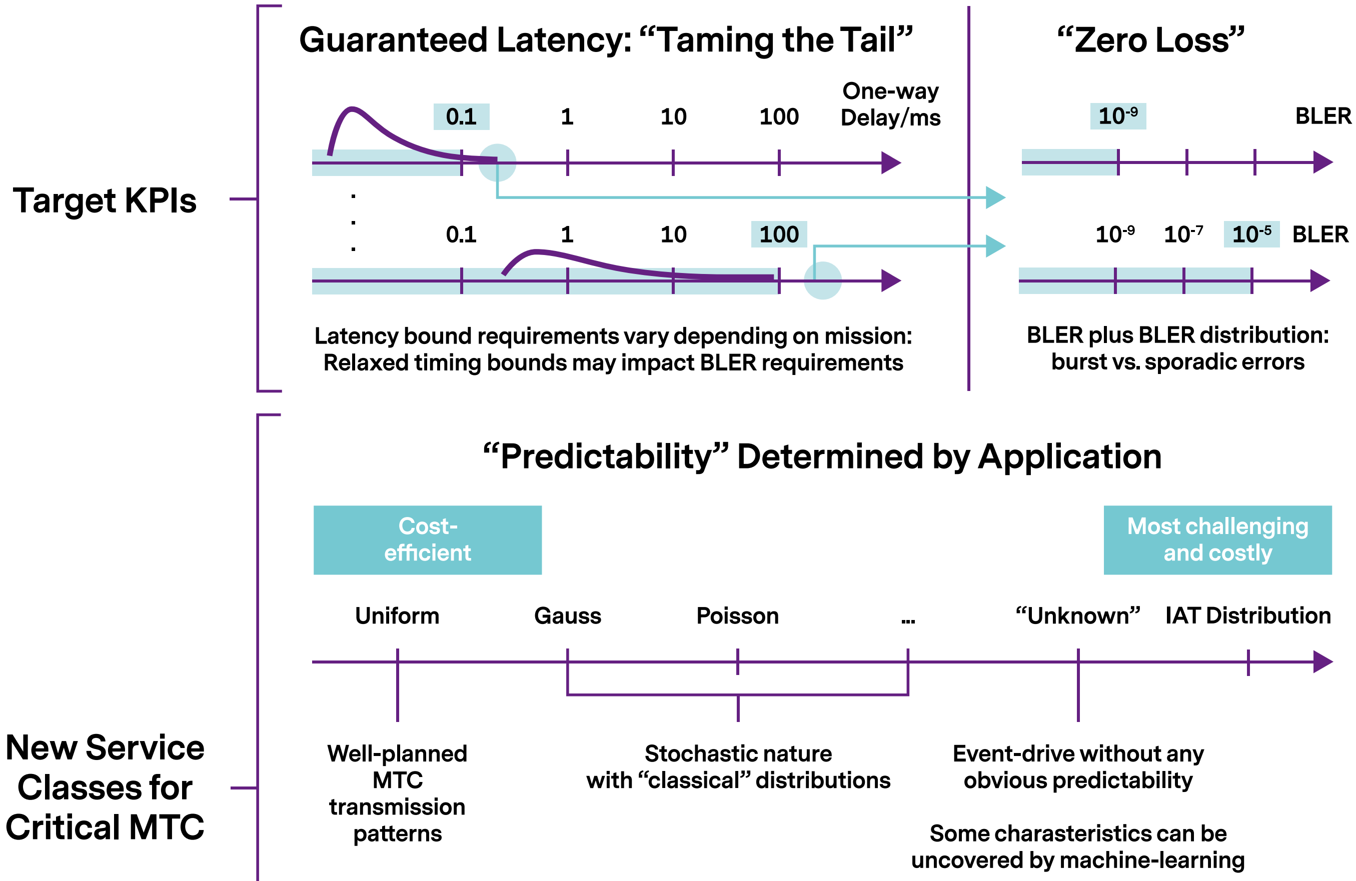


Figure 7: Simplification of higher layer operations.



Example Service Class	IAT/ms	IAT Distr.	Message Size/kB	Message Size Distr.	Laten-cy/ms	BLER	Desired BLER Distr.
cMTC -1	100	uniform	200	constant	5	10^{-9}	no burst
cMTC -2	event	unknown	10-50	unknown	0.1	10^{-9}	no burst
...							

Figure 8: Mission-critical MTC challenge: taming the tail of latency and error distribution.

However, this simplification also brings some challenges including synchronization (SYNC), privacy and security (cf. Section 3.5). To address the first issue a SYNC offset correction should be used which can exploit the information of UE status (e.g., position, speed), BS position, SYNC signals of multiple BSs, etc. It also implies that the time offset and frequency offset correction should be further investigated when the pilots of different users are randomly superimposed.

Point-to-Multipoint capabilities in 6G RAN and core networks

Point-to-multipoint (PTM) delivery is considered a suitable transport mechanism for simultaneously delivering the same content to multiple devices within the covered area with a defined and stable QoS. While an evolved multimedia broadcast multicast service (eMBMS) model can be considered a successful trend in 4G LTE for applications such as video-on-demand, it has not been considered in 5G because of its inefficiency in terms of resource utilization and energy consumption.

The support for PTM in the initial 6G design stages is therefore especially needed to address requirements of the forthcoming IoT deployments such as massive software updates. On the other hand, in current cellular IoT systems, devices still monitor service announcements, even though firmware/software updates are rare. In that sense, novel on-demand paging methods would allow 6G IoT devices not to monitor service announcements but instead to be paged to receive multicast data, thus reducing their energy consumption.

3.4 Mission Critical MTC

While 5G has already introduced mMTC for many IoT applications such as Smart City and Smart Home applications, we envisage that cMTC will be the primary focus of MTC in 6G. These applications require dependable service quality characteristics in terms of latency and error rates practically equivalent to wired communications, for example, in the context of life-critical alarm and control functions. In this sense, there is a close link to the URLLC requirements with the envisaged target KPI values of a latency bound of 0.1 ms combined with a BLER of 10^{-9}.

However, the extreme case of a very low absolute time boundary will only have practical relevance in a limited yet important number of use cases. In many other cases, higher absolute end-to-end time bounds are acceptable, as long as the corresponding violation of the time-bound—the "taming of the tail"—as well as jitter are near zero [46]. As depicted in Figure 8, some relaxation, both in terms of the absolute time-bound as well as the BLER and its distribution (burst vs. sporadic transmission), may be applicable to achieve resource-efficient and application-aware solutions [36]. Mission-criticality also mandates a very high-security level, combined with resource efficiency required in an IoT environment (cf. Section 3.5).

The current 5G approach of tweaking the system design to meet URLLC requirements, for example, through shorter TTIs and data duplication via multi-connectivity, is neither scalable nor efficient in meeting the challenges of cMTC applications. For cMTC, future 6G systems should leverage application-domain information about the predictability of actual resource requirements and conditions: while "classical" network dimensioning has had to consider the stochastic behavior of HTC through corresponding inter-arrival times (IAT) distributions of messages, the behavior of MTC can be far more controlled and eventually even deterministic. However, event-driven, emergency-like MTC needs to be especially supported by 6G systems, with no knowledge of the IAT distribution and practically unpredictable behavior. The cost of achieving certain KPIs will therefore be highly variable.

While regular transmissions can be efficiently scheduled within given time boundaries, scheduling of event-driven messages may require resource reservations and eventually lead to unused resources. AI tools can help to schedule algorithms to identify non-obvi-

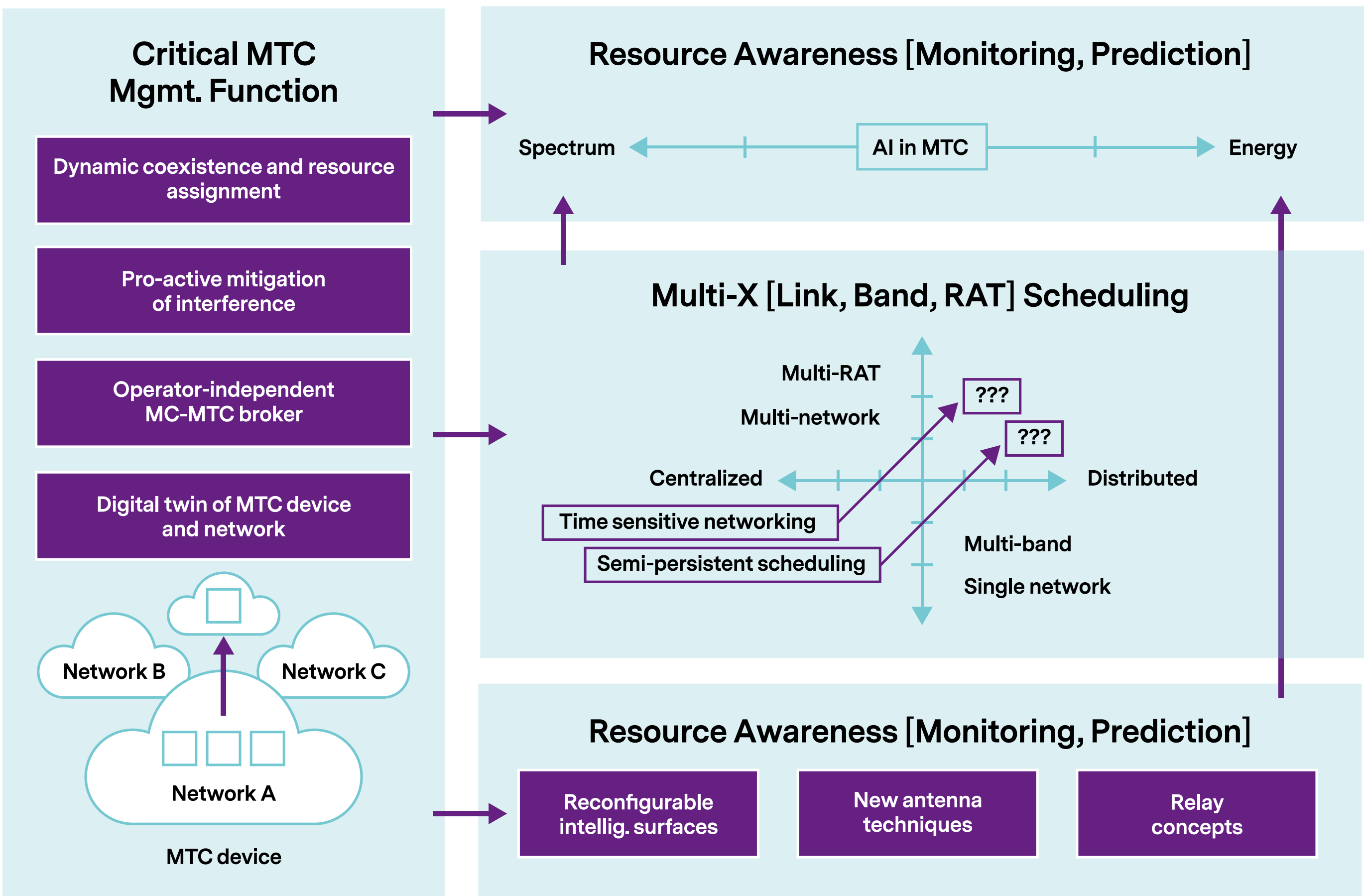


Figure 9: 6G Mission-critical MTC solution components.

ous regularities. Still, it might be a more effective way forward in 6G to allow cMTC applications to actively declare their transmission scheduling characteristics through newly introduced 6G cMTC service classes, each depending on "classical" parameters which are known from 5G, such as latency and BLER, but also on new parameters required for characterizing 6G requirements, such as predictability in terms of IAT distributions.

Based on these new cMTC-specific service classes, 6G systems need to allocate resources for cMTC appropriately within a multi-dimensional solution space comprising multi-RAT, multi-link, etc. In order to achieve solutions at acceptable costs, the absolute time bound needs to be chosen carefully and associated with a 'price tag' in terms of spectrum usage and energy consumption. To enable such decisions in a heterogeneous, non-cellular-centric environment, a dedicated cMTC management function is needed. As illustrated in Figure 9, this functionality should consider resource awareness information, gathered from devices to control the resource utilization of the networks (e.g., multi-RAT scheduling) and its environment (e.g., antennas and re-configurable intelligent surfaces (RIS)).

The key building blocks for 6G cMTC are:

Resource Awareness

The allocation of resources will require proactive monitoring of available resources and prediction of future resources for distributed user equipment as well as centralized network parts. Resource awareness should be supported by ML algorithms and new network quality parameters delivered by the various networks (such as their current load level, which is an essential criterion for resource allocation, especially in distributed MTC networks) [47].

The cMTC radio resource management function

To facilitate mission-criticality in multi-network, multi-operator, programmable wireless environments, MTDs—or a newly introduced broker functionality—need to address the trade-off between the available and estimated resources across different link options (multi-RAT) and take the final decisions about the resource choices (e.g. scheduling, RIS).

The cMTC broker function might be a new approach to off-load the resource-intensive decision process from the resource-constrained MTD. The idea of a broker function has been adopted from cognitive networking concepts, in which a spectrum broker has been introduced to manage spectrum across different spectrum owners, see for example the CBRS-Citizens Broadband Radio Service [48].

The broker function proposed to be introduced for cMTC does not only consider spectrum resources, but a broad range of radio resources, including scheduling options and the programmable wireless environment across different RATs. The broker function may also operate a digital twin of the cMTC device in the field and may act on behalf of it in order to not overload the resource-constrained MTD.

At the same time the digital twin allows for simulating and evaluating eventual decisions prior to their implementation. The idea of a digital twin corresponds well with architectural framework for ML in future networks outlined by ITU: in [49] a sandbox environment is introduced "in which machine learning models can be trained, tested and their effects on the network evaluated".

Network infrastructure and wireless environment resources

The key to achieving timing guarantees is the allocation of appropriate network resources, which can be allocated centrally or in a decentralized manner. Brute force approaches work but are highly inefficient, such as centrally assigned fixed resource reservations that might be actually used only very rarely.

More flexible approaches such as semi-persistent scheduling (SPS) and others are part of cellular vehicular to anything communication (C-V2X) and time-sensitive networking, yet they need to be evolved for 6G to work in multi-RAT and distributed environments. Finally, 6G is expected to offer not only network infrastructure components but also a programmable network environment to be controlled to serve cMTC devices.

Collision-friendly ultra-reliable transceiver design

There are many resource allocation strategies to prevent collisions via AI prediction and SPS. However, collisions cannot be fully prevented in some extreme cases where (i) the global information is missing, (ii) the network topology varies very quickly, and (iii) the transmissions are massive and frequent, e.g. high-density and high-mobility V2V in non-cellular domain. Therefore, a collision-friendly transceiver design is required to ensure reliability when collisions occur. As a collision means the transmission is randomly non-orthogonal, truly grant-free NOMA methods jointly using spatial, code and power domain can be used to separate multiple collided users, and full duplex is required to ensure the receiving reliability when the cMTC device is transmitting [50].

3.5 Privacy and Security for MTC

Privacy and security aspects play a central role in any communication network. These include anomaly detection, (low-cost) authentication, data integrity and confidentiality, and distributed trust, among others. Conventional solutions are not directly applicable to MTC networks owing to their fundamental differences, such as lack of humans in the loop, massive deployment, diverse requirements spanning across the whole cost-complexity spectrum, and wide range of deployment scenarios.

This section highlights privacy and security related issues and enablers of MTC towards 6G. Privacy and data authorization are first presented, followed by a discussion on smart contract and DLT technologies as distributed trust solutions. Finally, security issues and long-term, secure data encryption and authentication techniques are detailed.

3.5.1 Privacy

Though MTC has limited human involvement, there are some privacy threats that can be identified. In general, the threats are related to the exposition of data related to an individual's personal data in many of the identified use cases in [51]. For instance, services related to autonomous mobility may carry a person's location data (history data included), and possibly who they are with. In connected living use cases, personal data is related to personal health and in the Factories of the Future, there may be employee related data. All of these data fall under the European privacy legislation regulation (GDPR)[12]. This necessitates privacy considerations when developing MTC based solutions.

Data flow and authorization management are well-engineered technology domains, and modern solutions have been growing around OAuth: this is the building block for local trusted authorization (OAuth 2.0), identity provisioning (OpenID Connect) and user-centric, external authorization-as-a-service models (e.g., UMA - User Managed Access).

Various OAuth profiles are also under active development, e.g. for healthcare information exchange. There may be the need to develop a reference architecture for privacy management infrastructures where digitally signed consent would enable personal data to be reused between controllers under the individual's control, fulfilling the dynamic consent management related requirements of GDPR when consent is used as the legal basis of personal data processing. One such solution might be the use of the MyData approach[13].

3.5.2 Smart Contracts and DLT as Enabling Concepts

With a combination of features, DLT is a broader way of looking at digital privacy and security. Privacy and security are central to the DLT, including user identity security, transaction and communication infrastructure security, business security through transparency and auditing as well as security from malicious insiders, compromised nodes or server failure [52].

A smart contract can be defined as "a computerized transaction protocol that executes the terms of a contract" [53] where contractual clauses are translated into code. This allows a system to embed the contract clauses to enforce the contract.

Smart contracts, as part of DLT technologies, offer a way to manage privacy and authentication by design. This provides a mechanism to establish decentralized trust by eliminating the need for a third party as a medium to guarantee the transaction while assuring privacy by technology [53].

Smart contracts have been an integrated part of DLT from the very beginning, allowing contracts to be stored as scripts and transactions to be executed inside the DLT. Smart contracts are able to execute the contained code as they are triggered independently, allowing general purpose computation to occur.

From a privacy perspective, a decentralized smart contract system such as Hawk [54] does not store financial transactions in public and thus ensures transactional privacy. The main advantage is that users can write a private smart contract in an intuitive manner without having to implement cryptographic protocols, which is accomplished by the Hawk compiler.

On the other hand, Ethereum[14] allows users to write their own smart contracts and execute them in the DLT. The approach taken by Ethereum allows users to offer their services with smart contracts, where a contract is agreed upon through communication between the smart contracts of different parties.

The key research area in smart contracts for MTC are mainly two-fold. Firstly, adopting smart contracts for resource constrained IoT devices introduces some inevitable technical challenges that mandates some rethinking

[12] https://gdpr-info.eu/
[13] https://mydatafi.wordpress.com/
[14] https://www.ethereum.org/

of existing DLT/smart contact solutions. Secondly, MTC networks are conventionally uplink-oriented, with little to no peer-to-peer information exchange. Distributed trust requires a two-way data exchange between devices, introducing new requirements and design challenges for 6G MTC networks.

3.5.3 Security

Security is only as strong as the weakest link and may change over time. Based on this principle it is natural to assume that security vulnerabilities may be identified in the life-cycle of any system.

Even though designers can anticipate most vulnerabilities by design, it is not possible to mitigate all zero-day vulnerabilities or the impact of zero-day exploits. To effectively tackle this security challenge the primary step is the identification of abnormalities in the system when they occur even if it is a zero-day vulnerability.

Anomaly detection in software defined networks can be done using systems such as SPHINX. However, the SPHINX implementation is not a comprehensive solution due to limitations in detecting transient attacks, packet integrity, malicious ingress or egress switches and so on [55].

Another important aspect is the secure generation and exchange of cryptographic keys. A promising method is physical unclonable functions (PUF), which exploit physical fingerprints of devices that are inherently imposed by the manufacturing process to generate keys on-the-fly. Hence, cryptographic keys are generated on-the-fly rather than stored in a memory and thus are unknown to everyone, even the manufacturers.

3.5.4 Long-term Secure Data Encryption and Authentication

Conventional authentication, authorization and accounting processes are neither scalable nor cost-effective if directly applied to a large number of connected MTDs. For example, the traditional subscriber identity module (SIM) based authentication solution is not suitable for massive deployment of low power and/or low cost MTDs.

Lightweight and flexible solutions such as group-based authentication schemes, anonymous service oriented authentication strategies to manage a large number of authentication requests, lightweight physical layer authentication, and the integration of authentication with access protocols represent promising solutions that are likely to be adopted in 6G.

Another alternative is to use the unique properties of RF signatures (e.g., PUFs) to perform authentication. ML techniques can be used to uniquely identify and authenticate MTDs by utilizing the inherent process variation in the analog and RF properties of multiple wireless transmitters [56].

Long-term security, i.e. the protection of the confidentiality, authenticity and integrity of the transmitted and stored data, is another important aspect in MTC. In particular, the threat arising from attacks carried out on quantum computers need to be considered [11, 57]. While the security of symmetric encryption schemes such as the advanced encryption standard (AES) in the presence of quantum attacks can be recovered by adapting the key size, current asymmetric encryption, key-exchange and authentication schemes such as Rivest-Shamir-Adleman (RSA) and Elliptic-Curve cryptography (ECC) based schemes can be compromised by quantum computing algorithms.

To secure the data in MTC in the age of quantum computing, lightweight and flexible quantum computer-resistant (or post-quantum) encryption and authentication schemes need to be considered. Currently, there is an ongoing standardization drive towards quantum computer-resistant cryptosystems at the National Institute of Standards and Technology (NIST) [58].

Quantum key distribution (QKD) (also referred to as “quantum cryptography”) is another direction towards ensuring the long-term security of data. The main difference between QKD and post-quantum cryptography is that the security of QKD is based on quantum effects, whereas post quantum cryptography aims at mitigating the threat posed by quantum computers. Another important difference is that QKD requires an optical channel whereas post-quantum cryptosystems work with arbitrary channels.

Beside the use of computation-based security, such as AES, RSA, or ECC, 6G MTC may also consider physical layer security. In this case, cryptographic keys are not needed which leads to information theoretic security, where the mutual information between the transmitted data and the data received by an eavesdropper $I(X; E)$ is minimized. This type of security can be achieved by the development of coding schemes based on Polar or Raptor codes.

The interested reader is referred to [59] for a detailed discussion on the research challenges for trust, security and privacy in future 6G networks.

Conclusions

4

Assuming the trend of introducing a new cellular generation every decade holds, the 2030s will likely witness the introduction of 6G network. 5G service classes, namely URLLC, mMTC and eMBB, will be widely adopted and optimized with further enhanced requirements in 6G, while simultaneously introducing new use cases and service classes enabling the digitalization of society at large. MTC and IoT use cases will form the main backbone of a 6G network providing wireless connectivity in all aspects of our everyday lives.

This white paper provides an overarching view of MTC in the 6G era. The key drivers, potential use cases, evolving requirements and emerging service classes are first discussed. Future research directions considering different aspects of MTC considering both massive and critical MTC, ranging from the physical layer to the application layer and are then detailed in the rest of the paper.

The key synopses of the discussion are synthesized in the six research questions presented in the Executive Summary at the beginning of this white paper.

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Editors:
Nurul H. Mahmood · Onel López · Ok-Sun Park · Ingrid Moerman · Konstantin Mikhaylov · Eric Mercier · Andrea Munari · Federico Clazzer · Stefan Böcker · Hannes Bartz

Contributors:
Nurul H. Mahmood · Stefan Böcker · Andrea Munari · Federico Clazzer · Ingrid Moerman · Konstantin Mikhaylov · Onel López · Ok-Sun Park · Eric Mercier · Hannes Bartz · Riku Jäntti · Ravikumar Pragada · Yihua Ma · Elina Annanperä · Christian Wietfeld · Martin Andraud · Gianluigi Liva · Yan Chen · Eduardo Garro · Frank Burkhardt · Hirley Alves · Chen-Feng Liu · Yalcin Sadi · Jean-Baptiste Dore · Eunah Kim · JaeSheung Shin · Gi-Yoon Park · Seok-Ki Kim · Chanho Yoon · Khoirul Anwar · Pertti Seppänen

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