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REVIEW

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Machine type communications: key drivers and enablers towards the 6G era

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Abstract

The recently introduced 5G New Radio is the first wireless standard natively designed to support critical and massive machine type communications (MTC). However, it is already becoming evident that some of the more demanding requirements for MTC cannot be fully supported by 5G networks. Alongside, emerging use cases and applications towards 2030 will give rise to new and more stringent requirements on wireless connectivity in general and MTC in particular. Next generation wireless networks, namely 6G, should therefore be an agile and efficient convergent network designed to meet the diverse and challenging requirements anticipated by 2030. This paper explores the main drivers and requirements of MTC towards 6G, and discusses a wide variety of enabling technologies. More specifically, we first explore the emerging key performance indicators for MTC in 6G. Thereafter, we present a vision for an MTC-optimized holistic end-to-end network architecture. Finally, key enablers towards (1) ultra-low power MTC, (2) massively scalable global connectivity, (3) critical and dependable MTC, and (4) security and privacy preserving schemes for MTC are detailed. Our main objective is to present a set of research directions considering different aspects for an MTC-optimized 6G network in the 2030-era.

Keywords: 6G, E2E performance, Machine type communications, Random access, Ultra reliable low-latency communications, Zero-energy MTC

1 Introduction

Since the introduction of cellular wireless communication in the 1980’s, a new generation of wireless network has emerged every decade. While the first four generations of wireless networks focused on human type communications (HTC) as the primary use case, the current fifth generation (5G), known as 5G New Radio (NR), is specifically designed to serve machine type communications (MTC) along with HTC [1]. MTC allows machines to interconnect wirelessly without the need for human intervention, thereby allowing the formation of a network of interconnected machine type devices

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(MTD), also known as Internet of Things (IoT). This enables a wide spectrum of applications in various vertical sectors, ranging from connecting very simple low-cost, low-energy devices like sensors to complex networks of machines, e.g., in industrial automation use cases [2].

The wide variety of MTC use cases are grouped under ultra reliable low latency communication (URLLC) and massive machine type communication (mMTC) service classes in 5G NR. The initial 5G NR Release 15 framework includes various MTC specific designs such as shorter transmission slots [3], grant-free (GF) transmission as a low-latency random access scheme [4], and multi-connectivity for enhancing the reliability [5]. Building on this initial design, the second phase of 5G NR specified by Release 16 focuses on enhancing URLLC, e.g., through the support for private industrial IoT networks and time sensitive networking (TSN) [6].

Cellular networks like 5G NR are usually too complex, power-hungry and costly for many mMTC applications connecting simple and low-cost energy constrained devices. This specific market segment is served by low power wide area networks (LPWAN) encompassing a range of non-cellular technologies, such as SigFox, LoRA/LoRAWAN, Ingenu [4]. These networks provide low-power and long-range connectivity (up to tens of kilometers), though the data rates and the supported use cases are rather limited. On the other hand, many industrial automation use cases are enabled through different proprietary wired and wireless industrial communication networks, many of which have been around for decades [7]. However, their proprietary nature makes them inflexible with limited appeal.

The introduction of URLLC and mMTC service classes in 5G NR is seen as the first step towards designing a unified network architecture to support the wide range of MTC connectivity needs. While 5G NR and other wireless systems have enabled this under certain scenarios, the true vision of a flexible and agile all-encompassing MTC network is yet to be realized [8]. Owing to the fundamental differences between MTC and HTC, the current approach of modifying existing HTC-optimized networks to meet MTC connectivity requirements has proven to be rather inefficient and unscalable [9]. There is also a lack in considering end-to-end (E2E) aspects as part of the design, taking into account the full protocol stack from the physical layer (PHY) to the application layer, meaning a full connection between the source and the destination application layers [10].

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 sixth generation (6G) wireless network to meet the emerging requirements of 2030's. This is mainly motivated by two key factors. Firstly, a clean slate approach can lead to designing a network that can overcome the shortcomings of the existing solutions. Alongside, societal needs and emerging developments in the coming decade will result in new use cases and applications requiring MTC connectivity with more stringent and diverse requirements than those considered for existing systems [11], and hence will require the integration of multiple radio access technologies (RAT) to ensure robustness.

An initial vision of 6G is presented in [12], which is further elaborated in [13–19], among others. A comprehensive outline of the 6G research and deployment challenges beyond communication technologies are discussed in [20]. Considering a more specific perspective, potential key enablers for MTC in 6G are discussed in [10, 21]. Beyond an academic setting, the industrial sector have also started laying out their visions for 6G as evidenced by the growing number of industrial 6G white papers, e.g., [22, 23].

This paper intends to contribute to the ongoing discussions shaping *what 6G will be* by motivating a number of key research questions exploring the design of a holistic and intelligent MTC-optimized 6G network. We believe that, MTC-specific 6G key performance indicators (KPI) will be much more stringent than those considered for 5G, and include a diverse set of novel metrics not considered before. Such challenging design targets will be enabled through a combination of enhancements of existing technologies like non-orthogonal multiple access (NOMA) and GF transmissions, advanced machine-learning and artificial intelligence (ML/AI) tools, intelligent resource management algorithms [24], integration of non-cellular technologies like non-terrestrial networks (NTN) [25], and optimization of E2E service provisioning [26].

In the rest of the paper we use MTC to denote all technologies intended to be used for interconnecting versatile MTDs. Note, that this definition is more broad than the conventional definition of MTC used in 3GPP [1]. The terms URLLC and eMBB are used as they are understood in 3GPP. MTC applications requiring massively scalable connectivity with not-so-stringent latency and reliability requirements, including potential future applications not covered by current 3GPP releases, are denoted as mMTC (cf. Sect. 5). Finally, we use the umbrella term critical MTC (cMTC) to refer to the wide range of mission critical MTC use cases including URLLC and emerging *low latency hard real time communications* with strict guarantees on the dependability, jitter, synchronization accuracy and transmission delay.[1]

The rest of this paper is organized as follows. We begin by exploring the societal development and use cases pertinent to MTC towards 2030, followed by identifying relevant KPIs and requirements in Sect. 2. The holistic MTC network architecture presented in Sect. 3 provides a bird's eye view of the solution landscape and frames the forthcoming discussion. Energy efficient MTC design is presented next in Sect. 4, followed by a discussion on enablers for globally available and massively scalable MTC services in Sect. 5. Finally, mission-critical MTC serving the needs of the industrial sector and other similar verticals, and privacy and security aspects considering the heterogeneity of MTC devices and applications are discussed in Sects. 6 and 7 , respectively.

2 Key drivers and requirements

2.1 MTC drivers towards 2030

The development of MTC towards the 6G era will be led by various drivers and use cases spanning across multiple vertical sectors. Below, we highlight a few of these key drivers that we believe will have a significant impact in the coming decade.

2.1.1 Autonomous mobility

Autonomous vehicles [e.g., self-driving cars, automated guided vehicles (AGV) and unmanned aerial vehicles (UAV)] performing coordinated tasks (autonomous swarms)

[1] This roughly refers to wireless counterpart of Isochrounous real-time communication for wired industrial Ethernet.

in shop floors, in connected logistics and transport, and even as emergency response task-force, will most likely be consolidated as mainstream in the 2030 society. The number of sensors/actuators/edge systems integrated within an autonomous vehicle will increase by several orders of magnitude together with the level of driving automation [27]. This in turn increases the demand on the scale, complexity and QoS of the network connectivity, including extending the connectivity requirements to a three-dimensional (3D) landscape.

2.1.2 Connected living

By 2030, everything that can be connected, will be connected, enabled by the deployment of billions of IoT devices. Wearables like smart watches and glasses will be augmented with new seamlessly integrated devices (e.g., in clothes or implanted as skin-patches and bio-implants [19]) to usher in *smart living*. At the societal level, jobs, entertainment and public services in *smart connected cities* will rely on advanced human enhancement technologies.

2.1.3 Industry 5.0

Industry 4.0 converges digitization of manufacturing techniques through smart and autonomous systems fueled by data-driven technologies and machine learning (ML). Further evolution towards Industry 5.0 targets customized and personalized production in mixed sensing/actuation/haptics scenarios that will involve much more interactivity, including between humans and machines [28]. Industry 5.0-enabled future plants will consequently be fully agile and supported by massive connectivity of mobile and versatile production assets.

2.1.4 Full digital immersion

Advances on wireless brain-computer interactions and augmented/virtual/mixed reality (XR) will revolutionize the way we manipulate and interact with our surroundings [14]. Towards the 6G era, all human senses are expected to interact with machines through Internet of Senses, i.e., haptic interaction with sensory or perceptive feedback. This is key to enable truly immersive steering and control in remote environments.

2.1.5 Towards 'zero-energy'

Towards 2030, MTDs with limited computing and storage capabilities will mostly be energy-harvesting (EH)-powered and enhanced with ultra low power (ULP) circuit design. This is key to ensure they are *perpetually* alive, i.e., their service lifetime matches the product lifetime [29], thus mitigating the waste processing and periodic maintenance problem [30] and promoting sustainability.

2.1.6 Data as the new oil

Mining data from large-scale IoT deployments in various vertical sectors and providing value-added services empowered by artificial intelligence (AI) and distributed ledger technologies (DLT) to users, will be commonplace towards 2030 [31]. Specifically, MTC networks will expand DLT's application horizons because of the increasing need to

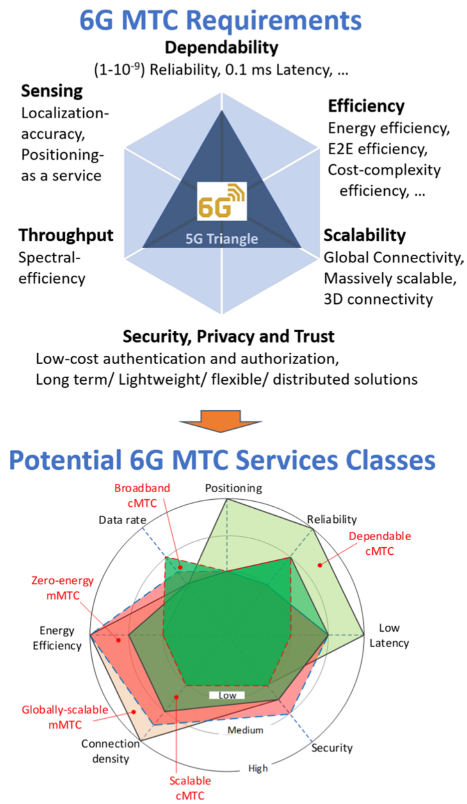


Fig. 1 MTC requirements and service classes towards 6G. Evolution of MTC requirements from the *5G triangle* to the *6G hexagon* (top), potential MTC specific service classes in 6G (bottom). The qualitative performance indicators of the potential new MTC services classes in 6G are collected from the different numbers predicted in various initial 6G vision papers (e.g., [13, 14, 18, 23])

transfer valuable, authenticated MTD data, services, or micropayments between multiple data sources/owners and other parties.

2.2 MTC requirements and emerging service classes

MTC in 5G is mainly grouped into URLLC and mMTC. The former is primarily focused on controlled environments with small-payloads and limited data rates, whereas the latter addresses large/dense deployments with sporadic traffic patterns from multiple devices. Towards the 6G era, MTC requirements will evolve to consider a more heterogeneous and multidimensional taxonomy being driven by the emerging use cases and the verticalization of the service provision discussed earlier. An overview of MTC requirements towards 6G is illustrated in Fig. 1(top).

2.2.1 Evolution of KPIs

6G QoS requirements will be more stringent than ever. The emerging need for ultra dense deployment of UAV swarms and industrial IoT devices will require 3D connectivity supporting up to 10 *connections per* m^3. Similarly, *Internet of Senses* applications and *Industry 5.0* use cases will demand high data rates with stricter reliability and latency targets than those of conventional mobile broadband (MBB) services supported by a peak spectral efficiency in the order of 40 bits per channel use (bpcu), up from around 25 bpcu in 5G NR (assuming a maximum download speed of 2.5 Gbps over a 100 MHz bandwidth).

Meanwhile, an evolution towards E2E KPIs is imperative. In industrial scenarios, this will allow real-time system optimization, collaboration between robots, and the introduction of wireless wearables and augmented reality on the shop floor. Closed-loop control applications will require E2E reliability of up to 99.99999%$(1 - 10^{-7})$ to maintain close synchronization at E2E latencies below 1 ms [32]. This in turn implies a per-link reliability of around 99.9999999%$(1 - 10^{-9})$ and user plane latency of around 0.1 ms [11].

In terms of energy efficiency, the total cost (including production, installation, maintenance and operational costs) and energy consumption per successfully delivered bit at application layer between the end devices including its environmental impact will be of utmost importance. Meanwhile, from the devices' point of view, the ultimate 6G vision is ZE MTDs, achieved through a combination of efficient ULP hardware design (supporting stand-by and active power consumption below 1 nanowatt (nW) and 1 microwatt (μW), respectively) and EH techniques [13].

2.2.2 New KPIs

In addition to above, new KPIs such as age of information (AoI) measuring information freshness (crucial for networked monitoring and control systems), interoperability (across future heterogeneous networks, and multiple access technologies), dependability and localization accuracy will play a key role in 6G system design. Dependability is an umbrella QoS term integrating the attributes of availability, reliability, security and system integrity and it will be used to characterize system life cycles and failures. Localization accuracy, which is already considered with limited applications in 5G NR, will be increasingly relevant for emerging applications using positioning as a service. Finally, another important emerging KPI is the connection set-up time, defined as the time starting from the arrival of a data packet at a transmitter until it is ready for transmission following the execution of the necessary control signaling.

A summary of the prospective MTC KPIs in 6G and their comparison with 5G KPIs is presented in Table 1.[2]

2.2.3 MTC service classes

Taking into account above requirements and foreseen use cases, we believe that URLLC and mMTC introduced in 5G NR will be further diversified into the following distinct service classes as also schematically illustrated in Fig. 1(bottom).

> *Dependable cMTC* will support extreme E2E reliability and low latency along with other measures of dependability (e.g., security) and accurate localization. This will serve use cases and applications currently considered by URLLC, e.g., autonomous mobility.

[2] Here we mix all use cases, i.e, certainly not all target KPIs are achievable at the same time (e.g. reliability and ultra low energy consumption).

Table 1 A comparison of selected MTC KPIs in 5G and 6G

KPI[a]	5G target	6G target
Per radio link reliability	$1-10^{-5}$	$1-10^{-9}$
Application level E2E reliability	*Not considered*	$1-10^{-7}$
Per radio link latency	1 ms	0.1 ms
Application level E2E latency	5 ms	$<$ 1ms
Connection set-up time	*Not considered*	$<$ 1ms
Connection density	1 device/m^2	Up to 10 device/m^3
Spectral efficiency (downlink)	$\sim$ 25 bpcu	$\sim$ 40 bpcu
Device lifetime	10 years	40 years
Energy consumption	*Low*	*Ultra-low*
Positioning accuracy	30 cm	10 cm
Jitter	1 μs	$<$ 0.1 μs
E2E optimization	*Not considered*	*Relevant*
Dependability	*Not considered*	*Relevant*

[a]There are also further 6G-relevant KPIs other than those listed here, but the community still needs to work out how to express them quantatively. One example of them is the AoI

Broadband cMTC will consider supporting MBB data with high reliability and low latency, e.g., multi-sensory XR, remote control of factories through digital twins, and robotic aided surgery applications.

Scalable cMTC will be a convergence of URLLC and mMTC, thereby supporting massive connectivity with high reliability and low latency where the reliability and latency requirements may not be as stringent as in *dependable cMTC*. Examples of potential use cases include personalized body area networks, critical monitoring of smart city applications and factory automation.

Globally-scalable mMTC refers to supporting ultra-wide network coverage throughout all space dimensions, including volumetric density of devices. The UAV swarms and NTN are fundamental enablers for global mMTC connectivity.

ZE mMTC covers massive deployments of EE radios with *perpetual* device and network lifetime, e.g., soil monitoring for precision agriculture. These will be driven by ZE radios, ULP hardware, EH techniques, backscatter communication and extreme EE resource allocation.

3 Holistic MTC network architecture

MTC RATs and their underlying architectures are today multifold and diverse. Moreover, the introduction of the new service classes and novel actors (e.g., backscatter communication, wireless power transfer (WPT) or satellites) will further diversify the technology landscape. Hence, multi-connectivity, coexistence and interoperability between multiple wired and wireless network segments should be inherent design goals of a future-proof holistic MTC network architecture. The rapid growth of the number of MTC devices happening these days makes the challenges especially timely and relevant. The key challenges and the key aspects of the holistic MTC network architecture design are elaborated in the rest of this section.

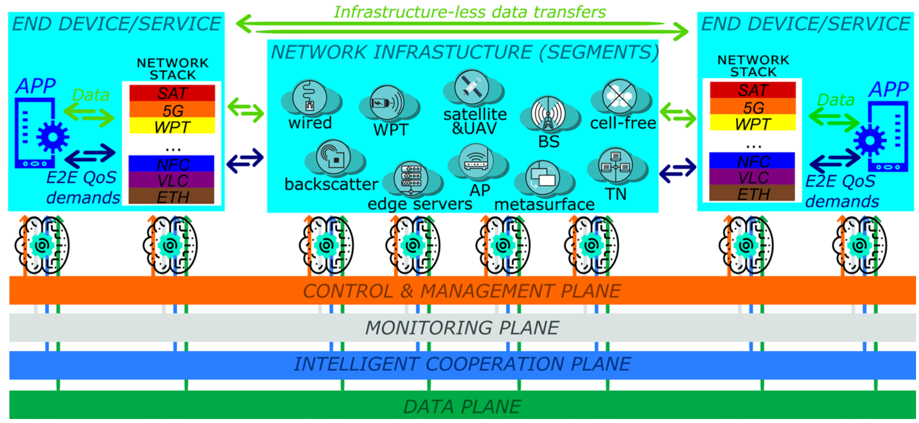


Fig. 2 MTC network architecture. Holistic MTC architecture driven by E2E QoS demands

3.1 Challenges towards holistic network architecture

Some of the new challenges arising from emerging use cases and technology developments which need to be addressed by the evolution of MTC network architecture are highlighted below.

As outlined is Sect. 2, future MTC networks need to meet a diverse range of KPIs. A single RAT cannot efficiently fulfill all these requirements, thus driving towards a multi-RAT network. Moreover, novel actors (e.g., local micro-operators [33]), types of data prosumers (producer + consumer), and infrastructure elements (e.g., NTNs or reflective surfaces) will further increase of the connectivity landscape heterogeneity.

Secondly, the introduction of concepts combining communication and other objectives (i.e., “beyond-connectivity” technologies) will require the network to share system resources for multiple (and possibly conflicting) objectives. As an illustrative example, wireless energy transfer (WET) technologies have the potential to enable sustainable and ubiquitous delivery of energy to a number of end devices, alongside conventional information transfer [34].

Another relevant development is the cell-free networks implying no connection pre-establishment between an MTD and its serving base station [35]. This approach allows reducing the signalling load, and can improve reliability by allowing several receivers to demodulate the uplink transmissions. This trend will be important for both micro- and nano-cells, which will appear due to the further increase of the carrier frequencies towards Terahertz bands; and for drones and NTNs [36].

Finally, the need for supporting highly dynamic and, as one extreme, cell-free MTC networks, is especially crucial in the context of the critical missions and operations in the areas with poor coverage or no connectivity, leading to a much more fluid and dynamic, potentially even “virtual”, network architecture.

3.2 Holistic MTC network vision

The envisaged holistic MTC network architecture is illustrated in Fig. 2. The architecture composes several layers, aiming to enable highly efficient dynamic utilization of the available resources and providing distributed intelligence at different levels (e.g., cloud, edge, end devices, and applications) while featuring software-defined easy-to-upgrade design [37].

The efficiency of the network is empowered through open and generic technology-agnostic interfaces for dynamic and collaborative orchestration between communicating E2E applications across multiple heterogeneous networks and "beyond-connectivity" domains. These interfaces should be designed in a technology-agnostic[3] and vendor independent way, meaning that the E2E applications will expose their demands and wishes to the network without having any knowledge of underlying technologies or vendor specific features.

Using open, technology/operating system agnostic and vendor independent interfaces allow easy collaboration between distributed agents in different network segments, leaving full freedom for participation by different actors (also smaller industrial players and end users) in the innovation process. It also allows easy integration of future technologies, simplifies the standardization processes, and democratizes innovation of QoS-aware applications.

Implementation-wise, the algorithms running on top of the open, generic descriptive interfaces for inter-segment coordination, negotiation and collaboration should be made open. Meanwhile, the intra-segment algorithms used for fine-grained resource allocation within a segment could be proprietary as long as the right level of information is exchanged via the open, generic interfaces and the local intra-segment orchestration meets the QoS targets. The algorithms will operate based on the E2E QoS requirements of the currently active and future applications, the environment situation, and the fairness considerations. ML and AI is a potential powerful tool to tackle this challenge.

Addressing the highly dynamic future connectivity challenge requires optimization of the scarce resource centrally, locally by individual devices or at the network edge. Efficient and pro-active mechanisms to sense the environment, predict the devices' needs and the communication channels coupled with distribution of optimization tasks across distributed mobile agents represent a viable way of implementing such wide-scale optimization. Importantly, the amount and granularity of the information collected, the speed of control loops, and the target prediction depth also have to be carefully selected. To give just one example, the central optimizations can be based or course-grained information and non-time-sensitive control loops, while more time-sensitive control loops can happen closer to the edge based on more fine-grained and localized context-aware information.

The holistic MTC architecture should feature both backward compatibility and future proofness not just for a single network operator, but also across different operators and administrative domains. Simultaneously, the interoperability across heterogeneous network technologies and their versions and releases must be ensured. The softwarization

[3] Technology in 'technology-agnostic' refers to any wired or wireless connection technology along the E2E patch between communicating applications. A 'technology-agnostic' interface means that the interface does not depend on a specific connection technology specification. Application and network interact in an expressive (descriptive) way. As such the application developer does not require any knowledge on the underlying connection technology specifications. No matter which underlying technologies, the application can express its end-to-end communication needs to the network. For example, the application does not have to be aware of the specific traffic or QoS classes supported by the underlying networks along the end-to-end path. The translation of application demands (communicated to the network in a descriptive way) and the mapping to traffic or QoS classes supported by underlying network technologies will happen transparently to the application.

of both radio and network-level functions, enabling their time- and cost-efficient updates and allowing the efficient introduction of the functionalities, in combination with open technology-agnostic interfaces represents a feasible way forward.

Last but not least, it is of pivotal importance to agree on the interoperable interfaces: (1) between application(s) and network(s), and vice versa, (2) between orchestrators of network segments (in the intelligent cooperation plane in Fig. 2), and (3) networking services access points or inter-segment ingress and egress gateways (in the data plane in Fig. 2). The holistic MTC architecture allows more freedom for implementation, monitoring, control and management within network segments compared to 5G, and limits the role of standardization to defining how information is exposed between distributed agents across segments in the intelligent cooperation plane. The involvement of many new actors and a significant extension of the coverage beyond connectivity, would also likely require revision of the current standardization practices in order to make these more efficient and transparent.

4 Energy efficient MTC devices

Energy efficiency is a central theme of 6G design considerations from its inception with the ultimate goal of making battery-powered operation obsolete for a majority of simple devices. Different radio technologies and architectures for energy efficient design are elaborated in this section.

4.1 Ambient backscatter communications

Ambient Backscatter Communications (AmBC) [38] is a promising new technology towards ZE mMTC. In AmBC, the device communicates by controlling the reflection coefficient of its antenna. The simplest possible modulator circuit consists of a switch and a load impedance in parallel. When the switch is closed, the device reflects the ambient signal impinging at its antenna and when it is open, the signal is absorbed by the load. Such a backscatter device consumes three orders of magnitude less power than typical active transmitter since voltage-controlled oscillators and power amplifiers are not needed. This also helps in reducing the device cost [39]. Potential use cases of AmBC in IoT scenarios include smart life [40], logistics [41], and biomedical applications [42].

However, an AmBC system needs to be carefully designed to fully realize its potential. The direct path interference is among the main technical challenges in using AmBC for MTC. The signal from the legacy transmitter can be several orders of magnitude stronger than the ambient signal, and hence needs to be canceled, e.g., in the spatial domain using null steering. On the other hand, the interference caused by AmBC transmitter to the legacy receiver depends on the legacy system design. For example, in the case of orthogonal frequency division multiplexing (OFDM) based legacy system, AmBC causes interference only if its symbol duration is short compared to the OFDM symbol duration [43]. Furthermore, the pathloss of AmBC system is inversely proportional to the fourth power of the utilized carrier frequency, severely restricting operations at higher frequencies (in the GHz range). The AmBC system model with the different involved links is shown in Fig. 3(top, left).

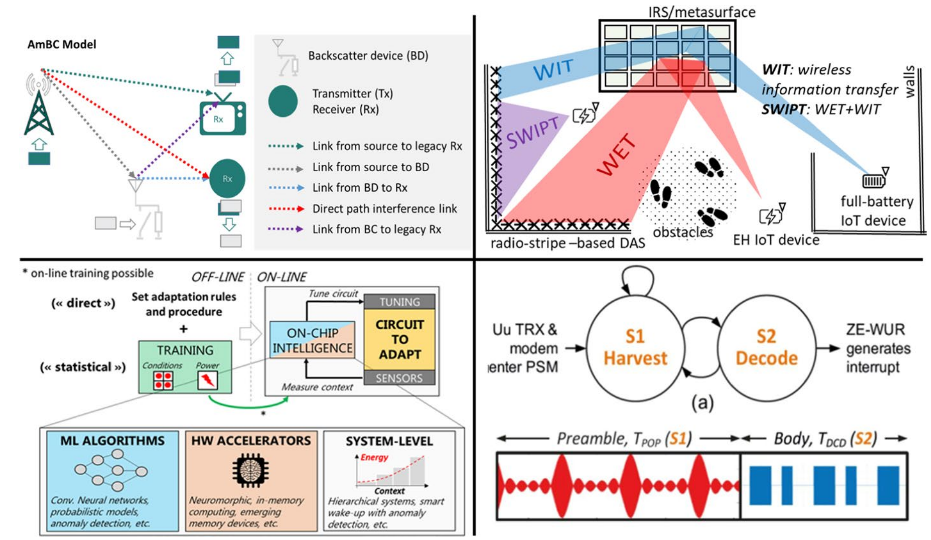


Fig. 3 Zero-energy MTC enablers. AmBC system model (top, left); Radio stripe and IRS-enabled efficient WET (top, right); Illustration on possible strategies for on-chip device intelligence (bottom, left); and Illustration of the ZE air interface operation (bottom, right)

4.2 Wireless energy transfer

AmBC systems enable low power communications by getting rid of active RF components. However, communication is not the only power consumption source in many MTDs, specifically those running relatively more complex sensing, data processing and actuation tasks. In such cases, special emphasis should be given to optimize EH such that it can provide the appropriate amounts of energy to power the device. Due to the limitations of EH based on natural energy sources like sun, dedicated RF WET has emerged to power more demanding MTDs with dependable QoS guarantees.

WET is currently being considered, analyzed and tested as a nascent stand-alone technology, and its wide integration to the main wireless systems can be envisioned in the coming years. However, increasing the E2E efficiency, supporting mobility at least at pedestrian speed, facilitating ubiquitous power accessibility within the network coverage area, resolving the safety and health issues of WET systems, compliance with regulations, and enabling seamless integration with wireless communications are the main challenges ahead [34].

Distributed antenna systems (DAS), the strategic deployment of metasurfaces and/or passive intelligent reflective surfaces (IRS), and energy beamforming (EB) schemes are among the most appealing techniques to enable WET as an efficient solution for powering future IoT networks [34, 44]. Due to their strong potential to eliminate blind spots and support ubiquitous energy accessibility, IRS/metasurfaces everywhere, and new DAS deployment scenarios such as the cost-efficient radio stripe systems [45], will play a key role in future WET-enabled networks. On the other hand, EB allows the transmitted signals to adapt to the propagation environment, thus optimizing the wireless energy delivery. In particular, CSI-limited EB schemes are especially appealing [46], and should be investigated in the DAS and IRS context as well.

4.3 Zero-energy and ultra-low power radios

Reducing the device energy consumption through ULP transceiver design is especially relevant for simple MTDs requiring sporadic transmissions of a small payload. The energy consumption of the entire MTD needs to be holistically optimized rather than considering the EE of individual elements like antennas and radio frequency (RF) transceivers separately. This can be done by compactly integrating the different elements and optimizing the interfaces between them. Furthermore, smaller radiating elements with narrower bandwidth that has better selectivity and stronger robustness to blocking signals can be beneficial, while band filtering can be split along the whole chain, from the antenna to the embedded digital intelligence. At the receiver end, it is important to consider the performance of the receiver chain as a whole while ensuring robustness to a wide-spectrum of operation.

Given the sporadic nature of many MTD transmissions, EE can also be achieved by designing an efficient sleep mode coupled with effective wake up architecture. This requires ULP operation when the device is active and a true ZE wake up architecture consists of a specific ULP receiver path used to decode the information contained in the wake up signals (WUS). It can be further supplemented by an EH front-end path for remote powering capabilities. The WUS can be made self-powered by including a power optimized preamble such that the device can harvest enough energy from it to decode and operate the information contained in the WUS control and body fields. An example of the ZE receiver architecture and the ZE air-interface operation is depicted in Fig. 3(right).

4.4 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. Typically, they intend to make the device adaptable to the current context, i.e., to optimize performance and power consumption to the current requirements, with the main objective of saving battery life [47]. Enabling on-device intelligence while limiting the device's power consumption remains a challenge [48], and hence a holistic strategy needs to be adopted, as illustrated in Fig. 3 (bottom, left). This potentially includes the adoption of ML algorithm with associated training (performed on-chip or off-chip), a hardware accelerator with associated circuitry to embed the ML algorithm, and a system-level strategy to adapt to the current context (workload, channel conditions, etc.).

In terms of strategy, context-adaptive systems usually trade off performance and energy consumption according to the perceived context. An example is the use of hierarchical systems with several stages activated only when the context and application require them (e.g. cascaded classifiers, dynamic circuit architectures) [49]. The adaptation can also happen at a higher level, for instance by selecting different communication protocols or communication speeds [47]. In terms of ML, the adopted algorithm should be task-dependent. Small-scale tasks (e.g. smart-wake up) should use low-power algorithms such as probabilistic classifiers, whereas more advanced algorithms such as deep learning based on neural networks are more suitable for large-scale tasks (e.g. on-device processing). Besides, hardware accelerators embedding the ML algorithm are becoming neuromorphic, i.e. inspired by the human brain's EE, which has the potential to substantially enhance the EE [50].

5 Massively scalable MTC

Massive MTC is characterized by a large number of simple devices with sporadic and small payload. The evolution towards 6G will witness the expansion of the design goals to include global availability and massive scalability, while providing efficient connectivity. This section details a number of fundamental technology enablers towards this aim, starting with the role played by NTNs. PHY considerations for designing efficient solutions capable of handling massive traffic are presented next, followed by the introduction of novel random access schemes and advanced (persistent) scheduling approaches at the MAC layer. Finally, we review the implications of point-to-multipoint (PTM) delivery on the core network.

5.1 Non-terrestrial networks

A key enabler towards true massive connectivity for MTC is represented by NTN, leveraging the use of low-Earth orbit (LEO) satellites, high-altitude platforms and UAVs. Within 6G, such additional network components can not only be adopted to dynamically offload traffic from the terrestrial infrastructure, but also to truly provide IoT service in otherwise unconnected or under-connected areas. Typical vertical sectors that could see dramatic improvements in this sense are maritime, farming, transportation and energy, among others.

The first steps in this direction are already being taken within 5G NR standardization. These efforts are so far focused on the adaptation of the existing waveform to cope with distinct propagation and latency conditions. Nonetheless, more profound modifications and waveform advancements may be a key challenge within 6G to reap the potential of NTN for massive MTC at its utmost. This is confirmed by the growth of novel commercial solutions providing global MTC connectivity via LEO constellations being witnessed in the market, with a revived interest in mega-constellations, i.e. satellite systems with hundreds or even thousands of communication satellites, guiding the so called *New Space* revolution.

It is thus becoming clear that NTN is a cornerstone component for the future 6G [25]. Coupled with the indubitable advantages, new engineering challenges arise. Coping with high Doppler spread or routing information via inter-satellite or inter-drone links call for novel waveform and network designs. Exploiting the presence of a large number of non-cooperative or cooperative receivers calls for multiple access techniques efficiently taking advantage of the additional diversity [51, 52].

5.2 Non-orthogonal PHY solutions

State-of-the-art solutions for efficient GF access allow multiple devices to share the same physical time and frequency resource separated through the use of orthogonal pilots. However, due to the sheer number of mMTC devices, it is not possible to assign orthogonal pilots to each individual device, requiring pilots to be reused. Pilot contamination is usually addressed by considering pilot detection as a compressed sensing problem, for which advanced algorithms like approximate message passing detection can be applied [53].

NOMA has emerged as an alternative solution to solve the resource collision issue in GF access by separating transmissions in the code or power domain. Advanced NOMA receivers call for a careful design of the multi-user detection (MUD) algorithm as well as iterative interference cancellation (IC) structure between MUD and channel decoders. The key principle is to design algorithms approaching the performance of maximum-likelihood detection at acceptable implementation cost, e.g., the expectation propagation algorithm proposed in [54]. Joint user activity detection and decoding can also be further considered to optimize the performance.

In code domain schemes, prior knowledge of the statistical properties of data (e.g., constellation shape), codebook, and cyclic redundancy code should be fully utilized for advanced blind detection [55]. Although spatial domain NOMA is quite effective in improving the spectral efficiency, the use of conventional pilots to acquire channel information causes severe pilot contamination. Possible solutions include blind (pilot-free) data-driven methods [56], channel predictions using non-RF data [9] and the enhancement of pilot design [57].

5.3 Modern random access schemes

Classical four-way handshake based scheduling approaches are neither scalable nor efficient for mMTC services where a massive number of transmitters send data intermittently and possibly with unpredictable traffic pattern. GF solutions based on the preemptive assignment of resources as proposed in 5G, also may become inefficient or entail unwanted latency. Uncoordinated random access solutions, where devices transmit data directly without first acquiring a transmission grant, appear as natural alternatives. In recent years, modern random access schemes [58] have been proposed focusing on simple repetition of the transmitted messages and the use of IC receivers [59, 60]. More recently advanced multi-user code constructions and MUD algorithms have been investigated [61–63] under the common umbrella of unsourced random access.

Further investigations on some of the practical implications is ongoing to render these very schemes as fundamental enablers for 6G MTC scenarios. Open problems in the research community include, detecting user activity, maintaining user time-synchronization, and keeping receiver complexity under control.

Finally, the tight connection between PHY and the medium access policy can only be harnessed by a dedicated error correcting code design. 5G NR employs low-density parity-check (LDPC) codes and polar codes as error correcting codes for eMBB services and the transmission of control information, respectively. However, none of these schemes are directly suitable for mMTC services, and require to be substantially adapted. The main challenges in this case are: (1) constructing efficient codes for short packet sizes ($\sim 100 - 1000$ bits); (2) achieving significant error detection capability at low overheads [64]; and (3) designing decoding algorithms that can operate with limited/outdated or no CSI [65]. Hence, moving towards 6G, there is a need to introduce codes specifically tailored for mMTC services that addresses the emerging challenges.

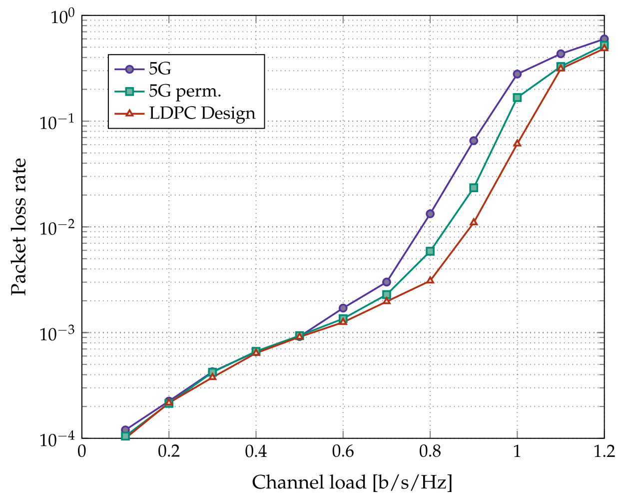


Fig. 4 Slot-asynchronous random access schemes performance. Slot-asynchronous random access schemes adopting time diversity, i.e. copies of the same physical layer packet are transmitted with random delays, and interference cancellation. It is shown that a dedicated low-density parity check (LDPC) code design outperforms standardized 5G error correcting codes. Details on the modern random access scheme and the code design can be found in [67, 68] respectively

An instance of the achievable gains of a dedicated error correcting code is reported in Fig. 4, focusing on the slot-asynchronous[4] GF access [67] case. The plot exemplifies how the standardized 5G codes, as well as an enhanced version thereof relying on an optimal interleaving to protect packet portions more prone to interference (the *5G perm.* curve), can be significantly outperformed by a tailored design. In this case, improvements are brought by a LDPC code (the *LDPC Design* curve) specifically devised to cope with the interference structure induced by the medium access control strategy (more details can be found in [67, 68]).

5.4 Persistent grant-free scheduling and resource allocation design

Modern random access schemes are a promising approach for applications with sporadic and unpredictable transmissions. On the other hand, the complex MTC ecosystem also foresees use cases where device traffic generation can be reliably predicted, as well as applications posing strict guarantees on time-dependent metrics such as jitter and latency.

In such scenarios, GF schemes such as semi-persistent scheduling, where exclusive transmission grants are pre-allocated to match the known/predicted traffic generation pattern, become especially appealing. These solutions reduce control signaling overhead and enable greater QoS-provisioning efficiency [69].

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

[4] In small-cell scenarios and considering a 5G-like waveform, the slot-asynchronous reception of packets may be within a cyclic prefix and can be accounted for with a careful waveform design coupled with suitable synchronization algorithms [66]. When larger cell scenarios came into play, delay exceeding a cyclic prefix may be experienced and proper synchronization techniques shall be adopted, e.g. based on correlation and alike.

be envisioned for mMTC towards 6G. Greater scalability can be achieved by exploiting the differences in the traffic and QoS characteristics across the different slices to jointly optimize the allocation of resources and meet the diverse requirements [70]. Such cross layer optimization also needs to consider the coexistence among multiple numerologies as well as orthogonal/non-orthogonal waveforms, and can be efficiently addressed using AI-inspired solutions.

5.5 Point-to-multipoint capabilities in 6G RAN and core networks

Sometimes a common message needs to be delivered to multiple receivers within a given area with a defined and stable QoS, e.g., in the case of firmware update, or broadcasting some common system information to the served users. PTM delivery is a suitable transport mechanism for such broadcast type transmissions, e.g., evolved Multimedia Broadcast Multicast Services (eMBMS) (also known as LTE Broadcast) specified in 4G LTE for applications such as video-on-demand. However, PTM interface has not been considered in 5G because of its inefficiency in terms of resource utilization and energy consumption.

The support of PTM from 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, the devices are still monitoring 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 the energy consumption.

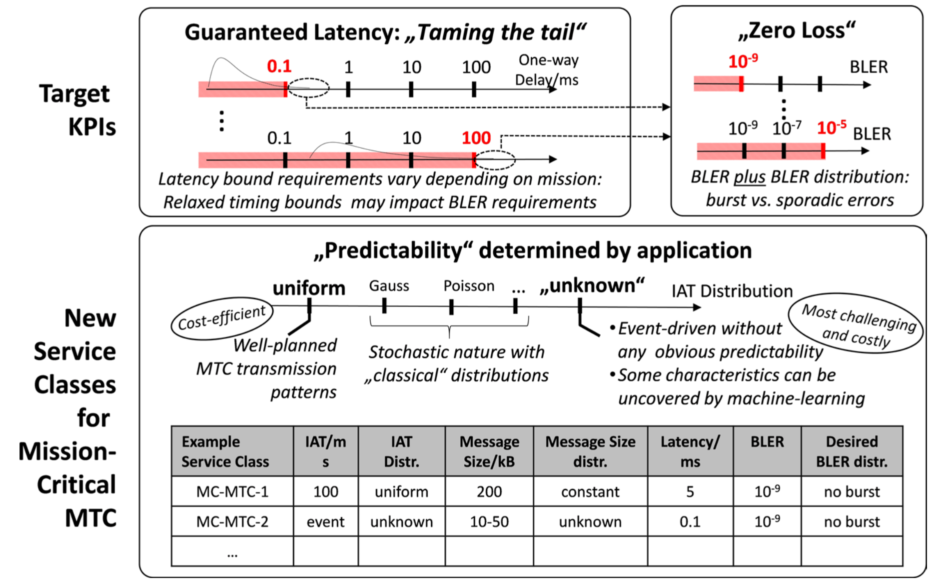
6 Mission critical MTC

In contrast to massive MTC, characterizing a steadily increasing number of distributed IoT devices with moderate requirements per node, mission-critical MTC imposes new, exceptionally demanding reliability requirements. Thus, this sections highlights diverse challenges and future aspects of mission-critical MTC on 6G enabling technologies. First, the need for new service classes and its characterization is discussed, highlighting the need for future 6G systems to leverage application-domain information about the predictability of resource requirements and conditions. Finally, a short overview of potential key building blocks for 6G cMTC is presented.

6.1 New service classes characterizing mission-critical MTC in 6G

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. This trend is further fueled by the emergence of dynamic cyber-physical systems (CPS) where time and safety-critical functionalities are distributed to the (edge) cloud, thereby resulting in cause-and-effect chains spanning multiple distributed embedded compute and wired/wireless communication resources [26].

Those applications require dependable service quality characteristics in terms of latency and error rates, for example, in the context of life-critical alarming and control, practically equivalent to wired communications. In this sense, there is a close link with



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

Fig. 5 Mission-critical MTC challenges. Mission-critical MTC challenge: *taming the tail of latency and error distribution*

URLLC requirements with its envisaged target KPI values of a latency bound of 0.1 ms combined with block error rate (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 cases, higher absolute E2E 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 [71]. As depicted in Fig. 5, 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 [9]. Mission-criticality also mandates a very high-security level, combined with resource efficiency required in an IoT environment (cf. Sect. 7).

Providing formal guarantees for cMTC requires analyzing the interference effects on shared resources to compute timing bounds on the link level latency of individual applications. However, bounding the timing effects of shared resources requires a careful analysis of requests arrival (inter-arrival times) at every resource and its corresponding scheduling policy. This is particularly challenging in 5G networks as both applications and resources are highly dynamic, especially when mobility is involved. Applications and resources (Multi-X) integrate and leave the system dynamically, thereby creating variable available services and variable available application loads. Formal guarantees for cMTC can be provided if both applications requirements (e.g. predictable inter-arrival times) and available resources are known or predicted apriori. Resources also need to be trusted to provide the required service and meet the applications requirements.

The current 5G approach of tweaking the system design to meet URLLC requirements, for example, through shorter transmission time intervals (TTI) 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

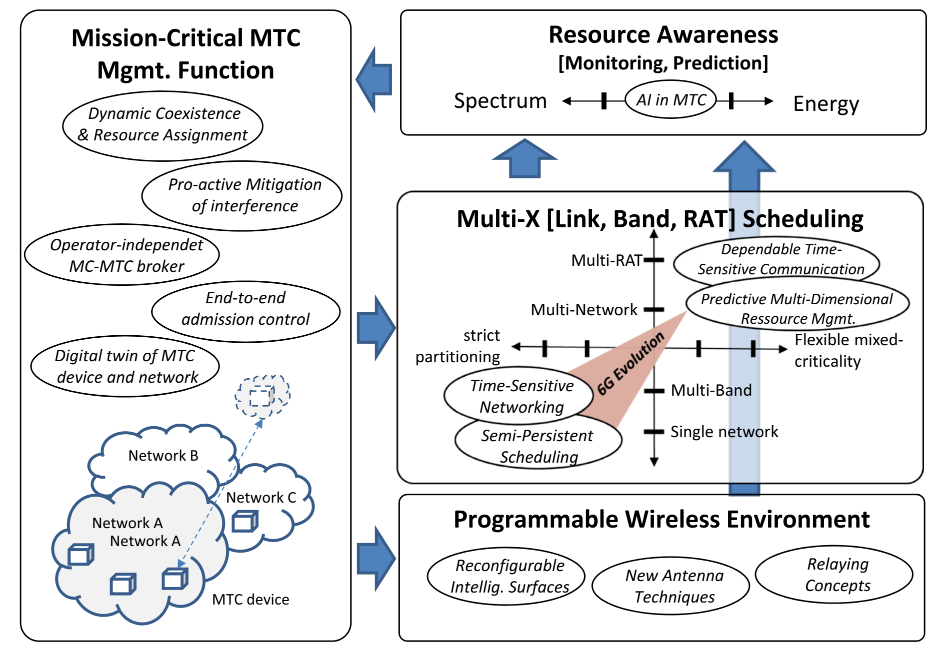


Fig. 6 6G cMTC enablers. 6G Mission-Critical MTC Solution Components

information about the predictability of actual resource requirements and conditions. While "classical" network dimensioning had to consider the stochastic behavior of humans through corresponding Inter-Arrival Times (IAT) distributions of messages, the behavior of MTC can be far more controlled and eventually even deterministic. Yet, especially event-driven, emergency-like MTC need to be supported by 6G systems, with unknown knowledge of the IAT distribution and practically unpredictable behavior. The cost of achieving certain KPIs will be very different.

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 can help to schedule algorithms to identify non-obvious 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 not only on "classical" parameters 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.

6.2 Outline of potential key building blocks for 6G mission-critical MTC

This section outlines key drivers that will be integral in enabling cMTC services in future 6G networks. In this context, Fig. 6 is illustrating key building blocks that are grouped in four cross-linked overarching cMTC network functionalities. Key building block functionalities are detailed below. Based on those new cMTC-specific service classes, 6G systems need to allocate resources for mission-critical MTC appropriately within a multi-dimensional solution space comprising multiple RATs, multi-link, etc. In order to achieve solutions with acceptable cost, the absolute time bound needs to be chosen carefully and associated with a 'price tag' in terms of spectrum usage, energy consumption, computational resource requirement, etc.. To enable such decisions in a heterogeneous, non-cellular-centric environment, a dedicated cMTC management function is needed. As illustrated in Fig. 6, this functionality considers resource awareness information, gathered from devices to control resource utilization of the networks (e.g., multiple RAT scheduling) and its environment (e.g., antennas and IRS).

The allocation of resources will require proactive monitoring of available resources and the prediction of future resources for distributed user equipment as well as centralized network parts. Resource awareness should be supported by ML 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) [72].

The "on-time" delivery of information as quantified by novel metrics like AoI is another important aspect of cMTC management function [73]. Today's wireless networks are lacking decent fine time granularity and scheduled networking capabilities, also called TSN features. Contrary to wireless networks, wired TSN supports time-sensitive applications using a number of features, such as: strict time synchronization, (semi-)persistent scheduling, flow filtering, transmission preemption of less sensitive flows, etc. [74]. In 5G, the first steps towards bounded latency are taken, but many issues, in particular related to synchronization, remain unresolved. To address TSN capabilities in future 6G MTC networks, tighter interactions between networks and application, and low-overhead verification of such interactions will be required. In case of time sensitive applications, determinism should be maintained during the whole operation time. Therefore, the network should be able to interpret application requirements and assess to what extent it can meet those requirements.

The cMTC management function can also be responsible of accommodating E2E admission control and time synchronization when successive dependent resources are involved. An application must generally acquire several heterogeneous shared resources, with independent arbiters and often provided by different vendors/providers. Moreover, resources may not be reserved in advance, i.e. packets are switched as soon as they arrive. Centralized E2E admission control [75] can be used as an alternative method to provide applications with a global resources arbitration. This allows to decouple the data transmission layer from the control layer responsible of flow admission and scheduling decisions. Arbitration between multiple applications is then shifted from individual (sub) resources to a centralized control unit which has a global view of the system (i.e., both applications and resources). E2E admission control allows additionally to simplify analytical timing analysis models that are used to bound interference effects and compute timing guarantees on the the E2E latency of individual transmissions.

7 Privacy and security for MTC

The highly heterogeneous requirements from the major categories of MTC make security and privacy a major concern towards 6G. Conventional security and privacy solutions are not directly applicable to MTC networks owing to their fundamental differences. Instead, lightweight, efficient and application-specific solutions addressing the

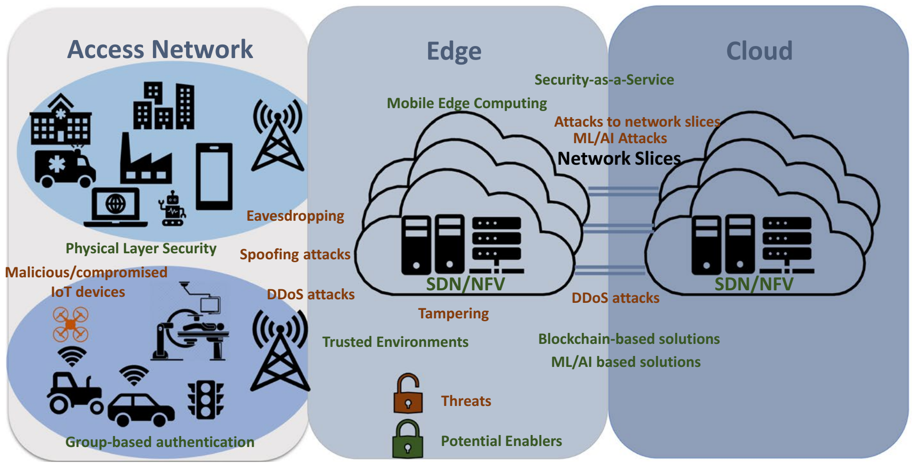


Fig. 7 6G security solution landscape. Security landscape for 6G MTC networks

divergent requirements of mMTC and cMTC networks are necessary. Figure 7 provides an overview of different security threats and potential counter mechanisms across an MTC network.

7.1 Related challenges in next generation MTC networks

7.1.1 Challenges in security

Advances in ML and AI techniques, expected to be a dominant part of 6G wireless networks, introduce a new dimension of security challenge in next generation MTC networks. Sophisticated attacks like distributed denial of service and proximity service intrusions can be orchestrated by harnessing advanced ML and AI techniques. The adoption of edge and cloud-based data storage and networking leads to increased exposure to such attacks, thereby further exacerbating these vulnerabilities. In addition, the problem of authentication will be especially relevant for future MTC networks. With billions of connected devices, conventional authentication, authorization and accounting (AAA) processes are neither scalable nor cost-effective. Other important aspect to be tackled is the threat arising from attacks performed on quantum computers, that can impact the long-term security, i.e. the protection of the confidentiality, authenticity and integrity of the transmitted and store data [20].

7.1.2 Challenges in privacy

Despite being limited to no human involvement, privacy threats for MTC traffic are centered around location tracking and other personally identifiable information. Data collection and storage is another major concern of privacy threat. The proliferation of cloud- and edge-based storage means that data can be stored across different countries and regions with different levels of privacy measures and enforcement, thereby raising serious privacy threats.

7.1.3 Challenges in trust

Considering the constrained and ubiquitous environment of MTC applications, trust is hard to attain among different entities involved in the networks. Mutual agreement and trust among the various stakeholders in an MTC network, such as the network operators, application users and the MTD owners/operators, are needed to ensure security and privacy with massive number of devices.

7.2 Potential security, privacy and trust enablers

The use of ML and AI tools can provide intelligence-driven security capabilities for more accurate detection of malicious attacks. For instance, security solutions specific to MTC networks can be formulated by leveraging on smart detection of MTC traffic through ML/AI techniques joint with software-defined networking (SDN) and network function virtualization (NFV) [76]. Security solutions need also to cover the service layer alongside the access layer, and consider E2E protection against security threats instead of focusing on particular links alone, as illustrated in Fig. 7. Disruptive technologies, such as SDN and NFV, allow the deployment of customized security configurations, thus enabling the deployment of security-as-a-service [77].

By exploiting the physical properties and randomness of wireless channels, physical-layer security techniques are considered promising solutions to complement upper layer schemes and provide compatible solutions with the requirements of MTC networks [78]. Thus, those techniques may find a place in the definition of 6G security solutions. AAA challenges can be addressed through lightweight and flexible solutions like group-based authentication schemes, anonymous service oriented authentication strategies to manage a large number of authentication requests, lightweight physical layer authentication, secure biometric authentication and the integration of authentication with access protocols [79].

In terms of privacy, a holistic approach adopting privacy-by-design principles from the beginning is needed. Network operators need to differentiate between sensitive and less sensitive data so that sensitive data can be stored locally or treated appropriately. DLTs are a broader way of looking at digital privacy and trust [80]. Therefore, DLT-based approaches, such as smart contracts, are highly probable to be adopted in order to provide decentralized privacy solutions for MTC networks/IoT. However, there are a set of challenges that need to be overcome before DLTs can be widely adopted as a digital privacy and trust solution in MTC networks.

First, there is a mismatch between some of the properties of DLT and the requirements of many MTC applications. For example, the immutable nature of blockchains makes it difficult to rectify errors embedded in the blockchain. As another example, blockchain technology is pseudo-anonymous, whereas machine type devices accessing an MTC network need to be authenticated for security and accounting reasons [81].

In addition, MTC communications are conventionally uplink-oriented, with little to no peer-to-peer information exchange. Distributed trust requires two-way data exchange between devices, introducing new requirements and design challenges for 6G MTC networks. Additionally, the use of DLT represent significant energy, delay, and computational overheads and hence may not be suitable for MTDs which in many cases have energy and computation-capability constraints. This can potentially be addressed by incorporating the capabilities of mobile edge computing with blockchain.

DLTs do not guarantee the trustworthiness of data capture that can present noise, bias, sensor drift, or manipulation by a malicious entity, which is especially important in MTC networks where nodes are not necessarily trustworthy. Trust and reputation models can be integrated with DLTs/blockchain and applied to rank the trustworthiness of nodes, thus improving the E2E trust [82].

Finally, the long-term protection of confidentiality, authenticity and integrity of the transmitted and stored data, is another important aspect in MTC. To secure MTC data in the age of quantum computing, lightweight and flexible quantum computer-resistant (or post-quantum) encryption and authentication schemes need to be considered.

8 Conclusions

The 2030s will surely witness the introduction of 6G as the next generation wireless system. With the most innovative service classes in 5G NR, namely URLLC and mMTC, widely adopted by then; the cornerstone of MTC in 6G will be focused on the optimization and further enhancements of URLLC and mMTC targeting new use cases and service classes. MTC and IoT networks will form the main backbone of a 6G network providing wireless connectivity in all aspects of our everyday life and enabling digitalization of the economy and society at large.

This paper provides an comprehensive view of MTC in the 6G era. The key drivers, potential use cases, evolving requirements and emerging service classes are first discussed, followed by an envisioned holistic MTC network architecture. Future research directions for enabling low-power, massive, critical and secure MTC, ranging from the physical layer to the application layer, are then detailed leading to identification of key research questions in each domain. The main contribution of this article is in shaping the vision of a holistically-optimized 6G MTC network.

Abbreviations

3D: Three dimensional; 5G: Fifth generation; 6G: Sixth generation; AAA: Authentication, authorization and accounting; AGV: Automated guided vehicles; AI: Artificial intelligence; AmBC: Ambient backscatter communications; cMTC: Critical MTC; CPS: Cyber-physical systems; DAS: Distributed antenna systems; DLT: Distributed ledger technology; E2E: End-to-end; EB: Energy beamforming; EH: Energy harvesting; eMBMS: Evolved multimedia broadcast multicast services; GF: Grant-free; HTC: Human type communications; IAT: Inter arrival times; IC: Interference cancellation; IoT: Internet of Things; IRS: Intelligent reflective surfaces; KPI: Key performance indicators; LDPC: Low-density parity-check; LEO: Low-earth orbit; LPWAN: Low power wide area networks; MBB: Mobile broadband; ML: Machine learning; mMTC: Massive MTC; MTC: Machine type communications; MTD: Machine type devices; MUD: Multi-user detection; NFV: Network function virtualization; NOMA: Non-orthogonal multiple access; NR: New radio; NTN: Non-terrestrial networks; OFDM: Orthogonal frequency division multiplexing; PHY: Physical layer; PTM: Point-to-multipoint; RAT: Radio access technologies; SDN: Software defined networking; TSN: Time sensitive networking; TTI: Transmission time intervals; UAV: Unmanned aerial vehicles; ULP: Ultra low power; URLLC: Ultra reliable low latency communications; WET: Wireless energy transfer; WPT: Wireless power transfer; WUS: Wake up signals.

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Author contributions

NHM, SB, AM, IM, KM, FC, OL, OSP, EM and HB have contributed equally by contributing to different sections and editing the overall paper. EK, JS, GYP and KA contributed to Sect. 2; YM and GL contributed to Sect. 3; RJ, RR, MA and JBD contributed to Sect. 4; YC, EG and YS contributed to Sect. 5; SS, CW, FB, CFL, HA, SK and CY contributed to Sect. 6, and DMO, EA, MK and PS contributed to Sect. 7. All authors read and approved the final manuscript.

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Declarations

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

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