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Evolution of Mobile Networks

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1.1 Introduction

The advent of mobile networks has ushered in a new era of communication. This in turn is playing a pivotal role in our interconnected world and has transformed the way we connect, work, and live. By enabling people to seamlessly communicate, access information, and utilize digital services anytime and anywhere, mobile networks increasingly bridge the digital divide and support businesses, e-commerce, and digital entrepreneurship, thus fueling economic growth and societal advances. Indeed, mobile communications can significantly contribute to achieving the sustainable development goals of the United Nations.[1] This is possible by offering infrastructure and access to digital services supporting growth, efficiency, and sustainability, especially for economies where existing services are limited or the related infrastructure is poor [1].

Digitalization of services delivered through mobile communications networks has shown immense benefit in developing economies in particular driving the uptake of micro-banking and micro-finance, micro-energy grids, and market creation [2]. Productivity enhancement may arise from remote work support and access to critical information and digital services, a capability that has become crucial in the face of global challenges such as the COVID-19 pandemic. In times of crisis, mobile networks even serve as vital lifelines, facilitating emergency communication and coordination.

There have been phenomenal advancements in mobile communications for more than a century and consistently since the first-generation (1G) networks

1 Refer to https://sdgs.un.org/goals.

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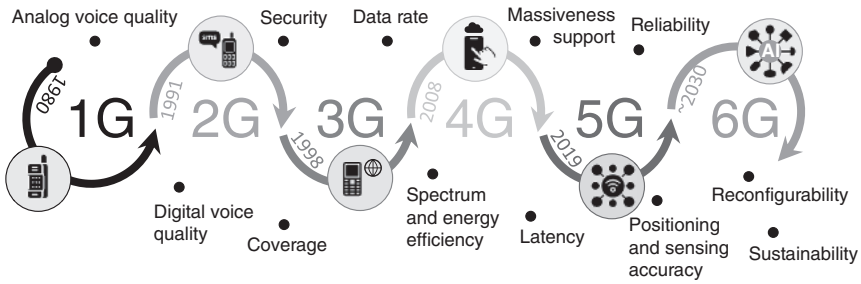


Figure 1.1 Evolution of mobile networks and emerging KPIs.

in the 1980s. A new generation has been introduced nearly every 10 years since then, with each iteration bringing significant improvements in terms of key performance indicators (KPIs). From the initial 1G networks that allowed only voice calls, mobile communication networks have progressed through the second generation (2G), third generation (3G), fourth generation (4G), and fifth generation (5G), enabling not only voice communication but also high-speed Internet access, mobile gaming, location tracking, online education, augmented reality applications, and foundation for the Internet of Things (IoT) [3]. A graphical representation of the evolution of mobile networks, including some distinctive KPIs that emerged during the evolution, is shown in Figure 1.1.

Understanding the evolution of mobile networks is of paramount importance for researchers, engineers, and academics, and constitutes the scope of this chapter. Such an understanding/knowledge drives innovation, informs policy, opens business avenues, and ensures the education of future generations. As mobile networks continue to evolve, staying informed and engaged in their development is vital for the betterment of society and the advancement of human, human-to-machine, and machine-to-machine connectivity.

1.2 Origins and Early Developments

Telecommunications have been critical to human society since ancient times. The discovery of the relationship between electricity and magnetism by Hans Christian Oersted in 1820 was a milestone. Further, Michael Faraday showed that a fluctuating magnetic field could induce electric current on a conductor in 1831, marking a turning point in the history of telecommunications by laying the foundation for subsequent advancements. This discovery laid the groundwork for wireless communication at non-line-of-sight distances.

Later on, two major telecommunication developments were the invention of the telephone by Alexander Graham Bell in 1876, allowing the transmission

of analog live signals, and Marconi's wireless telegraphy in 1896. The first amplitude-modulation radio broadcasting was demonstrated by Reginald A. Fessenden in 1906. Meanwhile, in 1935, Major Edwin H. Armstrong demonstrated high-quality music transmission using frequency-modulation radio broadcasts. The private telephone companies also started providing landline telephones and services. During the 1940s, the general public was offered a public mobile telephone, which was a wireless device that connected with the public switched telephone network [4]. The United States' Federal Communication Commission (FCC) started two-way radio service over a 460 MHz band in 1945, where millions of users used the same channel across the country. In 1947, radiotelephone systems, comprising small geographical areas called cells, were proposed by the Bell laboratories [5]. A base station (BS) transmitter setup was placed in each cell, and cell traffic was controlled by a central switch. A few decades later, in 1971, the first wireless computer network, called AlohaNet, was introduced [6]. AlohaNet could connect multiple low-data rate stations via a single radio channel to a central host without considering any access rule or synchronization [7]. In 1972, S-Aloha was proposed using a time-slotted channel, which could double the channel capacity. The cellular radio networks assign radio channels to mobile stations by employing a demand-assigned multiple-access protocol, where the uplink request channel is based on S-Aloha.

The initial cellular systems are referred to as mobile radiotelephone or zeroth generation (0G), pointing to the pre-cellphone mobile telephony. Such systems were usually mounted in vehicles' boot/trunk. Indeed, the transceiver was mounted in the vehicle boot and was usually placed on the head section and fixed close to the driver's seat. In 1979, Nippon Telegraph and Telephone Corporation launched 1G to the citizens of Tokyo, which was available nationwide in Japan by 1984 [8]. The cellular standards used in 1G included mainly Advanced Mobile Phone Services (AMPS) and Nordic Mobile Telephones (NMT). The AMPS was invented at Bell Labs [9] and also used in the United Kingdom under the name of Total Access Communication System [10]. The NMT system was simultaneously introduced in Denmark, Finland, Norway, and Sweden in 1981, which was the first mobile phone network with worldwide roaming [11]. Motorola's DynaTAC mobile phone was implemented by Chicago-based Ameritech in 1983 to build the first 1G network in the United States [12]. The world's first cell phone, DynaTAC 8000X, created by Motorola in 1983, was essentially a two-way frequency-modulation radio designed only for voice calls [13]. Several nations, including the United Kingdom, Mexico, and Canada, followed in the early to mid-1980s.

1G was completely an analog cellular system. The fundamental concept underlying 1G cellular networks is the division of the region into cells, each of which is serviced by a BS and usually spans 10–25 km. The small size of cells

allows for frequency reuse in nearby cells. In addition, smaller cells need smaller, less-expensive, and less-powerful equipment to send and receive data. However, these standards did not include any placement (i.e., coordinates of a certain object) instructions. The utilization of location data within the network garnered noteworthy interest from both, operators and application developers. Vehicle location (by using signal strength, time delay, or direction of arrival measurements) was targeted to improve the effectiveness of cellular calls through system control [14]. 1G cellular systems were additionally utilized for intelligent vehicle highway system (IVHS) applications [15]. Further, it supported emergency services based on proprietary location solutions. This included services such as those of Grayson Wireless with a joint time difference of arrival and angle of arrival solution or true position with an uplink time difference of arrival, both of which used AMPS signals [16]. 1G networks realized data rates up to 2.4 kbps, sufficient to support analog voice call services [10]. Meanwhile, these networks were concentrated in urban and densely populated areas with limited coverage and capacity, and faced network congestion, excessive call drop problems, reckless hand-off, and security threats.

The Groupe Spécial Mobile, established in 1982 by the European Conference of Postal and Telecommunications Administrations, started working on the harmonization of mobile communication systems in the 900 MHz band [9]. The primary service was telephony; however, it was also possible to use enticing nonvoice alternatives. The action plan included studies on market, tariff, technical, and regulatory needs. Further, in 1984, France and Germany contributed to the global system for mobile communications (GSM) [17]. A structure for the GSM specifications and an action plan for their completion was created. It was decided to employ smart cards as subscriber identity modules (SIMs), and support free circulation, mobile station licensing, international roaming, charging, and accounting. At a high-level meeting in Bonn in May 1987, the basic GSM specification was finally agreed upon.

The transition from 1G to 2G in the 1990s constituted the transition from analog to digital cellular systems, offering improved voice quality and paving the way for sophisticated mobile services and capabilities. The progression of mobile communications from several separate systems to standard systems across the nations was one of the primary factors that made this transition possible. The 2G system aimed to enhance spectrum efficiency while offering a fixed data rate of 64 kbps [18]. Additionally, 2G systems offered features like electronic mail (e-mail) and short message service (SMS). The first SMS message "Merry Christmas," was sent by Neil Papworth, a test engineer for Sema Group, from a computer to his colleague Richard Jarvis's Orbitel 901 phone on December 3, 1992 [19]. In 1993, Nokia's mobile phones were the first to support consumer SMS texting.

The major 2G cellular system standards were GSM, interim standard 95 (IS-95), and interim standard 136 (IS-136). The physical layer of GSM is based on time-division multiple access (TDMA) and frequency-division multiple access (FDMA). The TDMA of GSM was followed by digital standards such as digital AMPS or IS-54 (later on substituted by IS-136), integrated dispatch enhanced network (iDEN), and personal digital cellular [8]. The code-division multiple access (CDMA) was added to the IS-95 standard to improve the capacity of mobile cellular networks. CDMA also provided support for multiple data rate sets. The GSM's standard was split into two phases, enabling first, rapid implementation of common services such as telephone or SMS, and then, the introduction of technical advancements and additional services [20].

Notably, there were no positioning/location mechanisms within the standard. The positioning capability of GSM was limited to the use of training or synchronization signals to compute ranging requirements, and similar procedures were employed for the CDMA system. In 1996, the FCC approved the provision of enhanced 911 (also known as E-911 or E911, which was a system that gives 911 dispatchers the caller's location automatically in North America) for location requirements on the existing TDMA and CDMA cellular systems. Later on, global positioning system (GPS) receivers were incorporated to assist the cellular networks. Meanwhile, digital cellular networks were evolving toward GSM phase 2+ (i.e., 2.5G and 2.75G) and universal mobile telecommunications systems (UMTS). The 2.5G comprises a general packet radio system (GPRS) with a data rate of 50 kbps, and 2.75G comprises an enhanced data rate for GSM evolution (EDGE) with a data rate of 200 kbps, including packet-switched services like transport control protocol (TCP)/internet protocol (IP). The third generation partnership project (3GPP) was created in 1998 as a partnership of international members to standardize the evaluation of GSM and UMTS, with the European Telecommunications Standards Institute (ETSI) being one of the contributors and the main sponsor. In parallel, the Telecommunications Industry Association (TIA) and the Electronic Industries Alliance (EIA) established the 3GPP2 collaboration to carry out the standardization of IS-95 and CDMA2000 technologies.

Cellular networks were originally designed for circuit-switched speech communication and later offered data as an add-on. Data transfer via analog cellular telephone connections utilizing modems was a basic method of mobile data communication. For instance, analog and digital cellular networks such as EIA-553, AMPS, and ETSI GSM, provided modem-based circuit-switched transparent data service [7]. In this communication method, the network merely provides a voice link over which the mobile data modem can interact with a corresponding data modem in an office or computer center. The circuit-mode connection was largely underutilized, and the service was expensive if only brief

messages were sent back and forth over the network during a (long) interactive session. This was the driving force for the creation of mobile data networks that use end-to-end packet switching. The packet switch was an evolution of the GPRS with a more optimized functional split between the UMTS terrestrial radio access (UTRA) network and the core network.

1G and 2G network evolution was driven by the need to support analog and then digital voice communications. Spectrum allocation was relatively static, with fixed frequency bands designated for specific services. 1G networks, e.g., AMPS and NMT, operated primarily in the 800–900 MHz range, utilizing analog signals and simple frequency division. This period saw significant regulatory involvement to allocate and license the spectrum to the operators, ensuring minimal interference and promoting initial market growth. With the advent of 2G networks, like GSM, there was a shift to digital transmission, significantly improving the spectral efficiency by exploiting TDMA and FDMA technologies. Spectrum efficiency became crucial as 2G introduced SMS, basic data services, and even digital encryption for improved security. This period laid the foundation for more dynamic and competitive spectrum management practices as mobile communication started to scale globally.

1.3 Data-Centric Mobile Networks

The previous generations of cellular communication systems were based on circuit and packet switching modes while supporting poor data rates, capacity, and limited services. The explosive growth of the Internet (entailing worldwide access to information) and multimedia applications would become the driving force for the evolution into data-centric mobile networks. A mobile Internet, i.e., using a mobile device to access the Internet over a wireless connection, represented realizing ubiquitous access to data communications. With this technology, users could finally access various online services and content without a traditional wired connection to the Internet.

The International Telecommunication Union established the International Mobile Telecommunications 2000 (IMT-2000) framework as an international standard for 3G cellular networks in 1998 [21]. 3GPP aimed to develop globally applicable specifications for 3G mobile systems. 3GPP standards were designed for mobile systems based on evolved GSM core networks, as well as the supported radio access technologies, service capabilities, and security. 3GPP was the standards organization behind UMTS/wideband CDMA (W-CDMA), and 3GPP2 developed separate standards for 3G technologies, known as CDMA2000 [22]. The emerging 3G systems enabled universal access to a variety of services tailored

to mobile users as well as a wide range of basic and supplementary services supported by networks. The 3G architecture was evolved from 2G GSM, GPRS, and UMTS. Specifically, a set of extensions to GSM data services were designed and standardized, resulting in 2.5G systems viz., high speed circuit switched data (HSCSD), GPRS, and EDGE. The main 3G technologies were UMTS and CDMA2000, and are discussed below.

- The UMTS was a wideband CDMA (WCDMA) technology, also called UTRA. The frequency-division duplex (FDD) and time-division duplex (TDD) modes of the UTRA network were set up to produce data speeds of up to 2 Mbps. UMTS R99 allowed mobile networks to directly profit from the vast impetus behind the Internet's expansion and launch of new services. This evolution also enabled telecom providers to roll out a standard backbone (like IP) for all access types, significantly lowering capital and operating costs. Meanwhile, UMTS R00 introduced a next-generation network architecture for circuit and packet-switched domains. Both, stationary and mobile customers, were able to access a variety of services using UMTS. The World Administrative Radio Conference in 1992 designated the 1885–2025 MHz and 2110–2200 MHz frequency bands as the target radio interfaces for UMTS, which was designed to be extremely flexible and efficient.
- The CDMA2000 technology was based on the evolution of IS-95, which consists of multiple narrowband CDMA carriers of 1.25 MHz. To safeguard significant financial investment in the base of networks that have already been deployed, the design of the air interface was backward compatible with the deployed IS-95 networks and built on 2G. The cdma2000 supported an advanced medium access control feature to efficiently support several concurrent data (up to 2 Mbps) and voice services.

The progression of GSM, UMTS, and CDMA2000 toward 4G cellular systems aimed to support Internet browsing, interactive gaming, mobile TV, and streaming video and audio [23]. This was led by long-term evolution (LTE), which is regarded as a 3.9G technology since 3GPP Rel-8 [24] and Rel-9 [25] of the LTE standard do not completely comply with the International Mobile Telecommunications (IMT)-Advanced standards for 4G technology. The LTE technology was designated by 3GPP to support mobile data demand and multimedia applications. Its evolved-UTRA air interface uses single-carrier (SC) FDMA for uplink and orthogonal frequency-division multiple access (OFDMA) for downlink to achieve a data rate of up to 50 Mbps and 100 Mbps, respectively [26]. The multicarrier feature allows LTE to operate in different system bandwidths (between 1.4 and 20 MHz) by adjusting the number of subcarriers and their allocation to multiple users.

LTE operates in the FDD and the TDD modes. A time-frequency block is the fundamental LTE radio resource that can be addressed for data transfer. The resource block has a subframe duration of only 1 ms in the time domain. The inclusion of a short subframe allows for the exploitation of channel variations by scheduling users based on their channel quality. Further, it is feasible to achieve broadly scaled transport block sizes and a wide variety of user-data rates by assigning a variable number of resource blocks to a particular user and choosing a modulation and coding scheme to suit the present channel conditions. Furthermore, an LTE system was designed to operate as a packet-based system with fewer network components, which increases system capacity and coverage, and offers enhanced quality of service (QoS) in terms of high data rates, low access latency, flexible bandwidth operation, and seamless integration with other current wireless communication systems.

3GPP began establishing advanced LTE, aka LTE-A, standards in Rel-10 [27] and termed it 4G technology to fulfill the peak data rate of up to 1 Gbps and low data rate of up to 100 Mbps [28]. The heterogeneous networks (comprising of macro and small cells) were defined to fulfill new features, including carrier aggregation (CA), coordinated multipoint, and improved multiple-input multiple-output (MIMO) transmissions. With SC-FDMA for uplink and OFDMA for downlink, LTE-A's physical layer was backward compatible with LTE. The maximum system bandwidth of the LTE-A technology was 100 MHz. As a result, the operators were able to combine fragmented spectrum from several bands into one bigger spectrum resource. The implementation of CA networks has advanced well, enabling operators to convert their investment in more LTE carriers into commercially viable high data rates. Moreover, CA is considered a vital enabler for harnessing unlicensed spectrum opportunities within the 5 GHz band, as specified in 3GPP Rel-13 [29].

The LTE-A system improved the previous LTE systems by supporting significantly more data usage, lower latency, and better spectral efficiency. In addition, it introduced a new type of data communication between entities called machine-type communication (MTC). With MTC, machines can share and exchange data without any human intervention. In the vision of smart city applications such as online education, smart utility, online surveillance, environment monitoring, e-health, and connected vehicles, a large number of autonomously operated low-cost devices (i.e., actuators and sensors) are required to be connected to physical objects. MTC is a term used to describe the communications that take place between these independently operating devices. Contention-based random access is used to support MTC in LTE.

The further enhancements of the LTE standard in 3GPP Rel-13 are known as LTE-Advanced Pro and termed 4.5G. A fundamental component of this evolution is indoor location, which plays a crucial role in improving mobile broadband and connectivity QoS while maintaining full LTE-A backward

compatibility. Radiofrequency pattern matching (RFPM) was adopted to improve the existing positioning techniques dependent on radio access technologies such as observed time difference of arrival (TDoA), uplink TDoA, and enhanced cell-ID. Additionally, systems independent of radio access technologies, such as advanced global navigation satellite systems, terrestrial beacon systems, and WiFi/Bluetooth, were adopted to improve existing positioning techniques. The goal of LTE-A Pro's evolution was to offer a fresh 5G candidate technology.

The transition to 3G and 4G networks greatly reshaped spectrum management due to increasing data demands. 3G networks, e.g., UMTS and CDMA2000, leveraged wider frequency bands around 2 GHz and introduced technologies like WCDMA and CDMA, enabling higher data rates and more efficient spectrum use. Spectrum auctions became common, promoting a more competitive environment and better resource allocation. With the advent of 4G, the focus shifted to high-speed data and low latency. Spectrum management strategies in this generation included dynamic spectrum access and CA, which allowed operators to combine multiple frequency bands to enhance bandwidth and improve user experience. Additionally, the introduction of OFDMA enabled a more efficient use of the spectrum through time/frequency-domain multiplexing. Regulatory bodies played a critical role in standardizing these practices and ensuring that the spectrum was used efficiently and fairly.

1.4 5G Mobile Networks

Cellular mobile radio's communication and positioning functions are undergoing a revolution owing to the 5G technology. With the advent of 5G, connectivity provision has experienced significant improvements in wireless data rate, capacity, and coverage, together with a reduction of round-trip latency and energy usage. The 5G wireless standard envisions a network that is always available everywhere. Millions of 5G handsets and hundreds of operators have been involved in the commercial deployment of the 5G mobile networks globally. 5G-capable devices are not only limited to smartphones as they may also be found in a wide range of different forms, including head-mounted displays, laptops, drones, and fixed wireless access. 3GPP Rel-15 [30] in 2016 established the groundwork for 5G new radio (NR) by considering a variety of service needs, a broad spectrum (ranging from hundreds of megahertz to tens of gigahertz), and multiple deployment scenarios (indoor/outdoor, macro/small cells). Both, standalone and nonstandalone 5G mobile network architectures, such as those utilizing dual connection between LTE and NR, were defined to make it easier for operators to transition from 4G LTE to 5G NR.

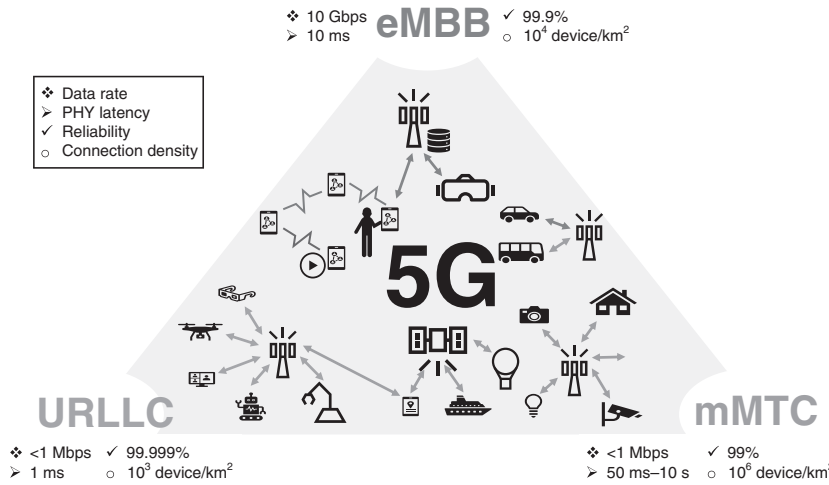


Figure 1.2 Capabilities of a 5G wireless network.

5G mobile networks are aimed to fulfill the recommendation of IMT for 2020, providing three main capabilities as illustrated in Figure 1.2 [31]:

- **Enhanced Mobile Broadband (eMBB)**: Hotspots and wide-area coverage for high throughput and a seamless user experience.
- **Ultrareliable and Low Latency Communications (URLLC)**: High availability and low latency.
- **Massive Machine Type Communications (mMTC)**: Very broad coverage and a large number of inexpensively linked devices with long battery life.

The 5G architecture offers better software services and network solutions for a variety of public and private sectors, including energy, agriculture, city administration, health care, manufacturing, and transportation. The device-centric feature of 5G is anticipated to make it possible for nearby devices to directly communicate while skipping cellular BS to share pertinent resources. Such MTC involves automated data generation, processing, transfer, and exchange amongst intelligent devices, with minimum human participation. This is a component of the IoT ecosystem, which envisions millions of simultaneous connections between various gadgets, connected homes, smart grids, and intelligent transportation systems. The 5G wireless technology's high bandwidth, widespread availability, and low latency are ensuring smart and intelligent vehicular communications. Technology developments in sensing and communication have created new opportunities for health monitoring. A paradigm shift in real-time remote patient health monitoring is made possible by the emerging 5G mobile networks and body area networks.

The 5G spectrum is divided into multiple frequency ranges (FRs). Specifically, FR1 corresponds to the region of 0.410–7.125 GHz, while FR2 covers 24.25–52.6 GHz (FR2-1) and 52.6–71 GHz (FR2-2). 5G mobile networks aim to provide a data rate of 10 Gbps in uplink and 20 Gbps in downlink, a 10-fold increase from the highest data rate of 150 Mbps for LTE cellular networks. Also, a latency below 1 ms is targeted, which is also a 10-fold improvement over the 10 ms round-trip duration of 4G mobile networks. To support an enormous number of linked devices as well as ultrahigh bandwidths for extended periods in a specific space, 1000 times greater bandwidth per unit area is required [32]. Moreover, longer battery life (up to 10 years) is supported to accommodate these and other emerging applications.

5G uses beam division multiple access (BDMA) and non- and quasi-orthogonal or filter bank multicarrier (FBMC) multiple access [33]. Within the BDMA framework, an orthogonal beam is assigned to each mobile station based on its position such that the mobile stations can receive numerous accesses, thus increasing the system's capacity [34]. Notably, the beamforming capabilities at the transmitter and receiver and the exploitation of spatial division multiple access allow greater frequency reuse.

Interestingly, the mobile industry's rising demand is pushing the transition from traditional cellular coverage to cell-free device-centric deployments. This can be realized by exploiting large beamforming gains, high frequency/bandwidth, and interference-taming capabilities of distributed massive MIMO (M-MIMO) networks. Note that millimeter-wave (mm-wave) propagation's small radio wavelengths make it possible to employ numerous small antennas. By utilizing array antennas to control the signal's phase and amplitude, electromagnetic waves can be enhanced in the desired direction while being canceled out in all other directions. Further, smart antennas support interference mitigation while preserving the best coverage area and transmit power reduction for both, mobile devices and BS. Therefore, it is crucial for the development of 5G wireless communications to have smart antenna designs that are optimized for directional gains, cost, and complexity.

The ultimate evolution to cell-free setups (in future systems) may initially require small-cell deployments. Indeed, deploying a large number of tiny cells, giving rise to heterogeneous networks (HetNets [35]), can help cope with the explosive growth of wireless traffic anticipated in the coming years. HetNets often include small, low-transmission-power cells in addition to the traditional macrocells. In such a dense 5G deployment, configuring and maintaining several servers and routers are challenging tasks that can be resolved by software-defined networks. This allows a division between the control and the data planes, bringing speed and flexibility to 5G networks, and may rebuild networks for fully automated management by stepping over open system interconnection (OSI) layers. Furthermore, cloud RAN aims to address the high data rate demands

and promises to lower the cost of network deployment and operation while simultaneously enhancing system architecture, mobility, coverage performance, and energy efficiency [36].

The 5G standard was expanded by 3GPP Rel-16 [37] to include new verticals like (i) NR sidelink, which focuses on public safety and vehicle-to-everything; (ii) 5G broadcast, which is an evolution of LTE-based enhanced TV; (iii) nonpublic networks; (iv) Industrial IoT applications; and (v) shared or unlicensed spectrum, which includes sub-6 GHz bands. Additional changes in Rel-17 include multicast and broadcast services, expansion into FR2-2, support for satellite communications for smartphones and IoT devices, and the introduction of reduced capability (RedCap) devices aimed at new device types (e.g., wearables, surveillance cameras, and industrial sensors).

Although 5G NR has many technical components, it is important to note salient features such as scalable OFDM-based air interface, advanced channel coding (via low-density parity check coding, which provides more efficient support of throughput per decoder chip area), M-MIMO, and mm-wave operation.

5G networks have revolutionized spectrum management by incorporating a wide range of frequencies, from sub-6 GHz to millimeter-wave bands (24–52 GHz). This is critical for supporting the varied requirements of 5G services, including eMBB, URLLC, and mMTC. Spectrum sharing and dynamic spectrum access have become more prevalent, allowing for more flexible and efficient use of available resources. Techniques like dynamic spectrum sharing (DSS) enable 5G to coexist with 4G, providing a smoother transition and better spectrum utilization. Beamforming and M-MIMO technologies enhance the efficiency and capacity of the network by directing signals precisely where needed. Meanwhile, regulatory frameworks and global spectrum harmonization efforts have evolved to support these advanced techniques and allow a seamless operation of the 5G services worldwide.

The spectrum use evolution from 1G to 5G and key features of each generation are respectively illustrated and summarized in Figure 1.3 and Table 1.1.

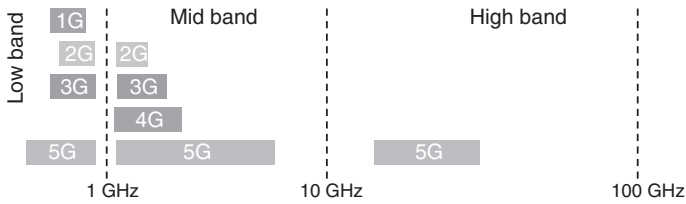


Figure 1.3 Spectrum utilization of different generations of cellular networks.

Table 1.1 Evolution of mobile networks.

Features	1G	2G	3G	4G	5G
Speed	2 kbps	64 kbps	2 Mbps	1 Gbps	> 1 Gbps
Latency	—	629 ms	212 ms	60–98 ms	< 1 ms
Access technology	AMPS, FDMA	GSM, TDMA, GPRS, EDGE	CDMA, UMTS, WCDMA, high-speed uplink packet access (HSUPA)/high-speed downlink packet access (HSDPA), EVDO	OFDMA/ SC-FDMA	BDMA, FBMC
Switching	Circuit	Circuit/Packet	Packet	Packet	Packet
Bandwidth	30 KHz	200 KHz	5 MHz	1.4–20 MHz	1–6 GHz
Forward error correction	NA	NA	Turbo codes	Turbo codes	Low density parity check codes
Application	Voice	Voice + data	Voice + data + video calling	Online gaming + high definition video	Ultra high definition video + virtual reality

Source: Adapted from [23, 38].

1.5 Beyond 5G and Prospects

After almost a decade of intense academic and industrial research on 5G mobile networks and the subsequent commercial deployment, it has become clear that 5G networks will fall short in supporting the vision of the Internet of Everything (IoE), i.e., the intelligent connection of people, processes, data, and things. Moreover, future networks are anticipated to connect many nodes in various proximity ranges, such as small cells, microcells, picocells, and femtocells, while there is an increasing need to support advanced bandwidth-hungry applications such as mixed reality, telepresence, and Industry 5.0 requiring infimum delay, highly reliable connections, and/or accessing the Internet via mm-wave/THz frequencies [39]. Given this, the research community has commenced intensive research on the Beyond 5G (B5G) successor technology, i.e., 6G mobile networks [39–41].

B5G networks are envisioned to overcome critical shortcomings of 5G mobile networks by adopting cell-free architectures and operating in sub-6 GHz, mm-wave, and THz spectrum. However, transforming such speculative ideas into real-time commercial deployments is a big challenge. Specifically, limited coverage is a key issue when operating in the mm-wave/THz spectrum and dedicated research is needed since current spectrum allocation methods are ineffective for such setups [42]. In this regard, Open RAN (O-RAN) may provide flexibility for spectrum occupancy in B5G mobile networks and thus facilitate spectrum management. Emerging open interface standards can be explored for minimizing interference between heterogeneous systems in a very congested B5G radio environment. In addition, O-RAN may permit operations in different spectrum bands, involving varied spectrum sharing (SS) levels over the mm-wave/THz spectrum. However, advanced SS techniques are required to deal with dynamically changing and highly heterogeneous environments.

Concerning M-MIMO, novel low-cost/complex hybrid architectures, and accompanied precoding techniques, are needed to promote sustainability and highly dense deployments [43]. In addition, artificial intelligence (AI) techniques can be used to predict channel characteristics and create dataset frameworks for beam-forming in M-MIMO [44]. Moreover, holographic displays are considered the next evolution in multimedia experience delivering 3D images from one or multiple sources to one or multiple destinations, providing an immersive 3D experience for the end user [45]. Interactive holographic capability in 6G networks will require a combination of very high data rates and ultralow latency. The key requirements will also include perfect synchronization, extreme resilience, and large computations. These requirements will serve as the backbone for advanced use cases such as Industry 5.0, which will need the expansion of digital twins so that visual models of the products, processes, and generation will allow better understanding and testing [46]. For Industry 5.0, 6G networks are expected to meet the intelligent information society standards to deliver ultrahigh reliability [47].

Mobile edge computing has been identified as the technology that will transform the 5G communication networks into distributed cloud computing platforms [48] and will continue its evolution over the next generations [49]. Mixed reality, autonomous driving, and holographic communications are all candidates for edge cloud coordination. The key network requirements include computing awareness of constituent edge facilities, joint network and computing resource scheduling, flexible addressing, and fast routing and rerouting.

The research community has already foreseen multiple techniques and applications that will leverage AI mechanisms in modern and future mobile networks [43, 50, 51]. For 6G networks, new network architectures comprising holistic network virtualization and pervasive AI will be required. The holistic network

virtualization will consist of network slicing and digital twin to provision services and demands thereby, incorporating service- and user-centric networking [52]. The pervasive network intelligence will integrate AI into 6G networks from the perspectives of networking for AI and AI for networking. In turn, such an architecture will facilitate interplay between (i) digital twin and network slicing paradigms, (ii) model-driven and data-driven methods for network management, and (iii) virtualization and AI, to maximize flexibility, scalability, adaptivity, and intelligence for 6G networks.

Note that existing virtualization techniques mainly focus on service provisioning for communication networks [53]. On the other hand, virtualization, with a focus on service provisioning, will enable 6G to handle diverse coexisting services. However, this may not suffice for 6G since the characteristics of end user service demand will be the key to achieving user-centric networking. Hence, virtualization must focus on both, the service provision capability of a network and the service demand of end users in the network. Existing research on AI mostly addresses specific functions, layers, network segments, or applications of a network, while it is necessary to investigate the integration of AI into the complete network architecture. Indeed, a major drawback of the 5G technology is that it does not standardize the convergence of various functions, such as communication, sensing, security, computing, etc., at least natively [54]. Hence, 5G networks do not, and will not, realize the unlimited potential of AI [55], but may just use it to optimize the networks' legacy architecture and functions. This points toward the need to natively provide/exploit intelligence within 6G technology wherein, various 5G functionalities may converge for IoE and fully immersive experience provisioning.

AI technologies hold massive potential to improve network performance and minimize the overall network cost (both, CapEx and OpEx) [56]. Furthermore, they may solve link and system-level problems in 6G by including features such as self-configuration, aggregation, opportunistic setup, and context awareness [57]. As an example, it has been reported in [58] that an AI-enabled 6G network can realize radio signaling and maximum cognition to intelligent radio transmission. Notably, AI has already been attractive for implementation at various layers of 5G technology [59]. In addition, concerning spectrum resource management, most of the encountered algorithms are combinatorial, and thus cannot be implemented in practice. Therefore, AI-enabled algorithms will be mandated to outperform the current suboptimal approaches. These algorithms may suffice for performing the management of resource tasks with reduced supervision including, power control, beamforming in M-MIMO and cell-free environments, predictive scheduling, resource allocation, etc. In 6G networks, AI technology will reside in the new local cloud environments and will aid in creating multiple advanced applications via the use of sensors that have already been embedded within every aspect of human life.

Overall, the B5G research must target spectral-efficiency gains, high protection against interference, network congestion avoidance, high and massive mobility support, and resiliency and dependability [3, 60, 61]. In this regard, a broader and deeper understanding of link quality in multiple scenarios and a robust statistical taming of all sources of delay/error are immediate challenges [61, 62]. As a possible solution, the holistic integration of model and data-driven approaches and the synthesis of artificial data using generative adversarial networks can be conducted [61, 63]. Moreover, the big data resources in B5G networks will require high-security/privacy guarantees that may be provided with decentralized management, such as the one offered by Blockchain [64]. Meanwhile, specific to THz/mm-wave communication, the key challenge is that of severe path and absorption loss as mm-wave/THz carriers are unable to penetrate physical obstacles making them highly susceptible to blockage [65]. To address this issue, prediction techniques must be designed to infer the incoming blockage in beam direction [66]. Guaranteeing low power consumption and/or high energy efficiency will emerge as key challenges for B5G/6G devices, triggering further research on maturing and advancing backscattering communications [43, 67], wireless power transfer [68–70], tinyML [43, 71], energy-aware protocols [43, 72], wake-up radio [43, 73], metasurface-assisted communications [74, 75], to name a few.

Finally, the limited data amount from 5G spectrum assignment decisions and high uncertainty of market data for spectrum study is an issue under intensive research [76]. In addition, adapting network resources to meet the end user's QoS demands while simultaneously reducing the networks' power consumption is a must [77]. In addition, B5G networks must intelligently adapt to the changes in physical infrastructure, equipment, and data, under the regulatory framework set by policymakers [78].

B5G networks must further enhance spectrum management to support more demanding applications, such as holographic communications and Industry 5.0. For this, they will likely expand the operation to higher-frequency bands, including the THz spectrum, and require advanced spectrum sharing and interference mitigation strategies. O-RAN and AI-enabled spectrum management will be pivotal in dynamically adapting to the anticipated highly heterogeneous and dense environments. Specifically, O-RAN will allow operators to use open interfaces and virtualize network functions, enabling more efficient and flexible spectrum use. Meanwhile, AI can optimize spectrum allocation in real time, predicting traffic patterns and adjusting resources dynamically to minimize interference and maximize efficiency. The regulatory landscape will need to adapt to these advances. Future spectrum policies will likely focus on enabling more dynamic and flexible access models, including greater use of unlicensed and shared spectrum, to accommodate the exponential growth in wireless connectivity demands.

1.6 Conclusion

This chapter detailed the evolution of wireless mobile networks. We characterized every wireless network generation, including the specific aims, implemented technologies, and advantages/disadvantages. It is highlighted that a new mobile network generation is introduced almost every decade after the precedent, bringing significant KPI improvements, viz., data speeds, network capacity, latency, and reliability.

Spectrum management has been a crucial aspect throughout such an evolution. In 1G and 2G networks, spectrum allocation was relatively static, focusing on voice communication. The shift to 3G and 4G came with the introduction of spectrum auctions and dynamic spectrum access to meet the rising data demands. 5G further revolutionized spectrum management by incorporating a wide range of frequencies, enabling advanced techniques like dynamic spectrum sharing and M-MIMO to enhance the efficiency and capacity. In the chapter, we over-viewed key use cases offered by 5G networks and the progress toward future mobile networks. In fact, B5G networks are expected to adopt even more sophisticated spectrum management strategies, including the use of higher frequency bands such as THz, advanced spectrum sharing, and open radio access network (ORAN)- and AI-enabled management techniques. These advancements will support emerging applications such as holographic communications and Industry 5.0. We discussed prospects and key research avenues that require timely solutions.

Overall, understanding the progression of spectrum management is vital for the development and optimization of future wireless networks, ensuring they meet the increasing demands for connectivity and data services efficiently.

References

1 Matinmikko-Blue, M., Aalto, S., Asghar, M.I. et al. (eds.) (2020). White paper on 6G drivers and the UN SDGs. *6G Research Visions*, vol. 2020. http://urn.fi/urn:isbn:9789526226699 (accessed 30 September 2024).

2 Huang, Y., Jin, J., Lou, M. et al. (2022). 6G mobile network requirements and technical feasibility study. *China Communications* 19 (6): 123–136.

3 Mahmood, N., Lopez, O.L.A., Park, O. et al. (eds.) (2020). White paper on critical and massive machine type communication towards 6G [white paper]. *6G Research Visions*, vol. 11.

4 Farley, T. (2005). Mobile telephone history, *Privateline.com*. https://cdn6.f-cdn.com/files/download/438936/kaNGwTelenorPage_022-034.pdf.

5 Rappaport, T.S. (2010). *Wireless Communications: Principles and Practice*, 2e. Pearson Education India.

6 Abramson, N. (1970). The ALOHA system: another alternative for computer communications. *Proceedings of the 1970 Fall Joint Computer Conference*, volume 37, 281–285.

7 Walke, B.H. (2013). The roots of GPRS: the first system for mobile packet-based global internet access. *IEEE Wireless Communications* 20 (5): 12–23.

8 Hillebrand, F. (2013). The creation of standards for global mobile communication: GSM and UMTS standardization from 1982 to 2000. *IEEE Wireless Communications* 20 (5): 24–33.

9 Hata, M. and Nagatsu, T. (1980). Mobile location using signal strength measurements in a cellular system. *IEEE Transactions on Vehicular Technology* 29 (2): 245–252.

10 Gupta, A. and Jha, R.K. (2015). A survey of 5G network: architecture and emerging technologies. *IEEE Access* 3: 1206–1232.

11 Knisely, D.N., Kumar, S., Laha, S., and Nanda, S. (1998). Evolution of wireless data services: IS-95 to CDMA2000. *IEEE Communications Magazine* 36 (10): 140–149.

12 Adedoyin, M.A. and Falowo, O.E. (2020). Combination of ultra-dense networks and other 5G enabling technologies: a survey. *IEEE Access* 8: 22893–22932.

13 Telecommunications Industry Association (1993). Mobile station-base station compatibility standard for dual-mode wideband spread spectrum cellular system *TIA/EIA/IS-95*.

14 Ott, G.D. (1977). Vehicle location in cellular mobile radio systems. *IEEE Transactions on Vehicular Technology* 26 (1): 43–46.

15 Rappaport, T.S., Reed, J.H., and Woerner, B.D. (1996). Position location using wireless communications on highways of the future. *IEEE Communications Magazine* 34 (10): 33–41.

16 Reed, J.H., Krizman, K.J., Woerner, B.D., and Rappaport, T.S. (1998). An overview of the challenges and progress in meeting the E-911 requirement for location service. *IEEE Communications Magazine* 36 (4): 30–37.

17 Manninen, A.T. (2002). *Elaboration of NMT and GSM Standards: From Idea to Market*, no. 60. University of Jyväskylä.

18 Kebede, T., Wondie, Y., Steinbrunn, J. et al. (2022). Multi-carrier waveforms and multiple access strategies in wireless networks: performance, applications, and challenges. *IEEE Access* 10: 21120–21140.

19 Linge, N. and Sutton, A. (2015). *30 Years of Mobile Phones in the UK*. Amberley Publishing Limited.

20 Halonen, T., Romero, J., and Melero, J. (2004). *GSM, GPRS and EDGE Performance: Evolution Towards 3G/UMTS*. Wiley.

21 V.K. Garg, (2002). IMT-2000 GOAL. *Wireless Network Evolution: 2G to 3G*, Prentice Hall, 347.

22 Wijting, C., Doppler, K., Kalliojarvi, K. et al. (2009). Key technologies for IMT-advanced mobile communication systems. *IEEE Wireless Communications* 16 (3): 76–85.

23 Chen, S., Sun, S., Wang, Y. et al. (2015). A comprehensive survey of TDD-based mobile communication systems from TD-SCDMA 3G to TD-LTE (A) 4G and 5G directions. *China Communications* 12 (2): 40–60.

24 Abdullah, M.F.L. and Yonis, A. (2012). Performance of LTE release 8 and release 10 in wireless communications. *Proceedings Title: 2012 International Conference on Cyber Security, Cyber Warfare and Digital Forensic (CyberSec)*, 236–241. IEEE.

25 Sengupta, A., Alvarino, A.R., Catovic, A., and Casaccia, L. (2020). Cellular terrestrial broadcast—physical layer evolution from 3GPP release 9 to release 16. *IEEE Transactions on Broadcasting* 66 (2): 459–470.

26 Cao, J., Ma, M., Li, H. et al. (2013). A survey on security aspects for LTE and LTE-A networks. *IEEE Communications Surveys & Tutorials* 16 (1): 283–302.

27 Sankaran, C. (2012). Data offloading techniques in 3GPP Rel-10 networks: a tutorial. *IEEE Communications Magazine* 50 (6): 46–53.

28 Ghosh, A., Ratasuk, R., Mondal, B. et al. (2010). LTE-advanced: next-generation wireless broadband technology. *IEEE Wireless Communications* 17 (3): 10–22.

29 Holma, H., Toskala, A., and Reunanen, J. (2016). *LTE Small Cell Optimization: 3GPP Evolution to Release 13*. Wiley.

30 Ghosh, A., Maeder, A., Baker, M., and Chandramouli, D. (2019). 5G evolution: a view on 5G cellular technology beyond 3GPP release 15. *IEEE Access* 7: 127639–127651.

31 M Series (2015). IMT vision–framework and overall objectives of the future development of IMT for 2020 and beyond. *Recommendation ITU* 2083: 1–21.

32 GSMA Intelligence (2014). Understanding 5G: perspectives on future technological advancements in mobile *White paper*, 1–26.

33 You, L., Gao, X., Li, G.Y. et al. (2017). BDMA for millimeter-wave/terahertz massive MIMO transmission with per-beam synchronization. *IEEE Journal on Selected Areas in Communications* 35 (7): 1550–1563.

34 Wang, C.-X., Haider, F., Gao, X. et al. (2014). Cellular architecture and key technologies for 5G wireless communication networks. *IEEE Communications Magazine* 52 (2): 122–130.

35 Xu, Y., Gui, G., Gacanin, H., and Adachi, F. (2021). A survey on resource allocation for 5G heterogeneous networks: current research, future trends, and challenges. *IEEE Communications Surveys & Tutorials* 23 (2): 668–695.

36 Checko, A., Christiansen, H.L., Yan, Y. et al. (2015). Cloud RAN for mobile networks—a technology overview. *IEEE Communications Surveys & Tutorials* 17 (1): 405–426.

37 Baek, S., Kim, D., Tesanovic, M., and Agiwal, A. (2021). 3GPP new radio release 16: evolution of 5G for industrial Internet of Things. *IEEE Communications Magazine* 59 (1): 41–47.

38 del Peral-Rosado, J.A., Raulefs, R., López-Salcedo, J.A., and Seco-Granados, G. (2017). Survey of cellular mobile radio localization methods: from 1G to 5G. *IEEE Communications Surveys & Tutorials* 20 (2): 1124–1148.

39 Saad, W., Bennis, M., and Chen, M. (2020). A vision of 6G wireless systems: applications, trends, technologies, and open research problems. *IEEE Network* 34 (3): 134–142.

40 Iyer, S., Patil, A., Bhairanatti, S. et al. (2022). A survey on technological trends to enhance spectrum-efficiency in 6G communications. *Transactions of the Indian National Academy of Engineering* 7 (4): 1093–1120.

41 Mahmood, N.H., Alves, H., López, O.A. et al. (2020). Six key features of machine type communication in 6G. n *2nd 6G Wireless Summit (6G SUMMIT)*, 1–5.

42 Alsheyab, H.Y., Choudhury, S., Bedeer, E., and Ikki, S.S. (2019). Near-optimal resource allocation algorithms for 5G+ cellular networks. *IEEE Transactions on Vehicular Technology* 68 (7): 6578–6592.

43 López, O.L.A., Rosabal, O.M., Ruiz-Guirola, D.E. et al. (2023). Energy-sustainable IoT connectivity: vision, technological enablers, challenges, and future directions. *IEEE Open Journal of the Communications Society* 4: 2609–2666.

44 Bai, L., Wang, C.-X., Huang, J. et al. (2018). Predicting wireless mmWave massive MIMO channel characteristics using machine learning algorithms. *Wireless Communications and Mobile Computing* 2018: 1–12.

45 Petkova, R., Poulkov, V., Manolova, A., and Tonchev, K. (2022). Challenges in implementing low-latency holographic-type communication systems. *Sensors* 22 (24): 9617.

46 López, O.L.A., Porambage, P., and Liyanage, M. (2023). *Society 5.0 and Security*, 135–155.

47 Sedlmeir, J., Buhl, H.U., Fridgen, G., and Keller, R. (2020). The energy consumption of blockchain technology: beyond myth. *Business & Information Systems Engineering* 62 (6): 599–608.

48 Tomkos, I., Klonidis, D., Pikasis, E., and Theodoridis, S. (2020). Toward the 6G network era: opportunities and challenges. *IT Professional* 22 (1): 34–38.

49 Zhang, Y. and Zhang, Y. (2022). Mobile edge computing for beyond 5G/6G. *Mobile Edge Computing* 9 37–45.

50 Alsharif, M.H., Kelechi, A.H., Albreem, M.A. et al. (2020). Sixth generation (6G) wireless networks: vision, research activities, challenges and potential solutions. *Symmetry* 12 (4): 676.

51 Albreem, M.A., Alsharif, M.H., and Kim, S. (2020). A low complexity near-optimal iterative linear detector for massive MIMO in realistic radio channels of 5G communication systems. *Entropy* 22 (4): 388.

52 Shen, X., Gao, J., Wu, W. et al. (2022). Holistic network virtualization and pervasive network intelligence for 6G. *IEEE Communications Surveys & Tutorials* 24 (1): 1–30.

53 Zangiabady, M., Garcia-Robledo, A., Aguilar-Fuster, C., and Rubio-Loyola, J. (2020). A holistic framework for virtual network migration to enhance embedding ratios in network virtualization environments. *Journal of Network and Systems Management* 28 (3): 502–552.

54 David, K. and Berndt, H. (2018). 6G vision and requirements: is there any need for beyond 5G?. *IEEE Vehicular Technology Magazine* 13 (3): 72–80.

55 Zhou, F., Lu, G., Wen, M. et al. (2019). Dynamic spectrum management via machine learning: state of the art, taxonomy, challenges, and open research issues. *IEEE Network* 33 (4): 54–62.

56 Letaief, K.B., Chen, W., Shi, Y. et al. (2019). The roadmap to 6G: AI empowered wireless networks. *IEEE Communications Magazine* 57 (8): 84–90.

57 Sarieddeen, H., Saeed, N., Al-Naffouri, T.Y., and Alouini, M.-S. (2020). Next generation terahertz communications: a rendezvous of sensing, imaging, and localization. *IEEE Communications Magazine* 58 (5): 69–75.

58 Li, R., Zhao, Z., Zhou, X., Ding, G. et al. (2017). Intelligent 5G: when cellular networks meet artificial intelligence. *IEEE Wireless Communications* 24 (5): 175–183.

59 Piran, M.J. and Suh, D.Y. (2019). Learning-driven wireless communications, towards 6G. *International Conference on Computing, Electronics & Communications Engineering (iCCECE)*, 219–224.

60 Mahmood, N.H., Atzeni, I., Jorswieck, E.A., and López, O.L.A. (2023). Ultra-reliable low-latency communications: foundations, enablers, system design, and evolution towards 6G. *Foundations and Trends® in Communications and Information Theory* 20 (5-6): 512–747.

61 López, O.L.A., Mahmood, N.H., Shehab, M. et al. (2023). Statistical tools and methodologies for ultrareliable low-latency communication—a tutorial. *Proceedings of the IEEE* 111 (11): 1502–1543.

62 Cerar, G., Yetgin, H., Mohorcic, M., and Fortuna, C. (2021). Machine learning for wireless link quality estimation: a survey. *IEEE Communications Surveys & Tutorials* 23 (2): 696–728.

63 Creswell, A., White, T., Dumoulin, V. et al. (2018). Generative adversarial networks: an overview. *IEEE Signal Processing Magazine* 35 (1): 53–65.

64 Li, X., Jiang, P., Chen, T. et al. (2020). A survey on the security of blockchain systems. *Future Generation Computer Systems* 107: 841–853.

65 Restuccia, F. and Melodia, T. (2020). Deep learning at the physical layer: system challenges and applications to 5G and beyond. *IEEE Communications Magazine* 58 (10): 58–64.

66 Alrabeiah, M. and Alkhateeb, A. (2020). Deep learning for mmWave beam and blockage prediction using sub-6 GHz channels. *IEEE Transactions on Communications* 68 (9): 5504–5518.

67 Toro, U.S., Wu, K., and Leung, V.C.M. (2022). Backscatter wireless communications and sensing in green Internet of Things. *IEEE Transactions on Green Communications and Networking* 6 (1): 37–55.

68 López, O.L.A., Alves, H., Souza, R.D. et al. (2021). Massive wireless energy transfer: enabling sustainable IoT toward 6G era. *IEEE Internet of Things Journal* 8 (11): 8816–8835.

69 Alves, H. and Lopez, O.A. (2021). *Wireless RF Energy Transfer in the Massive IoT Era: Towards Sustainable Zero-energy Networks*. Wiley-IEEE Press.

70 Rosabal, O.M., López, O.L.A., Alves, H., and Latva-aho, M. (2023). Sustainable radio frequency wireless energy transfer for massive Internet of Things. *arXiv preprint arXiv:2306.15051*.

71 Kallimani, R., Pai, K., Raghuwanshi, P. et al. (2023). TinyML: Tools, applications, challenges, and future research directions. *arXiv preprint arXiv:2303.13569*.

72 Valente da Silva, R., López, O.L.A., and Souza, R.D. (2023). Energy-aware federated learning with distributed user sampling and multichannel ALOHA. *IEEE Communications Letters* 27 (10): 2867–2871.

73 Ruíz-Guirola, D.E., Rodríguez-López, C.A., Montejo-Sánchez, S. et al. (2022). Energy-efficient wake-up signalling for machine-type devices based on traffic-aware long short-term memory prediction. *IEEE Internet of Things Journal* 9 (21): 21620–21631.

74 Basharat, S., Hassan, S.A., Pervaiz, H. et al. (2021). Reconfigurable intelligent surfaces: potentials, applications, and challenges for 6G wireless networks. *IEEE Wireless Communications* 28 (6): 184–191.

75 Zhang, Z., Dai, L., Chen, X. et al. (2023). Active RIS vs. passive RIS: which will prevail in 6G? *IEEE Transactions on Communications* 71 (3): 1707–1725.

76 Matinmikko-Blue, M., Yrjölä, S., Seppänen, V. et al. (2019). Analysis of spectrum valuation elements for local 5G networks: case study of 3.5-GHz band. *IEEE Transactions on Cognitive Communications and Networking* 5 (3): 741–753.

77 López-Pérez, D., De Domenico, A., Piovesan, N. et al. (2022). A survey on 5G radio access network energy efficiency: massive MIMO, lean carrier design, sleep modes, and machine learning. *IEEE Communications Surveys & Tutorials* 24 (1): 653–697.

78 Latva-aho, M. and Leppänen, K. (2019). 6G white paper, key drivers and research challenges for 6G ubiquitous wireless intelligence. *University of Oulu, Tech. Rep. Vers*, vol. 1.