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11. IMT 2020 MOBILE NETWORKS AS UNIVERSAL WIRELESS TRANSMISSION PLATFORM

11.1. Introduction

Digitalization, identified with the way in which information is represented, processed and transmitted, is currently one of the basic elements that define how the modern world works. Its usefulness, or even indispensability, was clearly revealed during the pandemic, when whole societies were forced to transfer a significant part of their activity to the virtual world. Thus, it turned out that social media made it possible to maintain social relations, digitalization of production processes - to manage them remotely, and access to the global Internet – to maintain the continuity of the education. Many more similar examples could be mentioned in this regard.

The work on the further development directions of the digital world has already intensified at the beginning of the second decade of the 21st century. Modern industries that are a part of the broadly defined e-economy have gained in importance. The concept of the fourth industrial revolution (Industry 4.0) was outlined, which is based on the use of robotics, machine processing, artificial intelligence, cloud services, and the Internet of Things[4]. Smart factories are talked about, depicted as complex cyber-physical systems capable of efficiently managing available resources and providing products tailored to individual consumer needs[5]. The combination of modern industry with the service sector,

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[4] Kagermann H., Wahlster W., Helbig J.: Securing the future of German manufacturing industry. Recommendations for implementing the strategic initiative INDUSTRIE 4.0. Final report of the Industrie 4.0 Working Group, Frankfurt 2013.

[5] Chen B., Wan J., Shu L., Li P., Mukherjee M., Boxing Y.: Smart Factory of Industry 4.0: Key Technologies, Application Case, and Challenges, IEEE Access, 2018, Vol. 6, pp. 6505–6519, DOI: 10.1109/ACCESS.2017.2783682.

which successfully finds its place also in the virtual world, results in the development of modern vertical industries/markets that specialize in carrying out specific types of task from the planning phase to the deployment of the final product. Among them, it is worth to mention, being actively supported by modern information and communication technologies, such the verticals as: education, health, public services, transport, energy management, which when properly integrated can create efficiently working complex ecosystems.

An example of that ecosystem can be a smart city, which as a vital organism, knows the needs of its inhabitants and responds accordingly[6]. Fast and reliable access to information plays a key role in efficient management of this dynamic environment. The changes ongoing in urban agglomeration concern not only the values of parameters characterizing the selected area of its functionality, but also the current structure of the city, which is formed, among others, by buildings, vehicles and the inhabitants themselves. Therefore, appropriate forms of information exchange are necessary that will not impose unnecessary restrictions on the operation and development of the city. Among the various modes of communication, mobile wireless networks are considered the most suitable type of infrastructure. They provide flexible access to the end user, who is now increasingly not only a human but also a machine. They also enable the provision of “anytime, anywhere”, “here and now” services.

11.2. Evolution of digital mobile networks

Mobile networks in their current form have undergone a rapid evolution from purely analog solutions (1G system) through digital 2G and 3G systems with the dominant role of circuit switching[7], to full implementation of packet switching [8] (in 4G systems and above) as a more efficient way of using available communication resources. At first, digital systems were dominated by voice transmission complemented by SMS services. The latter, despite their limitations and low reliability, have quickly found non-standard applications e.g. in measurement or monitoring data acquisition systems[9]. In subsequent

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[6] Law K.H., Lynch J.P.: Smart City: Technologies and Challenges, IT Professional, 2019, Vol. 21, No. 6, pp. 46–51, DOI: 10.1109/MITP.2019.2935405.

[7] A dedicated channel is established between two communicating endpoints, even if they are not currently exchanging information.

[8] Particular communication resources are utilized only when some part of information (a packet) must be transmitted between endpoints.

[9] Wang H., Zeng R., He J., Sheng X., Zou J.: Data acquisition in distribution system with the GSM network, Proceedings. International Conference on Power System Technology, 2002, Vol. 3, pp. 1768–1771 , DOI: 10.1109/ICPST.2002.1067836.

years, packet transmission, particularly including mobile Internet access popularized in 4G systems, finally sealed the universal nature of these networks. It should be emphasized at this point that the idea of a universal wireless network was first incorporated into 3G mobile systems. It was the fruit of years of work by standardization committees on the requirements for the global IMT-2000 system[10], which in the European edition was deployed at the beginning of the 21st century under the abbreviation UMTS (Universal Mobile Telecommunications System).

The IMT-2000 requirements first identified the need to build a network capable of supporting communications for a variety of digital services. Four traffic quality classes were identified: conversational, streaming, interactive, and background[11]. In retrospect, the requirements for these classes may not seem excessive. The maximum data rates for UMTS did not exceed 2 Mbit/s, and the minimum latencies were on the order of tens of milliseconds. By the standards of the time, which were dominated by text and voice data services, these were acceptable values[12]. After all, the era of smartphones was to begin only in a few years (the first iPhone running iOS in 2007, followed a year later by the HTC Dream running Android), and widespread communication under the Internet of Things remained in the realm of plans.

The proliferation of internet services has led to continuous improvements in UMTS. The priority was to enhance the efficiency of packet transmission. The modifications introduced in the physical layer of the link between the user's terminal and base station (Node B) have included, fast scheduling for better resource sharing among users, adaptive modulation and coding and fast retransmissions[13]. The most advanced extensions for UMTS, called HSPA+, set the upper limit for downlink at a theoretical level of 336Mbit/s, although implementations in mobile operators' networks usually offered a much lower value – 42Mbit/s. Interestingly, further development of the networks now referred to as 3.5G took place in parallel with the construction of infrastructure for new Long Term Evolution (LTE)[14] mobile networks to meet still rapidly growing demand for broadband Internet access.

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[10] International Telecommunication Union: Detailed specifications of the terrestrial radio interfaces of International Mobile Telecommunications-2000 (IMT-2000), Recommendation ITU-R M.1457, Geneva, May 2000.

[11] International Telecommunication Union: Performance and quality of service requirements for International Mobile Telecommunications-2000 (IMT-2000), Recommendation ITU-R M.1079, Geneva, May 2000.

[12] Rapeli J.: UMTS: targets, system concept, and standardization in a global framework, IEEE Personal Communications, Vol. 2, No. 1, pp. 20–28, Feb. 1995, DOI: 10.1109/98.350860.

[13] Das A. et al.: Evolution of UMTS toward high-speed downlink packet access, “Bell Labs Technical Journal”, 2003, Vol. 7, No. 3, pp. 47–68, DOI: 10.1002/bltj.10018.

[14] Astely D., Dahlman E., Furuskär A., Jading Y., Lindström M., Parkvall, S.: LTE: the evolution of mobile broadband, IEEE Communications Magazine, April 2009, Vol. 47, No. 4, pp. 44–51, DOI: 10.1109/MCOM.2009.4907406.

The general guidelines and analysis[15] were adopted to develop the next generation system. It was assumed that the maximum transmission speed should be about 100 Mbit/s for high mobility and about 1 Gbit/s for low mobility, and the maximum transmission delays should not exceed 10 ms. Concurrently, it was emphasized that the proposed solutions should take into account the current technological innovations and trends in development of new types of broadband services. The work undertaken resulted in a set of requirements for IMT-Advanced (4G) systems[16], first published in 2012, with reference to the specifications, considering the LTE-Advanced system as a natural evolution of the LTE system developed several years earlier.

Finally, peak data rates in the latest version of the LTE-Advanced specification (representing the next stage in the development of IMT-Advanced system) can reach values of 32 Gbps (downlink) and 13.6 Gbps (uplink). These values are many times higher than initially assumed and typical for next-generation systems. Among the transmission techniques of physical layer, OFDM (Orthogonal Frequency Division Multiplexing) modulation, which allows to organize simultaneous data transmission on many independent subcarriers, has established its position. Additionally, binary information can be encoded on a given subcarrier by means of complex signal constellations as large as 256 symbols. This means that a single symbol transmitted on a given subcarrier contains information represented by as many as 8 bits. An important role in the transmission of large amounts of data also plays the maximum bandwidth for a single transmission, which according to the specification is up to 640 MHz. The technique used here is carrier aggregation, which consists in simultaneous OFDM transmission on multiple carriers. But the developers of the system have even gone a step further. Recognising that bandwidth requirements may vary depending on the application, a support for Internet of Things (IoT) connectivity, including low bandwidth 200 kHz as part of the NB IoT service, is included in the set of specifications. Another addition is the extension of connectivity with a channel for direct communication of end devices without participation of base stations (sidelink), intended mainly for public safety services.

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[15] International Telecommunication Union: Framework and overall objectives of the future development of IMT-2000 and systems beyond IMT-2000, Recommendation ITU-R M.1645, Geneva, June 2003; International Telecommunication Union: Requirements related to technical performance for IMT-Advanced radio interface(s), Report ITU-R M.2134, 2008.

[16] International Telecommunication Union: Detailed specifications of the terrestrial radio interfaces of International Mobile Telecommunications-Advanced (IMT-Advanced), Recommendation , Geneva, Jan. 2012.

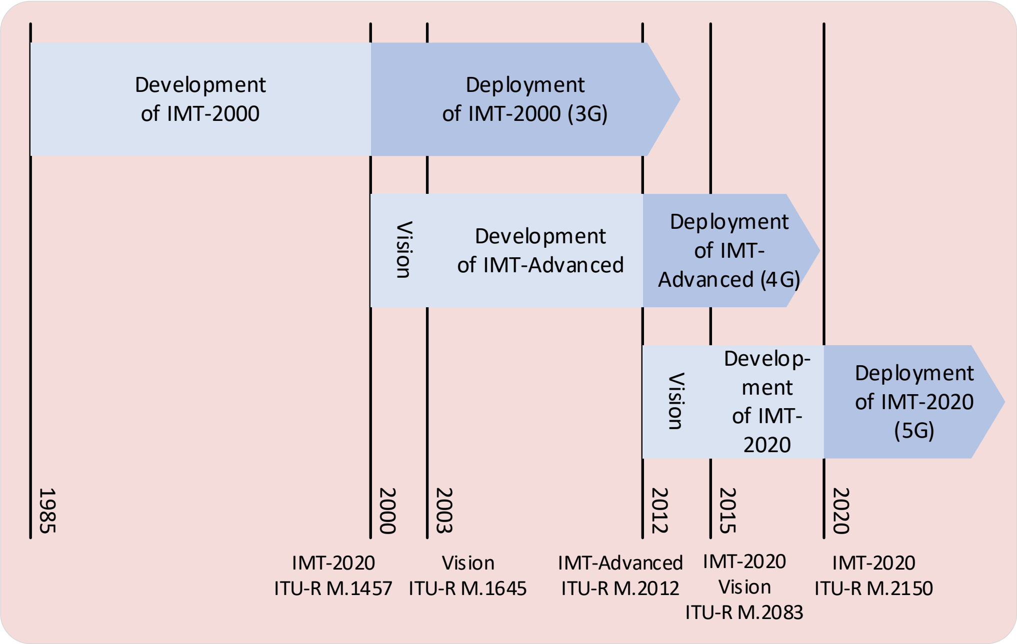

Fig. 11.1. Evolution of digital mobile systems – timeline
Rys. 11.1. Ewolucja cyfrowych systemów mobilnych – oś czasu

As in the case of previous generations (see Figure 11.1), the publication of the first release of the IMT-Advanced[17] system specification in 2012 initiated the start of conceptual work on its successor, called IMT-2020. The awareness of the growing importance of information and communication technologies in various areas of socio-economic life, including the rapidly growing market of electronic services, was reflected in the work of engineering teams on the conditions of the new system. A wide range of current and future applications with diversified demand for communication resources posed a serious challenge to the selection of transmission technology, frequency ranges, and network structure.

11.3. IMT-2020 – objectives and assumptions

The constant increase in the amount of information that is being exchanged is an undeniable fact. We need information to effectively shape and control the reality around us. Especially as this reality is becoming more and more complex due to growing automation and robotisation. Using today's technological advances in areas such as electronics, information and telecommunications technologies, we create new solutions or services that increase the comfort of life and, in addition, function more and more

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[17] International Telecommunication Union: Detailed specifications of the terrestrial radio interfaces of International Mobile Telecommunications-Advanced (IMT-Advanced), Recommendation , Geneva, Jan. 2012.

autonomously. The systems developed within the vertical branches of Industry 4.0 are often spatially extensive solutions with a large variability of the number of users and their mutual location. Moreover, the user group also includes devices. And it is machine-to--machine (M2M) or machine-to-human (M2H) communication, alongside traditional human-to-human communication, that becomes one of the key challenges for the new mobile system.

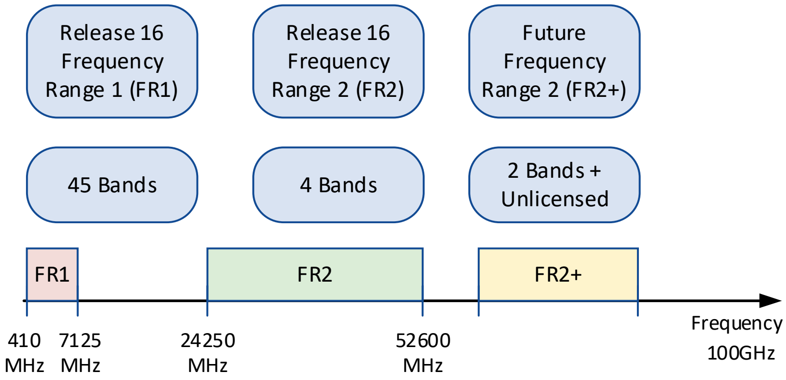

Fig. 11.2. Frequency bands for the IMT-2020 systems
Rys. 11.2. Pasma częstotliwościowe dla systemów IMT-2020

In response to the rapidly growing number of users and applications, bandwidth requirements are also increasing. Additional resources are requested in frequency bands above 6 GHz[18] because those below are already mostly occupied by the existing systems. Figure 11.2 shows the allocation of frequency bands for the IMT-2020 systems[19]. However, when high frequencies (including millimeter waves above 30GHz – mmWave transmission) are used, it is important to keep in mind the range limitations due to the nature of propagation of such signals. Besides growing attenuation along with the increase in the frequency of transmitted signals, additional factors that hinder transmission are e.g. atmospheric induced attenuation (including rain-induced attenuation), foliage-induced attenuation and higher material penetration loss[20]. On the other hand, the reduced transmission range, from perspective of the overall system throughput, may also be an advantage. Traffic in a given area can be handled by mutually non-interfering small picocells/femtocells, which increases area traffic capacity. However, it is impossible not to mention here the inconvenience associated with the large

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[18] International Telecommunication Union: Technical feasibility of IMT in bands above 6 GHz, Report ITU-R M.2376-0, Geneva, July 2015.

[19] MT Vision - Framework and overall objectives of the future development of IMT for 2020 and beyond Report M.2083-0 (09/2015).

[20] International Telecommunication Union: Technical feasibility of IMT in bands above 6 GHz, Report ITU-R M.2376-0, Geneva, July 2015.

number of base stations, as well as the control data that must be transmitted if the supported user moves within several such picocells during the connection. A separate challenge is the technological aspects of building silicon chips that support transmission in the millimetre wave band[21].

An approach supporting effective management of available capacity should take into account, at the design stage of a new system, the varying requirements for link characteristics. Different demands are imposed on access to multimedia services, and others on systems for traffic control, remote health monitoring, emergency warnings, etc. Therefore, for the designed IMT-2020 systems (and beyond), commonly referred to as the fifth generation (5G) systems, three usage scenarios have been initially distinguished[22]:

- **Enhanced Mobile Broadband (eMBB)** – a continuation and improvement of the popular mobile access to the broadband network. The focus is on higher bandwidth and mobility requirements for multimedia and data services over a large coverage area. A range of future services including VR (Virtual Reality) and AR (Augmented Reality) are considered.
- **Ultra-Reliable and Low Latency Communications (uRLLC)** – a new area of so--called critical applications, designed in particular for autonomous systems. The key factors for these applications are: high safety level, fast response, high operational reliability.
- **Massive Machine Type Communications (mMTC)** – an evolution of M2M services towards solutions that support communication between large number of low-cost and energy-efficient devices. The amount of information exchanged, speed rate and latency are not critical here.

Figure 11.3 presents examples of specialized applications (verticals) and their assignment to the usage scenarios[23].

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[21] Juneja S., Pratap R., Sharma R.: Semiconductor technologies for 5G implementation at millimeter wave frequencies – Design challenges and current state of work, "Engineering Science and Technology, an International Journal", 2021, Vol. 24, pp. 205–217.

[22] International Telecommunication Union: IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond, Recommendation ITU-R M.2083-0, Geneva, Sep. 2015.

[23] International Telecommunication Union: Minimum requirements related to technical performance for IMT-2020 radio interface(s), Report ITU-R M.2410-0, Geneva, Nov. 2017.

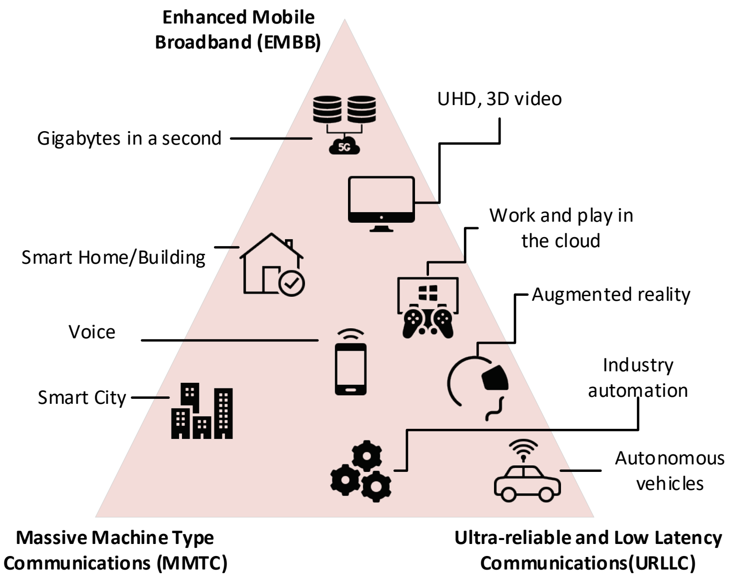

Fig. 11.3. Usage scenarios of IMT-2020 with system examples
Rys. 11.3. Scenariusze zastosowań IMT-2020 z przykładami systemów

To systematize the features of the future system, a set of Key Performance Indicators (KPIs)[24] has been defined and used as benchmarks in the evaluation of the IMT-2020 system proposals. The most characteristic KPIs are:

- Bandwidth (BW) – maximum aggregated range of frequency spectrum;
- Peak Data Rate (PDR) – maximum data rate per user in case of ideal error–free conditions when all radio resources designated for user data are utilized (i.e. excluding control and guard resources, reference signals etc.);
- User Experienced Data Rate (UDR) – achievable throughput, i.e. the number of bits per second delivered to higher layer of the system, measured as 5% of the CDF (Cumulative Distribution Function) user throughput;
- Peak Spectral Efficiency (PSE) – peak data rate normalized by the channel bandwidth;
- User Plane Latency (UPL) – the time necessary to deliver information between transmitter and receiver at the level of 2/3 Layer of the system;
- Control Plane Latency (CPL) – the time necessary for transition from idle state to active state of the device;
- Connection Density (CD) – total number of devices per unit area assuming that the predefined QoS (Quality of Service) conditions[25] are met;

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[24] International Telecommunication Union: Minimum requirements related to technical performance for IMT-2020 radio interface(s), Report ITU-R M.2410-0, Geneva, Nov. 2017.

[25] International Telecommunication Union: Guidelines for evaluation of radio interface technologies for IMT-2020, Report ITU-R M.2412-0, Geneva, Oct. 2017.

- Mobility (M) – maximum speed of the mobile device assuming that the predefined QoS conditions are met;
- Area Traffic Capacity (ATC) – is the total traffic throughput served per geographic area.

Table 11.1

Relation between KPI and the usage scenarios

KPI	**USAGE SCENARIOUS**	**IMT-2020**	**IMT-Advanced**
BW	eMBB	100 MHz – 1GHz (in bands above 6 GHz)	Up to 100 MHz
PDR	eMBB	DL: 20 Gbps UL: 10 Gbps	DL: 1 Gbps UL: 50 Mbps
UDR	eMBB	100 Mbps	10 Mbps
PSE	eMBB	DL: 30 bps/Hz UL: 15 bps/Hz	DL: 15 bps/Hz UL: 6,75 bps/Hz
UPL	eMBB. uRLLC	4 ms, 1 ms (uRLLC)	10 ms
CPL	eMBB, uRLLC	10 ms	100 ms
CD	mMTC	$1x10^6$ devices/km^2	$0{,}1x10^6$ devices/km^2
M	eMBB	500 km/h	350 km/h
ATC	eMBB	10 Mbps/m^2	0,1 Mbps/m^2

However, not all of these parameters are critical for every usage scenario. Table 11.1 shows the reference values for selected KPIs along with an indication of the usage scenarios for which each parameter is particularly important and how it compares to the original requirements for previous IMT-Advanced systems. As can be seen, most KPIs relate to applications that require fast, mobile network access. It is the most widespread and, in retrospect, mature type of service. Many times, this is the only way to connect the user to the global Internet. Nevertheless, in the physical structure of the same system, there should be separate resources (network slices) intended for building independent logical networks that implement specialized services/applications with different requirements (see Figure 11.4). Many of these applications are still under development or testing.

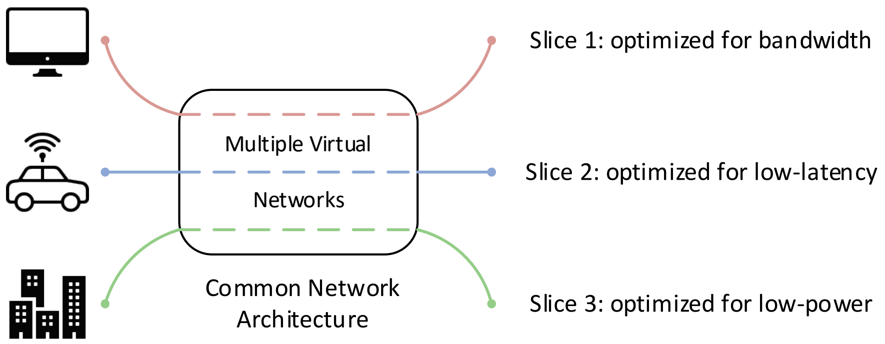

Fig. 11.4. Network Slicing
Rys. 11.4. Plasterkowanie sieci

The requirements for the 5G systems, due to the significant increase in the number of users, the traffic they generate, and the high demand for service diversification, were met by 4 specifications of mobile networks[26]. The New Radio (NR) proposal of the 3GGP consortium was among them in the standalone (SA) and non-standalone (NSA) versions. The second, NSA, assumes coexistence of the new solution with the LTE-Advanced network, whose EPC (Evolved Packet Core) network temporarily takes over the traffic generated in 5G terminals[27]. This incremental deployment of 5G is a very beneficial solution from the perspective of both mobile system operators and end device manufacturers. Coexistence of both radio interfaces can be used to increase throughput using dual connectivity, i.e. transmission on independent frequency bands and to different base stations, if such capabilities are supported by terminal equipment. In a situation where new frequency bands have not yet been made available, the Dynamic Spectrum Sharing mechanism comes to rescue, which is responsible for sharing frequency resources with LTE-Advanced during the migration phase from 4G to 5G[28].

The evolutionary and harmonious deployment of 5G as a new component of the multi-system mobile network (2G and 3G systems are still in operation, but their phase-out is ongoing) can be mostly attributed to its versatility and flexibility. The system architecture at the logical/virtual level is service-oriented as never before. These services, due to their specific nature and in order to maintain high standards of quality and efficiency of network operation as a whole, require access to diverse physical resources at the radio network plane. The allocation of these resources is handled by the physical layer of the system, which has appropriate mechanisms for this purpose.

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[26] International Telecommunication Union: Detailed specifications of the terrestrial radio interfaces of International Mobile Telecommunications-2020 (IMT-2020), Recommendation ITU-R M.2150-1, Geneva, Feb. 2022.

[27] Liu G., Huang Y., Chen Z., Liu L., Wang Q., Li N.: 5G Deployment: Standalone vs. Non-Standalone from the Operator Perspective, IEEE Communications Magazine, November 2020, Vol. 58, No. 11, pp. 83–89, DOI: 10.1109/MCOM.001.2000230.

[28] Xin J., Xu S. and Zhang L.: Dynamic Spectrum Sharing for NR-LTE Networks, 2021 2nd Information Communication Technologies Conference (ICTC), 2021, pp. 161–164, DOI: 10.1109/ICTC51749.2021.9441612.

11.4. Key methods and technologies in physical layer of 5G systems

Radio transmission between end terminals is becoming more and more sophisticated nowadays. It is carried out at specific moments in time and frequency ranges. Data security can be adjusted to current transmission conditions and the communicating devices can even be “aware” of each other's position in space. All this is done in order to most effectively use and share limited communication resources with other users.

During the development of the specification for the 5G system, particular attention was paid to improving the reconfigurability of the system in the physical layer plane. The applied techniques and processing methods presented below, on the one hand, support the coexistence with the existing LTE system, and on the other hand, meet the new requirements for IMT-2020 systems.

11.5. Orthogonal Frequency Division Multiplexing (OFDM)

Successful transmission of digitally represented information requires its transformation into a physical signal with parameters corresponding to the current transmission conditions. This process is performed in a processing block called a digital modulator. In the 21st century, among many available solutions, Orthogonal Frequency Division Multiplexing (OFDM) modulation has gained wide popularity[29]. It is characterized by high flexibility in both time and frequency domain. The transmitted digital data are encoded in OFDM modulation symbols, with a duration that can be selected so that the transmission of a single symbol takes place during the unchanged properties of the transmission channel. Moreover, the information contained in a single OFDM symbol is transmitted over many frequency subchannels/subcarriers independent/orthogonal to each other. This is especially important in wireless systems. The principle of radio wave propagation causes that the properties in the frequency domain of the transmission channel are very diverse. Both, the attenuation characteristics and the phase delays vary greatly as a function of frequency. They introduce distortions into the transmitted information, which are removed at the receiver in a block called the equalizer. The independence of the individual subchannels in OFDM modulation greatly

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[29] Weinstein S.B.: The history of orthogonal frequency-division multiplexing [History of Communications], IEEE Communications Magazine, November 2009, Vol. 47, No. 11, pp. 26–35, DOI: 10.1109/MCOM.2009.5307460.

simplifies the operation of the equalizer. Finally, it is also possible to exclude a subchannel of any frequency from transmission in case of very high distortions or when it results from the organization of the transmission.

OFDM modulation has been implemented in the physical layer of many wireless systems[30] including WiFi computer networks, DVB digital television, and LTE. Due to the compatibility of the radio interface with LTE-Advanced systems, it has also become the solution adopted in 5G NR networks. Its success, in addition to the above properties, is attributed to the simple implementation scheme that uses the Fast Fourier Transform (FFT) at its core. The size of the FFT determines the maximum number of frequency subchannels on which simultaneous data transmission can be carried out. In practice, some of them are intended to transmit training signals, and those at the band edges are switched off in order to adjust the bandwidth and minimize interference in adjacent transmission channels. In a single subchannel, the binary data is encoded using complex numbers belonging to a set called a signal constellation. The most common constellations are Quadrature Phase-Shift Keying (QPSK) and M-Quadrature Amplitude Modulation (M-QAM) where M denotes the number of symbols in the set. As the complexity of the constellation increases, the spectral efficiency of the modulation is enhanced, unfortunately with an increase in susceptibility to transmission errors due to distortion and noise.

The OFDM modulation specification for the 5G NR system is a development of the one in the LTE-Advanced system. The length of the physical frame (10 ms) has been preserved, in which there are 10 subframes of 1 ms with a variable number of slots. Each slot consists of 14 OFDM symbols, which, depending on the selected transmission format, can be downlink (DL), uplink (UL), or flexible (DL or UL). The main change in relation to LTE is the doubling of the size of the FFT (4096) and the introduction of numerology. This term is used to specify the range of variations in the subcarrier spacing, starting from the value of 15 kHz (as for LTE) through subsequent doubling, up to the value of 960 kHz for mmWave transmission (Release 17 of the New Radio specification[31]). An increase in the subcarrier spacing corresponds to a decrease in the symbol length (greater number of slots in the subframe), and consequently to an increase in available bit rate. In the case of OFDM modulation, it is possible to easily control the allocation of time-frequency resources, depending on the actual amount of transmitted data, services provided, or the number of users. In the 5G system, similarly to LTE, the

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[30] Hwang T., Yang C., Wu G., Li S., Ye Li G.: OFDM and Its Wireless Applications: A Survey, IEEE Transactions on Vehicular Technology, May 2009, Vol. 58, No. 4, pp. 1673–1694, DOI: 10.1109/TVT. 2008.2004555.

[31] European Telecommunications Standards Institute: 5G, NR, Physical channels and modulation, 3GPP TS 38.211 version 17.1.0 Release 17, Sophia Antipolis, France, Apr. 2022.

basic unit of data allocation has been defined - Physical Resource Block (PRB) – consisting of 12 consecutive subcarriers with a variable number of OFDM symbols[32]. The control mechanisms of the system are responsible for efficient adjustment of PRB to current transmission requirements.

11.6. Massive Multiple Input Multiple Output (mMIMO) and Beamforming

There are many adversities in wireless signal transmission. Unpredictable and variable conditions of multipath signal propagation and users mobility cause phenomena of deep fades that significantly reduce the power of received signal observed in the frequency and time domain. Poor transmission conditions result in loss of transmission quality despite methods minimizing distortions introduced by the channel. Error correction coding can improve the performance, but the price is lower transmission speed.

However, the multipath, which is an inherent feature of wireless propagation can also be successfully exploited to increase system throughput by modifying the radio part of the transmitter and receiver with multi-antenna systems. Each wireless link between any transmitting and receiving antenna is considered as a separate transmission subchannel in a multiple-input-multiple-output (MIMO) type channel structure[33]. Providing spatial sub--channel independence by mutually spacing the transmitter (receiver) antennas more than half a wavelength apart, the data rate (using spatial multiplexing) or the transmission reliability (using spatial diversity) of the entire transmission can be increased. In the former case, each transmitting antenna sends a unique data stream, while in the latter case, one and the same stream (with some modification) is sent by all antennas. On the transmitter side, it is also possible to shape the directional characteristics of the antenna array (beamforming) by introducing, for example, appropriate phase delays of the signal delivered to individual antennas or more advanced precoding algorithms in the baseband processor.

Advanced MIMO techniques are already successfully used in bands up to 6 GHz (sub-6 GHz) by legacy mobile systems (e.g., LTE). The relatively small wavelength allows to place up to several antennas on users' terminals (ongoing research assumes up

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[32] European Telecommunications Standards Institute: 5G, NR, Physical layer procedures for data, 3GPP TS 38.214 version 17.1.0 Release 17, Sophia Antipolis, May 2022.

[33] Paulraj A.J., Gore D.A., Nabar R.U., Bolcskei H.: An overview of MIMO communications – a key to gigabit wireless, Proceedings of the IEEE, Feb. 2004, Vol. 92, No. 2, pp. 198–218, DOI: 10.1109/JPROC.2003.821915.

to 10 antennas[34]) and, in the case of base stations, matrices consisting of a dozen or even several dozen radiating elements (massive MIMO)[35]. The signal emitted by such a matrix can be freely directed in all dimensions of space[36] (3D/full dimension beamforming; vertical beam positioning is a novelty here in particular), including the creation of multiple independent beams for connections to different users (multiuser MIMO)[37]. Knowing the transmission direction allows for more efficient power management and increases system capacity.

MIMO techniques become particularly important at millimeter wave[38]. With a large number of devices communicating at distances not exceeding several hundred meters, when any object in the transmission path can effectively block the signal, the ability of the devices to actively control the beam becomes an essential component of the communication system.

11.7. Carrier Aggregation (CA)

Improvements in transmission performance through the use of multi-antenna techniques have their limitations due to the physical size of the devices (especially important in the case of user terminals) and the complexity of the antenna modules. Further throughput increase within a given communication link can be supported by additional frequency resources. Due to OFDM modulation and arrangement of the transmission in the PRB structure, 5G systems already have quite extensive possibilities of flexible control of the allocated frequency spectrum. In the millimeter band, the demand for high bit rates can be effectively satisfied by large values of OFDM modulation subcarrier spacing (new numerologies introduced in Release 17 of the New Radio specification[39]). However, this will be a short range transmission.

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[34] Khan J., Ullah S., Ali U., Tahir F.A., Peter I., Matekovits L.: Design of a Millimeter-Wave MIMO Antenna Array for 5G Communication Terminals, Sensors, 2022, 22, 2768. doi.org/10.3390/s22072768.

[35] Borges D., Montezuma P., Dinis R., Beko M.: Massive MIMO Techniques for 5G and Beyond--Opportunities and Challenges, "Electronics" 2021, 10, 1667. doi.org/10.3390/electronics10141667.

[36] Nadeem Q., Kammoun A. Alouini M.: Elevation Beamforming With Full Dimension MIMO Architectures in 5G Systems: A Tutorial, IEEE Communications Surveys & Tutorials, 2019, Vol. 21, No. 4, pp. 3238–3273, DOI: 10.1109/COMST.2019.2930621.

[37] Spencer Q.H., Peel C.B., Swindlehurst A.L., Haardt M.: An introduction to the multi-user MIMO downlink, IEEE Communications Magazine, Oct. 2004, Vol. 42, No. 10, pp. 60–67, DOI: 10.1109/MCOM.2004.1341262.

[38] Bjornson E., Van der Perre L., Buzzi S., Larsson E.G.: Massive MIMO in Sub-6 GHz and mmWave: Physical, Practical, and Use-Case Differences, IEEE Wireless Communications, April 2019, Vol. 26, No. 2, pp. 100–108, DOI: 10.1109/MWC.2018.1800140.

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The current coexistence with LTE on sub-6GHz bands imposes its own constraints on the time-frequency distribution of shared resources. As a result, for a 5G system, the maximum transmission rates over a single 100 MHz wide frequency channel using MIMO do not exceed 5 Gbps[40]. This is the result that does not meet the requirements expected for IMT-2020 systems. The solution here is brought by a technique called Carrier Aggregation, also implemented in LTE-Advanced[41].

Data transmission is carried out simultaneously over several OFDM channels called Carrier Component. Various combinations of these channels are possible. They may be in close vicinity (intra-band contiguous) or distant (intra-band non-contiguous) or even located in separate bands (inter-band non-contiguous). The IMT-2020 specification assumes aggregation of up to 16 CCs. Analyses of such transmission for sub-6GHz bands report that the maximum throughput values are at the level of 80 Gbps (DL) and 40 Gbps (UL) at a total bandwidth occupancy of 1.6 GHz[42]. This applies only to the licensed band. In the longer term, the possibility of including unlicensed bands in the transmission is also being considered.

Although multiband transmission via CA seems conceptually simple, there are many challenges from a device design perspective. A solution with the least hardware complexity that consists of a single radio path can be proposed, especially for the intra-band cont. CA scenario. In this case, the channel aggregation procedure is performed all in the digital domain in the baseband processor. Since the result of CA is a wideband signal, special attention is paid to the linearity of analog circuits to minimize spurious in-band interferences. In a system of multiple independent analog paths (for non-cont. CA), additional efforts must be made to ensure proper isolation between them and to compensate for the attenuation contributed by the analog combiner[43].

11.8. Non-Orthogonal Multiple Access (NOMA)

In mobile systems, there is a clear increase not only in the amount of data transferred, but also in the number of simultaneously supported devices. This trend will continue in

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[40] Fuentes M., et al.: 5G New Radio Evaluation Against IMT-2020 Key Performance Indicators, IEEE Access, 2020, Vol. 8, pp. 110880–110896, DOI: 10.1109/ACCESS.2020.3001641.

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the future, given the range of highly specialized services proposed especially in the IoT area. Although most of them are only at the planning or concept stage, it is anticipated that the link resource allocation methods used so far may prove to be insufficient in the face of massive M2M communication.

The applied transmission technologies in natural way allow individual users to be allocated separate time and frequency resources (OFDM), and approximately – with precise beamforming – also spatial resources. This method of accessing the system is called Orthogonal Multiple Access (OMA) because, by principle, the transmissions of individual users are mutually separated and independent. In currently proposed IMT-2020 systems, this is the only form of sharing radio resources. However, research is underway to increase the capacity of the system by using a Non-Orthogonal Multiple Access technique in which the transmissions of several users interfere with each other.

Among the NOMAs, two variants can be distinguished: Power domain NOMA and Code domain NOMA[44]. Multi-access in the power domain implies the simultaneous transmission of multiple users' signals with different power levels at the same time, at the same frequency, and in the same direction in space (e.g., by a base station). The power value assigned to a given component depends primarily on the distance over which the signal is to be transmitted. In the receiver, all components are analyzed simultaneously as one combined signal. The component with the highest power is received first, the others represent unwanted interference to it. If the receiver was the recipient of the signal this stage of detection is completed. If not, using the Successive Interference Cancellation (SIC) method, the receiver removes the decoded component from the received signal and the detection process begins again. In the case of code multi-access, each pair of connection participants is assigned a different user-specific spreading sequence based on which a decision is made to whom the transmission is directed.

Besides increasing the system capacity, non-orthogonal multi-access reduces the transmission latency due to less restrictive rules in time resource allocation. The lack of strict resource management also affects the smaller amount of necessary signaling data transmitted in the system during scheduling process. However, the use of this approach increases the computational complexity of the detection algorithms, which in the case of user terminal must be taken into account, at least in terms of increased energy consumption. Some additional processing steps include the determination and transmission of channel state information or error correction features during SIC.

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11.9. Low Density Parity Check (LDPC) and Polar codes

Compared to LTE and LTE-Advanced, an important new element of the physical Layer processing in 5G are new error correction (channel) coding schemes, namely LDPC and Polar codes in data channels and control channels respectively.

Due to the excellent correction performance and parallelized decoding algorithm, LDPC codes were previously incorporated in a number communication standards, like DVB-T2, Wi-Fi 802.11n and WiMAX. The main advantages in comparison with Turbo codes used in LTE are better area throughput efficiency, higher achievable peak throughput, improved decoding latency and improved performance, with error floors below the block error rate of 10^{-5} for all code sizes[45]. The high throughput of multiple Gbps, especially for eMBB 5G deployment scenarios, can be handled effectively by the encoding and decoding schemes of the designed LDPC codes.

LDPC codes are one of the best known block error correction coding schemes. The scheme designed for 5G NR uses a quasi-cyclic structure of LDPC parity check matrices (PCM), where the PCM is defined by a smaller base matrix and a set of cyclic shifts values (CSVs). The base matrix defines positions of square submatrices in PCM that are identity matrices shifted by a corresponding CSV. This developed scheme allows for a dynamic configuration of PCM size (by changing the submatrix size) as well as code-rate adaptation, by the rate-matching technique. Besides the LDPC coding, the processing chain includes cyclic-redundancy-check (CRC) attachment, rate matching and bit-interleaving. The CRC is attached for additional error detection, thanks to which a very low probability of undetected errors can be achieved. The CRC is used in retransmission protocol procedures.

For control channels, in 5G NR, Polar codes replaced tail-biting convolutional codes (TBCC) of LTE. Polar codes, are the class of channel codes, which can be perceived as a special class of block codes with a portion of code-vector that is frozen to specific values. Polar coding was proven to achieve the symmetric capacity of a binary input discrete channel, using a low-complexity successive cancelation (SC) decoding. The main advantage of over the TBCCs, but also turbo codes and typical LDPC codes, is that polar codes with SC-List decoding with outer CRC, typically outperform them at moderate codeword sizes of the order 50…500 bits, which is sufficient for typical control information payloads.

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11.10. Conclusions

The introduction of 4G networks a decade ago sealed the changes in the use of mobile networks at that time. Popular voice calls have been dominated by broadband access to Internet services. It gave mobile networks the hallmarks of universality. Even then, it was recognized that this universality should be supported by optimal use of radio resources. Improvements made in the following years became the basis for the development of new IMT-2020 systems, for example the 5G New Radio system proposed by the 3GPP consortium.

The 5G system is based on the idea: many services over one network. The network that already at the physical layer is able to flexibly allocate appropriate amounts of resources depending on the type of service provided. This is possible thanks to the applied transmission techniques, which discretise physical resources. With elementary units of throughput defined in the time, frequency and even spatial domain, it is possible to manage the efficient operation of the entire system on an ongoing basis.

However, the true potential of the 5G network will only be revealed when it is widely deployed in the mmWave bands. Then the structure of the network infrastructure will change. Short-range transmissions will force the construction of a large number of additional base stations, not necessarily stationary ones. Direct communication between terminals (so-called sidelink) will gain in importance. Many modern vertical services will have a chance to spread. In Europe, two public-private partnerships, “5G Infrastructure Public Private Partnership” (5G PPP) and “Smart Networks and Services Joint Undertaking (SNS JU)” have undertaken this task through numerous projects including those related to Smart City idea[46].

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[46] Full 5G Consortium Parties: The European 5G annual Journal/2021, TO-EURO-5G Project, grant agreement number: 761338 under Horizon 2020 funding programme https://bscw.5g-ppp.eu/pub/bscw.cgi/d424095/5G%20European%20Annual%20Journal%202021.pdf.