Implementation and Development of Mobile Networks

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Abstract: The development of mobile networks has been one of the most important technological processes of the past decades, fundamentally changing the way people communicate. From the simple radio telephone systems of the zero generation to today's state-of-the-art 5G networks offering high-speed data transmission, each new generation has brought new possibilities and services. Analog voice transmission has been replaced by digital communication, which has enabled better quality, greater capacity, and more secure operation, and the spread of mobile internet has triggered the development that has resulted in today's world of smart devices and networked devices. The central elements of the network's operation are base stations, which provide interconnection between wired and wireless networks. The development of base stations has closely followed the evolution of mobile generations, with earlier copper-based cabling solutions gradually being replaced by optical data transmission, which involves less attenuation and energy consumption. Modern 4G and 5G stations now operate with more efficient, compact devices that significantly improve network coverage and quality. Antennas are key components of base stations, ensuring signal transmission and reception. The operating principle, structure, and properties of antennas, such as gain, polarization, or directional characteristics, fundamentally determine the performance of the network. In this chapter of the publication, we present radio data transmission characteristics such as the phenomenon of fading, various modulation methods, and duplex technologies. The chapters covered so far provide a comprehensive overview of the development of mobile networks, describe the structure and operation of base stations, and present the most important characteristics of antennas and radio data transmission.

Keywords: Mobile network; 4G; 5G; Base stations; Antennas

6 Mobile network generations to today

Telephone networks are communication systems that enable voice and data communication between people and places that are far apart. This system is based on wired and wireless technologies. In this chapter, we will present the generations of these mobile networks up to the most modern ones available today.

The development of mobile networks really took off after World War II, when the first commercially available radiotelephone systems appeared in 1945. The devices used for these were still a long way from today's mobile phones, but they represented a significant milestone in wireless voice transmission. This is why they are referred to as zero generation (0G), because due to their size and weight, the devices available at the time could only be used in buildings and in the trunks of vehicles, and were not really characterized by mobility. In vehicles, the transceiver unit was placed in the trunk, while the handset was placed in the passenger compartment. These 0G systems operated in a so-called Push-to-Talk mode, in which a button was pressed to switch between transmission and reception. They used an analog base station cellular network structure developed by Bell Labs engineers, in which the connection was interrupted when the cell was left. First-generation, or 1G, mobile networks appeared in the early 1970s and late 1980s, enabling truly mobile wireless voice communication. The analog radio communication system remained in place, but thanks to the seamless handover technology associated with Amos Bell, mobile devices were able to switch from one cell to another without losing connection and were able to automatically switch base stations. Real-time voice calls were now transmitted using analog FM modulation. An iconic moment of the era was when Martin Cooper, president of Motorola, made the first real mobile phone call in 1973 on a Motorola DynaTAC device, which weighed nearly 1 kg and was 23 cm tall. The early 1990s marked the beginning of a new era in mobile communications. Analog systems, on which 1G networks were also based, gradually faded into the background due to their low capacity and unreliability. Technological advances enabled the introduction of digital signal transmission, which was a huge step forward. Digital signals provided better sound quality, greater network capacity, and higher levels of data security. These innovations led to the emergence of second-generation (2G) mobile networks. The best known and most widespread standard is GSM (Global System for Mobile Communication), which was originally developed for European purposes but very quickly grew to global proportions. In Europe, it was launched primarily in the 900 MHz and 1800 MHz frequency bands, while in the United States, for example, it was launched in the 1900 MHz band. One of the best-known innovations in GSM network technology was the introduction of the SIM (Subscriber Identity Module) card. This is a small, replaceable chip card that is responsible for uniquely identifying the user. New multiplexing techniques have emerged to make communication more efficient. In Europe, the TDMA (Time Division Multiple Access) system was used, in which time slots were allocated to individual calls on a single frequency. In the United States, the CDMA (Code Division Multiple Access) system became widespread, in which individual users were separated on given frequencies by means of coding. The introduction of 2G networks not only improved voice transmission quality, but also enabled the introduction of new services. The best known of these was SMS (Short Message

Service), which enabled the sending and receiving of text messages. The next major milestone was the introduction of packet-switched data transmission systems, known as GPRS (General Packet Radio Service) or 2.5G. These mobile networks made it possible to maintain a continuous Internet connection. The GPRS system was followed by EDGE (Enhanced Data Rates for GSM Evolution), which further improved data transmission capabilities and enabled speeds of between 150 and 350 Kbit/s. Third-generation 3G mobile networks continued the trend that began with the development of 2G networks, as they aimed not only to further develop voice-based services, but also to make mobile data transmission even faster and more reliable. The 3G mobile network enabled the introduction of new multimedia services such as video telephony and video conferencing, which provided real-time visual communication with simultaneous image and sound transmission. Broadband mobile internet appeared, allowing users to watch online TV broadcasts and play online games. The UMTS network was also developed as its successor. With the HSDPA and later HSPA+ standards, it became possible to achieve ever greater bandwidth.

Furthermore, newer generations such as 4G and 5G already operate at the highest bandwidths available today, providing speeds comparable to those of average wired internet with minimal latency. [1], [2], [3], [4]

7 The Base stations

In this chapter, we will introduce the final key element in the structure of mobile networks: the base station. We will discuss base stations and their components and devices in more detail below.

There are base stations all over the world, where various service providers offer access to their networks. We can distinguish between several types of service providers depending on the purpose of the network. There are those, such as Magyar Telekom Nyrt. or Yettel Magyarország Zrt. in Hungary, which mainly provide mobile and data connections for the general public, but also provide unique, specific solutions for companies that meet their requirements. However, the state itself also provides mobile and data connection services to its own organizations, such as the ambulance service, the police, and the military. In the following, I will detail the operation and structure of base stations.

Base stations form a subsystem called the Base Station Subsystem (BSS). This system has several parts, including the base station (BS) or, in more modern networks, the Base Transceiver Station (BTS). These stations are connected by a base station controller (BSC). In more modern networks, such as 4G or 5G, there is no longer a BSC, but the base stations themselves communicate with each other in such a way that they are able to perform the tasks of the BSC, so these elements are no longer necessary. Base stations form a subsystem called the Base Station Subsystem (BSS). This system has several parts, including the base station (BS) or, in more modern networks, the Base Transceiver Station (BTS). These stations are connected by a base station controller (BSC). In more modern networks, such as 4G or 5G, there is no longer a BSC, but the base stations themselves communicate with each other in such a way that they are able to perform the tasks of the BSC, so these elements are no longer necessary. A base station consists of several parts. The composition of these parts has changed over time as mobile network communications have evolved. I will discuss the components that make up base stations, including the structure of older base stations, because it is not only the current or most modern implementations that are in use around the world. There are countries where modernization processes are slower, so base stations used in 2G networks may still be common. Hungary is a good example of a country where modernization is happening more quickly. Over the past 20 years, there have been two nationwide modernizations of base stations as part of the transition to the new generation. It should be noted that the construction of base stations is closely linked to the construction of the current antenna system. This is a key factor that has influenced the current state of development of base stations in terms of construction. A typical tower base station can be thirty or even fifty meters high, depending on how high the point to be served is located in the area to be served, or what topographical factors need to be taken into account when serving the given area. This is an important factor because older base stations did not yet use optical data cables, which have negligible attenuation over the distances covered by tower heights, unlike copper-based cables. The antennas are located at the top of a station and are connected to a Remote Radio Unit (RRU), which is responsible for processing and transmitting signals that the antenna converts into radio frequency signals. In older base stations, the RRU was located at the base of the tower, together with all the other equipment. At the bottom of the base station, there is usually a container or a small, lightweight building that houses the main data connection components and their power supply.

At the bottom of the tower is the Baseband Unit (BBU), which receives data cables from a greater distance, formerly coaxial cables, but now optical cables. The BBU is responsible for processing the entire base station signal, which it transmits to the RRU. This device has a modular design that can be placed in rack cabinets. Since the BBU and RRU were located at the bottom of the old stations, the data cable coming from the RRU had to be routed up to the antennas. At that time, optical cables were not used here either, but thick copper cables, which had much higher attenuation. These cables were thick so that they could transmit data with as little attenuation as possible. In addition to these cables, the power cables for the antennas were also routed. This type of solution was more energy-intensive and also involved greater attenuation in terms of data transmission than today's optical cable implementations. The base station structure described above is an older design. Over time, RRUs have become smaller, allowing them to be placed closer to the antennas, thereby reducing the distance between the two and attenuation. In even more modern implementations, copper-based data cables were replaced with fiber optic cables, which made it possible to avoid having to run copper data cables to the top of the tower, further reducing attenuation. The RRUs were still placed next to or below the antenna, but the data was now transmitted via thin optical cables from the BBU below, and in this solution, their name was changed to Remote Radio Head (RRH). This is how the structure of today's 4G and 5G base stations evolved, with only the BBU and power equipment located in the room at the bottom of the tower. Due to the use of optical cables and smaller, more energy-efficient equipment, the energy network requirements of the base station have been significantly reduced, and attenuation values have also decreased considerably. [7], [8], [9]

8 Mobile Network Radio Element of the Antenna

In the following, we will present the radio and wireless data transmission characteristics and structure of the base stations described in the previous chapter, which are an essential part of the theory required for radio design. An antenna is a device that converts electromagnetic energy fed into it into radiated electromagnetic waves and back again. This is important because an antenna can both transmit and receive radio signals at the same time. In addition, it is capable of modifying the distribution of the electromagnetic field, i.e., scattering. The simplest resonant structure of an antenna is the so-called half-wave dipole. The term dipole refers to two poles, from which we can conclude that its structure consists of two poles. This half-wave dipole radiator is broken at its geometric center, and the feed can be connected to the two poles thus created. the transmitter or receiver. An important feature is that its geometric length is equal to half the wavelength (λ) of its operating frequency (λ/2). There is a 90-degree phase shift between the current and voltage distribution in a half-wave radiator. Thus, the phase difference between the voltages at the ends of the radiator will be 180 degrees. The current is at its maximum at the center of the radiator, and the voltage is at its maximum at the ends. Furthermore, the impedance formed by the radiator can be determined at any point along its entire length based on the ratio of the voltage and current measured at that point. [10], [11]

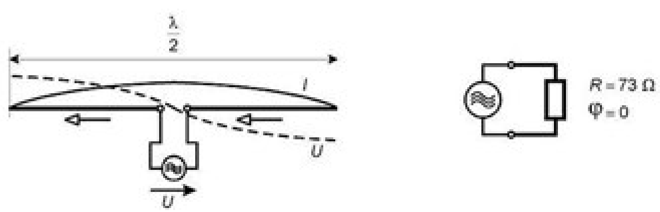

Figure 1. Center-fed half-wave dipole antenna
Source: https://wiki.ham.hu/index.php?title=Dip%C3%B3l

Antenna Characteristics: It is important to clarify the concept of antenna gain, which is one of the main characteristics of antennas. This requires the concept of an isotropic antenna, which is an antenna that exists only in theory and radiates energy evenly in all directions. Such an antenna cannot be built in reality, so it only serves as a basis for theoretical comparison. The latter concept can be used to define antenna gain, which expresses the power ratio in dB, showing how much power density a real antenna radiates in its main direction of radiation compared to an isotropic antenna fed with the same input power. The concept described above can also be expressed in the form of an equation

$$G = \frac{4 \cdot \pi \cdot A}{\lambda^2}$$

- G antenna gain
- A effective surface

The next important characteristic of antennas is their polarization, which determines the direction in which the electric field vector of electromagnetic waves propagates in space. In simpler terms, it determines the form and direction in which the signal emitted by the antenna propagates. This can be linear polarization, of which there are several types, such as horizontal or vertical polarization, but there is also what is known as cross or X polarization, in which the latter two implementations appear simultaneously, with the horizontal shifted by +45 degrees and the vertical shifted by -45 degrees from their original positions. The latter implementation allows two antenna systems to be implemented in one antenna, and such antennas are already found mainly in 4G and 5G systems. There are also so-called circularly polarized antennas, which have right- or left-handed rotation polarization. Another key feature is the antenna's beamwidth, which determines the angle range within which the peak power is reduced by half, the so-called -3 dB point. This angle is usually 60 degrees, because the -3dB point is generally located 30 degrees to the right and left of the main radiation direction. Nowadays, there are also antennas with beam widths of 65, 90, and 120 degrees, all of which have different characteristics depending on the intended purpose. This brings us to the concept of antenna directional characteristics, which is used in actual radio design. These characteristics are displayed in both 2D and 3D formats. Most antenna catalogs show the horizontal directional characteristics from a top view and the vertical directional characteristics from a side view in 2D format.

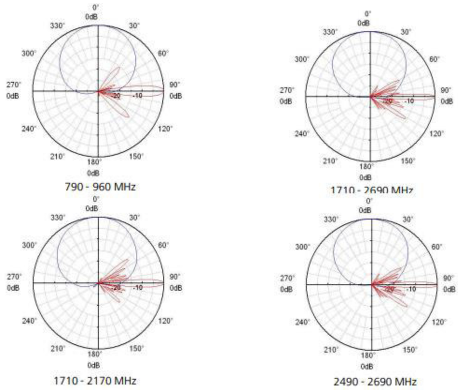

Figure 2. Directional characteristics from catalog

Source:https://www.bbrc.ru/upload/iblock/407/8bbc895f_92a1_11e9_80da_0cc47a1243ef_4ba5654c_92a2_11e9_80da_0cc47a1243ef.pdf

The datasheet for an antenna contains all the parameters that the antenna has and can be used with. The figure above shows the directional characteristics of a Huawei AQU4518R0 antenna broken down by frequency range. The horizontal directional characteristics are shown in blue and the vertical directional characteristics in red. [10], [11], [12]

9 Radio Data Transmission Characteristics

An antenna's datasheet contains all the parameters that the antenna has and can be used with. The figure above shows the directional characteristics of a Huawei AQU4518R0 antenna broken down by frequency range. The horizontal directional characteristics are shown in blue and the vertical directional characteristics in red.

Antennas, as radio devices, are located in free space, which acts as a transmission medium. However, it is important to note that this free space may contain various vegetation, objects, or even living organisms that have a negative effect on the propagation of the emitted electromagnetic waves. Free space itself also has attenuation, which can be determined by a formula.

$$a_0^{dB} = 10\log\left(\frac{\lambda}{4\pi R}\right)^2 = -32{,}4\, dB - 20logf^{MHz} - 20logR^{km}$$

- a_0 Outdoor attenuation
- λ frequency
- R distance

Outdoor attenuation depends on frequency and distance, and can also be influenced by weather conditions. As we increase the frequency of the transmitted signal, attenuation will also increase, as will the distance. Therefore, systems operating at higher frequencies have a shorter range than those operating at lower frequencies.

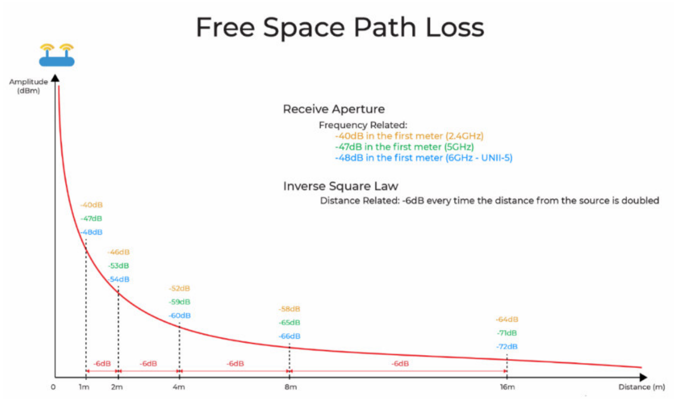

Figure 3. Outdoor attenuation
Source: https://semfionetworks.com/blog/6ghz-free-space-path-loss/

One of the most critical aspects of designing wireless communication systems is having a precise understanding of radio channel behavior. While free space path loss describes a deterministic power loss that decreases quadratically with distance, signal propagation in real-world environments is much more complex. Signals are reflected, scattered, and deflected by terrain features, resulting in random fluctuations in signal level at the receiver, known as fading. Fading phenomena can be divided into two main groups based on the speed of change and the nature of environmental effects: large-scale and small-scale fading.

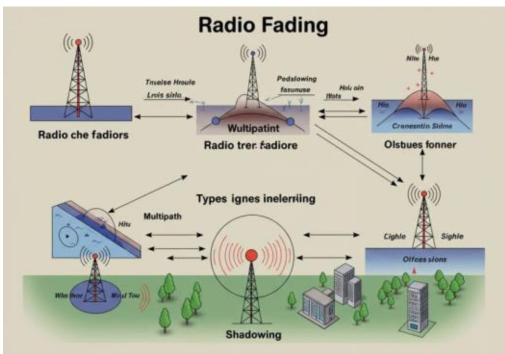

Figure 4. Fading types
Source: https://elo.hu/fading-a-jelenseg-magyarazata-es-tipusai-a-radiotechnikaban/

The most common type of large-scale fading is blanket fading, also known as the shadowing effect. This phenomenon occurs when large objects such as buildings, mountains, or dense vegetation are in the path of the radio wave. The terrain features absorb or reflect a significant portion of the signal, causing the average reception power to fluctuate over long distances. Statistically, this distribution is often modeled using a log-normal distribution. Small-scale fading is caused by multipath propagation. The signal can reach the receiving antenna not only via direct line of sight (LOS), but also via numerous reflected paths. The phase and amplitude of these components vary randomly, creating constructive or destructive interference in the receiver. If there is no dominant direct component, the envelope of the received signal follows a Rayleigh distribution, hence the name Rayleigh fading.

Within Rayleigh fading, we distinguish further subgroups based on the relationship between the channel and signal parameters:

Fast vs. Slow fading: This classification compares the channel change rate (coherence time) with the symbol time of the signal.

Fast fading: The channel impulse response changes faster than the symbol duration, causing distortion within the symbol.

Slow fading: The channel state remains constant for several symbol durations.

Flat vs. Frequency selective fading: This classification examines the relationship between signal bandwidth and channel coherence bandwidth.

Flat fading: The signal bandwidth is smaller than the channel coherence bandwidth, so fading affects all frequency components of the signal equally.

Frequency-selective fading: The signal bandwidth is greater than the coherence bandwidth, so different parts of the spectrum suffer different degrees of attenuation, which can cause severe intersymbol interference (ISI). Parallel to the development of mobile communication generations, increasingly sophisticated methods have emerged to eliminate the effects of fading and increase spectral efficiency.

In second-generation (e.g., GSM) systems, equalizers (channel equalizers) were used to reduce distortions caused by frequency-selective fading and intersymbol interference (ISI). These circuits attempt to inversely restore the channel transfer function on the receiver side, thereby recovering the original signal shape. Third-generation (CDMA-based) systems treated multipath propagation not as an error, but as an opportunity to be exploited. The Rake receiver consists of several correlators, each of which processes a component of a delayed signal path. By summing these components in phase, the signal-to-noise ratio (SNR) can be significantly improved by exploiting multipath diversity. In 4G networks, which typically use OFDM (Orthogonal Frequency Division Multiplexing) technology, the key to combating fading is accurate channel estimation. To do this, known pilot signals (reference signals) are transmitted, which the receiver uses to assess the current state of the channel. This is the basis for adaptive modulation and coding (AMC), which dynamically changes the transmission parameters (e.g., switching from QPSK to 64QAM) to match the channel quality, ensuring more robust transmission in poor fading conditions and faster transmission in good conditions.

Fifth-generation networks (5G NR) use the spatial dimension to overcome fading and increase capacity.
MIMO (Multiple Input Multiple Output): By using multiple transmitter and receiver antennas, multiple independent data streams can be transmitted on the same frequency, utilizing multipath propagation to increase bandwidth efficiency.
Beamforming: The antenna system focuses the radiated energy specifically in the direction of the user. This not only increases the range, but also drastically reduces interference and compensates for the significant outdoor attenuation that occurs at higher frequencies.

Az átviteli jellemzők tárgyalásakor elengedhetetlen a használt modulációs eljárások áttekintése, mivel ezek határozzák meg a spektrális hatékonyságot és a rendszer zavartűrését. A technológiai generációk váltásával egyre magasabb rendű modulációk váltak elérhetővé:
2G (GSM): Used only GMSK (Gaussian Minimum Shift Keying) modulation, which provided robust transmission with a constant envelope curve, but with limited data rates.
3G (UMTS): Techniques combining phase and amplitude modulation, such as QPSK (Quadrature Phase Shift Keying) and 16QAM, appeared, enabling higher data transfer rates.
4G (LTE): The system is now able to switch adaptively between QPSK, 16QAM, and 64QAM depending on the current channel quality.
5G (NR): Scalability has been further increased with the introduction of 256QAM, which is combined with OFDM and SC-OFDM (Single Carrier OFDM) waveforms to achieve maximum capacity. [14], [15], [16]
In radio communication, it is essential to separate the uplink and downlink directions so that the signals in the two directions do not interfere with each other. Two main methods, as well as a combination of these, have become widespread for this purpose:

FDD (Frequency Division Duplexing): In frequency division duplexing, transmission and reception take place in two separate frequency ranges separated by a guard band. This enables continuous, simultaneous two-way communication. The disadvantage is that it always requires paired spectrum, which is a constraint in terms of frequency management. It is typically used in early mobile generations (e.g., GSM) and is dominant in LTE systems.

TDD (Time Division Duplexing): In time division duplexing, transmission and reception occur on the same frequency but in different time slots. This method is extremely flexible, as the ratio of uplink and downlink time slots can be set asymmetrically according to traffic demands (e.g., more time slots are allocated to the downlink direction when there is a greater demand for downloads). 5G networks, especially in the high frequency (mmWave) ranges, prefer TDD due to more efficient spectrum utilization and beamforming support.

Half-duplex FDD: In some special cases (e.g., cheaper IoT devices), the half-duplex FDD method is used, where although the frequencies are separated, the terminal equipment is not capable of transmitting and receiving simultaneously. This simplifies the design of the radio unit (no duplexer required) but reduces the achievable transmission speed. [17]

Conclusions

The development of mobile communication networks has been one of the most dynamic technological processes of recent decades, fundamentally transforming social and economic interactions. This article reviewed the most important stages of this evolution, starting with the initial analog systems (0G, 1G), through the GSM (2G) and UMTS (3G) standards that brought about the digital revolution, to the modern 4G and 5G networks offering high bandwidth and low latency. It is clear that each generational change has brought not only an increase in speed, but also a structural paradigm shift. Looking at the physical implementation of the network, it can be seen that the architecture of base stations has undergone a significant transformation. Traditional, large-footprint, copper-based solutions have been replaced by compact, energy-efficient, fiber-connected RRU-BBU systems. This design not only reduces signal loss, but also allows for more flexible installation and operation, which is essential for serving densely populated urban environments. The analysis of the radio interface highlighted that overcoming the physical limitations of the wireless channel, in particular outdoor attenuation and fading phenomena resulting from multipath propagation, is the greatest challenge from an engineering perspective. Our article showed that while early systems (2G) used simpler equalization techniques, modern standards (4G, 5G) respond to these challenges with complex adaptive modulation techniques, orthogonal frequency division, and advanced antenna techniques. The development of duplexing techniques has also been key to the flexible and efficient use of the available frequency spectrum. Overall, it can be said that the development of mobile networks is a continuous optimization process in the triangle of coverage, capacity, and quality. From fine-tuning the directional characteristics of antennas to anti-fading coding, the technologies presented here all serve the purpose of making the uncertainties of the physical environment invisible to users, ensuring stable and fast connections in the digital ecosystem of the future.

References

[1] *A Mobilhálózatok Fejlődése: 2G, 3G, 4G és 5G*, Online. Available: https://www.bestfleet.hu/post/a-mobilh%C3%A1l%C3%B3zatok-fejl%C5%91d%C3%A9se-2g-3g-4g-%C3%A9s-5g

[2] *A mobilinternet története és felhasználása*, Online. Available: https://www.smartos.hu/a-mobilinternet-tortenete-es-felhasznalasa-62?srsltid=AfmBOoq5uircPbJnRZb0lwi7vHk4l2N2Ew0TU4S4Bg9fRCLBKEz8VuGv

[3] *Egy kis mobiltelefon történelem*, Online. Available: https://www.sopronmedia.hu/cikkek/egy-kis-mobiltelefon-tortenelem

[4] *Mi az a sok G, avagy a mobilhálózatok története*, Online. Available:https://index.hu/tudomany/til/2020/10/30/5g_szajbarago_az_elso_negy_g/

[5] *A mobil technológia műszaki háttere*, Online. Available:https://www.telekom.hu/statictr/sw/file/a_mobil_technologia_muszaki_hattere.pdf

[6] *Mobilarena Tudástár – A GSM hálózatok működése (BSS, BTS, BSC)*, Online. Available:https://mobilarena.hu/teszt/a_gsm_halozatok_mukodese/bazisallomas_alrendszer_bss.html

[7] *A bázisállomás alrendszer (BSS)*, Online. Available: https://www.eirene.hu/?id=bss

[8] *Base Stations*, Online. Available: https://www.geeksforgeeks.org/electronics-engineering/base-stations/

[9] *What Is A Base Station?*, Online. Available: https://www.sannytelecom.com/what-is-a-base-station/

[10] HA5KFU (BME Rádióamatőr Klub): *Antennák – oktatási anyag*, Online. Available: https://ha5kfu.hu/wp-content/uploads/2021/11/6b-Antennak-2021-osz.pdf

[11] Puskás Tivadar Távközlési Technikum: *Antennák és tápvonalak*, Online. Available: http://www.puskas.hu/r_tanfolyam/antennak_tapvonalak.pdf

[12] Tutorialspoint: *Antenna Theory & Radiation Pattern*, Online. Available:https://www.tutorialspoint.com/antenna_theory/antenna_theory_radiation_pattern.htm

[14] Helsinki University of Technology: *RAKE Receiver & Multipath Diversity*, Online.Available:http://www.comlab.hut.fi/opetus/333/2004_2005_slides/RAKE_text.pdf

[15] Stanford University: *The Wireless Channel (Lecture Notes)*, Online. Available:https://web.stanford.edu/~dntse/Chapters_PDF/Fundamentals_Wireless_Communication_chapter2.pdf

[16] *Comparison of QPSK and 16-QAM for OFDM System*, ResearchGate, Online.Available:https://www.researchgate.net/publication/340081645_Comparison_of_Traffic_Performance_of_QPSK_and_16QAM_Modulation_Techniques_for_OFDM_System

[17] Qualcomm: *FDD vs TDD Spectrum*, Online. Available: https://www.qualcomm.com/media/documents/files/fdd-tdd-comparison.pdf