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EVOLUTION OF MULTIPLE-ACCESS NETWORKS — CELLULAR AND NON-CELLULAR — IN HISTORICAL PERSPECTIVE. PART 1

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Introduction: *The goal of this review is the analysis of evolution of the current and novel wireless networks, from second generation (2D) to fifth generation (5G), as well as changes in technologies and their corresponding theoretical background and protocols – from Bluetooth, WLAN, WiFi and WiMAX to LTE, OFDM/OFDMA, MIMO and LTE/MIMO advanced technologies with new hierarchy of cellular maps design — femto/pico/micro/macro.* ***Methods:*** *We use new theoretical frameworks to describe advanced technologies, such as multicarrier diversity technique, OFDM and OFDM novel approach, new aspects of MIMO description based on multi-beam antennas, design of various cellular maps based on new algorithms of femto/pico/micro/macrocell deployment, and the methodology of a new MIMO/LTE system integration based on multi-beam antennas.* ***Results:*** *We have created a new methodology for multi-carrier diversity description of novel multiple-access networks, for the usage of OFDM/OFDMA modulation in order to overcome inter-user and inter-symbol interference in multiple-access networks, as well as multiplicative noises in multiple-access wireless networks caused by multi-ray phenomena. Finally, we have suggested how to overcome the propagation effects occurring in the terrestrial communication channels by using a combination of MIMO and LTE technologies based on multi-beam antennas. For these purposes, we present a new stochastic approach which takes into account the terrain features, such as buildings' overlay profile, buildings' density around the base station and each user's antennas, and so forth. These parameters allow us to estimate the effects of fading as a multiplicative noise source.* ***Practical relevance:*** *The new methodology of estimating the effects created by multiplicative noise and inter-user and inter-symbol interference in terrestrial wireless networks allows us to predict a-priory practical aspects of the current and new multiple-access wireless communication systems, like the potential number of users or the spectral efficiency of user channels for various configurations of cell deployment: femto, pico, micro, and macro, as well as the novel MIMO/LTE system configurations for future networks of the 4th and 5th generations.*

Keywords — *Additive White Gaussian Noise, AWGN, Code Division Multiple Access, CDMA, Direct Fast Furrier Transform, DFFT, Direct Sequence Spread Spectrum, DS-SS, Global System for Mobile Communications, GSM, Frequency Division Multiple Access, FDMA, Inverse Fast Fourier Transform, IFFT, Inter-Channel Interference, ICI, Inter-Symbol Interference, ISI, Inter-User Interference, IUI, Long-Term Evolution Releases, LTE, Medium Access Control, MAC, Multicarrier Diversity, Orthogonal Frequency Division Multiplexing, OFDM, Orthogonal Frequency Division Multiple Access, OFDMA, Orthogonal Time Division Multiple Access, OTDMA, Multiple-Input-Multiple-Output, MIMO, Single-Input-Multiple-Output, SIMO, Signal-to-Noise Ratio, SNR, Time Division Multipole Access, TDMA, User Equipment, UE, Wireless Fidelity Network, WiFi, Wireless Local Area Network, WLAN, Wireless Metropolitan Area Network, WiMAX, Wireless Personal Area Network, WPAN.*

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1. Introduction to Overview of Current Wireless Networks

Scanning the existing literature related to the description of the wireless multiple access technologies, we notice that there are a lot of excellent works (see for example, references [1–20]), in which the multichannel, multiuser and multicarrier accesses were described in details for cellular and non-cellular networks beyond third (3G) and fourth (4G) generations. However, all these works mostly described the corresponding techniques and technologies via a prism of additive white Gaussian noise (AWGN) and lesser via prism of multiplicative noise depending on fading phenomena, fast and slow. So, they ignore the multiplicative noise caused by fading phenomena. In references [1–20], the authors dealt mostly with classical AWGN channels or channels with the inter-user interference. As was shown there, the "response" of such channels is not time-varied or frequency-varied, that is, such propagation channels were not time or/and frequency dispersive. In [21, 22] were described the main features of the multiplicative noise caused by slow and fast fading that occur in terrestrial, atmospheric and ionospheric wireless communication links and networks. As was shown in [21, 22], the aspects of fading are very important for predicting the multiplicative noise in various radio channels, terrestrial, atmospheric and ionospheric, for the purpose of increasing the efficiency of land-land, land-aircraft, and land-satellite communication networks. The proposed approaches were then extended for description of multimedia and optical communications based on the stochastic and other statistical models [23–27] and on usage of special non-standard matrices [28, 29].

As was shown in [21, 22], due to the "time-dispersion" and "frequency-dispersion" of each specific wireless communication channel, the signal data, as a stream of sequences of symbols (e.g. bits), can be corrupted by fading and, finally, a new phenomenon called *inter-symbol interference* (ISI) is observed at the receiver. Moreover, in multiple accesses servicing, if any subscribers use the same or close frequency bands, they can be affected by another subscribers located in their vicinity. In this situation, a new "artificial noise" takes place, which causes the so-called *inter-user interference* (IUI) or *inter-channel interference* (ICI). An example of how multipath fading causes ISI.

To overcome such kinds of effects caused by multiplicative noise, some canonical techniques were introduced in modulation schemes of current networks, defined and briefly described in [22], such as the *spread spectrum modulation techniques* (DS-SS, FH-SS, TH-SS, respectively). Additionally, to explain how the IUI can be overcame, the classical multiple access technologies, such as CDMA (code division multiple access) on the basis of DS-SS modulation, FDMA (frequency division multiple access) on the basis of FH-SS modulation technique, and TDMA (time division multiple access), on the basis of TH-SS modulation technique is briefly described in [22]. There were briefly introduced these techniques based on space, time, and frequency and polarization diversities for multi-beam adaptive antenna applications. In this section, we introduce the orthogonal frequency division multiplexing (OFDM) techniques and the corresponding orthogonal frequency division multiple accesses (OFDMA), occurring in the frequency domain, as well as the orthogonal time division multiple access (OTDMA), occurring in the time domain.

Below in our special issue, in Section 1, we briefly introduce the existing classical recently performed networks via their historical perspective, such as the Global System for Mobile Communications (GSM), the Wireless Personal Area Network (WPAN), also called Bluetooth (BT), the Wireless Local Area Network (WLAN), related to the Wireless Fidelity (WiFi) System, the Wireless Metropolitan Area Network (WirelessMAN or WiMAX), and the Long-Term Evolution (LTE) standards. All these systems and technologies cover the time period of the last four decades in wireless generation's developments — from the past 2nd generation to the new 4th generation. It is important to notice that all modulation techniques, the conventional CDMA/TDMA/FDMA and advanced OFDM/OFDMA/OTDMA, related to above networks, fully depend on the fading phenomena that occur in such networks and described by the corresponding channel parameters [21].

We do not focus in description of the respective current and advanced protocols, such as 802.15, 802.11, 802.16, for LTE-releases, which are usually used in the above networks, as well as on the architecture of these networks, because these aspects are beyond the scope of this special issue and are fully described in other references [1–9, 11–20]. At the same time, based on the fading parameters introduced above, we will show the advantages and disadvantages of the corresponding techniques and will propose for practical applications more attractive and advanced technologies.

Let us briefly introduce the reader to the current wireless networks and the corresponding technologies below fourths generation (4G).

We will start to describe the matter by presenting first the **Bluetooth–WPAN Networks**, was originally created by Ericsson Company (Sweden) in 1998 before other companies started to launch this system and the corresponding technology and protocols. The WPAN system was named "Bluetooth" according to the name of Danish King Harald Bluetooth living at the 10th century. BT technology is based on 802.15 protocol and is called 802.15.1 protocol [30]. This protocol was performed for management and control of low-cost, low-power radio devices operated within small local areas (up to ten meters), which allows stable communication at short distances between personal devices such as notebooks, cellular phones, personal computers, and so on.

Such type of small-range areas were defined in [31, 64] as "piconets". Currently, the protocol for BT technology allows sending a data stream through each channel with the maximal rate of 1 Mbps, that is, it allocates for each channel of WPAN system the nominal bandwidth of 1 MHz. The WPAN system operates at the carrier frequency of 2.4 GHz using frequency-hopping spread spectrum (FH-SS) modulation technique described in details in [30]. Thus, the whole bandwidth, consisting of 79 hopping channels is ranged from 2.402 to 2.480 GHz with minimum hopping range of 6 channels. Piconet is presented as a cluster of up to 8 radio devices that are differentiated as "master" and "slaves". The rate of frequency changing equals 1600 times per second. WPAN–BT system is based on TDD (time-division duplexing) technique, according to which the channel is divided into slots with the time-slot of 625 μs.

Let us now briefly state the advantages and disadvantages of the WPAN–BT system. The advantages are:

— effective and inexpensive wireless solution both for data and for voice at short distances from the receiver;

— applicable for stationary and mobile environments;

— no setup needed for work;

— inexpensive;

— voice/data compatible;

— low power consumption.

The disadvantages are:

— short range of antenna (up to 10–20 m);

— low data rate;

— existence of interference from other networks operating at the same frequency bands;

— absence of data security.

The second more popular and effective combined with WLAN network was the **WiFi–WLAN Network**. In 1990, the Institute of Electrical and Electronics Engineers (IEEE) established the 802.11 working group to create a wireless local area network (WLAN) providing a set of standards for WLANs. The wing ".11" refers to a subset of the 802 group which is the wireless LAN working group [32, 33]. Then, WLANs were associated with WiFi networks. The IEEE 802.11 working group and the WiFi Alliance [34] came out as the key groups in creating different standard 802.11 protocol standards. Thus, we will also associate WLAN technologies and the corresponding protocols with WiFi networks and the corresponding protocols.

Thus, the WLAN systems, which were performed for pico/micro cell servicing (up to 1–2 km) are based on the standard protocol 802.11, the physical layer of which is signal processing operating on the basis of the standard Frequency Hopping Spread Spectrum (FH-SS) modulation technique (see [22]). Modern WLANs are now widely accepted and performed in private and local commercial areas to support subscribers, stationary and mobile, with special terminals, called access points (APs). Then, for WLAN networks a *medium access control* (MAC) technique was performed for providing quality of service (QoS) in packet-switched services of multiple subscribers located in picocell and microcell local areas (the corresponding protocol is called IEEE 802.11 MAC Standards) [35–37]. The main goal of IEEE 802.11 Mac was to support voice-over-IP (VoIP) services that are to support QoS for real-time services, such as telephony, multimedia (video and audio) communications.

As for VoIP, it is a popular service where the corresponding network converts voice data in digital form, and conversely. However, since today's VoIP calls are possible in a WLAN environment, there are a number of factors that negatively affect the use and acceptance of VoIP. Current WLANs have limited ability to support multimedia communications. Therefore, as will be mentioned briefly below, QoS provisions must be incorporated with the current WLAN systems to support the requirements of real-time services such as VoIP. For further reading on advanced techniques to support real-time voice service in WLAN systems the reader is referred to references [38–45].

We should mention that different modifications of IEEE 802.11 technology and its protocol were introduced during the last two decades, such as protocols 802.11a/b/g and 802.11n/e on the basis of OFDM/OFDMA modulation techniques.

Why such a broad set of 802.11 standards were created? To answer this question, let us briefly describe some of the popular standards of 802.11 technologies, to help the reader understand how the standard technologies, networks and the corresponding protocols allow designers of WLAN/WiFi systems to increase efficiency of grade of service (GOS) and quality of service (QOS) of WLANs, how to eliminate the ISI and the ICI in each channel (e.g. for each carrier) of the desired system. A WLAN and the corresponding 802.11b technology and protocol were adopted in 1999 by moving from fixed wire networks (such as Bluetooth) to wireless networks.

The protocol 802.11b is based on Direct Sequence Spread Spectrum (DS-SS), described in [21]. This technology was focused on the physical layer and data link layer, simultaneously [38]. Ranging up to distances of 100 m, and supporting send data streams with the maximal rate of 11 Mbps with fallback rates of 1, 2, 5.5 Mbps, all depend on effects of noise, clutter conditions, distance between APs, and so forth. The 802.11b technology and its protocols allow the connection of hundreds of computers and users using DS-SS modulation technique with a 2.4 GHz carrier frequency.

The logical structure of 802.11 technologies allows usage at the physical layer, not only with DS-SS modulation, but also using FH-SS modulation, combining with logical link control (LLC) layer and MAC layer. The first one provides addressing and data link control, independently from any topology and medium, and connecting to MAC access, which provides access to wireless medium.

Using 14 non-overlapping channels, each of 22 MHz wideband, placed 5 MHz apart each other (e.g., channel 1 is placed at central frequency, 2.412 GHz, channel 2 is at 2.417 GHz, and so on, up to channel 14 placed at 2.477 GHz). Such logical structure of 802.11 protocols give a lot of benefits such as:

— wide coverage range in an indoor/outdoor picocell/microcell environment;

— free and stable work both with stationary and mobile subscribers;

— possibility to work with other picocell networks, such as WPAN, using the same 2.4 GHz frequency band;

— scalability and security for each subscriber located in area of service.

Recently, the enhancement of the existing protocols, called IEEE 802.11e standard, was performed for VoIP [41–47]. The VoIP technology has advanced rapidly during recent years. This enhanced technology is better than the previous ones, since it allows transmitting low-power signal data with lower time delay and supports better duplex transmission, like VoIP, by sending each voice signal separately via network channels [35, 37, 45, 48]. Using beam-forming antennas, as additional attributes of this technology, the 802.11n network allows to eliminate multipath fading effects and, therefore, eliminate ISI and ICI usually occur in wireless communication in environments with fading (see details in [49–110]).

To be objective, we should also mention on **WiMAX Networks** and 802.16 protocol, despite the fact that they till nowadays did not find their “applicable layer” among other technologies below 4G. They relate to broadband wireless systems operating on the basis of adaptive multibeam or phased array antennas, which were performed from 2002 for macro-cell servicing (up to tens of kilometer), their physical layer is operated on the basis of the standard protocol 802.16 [111–118]. This wireless network is called WiMAX. A WiMAX antenna can cover metropolitan areas of several tens of kilometers for fixed stations and up to ten kilometers for mobile stations. Therefore, initially (on April 2002) the IEEE Standard 802.16-2001 was defined as wireless metropolitan area network (WirelessMAN) [112].

Wireless-MAN offers alternative networks based on wire communications (via cables or fiber optics) with their modems and digital subscriber line (DSL) links. Despite this fact, wireless WiMAX networks have a huge capacity to address broad geographic areas without additional infrastructure required in cable links installation in each individual site or for each individual subscriber, In such a scenario, WiMAX technology brings the network to subscribers located inside which are connected with conventional indoor networks such as Ethernet (IEEE Standard 802.3) or wireless local area networks (LANs) [Standards 802.11a-e described above]. With MAC technology expanding in this direction, it is important to emphasize that 802.16 MAC standard technology could accommodate all connections with full QOS and increase of GOS.

The signal processing technique implemented in a WiMAX system is based on OFDM/OFDMA modulation techniques that will be described in Section 2 and operates at frequencies from 2 to 10 GHz. A WiMAX antenna can transfer information data with a maximum rate of up to 70 Mbps. The main goal of such technology is to handle any effects of NLOS in urban and sub-urban environments that usually occur in the built-up scene (see [21, 22]). The main features of WiMAX networks are [111–116]:

a) it uses advanced OFDMA technique;

b) its bandwidth varies from 1.25 to 28 MHz;

c) it additionally uses TDD and FDD (frequency division duplex) techniques (see definitions in [22]);

d) it uses MIMO antenna systems based on a beam forming technology of each element of BS (base station), AP and MU antenna performance;

e) it uses advanced signal modulation techniques;

f) it uses advanced coding techniques such as space-time coding and turbo coding.

Recently, to obey several vivid drawbacks, the WiMAX technology was deployed to operate simultaneously with macro-cell BS antennas and Femto-Access Point antennas and this was the main goal performing the 4th generation of wireless networks (on such a configuration we will talk below in Section 4). Moreover, a tendency of integration of narrow-range WiFi networks with a wide-range WiMAX networks, operating at different rates and having different mobility, are sensitive to blocking of users’ calls, dynamic spectrum assignment for each user, stationary or mobile, and to energy-efficient handover schemes with the geographic mobility awareness. The problems of integration of different systems having limited possibilities either in mobility or in speed, such as WiFi and WiMAX systems were discussed in references [119–124], where the main goal of the researchers was to decrease a blocking probability and increase the efficiency of handover schemes and frequency spectrum sharing among user’s channels. Following References [119–124], we briefly introduce the reader to some of the problems and tools used algorithms overcome them.

A **WiFi/WiMAX integrated network** was proposed to achieve high-quality communication by using WiFi and WiMAX as complementary access resources. The integrated network, according to researchers’ main aim, will enable support a load balancing between WiFi and WiMAX by using each system selectively in response to the demands of subscribers, stationary and/or mobile, and the usage status of each system. According to such an idea, in the integrated WiFi/WiMAX network each wireless system will use the spectrum band prescribed by law, so that even if the WiMAX system has unused spectrum temporarily, it cannot be used by WiFi wireless systems.

The first problem, investigated in reference [122], was to find an effective spectrum sharing method for WiFi/WiMAX integrated mesh network. Resolving the problem of spectrum sharing in WiFi networks, allows connecting the WiFi mesh network to a WiMAX base station, obtaining an increase of throughput. The problem is that in a WiFi mesh network, several WiFi APs are interconnected by wireless links and the communication with the backbone network transits through the gateway AP connected by wire cables. It was expected to reduce the cost of infrastructure and to adapt it not only to urban, but also to rural areas. In addition, in a multi-channel, multi-interface mesh network, where each AP can use two or more channels simultaneously, it was found possible to increase the network capacity by dynamic channel assignment for each wireless link. However, when many mobile users communicate with the backbone network, the network throughput decreases due to congestion around gateway APs [122].

To overcome this problem, a WiFi/WiMAX integrated mesh network was proposed in [122], where WiMAX is used as backhaul for the WiFi mesh network. In such a combined network, there are two kinds of gateway APs:

a) one is a traditional gateway AP directly connected to the backbone by a wired cable; and

b) the other is an AP which is wirelessly connected with the WiMAX BS and works as a gateway.

Also, dynamic spectrum assignment based on call blocking probability prediction in WiFi/WiMAX integrated network was investigated in [123]. The main idea of this research was to allow WiFi systems to use a spectral band of WiMAX systems, temporally, in an integrated network of operation stages. Thus, because the WiFi system uses the spectrum in units of 20 MHz, the WiMAX system divides its spectrum into channels of 20 MHz and assigns one of them to the WiFi APs, which leads to more effective use of spectrum in the integrated network. To achieve this, a channel in the WiMAX system should be assigned to as many WiFi systems as possible, as long as they are not adjacent. Specifically, a WiMAX system provides 74.8 Mbps per channel and a WiFi system provides 54 Mbps per channel at maximum. Therefore, if two or more WiFi APs use one channel of the WiMAX system, the spectrum utilization efficiency can be enhanced for the whole integrated network. The proposed method is based on the predicted numbers of blocked calls, an analytical analysis of which is fully presented in reference [123]. The proposed method in reference [123] introduces an effective dynamic spectrum assignment, where the same spectrum can be repeatedly used by assigning a channel of the WiMAX system to two or more WiFi systems without causing interference between adjacent WiFi APs.

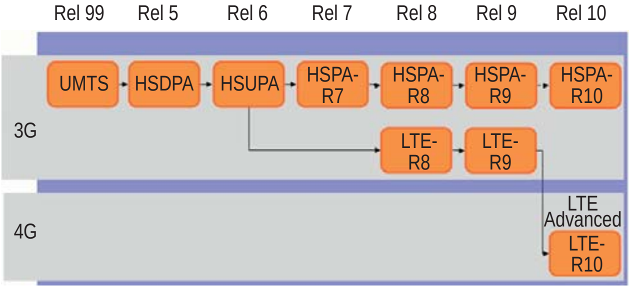
Special discussion should be done on so-called **LTE technology** and the corresponding networks. The LTE technology, networks and the corresponding protocols were developed recently to increase the capacity and speed of wireless data passing wireless communication links and networks, using modern hardware (compared to WiMAX networks) and advanced digital signal processing techniques [125–137]. LTE was defined in 2009 by the 3rd Generation Partnership Project (3GPP) as a highly flexible broadband radio system with high user data rate (up to 30 Mbps), with a data stream and radio sensors/networks delay not exceeding 5 ms, with simple network architecture, efficient spectra allocations, and so on. As was mentioned in [131]: "*LTE is designed to meet carrier needs for high-speed data and media transport as well as high-capacity voice support well into the next decade*".

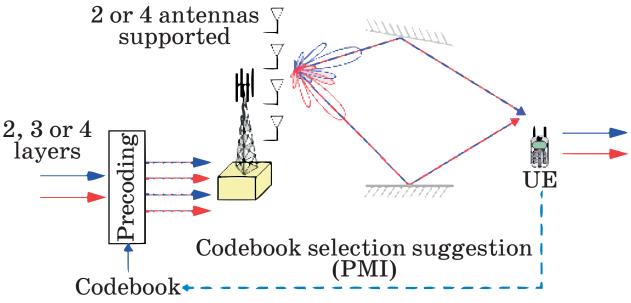
Moreover, the main goal of the first nine releases of LTE was to support both FDD and TDD combined with a wideband system in order to achieve a large number of various spectra allocations [130, 131]. All these nine standard releases (Table 1) were implemented recently to overcome the well-known WiMAX technologies, such as enhanced IEEE 802.16e, performed in 2005. Thus, for example, the LTE-E-UTRAN technology has much better parameters regarding data speed and data protection within communication channels with respect to WiMAX with enhanced IEEE.802.16e protocol.

Recently, LTE was introduced to support the systems that can be considered as a continuous evolution from earlier 3GPP networks, such as TD-SCDMA (time-division synchronous code-division multiple access) and wide-band code-division multiple access (WCDMA) combined with high-speed packet access (HSPA). The current Releases 8 and 9 of LTE technology, denoted sometimes as 3GPP-LTE (or E-UTRAN), include many of features of 4G systems. Therefore, they were considered as the best candidates for 4G generation of networks and as a major step toward the advanced international mobile telephony (ITM-Advanced) [127–145].

Namely, LTE Release 8 was performed for single user (SU) network to service of each user equipment (UE). Its arrangement is presented schematically in Fig. 1.

■ ***Table 1.*** Evolution of LTE releases (Rel) during recent years (extracted from Internet)





■ ***Fig. 1.*** Scheme of SIMO-LTE, supports 2 or 4 antennas at the BS with spatial multiplexing, using the LTE Release 8 technology (rearranged from [131, 144])

It has the following characteristics [144]:

— it combines TDD and FDD modes and OFDM technique in downlink (DL) and SC (single carrier) – FDMA technique in uplink (UL), using adaptive modulation and coding such as QPSK/16QAM/64QAM in both DL and UL channels;

— data rate for 20 MHz-bandwidth: 100 Mbps in downlink and 50 Mbps in UL channel;

— spectral efficiency for 20 MHz-bandwidth: 5 (bits/sec/Hz) in DL and 2.5 (bits/sec/Hz) in UL;

— latency (e. g. delay of data for each desired user) is less than 5 ms for small IP packets.

The LTE Release 9 standard was performed as an enhanced version of LTE Release 8 standard [132, 133], where for demodulation purposes a virtual antenna with pre-coded UE specific reference signals was added. Here also both *paired* and *unpaired* bands of the radio spectra was proposed depending on the types of environment, rural, sub-urban, urban, on the built-up terrain features, and on the configuration of the bandwidth allocated for users' servicing. The paired frequency bands correspond to configurations where UL and DL transmissions are assigned separate frequency bands, whereas the unpaired frequency bands corresponds to configurations where UL and DL must share the same frequency band. As illustrated from Fig. 1 (extracted from [131]), LTE technology allows for an overall system bandwidth ranging from as small as 1.4 MHz up to 20 MHz, where the latter is required to provide the highest data rate within LTE system communication channels.

All user terminals support the widest bandwidth. Unlike previous cellular systems of 3rd generation mentioned above, the LTE system provides the possibility for different UL and DL bandwidths, enabling asymmetric spectrum utilization. Usage of effective and flexible spectra sharing not only in different frequency bands, but also different bandwidths, combining with efficient migration of other radio-access technologies to LTE technology, are the main keys of the LTE radio access that provide a good foundation for further 4th generation evolution.

Below, in Section 5, we will present combination of LTE advanced technology with MIMO system that is planned to be useful for 4th and 5th generations.

Now, in Section 2, we will introduce some advanced diversity techniques adapted for the multi-carrier accessing networks. Then, in Section 3, we will describe the advanced MIMO spatial-time diversity and spatial multiplexing techniques, focusing the special attention on how fading phenomena affect the capacity and spectral efficiency of MIMO channels. Fading propagation effects are described in terms of the unified stochastic approach introduced in [21, 22] for land communication networks. In Section 4 we introduce the femtocell-microcell and femtocell-macrocell (indoor/outdoor) configurations for different types of femtocell advanced deployment strategies, and, finally, in Section 5, we show advances of the combined femtocell-microcell layout with MIMO/LTE modern concept for future 4th and 5th generation performance.

2. Novel Multicarrier Diversity Techniques

Diversity is a powerful communication receiver technique, which can be used to handle fading phenomena occurring in different wireless communication links, terrestrial, atmospheric and ionospheric (described in [21, 22]). Using diversity techniques, one can improve the multiple access system performance operating in indoor/outdoor multipath environments. These techniques are based on the very simple principle of sending M copies of the desired signal data sequence (related to the desired user) via M different channels, instead of usage only one channel to transmit and receive this desired information data.

There are different kinds of diversity techniques which are currently used in canonical (e.g. current) and modern networks. We briefly described these techniques in Section 5 regarding the adaptive multi-beam antenna applications. Here, we introduce some advanced techniques based on the proposed concept.

The analysis of fading, time-varying and frequency-varying, leads to the use of time varying (adaptive) equalizers for stable communication achievement [3–5]. However, the design and use of time varying and adaptive equalizers are difficult in practice, especially for broadband channels operating on the basis of adaptive/smart antennas. Only one solution currently exists, which is to use multicarrier (e.g., multichannel) techniques, based on frequency and time diversity algorithms, or on the space diversity principle currently adapted for the MIMO systems. This means that instead of one carrier, M carriers will be used to eliminate all kinds of noises, naturally or artificially generated.

2.1. Advantages of Multicarrier Diversity Techniques

Before starting to analyze the methods of frequency, time and space diversity, let us, first of all, determine quantitatively and show analytically the advantages that can be achieved using multicarrier diversity methods. For this purpose, let us consider M independent Rayleigh fading channels, i.e., operated in worst-case scenarios with the absence of LOS components, that is, for a fading parameter $K = 0$ (see definitions in [3–10, 21, 22]). We call each channel a *diversity branch*. The corresponding scheme of how to combine and separate all carriers at the transmitter and then select the desired carrier at the receiver, is shown in Fig. 2.

We also assume that each branch has the same average signal-to-multiplicative noise ratio (SNR) defined as $\Gamma = (E_b/N_0)\langle\alpha^2\rangle$, where E_b is the energy of the bit of information data passing the channel with strong fast fading, $\langle\alpha^2\rangle$ is the normalized deviation of signal data energy due to fading, and N_0 is the energy of the AWGN. Each branch has an instantaneous SNR $= \gamma_i$. Then the PDF (plural distribution functions) of such a multiplicative noise, caused by fast and/or slow fading, can be written for $\gamma_i \geq 0$ as

$$p(\gamma_i) = \frac{1}{\Gamma}\exp\left(-\frac{\gamma_i}{\Gamma}\right), \tag{1}$$

where now Γ is the average SNR for each branch. The probability that a single branch has a SNR less than some threshold of multiplicative noise, γ, is the cumulative distribution function (CDF) defined for Rayleigh channel with fading as

$$CDF(\gamma_i) \equiv P[\gamma_i \leq \gamma] = \int_0^{\gamma} p(\gamma_i)\mathrm{d}\gamma_i =$$

$$= \int_0^{\gamma}\frac{1}{\Gamma}\exp\left(-\frac{\gamma_i}{\Gamma}\right)\mathrm{d}\gamma_i = 1-\exp\left(-\frac{\gamma}{\Gamma}\right). \tag{2}$$

Now, the probability that all M independent diversity branches receive signals which are simultaneously less than some specific SNR threshold γ can be presented as

$$P[\gamma_1, \ldots, \gamma_M \leq \gamma] = \left[1-\exp\left(-\frac{\gamma}{\Gamma}\right)\right]^M \equiv P_M(\gamma). \tag{3}$$

This probability describe situation when all branches cannot achieve this threshold. If any branch with number i achieves this threshold, i.e., SNR $> \gamma$, then

$$P[\gamma_i > \gamma] = \equiv 1 - P_M(\gamma) = 1 - \left[1-\exp\left(-\frac{\gamma}{\Gamma}\right)\right]^M. \tag{4}$$

Formula (4) describes the situation of exceeding of the threshold when *selection diversity* is used. For low Γ, that is, for strong fading effects, (4) reduces to

$$P \propto \left(\frac{\gamma}{\Gamma}\right)^M. \tag{5}$$

For selection diversity the PDF is found as the derivative of CDF of all braches to achieve threshold, that is,

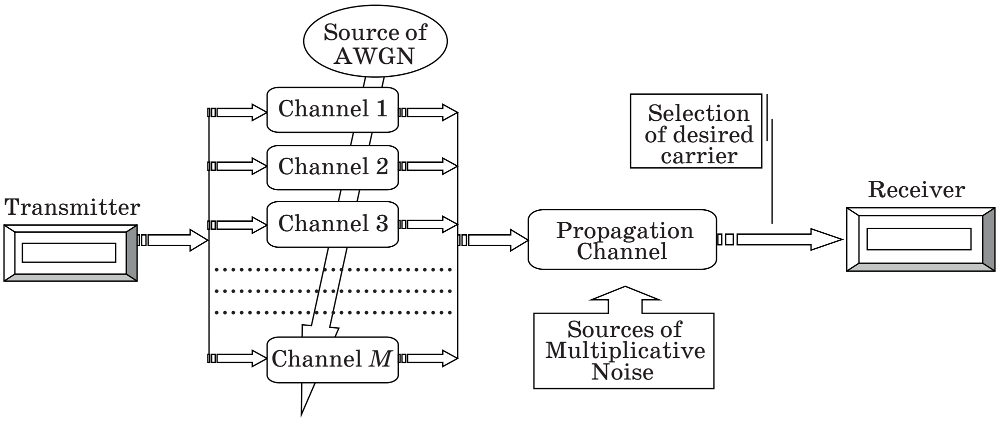
$$p_M(\gamma) = \frac{\mathrm{d}P_M(\gamma)}{\mathrm{d}\gamma} = \frac{M}{\Gamma}\left[1-\exp\left(-\frac{\gamma}{\Gamma}\right)\right]^{M-1}\exp\left(-\frac{\gamma}{\Gamma}\right). \tag{6}$$

Then, the mean SNR, $\overline{\gamma}$, can be defined as

$$\overline{\gamma} = \int_0^{\infty}\gamma \cdot p_M(\gamma)\mathrm{d}\gamma = \Gamma\int_0^{\infty}Mx\left[1-e^{-x}\right]^{M-1}e^{-x}\mathrm{d}x, \tag{7}$$

where $x = \gamma/\Gamma$. Formula (7) is evaluated to obtain the average SNR improves offered by the selection diversity

$$\frac{\overline{\gamma}}{\Gamma} = \sum_{k=1}^{M}\frac{1}{k}. \tag{8}$$



■ ***Fig. 2.*** Multicarrier diversity principle for desired user selection

As was shown by numerous computations, for the independent Rayleigh fading branches, as channels with the average multiplicative noise, the probability that the SNR drops below some specific threshold for one branch is of 2–3 times greater in magnitude than if several independent (separated) branches are used in the multicarrier diversity technique.

2.2. Frequency Multicarrier Advanced Diversity Technique

This technique allows for modulating the information data signal (e.g., the baseband signal) through different M carriers. Frequency diversity transmits information on more than one carrier frequency. Here frequencies are separated by less (or equal) to the coherent bandwidth of the channel and, therefore will not experience the frequency selective or time-selective fades (see definitions above). Here, we need to choose the symbol duration T_s in such a manner that the coherence bandwidth of each sub-channel, denoted as $b_w \equiv b_c = B_c/N$, where N is the number of carriers, will be much smaller than the bandwidth of the channel B_w. In this case, slow and flat fading will take place and effects of frequency-selective fast fading will be minimized. The above assumption leads to the following constraint:

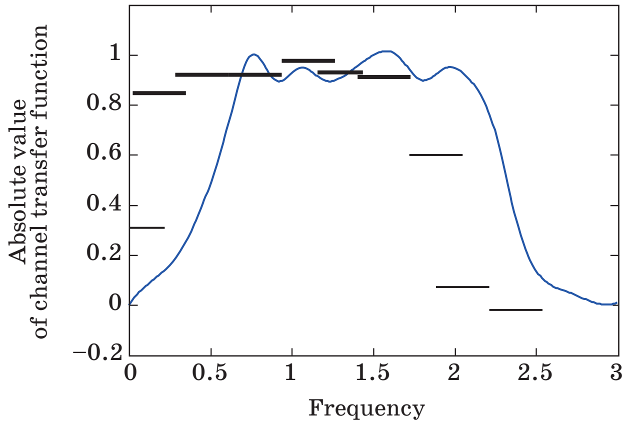
$$B_w > \frac{1}{T_s} \equiv b_c. \tag{9}$$

By using N carriers, we finally have

$$N = \frac{B_w}{b_c} = \frac{B_w}{1/T_s} = B_w T_s. \tag{10}$$

All definitions of the parameters presented above in Section 1.

Figure 3 depicts an example of how we can split the channel bandwidth B_w in N sub-channels with a bandwidth b_c that is enough narrow to exclude effects of deep fading and narrowband ICI. Then, each independent symbol signal will have, in frequency domain, a rectangular shape of power spectral density (PSD), which in the time domain has a sharp δ-*function* presentation. Conversely, the rectangular shaping function $g(t)$ in the time domain (i.e., a pulse with data), has in the frequency domain a shape of the *sink-function* that in the literature is called the Nyquist-shaped filter or the ideal filter [1–7].



■ ***Fig. 3.*** The principle of splitting of the whole channel bandwidth on N sub-channels where effects of signal deviations are minimal

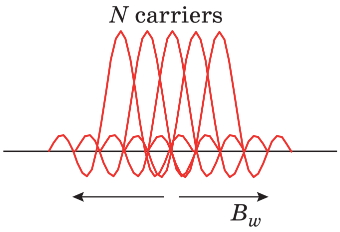
2.3. OFDM and OFDMA Novel Technologies

As it follows from the description of FDD and FDMA techniques, described in [22], the spectral efficiency of the above techniques are too weak because of the existence of guard intervals (i.e., the loss of useful bandwidth spectra) [46]. To eliminate this problem, it is more effective to use the independent (e.g., orthogonal) subcarriers, as shown in Fig. 4.

In such a technique, one can split the total frequency-band spectra of the system on separate overlapping subcarriers (sub-bands or sub-channels) with independent properties. This technique is called the *Orthogonal Frequency Division Multiplexing* for resolving the problem of spectral overlapping, because each individual subcarrier, being orthogonal with respect to other subcarriers, can be easily recovered despite the overlapping in the total spectra. Thus, there is no need of guard intervals as in FDD or FDMA techniques [22, 64].

Orthogonal Frequency Division Multiplexing. Let us now consider the OFDM procedure as a pure mathematical problem. We assume that the transmitted signal passing the fading channel consisting of N subcarrier (corresponding to N paths) can be generally presented through the fading factor introduced above. If so, a total data signal (e.g., baseband signal) can be presented as a function of the amplitude of the signal received in nth sub-channel, denoted by α_n, and its own phase, $\Delta\varphi n = n\Delta\omega t$, as

$$s(t) = \sum_{n=0}^{N-1} \alpha_n \cos\left[\left(\omega_0 + n\Delta\omega\right)t + \varphi_n\right], \quad 0 < t < T_s, \tag{11}$$



■ ***Fig. 4.*** The spectral overlapping for each subcarrier in OFDM technique, when each peak of any subcarrier corresponds to zeros positions of other subcarriers due to their orthogonality where

$$\omega_0 = \frac{2\pi L}{T_s};\ \Delta\omega = \frac{2\pi}{T_s} \tag{12}$$

and L is the length of the channels.

The subcarriers of OFDM are orthogonal on the interval $[0, T_s]$, from which it follows that

$$\int_0^{T_s} s(t)\cdot\cos\Big[\big(\omega_0 + n\Delta\omega\big)t\Big]\mathrm{d}t = \alpha_n T_s \cos\varphi_n;$$

$$\int_0^{T_s} s(t)\cdot\sin\Big[\big(\omega_0 + n\Delta\omega\big)t\Big]\mathrm{d}t = \alpha_n T_s \sin\varphi_n. \tag{13}$$

The corresponding splitting allows us to obtain a signal for the each carrier in the following manner:

$$s^{(q)}(t) = A_c \sum_{n=0}^{N-1} \alpha_n^{(q)} \cos\Big[\big(\omega_0 + n\Delta\omega\big)t + \varphi_n^{(q)}\Big],$$

$$(q-1)T_s < t < qT_s, \tag{14}$$

where

$$a_n^{(q)} \equiv \alpha_n^{(q)} \exp\Big\{-j\varphi_n^{(q)}\Big\}, \tag{15}$$

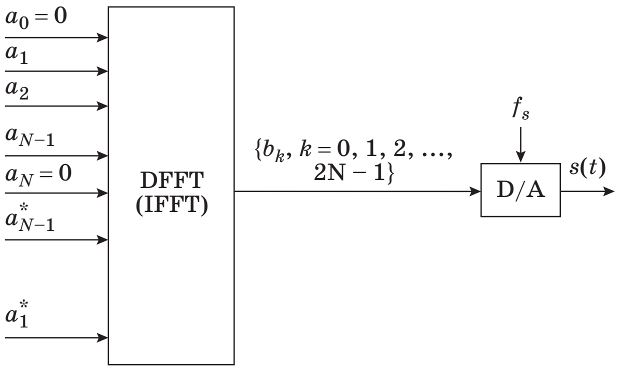
$a_n^{(q)} \in A,$ and A is a set of constellation's points containing L points

$$\mathbf{a}^{(q)} \equiv \Big(a_0^{(q)}, a_1^{(q)}, \ldots, a_{N-1}^{(q)}\Big), \tag{16}$$

or for orthogonal (independent) sub-channels $a_n^{(q)} \in A,\ n = 0, 1, \ldots, N-1$.

From the beginning, the OFDM-technique implementation was based on the *discrete Fourier transform* (DFT), mathematically described by (11) or (14) [64]. Simply speaking, the DFT converts the time domain representation of the desired signal with data to the frequency domain representation. Conversely, the *inverse DFT* (IDFT) converts the signal spectrum, that is, the frequency domain signal data representation to the time domain representation. Later, instead of the DFT/IDFT technique, the direct and inverse fast Fourier transform (denoted DFFT and IFFT, respectively) were used to significantly decrease the implementation complexity and time of the proposed technique. Mathematically both methods are similar, but FFT is much more efficient for the implementation. Below we will briefly present the mathematical aspects of the FFT technique for the OFDM implementation.

First of all, we should state that the corresponding block-diagrams of the IFFT for the transmitter and of the DFFT for the receiver are circuit-wise and have similar blocks (only the block of discrete-to-analogue (D/A) should be changed to A/D, correspondingly).



■ ***Fig. 5.*** Block-scheme of the fast Fourier transform technique, inverse (IFFT) at the transmitter and direct (DFFT) at the receiver; D/A is the digital/analogue transformer

Therefore, we present in Fig. 5 the block-diagram of the receiver, where the samples of the multicarrier signal can be obtained by the DFFT of the data symbols.

According to the key goal of the OFDM modulation technique, the corresponding discrete-form presentation of the IFFT algorithm at the transmitter is the following: a sequence of the discrete signals with the noises, $\{b_k\}$, for each independent subcarrier (or sub-channel), is presented in the following manner:

$$b_k = \frac{1}{\sqrt{2N}} \sum_{n=0}^{2N-1} a_n \exp\{j2\pi nk/2N\} =$$

$$= \frac{1}{\sqrt{2N}} \left(\begin{array}{l} \sum\limits_{n=1}^{N-1} a_n \exp\{j2\pi nk/2N\} + \\ + \sum\limits_{n=N+1}^{2N-1} a_{2N-n}^* \exp\{j2\pi nk/2N\} \end{array} \right) =$$

$$= \frac{1}{\sqrt{2N}} \left(\begin{array}{l} \sum\limits_{n=1}^{N-1} a_n \exp\{j2\pi nk/2N\} + \\ + \sum\limits_{m=N-1}^{1} a_m^* \exp\{j2\pi(2N-m)k/2N\} \end{array} \right), \tag{17}$$

where for the second sum we placed at the bottom and top limits $m = 2N - n$, and therefore, the upper limit will equal $m = 2N - (N - 1) = 1$. In (17), the amplitude of each subcarrier can be presented in the baseband form:

$$a_n = \alpha_n \exp\{j\varphi_n\}. \tag{18}$$

Finally, using direct FFT (DFFT), we finally get

$$b_k = \frac{1}{\sqrt{2N}} \sum_{n=1}^{N-1} \alpha_n \left[\begin{array}{l} \exp\big\{j\big(2\pi nk/2N + \varphi_n\big)\big\} + \\ + \exp\big\{-j\big(2\pi nk/2N + \varphi_n\big)\big\} \end{array} \right] =$$

$$= \frac{2}{\sqrt{2N}} \sum_{n=1}^{N-1} \alpha_n \cos\big[2\pi nk/2N + \varphi_n\big]. \tag{19}$$

In (19) the following parameters were introduced:

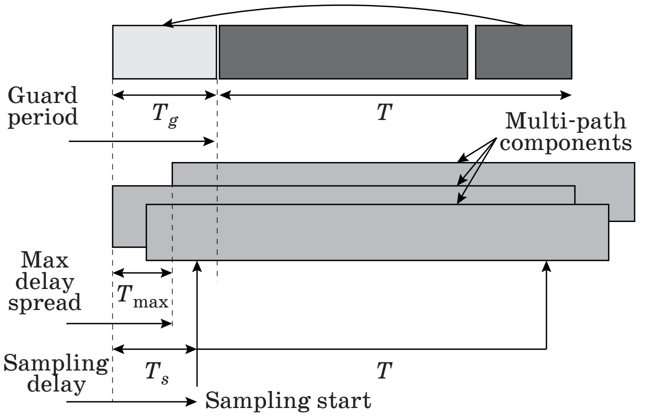
$$\Delta f = \frac{1}{T_s};\ \Delta t = \frac{T_s}{2N} = \frac{1}{2N\Delta f};\ f_s = \frac{1}{\Delta t}.$$

Now we put a question: what does it mean that in (17) was extended the OFDM symbol sequence by introducing the second term? If a-priory, due to the multiplicative noise occurring in the multipath channel with fading (defined by the maximum delay spread), the previous part of each OFDM symbol will be corrupted by the delay sample of the neighboring OFDM symbol, the orthogonality between symbols will be lost leading to the so-called ISI or ICI [64].

Since OFDM technique excludes usage of the guard intervals compared to the FDMA system (see [22]), it is possible to extend the OFDM symbol sequence with additional replica consisting of N symbols of "zeros" corresponding to the so-called "virtual guard" with a period of T_g.

If so, we can convert the symbol sequence in the time domain at the transmitter using IFFT in such a manner that its time period T_s will be extended on T_g, that is, $T = T_s + T_g$ (Fig. 6). This procedure is called the *prefix cycling* [64].

Using this IFFT technique, described mathematically by (17), we obtain that the first term in (17) will present a desired signal of symbol data, from which at the receiver the transmitted symbol sequence $\{b_k\{$ can be easily recorded. The second term in (17) corresponds to the part of the symbols that can be corrupted by fading during passing via the communication sub-channel. In other words, the second sequence of samples will be transmitted in the guard period (see Fig. 6) as a cycle process. Therefore, this sequence in the literature is called *cycle prefix* [64]. This extracted sequence finally will be eliminated at the receiver, if the elements of the second sum in (17) will be substituted as a "zeros" with the time-scale of the "virtual" guard interval T_g.



■ ***Fig. 6.*** The procedure of obeying the part of the data of OFDM signal corrupted by fading (defined by the sampling delay time) by extension of the symbol time T with the "virtual" guard period (cyclic prefix)

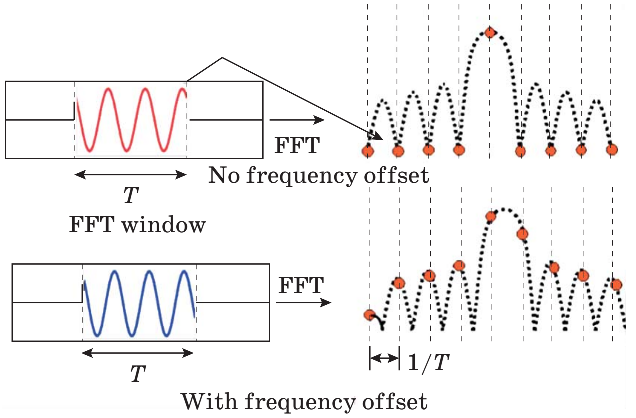
After such a procedure, we can obtain expression (19) as a real symbol replica recorded at the receiver after implementation of the DFFT procedure. Using the above notations, we finally present for each independent sub-channel the signal shaped function at the receiver in the following form, using just a DFFT on a sampled symbol signals $s(t)$:

$$s(k\Delta t) = \sum_{n=1}^{N-1} \alpha_n \cos\left[2\pi n\Delta f k\Delta t + \varphi_n\right] =$$
$$= \sum_{n=1}^{N-1} \alpha_n \cos\left[2\pi n\Delta f k \frac{1}{2N\Delta f} + \varphi_n\right] = \frac{\sqrt{2N}}{2} b_k. \quad (20)$$

Indeed, at the receiver, the N independent copies are combined in such a manner to give an optimal replica of the signals with date sequences of samples that are not corrupted by fading. Unfortunately, what is easily to perform using mathematical algorithms cannot be ideally obtained in practice of wireless communication, where the sub-channel time-scale (or length) is not constant, and therefore the preface cycle parameters are also not constant.

Another problem that should be avoided by using the OFDM technique is the frequency shift of the received signal spectrum called the *frequency offset* [64]. Due to this effect the IFFT procedure at the transmitter and DFFT procedure at the receiver are not "symmetrical", i.e., they do not correspond strictly to each other. The effect of the frequency offset is clearly seen in Fig. 7.

According to frequency shifting, the adjacent subcarriers can be affected by ICI caused by the energy leakage of the neighbor symbol signals to each other. As was shown in [46], the overall energy of

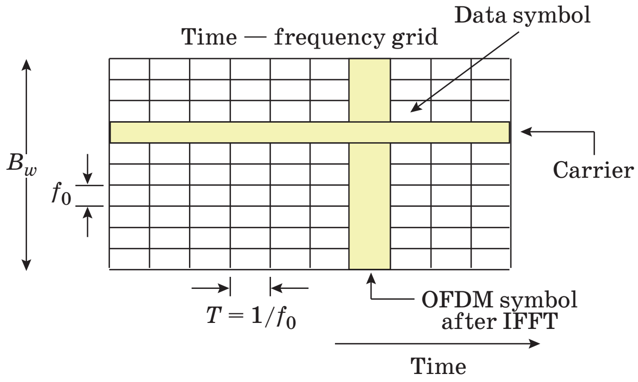


■ ***Fig. 7.*** Effects of frequency offset on OFDM FFT modulation technique

ICI grows with the frequency offset. To avoid this effect, a frequency domain equalization by using N separate equalizers for each subcarrier is needed that significantly increase the complexity of the receiver implementation. For further reading on this approach, we refer the reader to the references [13, 18–20, 64].

To complete our explanation of the OFDM technique we should mention that before starting for the specific channel splitting into N sub-channels, the coherent bandwidth b_{cn} of the sub-channel (we assume that they have the same bandwidth $\Delta f_n \equiv f_0$, $n \in [1, N-1]$) should be estimated a-priory. Thus, as was shown experimentally and was described in [102] during a special campaign carried out in the city of Tokyo for two scenarios of heavy (the first scenario) and lower layout (the second scenario) of buildings, in the first scenario was obtained $b_{cn} \approx 70 \div 90$ kHz, with an average value of $b_{cn} \approx 80$ kHz, whereas for the second scenario $b_{cn} \approx 390 \div 420$ kHz. If now, after the OFDM division procedure on N sub-channels, the bandwidth f_0 of each sub-carrier was decided to be $f_0 = 100$ kHz, as it follows from the second scenario, f_0 is smaller than the corresponding bandwidth b_{cn}, and the OFDM procedure fully obeys fading phenomena in each sub-channel for the second scenario. However, such a division procedure is not effective in obeying any fading phenomena for the first scenario, where $f_0 \geq b_{cn}$. Finally, a strong frequency selective fading occurring in the dense urban scene can affect each sub-channels by corrupting the signal data for each subscriber located in the area of service. This example emphasizes the fact that before using the OFDM procedure, each designer of wireless network should estimate the fading parameters for each urban scenario, such as the time delay spread and coherence bandwidth (for stationary channels) and the Doppler shift bandwidth and time of coherency (for dynamic channel).

Orthogonal Frequency Division Multiple Access. From equation (20) it is clearly seen that the OFDM is a one-dimensional (1-D) technique because the branches are splitting in the frequency domain only. A new multiple access technique was introduced during the 1st decade (see references [13, 18–20, 64]), which is two-dimensional (2-D) splitting the signal in bins both in time and frequency domain. This multicarrier access procedure is called Orthogonal Frequency Division Multiple Access. Here, we will briefly explain its algorithm and difference with respect to standard OFDM modulation technique. For this purpose, we arrange the corresponding scheme of each carrier signal data presentation in the joint 2D time-frequency domain, as shown in Fig. 8. One can that in an OFDMA system for each carrier we get the narrow bandwidth $f_0 = B_w/N$ with the inter-carrier separation that equals $1/T_s \ll f_0$.



■ ***Fig. 8.*** 2D time-frequency signal presentation according to OFDMA technique

We should also mention that during this procedure of splitting the total bandwidth B_w into N sub-channels, the each carrier bandwidth f_0 must be shorter than the bandwidth of coherency of each sub-channel, that is, $f_0 < b_{cn}$, as was proved experimentally in [102]. Taking into account the above constrain, we can, by using OFDMA technique, fully exclude the ICI, that is, the overlapping between each separate bin and, finally, we do not spend bits for guarding effects, as was used in narrowband technologies, such as the FDMA and TDMA, definitions of which were introduced in [22]. Therefore, the OFDMA technique can be considered as a hybrid FDMA/TDMA scheme described above, because it allows users to flexibly share both the frequency sub-band (e.g., the carrier) and the time slot. Mentioned above allows us to state the following features of OFDMA:

— OFDMA is based on OFDM, the multiple narrow-band subcarriers modulated in parallel;

— OFDMA combines OFDM modulation and a multiple access scheme, let say TDMA, as it is shown in Fig. 9, *a*;

— OFDMA combines time division and frequency division multiple access techniques, that is, OFDMA = TDMA+FDMA (Fig. 9, *b*).

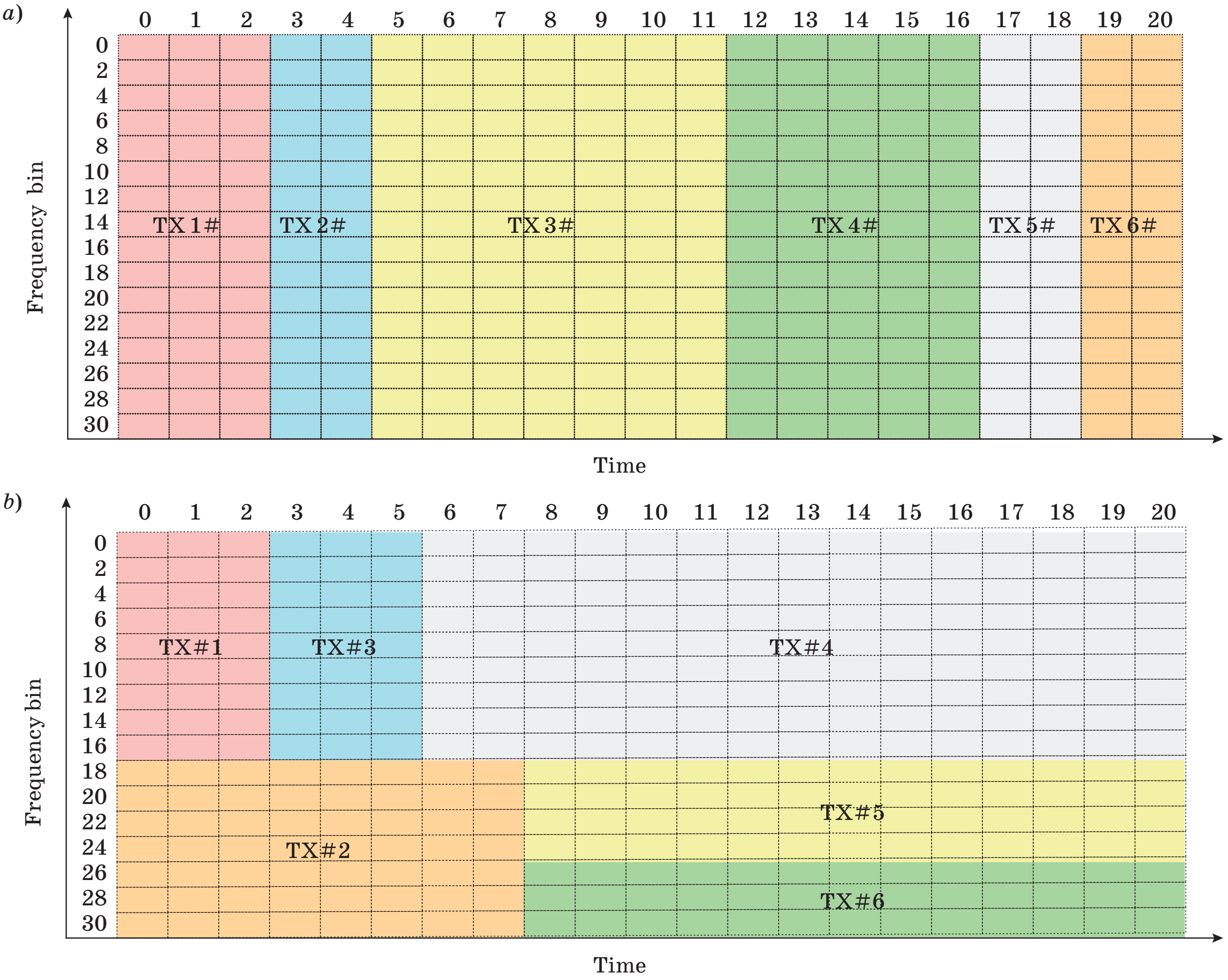
Moreover, the above analysis allows us to notice that using a large number of parallel narrowband sub-carriers instead of a single wideband carrier to transport information, we can:

— very easy and efficiently deal with time-dispersive multipath fading;

— protect against narrow-band interference due to the orthogonality of the sub-carrier channels;

— offer the flexibility to adapt the transmission rate per narrowband sub-channel (e.g. sub-carrier) to the most suitable transmission electronic schemes at the transmitter;

— reduce some of the electronic elements at the receiver, because using such a technique, we do not need to implement the N oscillators, filters, and so forth, for each carrier.



■ ***Fig. 9.*** OFDMA as a combination of OFDM modulation and TDMA technology (*a*) and OFDMA as a combination OFDM modulation simultaneously with FDMA and TDMA technologies (*b*)

At the same time we notice that the OFDM/OFDMA techniques have some disadvantages of this technique, such as:

— this technique is sensitive to frequency and phase offsets;

— it has a peak-to-average problem that reduces the power efficiency of the RF amplifier at the transmitter (for any multicarrier technique).

Despite the fact that the OFDM/OFDMA techniques have the above disadvantages, they were taken strong candidates for most of the 3G and 4G wireless networks and were adapted in various modern standard technologies, such as WPAN or Bluetooth, WLAN, which is equivalent to WiFi, WiMAX, LTE, and so on. Currently, the OFDMA technology is intensively used in IEEE 802.16/WiMAX standard networks and in their combination with MIMO systems (see brief descriptions of the corresponding networks below in Section 4).

2.4. Time Advanced Multicarrier Diversity Techniques

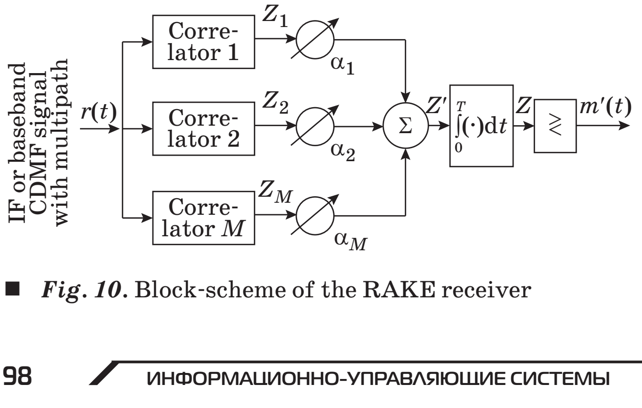
As was defined in [21, 22], in situations when the signal bandwidth is larger than the coherence bandwidth of the channel, that is, $B_w \gg B_c$, the channel is frequency selective and fast. If the same channel is subdivided into a number of orthogonal frequency-division multiplexing sub-channels having a mutual separation in center frequencies of at least $\Delta f \equiv B_c$, the effects of fading on the signal data transmitted via each sub-channel can be eliminated.

However, in the case of wideband modulation, such as in the CDMA technique, the multiple sequences of the data signal from each subscriber arriving at the receiver can destroy the independence between the codes (i.e., their orthogonal properties) if their delays will exceed a single chip duration. This usually occurs, if the chip rate exceeds the coherent bandwidth of the sub-channel, that is,

$R_c > b_{cw}$. In such scenarios an alternative method is usually used on the basis of a so-called Rake detector [5–7]. Here a time diversity technique is used, assuming $T_s \gg T_c = 1/b_{cw}$, that is, the information signals duration exceeds the coherence time of the sub-channel. In this case multiple repetitions of the signal will be received with independent fading conditions. In other words, we can obtain time diversity by transmitting the same signal multiple times, separated signals apart in time in such a manner that the channel multipath fading will be decorrelated between replicas.

As was shown in references [5–7], the one modern implementation of time diversity involves the use of a RAKE receiver, working as *n*-delay line through which the received signal is passed. Its action is somewhat analogous to an ordinary garden rake, and consequently, the name "RAKE receiver" has been used for this device by Price and Green in 1958 [5–7].

As we mentioned in Section 1 (see also [22]), in DS-SS system (or CDMA), the chip rate is much greater than the fading bandwidth of the channel. CDMA spreading PN-codes are designed to provide very low correlation between successive chips. Thus, propagation delay spread in the wireless channel merely provides multiple versions of the transmitted signal at the receiver. If these multipath components are delayed in time by more than the chip duration, they appear like uncorrelated noise at the CDMA receiver, and an equalizer is not required. However, since there is useful information in the multipath components, CDMA receivers can combine the time-delayed versions of the original signal transmission in order to improve the SNR at the receiver. The RAKE receiver is usually used for such purposes. This receiver, using the tapped delay line structure with discrete time intervals equal to the chip period T_c, multiplies several copies of the received signal by versions of a spreading code, shifted by multiples of T_c. Finally, a Rake detector collects the time-shifted versions of the original signal by provide a separate correlation receiver for each of the multipath signals. The RAKE receiver, shown in Fig. 10, is essentially a diversity receiver designed specially for CDMA, where the diversity is provided by the fact that the multipath components are practically uncorrelated from one another, when their relative propagation delays exceed a chip period T_c.



■ ***Fig. 10.*** Block-scheme of the RAKE receiver

As it is seen from Fig. 10, a RAKE receiver utilizes multiple correlators to separately detect the M multipath components with deep fading (i.e., strongest multipath components). Such a procedure allows the components of the desired signal with data (e.g., with a original bits' sequence) to be recovered and recombined with the corresponding time shifts due to the channel removing.

Let us briefly analyze the RAKE receiver working process in more details following block-scheme presented in Fig. 10. The outputs of each correlator are weighted to provide a better estimate of the transmitted signal. Demodulation and bit decisions are then based on the weighted outputs of the M correlators. Assume M correlators are used in a CDMA receiver to capture the M strongest multipath components. A weighting network is used to provide a linear combination of the correlator output for bit detection.

The first correlator is synchronized to the strongest multipath component of the signal $r(t)$ with data and multiplicative noise due to fading. The multipath component m_2 arrives τ_1 later than component m_1. The second correlator is synchronized to the component m_2. It is correlated strongly with m_2, but has low correlation with m_1. Note, if one correlator is used, as it usually done for single-carrier systems, such as FDMA and TDMA, the strong fading corrupted the channel cannot be eliminated by single receiver. Then bit decisions based on only a single correlation may produce a large bit rate of the information data passing through such single-carrier channel. In a RAKE receiver, if the output from one correlator is corrupted by fading, the others may not be, and the corrupted signal may be discounted through the weighting process. Decisions based on the combination of the M separate decision statistics offered by the RAKE provide a form of diversity which can overcome fading and thereby improve CDMA reception. The M decision statistics are weighted to form an overall decision statistics, as shown in Fig. 10.

The outputs of the M correlators are denoted as $Z_1, Z_2, \ldots, Z_M$. They are weighted by $\alpha_1, \alpha_2, \ldots, \alpha_M$, respectively. The weighting coefficients are based on the power or the SNR from each correlator output. If the power or SNR is small out of the particular correlator, it will be assigned a small weighting factor. As in the combining diversity scheme, the overall signal Z' is given

$$Z' = \sum_{m=1}^{M} \alpha_m Z_m. \quad (21)$$

The weighting coefficients, α_m, are normalized to the output signal power of the correlator in such a way that the coefficients sum is equal to one, shown by the following formula:

$$\alpha_m = \frac{Z_m^2}{\sum_{m=1}^{M} Z_m^2}. \qquad (22)$$

As in the case of adaptive equalizers and diversity combining, there are many ways to generate weighting coefficients. Choosing weighting coefficients based on the actual outputs of the correlators yields better RAKE receiver performance. This performance gives a conditional error probability in the form of

$$P(\gamma_b) = Q\left(\sqrt{\gamma_b(1-\rho_r)}\right), \qquad (23)$$

where $\rho_r = 0$ for the orthogonal signals and $\rho_r = -1$ for antipodal signals; the Q-function was defined in the literature via the error function [1–22]. Here γ_b is the current SNR, which equals:

$$\gamma_b = \frac{\mathrm{E}_b}{N_0} \sum_{k=1}^{M} \alpha_k^2 = \sum_{k=1}^{M} \gamma_k. \qquad (24)$$

For Rayleigh fading channel, we can finally obtain the probability for instantiations SNR, γ_k:

$$p(\gamma_k) = \frac{1}{\bar{\gamma}_k} \exp\left\{-\frac{\gamma_k}{\bar{\gamma}_k}\right\}, \qquad (25)$$

where, as above, $\bar{\gamma}_k = \mathrm{E}_b \left\langle \alpha_k^2 \right\rangle / N_0$ is an average SNR for the k^{th} path (k^{th} subcarrier or sub-channel).

To be continued.

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Эволюция многопроцессорных систем связи — сотовых и несотовых — в исторической перспективе. Часть 1

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Постановка проблемы: целью данного обзора является анализ эволюции систем беспроводной связи от второй генерации (2D) до пятой генерации (5G), а также изменения технологий и их существующих теоретических основ и протоколов — от Bluetooth, WLAN, WiFi и WiMAX до LTE, OFDM/OFDMA, MIMO и LTE/MIMO — продвинутых технологий с новой иерархической структурой дизайна сотовых карт femto/pico/micro/macro. **Методы:** использованы новые теоретические подходы для описания продвинутых технологий, таких как многопользовательская техника разделения пользователей, OFDM и OFDM-новейший подход, новые аспекты описания MIMO-систем на базе использования многолучевых антенн, дизайн различных сотовых карт на основе новых алгоритмов построения фемто/пико/микро/макро сот, а также новой методологии интегрирования новой MIMO/LTE-системы с помощью многолучевых антенн. **Результаты:** создана новая методология описания многопользовательского разделения, использования комбинированной OFDM/OFDMA-модуляции для обхождения интерференции между пользователями и между символами в новых многопроцессорных системах, мультипликативных шумов, имеющих место в беспроводных многопроцессорных системах связи, вызванных явлениями многолучевости. В итоге предложено, как обойти эффекты распространения, имеющие место в наземных каналах связи, используя комбинацию MIMO- и LTE-технологий, основанных на применении многолучевых антенн. Для этих целей разработан новый стохастический подход к проблеме, учитывающий особенности застройки земной поверхности, такие как профиль застройки домов, плотность застройки домов вокруг антенн базовой станции и пользователей и т. д. Эти характеристики позволяют в итоге оценить эффекты фединга как источника мультипликативного шума. **Практическая значимость:** новая методология оценки эффектов, созданных мультипликативным шумом, интерференцией между пользователями и между символами, имеющими место в наземных системах беспроводной связи, позволяет прогнозировать практические аспекты существующих и новых многопроцессорных беспроводных систем связи, такие как емкость (количество) пользователей и спектральная эффективность каналов пользователей для различных конфигураций построения сот — фемто/пико/микро/макро, а также новейших конфигураций систем MIMO/LTE для построения будущих систем 4-го и 5-го поколений.

Ключевые слова — аддитивный белый гауссов шум, AWGN, процесс многократного разделения по кодам, CDMA, прямое быстрое преобразование Фурье, DFFT, прямое уширение спектра последовательности, DS-SS, глобальная система подвижной связи, GSM, процесс многократного разделения по частотам, FDMA, обратное быстрое преобразование Фурье, IFFT, внутриканальная интерференция, ICI, внутрисимвольная интерференция, ISI, внутрипользовательская интерференция, IUI, долгосрочные эволюционные реализации, LTE, процесс контроля среды, MAC, мультиплексирование за счет разделения по ортогональным частотам, OFDM, процесс мультиплексирования за счет разделения по ортогональным частотам, OFDMA, процесс мультиплексирования за счет разделения по ортогональным временным частотам, OTDMA, многократный вход — многократный выход, MIMO, единственный вход — многократный выход, SIMO, отношение сигнала к шуму, SNR, процесс многократного разделения по временам, TDMA, оборудование пользователя, UE, беспроводная пользовательская сеть, WiFi, локальная беспроводная сеть,WLAN, беспроводная сеть метрополии, WiMAX, беспроводная пользовательская сеть, WPAN.

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