A Review on Digital Modulation in 4G LTE/4G LTE Advanced

Andres Solano-Escorcia, Juan Sanjuanelo-Barraza, Bessy Cujavante-Hernandez, Alejandro Cama-Pinto and Dora Cama-Pinto

March 28, 2022

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***Abstract*—Since the last century, mobile telephony has taken an important role in telecommunications, increasing the volume of data traffic supported by its network over the years. From 2.5G telephony experienced the use of data to be used on the internet and in the following generations passing through 3G, 4G and 5G the speed rate has increased. In this sense, this paper presents the evolution of mobile phone technologies, specifically the fourth generation (4G), also called LTE (Long Term Evolution). It also explains the relevance of using digital modulations that work in conjunction with OFDM in 4G to achieve high data rates combined with MIMO systems for this purpose.**

***Index Terms*—4G networks, OFDMA, QAM, QPSK, telecommunications.**

I. Introduction

Wireless systems keep growing and evolve to meet increasing traffic requirements through the deployment of 4G LTE, LTE Advanced (LTE-A) networks, continuing the evolution to 5G systems [1]. The International Telecommunication Union (ITU) mentions that 4G connections accomplish a minimum of 100 MBps of data transmission on mobile phones and laptops with a wireless data card [2]. Considering the actual definitions of ITU - Radiocommunication (ITU-R) requirements, fourth generation mobile systems strictly refer to LTE-Advanced technologies. However, LTE is widely known as 4G [3].

LTE (Long Term Evolution) is a mobile communications system designed by the 3GPP (Third Generation Partnership Project), and WiMAX (Worldwide Interoperability for Microwave Access). It is a wireless technology that contributes to high-speed mobile communications based on IEEE 802.16 standards body. LTE supports frequency division duplex (FDD) and time division duplex (TDD) modes, offering greater deployment flexibility versus past 3G systems. In addition, they use scalable bandwidths with frequency-spaced subcarriers [4]. LTE offers a flexible dynamic approach between its base stations, coordinating interference through signalling that includes the use of reactive uplink overload indicators (OI) and proactive high interference indicators (HII) [5].

Multimedia data traffic transmitted on mobile phones continues to increase. According to the Cisco Annual Internet Report (2018-2023), by the year of 2023, 4G connections will represent 46% of mobile connections, in contrast to 2018 with 42%. 4G connections worldwide will raise from 3.7 billion to 6 billion from 2018 to 2023, respectively, at a compound annual growth rate (CAGR) of 10% [6]. This growth is mainly due to inter-machine communications (M2M) and the dominance of smartphones, laptops, tablets [7].

The deployment and global coverage of 4G enables significantly greater implementation of the Internet of Things (IoT). IoT facilitates the worldwide communication of intelligent devices that collect information through sensors, actuators, manipulated and administered in real time via Internet [8]. LTE is designed to enhance users' mobility experiences. LTE uses Internet Protocol (IP), to send and receive data with good quality, in the same way with voice signals, allowing better integration with multimedia services [9].

An analysis of 4G technology enables us to better understand the current dominant mobile network, where many of the important features will be maintained and improved in the next generation (5G), something which is in its deployment phase worldwide. For this reason, the objectives of our work are:

- Detail interaction between OFDM and digital modulations in 4G.
- Understand how data rates are achieved in 4G clients.

Andres Solano-Escorcia, Juan Sanjuanelo-Barraza, Bessy Cujavante-Hernandez and Alejandro Cama-Pinto are with the Department of Computer Science and Engineering Electronic, Universidad de la Costa, Barranquilla, Colombia (e-mail: acama1@cuc.edu.co).

Dora Cama-Pinto is with the Department of Computer Architecture and Technology, University of Granada, Granada, Spain. (e-mail: doracamapinto@correo.ugr.es).

II. MATERIALS AND METHODS

A systematic search and review of documents related to 4G LTE and LTE - Advanced digital communication and OFDM modulation was carried out. Firstly, base documents that helped to understand the subject in a general way, such as articles and books, related to 4G LTE technology were taken into account. This was followed by a search in Scopus of documents such as articles, systematic literature reviews and books published by different journals. This was done using the following key words: 4G and LTE and OFDM, filters were applied from Journal, Conference paper, Book chapter and Book. On the other hand, the bibliographic references of the selected articles were analyzed, with the objective of obtaining other studies potentially including for the present investigation. We also found reports related to Internet data traffic using 4G.

The search included papers that related 4G modulation to orthogonal frequency division multiplexing (OFDM). The inclusion criteria were that they incorporated concepts related to QAM and QPSK modulations and how they relate to OFDM. After the initial search in Scopus, 51 papers were selected: 36 articles, 9 conference papers and 6 books. For the selection of the previous documents, the abstracts and conclusions were analyzed, and if necessary, the complete articles were analyzed in order to decide whether the information they contained was related to the objective or not. The information analyzed was structured in two sub-sections: the first dedicated to explaining multiple access techniques, digital modulation used in 4G architecture, OFDM and OFDMA. The second describes bandwidth, MIMO technology and 4G data rate.

III. BACKGROUND

On June 17, 1946, a team of Bell Labs engineers made the first radiotelephone call from an automobile. Since then, many companies throughout the world researched commercializing this technology, achieving the first mobile phone call on April 3, 1973, using the mobile phone model: Dyna-TAC (Dynamic Adaptive Total Area Coverage), developed by Dr. Martin Cooper and his team at Motorola. A decade later, the first network based on the Advanced Mobile Phone System (AMPS) was inaugurated in the United States [10]. The original AMPS cellular technology used analog modulation (frequency modulation - FM), and was known as the first generation of mobile telephony (1G). The first digital cell phones are called second generation phones (2G). Currently, third generation (3G), fourth generation (4G) telephones and cellular systems are in use and the deployment of fifth generation (5G) base stations continuing their expansion. However, in some regions of the world, 2G networks are still operational for voice communication as well as sending data to the cloud in applications that do not demand much channel capacity (kbps), for example, in remote monitoring systems that use modules GPRS (General Packet Radio Service) [11], also because of poor coverage or non-existent infrastructure of 3G, 4G or 5G networks.

From the aggregation of GPRS in the 2G architecture was introduced the initial capacity of data transfer at tens of kbps in a mobile phone network. On the other hand, with the launch of the first smartphone on January 7th, 2007 (Apple's iPhone 2G), it encouraged the demand to grow the data rate of the mobile phone network for subsequent generations (3G, 4G, 5G) [10]. The third generation (3G) had technical limitations in the use of circuit switching, because it only provides a maximum rate of 3.84 MBps (maximum nominal rate of 2Mbps) and is not capable of satisfying user requirements, for example, in streaming. For this reason, the next generation provides higher data rates, greater capacity, and increased bandwidth [12].

Likewise, 3GPP considers LTE-Advanced technology, publishing feasibility studies in Technical Report 36.912, showing that LTE-A meets the IMT (International Mobile Telecommunications) requirement. LTE-A seeks to increase data rate using a wider transmission bandwidth. 3GPP states that the maximum data rate in LTE-A is 1.5 Gbps on the uplink and 3 Gbps on the downlink, with 20 MHz to 100 MHz scalable bandwidths [13].

The most important technologies that make LTE-Advanced possible are the following:

- Aggregation of ports made up of multiple 20 MHz components for 100 MHz bandwidth devices.
- Multi-hop retransmission (adaptive transmission, fixed transmission stations, configurable cell rates) to upgrade coverage and data rates.
- Schemes to advanced interference cancellation.
- OFDM transmission technique, MIMO systems, hierarchical constellations, among others multi-resolution schemes [14].

IV. 4G NETWORKS

A. Multiple access techniques and digital modulation in 4G

The demand for broadband communications is increasing daily. Multi-carrier technology is used to fill that need. Frequency division multiplexing (FDM) is a multi-carrier technique that divides the width of the communication channel that transmits information in parallel using multiple carriers [15]. In multi-carrier modulation, the data flow is separated into N subcarriers or lower data rate subchannels. This multiplexing technique does not change the total bandwidth (W). Each subcarrier is separated W/N, while the symbol period (T) is raised by a factor of N. This is a key to understanding Orthogonal Frequency Division Modulation (OFDM), which admits the concurrent transmission of N subcarriers orthogonally between them, without interference [16].

4G LTE /LTE-A mobile systems implement 16 quadrature amplitude modulation (QAM), 64-QAM and quadrature phase shift keying (QPSK), on each orthogonal frequency division multiplexed sub-carrier, as determined by Release 8 of the 3GPP standards [17]. QAM is used due to its high data rates, and high BER (Bit Error Ratio). QPSK has a high data rates, but has a much lower BER than QAM, therefore these modulation schemes are combined. QAM is used in zones close to the base station (BS), and QPSK next to the cell, accepting low data rate, because here the BER is low [18].

Multicarrier systems using orthogonally overlapping subcarriers have been investigated since the 1960s. Nevertheless, at that time it was difficult to use it because of the great amount of filters and modulators needed. Later, the equipment complexity was reduced by employing the Discrete Fourier Transform (DFT) to process OFDM signals [19]. In addition to the improvement in the data rate obtained with OFDM, the basic technology in 4G LTE systems and 5G new radio (NR) increases the spectral performance and system capacity by means spatial multiplexing with the MIMO technology (multiple-input and multiple-output), also called multiple antenna technology [20].

B. 4G Architecture

The 4G technology is called LTE (Long Term Evolution), this generation differs from the previous ones by a higher data rate with new and amazing hardware/software capabilities of the cellular equipment, with features to receive, generate and send videos [10]. As detailed in Fig. 1, an LTE network has the EPC (Evolved Packet Core) in the LTE a packet-switched backbone network, completely IP, and E-UTRAN (Evolved-Universal Terrestrial Radio Access Network) systems [21]. The E-UTRAN network incorporates the eNodeBs (Evolved Universal Terrestrial Radio Access Network Base Stations) also termed eNBs, communicated with the UE (User Equipment) [22].

The LTE voice service is managed by the IP multimedia subsystem (IMS) network replacing the traditional circuit-switched network. The EPC has a MME (Mobility Management Entity), SGW (Serving Gateway), PDN GW (Packet Data Network Gateway) and HSS (Home Subscriber Server). When a UE is attached to the EPC, the MME represent the EPC for mutual authentication with the UE [21]. In LTE / LTE-A, femtocell base stations, recognized as Home evolved NodeBs (HeNBs), are designed to be set up indoor, filling the coverage gaps produce by unsteady signals from macrocell base stations called evolved NodeBs (eNBs) [23].

A new type of communications called MTC (Machine Type Communication) is expected to be used in LTE-A, connecting devices to each other or to central servers through their own network and Internet. MTC enables a wide range of automatic or low human intervention applications by exchanging data [24] [25].

OFDM is utilized in countless digital broadband communications, e.g., digital television, digital broadcasting, wireless networks and obviously 4G [26]. This technique partitions a given bandwidth into many cramped sub-carriers. The space chosen between the sub-carriers gives them orthogonality, this means that they do not interfere with each other, even though OFDM does not use protective bands between them [27]. Moreover, the subcarriers can be modulated by different techniques: QPSK, 16-QAM or 64-QAM.

C. Digital modulation 4G

1) QPSK – (Quadrature Phase Shift Keying)

QPSK is also called 4-PSK, in this modulation the message is sent every two bits, therefore, the message has four possible combinations (2^2 = 4). In QPSK each output of the modulator is separated from the others by 90° (45°, 135°, -45° and 135°). The baud rate is half the bit rate, requiring less bandwidth than BPSK [28][29].

2) QAM – (Quadrature Amplitude Modulation)

QAM is both an analogue and a digital modulation technique, combining FSK and ASK, i.e., phased components (real OFDM values) and amplitude components (imaginary OFDM values) of the sinusoidal carrier to achieve high wireless transmission data rates, especially in OFDM systems [30]. Diverse predominant and emerging wireless communication standards define 16-QAM and 64-QAM, with four and six bits respectively per symbol (see Fig. 2), as a modulation scheme in OFDM systems for high data rate support. Other applications are Digital Video Broadcasting (DVB) and Digital Multimedia Broadcast (DMB) [30] [31].

D. OFDM (Orthogonal Frequency Division Multiplex)

The OFDM technique divides the frequency spectrum into N sub-channels or parallel data channels that are orthogonal sub-carriers, allowing dense packing to achieve efficiency in the use of the total bandwidth and ensuring minimum interference between the sub-channels. Each sub-carrier is mapped in symbols (digitally modulated), with BPSK, QPSK, M-QAM [33] [34]. As shown in Fig. 3, in the frequency domain, when using orthogonal carriers, each contiguous subcarrier has a null in the center frequency carrier neighbor [35].

An OFDM system with its functional blocks is shown in Fig. 4. In OFDM transmitters and receivers, bits are mapped by QAM or QPSK encoders, to which Inverse fast Fourier transform (IFFT) is applied, guaranteeing orthogonality at this stage. Immediately, the output changes to a serial signal to modulate it to a carrier and be transmitted wirelessly [36].

Inverse Fast Fourier Reverse Transform (IFFT) processing makes frequency subcarriers orthogonal. This orthogonality is maintained over a time-dispersed wireless channel by implementing a Cyclic Prefix (CP) to the transmitter, thus obtaining an exact reproduction of the final section of the

OFDM symbol [37]. By using a CP, it facilitates the location of the OFDM wave in the receiver, in addition, it allows to take in signals from different transmitters working with a single FFT in the Rx (receiver) side [38].

In LTE, information is organized according to frequency and time, using a resource grid, or also known as a resource block (RB), providing not only high speeds but also greater signal reliability [39]. Fig. 5 shows an RB of a typical cyclic prefix. The RB are formed by the information signals in the frequency domain, each encompassing 0.5 ms of one slot, by 180 KHz in twelve subcarriers. The information is conveyed in packets or frames, in a 15 kHz subcarrier channel, the basic data rate is 15 kbps [40].

E. *OFDMA (Orthogonal Frequency Division Multiple Access)*

To obtain flexible bandwidth and high data rates, OFDMA is used, which is a technology that combines OFDM and FDMA (Frequency Division Multiple Access) [41]. In this way, each symbol used in the resource block transmits information to and from various users using different subcarriers [42]. OFDMA is used in standards like 4G and WiMAX for broadband access. OFDMA facilitates high speeds of wireless broadband data transmission, as otherwise the signal would be distorted by inter-symbol interference (ISI) as a result of the selective nature of the frequency [43].

OFDMA has some features different from OFDM such as high flexibility, channel fading robustness, easy equalization, and great spectral efficiency [44]. OFDMA's great advantage over OFDM is its ability to support multi-user scenarios, serving different users at the same time, each user is assigned a subcarrier package, contrary to OFDM where all subcarriers are granted to a single user [45].

V. RESULTS AND ANALYSIS

A. *Bandwidth*

LTE provides the ability to have different uplink and downlink transmission bandwidths. The reason for this is the amount of spectrum available for LTE deployment, which varies significantly across all frequency bands [46]. LTE achieves high data transmission speeds at different bandwidths. Adaptive bandwidth in LTE ranges from 1.4 MH to 20 MHz, going through 3, 5, 10, 15 MHz, has peak speeds of 326.5 Mbps for 4x4 MIMO and 172.8 Mbps for 2x2 MIMO downlink, while uplink they reach 86.5 Mbps, using 64-QAM modulation on both links [47].

The basic bandwidth of an OFDM signal is equal to the number of subcarriers multiplied by the space between each subcarrier. In practice, typically 10% of the guard band is required for an OFDM signal, implying that, in a 5 MHz spectrum allocation, the basic OFDM bandwidth would be 4.5 MHz assuming a subcarrier space of 15 kHz in LTE, thus corresponding to approximately 300 subcarriers in 5 MHz [48]. However, the OFDM system has a significant disadvantage, the PAPR (Peak-to-Average Power Ratio) is very large, contributing to lower power capacity and non-linear distortion in the transmit power amplifier device increasing the mobile equipment battery consumption [49].

With multipath resistance and flexible OFDMA frequency assignment, the SC-FDMA was adopted because it merges low PAPR techniques from single-carrier transmission systems such as GSM and CDMA, a cheaper power amplifier, and higher robustness for null spectra. These relevant characteristics make SC-FDMA effective in the uplink channel [44] [50]. Data is in the frequency domain and were passed form time domain previously with Discrete Fourier Transform (DFT), to be located at the desired position within the bandwidth and passed again to the time domain applying the Inverse Fourier Transform (IFFT), lastly, the CP is assigned. Due to the above, SC-OFDMA is also named Discrete Fourier Transform Spread OFDM (DFT-SOFDM) [50]. In addition, the LTE frequency bands are in a paired and unpaired frequency spectrum, which requires flexibility in the duplex arrangement. To this end, LTE supports FDD (frequency division duplex) and TDD (time division duplex) [46]. TDD establishes communication without changing the frequency channel, but transmission and reception is done at different times, whereas FDD receives and transmits simultaneously on two separate symmetric frequency channels [51].

The LTE network works in several of the current cellular bands but was also assigned specific new bands. They are shown in Table I [27].

As shown in Table I, LTE bandwidths 1 to 28 use different bandwidths for uplink and downlink, applying the FDD principle. The LTE bandwidths from 33 to 44 use TDD, therefore the uplink and downlink frequencies employed are the same.

B. *MIMO in 4G*

MIMO technologies in LTE along with beamforming, multiplexing and spatial diversity in 4G LTE-Advanced, increase the performance cell and cell edge averages [52]. With the use of MIMO system, takes advantage of multipath fading, improving link reliability, network coverage, channel capacity and data rates, compared to a single input/output communication system (SISO) [53].

MIMO technology is employed in 4G system with a frequency of 2.6 GHz [54]. In the eighth version of LTE, the maximum number of antennas is 4 in the base and 2 in the mobile equipment and in LTE-A, the number is greater, therefore 8x8 schemes can be used in the downlink and 4x4 in the uplink [55].

The antennas are in the base station as in the mobile terminal. Therefore, antenna systems are requested to be fitted inside the mobile terminal which covers a limited size (normally not more than 60-100 mm^2). The primary consideration in tuning all antenna systems is a balance between efficiency, device size, and maximum bandwidth [56].

C. 4G Data rate

4G LTE is contingent upon the bandwidth and the type of modulation, the MIMO settings, and the wireless path quality. In unfavorable cases, the data rate might be several Mbps, but in satisfactory conditions, the data rate increases to more than 300 Mbps [27]. On average, the mobile broadband downlink speeds on 4G LTE are 10 Mbps [57].

Table II shows some of the most relevant features of LTE and LTE-A technology [58].

VI. Conclusion

Our work provides a synthesis of concepts in the field of 4G Mobile Telephony for a pragmatic understanding and introduction to this area of technology for researchers. There are very few publications that interrelate the concepts of digital modulation, OFDM, MIMO, frequency bands with the high data rates to users, greater capacity, and bandwidth. This article also serves as a starting point for the theoretical assimilation of techniques still used in the new 5G networks.

References

[1] A.L. Imoize, K. Orolu, A.A. Atayero, Analysis of key performance indicators of a 4G LTE network based on experimental data obtained from a densely populated smart city, Data in Brief. 29 (2020) art. no. 105304. http://dx.doi.org/10.1016/j.dib.2020.105304.

[2] N.P. Singh, The theoretical and real world of 4G technologies, International Journal of Mobile Network Design and Innovation. 5 (2013) 97-118. http://dx.doi.org/10.1504/IJMNDI.2013.060227.

[3] A. Sutton, N. Linge, Mobile network evolution within the UK, Journal of the Institute of Telecommunications Professionals. 9 (2015) 9-16.

[4] X. Li, B.S. Chen, C.M. Liu, X.R. Wang, K.R. Cho, F. Li, Spectrum modelling and regrowth for 4G wireless signals, Electronics Letters. 48 (2012) 244-245. http://dx.doi.org/10.1049/el.2011.3784.

[5] G. Boudreau, J. Panicker, N. Guo, R. Chang, N. Wang, S. Vrzic, Interference coordination and cancellation for 4G networks, IEEE Communications Magazine. 47 (2009) 74-81. http://dx.doi.org/10.1109/MCOM.2009.4907410.

[6] Cisco, Cisco Annual Internet Report (2018–2023), pp. 11. 2020. Last accessed: May 27, 2020. URL: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html.

[7] S. Yang, L. Hanzo, Fifty years of MIMO detection: The road to large-scale MIMOs, IEEE Communications Surveys and Tutorials. 17 (2015) 1941-1988. http://dx.doi.org/10.1109/COMST.2015.2475242.

[8] E. Soltanmohammadi, K. Ghavami, M. Naraghi-Pour, A Survey of Traffic Issues in Machine-To-Machine Communications over LTE, IEEE Internet of Things Journal. 3 (2016) 865-884. http://dx.doi.org/10.1109/JIOT.2016.2533541.

[9] O. Chamorro-Atalaya, E. Pizarro-Mayta, D. Arce-Santillan, Evaluation of the quality parameters of a 4G-LTE communications base station, installed in a rural area of Peru, Advances in Science, Technology and Engineering Systems. 5 (2020) 71-76. http://dx.doi.org/10.25046/aj050109.

[10] N. Linge, A. Sutton, The road to 4G, Journal of the Institute of Telecommunications Professionals. 8 (2014) 9-16.

[11] Y. Cetinceviz, D. Uygun, Y. Gungor, An effective speed controller and GPRS based data acquisition system design for DC motors, Review of Scientific Instruments. 91 (2020) art. no. 035120. http://dx.doi.org/10.1063/1.5110789.

[12] D. QingXia, D. Gang, C. HaiYan, Research on key technology of TD-LTE standard 4G mobile communications network, Open Cybernetics and Systemics Journal. 9 (2015) 1436-1442. http://dx.doi.org/10.2174/1874110X01509011436.

[13] W. Mostafa, E. Mohamed, A. Zekry, Software implementation of LTE-advanced using matlab Simulink, International Journal of Engineering and Technology. 6 (2017) 116-123. http://dx.doi.org/10.14419/ijet.v6i4.7876.

[14] M.M. Da Silva, A. Correia, N. Souto, J. Seguro, P. Gomes, R. Dinis, On the multi-resolution techniques for LTE-Advanced, Wireless Personal Communications. 66 (2012) 833-853. http://dx.doi.org/10.1007/s11277-011-0366-8.

[15] K. Mahender, T. A.Kumar, K. S. Ramesh, Performance study of OFDM over multipath fading channels for next wireless communications, International Journal of Applied Engineering Research. 12 (2017) 10205-10210.

[16] B.U. Rindhe, D.C. Shah, S.K. Narayankhedkar, OFDM in 4G networks: A comparison with MC-CDMA, International Conference and Workshop on Emerging Trends in Technology 2011, ICWET - Conference Proceedings. (2011) 928-932. http://dx.doi.org/10.1145/1980022.1980220.

[17] H. Otsuka, R. Tian, K. Senda, Transmission performance of an OFDM-based higher-order modulation scheme in multipath fading channels, Journal of Sensor and Actuator Networks. 8 (2019) 2. http://dx.doi.org/10.3390/jsan8020019.

[18] Md.S. Islam, A. Al Amin, S. Paul, I. Tahmid, Reliability checking for digital modulation schemes in 4G - 5G communication system: Comparison between QPSK and QAM modulation techniques for beyond LTE, ACM International Conference Proceeding Series. (2015) 442-446. http://dx.doi.org/10.1145/2818567.2818690.

[19] E. Yaacoub, Z. Dawy, A survey on uplink resource allocation in OFDMA wireless networks, IEEE Communications Surveys and Tutorials. 14 (2012) 322-337. http://dx.doi.org/10.1109/SURV.2011.051111.00121.

[20] S. Chen, S. Sun, G. Xu, X. Su, Y. Cai, Beam-Space Multiplexing: Practice, Theory, and Trends, From 4G TD-LTE, 5G, to 6G and Beyond, IEEE Wireless Communications. 27 (2020) 162-172. http://dx.doi.org/10.1109/MWC.001.1900307.

[21] J. Cao, M. Ma, H. Li, Y. Zhang, Z. Luo, A survey on security aspects for LTE and LTE-A networks, IEEE Communications Surveys and Tutorials. 16 (2014) 283-302. http://dx.doi.org/10.1109/SURV.2013.041513.00174.

[22] N. Abu-Ali, A.-E.M.Taha, M. Salah, H. Hassanein, Uplink scheduling in LTE and LTE-advanced: Tutorial, survey and evaluation framework, IEEE Communications Surveys and Tutorials. 16 (2014) 1239-1265. http://dx.doi.org/10.1109/SURV.2013.1127.00161.

[23] Y. L. Lee, J. Loo, T. C. Chuah, A. A. El-Saleh, Multi-objective Resource Allocation for LTE/LTE-A Femtocell/HeNB Networks Using Ant Colony Optimization, Wireless Personal Communications. 92 (2017) 565-586. http://dx.doi.org/10.1007/s11277-016-3557-5.

[24] C. H. Lee, S. J. Kao, F. M. Chang, LSTM-based ACB scheme for machine type communications in LTE-A networks, Computer Communications. 152 (2020) 296-304. http://dx.doi.org/10.1016/j.comcom.2020.01.047.

[25] T. H. Chuang, M. H. Tsai, C. Y. Chuang, Group-Based Uplink Scheduling for Machine-Type Communications in LTE-Advanced Networks, Proceedings - IEEE 29th International Conference on Advanced Information Networking and Applications Workshops, WAINA. (2015) 652-657. http://dx.doi.org/10.1109/WAINA.2015.54.

[26] R. Van Nee, R. Prasad, OFDM Wireless Multimedia Communications, 2000, Applications of OFDM, pp. 229-231.

[27] L. Frenzel, Principles of Electronic Communication Systems, 2016, Cell Phone Technologies, pp. 775-814.

[28] S-M.M. Yang, Modern Digital Radio Communication Signals and Systems, 2018, Digital Modulation, pp. 29-112. http://dx.doi.org/10.1007/978-3-319-71568-1.

[29] K. Wang, K. Zhu, Y. Wang, B. Yan, J. Yuan, X. Sang, X. Xin, OOK-to-QPSK modulation-format conversion based on two gain-transparent SOAs, Optik. 124 (2013) 4486-4489. http://dx.doi.org/10.1016/j.ijleo.2013.03.009.

[30] K. Abdullah, A. F. Ismail, W. Hashim, Z. M. Hussain, An optimal circular 16-QAM modulation technique for wavelet and fourier based OFDM, International Conference on Computer and Communication Engineering 2010. (2010) art. no. 5556821. http://dx.doi.org/10.1109/ICCCE.2010.5556821.

[31] S. Mazahir, S. A. Sheikh, On Companding Schemes for PAPR Reduction in OFDM Systems Employing Higher Order QAM, IEEE Transactions on Broadcasting. 62 (2016) 716-726. http://dx.doi.org/10.1109/TBC.2015.2511627.
[32] Halberd Bastion, Estimating LTE Data Rates. Last accessed: June 11, 2020. URL: https://halberdbastion.com/technology/cellular/4g-lte/estimating-lte-data-rates.
[33] S.S. Haque, M.M. Mowla, M.M. Hasan, S.K. Bain, An algorithm for PAPR reduction by SLM technique in OFDM with hadamard matrix row factor, 2nd International Conference on Electrical Engineering and Information and Communication Technology, iCEEiCT 2015. (2015) art. no. 7307348. http://dx.doi.org/10.1109/ICEEICT.2015.7307348.
[34] M. Mowla, S. M. Hasan, Performance improvement of PAPR reduction for OFDM signal in LTE system, International Journal of Wireless & Mobile Networks (IJWMN). 5 (2013) 35-47. http://dx.doi.org/10.5121/ijwmn.2013.5403.
[35] S. Nagarani, Nature inspired metaheuristics techniques based dynamic subcarrier, bit and power allocation for OFDMA-based relay networks, Life Science Journal. 10 (2013) 4241-4251.
[36] A. Perez, M. Realp, Cross-Layer Resource Allocation in Wireless Communications, 2009, Orthogonal frequency division multiplexing, pp. 151-162. http://dx.doi.org/10.1016/B978-0-12-374141-7.00008-7.
[37] A.R. Castro e Souza, J. R. De Almeida Amazonas, T. Abrão, Energy-efficiency maximisation for cooperative and non-cooperative OFDMA cellular networks - A survey, Transactions on Emerging Telecommunications Technologies. 27 (2016) 216-248. http://dx.doi.org/10.1002/ett.2850.
[38] G. Berardinelli, K. Pajukoski, E. Lahetkangas, R. Wichman, O. Tirkkonen y P. Mogensen, On the Potential of OFDM Enhancements as 5G Waveforms, IEEE Vehicular Technology Conference. (2014) art. no. 7023019. http://dx.doi.org/10.1109/VTCSpring.2014.7023019.
[39] P. Phunchongharn, E. Hossain, D. Kim, Resource allocation for device-to-device communications underlaying LTE-advanced networks, IEEE Wireless Communications. 20 (2013) 91-100. http://dx.doi.org/10.1109/MWC.2013.6590055.
[40] C. Cox, An Introduction to LTE: LTE, LTE-Advanced, SAE, VoLTE and 4G Mobile Communications, 2014, Architecture of the LTE Air Interface, pp. 105-123 http://dx.doi.org/10.1002/9781118818046.
[41] G. Ku, J.M. Walsh, Resource allocation and link adaptation in LTE and LTE advanced: A tutorial, IEEE Communications Surveys and Tutorials. 17 (2015) 1605-1633. http://dx.doi.org/10.1109/COMST.2014.2383691.
[42] C. Vargas, W. Lopez, C. Da Rocha, Sistemas de comunicación inalámbrica MIMO - OFDM, Acta Nova. 3 (2007) 750 – 760.
[43] G.C. Sekhar, S. Parakh, A.K. Jagannatham, Optimal 4G OFDMA dynamic subcarrier and power auction-based allocation towards H.264 scalable video transmission, Defense Scientific Information and Documentation Centre. 63 (2013) 15-24. http://dx.doi.org/10.14429/dsj.63.3759.
[44] A. Navita, Performance analysis of OFDMA, MIMO and SC-FDMA technology in 4G LTE networks, Proceedings of the 2016 6th International Conference - Cloud System and Big Data Engineering, Confluence 2016. (2016) 554-558. http://dx.doi.org/10.1109/CONFLUENCE.2016.7508181.
[45] H.H. Alyazidi, I. Kostanic, OFDMA feedback optimization in 4G-LTE systems, 2012 IEEE17th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks, CAMAD 2012. (2012) 70-74. http://dx.doi.org/10.1109/CAMAD.2012.6335382.
[46] E. Dahlman, S. Parkvall, J. Sköld, 4G LTE/LTE-Advanced for Mobile Broadband, 2011, LTE Radio Access: An Overview, pp. 102-103. http://dx.doi.org/10.1016/C2010-0-66332-2.
[47] C.D. Radicelli-García, M. Pomboza-Floril, L. Cepeda-Astudillo, Connectivity to the Internet in rural areas using DTT (DVB-RCT2) technologies, or mobile telephony (4G-LTE), DYNA. 85 (2018) 319-324. http://dx.doi.org/10.15446/dyna.v85n204.62690.
[48] E. Dahlman, S. Parkvall, J. Sköld, 4G LTE/LTE-Advanced for Mobile Broadband, 2013, OFDM Transmission, pp. 29-48. http://dx.doi.org/10.1016/C2013-0-06829-6.
[49] S. Sreenivasan, M. Poojitha, A. Chandran, S. Manush, S. Sujatha, Optimization of PAPR for OFDM systems using clipping and tone reservation, Test Engineering and Management. 83 (2020) 15238-15244.
[50] S. Jimaa, K. K. Chai, Y. Chen, Y. Alfadhl, LTE-A an overview and future research areas, 2011 IEEE 7th International Conference on Wireless and Mobile Computing, Networking and Communications. (2011) 395-399. http://dx.doi.org/10.1109/wimob.2011.6085370.
[51] Comisión de Regulación de Comunicaciones, Redes Móviles en Colombia: Análisis y hoja de ruta regulatoria para su modernización, pp. 15. 2019. Last accessed: June 11, 2020. URL: https://www.crcom.gov.co/uploads/images/files/Documento-Modernizacion-redes-moviles.pdf.
[52] I. F. Akyildiz, D. M. Gutierrez-Estevez, E. C. Reyes, The evolution to 4G cellular systems: LTE-Advanced, Physical Communication. 3 (2010) 217–244. http://dx.doi.org/10.1016/j.phycom.2010.08.001.
[53] S. Salihah, M. H. Jamaluddin, R. Selvaraju, M. Hafiz, A MIMO H-shape dielectric resonator antenna for 4G applications, Indonesian Journal of Electrical Engineering and Computer Science. 10 (2018) 648-653. http://dx.doi.org/10.11591/ijeecs.v10.i2.pp648-653.
[54] N. O. Parchin, H. J. Basherlou, Y.I.A Al-Yasir, A. Ullah, R.A. Abd-Alhameed, J. M. Noras, Multi-band MIMO antenna design with user-impact investigation for 4G and 5G mobile terminals, Sensors (Switzerland). 19 (2019) art. no. 456. http://dx.doi.org/10.3390/s19030456.
[55] M. Nahas, A. Saadani, J. P. Charles, Z. El-Bazzal, Base stations evolution: Toward 4G technology, 19th International Conference on Telecommunications, ICT 2012. (2012) art. no. 6221277. http://dx.doi.org/10.1109/ICTEL.2012.6221277.
[56] S.S. Phule, A.Y. Kazi, MIMO antenna system for LTE (4G), Proceedings on 2012 1st International Conference on Emerging Technology Trends in Electronics, Communication and Networking. (2012) art. no. 6470110. http://dx.doi.org/10.1109/ET2ECN.2012.6470110.
[57] N. Saxena, B. J. Choi, Authentication Scheme for Flexible Charging and Discharging of Mobile Vehicles in the V2G Networks, IEEE Transactions on Information Forensics and Security. 11 (2016) 1438-1452. http://dx.doi.org/10.1109/TIFS.2016.2532840.
[58] G. L. Stüber, Principles of Mobile Communication, 2017, Introduction, pp. 1-32. http://dx.doi.org/10.1007/978-3-319-55615-4.

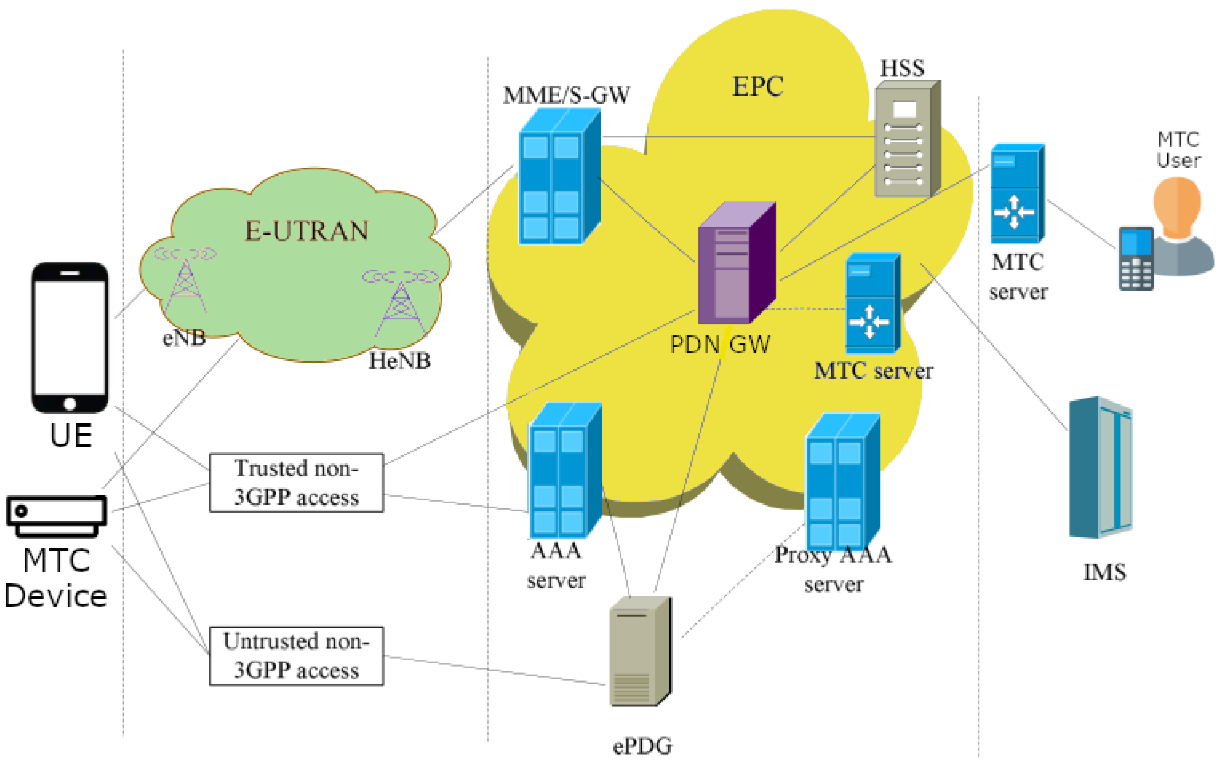

Fig. 1. Network architecture of LTE/LTE-A [21].

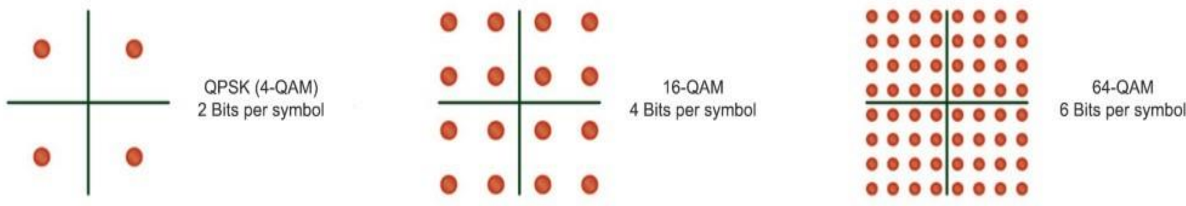

Fig. 2. Constellation diagram of the QPSK, 16-QAM and 64-QAM modulations [32].

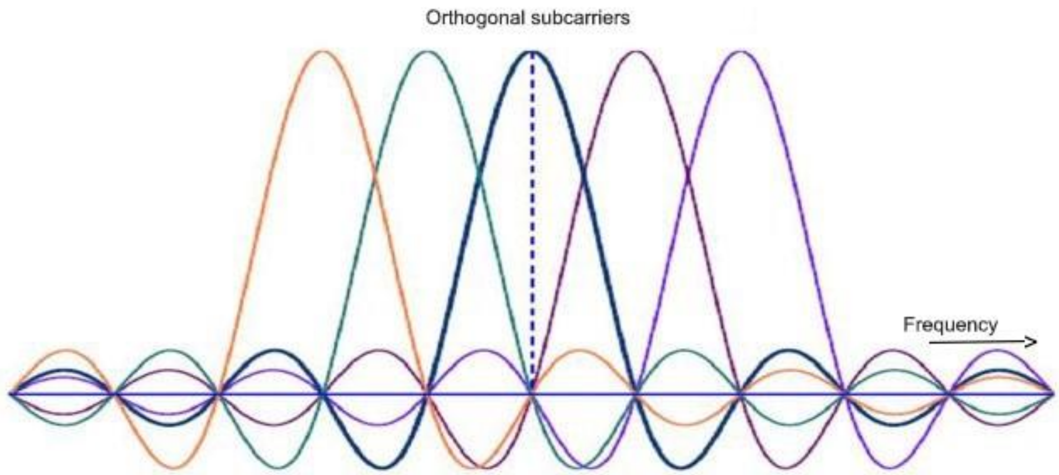

Fig. 3. OFDM signal spectrum with five subcarriers [35].

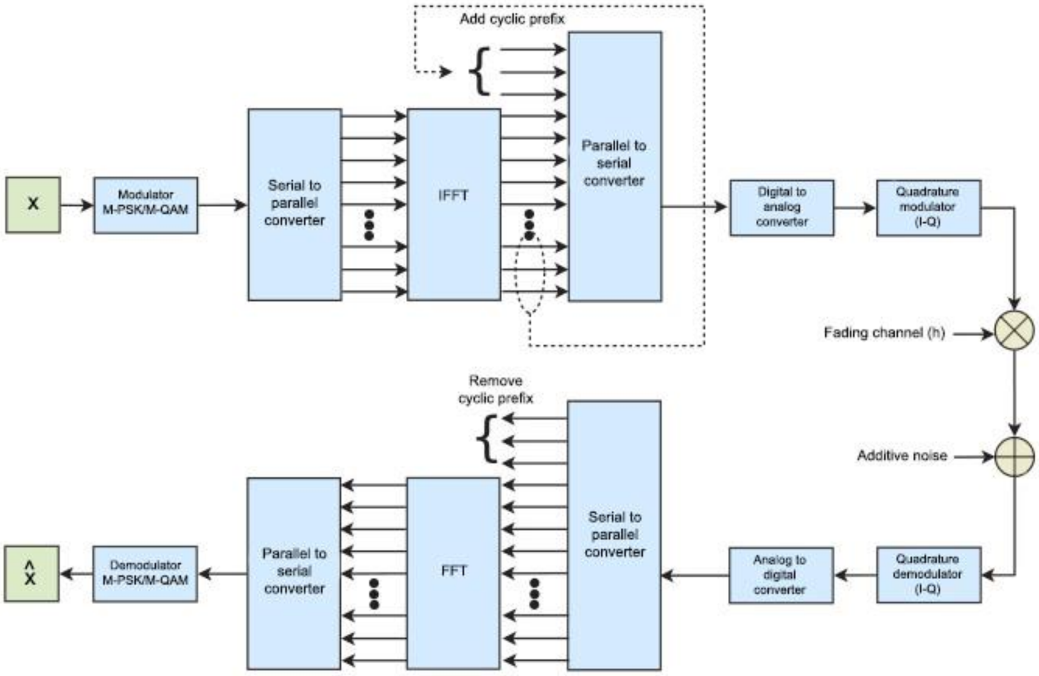

Fig. 4. Block diagram of the OFDM system [37].

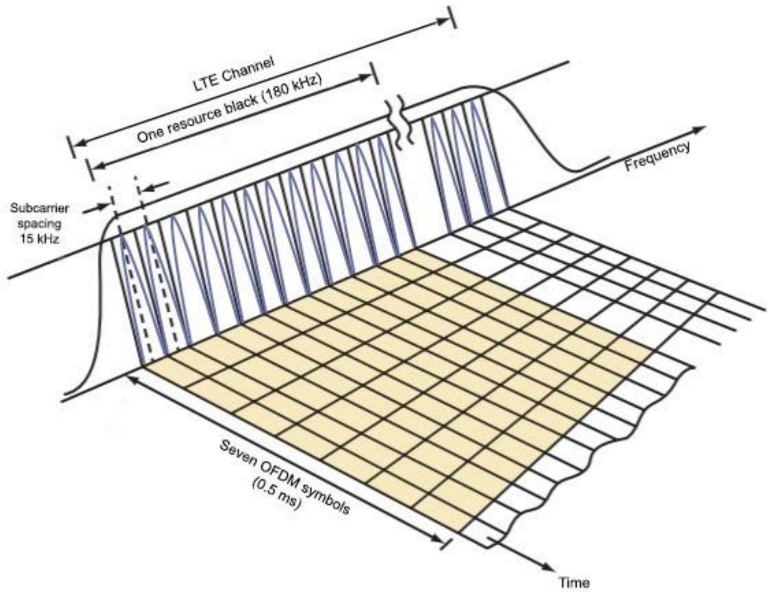

Fig. 5. Data is transmitted by separating it into parallel paths that modulate a group of subcarriers on the designated channel [27].

TABLE I
FREQUENCIES FOR DIFFERENT CELLULAR BANDS IN 4G

LTE band number	LTE Bands		Regions
	Uplink (MHz)	Downlink (MHz)	
1	1920-1980	2110-2170	Europe, Asia
2	1850-1910	1930-1990	America, Asia
3	1710-1785	1805-1880	Europe, Asia, America
4	1710-1755	2110-2155	America
5	824-849	896-894	America
6	830-840	875-885	Japan (only for UTRA)
7	2500-2570	2620-2690	Europe, Asia
8	880-915	925-960	Europe, Asia
9	1749.9-1784.9	1844.9-1879.9	Japan
10	1710-1770	2110-2170	America
11	1427.9-1452.9	1475.9-1500.9	Japan
12	698-716	728-746	USA
13	777-787	746-756	USA
14	788-798	758-768	USA
15	1900-1920	2600-2620	---
16	2010-2025	2585-2600	---
17	704-716	734-746	USA
18	815-830	860-875	Japan
19	830-845	875-890	Japan
20	832-862	791-821	Europe
21	1447.9-1462.9	1495.9-1510.9	Japan
22	3410-3500	3510-3600	---

23	2000-2020	2180-2200	---
24	1625.9-1660.9	1525-1559	---
25	1850-1915	1930-1995	---
26	859-894	814-849	---
27	852-869	807-824	---
28	758-803	703-748	---
33	1900-1920	1900-1920	Europe, Asia (no Japan)
34	2010-2025	2010-2025	Europe, Asia
35	1850-1910	1850-1910	America
36	1930-1990	1930-1990	America
37	1910-1930	1910-1930	---
38	2570-2620	2570-2620	Europe
39	1880-1920	1880-1920	China
40	2300-2400	2300-2400	Europe, Asia
41	2496-2690	2496-2690	USA
42	3400-3600	3400-3600	---
43	3600-3800	3600-3800	---
44	703-803	703-803	---

TABLE II
FEATURES OF LTE AND LTE-A TECHNOLOGY

Features	LTE	LTE-A
Multiple access	Forward Link: OFDMA	FL: OFDMA
	Reverse Link: SC-FDMA	RL: The single-carrier property is not conserved for SC-FDMA uplink
Carrier spacing (MHz)	1.4,3,5,10,15,20	Additionally, it supports up to 100MHz and 40 MHz, in the downlink and uplink, respectively, with carrier integration
Duplexing	FDD, TDD, half-duplex FDD	FDD, TDD, half-duplex FDD
Mobility (km/h)	500	500
Modulation	FL: QPSK, 16-QAM, 64-QAM	FL: QPSK, 16-QAM, 64-QAM, 256-QAM
	RL: QPSK, 16-QAM, 64-QAM (Optional)	RL: QPSK, 16-QAM, 64-QAM (Optional)
MIMO	FL: 2 x 2, 4x2, 4x4	FL: up to 8x8
	RL: 1x2, 1x4	RL: up to 4x4
Peak data rate	FL: 150 Mbps (2x2 MIMO, 20MHz), 300 Mbps (4x4 MIMO, 20 MHz)	FL: 3 Gbps (8x8 MIMO, 100 MHz)
	RL: 75 Mbps (20 MHz)	RL: 500 Mbps (4x4 MIMO, 40 MHz)
Latency (ms)	≈ 10	< 5