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Analytical Review of Orthogonal Frequency Division Multiplexing (OFDM)

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***Abstract*— From high speed internet and broadband connections to HD digital TV transmission, humans have experienced a roller coaster ride development in every phase of life. Mobile communication has become a part and parcel of life. Telecom companies are developing newer ideas in providing better and better services to each customer. Various techniques have been proposed by various genres in order to support insatiable thirst of high speed data. This paper addresses the transmission technique known as Orthogonal Frequency Division Multiplexing (OFDM) which has the potential to support the increasing communication demands. It is said to be the de facto air-interface of most modern wireless broadband standards including 3GPP Long Term Evolution (LTE) and WiMAX. The paper starts with a brief introduction to the OFDM. Later, its strengths and weaknesses are discussed. An application point of view of OFDM is also presented in this paper.**

***Index Terms*— Intersymbol interference (ISI), Long Term Evolution (LTE), Orthogonal Frequency Division Multiplexing (OFDM), Peak to Average Power Ratio (PAPR), Worldwide Interoperability for Microwave Access (WiMAX).**

I. Introduction

In today's world, the demand to provide high bit rate and better coverage in hostile environments is of prime importance. With such bandwidth demands in communication systems, new transmission formats like OFDM has gained lot of popularity. Orthogonal Frequency Division Multiplexing (OFDM) modulation technique and associated Orthogonal Frequency Division Multiple Access (OFDMA) channel access mechanism have become a major element in modern wireless broadband communication systems [1]. This is due to OFDM's spectral efficiency, achievable data rates, and robustness in multipath fading environments. Wireless Local Area Network (WLAN) technologies based on the IEEE 802.11a, 802.11g, 802.11n, 802.11ac, and 802.11ad standards all use OFDM. It is also used in Wireless Metropolitan Area Network (WMAN) technologies based on the IEEE 802.16d, 802.16e, and 802.16m standards [2]. In addition, Long Term Evolution (LTE), the leading cellular broadband technology, relies on OFDM for its air-interface become more popular in modern communication systems such as the worldwide interoperability for microwave access (WiMAX) and digital video broadcasting (DVB).

Multicarrier communication systems were first introduced in the 1960s, with the first OFDM patent being filed at Bell Labs in 1966. Initially only analogue design was proposed, using banks of sinusoidal signal generators and demodulators to process the signal for the multiple subchannels [1]. In 1971, the use of the Discrete Fourier Transform (DFT) was proposed, which made OFDM implementation cost-effective. Further complexity reductions were realized in 1980 by the application of the Fast Fourier Transform (FFT) [12]. Following the development, OFDM then became the modulation of choice for many applications for both wired systems (such as Asymmetric Digital Subscriber Line (ADSL)) and wireless systems. Wireless applications of OFDM tended to focus on broadcast systems, such as Digital Video Broadcasting (DVB) and Digital Audio Broadcasting (DAB), and relatively low-power systems such as Wireless Local Area Networks (WLANs) [13]. Such applications benefit from the low complexity of the OFDM receiver, while not requiring a high-power transmitter in the consumer terminals. Despite the advantages of OFDM signals such as high spectral efficiency and robustness against intersymbol interference (ISI), the OFDM system is not devoid of disadvantages. It suffers from some severe disadvantages, for example, high PAPR, spectral leakage, sensitivity to offsets, etc [14].

A rich literature has been since the idea of OFDM came in vision. In [2], the authors have investigated many alternative modulation schemes which are actually variants of OFDM and have shown their potential to replace OFDM for radio systems. Considering their weak points, an improved FBMC/OQAM concept is proposed, which has proved to be able to maximize the benefits. In [3], the authors have reviewed the robustness of the existing OFDM waveform in the presence of noise, multipath fading, and interference**.** This paper has also investigated the robustness of OFDM under AWGN noise and noise-like jamming attack scenarios**.** In [4], the authors described the CR systems and their requirements to have a flexible physical layer. The authors have investigated orthogonal frequency division multiplexing (OFDM) technique as a candidate transmission technology for CR.OFDM-based CR system block diagram is given and interaction among different layers is also discussed. Various challenges that arise from employing OFDM in CR systems are identified. The cognitive properties of some OFDM-based wireless standards are also discussed in this paper. In [5], authors have briefly described OFDM for wireless communications. Estimation of channel coefficients and synchronization parameters are mentioned as the two main challenges in realization of MIMO-OFDM systems which are practical. It is also mentioned that for exact estimation of fading channel status, it's necessary to keep the created frequency synchronously between transmitter and receiver uninterrupted. In [6], the authors have presented a descriptive survey on OFDM for wireless communications with an intention to cover almost every aspect. The authors mentioned OFDM as a special form of multicarrier modulation (MCM) and gave a basic description of OFDM along with its use to deal with impairments in wireless systems, including channel estimation, timing-offset and frequency-offset estimation, ICI mitigation, and PAPR reduction. The authors also introduced related modulation and access schemes. The authors also summarized the MIMO techniques for OFDM and the wireless applications of OFDM. In [7], a reference symbol is proposed and a range of correlation techniques are suggested for coarse and fine synchronization. Their performance is studied over time-dispersive Rayleigh fading channels, with the conclusion that the proposed synchronization techniques result in virtually unimpaired BERs over the range of wideband channels investigated in comparison to a perfectly synchronized system. In [8], the authors have discussed that high peak-to-average power ratio of the transmit signal is a major drawback of multicarrier transmission. This paper has described some of the important PAPR reduction techniques for multicarrier transmission including amplitude clipping and filtering, coding, partial transmit sequence, selected mapping, interleaving, tone reservation, tone injection, and active constellation extension.

In this paper, an insight description of OFDM is given with brief description of applications at the end.

II. OFDM (ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING)

OFDM is a special case of broadband multicarrier modulation method. A simple illustration of multicarrier modulation is shown in figure 1. The principle of multi-carrier transmission is to convert a serial high-rate data stream onto multiple parallel low-rate sub-streams. Each sub-stream is modulated on another sub-carrier. Since the symbol rate on each sub-carrier is much less than the initial serial data symbol rate, the effects of delay spread, i.e., ISI, significantly decrease, reducing the complexity of the equalizer [1].

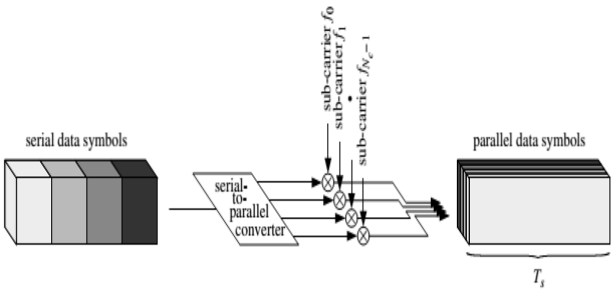

Fig.1 Multi-carrier modulation with Nc = 4 sub-channels

The principle of multi-carrier transmission is to convert a serial high-rate data stream onto multiple parallel low-rate sub-streams. Each sub-stream is modulated on another sub-carrier. Since the symbol rate on each sub-carrier is much less than the initial serial data symbol rate, the effects of delay spread, i.e., ISI, significantly decrease, reducing the complexity of the equalizer [2]. OFDM is a low-complex technique to efficiently modulate multiple sub-carriers by using digital signal processing. Based on this basic idea of multicarrier modulation, OFDM technique separates the main channel into a lot of orthogonal sub-channels, in which a higher rate single data stream is transmitted over a number of lower rate subcarriers [3]. Actually, OFDM distribute the data over a large number of carriers that are spaced apart at precise frequencies. This spacing provides the 'orthogonality' in this technique which prevents the demodulators from seeing frequencies other than their own.

OFDM is probably one of the most striking advances in transmission technologies. It facilitates higher transmission rates with a reasonable equalization and detection complexities. This high transmission is achieved through modulating a set of narrowband orthogonal subcarriers. In particular, an OFDM block is built as shown in Figure 2. The sequence of L modulated symbols, $x_0, x_1, \dots \dots x_{L-1}$ are converted into L parallel streams before taking the N -point Inverse Fast Fourier Transform (IFFT) of each. The possible mismatch between L and N is overcome by zero padding the remaining $N-L$ inputs of the IFFT block. Next, the N outputs, $s_0, s_1 \dots \dots . s_{N-1}$ are converted back to a serial stream before adding the Cyclic Prefix (CP).

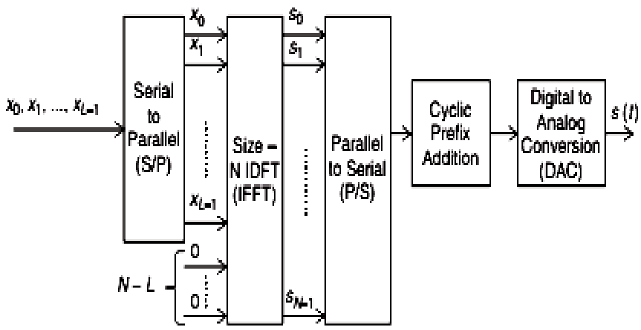

Fig. 2 OFDM Transmitter

Finally, the resulting OFDM block is converted to its analog form prior to sending it over the channel. Using this architecture, an OFDM block can resist the Inter-Carrier Interference (ICI) by employing orthogonal subcarriers, that is, as a result of using the IFFT. It is also capable of mitigating the channel time dispersion by inserting the CP [3].

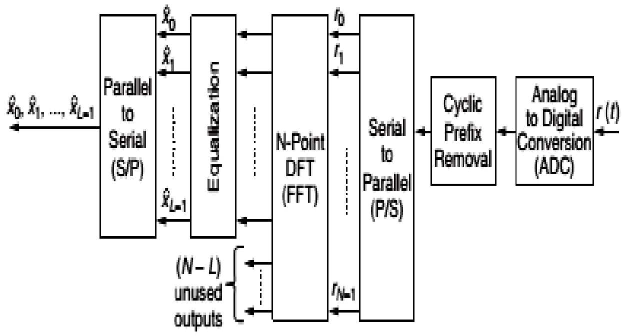

Fig 3. OFDM receiver

In fact, the insertion of the CP is a widely used technique to create a so called guard period between successive OFDM symbols. The CP is simply a repetition of the last part of the preceding OFDM symbol. The length of this repetition is made long enough to exceed the channel delay spread, hence mitigating the channel delay spread causing Inter-Symbol-Interference (ISI) [1]. In addition, the detection process turns to a circular convolution process which enhances the signal detection capabilities and simplifies the equalization process. OFDM demodulation reverses the aforementioned processes. After converting the received signal back into the digital domain, the CP is removed. Next, the signal is converted into a parallel *N* data streams before performing an *N* –point FFT. Finally, the sequence is returned back into a serial one as shown in Fig 3.

In practice, OFDM systems are implemented using a combination of fast Fourier Transform (FFT) and inverse fast Fourier Transform (IFFT) blocks that are mathematically equivalent versions of the DFT and IDFT, respectively, but more efficient to implement. An OFDM system treats the source symbols (e.g., the QPSK or QAM symbols that would be present in a single carrier system) at the transmitter as though they are in the frequency-domain. These symbols are used as the inputs to an IFFT block that brings the signal into the time domain. The IFFT takes in N symbols at a time where N is the number of subcarriers in the system. Each of these N input symbols has a symbol period of T seconds. Recall that the basis functions for an IFFT are N orthogonal sinusoids. These sinusoids each have a different frequency and the lowest frequency is DC. Each input symbol acts like a complex weight for the corresponding sinusoidal basis function. Since the input symbols are complex, the value of the symbol determines both the amplitude and phase of the sinusoid for that subcarrier. The IFFT output is the summation of all N sinusoids. Thus, the IFFT block provides a simple way to modulate data onto N orthogonal subcarriers. The block of N output samples from the IFFT make up a single OFDM symbol. At the receiver, an FFT block is used to process the received signal and bring it into the frequency domain. Ideally, the FFT output will be the original symbols that were sent to the IFFT at the transmitter [7].

III. ADVANTAGES AND DISADVANTAGES OF OFDM

The following description gives information about the strengths which make OFDM an interesting transmission medium and the weaknesses which degrade system performances in practical implementations.

A. Advantages of OFDM

OFDM is the basic transmission medium in various modern technologies. This is because of the numerous advantages of this technique [6].

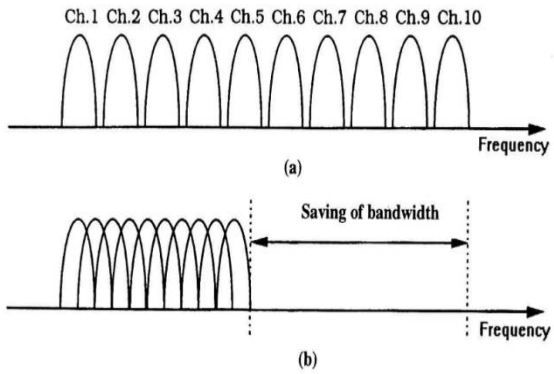

Fig 4 (a) Conventional Multicarrier Modulation
(b) OFDM

The reason to choose OFDM is that bandwidth can be saved. OFDM obviously can be compared with the conventional non-overlapping multi-carrier technique. As is shown in Fig 4, almost 50% of the bandwidth can be saved by using OFDM. The orthogonal nature of sub-carriers has helped in increasing bandwidth efficiency. In other words, overlapping is useful here only due to orthogonal nature of sub carriers. The orthogonality of the carriers means that each carrier has an integer number of cycles over a symbol period. Due to this integer number of cycles, the spectrum of each carrier has a null at the center frequency of each of the other carriers in the system that results in no interference between the carriers, allowing them to be spaced as close as possibleFig 5 presents the spectra of subcarriers showing how these sub carriers overlap.

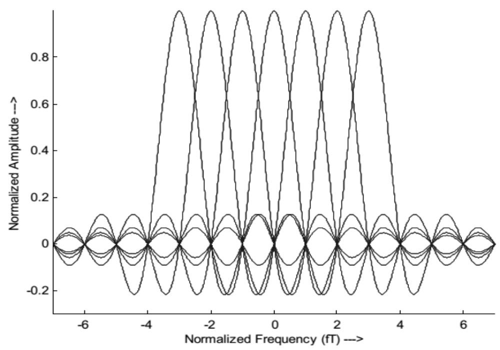

Fig 5. Spectra of individual sub carriers

OFDM plays an important role in broadband communications due to its ability to mitigate the intersymbol interference (ISI), intercarrier interference (ICI) and provide high spectral efficiency. One of the key strengths of OFDM is its ability to handle multipath propagation. It is capable of combating multipath fading with greater robustness and less complexity [7]. ISI caused by multipath propagation is less of a problem with OFDM because low data rates are carried by each carrier. Since low symbol rate modulation schemes (i.e., where the symbols are relatively long compared to the channel time characteristics) suffer less from ISI, it is advantageous to transmit a large number of low-rate streams in parallel instead of a single high rate stream. Since the duration of each symbol is long, it is feasible to insert a guard interval (GI) between the symbols. Using a cyclic prefix (CP) greater than the coherence bandwidth during the GI ensures eliminating most ISI. However, it comes at the price of spectral efficiency. OFDM system, due to avoidance of ISI, can easily adapt to severe channel conditions without the need for complex channel equalization algorithms being employed. For example, frequency-selective fading caused by multipath propagation can be considered as constant (flat) over an OFDM subchannel if the sub-channel is sufficiently narrow-banded. This makes frequency domain equalization possible at the receiver, which is simpler than the time domain equalization used in conventional single-carrier modulation. OFDM waveforms are also resilient when combating narrowband co-channel interference (CCI) [1][6].

The above mentioned advantages can be summarized as under

- Spectrally efficient transmission scheme
- Robust against frequency selective fading
- Capability to combat multipath fading
- Resistant to Inter symbol interference (ISI) and inter frame interference (IFI) by using cyclic prefix (CP).
- Compatible with utilizing frequency diversity.
- Computationally efficient with FFT techniques
- Simple digital realization by using the FFT operation
- Low complex receivers due to simpler equalization needed.
- Flexible spectrum adaptation can be realized
- Different modulation schemes can be used on individual sub-carriers which are adapted to the transmission conditions on each sub-carrier

B. *Disadvantages of OFDM*

Despite the many advantages of OFDM, actual implementations revealed some challenges. It has been found that that OFDM technique is sensitive to carrier frequency offset and time-varying channels [7].The orthogonality of OFDM relies on the condition that transmitter and receiver operate with exactly the same frequency reference. If this is not the case, the perfect orthogonality of the subcarriers is lost, causing subcarrier leakage, also known as Inter-Carrier Interference (ICI). Frequency errors typically arise from a mismatch between the reference frequencies of the transmitter and the receiver local oscillators. This difference between the reference frequencies is widely referred to as Carrier Frequency Offset (CFO). OFDM system is also affected by time offset. Actually a tight timing and frequency synchronization is needed. Frame synchronization at receiver side is needed to make a decision about the starting time of the FFT symbol. Errors in frame synchronization can cause ISI and intercarrier interference (ICI) in OFDM systems. In order to minimize these interferences detection of the carrier frequency of the received signal and finding the start point of the OFDM symbols are required. Therefore it is an essential requirement for the OFDM systems to have frame synchronization. Further, as we know the typical OFDM system has smaller subcarrier spacing and these can be vulnerable to Doppler shift observed in high mobility situations. Doppler shift can cause significant ICI [1][14].

Among all these disadvantages, the most famous one is the high Peak to Average Power Ratio (PAPR) problem. This high PAPR results from the coherent addition of the modulated subcarriers. This high PAR of OFDM is one of the most important implementation challenges because it reduces the efficiency. When transmitted through a nonlinear device, such as a high-power amplifier (HPA) or a digital-to-analog converter (DAC), a high peak signal generates out-of-band energy (spectral regrowth) and in-band distortion (constellation tilting and scattering) [8]. These degradations may affect the system performance severely. The nonlinear behavior of an HPA can be characterized by amplitude modulation/amplitude modulation (AM/AM) and amplitude modulation/phase modulation (AM/PM) responses. Fig 6 shows a typical AM/AM response for an HPA, with the associated input and output back-off regions (IBO and OBO, respectively). To avoid such undesirable nonlinear effects, a waveform with high peak power must be transmitted in the linear region of the HPA by decreasing the average power of the input signal. This is called (input) backoff (IBO) and results in a proportional output backoff (OBO). High backoff reduces the power efficiency of the HPA and may limit the battery life for mobile applications. In addition to inefficiency in terms of power, the coverage range is also reduced. Further, a high PAPR requires high resolution for both the transmitter's DAC and the receiver's ADC, since the dynamic range of the signal is proportional to the PAR. High-resolution D/A and A/D conversion places an additional complexity, cost, and power burden on the system [8].

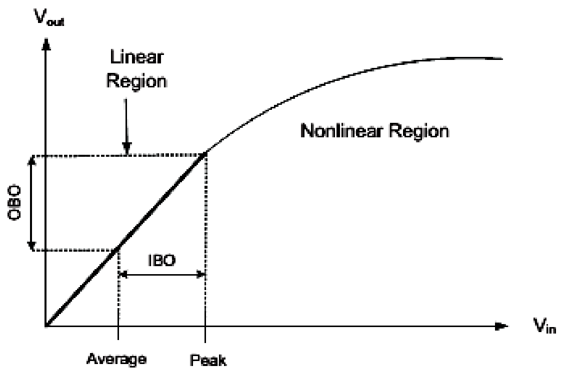

Fig. 6 A typical power amplifier response

These disadvantages can be summarized as under

- Loss in spectral efficiency due to the guard interval.
- Sensitive to frequency offset and time offset.
- More sensitive to Doppler spreads then single-carrier modulated systems.
- Phase noise caused by the imperfections of the transmitter and receiver oscillators influence the system performance.
- Accurate frequency and time synchronization is required.
- Accurate frame synchronization is needed
- More sensitive to frequency offset an Doppler spread

- High PAPR reduces system performance.

IV. Applications of OFDM

OFDM is the key element of many wireless communication standards such as third generation project (3GPP) long-term evolution (LTE) and digital video broadcasting [10]. OFDM has been successfully used in DAB and DVB systems. For DAB, OFDM forms the basis for the Digital Audio Broadcasting (DAB) standard in the European market. For ADSL, OFDM forms the basis for the global ADSL (Asymmetric Digital Subscriber Line) standard. For Wireless Local Area Networks, development is ongoing for wireless point-to-point and point-to-multipoint configurations using OFDM technology. In a supplement to the IEEE 802.11 standard, the IEEE 802.11 Working Group published IEEE 802.11a which outlines the use of OFDM in the 5.8 GHz band. Fixed wireless broadband over a short distance is provided by Wi-Fi, which uses OFDM in versions IEEE 802.11a, 802.11g, 802.11n, and 802.11ac. For fixed wireless broadband over long distance, the IEEE 802.22 standard describes an OFDM based Wireless Regional Area Network (WRAN) which utilizes white spaces in the TV frequency bands. In terms of cellular technologies, OFDM is the transmission scheme of choice in the physical layer of the worldwide interoperability for microwave access (WiMAX) and long term evolution (LTE) standards This technology is starting to play an important role in development of fourth-generation networks [11].

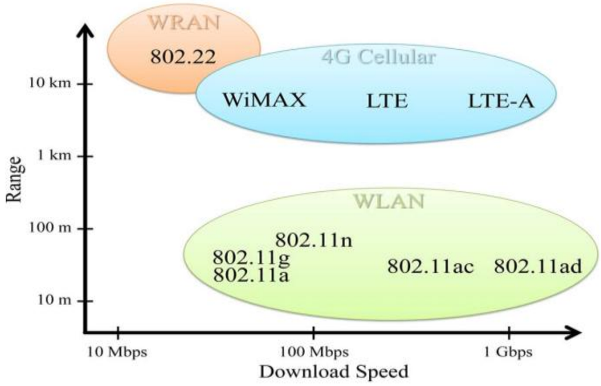

Fig. 7 OFDM-based wireless broadband technologies, mapped according to typical range and data rate

Fig. 7 illustrates OFDM-based technologies used to provide wireless broadband over a variety of distances. Thus, one can OFDM is making its way in almost every newer communication techniques, for example, IEEE 802.11a , IEEE 802.11g for high bit rate data transmission over wireless LANs, European HIPERLAN/2 , Japanese multimedia mobile access communications (MMAC) etc. It has also been used by a variety of commercial applications such as digital subscriber line (DSL), digital video broadcast handheld (DVB-H) and MediaFLO. OFDM is also considered as the transmission technique of Cognitive Radio Systems which have the potential to sense the radio environment and provide accessibility of the underutilized bands to the unlicensed users. Thus, OFDM in the form of cognitive radio has a promising potential to alleviate the apparent spectrum scarcity.

V. Conclusion

OFDM is the most potential transmission scheme capable to support the insatiable thirst of high speed data. It is a multicarrier modulation in which high speed data stream is split into low speed data stream leading to formation of a spectrally efficient transmission schemes. This paper presents a brief idea of OFDM and its features. OFDM finds its use in various modern communication technologies as mentioned in this paper. It is the universally acclaimed truth that OFDM is the future of communication technologies like cognitive radio network, but the some inherent disadvantages of OFDM pose severe challenge.

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REFERENCES

[1] Hermann Rohling "OFDM: Concepts For Future Communication Systems", Springer, 2011
[2] Hao Lin and Pierre Siohan, "An Advanced Multi-carrier Modulation for Future radio Systems", IEEE International Conference on Acoustic, Speech and Signal Processing (ICASSP), 2014
[3] Chowdhury Shahriar et al., "PHY-Layer Resiliency in OFDM Communications: A Tutorial", IEEE Communication Surveys & Tutorials, Vol. 17, No. 1, First Quarter 2015
[4] Hisham A. Mahmoud, Tevfik Yucek, and Huseyin Arslan "OFDM for Cognitive Radio: Merits and Challenges", Department of Electrical Engineering, University of South Florida
[5] Navid Daryasafar "OFDM and its Applications in Multi-Antenna Systems: A Survey", Journal of Basic and Applied Scientific Research, 2(10)9950-9960, 2012
[6] Taewon Hwang et al., "OFDM and Its Wireless Applications: A Survey", IEEE Transactions on Vehicular Technology, Vol. 58, No. 4, May 2009
[7] Thomas Keller et al., "Orthogonal Frequency Division Multiplex Synchronization Techniques for Frequency-Selective Fading Channels", IEEE Journal on Selected Areas in Communications, Vol. 19, No. 6, June 2001
[8] Seung Hee Han et al., "An Overview of Peak-to-Average Power Ratio Reduction Techniques for Multicarrier Transmission", IEEE Wireless Communications , April 2005
[9] Yasir Rahmatallah,, Seshadri Mohan, "Peak-To-Average Power Ratio Reduction in OFDM Systems: A Survey And Taxonomy", IEEE Communications Surveys & Tutorials, May 2013
[10] J Vijay Franklin et al., "3GPP: LTE- An Innovative Technology Towards 4G Wireless Networks", Proceedings of 1st Annual International Interdisciplinary Conference, Portugal, *AIIC 2013*, 24-26 April, 2013
[11] David Astély et al., "LTE: The Evolution of Mobile Broadband", IEEE Communications Magazine, April 2009
[12] Ajay R. Mishra, " Cellular Technologies For Emerging Markets, Wiley Publications, 2010
[13] Henrik Schulze, Christian Luders, "Theory and Applications of OFDM and CDMA", Wiley Publications, 2005
[14] Ramjee Prasad, "OFDM for Wireless Communications Systems", Artech House, Inc., London, 2004