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Suitability of OFDM in 5G Waveform - A Review

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Abstract

Systematic pursuits are being developed to set forth the framework for the Fifth Generation (5G) wireless standards. This paper emphases on the most extensively deployed technology - Orthogonal Frequency Division Multiplexing (OFDM) that has outpaced other waveform aspirants for Fourth Generation (4G) communication standards. Irrespective of the beneficial features, it does possess a number of significant limitations that mark it as an incompatible candidate for the upcoming 5G standard. This paper highlights on its major drawback i.e high Peak-to-Average Power Ratio (PAPR). Results state that PAPR does cause sudden upsurge to the output signal envelope causing further other damages. There exists a need for more flexible waveforms to replace the conventional OFDM in order to address the unprecedented challenges. The future research directions in the domain are presented.

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Orthogonal Frequency Division Multiplexing;
PAPR;
Peak to Average Power Ratio;
Wireless Technology;
5G.

Introduction

Exploration as well as upgradation to 5G mobile wireless technologies have been the current topic of research in both the academia and industries. Though Code-Division Multiple Access (CDMA) was used extensively in the Third Generation (3G) technologies, it had certain disadvantages like Inter-Symbol-Interferences and High power consumptions. The CDMA was replaced with OFDM as it possessed higher ease of implementation, resistant to external interference with faster high data-rate. The OFDM is a multicarrier orthogonal digital communication scheme , it divides the whole available bandwidth into many streams of low data rates that are then modulated simultaneously by multiple carriers. The modulation schemes deployed defines the spectral efficiency and application of the waveform in wireless communication standards.[1]

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The OFDM enjoys superiority in a number of technological and performance aspects. To mention a few, it has lowest complexity when compared to other waveforms due to the use of Fast Fourier Transform (FFT) / Inverse Fast Fourier Transform(IFFT), highest bandwidth efficiency, higher resistance to frequency selective fading, exceptional symbol structure and simplified synchronization. The OFDM does possess two major drawbacks, very high Peak to Average Power Ratio and Out-Of-Band (OOB) emissions that significantly reduce system performance and throughput. Others include Cyclic Prefix and bigger side lobes that limits the spectrum efficiency. Even though OFDM marks a tremendous leap in the technological advancement in 4G, the above mentioned defects overshadows it to be deployed for 5G standards.

Research studies show the proposal and development of other multicarrier waveforms in recent years to improve PAPR and OOB emissions for 5G. This paper provides the flaws in the design of OFDM system and the current research trend in this field. Section 2 provides the historical development of OFDM. Section 3 briefly explains OFDM system model. The problems and issues related with OFDM are discussed in Section 4. Finally, Section 5 concludes with future scope.

Developments in OFDM

Classical Multicarrier Communication (MCC) systems KINEPLEX and KATHRYN were initially developed by armed forces during the 1950s. The OFDM in its initial stages lacked of technology to support high integrated electronic circuitry, thus was not deployed for broadband services. The OFDM transmitted data on non-overlapping orthogonal signals that were band limited in nature. The circuitry required the need for analog filters of larger bandwidth with severe cut-off frequency. Subcarrier were recovered at the receiving end with inter-carrier interference. Hence, OFDM had not gained much attention then. But, during the 1960s, several studies[2 - 4] were dedicated to develop overlapped band-limited orthogonal signals. Research study[5] developed a multicarrier communication system deploying Quadrature Amplitude Modulation in OFDM with time-staggered carriers. The research work of Chang[3] and other scholars in 1966 dealt with the fundamental formulation of OFDM concept that had brought RF communication standards to a new realm.

In January 1970, the concept of OFDM was the first name patented in United States of America.[6] In 1971, implementation of Discrete Fourier Transform (DFT)/Inverse Discrete Fourier Transform (IDFT) with integrated circuit technology to transmit orthogonal signals was brought OFDM to lime light.[7-8] Subcarrier oscillators at the transmitter and receiver were significantly reduced further enhancing the ease of the implementation in OFDM at reduced cost.

During 1980s research works proposed the structure of DFT for OFDM to be used specially for high-speed digital wireless communication. Among those works, there was a work of Hirosaki,[9] who proposed enhanced work of Saltzberg's OFDM/OQAM system, and also a US patent in June 1980 that deployed OFDM in high speed modems.[10] Further, in 1985, Cimini[11] delivered simulation analysis on OFDM in mobile communication and critically praised its impressive performance. Semiconductor industries' revolutionary growth had given much opportunities and challenges.[12 - 15]

The Broadband applications and evolution in Very-Large-Scale Integrated circuits (VLSI) and Complementary Metal–Oxide–Semiconductor (CMOS) chips in the 1990s, further dominated by OFDM in the market. The acceptance of OFDM by the European Digital Audio Broadcasting (DAB) standard defies the milestone achievement for its widespread commercial implementation in all domains. The suitability of OFDM system in different environments experimentally over frequency selective channel with Rayleigh fading was the scope of the research which were presented by researchers.[16 - 18] Further, the research works[19 - 21] conducted the OFDM system performance in different channel conditions with offset in frequency. To brief it all, this technology from 1960s, improved from a mere mathematical model to implementation in the 90s, thanks to technological progress implementing DFT in digital circuits. The 4G technology Long Term Evolution (LTE) deploys OFDM wherein large closely set orthogonal subcarriers carry data.[22] Even though sidebands from carriers overlap, the received signal is detected without interference due to their orthogonal positioning with each other. Guard bands are not needed to separate subcarriers. A cyclic prefix is added to the end of each OFDM symbol to maintain he orthogonality in the sub-carriers.

Modelling of OFDM System

The OFDM make use of a sophisticated divide-and-conquer methodology to transmit high speed frequency-selective channels.[23] It is a multicarrier block modulation scheme wherein the whole available bandwidth is divided into different sequence of symbols of low data rates and then modulated simultaneously by multiple partially overlapped subcarriers which are orthogonal to each other and transmitted in parallel form to achieve high aggregate data rates and bandwidth efficiency. Flat frequency response is generated in individual sub-carriers with constricted bandwidth in sub-channel, avoiding complex equalization in time-domain. Thus, frequency-selective channel is transformed into individual flat-fading channel enhancing receiver signal[9] robust to multi-path fading and bit error rate. Orthogonality[5] in the carriers also eliminates the inter-carrier interference. Insertion of spectral guard bands for partially overlapped sub-carriers provides higher spectral efficiency with respect to conventional Frequency Division Multiplexing (FDM). Digital data is transformed and mapped in accordance to sub-carrier amplitude and phase. Spectral data in mapped to the time domain using Inverse Discrete Fourier Transform. The implementation of IFFT in place of IDFT further adds to computational efficiency at the cost slight increase in operational infrastructure. Hence IFFT/FFT is now deployed in all practical systems. Reverse operation is performed at the receiver section, where RF signals are added to baseband proceeded by FFT that analyses the the received signal in frequency domain. Digital data is generated out of the subcarrier's amplitude and phase. FFT and IFFT are complementary in nature[24] (see Figure 1).

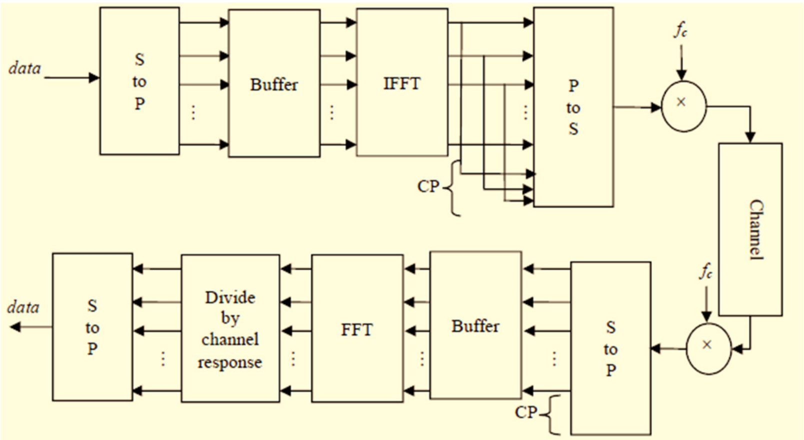

Fig.1: Block Diagram of OFDM24

Explaining mathematically,[25] high-data-rate bit stream of frequency bandwidth B is de-multiplexed into M lower-rate streams that modulate M equally spaced subcarriers that are non-overlapped orthogonal where $B=M\Delta f$ and $\Delta f=1/MT$. Each sub-carrier of a given OFDM symbol is modulated by a known constellation. The input data symbols in frequency domain $A= [A_0, A_1, A_2,....,A_{m-1}]^T$ where A_n characterizes complex information of the m^{th} sub-channel. After performing M length IFFT on *a'*, we obtain time domain OFDM sequences $y= [a, a_1, a_2,....,a_{m-1}]^T$ where $\Delta f = 1 / MT$ the subcarrier spacing[6] is.

$$x(t) = \frac{1}{\sqrt{M}} \sum_{m=0}^{M-1} A_m . e^{j2\pi\Delta f t}; 0 \le t \le MT \qquad ...(1)$$

Multi-level modulation,[26] M-ary QAM, may be deployed in Single-Carrier modulation, Frequency Division Multiplexing and OFDM. If we consider f_1 be the sinusoidal complex Quadrature Amplitude

Modulated character, X_i- jY_i, where values of X_i and Y_i depends on constellation of QAM, signal can be expressed as:

$$a_1(t) = X_1 \cos(2\pi f_1 t) - X_1 \sin(2\pi f_1 t) \quad ...(2)$$

In-phase and quadrature portions of signal are denoted by the two terms respectively $a_1(t)$ and $a_2(t)$, where $a_2(t)$ is signal modulated by QAM on sub-carrier f_2, can be ensured to be orthogonal by satisfying the following condition.

$$\int_0^T a_1(t)a_2(t)dt = 0 \quad ...(3)$$

Condition must validate for all $a_n(t); a_m(t), n=0,1,2,3\ldots N-1; m=0,1,2,3\ldots N-1; n\neq m$. Validation of the condition ensures generation of orthogonal OFDM signals. It satisfies only when the subcarrier frequencies are integer multiples over the symbol time as

$$f_n = n/T+f_{RF} n = 0,1,2\ldots N-1 \quad ...(4)$$

In Equation (4), the term f_{RF} denotes different radio frequencies.

Substituting Equation (2) into (3) for all $s_n(t)$, $s_m(t)$, $n \neq m$ and, it can readily be shown that all subcarriers will indeed be orthogonal to each other, in the same frequency space without interfering stating the possibility of partially overlap of OFDM subcarriers in frequency devoid of interference. Adding equations (2), (4) combines to give us the complete electrical OFDM signal as follows in Equation (5) wherein $g(t)$ represents impulse response of baseband pulse

$$a_{OFDM}(t) = \sum_{n=0}^{N-1} A_n g(t)\cos(2\pi f_n t) - B_n g(t)\sin(2\pi f_n t) \quad ...(5)$$

5G and OFDM - Drawbacks and Issues

The big difference between 5G and its previous generations lies in the fact that 3G and 4G focused high mobility to be an afterthought. However, in 5G communication high mobility is treated as an integral part of communication and network architecture design. Even though systems using OFDM have grown importance in recent years, OFDM faces many challenges in the aspect of its adoption in wireless networks. One of the biggest hurdles in OFDM is PAPR, which significantly reduces the performance, spectral characteristics, and efficiency. Literature review[27] reveals significant drawbacks in OFDM. Firstly, PAPR problem arises when sinusoidal signals of OFDM subcarriers constructively add in the time domain, resulting in sharp amplitude peaks higher than average amplitude of the signal. Also use of cyclic prefix or guard band, 10% of the bits are repeated which decreases spectral efficiency. Secondly, OFDM displays major amplitude fluctuations over time, generating a high peak-to-average power ratio. This is due to nonlinearity in amplifier at the transmitter. Thirdly, Gaussian amplitude distribution of the OFDM signal with large number of subcarriers results in transmitted signal with high peaks. Fourthly, Carrier and timing synchronization are challenging tasks. Lastly, Carrier Aggregation in OFDM-based systems that generated when digital data is transmitted in non-contiguous frequency ranges. Further, significant out of band noise is introduced in these systems, that pick-up interference from nearby channels. Because of these significant drawbacks, it does not appear that OFDM would continue to serve as a proficient technique for 5G communications.

Peak to Average Power Ratio (PAPR)

The OFDM signal is made up of several modulated sub-channels. In a situation, where M channels to get added in phase, a sudden shoot up in output envelope which causes a 'peak' power. The peak power is produced *M* times its usual power bringing about PAPR.[28] The PAPR is the ratio of peak power to the average power of a signal. It is expressed in the units of dB. Due to high peaks in a signal, the power amplifier goes to its non-linear region.

Since PAPR requires increased complex Digital to Analog Convertor and High Power Amplifier to evade clipping of amplitude. Hence, power consumption and transceiver cost increases. Orthogonality is destroyed between carriers introducing intermodulation distortion. Adjacent channel interference increases degrading Bit Error Rate (BER) and battery life of mobile terminal. PAPR is more disastrous in uplink due to limited coverage, range and battery of mobile terminal. Therefore PAPR ought to be reduced for making the system efficient. Coverage and reliable power output remains the critical focus of study for tactical communications.[22] The peak to average power ratio for a signal is defined as,

$$PAPR_{dB} = 10 \log_{10} (P_{Peak}/P^{Avg}) \qquad ...(6)$$

Equation (7) describes OFDM signal as a sum of several sub-carriers saperated by frequency 1/*T*. Equations (8) and (9) denote the peak and average power of the output envelope respectively.

$$x(t) = \sum_{m=0}^{M-1} A_m . e^{j\frac{2\pi\Delta f t}{T}}; 0 \leq t \leq MT \qquad ...(7)$$

$$max[x(t)x^*(t)] = \max\left[\sum_{m=0}^{M-1} A_m . e^{j\frac{2\pi\Delta f t}{T}} \sum_{m=0}^{M-1} A_m{}^* . e^{j\frac{2\pi\Delta f t}{T}}\right]$$

$$= \max\left[A_m A_m{}^* \sum_{m=0}^{M-1} e^{j\frac{2\pi\Delta f t}{T}} . \sum_{m=0}^{M-1} e^{j\frac{-2\pi\Delta f t}{T}} .\right]$$

$$= K \qquad ...(8)$$

$$E[x(t)x^*(t)] = \mathrm{E}\left[\sum_{m=0}^{M-1} A_m . e^{j\frac{2\pi\Delta f t}{T}} \sum_{m=0}^{M-1} A_m{}^* . e^{j\frac{2\pi\Delta f t}{T}}\right]$$

$$= K \qquad ...(9)$$

Thus , PAPR of an OFDM signal with K subcarriers can be defined as:

$$PAPR = \frac{max[x(t)x^*(t)]}{E[x(t)x^*(t)]} = \frac{k^2}{k} = k \quad [where\ ()^* \ is\ the\ conjagate\ operator] \qquad ...(10)$$

The corresponding matlab script to simulate the average PAPR of an OFDM transmit waveform using BPSK modulator that contains 52 sub-carriers. In that case, the maximum expected PAPR should be 52 that amounts to 17dB.

```
Size_of_IFFT = 64;
No_of_Subcarriers = [-26:-1 1:26];
No_of_Bit = 10000;
ip = rand(1, No_of_Bit) > 0.5;
no_of_Bits_Per_Symbol = 52;
no_of_Symbols = ceil(No_of_Bit /no_of_Bits_Per_Symbol);

% In BPSK modulation, bit0 is assigned level --> -1; bit1 is assigned the level --> +1
ipMod = 2*ip - 1;
ipMod = [ipMod zeros(1, no_of_Bits_Per_Symbol* no_of_Symbols - No_of_Bit)];
ipMod = reshape(ipMod, no_of_Symbols, no_of_Bits_Per_Symbol);
st = []; % empty vector
for ii = 1: no_of_Symbols
input_of_iFFT = zeros(1, Size_of_IFFT);
input_of_iFFT (No_of_Subcarriers + Size_of_IFFT/2+1) = ipMod(ii,:);
input_of_iFFT = fftshift(input_of_iFFT);
output_of_iFFT = 64*ifft(input_of_iFFT, Size_of_IFFT);
output_of_iFFT_with_CP = [output_of_iFFT (49:64) output_of_iFFT];

% To compute the peak to average power ratio
Mean_Square_power = output_of_iFFT * output_of_iFFT'/length(output_of_iFFT);
Peak_Value_power = max(output_of_iFFT.*conj(output_of_iFFT));
Papr_value(ii) = Peak_Value_power / Mean_Square_power;
st = [st output_of_iFFT_with_CP];

end
close all
papr_in_dB = 10*log10(Papr_value);
[n x] = hist(papr_in_dB,[0:0.5:15]);
plot(x,cumsum(n)/ no_of_Symbols,'LineWidth',4)
xlabel('PAPR Value, x dB')
ylabel('Probability of occurance, X <=x')
title('CDF plots of PAPR tx with BPSK Modulator based on IEEE 802.11a')
grid on
```

The corresponding CDF plot obtained is as follows. Its states that the PAPR varies around +3.5dB to a extreme limit of 10dB.

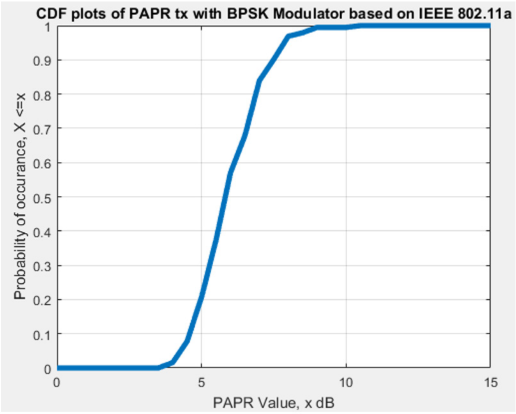

Fig. 2: CDF plots of PAPR tx with BPSK Modulator

The PAPR reduction technique in commercial communication structures is vital to save power and enhance coverage gain. Considering the above facts, the sole purpose in the implementation of real time OFDM must be to reduce high PAPR. Research studies have taken the current imminent study in a vigorous manner and recommended various approaches. Waveform is the fundamental issue for 5G mm-wave communication. Key Performance Indicators (KPIs) such as computational complexity, filter length, PAPR, spectral efficiency and latency assess the 5G waveform candidates. An ideal waveform primarily has very low PAPR, very high spectral efficiency and data rate to allow power amplifier design; robust to Doppler shift and support asynchronous transmission. The current cutting edge research progresses towards reduction in PAPR in the 5G waveforms candidates that can be classified into two categories I.e Single carrier Waveforms and multi-carrier waveforms. Single carrier transmission uses single carrier is used to carry the information with broad spectrum. Multi-Carrier transmission uses *multiple carriers* at different frequencies, sending some of the bits on each channel. An in-depth survey in the following research papers[9, 18, 28, and 29] explains the differences between Single carrier and Multiple Carrier waveforms which is explicity explained in Tables I, II.

Table: 1 Advantages of Single Carrier vs Multicarrier Wavefroms

Advantages	SC Waveforms	MCM Waveforms
PAPR	Low	Very High
Code Rate	Very High	Low
Battery Life	Extended	Less
Synchronization	Simple	Complex

Table: 2 Disadvantages of Single Carrier vs Multicarrier Wavefroms

Complexity	SC Waveforms	MCM Waveforms
Complexity	High	Moderate
Resistance to Multi -Path Fading	Poor	Excellent
Phase Noise	Less Susceptible	More susceptible
Spectral Efficiency & Coverage	Low	High
MIMO Compatibility[30,31]	Low to moderate	Very high

Because Single Carrier Wavefroms has a very low PAPR, and extended battery life, current 4G LTE uses Discrete Fourier Transform spread OFDM (DFT-S-OFDM), a low PAPR SC variant of OFDM[30 - 33] for uplink communications and LTE-OFDM for downlink communication to reduce overall power consumption and increase coverage range. There lies two major future trends for conducting research in this domain. Firstly major research direction is the development of low-complexity OFDM-like multicarrier waveforms for downlink communication and variants of DFT-s-OFDM single carrier waveforms for uplink communication that derive efficient PAPR reduction in 5G.[34 - 38] The Single Carrier waveform include DFT-s-OFDM family such as Zero-Tail- (ZT) DFT-s-OFDM, Unique Word (UW) DFT-s-OFDM, Differential-QAM, Constrained Envelope-CPM-SC as well as DFT-s-FBMC and DFT-s-UFMC to name a few. DFT-s - Waveform unlike conventional OFDM first spread the input data with DFT block, then de-spread with IDFT block as shown in Figure 3. This simple architecture achieves major reduction in power consumption.

The Multi-Carrier waveforms consists of Cyclic Prefix OFDM (CP)-OFDM, Unique-Word OFDM (UW)-OFDM, Universal-Filtered OFDM (UF)-OFDM, Windowed-OFDM (W-OFDM), Filter Bank Multicarrier (FBMC), and Generalized-FDM (GFMC) among others. Secondly major research direction is the impemention of PAPR reduction methods for the above mentioned waveform variants to achieve desired results.

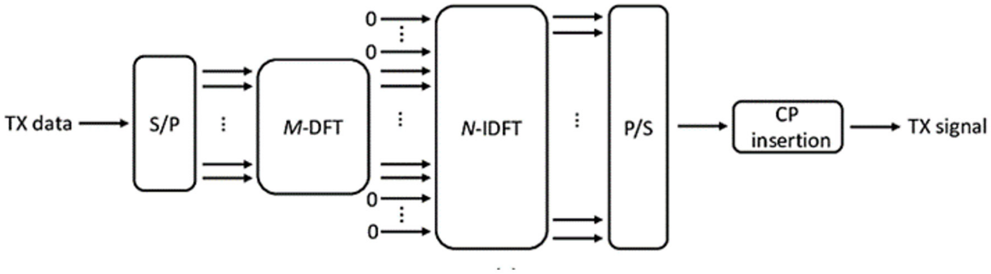

Fig. 3: Basic Block Diagram of DFT spread Waveforms

Conclusion

This paper presents a complete summary of OFDM, focusing the following issues such as technological ideologies, real-world dominance and challenges, current advancement and upcoming exploration in 5G standard. In overall, OFDM cannot be considered for 5G due to its serious drawbacks of transmitting highly correlated signals with very high PAPR. PAPR reduction is only possible at increased transmission power, reduced data loss, low BER performance, computational complexity. Hence, the subject of PAPR reduction is of eminent importance as the upcoming wireless standards are expected to develop new waveform candidates to eliminate the drawbacks of OFDM with better PAPR reduction.

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Conflict of Interest

All authors the authors declare that there is no conflict of interest.

Reference

1. Chen, D.; Tian, Y.; Qu, D.; Jiang, T.OQAM-OFDM For Wireless Communications In Future Internet Of Things: A Survey On Key Technologies And Challenges. *IEEE Internet*

Of Things Journal, Volume 5 (5), 2018, Pp. 3788 - 3809.

2. Chang, R. W. Synthfesis Of Band-Limited Orthogonal Signals For Multichannel Data Transmission, *Bell Syst. Tech. J.*, Volume 45, 1966, Pp. 1775 - 1796.
3. Chang, R. W.; Gibby, R. A. A Theoretical Study Of Performance Of An Orthogonal Multiplexing Data Transmission Scheme, IEEE Trans. Commun. Tech., Volume COM-16, 1968. Pp. 529 - 540.
4. Saltzberg, B. R. Performance Of An Efficient Parallel Data Transmission System, IEEE Trans. Commun. Tech., Volume COM-15, 1967, Pp. 805 - 813.
5. Marmuth, H. F. On The Transmission Of Information By Orthogonal Time Functions, Alee Trans. (Communication And Electronics), Volume 79, 1960, Pp. 248 - 255.
6. Orthogonal Frequency Division Multiplexing, U.S. Patent No. 3488445, Filed Nov. 14, 1966, Issued On Jan. 6, 1970.
7. Weinstein, S. B.; Ebert, P. M. Data Transmission By Frequency-Division Multiplexing Using The Discrete Fourier Transform, IEEE Trans. Commun. Tech., Volume COM-19, 1971, Pp. 628 - 634.
8. Ghani F.; Ahmad, A. Signal Design And Detection For A Class Of CDM Data Transmission System For Use Over Switched Telephone Networks, Proceedings Of IEEE 23rd Midwest Symposium On Circuits And Systems (CAS), Held At University Of Toledo (Ohio, USA), Aug.4 - 5, 1980, Pp. 7 – 12.
9. Hirosaki, B. An Analysis Of Automatic Equalizers For Orthogonally Multiplexed QAM Systems, IEEE Trans. Commun., Volume COM-28, 1980, Pp. 73 - 83.
10. Keasler, W. E.; Bitzer, D. L. High Speed Modem Suitable For Operating With A Switched Network, U. S. Patent No. 4206320, June 1980.
11. Cimini, L. J. Analysis And Simulation Of A Digital Mobile Channel Using Orthogonal Frequency Division Multiplexing, IEEE Trans. Commun., Volume COM-33 (7), 1985, Pp. 665 - 675.
12. Elgawi, O; Mutawa, A. M.; Ahmad, A. Energy-Efficient Embedded Inference Of Svms On FPGA, IEEE Computer Society Annual Symposium On VLSI, To Be Held At Miami, Florida, USA, 15-17 July 2019, Pp. 1 - 5.
13. Ahmad, A. (Keynote/Invited – Talk). Reliable And Fault Tolerant Systems On Chip Through Design For Testability", IEEE Conference: 2019 Amity International Conference On Artificial Intelligence – (AICAI'19), Amity University, Int'l Academic City, Dubai, UAE, Feb. 4 - 7, 2019, Pp. 50 - 53.
14. Ahmad, A. (Keynote/Invited – Talk). Challenges For Test And Fault-Tolerance Due To Convergence Of Electronics, Semiconductor Systems And Computing, IEEE Conference: 2017 International Conference On Infocom Technologies And Unmanned Systems (Trends And Future Directions) (ICTUS), Amity University, Int'l Academic City, Dubai, UAE, 18 - 20 Dec. 2017, Pp. 64 - 68.
15. Ahmad, A. Testing Of Complex Integrated Circuits (Ics) – The Bottlenecks And Solutions, *Asian Journal Of Information Technology,* Volume 4 (9), 2005, Pp. 816 – 822, 2005.
16. Bingham, J. A. C. Multicarrier Modulation For Data Transmission: An Idea Whose Time Has Come, IEEE Commun. Mag., Volume 28, 1990, Pp. 5 - 14.
17. Casas, E. F.; Cyril Lung. OFDM For Data Communication Over Mobile Radio FM Channels-Part I: Analysis And Experimental Results, IEEE Trans. Commun., Volume 39 (5), 1991, Pp. 783 - 793.
18. Casas, E. F.; Cyril Lung. OFDM For Data Communication Over Mobile Radio FM Channels-Part II: Performance Improvement, IEEE Trans. Commun., Volume 40 (4), 1992, Pp. 680 -683.
19. Sathananthan, K.; Tellambura, C. Probability Of Error Calculation Of OFDM Systems With Frequency Offset, IEEE Trans. On Commun. Volume 49 (11), 2001, Pp. 1884-1888.
20. Rugini, L.; Ban¬elli, P. BER Of OFDM Systems Impaired By Carrier Frequency Offset In Multipath Fading Channels, IEEE Trans. On Wireless Commun., Volume 4 (5), 2005, Pp. 2279 - 2288.
21. Dharmawansa, P.; Rajatheva, N.; Minn, H. An Exact Error Probability Analysis Of OFDM Systems With Frequency Offset, IEEE Trans. Commun., Volume 57 (1), 2009, Pp. 26-31.
22. Sandoval, F.; Poitau, G.; Gagnon, F. Hybrid

Peak-To-Average Power Ratio Reduction Techniques: Review And Performance Comparison, IEEE Access, 5, 2017, Pp. 27145 -27161.
23. Blouza, S.; Karaki, J.; Brochier, N.; Le Rouzic, E.; Pincemin, E.; Cousin, B. Multi-Band OFDM For Optical Networking, IEEE EUROCON - International Conference On Computer As A Tool, 2011.
24. Ghassan M. T. A. Orthogonal Frequency Division Multiplexing Theory And Challenges, *University Of Khartoum Engineering Journal,* Volume 1 (2), 2014, Pp. 1 - 8.
25. Goebel, B.; Hellerbrand, S.; Haufe, N.; Hanik, N. PAPR Reduction Techniques For Coherent Optical OFDM Transmission, 11th International Conference On Transparent Optical Networks, 2009. Doi:10.1109/ Icton.2009.5184979
26. Cvijetic, N. OFDM For Next-Generation Optical Access Networks. *Journal Of Lightwave Technology,* Volume 30 (4), 2012, Pp. 384 - 398.
27. Wang, Z.; Sun, E; Zhang, Y. An Overview Of Peak-To-Average Power Ratio Reduction Techniques For OFDM Signals, *International Journal Of Mobile Network Communications & Telematics*, Volume 6 (3), 2016, Pp. 1 - 20.
28. Zaidi, A. A.; Luo, J.; Gerzaguet, R.; Wolfgang, A.; Weiler, R. J.; Vihriala, J.; Miao, H. A Preliminary Study On Waveform Candidates For 5G Mobile Radio Communications Above 6 Ghz, 2016 IEEE 83rd Vehicular Technology Conference (VTC Spring). Doi:10.1109/ Vtcspring.2016.7504096
29. Elavarasan, P.; Nagarajan, G. A Summarization On PAPR Techniques For OFDM Systems, *Journal Of The Institution Of Engineers*, India. Series B, Volume 96 (4), 2014, Pp.381-389.
30. Khan, K.A.; Ahmad, A. On Multi-Port Active RC Synthesis Of A Current Gain Matrix With Grounded Ports, *Journal Of IETE*, Volume 25 (11), Pp. 445 - 449, Taylor & Francis Online (11 July, 2015).
Http://Dx.Doi.Org/10.1080/03772063.1979.11451977
Http://Www.Tandfonline.Com/Doi/Abs/10.1080/03772063.1979.11451977
31. Khan, K.A.; Ahmad, A. Active RC Multiport Synthesis Of A Current Gain Matrix - A Computer Aided Design, Proceedings Of 14th National System Conference (NSC-90), Held At Aligarh (India), March 12 - 14, 1991, Pp. 21 - 24.
32. Khan, K.A.; Ahmad, A. Active RC Multi-Port Synthesis Of A Transfer Admittance Matrix With Minimum Number Of Capacitors - A Computer Aided Design, Proceedings Of IEEE International Conference On Signals & Systems, Held At Al-Ain (UAE), Jan.29 - 31, 1990, Volume 2, Pp. 63 – 74.
33. Khan, K.A.; Ahmad, A. Active RC Multi-Port Synthesis Of A Transfer Admittance Matrix With Minimum Number Of Capacitors, Proceedings Of 14th Annual Allerton Conference On Circuits And Systems (CAS), Held At University Of Illinois (Urbana-Champaign, USA), Sept. 29 - Oct.1, 1976, Pp. 569 - 575.
Https://Squ.Pure.Elsevier.Com/En/Publications/Active-Rc-Multiport-Synthesis-Of-A-Transfer-Admittance-Matrix-Wit
34. Yekani, Amin, and Leslie A. Rusch. “Numerical Study of a Hybrid Optical DMT/DFT-S QAM Modulation.” *Journal of Lightwave Technology,* vol. 37, no. 3, 1 Feb. 2019, pp. 815–823, 10.1109/jlt.2018.2881380. Accessed 4 Aug. 2019.
35. Hossain, Md. Rabiul, and Kazi Tanvir Ahmmed. “Non-Linear Companding Based Hybrid PAPR Reduction Approach for DCT-SCFDMA System.” IET Communications, vol. 12, no. 12, 31 July 2018, pp. 1468–1476, 10.1049/iet-com.2017.0921. Accessed 4 Aug. 2019.
36. Nissel, Ronald, and Markus Rupp. “Pruned DFT-Spread FBMC: Low PAPR, Low Latency, High Spectral Efficiency.” IEEE Transactions on Communications, vol. 66, no. 10, Oct. 2018, pp. 4811–4825, 10.1109/tcomm.2018.2837130. Accessed 4 Aug. 2019.
37. Na, Donj-jun, and Kwonhue Choi. “New DFT-Spread Filter Bank Based Multi-Carrier Transmission.” *The Journal of Korean Institute of Communications and Information Sciences*, vol. 42, no. 7, 31 July 2017, pp. 1297–1305, 10.7840/kics.2017.42.7.1297.
38. An, Changyoung, and Heung-Gyoon Ryu. “PAPR Evaluation and Analysis of Candidate

Waveforms Using DFT Spreading for 5G Mobile Communications." *The Journal of Korean Institute of Electromagnetic Engineering and Science*, vol. 26, no. 12, 31 Dec. 2015, pp. 1091–1099, 10.5515/kjkiees.2015.26.12.1091.