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Demonstration of Effectiveness of OFDM for Mobile Communication Systems

Isiaka A. Alimi*

Department of Electrical and Electronics Engineering, School of Engineering and Engineering Technology, Federal University of Technology, Akure, Nigeria

Abstract

Orthogonal Frequency Division Multiplexing (OFDM) has been employed for broadband wireless transmission due to the related advantages such as robustness against multipath fading, high data rate and high spectral efficiency. However, the issue of the associated high peak-to-average power ratio (PAPR) needs further consideration to prevent intermodulation noise and out-of-band radiation between the OFDM subcarriers that bring about bit error rate (BER) degradation. High PAPR put a stringent need for linear power amplifier on the system and as a result, it causes an increase in the system cost. This paper focuses on experimental demonstration of effectiveness of OFDM in mobile communication systems. To investigate this, the performance of OFDM over both Rayleigh and additive white Gaussian noise (AWGN) channels is compared with the equalization schemes such as ZF and MMSE. Furthermore, the OFDM technical issue based on the associated PAPR and its reduction are investigated. The simulation results show that the OFDM scheme significantly reduced the effect of multipath fading in wireless communication systems with improved BER value. Also, it is observed that the selected mapping (SLM) scheme considerably reduce PAPR of OFDM signal.

Keywords

CCDF, OFDM, PAPR, PTS, SLM

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1. Introduction

There is exponential increase in the deployment and usage of various wireless devices and applications which demands for high performance, high capacity and reliable wireless communication systems. This bring about researches on viable ways for effective channel bandwidth utilization [1]. There are some generational networks such as 3G and 4G that have been developed and deployed to address the bandwidth demand, however, the quest for sufficient bandwidth to support the current and future demand lead to further researches on the feasible novel architectures and technologies that will address the envisioned capacity and service demands for 5G which is in the pipeline for deployment by 2020 [2], [3], [4]. One of the factors that determine the performance of wireless systems is the communication channel which is characterized by time varying propagation medium [5]. Also, because of dispersive nature of the wireless communication channel and the associated obstacles, impairments are introduced by lack of line-of-sight (LOS) and multiple reflection of radiated energy [1]. This result in multipath effects that lead to inter symbol interference (ISI) and eventually fading which not only cause signal degradation but also limits the speed and reliability of the system [6].

In order to address the demand of wireless communication systems, multi-carrier modulation schemes such as orthogonal frequency-division multiplexing (OFDM) have

* Corresponding author
E-mail address: compeasywalus2@yahoo.com

been proposed in the literature [7]. This scheme has the potential to address the issue of channel frequency selectivity as well as combating multipath fading effects [6], [8]. The implementation of OFDM has been shown in the literature to be a feasible solution to increase the system data rate by improving the bit error rate (BER) performance of the wireless communication systems [6], [8].

This paper focuses on experimental demonstration of effectiveness of OFDM in mobile communication systems. To investigate this, the performance of OFDM over both Rayleigh and additive white Gaussian noise (AWGN) channels is compared with the equalization schemes such as ZF and MMSE. Also, the OFDM technical issue based on the associated high peak-to-average-power ratio (PAPR) and its reduction are investigated. In the next section, the concept of multipath propagation in wireless communication systems is presented with extensive discussion on the categories of fading in the propagation channel. Section 3 discusses the principle of orthogonal frequency division modulation (OFDM) and its application in some wireless transmission standards. Section 4 presents the technical issue of OFDM and focuses on the mathematical descriptions of the associated high PAPR and its reduction. Section 5 contains simulation results and discussions with reference to the performance curves generated based on simulation models developed in MATLAB® and conclusions are drawn in Section.

2. Multipath Propagation

Multipath propagation occurs when multiple radio signals emanating from different path are received by the antenna. This phenomenon is mainly caused by factors such as atmospheric ducting, ionospheric reflection and refraction. Also, reflection from terrestrial objects such as mountains and buildings is one of the causes of multipath propagation [9]. The time varying nature of the propagation medium influences the quality of signals being transmitted causing them to vary rapidly [5]. The received signals may be impaired by multipath effects and the resultant effect of the impairments could be constructive or destructive interference and phase shifting of the signal. This may lead to multipath fading on the received signal and can eventually affect the quality of communication [9].

In wireless communication systems, fadings in the propagation channel are categorized as large scale and small scale fading [5], [10]. Furthermore, the large scale fading is associated with the attenuation caused by the path loss over large distances and shadowing effects while the small scale fading occurs in the range of the signal wavelength. The main cause of small scale fading is the multipath components that result in interference in the system. The effect is more pronounced when there is no line of sight (LOS) component between the transmitter and the receiver. In this scenario, the received power follows a Rayleigh distribution [11]. Therefore, effect of fading result in rapid fluctuations of the amplitudes and phases of the radio signal.

There are four different types of fading namely, flat fading [12], frequency selective fading, fast fading and slow fading [12] which a signal that passes through the mobile communication channel may experience. This is based on the signal parameters such as bandwidth and symbol period as well as the channel parameters such as root mean square (RMS) delay spread and Doppler spread. Therefore, flat fading and frequency selective fading are based on the relative length of the delay spread and the symbol length while fast fading and slow fading are based on the relative magnitude of the channel coherence time and the symbol duration [13]

2.1. Fast Fading

A fast fading channel is characterized by a situation in which the channel coherence time T_C is lower than the signal symbol period T_S [12] as expressed in (1). This result in comparatively high channel impulse response variations with respect to the symbol duration of the transmitted signal. Furthermore, a fast fading scenario can be expressed by (2) in which the Doppler spread B_D is larger than the transmitted signal bandwidth B_S.

$$T_S > T_C \tag{1}$$

$$B_S < B_D \tag{2}$$

2.2. Slow Fading

A slow fading channel is one in which the channel coherence time T_C is larger than the signal symbol period T_S [12] as expressed in (3). This result in relatively low channel impulse response variations with respect to the symbol duration of the transmitted signal. In addition, a slow fading scenario is expressed by (4) in which the Doppler spread B_D, is lower than the transmitted signal bandwidth B_S.

$$T_S \ll T_C \tag{3}$$

$$B_S \gg B_D \tag{4}$$

2.3. Flat Fading

Flat fading is a type of fading that a transmitted signal experiences when its bandwidth B_S is lesser than the channel coherence bandwidth B_C [11] as expressed in (5). Similarly, in the time domain, if the signal symbol period T_S is larger than the channel RMS delay spread σ_τ [11], [14] as expressed in (6). This scenario gives an indication that ISI will not

occur as all frequencies of the transmitted signal relatively experience the same channel condition [14].

$$B_S \ll B_C \tag{5}$$

$$T_S \gg \sigma_\tau \tag{6}$$

2.4. Frequency Selective Fading

Frequency selective fading in contrast to flat fading happens when the bandwidth B_S of the transmitted signal is larger than the channel coherence bandwidth B_C [15] as expressed in (7). This corresponds to the signal symbol period T_S lesser than the channel RMS delay spread σ_τ [14] in the time domain as expressed in (8). In this situation, the received signals present different phases and amplitudes that result in signal distortion. Also, due to the fact that the delay experienced by some paths is larger than the symbol period, the symbols spread out in time and interfere with each other causing ISI. In wireless communication systems, for highly reliable and fast communication system to be realized, the detrimental effects of ISI should be mitigated or canceled. This can be achieved with the implementation of different channel equalization techniques such as zero-forcing, minimum mean square error (MMSE), least mean squared (LMS) and maximum likelihood [16], [17], [18], [19]. However, because the channel equalization is alleviated with the implementation of the OFDM, it has been considered as a viable solution for ISI mitigation.

$$B_S > B_C \tag{7}$$

$$T_S < \sigma_\tau \tag{8}$$

3. Orthogonal Frequency Division Modulation (OFDM)

Orthogonal frequency division modulation (OFDM) is a multicarrier transmission technique in which the concept of single carrier scheme is extended by employing multiple subcarriers in a channel. This is achieved by partitioning the input high rate single data stream into low rate streams which are transmitted over a number of lower rate parallel subcarriers [6]. The orthogonal subcarriers are modulated separately at low symbol rate with the conventional digital modulation scheme [20]. Figure 1 shows the OFDM signal in frequency domain with orthogonal overlapping subcarriers while Figure 2 depicts the shape of a typical OFDM spectrum with N subcarriers. With OFDM, effect of multipath delay spread on the transmitted signal is reduced because, it converts wideband frequency selective channel into a set of parallel frequency flat channels and randomizes the burst errors caused by a wideband-fading channel [6], [18], [21]. Furthermore, as the symbol duration increases with low rate stream transmission, then, OFDM offers a higher tolerance to ISI and this advantage makes it a right candidate for high capacity wireless communication systems [22].

Furthermore, the multipath effects can be mitigated within the transmitted symbol by appending guard interval (GI) in the beginning of each OFDM symbol. If the duration of the guard is longer than the maximal delay spread of the radio channel, all the multipath components would arrive within this guard, and the useful symbol would not be affected, therefore, ISI is eliminated [23]. In this guard time, cyclic extension of the OFDM symbol is used to prevent inter-carrier interference (ICI) [23]. The cyclic extension is normally implemented by the cyclic prefix (CP) [24]. This is achieved by copying the last part of the useful OFDM symbol to the beginning of the same symbol. This arrangement simplifies the design of the receiver because orthogonality of the system is maintained and equalization might not be necessary. Nevertheless, the CP implementation weakness is in the reduction of spectral efficiency of the system [25]. Figure 3 illustrates a block diagram of an OFDM system [24], [26].

OFDM has been widely employed in numerous wireless transmission standards such as digital audio broadcast (DAB) for providing high quality audio broadcast [24], digital video broadcast terrestrial (DVB-T) for providing high resolution television [24], worldwide interoperability for microwave access (WiMAX), the Third-Generation Partnership Project (3GPP) Long-Term Evolution (LTE) and wireless local area networks (WLANs) according to the Institute of Electrical and Electronics Engineers- IEEE802.11a/g/n standards [27] [28]. Its employment in the standards is mainly due to its high performance and robustness in multipath fading channel [28].

The problem that is associated with the implementation of OFDM system when parallel analog modulators are employed is high system complexity. This is due to the fact that the number of component such as analog modulator, receiver filter and demodulator the will be required will be equal to the number of subcarriers N. However, with the advancements in digital signal processing and very large scale integrated circuits, a simplified OFDM system can be realized in a cost-effective way when the sub channel modulators/demodulators are implemented with the computationally efficient pair of inverse fast Fourier transform (IFFT) and fast Fourier transform (FFT) [29]. Furthermore, another technical issue of OFDM lies in the associated high peak-to-average-power ratio (PAPR) of the transmitted signal which is due to the combination of N modulated subcarriers which cause reduction in the achievable gain of OFDM [22], [24], [27].

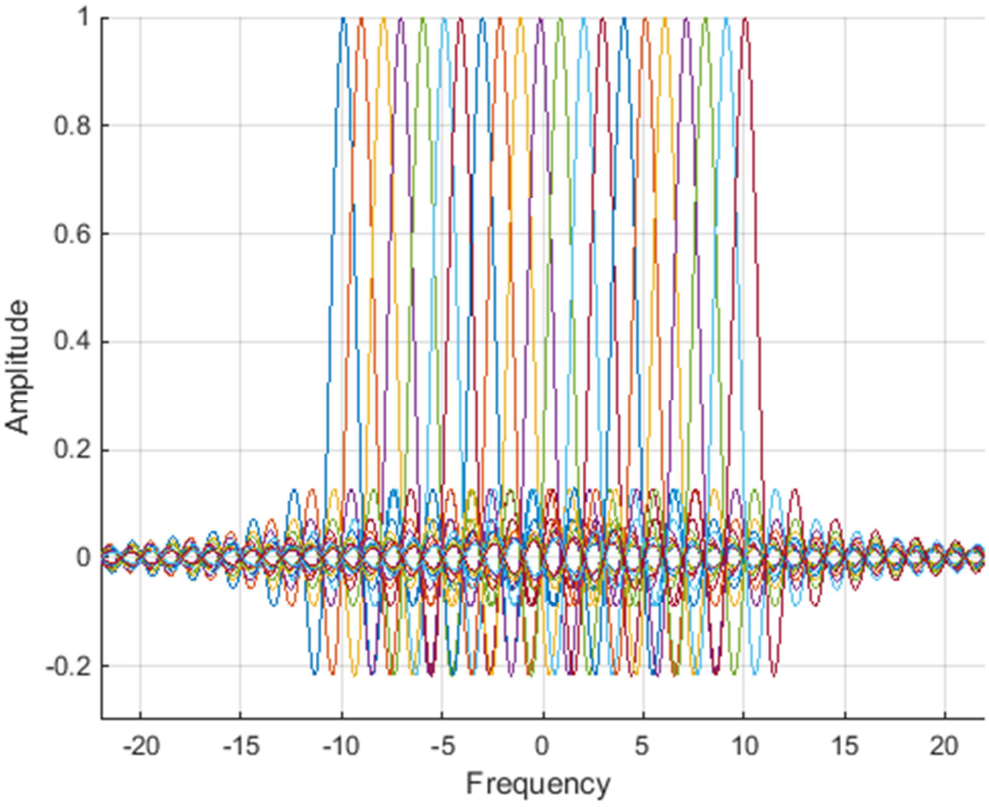

Figure 1. OFDM Signal in Frequency Domain.

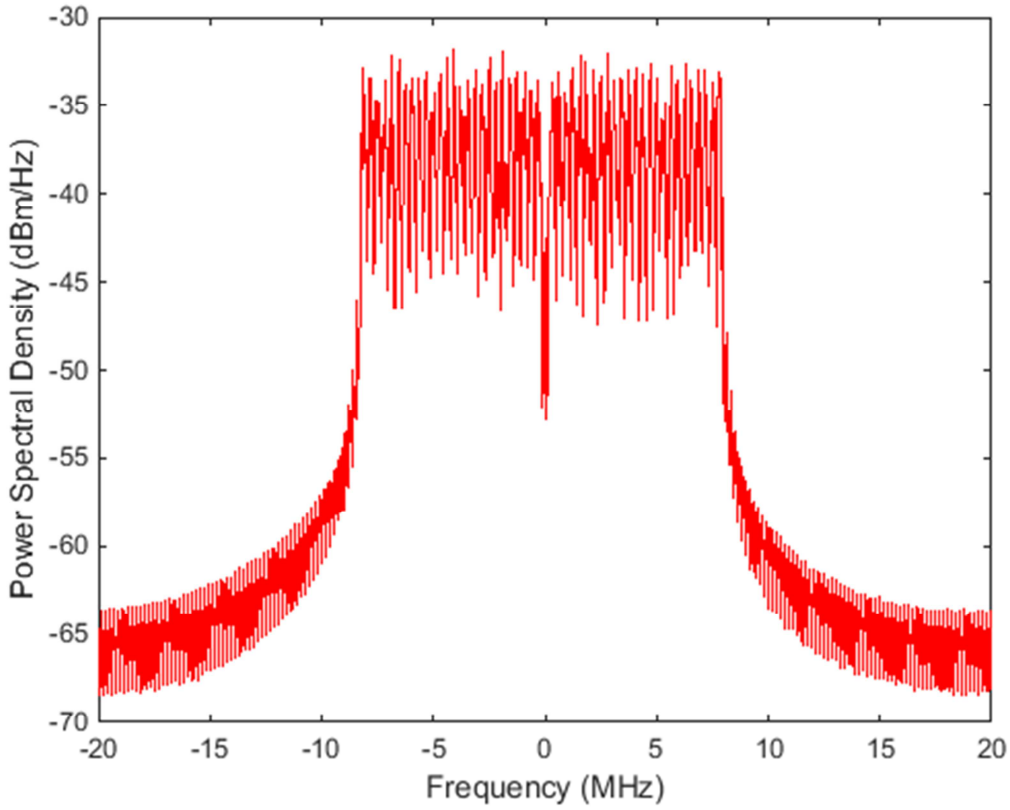

Figure 2. Typical OFDM Spectrum with N Subcarriers.

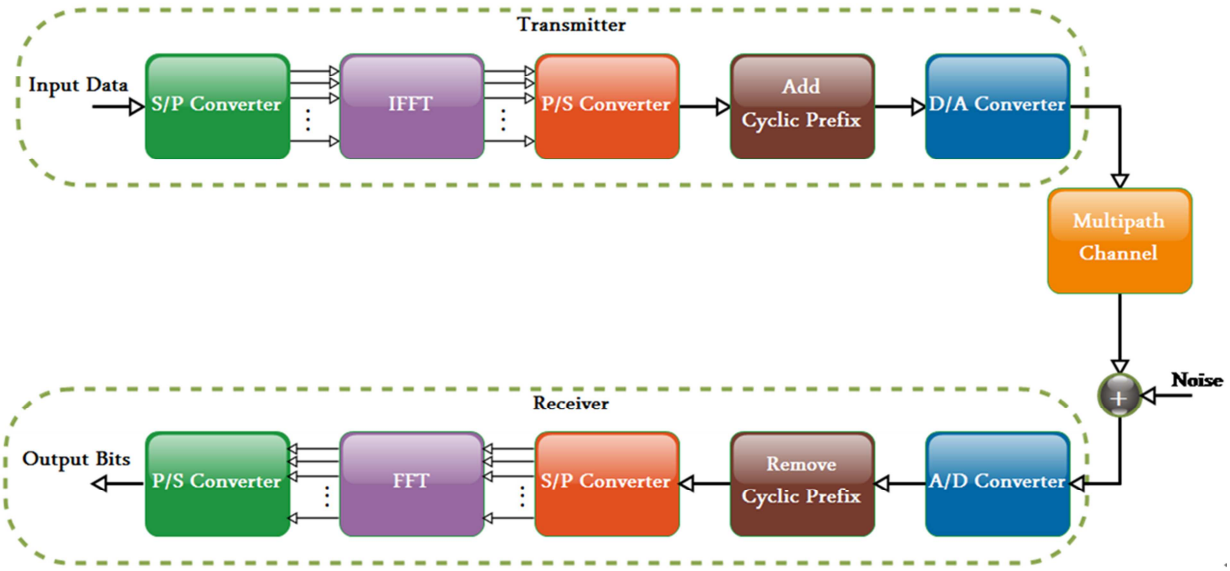

Figure 3. Block Diagram of an OFDM System.

4. OFDM System and Peak to Average Power Ratio (PAPR) Reduction

The OFDM signal is generated from the input symbols X_k for $k = (0,1,2,\cdots,N-1)$ as [30], [31]

$$x(t) = \frac{1}{\sqrt{N}}\sum_{k=0}^{N-1} X_k\, e^{j(2\pi f_k t)}, 0 \le t \le NT \quad (9)$$

where N is the total number of subcarriers, T is the symbol period, $f_k = k\Delta f$ and $\Delta f = 1/(NT)$. Similarly, the discrete form of OFDM signal $x(n)$ is expressed as [26], [32]

$$x(n) = \frac{1}{\sqrt{N}}\sum_{k=0}^{N-1} X_k\, e^{j\left(\frac{2\pi nk}{N}\right)}, n = 0,1,2,\cdots,N-1 \quad (10)$$

PAPR is the ratio between the maximum instantaneous power and the average power. High PAPR bring about distortions as well as loss of orthogonality between OFDM subcarriers in the transmission chain [33]. The PAPR of the OFDM signal in decibel (dB) is expressed as [7]

$$PAPR = 10log_{10}\left\{\frac{P_{peak}}{P_{avg}}\right\} \quad (11)$$

The PAPR of a continuous-time signal $x(t)$ is given as [8], [26]

$$PAPR = \frac{max\{|x(t)|^2\}}{E\{|x(t)|^2\}},\ 0 \le t < NT \quad (12)$$

where $E\{.\}$ is an expectation operator, $E\{|x(t)|^2\}$ is average power of $x(t)$ and PARP reduction techniques focus on minimizing the $max|x(t)|$.

Similarly, the PAPR of a discrete-time signal $x(n)$ is denoted as [18], [33], [34]

$$PAPR = \frac{max\{|x_n|^2\}}{E\{|x_n|^2\}}, n = 0,1,2\cdots LN-1 \quad (13)$$

The corresponding complementary cumulative distribution function (CCDF) of the PAPR which is normally employed for performance measure of PAPR reduction techniques is expressed as [35]

$$CCDF(x) = Prob[PAPR > PAPR_{th}] \quad (14)$$

Therefore, CCDF is the probability that the PAPR of a data block exceeds a given threshold $\gamma = PAPR_{th}$. When the number of the subcarriers N is relatively small, the CCDF of OFDM signals is written as [36]

$$Prob\{PAPR > \gamma\} = 1 - (1 - e^{-\gamma})^N \quad (15)$$

High PAPR may eventually introduce intermodulation noise in addition to out-of-band radiation between the OFDM subcarriers. Consequently, it causes BER degradation in the system by forcing the HPA to operate in the nonlinear region of the characteristic curve and also make it to consume more power [7], [20], [23], [36], [37]. Consumption of high power makes the system feasibly for portable wireless devices which are powered by the battery much more challenging [18], [34]. Furthermore, it put a stringent need for linear power amplifier on the system and as a result it causes an increase in the system cost [24], [30].Therefore, reduction of PAPR enables a power efficient system by providing lower power requirements as well as extending the battery operation and life span [37].

There are different PAPR reduction techniques such as amplitude clipping, active constellation extension (ACE),

tone injection (TI), tone reservation (TR), block coding and multiple signal representation techniques such as interleaving, selected mapping (SLM) and partial transmit sequence (PTS) that have been proposed in the literature [28], [30], [34], [35] [38]. However, techniques such as SLM and PTS are widely used because they exhibit good PAPR reduction performance without the BER degradation. Nevertheless, they have high computational complexity and require the transmission of several side information (SI) bits [1], [8], [30], [32], [39].

4.1. Partial Transmit Sequence (PTS) Technique

The Partial Transmit Sequences is one of the multiple signal representation techniques in which the input data block X of length N are first mapped into consecutive OFDM symbols. Then, each OFDM symbol is partitioned into M distinct sub-blocks $X_m = [X_{0,m}, X_{1,m}, X_{2,m}, \cdots, X_{N-1,m}]^T$, where T is a transpose operator and $m = 1, 2, \cdots, M$. Also, the operation is done in such a way that $\sum_{m=1}^{M} X_m = X$ and at any time n only one $D_{n,m}$ is nonzero [40]. The inverse fast Fourier transform (IFFT) operations are implemented on each sub-block to obtain time-domain signal that is given by [41]

$$x_m = IFFT(X_m) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k^{(m)} e^{j\left(\frac{2\pi nk}{N}\right)}, m = 1,2,3,\cdots,M \quad (16)$$

The outputs of the operations are then multiplied by a set of complex phase rotation factors $b_m = [b_{0,m}, b_{1,m}, b_{2,m}, \cdots, b_{N-1,m}]^T$ written as [41]

$$b_m = e^{j(\emptyset_m)}, \ \emptyset_m \epsilon [0, 2\pi] \quad (17)$$

where $\emptyset_m = (2\pi\omega)/W$, $\omega = 0,1,2,\cdots,W-1$ and W is the number of allowed phase angles [41].

The subsequent OFDM symbol is the sum of all multiplied sub-block outputs and it is expressed as

$$x = \sum_{m=0}^{M-1} b_m . IFFT(X_m) = \sum_{m=0}^{M-1} b_m x_m \quad (18)$$

The rotation factors vector is normally optimized in order to reduce the PAPR. The information about the rotation factors employed for the multiplication in each OFDM symbol is required at the receiver to be able to decode the original information correctly. This information is called side information (SI) [42]. Figure 4 shows a block diagram of the PTS technique [34], [41], [42].

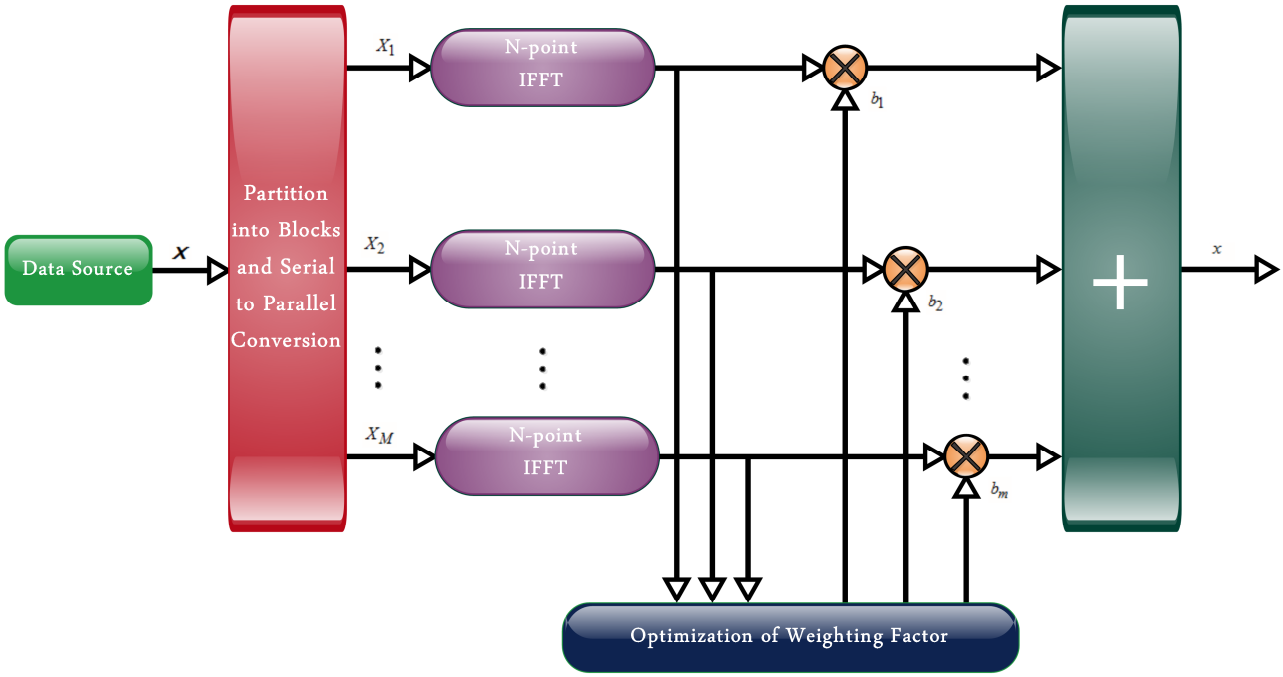

Figure 4. Block Diagram of PTS Technique (Adapted from [41]).

4.2. Selected Mapping (SLM) Technique

The basic concept of selected mapping (SLM) technique is based on generation of a number of alternative OFDM signals from the original data block. The alternative OFDM signal with minimum PAPR is then transmitted instead of the original data block. Figure 5 shows a block diagram of the SLM technique [38]. According to the concept, a signal with minimum PAPR is selected from a set of signals in which each signal basically represents the same information [8], [30]. Each data block is multiplied by U different phase sequences with length N that is equal to the data block size.

The multiplication results in U modified data blocks $X^{(u)}$ where $u = 1,2,\cdots,U$. Assuming that the u^{th} phase vector is $B^{(u)}$ and the corresponding generated u^{th} vector after the multiplication of data block with the phase vector is represented as $X^{(u)}$ and expressed as

$$X^{(u)} = X(k)\, B^{(u)}(k) \tag{19}$$

The IFFT operation is then implemented on each corresponding data block to obtain the alternative OFDM signals $x^{(u)}$ that is expressed as

$$x^{(u)}(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X^{(u)}(k)\, e^{j\left(\frac{2\pi nk}{N}\right)} \tag{20}$$

The u^{th} signal of the alternative OFDM signals that has minimum PAPR is then selected for transmission. Furthermore, the reverse operation is performed at the receiver but in order to be able to extract the original information at the receiver, some additional information about the phase vector set that gives the lowest PAPR should be transmitted with the OFDM signal. This required SI bits that significantly increases the system overhead [30]. There are various SLM and PTS techniques that have been proposed in which the SI is not required. One of such is the employment of the natural diversity of phase constellation for different candidates by the detector to recover the original signal without side information as proposed in [39]. Similarly, [32] presented an improved constellation extension (CE) scheme that has fewer extendable constellation points and more corresponding extended constellation points that gives better BER performance with almost the same PAPR reduction compared with existing CE schemes. Moreover, [8] proposed an impulsive noise detection that exploits the statistical properties of the OFDM envelope when applying SLM to improve the BER of the communication system.

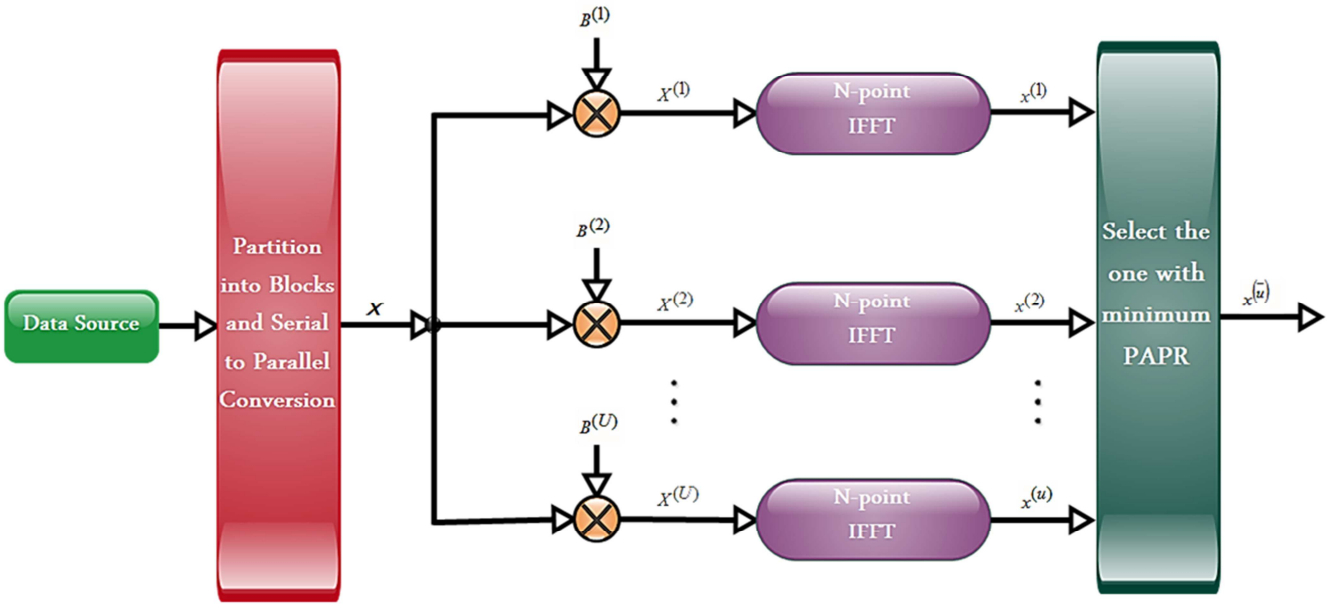

Figure 5. Block diagram for SLM technique (Adapted from [38]).

5. Simulation Results and Discussions

This section presents experimental demonstration of effectiveness of OFDM in communication systems in terms of error probability. Furthermore, the selected mapping technique is implemented for OFDM signal PAPR reduction. Simulations are developed in MATLAB® and the results obtained are presented in the following sub-section.

5.1. OFDM Scheme Implementation

This sub-section compares performance of OFDM scheme with the ZF and MMSE schemes. To demonstrate multipath effect on the transmitted signal, BPSK modulation and Rayleigh channel are employed in the simulation. The simulation and theoretical results using Rayleigh channel are compared with the effect in additive white Gaussian noise (AWGN) channel. Different numbers of taps are used in the simulation to show that ISI leads to high error rate in the system. The simulation result is shown in Figure 6. It is observed that the simulation and theoretical results using Rayleigh channel are similar, however, AWGN channel gives better BER performance and requires less power. For instance, it is observed that, to achieve BER of 10^{-4} in AWGN channel, 8dB of signal power is required while for the same BER, 33dB is required for the Rayleigh channel. This shows that, to achieve the same BER as AWGN channel 25dB additional power is required by system with ISI. The

classical approach to solve this problem of high error rate caused by ISI is to employ channel equalization. The use of ZF and MMSE equalizers are simulated and shown in Figure 7. The result shows that MMSE scheme gives relatively better BER performance.

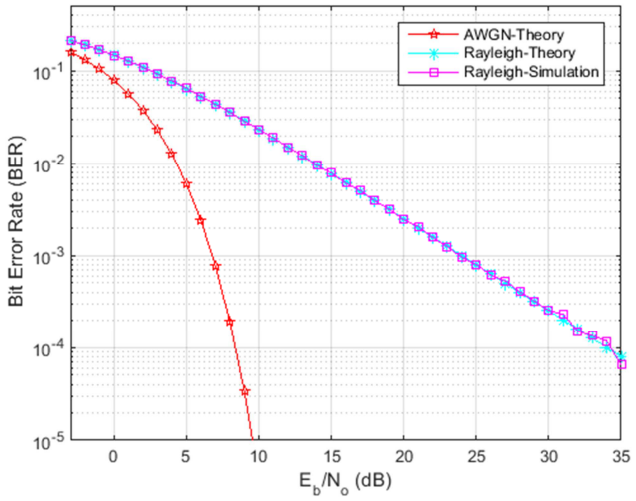

Figure 6. BER Curve for BPSK Modulation in AWGN and Rayleigh Channels.

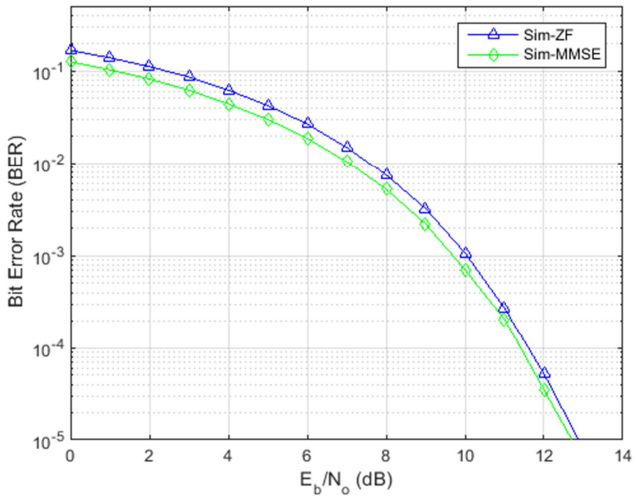

Figure 7. BER Curve for BPSK with ZF and MMSE Equalizers.

Furthermore, OFDM modulation that is able to adapt to multipath channel parameters is employed in the simulation. The results show that, the simulation and theoretical results are the same and that OFDM technique gives relatively better BER performance and requires less power. The superior performance of OFDM scheme in multipath channels is due to the fact that multiple parallel subcarriers transmission are employed and as the number of the carriers increases, the symbol period also increases. Therefore, this will make the symbol period to be longer than the channel impulse response ($T_S \gg \sigma_\tau$). The channel transfer function can then be considered as flat for each subcarrier. The result for the implementation of OFDM scheme is shown in Figure 8.

Moreover, to show the supremacy of OFDM scheme in multipath fading channels, performance of OFDM scheme is compared with that of ZF and MMSE. The performance curves for the schemes are shown in Figure 9. The result presented in the Figure shows that OFDM performance curve overlap with that of AWGN and that OFDM outperformed ZF and MMSE. For instance, it is observed that, to achieve BER of 10^{-4}, OFDM implementation requires 8dB of signal power is required while for the same BER, 33dB is required for the Rayleigh channel. This shows that, to achieve the same BER as OFDM 25dB additional power is required by system with ISI. Also, comparing OFDM implementation with ZF and MMSE, it is observed that to achieve BER of 10^{-5}, OFDM scheme requires 9dB of signal power while for the same BER, about 13dB is required by ZF and MMSE implementations. Therefore, it shows that, to achieve the same BER as OFDM, 4dB additional power is required by ZF and MMSE schemes.

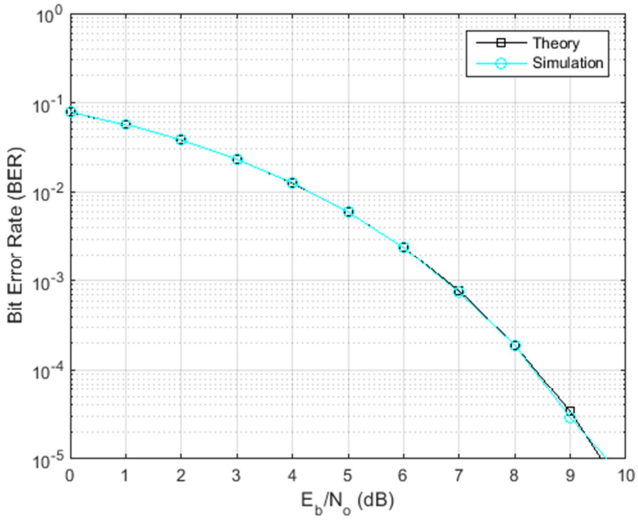

Figure 8. BER Curve for BPSK Modulation with OFDM.

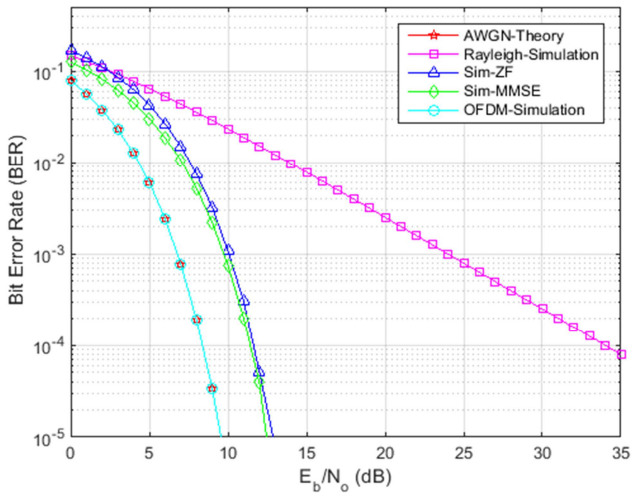

Figure 9. Comparative BER Curve for BPSK with OFDM and Equalizers

5.2. Selected Mapping Implementation

The selected mapping (SLM) technique is implemented by generating a number of alternative OFDM signals from the original data block and then transmit the alternative OFDM signal with minimum PAPR. To achieve this, the PAPR reduction proficiency of SLM is investigated by considering an OFDM system with 128 subcarriers and 16-QAM mapping. Also, the oversampling factor of 4 is used to estimate the PAPR reduction. In the simulation, 10^6 input symbol sequences are randomly generated and phase factors of 4 with each element of the phase rotation vectors randomly selected from $\{\pm 1, \pm j\}$ are employed. Figure 10 (a) shows the original OFDM signal while (b) shows the OFDM signal with the SLM reduction scheme. It is observed that the SLM scheme gives a better PAPR reduction performance relative to the original OFDM signal.

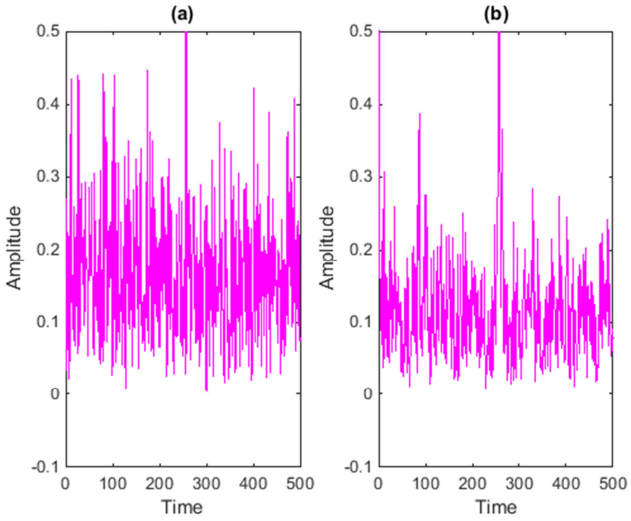

Figure 10. (a) Original OFDM Signal (b) OFDM Signal with SLM Reduction Scheme.

6. Conclusion

Orthogonal Frequency Division Multiplexing (OFDM) is a robust multicarrier modulation for high-data rate transmission that is able to address the issue of multipath fading. However, one of the challenges of OFDM is the associated high peak-to-average power ratio (PAPR) that lead to bit error rate (BER) degradation of wireless communication systems. With high PAPR, the system cost increases because of the stringent need for linear power amplifier. This paper focuses on experimental demonstration of effectiveness of OFDM in mobile communication systems by considering the performance of OFDM over both Rayleigh and additive white Gaussian noise (AWGN) channels. Also, the PAPR reduction schemes for OFDM are investigated. The simulation results show that the OFDM scheme significantly reduced the effect of multipath fading and also enables more data transmission with less error rate in wireless communication systems. Also, it is observed that the implementation of selected mapping (SLM) scheme considerably reduce PAPR of OFDM signal.

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Biography

Alimi Isiaka Ajewale earns B.Tech. (Hons) and M.Eng. in Electrical and Electronics Engineering (Communication) from Ladoke Akintola University of Technology, Ogbomoso, Nigeria in 2001, and the Federal University of Technology, Akure, Nigeria in 2010 respectively. He is a Lecturer in the Department of Electrical and Electronics Engineering, Federal University of Technology, Akure, Nigeria. He has published 3 refereed international journals. He has extensive experience in radio transmission, as well as in Computer Networking. His areas of research are in Computer Networking and Security, Advanced Digital Signal Processing and Wireless communications. He is a COREN registered engineer.