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Research Article

Analysis of WOFDM over LTE 1.25 MHz Band

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Orthogonal Frequency Division Multiplexing (OFDM) is the one of the most preferred multiplexing technique for realizing high-speed wireless communication, like Long Term Evolution (LTE) and LTE-Adv. In the era of digital wireless communication, applications of wavelet theory have been favorably applied in many areas of signal processing. Orthogonality, flexible time-frequency analysis, and the ability to characterize signals accurately have attracted the attention of the telecommunication community to use wavelet as a basis function for OFDM. In this paper, discrete wavelet transform (DWT) has been proposed as an alternative signal analysis with multiple merits such as support high-speed applications, immune to distortion, wavelet diversity, better error performance, and efficient bandwidth utilization. A simulative analysis of various wavelets, at different modulation techniques, over OFDM has been presented to demonstrate the improvement in BER performance. Further, in accordance with the LTE parameterization over 1.25 MHz band, the performance of wavelet-based OFDM (WOFDM) is found significantly higher in terms of maximum achievable data rate and system spectral efficiency.

1. Introduction

OFDM distributes the offered spectrum among multiple subcarriers where each subcarrier gets modulated by information signal stream to efficiently utilize available bandwidth [1, 2]. Apparently, whole information carrying data stream is fragmented into multiple subsets, separately modulated with orthogonal carriers. Each subcarrier is orthogonal to each other in time domain; however, frequency domain overlapping of multiple signals is well visible. However, information transmitted in the shape of closely packed symbols is expected to interfere each other to generate intersymbol interference (ISI) [3, 4]. To avoid ISI, cyclic prefix (CP) is used but at the cost of bandwidth consumption; this may even consume more than 25% of total available bandwidth. In order to save this precious bandwidth, discrete wavelet transform (DWT) provides a better solution as it does not use CP to sideline the ISI.

DWT is the multiresolution analysis (time-frequency), i.e., excellent time resolution properties at high frequencies and poor frequency resolution properties at low frequencies. Wavelet is like a tiny waveform that exhibits useful properties to analyze edges of a signal to better represent local features. DWT can be the best alternative to the Discrete Fourier Transform (DFT) based signal analysis for OFDM system, with multiple advantages such as high energy consumption, compact support, multiresolution analysis in frequency-time domain, interference immunity, better phase linearity, no CP requirement, flexibility to choose suitable wavelet, and wavelet diversity [5]. There is a significant bandwidth advantage associated with wavelets, as it does not need cyclic prefix because in wavelet decomposition, symbols overlap in both time and frequency domain [6]. Wavelet offers a higher degree of suppression to the side lobes (thus wavelet-based OFDM ought to have longer basis functions). Also, the wavelet-based multicarrier communication system bears less complexity as compared to the DFT-based system [7–9]. Large spectrum efficiency, high-speed data transmission support, and MIMO compatibility make OFDM a preferred access technique for advanced wireless mobile communication [10]. Wavelet-based OFDM systems are spectrum efficient as they do not seek CP to restrict ISI. Moreover, pilot tones are not necessary in wavelet transform, thus providing an additional 8% of bandwidth efficiency as compared to the conventional OFDM. For a conventional OFDM system, power amplifier's (PA) energy consumption can go as high as 60% of the energy consumption of BTS transmitter [4]. Wavelet implication improves PA efficiency, thereby restricting energy expenditure at mobile equipment (batteries that last longer) and at the base stations (energy savings) [11]. Many researchers have demonstrated the BER analysis for WOFDM [12, 13] and standard OFDM systems to highlight the benefits of different types of wavelets in an OFDM system, i.e., db2, db4, db6, db10, db8, db32, haar, symlet, biorthogonal, reverse biorthogonal [14–17] under AWGN, and Rayleigh fading channel over a wide SNR range.

In this paper, a quantitative analysis of maximum achievable data rate and spectral efficiency for WOFDM is performed with different modulation levels at 1.25 MHz LTE spectrum band. Simulative analysis of BER performance of WOFDM with respect to five different wavelets is also performed to attain the improvements against standard OFDM. Further, this paper is organized as follows: Section 2 describes the technological concept of LTE and its functions. Section 3 investigates the operational parameterization of LTE. Section 4 summarizes the related work and associated literature. Section 5 presents the proposed WOFDM using various wavelets. Section 6 presents the results and analysis. Finally, Section 7 summarizes and concludes the paper.

2. Long Term Evolution (LTE)

LTE is the technological upgradation and advancement of the Universal Mobile Telecommunications System (UMTS) through many evolutions. 3GPP (3rd Generation Partnership Project) worked over the decade (since 2004) to make LTE roll-out possible where high mobile data usage and advent of new applications have motivated it to touch extremities [18]. 3GPP working committee members organize to build up a framework keeping prime objectives aligned to evolve 3GPP radio-access technology for achieving high-data-rate, low-latency, and packet-optimized radio-access technology. LTE Radio Access delivers significant improvement in end to end user throughput, spectrum efficiency and offers a substantial improvement in mobility experience by exploiting OFDM and Multi-in Multi-Out (MIMO) antenna schemes [19].

The 3GPP working committee provides LTE specifications, the performance requirements pertaining to control plane, and user plane protocols for commercial deployments [20].

The following is the summary of the performance parameters:

(i) *Peak data rate*: up to 300 Mbps in downlink and 100 Mbps in uplink.

(ii) *Latency*: one-way transit time shall be less than 5 ms.

(iii) *Spectrum efficiency (bit/sec/Hz/site)*: up to 5 bit/sec/Hz.

(iv) *Mobility*: high performance up to 120 km/h and support maintained for 120-350 km/h.

(v) *Coverage*: high performance up to 5 km and compromised performance till distance increases up to 100 km.

(vi) *Spectrum allocation*: Frequency Division Duplex (FDD) and Time Division Duplex (TDD) support.

(vii) *Capacity*: 200 users/cell to 400 users/cell support.

(viii) *Spectrum flexibility*: support different spectrum sizes: 1.25 MHz, 2.5 MHz, 5 MHz, 10 MHz, and 20 MHz.

(ix) *Interworking*: uninterrupted backward compatibility with legacy systems.

(x) *Costs*: Reduced Capital Expenditure (CAPEX) and Operational Expenditure (OPEX).

Power consumption is a key attention to choose user equipment (UE), and therefore, LTE uplink requirements differ from downlink requirements. The high PAPR and related loss allied with OFDM leads to a search for an alternative low power consumption technique for LTE uplink transmission. Thus, LTE uplink transmission is designed with Single Carrier Frequency Division Multiple Access (SC-FDMA) scheme to save UE battery power. The potential merit of SC-FDMA over OFDM is low PAPR and which makes it accountable for a low cost implementation of power amplifiers [21]. Unlike the non-3GPP compliance, LTE deployed with OFDM for downlink and SC-FDMA for uplink, FDD/TDD duplex mode and have greater VoIP capacity (80 users/sector/MHz) [22]. The higher the performance of OFDM (either spectral efficiency or data rate), the more would be the attribution to achieve performance goals of 4G-5G systems. Where legacy cellular systems worked on circuit-switched model, 3GPP defined a new System Architecture Evolution (SAE) that operates with less network elements and works for both data and voice traffic through only IP-based protocol. Figure 1 shows a simplified LTE architecture, where LTE core network EPC (Evolved Packet Core) provides IP connectivity through Packet Data Network (PDN) Gateway for accessing the Internet.

LTE is provisioned to support packet-switching services between UE to Packet Data Network (PDN), without interfering consumer's applications during mobility. The LTE evolved base station (eNodeB), which is a part of E-UTRAN and gets connected to EPC through S1AP protocol. As shown in Figure 1, Mobility Management Entity (MME) is the heart of EPC, and it manages control plane signaling as well as user plane data S1U interface (handled by Serving Gateway). PDN gateway (PGW) acts as a mobility anchor for interworking, IP address allocation for the UE, and flow-based charging. In order to establish multiple bearers

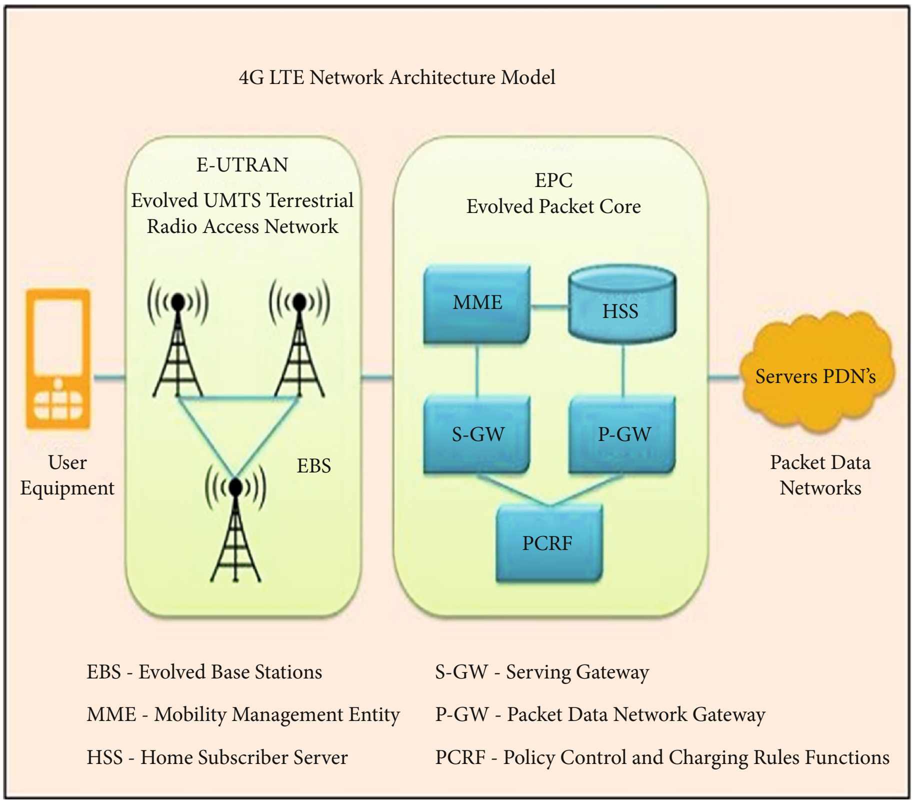

Figure 1: LTE network elements [18].

to a user, different connectivity to different PDNs is granted gracefully. For example, a user busy with web browsing or media streaming while simultaneously might be performing a voice over IP (VoIP) call. Serving gateway (SGW) acts as the mobility anchor for inter 3GPP eNodeB handovers. The Policy Control and Charging Rules Function (PCRF) administrates the policy control and decision-making, QoS authorization, and bit rate according to the subscription. The Home Subscriber Server (HSS) retains the user data and MME identification with which it is registered.

3. LTE Parameterization

LTE supports both TDD and FDD mode of operations in downlink and uplink transmission. Since LTE adopts two different access techniques, i.e., OFDMA for downlink and SC-FDMA for uplink transmissions, physical layer parameters and system requirements become different, and thus, that must be treated separately for uplink case and downlink case [20]. There are two radio frames, each one of 10 ms duration.

The following are the two types of radio frame structures:

(i) *Type 1*: supports FDD mode.

(ii) *Type 2*: supports TDD mode.

The type 1 FDD-based radio frame structure is shown in Figure 2. It consists of 20 equal-sized time slots. The

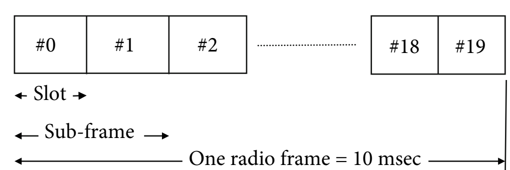

Figure 2: Frame structure type 1.

whole radio frame is also grouped into 10 equal-sized subframes where each one of the subframes consists of two equal-size radio time slots. In type1 structure (FDD mode), the whole frame is equally distributed for uplink and downlink transmission, i.e., 5 subframes are made available for downlink and 5 subframes for uplink. So each subframe is of 1 ms duration where each time slot occupies 0.5 ms time duration.

Type 2 TDD-based radio frame structure is shown in Figure 3. It consists also of 20 equal-sized time slots that are grouped into 10 subframes of 1 ms duration each. Now, one radio frame is divided into two equal portions of TDD frames (5 ms each) where each half portion of the frame is structured with 8 slots of duration 0.5 m, and one subframe consists of three special fields related to the guard period (GP), downlink pilot time slot (DwPTS), and uplink pilot time slot (UpPTS). The time duration of DwPTS and UpPTS is variable enough to satisfy the condition of 1 ms length of the subframe. In this frame structure, subframe number 1 and subframe number 6 with half-frame periodicity (5 ms switch-point) consist of DwPTS, GP, and UpPTS; however,

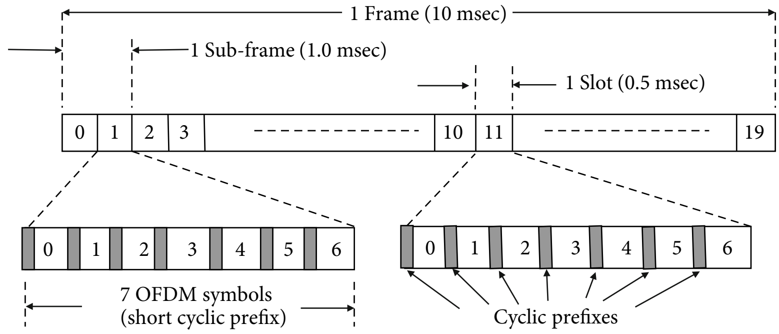

Figure 3: LTE frame structure type 2.

Table 1: LTE parameters for downlink [21].

Parameters	OFDM					
Bandwidth (MHz)	1.25	2.5	5	10	15	20
Subcarrier spacing	15 kHz					
Symbol time	66.7 μs					
FFT size	128	256	512	1024	1536	2048
No. of subcarrier	76	151	301	601	901	1201
Error coding	Convolution coding					

the rest of the subframes contain two equally sized radio slots. In TDD mode, downlink and uplink operations are separated in the time domain.

OFDM technique with CP is used for downlink communication, maintaining the subcarrier spacing $\Delta f = 15\,\text{kHz}$. Subcarrier spacing ($\Delta f$) is related to OFDM symbol duration (T_S) by $\Delta f = 1/T_S$. Therefore, it is essentially important to choose an appropriate size of T_S to enable Δf sufficient enough to sustain against Doppler offset and other sources of frequency offset. There are two variants of CP length (normal cyclic prefix and extended cyclic prefix) used for OFDM symbol (seven and six OFDM symbols per radio slot) having 15 kHz subcarrier spacing.

For a channel delay spread "T_d" and maximum Doppler frequency "$f_{D_{\max}}$," the following is the design criteria for choosing the CP duration "T_{CP}":

$$\begin{cases} T_{CP} \geq T_d & \text{to avoid ISI,} \\ \dfrac{f_{d\ \max}}{\Delta f} \ll 1 & \text{to maintain ICI sufficient low,} \\ T_{CP}\Delta f \ll 1 & \text{to maintain OFDM spectral efficient.} \end{cases} \quad (1)$$

In compliance with the LTE specifications defined by 3GPP, Table 1 presents the OFDM parameters to be adopted for downlink communication. According to LTE parameterization [21], for all available spectrum bands, there should be 15 kHz subcarrier spacing maintained for orthogonality, and thus, the symbol rate comes out to be $(1/15\,\text{kHz}) = 66.7\,\mu\text{s}$.

Utilization of higher spectrum bands with dynamic career aggregation technique is still a matter of future research and exploration to alleviate the spectrum scarcity and capacity limitations of current/future wireless communication systems [23]. Advanced technological developments like 5G, Internet of Things (IoT), and Machine to Machine (M2M) are aligned with many revolutionary ideas to explore the possible enhancements in energy efficiency, network latencies, and reliable interconnectivity [24].

4. Related Work

OFDM is used in LTE systems. OFDM provides higher data rates, but at the same time, it has two major drawbacks: (i) High Peak to Average Power Ratio (PAPR) and (ii) Intercarrier Interference (ICI). It is desirable to have low PAPR and nill ICI for a better quality of service. Many researchers have worked on different algorithms to reduce PAPR like Signal Scrambling Techniques, Signal Distortion Techniques, and Hybrid Techniques; a brief overview of these techniques is given in [25]. Techniques to combat ICI are also proposed like ICI Self Cancellations; recently, an overview of different ICI self-cancellation techniques based on conventional OFDM based on simulink is presented in [26–28] and also reported in [29]. Now, all these techniques are based on conventional OFDM in which IFFT/IDFT is used at the transmitter side and FFT/DFT is used in the receiver side. Sarowa et al. and Kaur et al. [6, 30] have focused their research on wavelet-based OFDM, i.e., replacing the IFFT/DFT with IDWT and FFT/DFT with DWT to improve the system performance. A comparative analysis of conventional OFDM with wavelet-OFDM is also presented for PAPR reduction [31] and ICI cancellations [32]. As in conventional OFDM, orthogonality among subcarriers is lost, and thus, the problems of high PAPR and ICI arises; along with this, the cyclic prefix is also used. Cyclic prefix consumes almost 20% of bandwidth and hence makes the system less bandwidth efficient. In cases of wavelets, as they maintain orthogonality and at the same time subcarriers are not required, the PAPR and ICI problems can be handled in a better way. Recently, wavelet-based OFDM is used in many other applications in including 5G and underwater acoustic communications [33, 34]. It is desirable that if wavelet-based OFDM is used in LTE, it can enhance its performance. The present article is focused on the use of wavelet-based OFDM in LTE 1.25 MHz band to test its feasibility in LTE systems. Initially, the AWGN channel is considered for

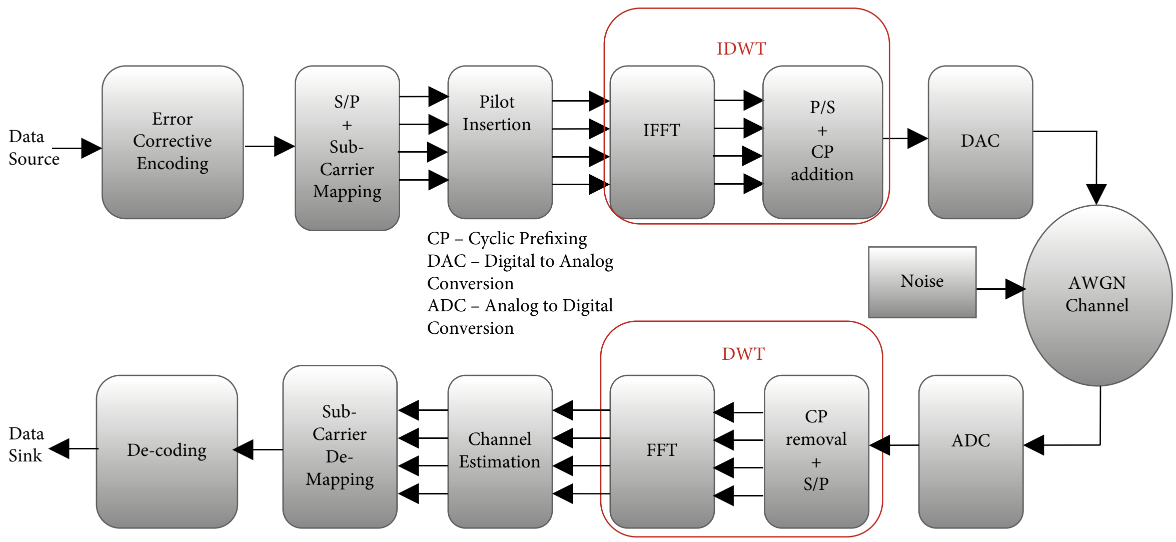

Figure 4: Building blocks of wavelet-based OFDM system.

simulation purposes; work can further be extended with Rayleigh fading and Rician fading channels also. As the AWGN channel is simple to implement and at the same time it is easy to analyse the system, simulations are carried using AWGN channels. Conventional OFDM and wavelet-OFDM are compared at different modulations and with different wavelet families.

5. WOFDM System

Discrete wavelet transform deals with the multiresolution analysis of signals under consideration in both frequency domain and time domain through wavelet coefficients. Wavelets are small waveforms having some set oscillations in the time domain, with some additional properties useful for analyzing edges and transient properties of a signal to better represent sharp changes and local features. Wavelet gives better orthogonality among subcarriers against multipath signal propagation and has localization in both time and frequency domain. Wavelets have higher energy compaction since side lobes are of very small magnitude. In wavelet-based OFDM, there is no requirement of cyclic prefix and pilot tones which are potential advantages of this scheme where bandwidth saving is achieved significantly.

The merits of the wavelet transform are summarized below:

(i) Compact support (localization) both in time and frequency domain

(ii) Better orthogonality to reduce ISI power and make the system less affected by Doppler shift

(iii) No cyclic prefix requirements, which makes OFDM system 20% more bandwidth efficient

(iv) No major requirements to use pilot tones, which may further save 8% of valuable bandwidth

(v) High energy compaction, which makes side lobes to bear a small amount of energy

(vi) The adverse effect of the channel can be further reduced by suitably choosing the appropriate type of wavelet with desired modulation technique as different wavelet produces different performance under the undesirable channel conditions

(vii) Wavelet transform renders the flexibility of configurable transform size which eventually makes a number of subcarriers configurable in accordance with the different channel conditions

Keeping all the benefits of wavelet transform in view, we propose a wavelet-based OFDM system as shown in Figure 4. In this system, cyclic prefix block is missing which otherwise could have consumed more than 20% of precious bandwidth. In this WOFDM system, IFFT and CP blocks (transmitter side) are replaced with inverse discrete wavelet transform (IDWT) block. At the receiver side, FFT and CP removal blocks are replaced with the discrete wavelet transform (DWT) block.

Here, source data is encoded with a convolution coder (error corrective encoder as same as that used for FFT-based OFDM for simulative comparison). Pilots are inserted (for better tracking of the signal at the receiver side) after modulation (QPSK/QAM both techniques give better performance) which is followed by subcarrier mapping. Subcarrier mapped symbols are then processed by inverse discrete wavelet transform. IDWT section consists of perfectly reconstructed quad mirror filter banks that employ half band low pass filter (LPF) having impulse response "g" and half band high pass filter (HPF) having impulse response "h." For IDWT and DWT processing, one can choose any type of wavelet family-like Haar, db, symlet, bior wavelets, etc. At the receiver side, respective functions are suitably reversed to reconstruct the original information signal.

Haar wavelet and db wavelet are the most commonly used wavelets due to their simplicity and easy synthesis.

The descriptions of Haar wavelet $\psi(t)$ is:

$$\psi(t) = \begin{cases} \frac{1}{\sqrt{T_0}} & \text{if} \quad 0 \le t \le \frac{T_0}{2} \\ -\frac{1}{\sqrt{T_0}} & \text{if} \quad \frac{T_0}{2} \le t \le T_0 \\ 0 & \text{else} \end{cases}, \tag{2}$$

WOFDM output is:

$$X(t) = \left[\left(\sum_{n=0}^{N_s} C_k \psi(t - nT_s) \right) \right], \tag{3}$$

where C_k and T_s are complex representations of the subcarrier symbols and symbol period. The Haar wavelet is the oldest and simplest wavelet and has a closed-form expression in the time and frequency domains.

6. Results and Analysis

BER performance of the standard OFDM system is evaluated against the WOFDM system to analyze the performance improvement. Performance improvement in BER at different SNR values for conventional FFT-based OFDM system and WOFDM system are analyzed with a set of five different wavelets, i.e., "haar," "db2," "sym2," "coif1," "bior1.1." As BER is dependent on the signal to noise ratio, so the performance curve of BER is plotted with respect to SNR. However, the BER performance of the OFDM system is also dependent on coding schemes, modulation techniques, multipath propagation, fading environment, channel noise, etc. In the present simulation model, an error corrective encoding (convolution coding) is used to get better BER performance of the system. Pilots are inserted suitably with respect to the volume of data and modulation scheme (to track the signal at the receiver side). Different modulation techniques (4 QAM, 16 QAM, and 64 QAM) for FFT-based OFDM and WOFDM are simulated to compare the BER performance of the OFDM system. Available bandwidth plays a crucial role in deciding data rate, number of subcarriers used, and further separation between subcarriers in the frequency domain. The wireless communication channel is considered to be an AWGN channel under a flat fading environment. Data signals are transmitted through a large number of orthogonal subcarriers, and each subcarrier bears a limited bandwidth.

The simulative parameters used here in the analysis for FFT and wavelet-based OFDM configuration are in compliance with the LTE specifications defined by 3GPP, tabulated in Table 1. According to LTE parameterization [11], subcarrier spacing = 15 kHz, for keeping orthogonality; symbol rate should be $(1/15\,\text{kHz}) = 66.7\,\mu$s. If the CP used here is of 20% of the OFDM symbol time, then the overall symbol duration becomes $66.7 + 13.3 = 80\,\mu$s. Also, wavelet-based OFDM does not use CP, and thus, the symbol duration will remain $66.7\,\mu$s. As shown in Table 1, the number of subcarriers used is 76, and the symbol duration is $80/66.7\,\mu$sec for WOFDM/OFDM. Now the number of bits carried by modulation symbol is 6 for 64 QAM, and it will be different for different modulation techniques.

Table 2: Spectral efficiency vs. max attainable data rate.

Modulation	Parameters	OFDM	WOFDM
4 QAM	Max data rate	0.95 Mbps	1.13 Mbps
	Spectral efficiency	0.76 bps/Hz	0.9 bps/Hz
16 QAM	Max data rate	1.9 Mbps	2.27 Mbps
	Spectral efficiency	1.52 bps/Hz	1.81 bps/Hz
64 QAM	Max data rate	2.85 Mbps	3.415 Mbps
	Spectral efficiency	2.28 bps/Hz	2.73 bps/Hz

$$\begin{aligned} &\text{Number of bits/OFDM symbol} \\ &\quad = \text{no of subcarriers} \times \text{no.of bits/QAM symbol} \\ &\quad = 76 \times 6 = 456\ \text{bits/OFDM symbol}, \end{aligned} \tag{4}$$

$$\begin{aligned} &(\text{Max data rate})_{\text{OFDM}} \\ &\quad = \text{number of bits per OFDM symbol/OFDM symbol time} \\ &\quad = 456/80 = 5.7\ \text{Mbps}, \end{aligned} \tag{5}$$

$$(\text{Max data rate})_{\text{WOFDM}} = 456/66.7 = 6.83\ \text{Mbps}. \tag{6}$$

For error-correcting codes where conventional coder 1/2 rate is used:

$$(\text{Max data rate})_{\text{OFDM}} = 5.7/2 = 2.85\ \text{Mbps}, \tag{7}$$

$$(\text{Max data rate})_{\text{WOFDM}} = 6.83/2 = 3.415\ \text{Mbps}. \tag{8}$$

Now, $(\text{Spectral efficiency})_{\text{OFDM}} = \text{max.data rate/allocated bandwidth} = 2.85\ \text{Mbps}/1.25\ \text{Mbps} = 2.28\ \text{bps/Hz}$.

$$(\text{Spectral efficiency})_{\text{WOFDM}} = 3.415/1.25 = 2.73\ \text{bps/Hz}. \tag{9}$$

In a similar manner, spectral efficiency and max data rate are calculated for other modulation techniques, i.e., 4 QAM and 16 QAM are tabulated in Table 2.

A comparative analysis is separately plotted for spectral efficiency and maximum attainable data rate for each 4 QAM, 16 QAM, and 64 QAM to highlight the significant improvements. Figure 5 depicts the comparative improvements in spectral efficiency where WOFDM can be able to achieve 16.5% higher spectral efficiency to standard OFDM.

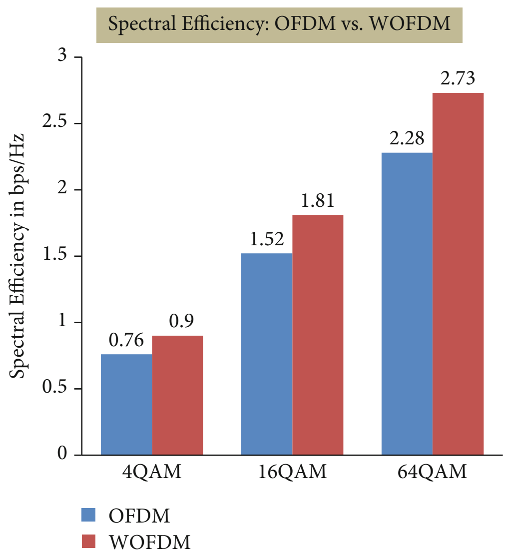

Figure 5: Spectral efficiency improvement in WOFDM.

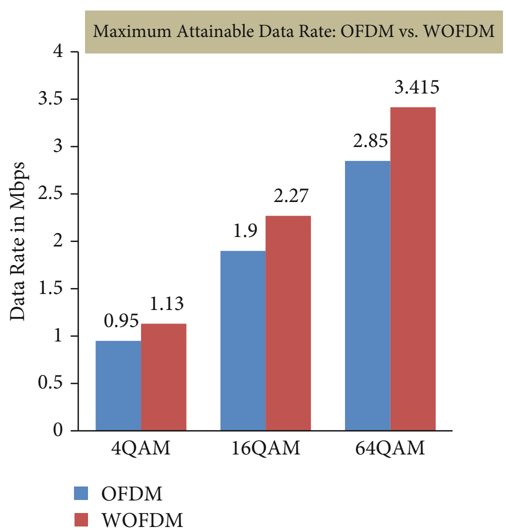

Figure 6: Data rate improvements in WOFDM.

Table 3: Simulation parameters.

Specification	FFT-based OFDM	Wavelet-based OFDM
Bandwidth	1.25 MHz	1.25 MHz
FFT size	128	NA
No. of subcarriers	76	76
No. of bits	19200	19200
Number of symbols	100	100
Max data rate	2.85 Mbps	3.41 Mbps
Spectral efficiency	2.28 bps/Hz	2.73 bps/Hz
Cyclic prefixing	20%	Nil
Channel	AWGN	AWGN
Modulation	64 QAM	64 QAM
Convolution coding	1/2	1/2

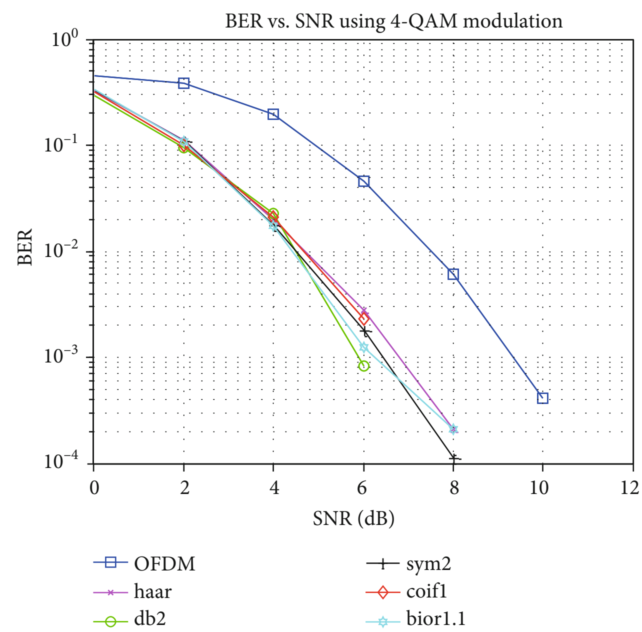

Figure 7: BER vs. SNR for different wavelet-based OFDM at 4 QAM.

Similarly, Figure 6 depicts the comparative improvements in maximum attainable data rate where WOFDM can be able to achieve a 16.6% higher data rate than the standard OFDM.

The simulation parameters for BER vs. SNR analysis of different wavelet-based OFDM are tabulated in Table 3 for 1.25 MHz spectrum band over AWGN channel condition.

Simulative analysis is shown in Figures 7, 8, 9, where different wavelet-based OFDM (five wavelets) are evaluated against the BER performance. Spectral efficiency and max data rate of M-ary PSK comes out similar to M-ary QAM; however, its BER performance deteriorates significantly, and therefore, M-ary PSK is not an advisable configuration for LTE deployment.

In Figure 7, BER vs. SNR for WOFDM and FFT-based OFDM with 4 QAM modulation scheme is plotted to demonstrate the 3 dB gain. In this plot, db2 wavelet outperforms other under-considered wavelet variants.

In Figure 8, BER vs. SNR for 16 QAM modulation scheme is plotted to demonstrate nearly 4 dB gain over standard FFT-based OFDM. In this plot, coif1 wavelet seems to be performing better than other under-considered wavelets.

However, there is almost a 4 dB difference observed in BER performance when 4 QAM and 16 QAM configurations are compared.

In Figure 9, the BER performance of conventional OFDM and WOFDM is compared where it is investigated that Haar wavelet (outperforms other wavelet variants by more than 1 dB) delivers more than 4 dB better performance to OFDM.

Also, it is almost a 6 dB difference observed in SNR to achieve the same BER performance when 16 QAM and 64 QAM configurations are compared.

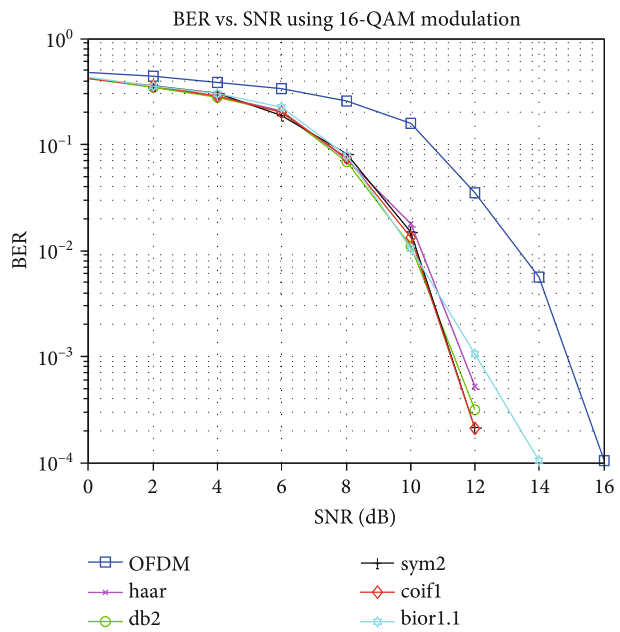

Figure 8: BER vs. SNR for different wavelet-based OFDM having 16 QAM.

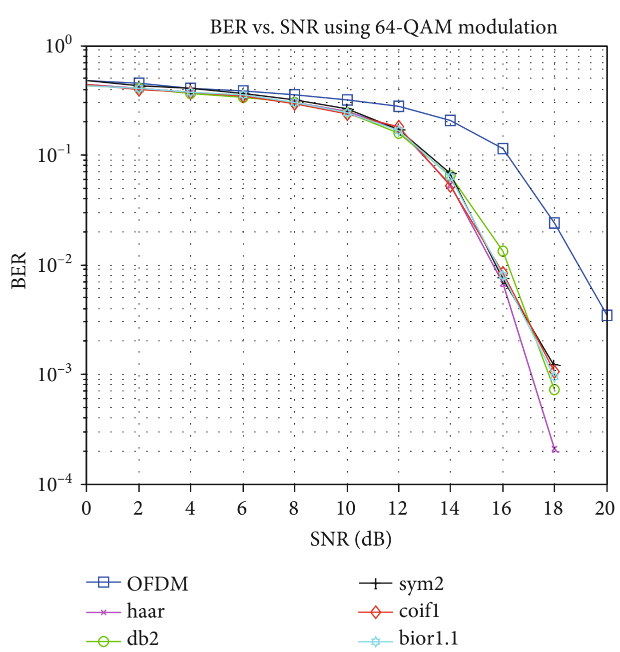

Figure 9: BER vs. SNR for different wavelet-based OFDM having 64 QAM.

7. Conclusion and Future Scope

A quantitative analysis of maximum attainable data rate and spectral efficiency for WOFDM demonstrates more than 16% improvement as compared to conventional OFDM. Simulative analysis of standard OFDM against five different wavelet-based OFDM, i.e., "haar," "db2," "sym2," "coif1," "bior1.1," is performed to investigate the BER performance. For all different modulation levels, i.e., 4 QAM, 16 QAM, and 64 QAM, it is found that WOFDM significantly outperforms conventional OFDM in terms of BER performance. However, the BER performance of one wavelet type OFDM over other wavelet type OFDM (under-considered five wavelets) relies on the modulation level. Apparently, the BER performance is a tradeoff between spectral efficiency and maximum data rate. As the modulation level increases (more number of bits per modulated signal), spectral efficiency and data rate improve but BER performance degrades. As observed in the above plots, the BER performance gets degraded (up to 10 dB) as the modulation level increases from 4 QAM to 64 QAM; however, spectrum efficiency and data rate increases by 1.83 bps/Hz and 2.285 Mbps, respectively. In the view of future scope and depth of research, potential can be further exploited through the exploration of wavelet diversity and the impact of different fading channels, viz., Rayleigh and Rician, over the WOFDM system. In the future, the proposed solution can be further evolved to explore the performance deliverables at the upper spectrum band (20 MHz) with higher offset errors.

Data Availability

No standard database was used.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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