ISSN 2047-3338

Performance Comparison of Cyclic Prefix OFDM and Unique Word OFDM in the LTE Downlink

Amevi Acakpovi, Abdul-Shakud Iddrisu, Nana Yaw Asabere and John Kwofie

Abstract—**The Long Term Evolution (LTE) downlink frame structure currently uses Cyclic Prefix Orthogonal Frequency Division Multiplexing (CP-OFDM) where the bandwidth occupied by the prefix is not utilized. Optimization of this prefix could result in increased throughput and bandwidth efficiency. This paper investigates the benefits of exploiting the unused bandwidth occupied by CP in the LTE downlink frame structure by replacing it with a newly recognized bit sequence known as the unique word (UW). A modelling and simulation approach under Matlab Simulink software was adopted. The Orthogonal Frequency Division Multiplexing (OFDM) was first modelled and tested with a 2 x 2 Multiple-In-Multiple-Out (MIMO) system while the CP and UW where implemented and tested respectively for the same input parameters. Metrics of comparison included Channel Bandwidth, number of control symbols, Modulation type, coding rate and Signal-to-Noise-Ratio (SNR) as per the LTE standard. In short, the power spectral densities of the two systems were found to be similar at about 75dBW/Hz. The Bit Error Rate (BER) of the CP-OFDM was however found to be better than BER of the UW-OFDM. In terms of throughput and Spectral efficiency, the UW-OFDM was found to outperform the CP-OFDM by 15% and 7% respectively. In this study the overall performance of the UW-OFDM is found to be better than the CP-OFDM in the LTE downlink. By eliminating cyclic prefix, bandwidth efficiency was improved. This paper therefore recommends the adoption of the UW sequence instead of the CP sequence for the LTE downlink frame structure.**

Index Terms—**Cyclic Prefix OFDM, Unique Word OFDM, OFDMA, LTE, BER and PSD**

I. INTRODUCTION

ORTHOGONAL Orthogonal Frequency Division Multiplexing (OFDM) is one of the enabling techniques for technologies and systems that are becoming common, for example LTE, LAN802.11a and other advanced wireless access technologies. In recent years, OFDM has become an important modulation technique in the field of telecommunications [1]. In the case of OFDM, the receiver design architecture is made simple and it provides a very efficient and simplified way of equalizing the effects caused by the frequency-selective multipath channels [2]. OFDM has been implemented in different parts of the world in applications such as in the IEEE 802.11 and 802.16 Wireless standards like Wimax [3], Multimedia Mobile Access Communications (MMAC), Digital Audio Broadcasting (DAB) and Digital Video Broadcasting (DVB) systems [4]. Major research continues to be done on implementing the OFDM and OFDMA techniques in cellular mobile communication systems [5].

The symbols in OFDM are separated by guard intervals which are usually implemented by Cyclic Prefixes (CP). These guard intervals provide a safeguard against Inter-channel or carrier Interference (ICI) and Inter Symbol Interference (ISI). CP is a random sequence and is solely created in time domain by copying the last part of the output of Inverse Discrete Fourier Transform (IDFT). The output of the IDFT and the prefix are combined to form the whole OFDM symbol. Some alternative implementation approaches to the conventional CP-OFDM have been proposed in [2], [6], [7]. A similar structure to CP-OFDM, the Known Symbol Padded (KSP)-OFDM is introduced in [6], where the random CP is replaced by a known symbol (KS) sequence. On the other hand, the zero padded OFDM (ZP-OFDM) [7] occurs when the known sequence in KSP-OFDM is set to zero. In [3], a new OFDM signaling scheme, where the usual cyclic prefixes are also replaced by deterministic sequences was proposed. This deterministic sequence is often addressed as Unique Word (UW) and the scheme is referred to as UW-OFDM. The most important difference between KSP-OFDM and CP-OFDM, and UW-OFDM is the fact that, the UW is part of the Discrete Fourier Transform (DFT) interval, whereas in KSP-OFDM and CP-OFDM the Known Symbol and Cyclic Prefix are not part of the DFT interval. The insertion of the UW within the DFT interval requires the introduction of some correlations in the frequency domain, which can advantageously be exploited by the receiver to improve the Bit Error Ratio (BER) performance [8]-[11], whereas the KSP-OFDM does not feature these correlations.

Amevi Acakpovi is with the Department of Electrical/Electronics Engineering, School of Engineering, Accra Polytechnic, Accra, Ghana (Email: acakpovia@gmail.com).

Abdul-Shakud Iddrisu is with the Department of Telecommunications, Ghana Technology University College, Accra, Ghana (Email: nzoyiri@gmail.com).

Nana Yaw Asabere is with the Department of Computer Science, School of Applied Sciences and Arts, Accra Polytechnic, Accra, Ghana (Email: yawasabere2011@yahoo.com).

John Kwofie is with the Department of Telecommunications, Ghana Technology University College, Accra, Ghana (Email: joeperko2001@gmail.com).

The CP-OFDM performs very well as per the standard; however the performance is achieved at the expense of bandwidth that could be used for application data [8]. The rapid development of applications with demand for higher data throughputs has necessitated the continuous extension of the 3rd Generation Partnership Project (3GPP) standards to derive efficiencies from the available and limited spectrum. OFDM is one of the technologies that improve the drive towards higher throughput capacities. CP has been used in OFDM for a variety of purposes including channel estimation and elimination of ISI. There is a constant need to optimize bandwidth efficiency and increase throughput in the access networks. It is observed that in CP-OFDM a part of the bandwidth which is used to generate is unused and therefore maximum bandwidth efficiency may not be achieved.

This paper therefore focuses mainly on the investigation of the performance analysis of UW-OFDM compared to the CP-OFDM in the LTE downlink scenario. The paper aims at analytically evaluating the performance of UW against CP for OFDM system in LTE downlink channel environment. An OFDM/LTE network model will be first developed and both the Cyclic-Prefix CP-OFDM and Unique-Word UW-OFDM will be respectively implemented on the models using Matlab software. Performance metrics will be measured by simulation to achieve the comparison.

II. MATHEMATICAL MODELING

A. *OFDM Model*

OFDM divides a high-rate transmit data stream into *N* lower-rate streams with each of the symbols having a duration larger than the channel delay spread. This serves to mitigate inter-symbol interference (ISI). The individual sub-streams are sent over *N* parallel sub-carriers which are orthogonal to each other. With the help of an Inverse Fast Fourier Transform (IFFT), the OFDM can be transmitted using a single radio. The OFDM Modulator System modulates an input signal using orthogonal frequency division modulation. The modulated signal is mathematically described as follows [12]:

$$v(t) = \sum_{k=0}^{N-1} X_k e^{j2\pi k\Delta f t}, 0 \le t \le T \qquad (1)$$

where $\{X_k\}$ represents data symbols, *N* is the number of subcarriers whiles *T* represents the OFDM symbol duration. The subcarrier spacing of $\Delta f = 1/T$ makes them orthogonal over each symbol period. This is expressed as:

$$\begin{aligned}\frac{1}{T}\int_0^T \left(e^{j2\pi m\Delta f t}\right)^* \cdot \left(e^{j2\pi n\Delta f t}\right) dt \\ = \frac{1}{T}\int_0^T \left(e^{j2\pi(m-n)\Delta f t}\right) dt \qquad (2) \\ = 0 \text{ for } m \ne n\end{aligned}$$

The data symbols, X_k, are usually complex and can be from any modulation alphabet, e.g., QPSK, 16-QAM, or 64-QAM. Fig. 1 shows an OFDM modulator. It consists of a bank of *N* complex modulators, where each corresponds to one OFDM subcarrier.

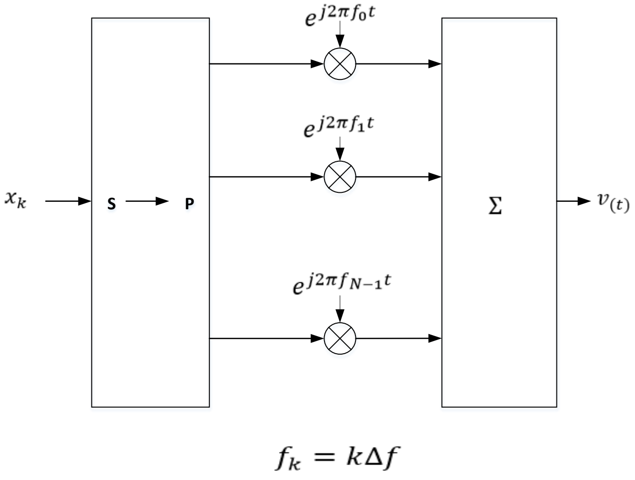

Fig. 1. OFDM Modulator

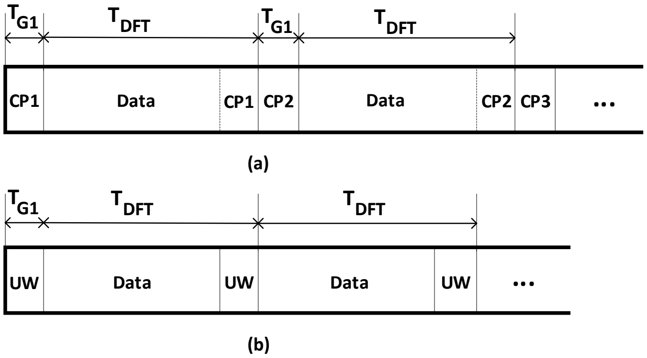

Fig. 2. Transmit Symbol Structures for (a) CP-OFDM and (b) UW-OFDM [3]-[9]

B. *Generation of UW-OFDM Signal*

Fig. 2 reveals the differences between the conventional CP-OFDM and the UW-OFDM transmit symbol structures. Some key differences between a UW and a CP based OFDM system can be pointed out:

- the UW lies inside the Discrete Fourier Transform (DFT) window, while the CP lies outside the DFT interval.
- the CP is based on the transmitted data. Since the OFDM data symbol varies from symbol to symbol the CP is observed to be random.
- the UW is deterministic and therefore the same for all OFDM symbols.

Similar to conventional OFDM systems, a vector of complex QAM/PSK data symbols, $\tilde{\mathbf{d}} \in \mathbb{C}^{N_d \times 1}$, which are defined in frequency domain, is considered. In general, zero subcarriers are inserted at the DC position and at the band edges. Let the number of zero subcarriers to be inserted be Nz. After inserting these zero subcarriers, the OFDM symbol in the frequency domain $\tilde{x} \in \mathbb{C}^{N \times 1}$ can be written as:

$$\tilde{x} = B\tilde{d} \quad (3)$$

$B \in C^{N\times N_d}$ contains zero row vectors at the positions of zero subcarriers, unit row vectors at the appropriate positions of the data subcarriers, and N represents the DFT window length. The time domain OFDM symbol $x \in C^{N\times 1}$ is calculated as

$$x = F_N^{-1}\tilde{x} \quad (4)$$

where F_N^{-1} represents the N-point DFT matrix with $[F_N]_{k,l} = e^{\frac{-j2\pi kl}{N}}$ and k= 0, 1,… ,N-1.

The above explained procedure is valid for any OFDM system. However, in UW-OFDM, a deterministic sequence called UW $x_u \in C^{N_u\times 1}$ is introduced at the end of each time domain OFDM symbol. This can be formulated as $x = [x_d^T\ x_u^T]^T$. Here, $x_d \in C^{(N-N_u)\times 1}$ denotes the vector containing the random time domain samples affected by the data $\tilde{d}$.

To generate an UW-OFDM symbol with the desired properties, it is shown in [39] that a two-step approach is beneficial, or else the symbol energy will almost explode.

- **Step 1:** An OFDM time domain symbol is generated with a zero UW such that $x = \left[x_d^T\ 0^T\right]^T$, where x can be obtained from the equation $x = F_N^{-1}\tilde{x}$.
- **Step 2:** The desired UW sequence x_u is added to the vector x to obtain the final UW-OFDM time domain symbol $x' = x + [0^T\ x_u^T]^T$.

C. Spectral Efficiency

According to [2], for a QPSK mapping without coding, the spectral efficiencies of both CP and UW systems are calculated as:

$$\eta_{cp} = \frac{2N_d}{T_N(1+\frac{N_{cp}}{N})}\cdot\frac{1}{\Delta f N} \quad (5)$$

$$\eta_{uw} = \frac{2N_d}{T_N}\cdot\frac{1}{\Delta f N} \quad (6)$$

Where N_d is the number of data carriers, N = number of carriers, η_{cp} length of the guard interval or CP.

The structure of the LTE subframe with a CP and with UW is illustrated in Fig. 3 and Fig. 4:

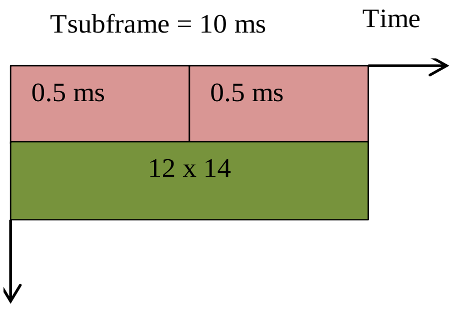

Fig. 3. LTE OFDM Subframe with CP

III. SIMULATION SETUP

A 2 x 2 MIMO was first implemented in Matlab with a code derived from [11] as presented in appendix I and II. Some parameters called in the code in appendix I have been provided in a separate file (appendix III). Furthermore, a UW sequence was generated based on a new code illustrated in appendix III. The codes were then combined to simulate the CP-OFDM first and later, the UW-OFDM. Fig. 5 shows the strategy adopted to run the simulations. On start, the parameters for the simulation scenario are set in a function designed for the parameter structures. The next step is to initialize the parameters. After initialization the parameters, the main part of the Matlab code is called. The maximum number of iterations maxIter, the maximum number of errors generated by the simulated system maxError and the maximum number of bits maxBits processed are the main decision points for the simulation. When the system reaches the maximum allowable error, the simulation is terminated. If all the above conditions are not exceeded and all the payload data maxBits is processed, the simulation is equally terminated. The simulation is respectively run for the CP-OFDM and UW-OFDM and the generated results are recorded.

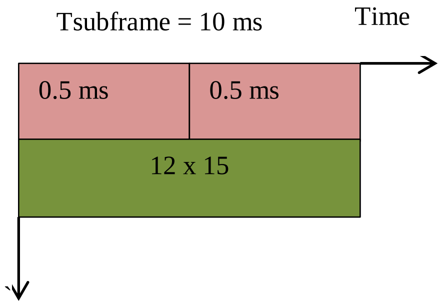

Fig. 4. LTE OFDM Subframe with UW

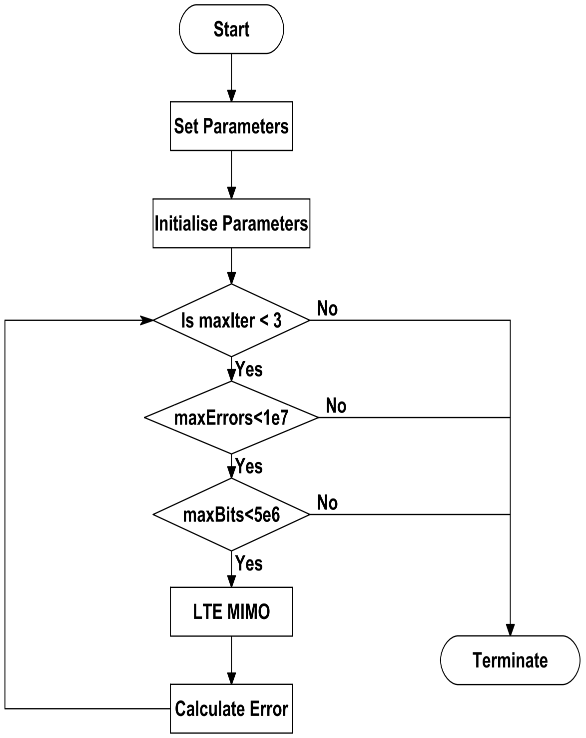

Fig. 5. Flowchart Depicting the Simulated Algorithm

IV. RESULTS AND ANALYSIS

A. *Summary of Parameters Adopted for the Simulation*

Table 1 shows a summary of parameters used in the simulation setup. The setup is focused on a 2x2 MIMO LTE downlink.

TABLE I
LIST OF PARAMEETERS ADOPTED FOR THE SIMULATION

Parameters	Values	Comment
txMode	2	Transmission mode one of {1, 2, 4}
numTx	2	Number of transmit antennas
numRx	2	Number of receive antennas
chanBW	6	Index to channel bandwidth used [1, ...6]
contReg	1	No. of OFDM symbols dedicated to control information
modType	5	Modulation type [1, 2 ,3] for ['QPSK, '16QAM', '64QAM']
cRate	3/4	Rate matching target coding rate
maxIter	6	Maximum number of turbo decoding iterations
fullDecode	1	Whether "full" or "early stopping" turbo decoding is performed
chanMdl	'flat-high-mobility'	Channel model
corrLvl	'Low'	Correlation level
Eqmode	2	Equalizer type used
chEstOn	1	0,1,2,3 for different types
snrdB	16	Signal to Noise ratio
maxNumErrs	10^5	maximum number of errors found
maxNumBits	10^7	Maximum number of bits processed
visualsOn	1	To visualize channels in scope 1 or 0

A. *Comparison of Constellation Diagrams*

For both CP-OFDM and UW-OFDM, Fig. 6 shows the constellations diagrams from the two receive antennas from a frame of data after it is processed by the equalization function. Similarly when the simulation was run for UW-OFDM Fig. 7 was obtained for the two receive antennas after equalization. The two sets of constellation diagrams after equalization are very similar.

The two systems CP-OFDM and UW-OFDM at an SNR = 16dB exhibit a power spectral density (PSD) of about 75dBW/Hz. The PSD performance of the UW-OFDM is therefore satisfactory as compared to CP-OFDM considering the fact that the UW-OFDM system is carrying more user data than the CP-OFDM. In actual fact, the CP-OFDM is processing 168 symbols per radio frame whiles the UW-OFDM is processing 180 symbols per radio frame, 7% more symbols than the CP-OFDM system.

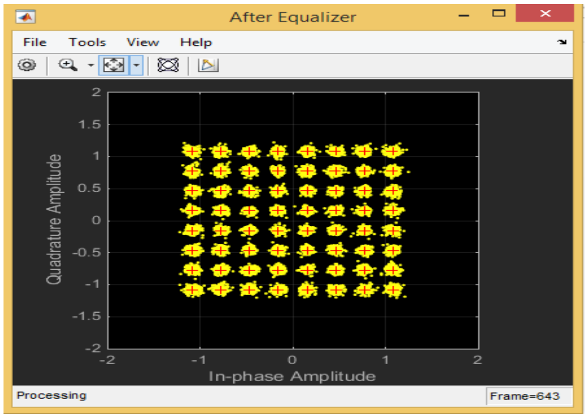

Fig. 6. Constellation Diagram after Equalization for CP

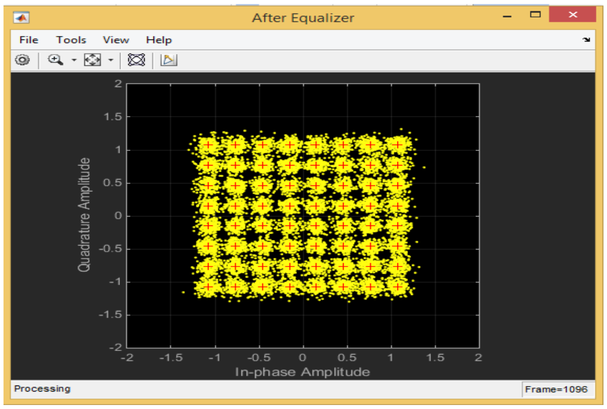

Fig. 7. Constellation Diagram after Equalization for UW

B. *Comparison of Spectral Density*

With the help of a spectrum analyzer, Fig. 8 and Fig. 9 were obtained for CP-OFDM for both antennas. When compared with Fig. 10 and Fig. 11, obtained for the UW-OFDM, a high similar performance is observed.

The performance of the PSD of UW and CP are very close. This is explained by the fact that the energy expended on the redundant cyclic prefix is now used for transmitting user data. Essentially the energy per symbol is the same for both CP-OFDM and UW-OFDM. Further to this we can postulate that the UW-OFDM uses the energy of the system more efficiently than CP-OFDM.

C. *BER Comparison*

The BER of the CP-OFDM and UW-OFDM are shown Fig. 14. For an SNR of 0 – 25dB the BER of the UW system varies between 0 - 10^{-4} whiles that of the CP varies between 0 - 10^{-2}. This is expected as the BER is a function of the SNR. Since more symbols are packed into an UW radio frame there will be degradation in the BER of the UW as compared to CP which has fewer symbols. Results show that the CP-BER outperforms the UW-BER by about 5dB as the SNR increases.

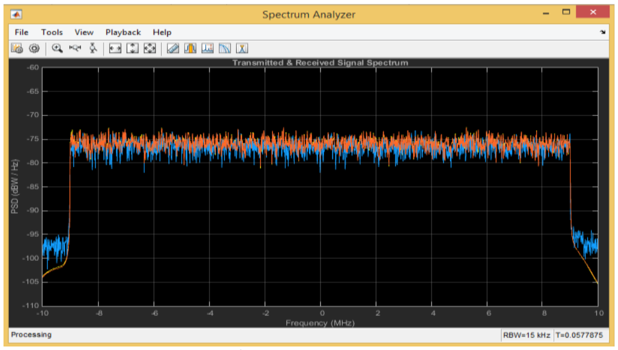

Fig. 8. Spectral Diagram for Transmit Signal 1 and Receive Signal 1 for CP-OFDM

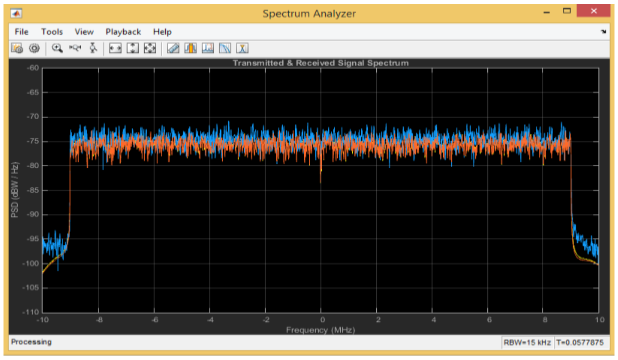

Fig. 9. Spectral Diagram for Transmit Signal 2 and Receive Signal 2 for CP-OFDM

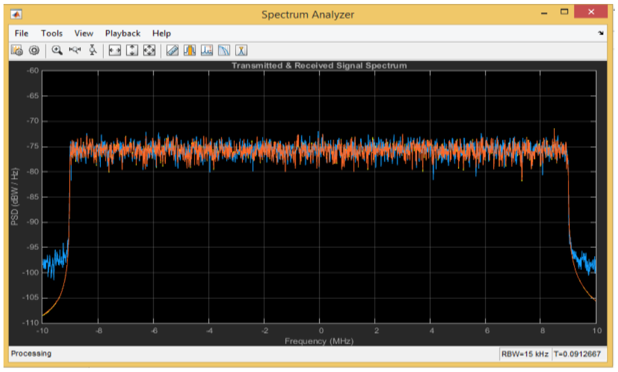

Fig. 10. Spectral Diagram for Transmit Signal 1 and Receive Signal 1 for UW-OFDM

D. *Throughput and Spectral Efficiency Comparison*

The throughput is a measure of the system capacity and a function of the spectral efficiency. Table 2 compares the throughput of the two systems and Table 3 compares the spectral efficiencies. The CP LTE downlink has a system throughput of between 3.52 – 63.78 Mbps for the specified 2x2 MIMO system and 4.1 – 73.6 Mbps for UW. From table 2 the throughput of the UW-OFDM is on average observed to be 15% higher than that of the CP-OFDM.

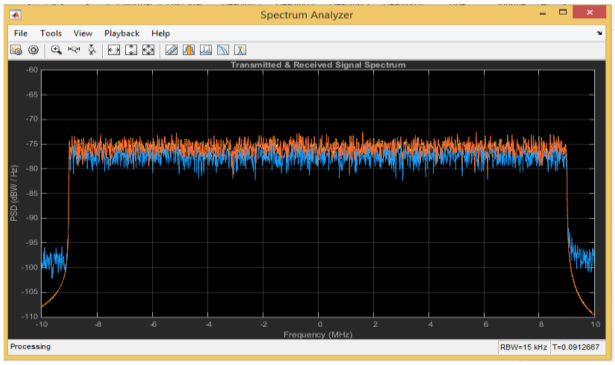

Fig. 11. Spectral Diagram for Transmit Signal 2 and Receive Signal 2 for UW-OFDM

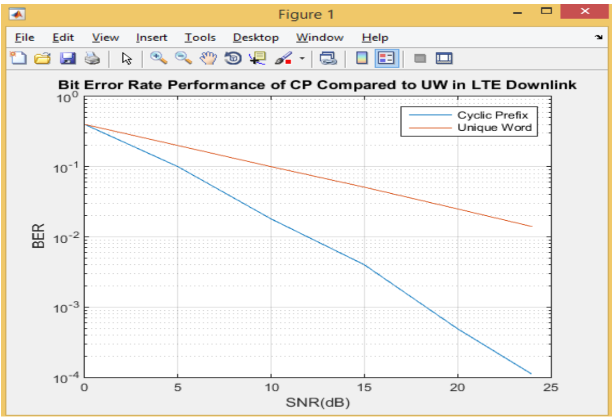

Fig. 12. Comparison of BER to SNR for UW-OFDM and CP-OFDM

TABLE II
THROUGHPUT RESULTS

Channel Bandwidth	**CP Mbps**	**UW Mbps**	**UW/CP %**
1.4 MHz	3.52	4.1	**116%**
3 MHz	9.34	10.65	**114%**
5 MHz	15.61	17.84	**114%**
10 MHz	31.59	36.20	**115%**
15 MHz	46.89	54.24	**116%**
20 MHz	63.78	73.06	**115%**

TABLE III
SPECTRAL EFFICIENCY OF THE CP-OFDM AS COMPARED TO THE UW-OFDM

Modulation Type	**CP bits/sec/Hz**	**UW bits/sec/Hz**	**UW / CP %**
64QAM	5.60	6.00	**107%**
16QAM	3.73	4.00	**107%**
QPSK	1.87	2.00	**107%**

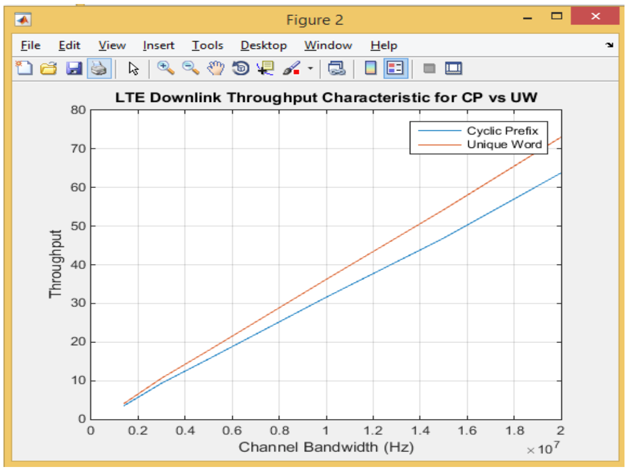

Fig. 13. Comparison of Throughput of UW-OFDM and CP-OFDM

This paper set out to analytically evaluate the performances of CP-OFDM and UW-OFDM in the LTE downlink, from the eNodeB to the user terminal. The spectral efficiencies are computed as illustrated in table 3 for the different modulation types specified by 3GPP in the LTE specifications. A comparison of the results shows that the UW-OFDM performs better than the CP-OFDM with respect to spectral efficiency at a rate of 7% increase.

The second objective was to simulate the CP OFDM and UW OFDM in the LTE downlink in the Matlab environment. The approach used by [13] was largely used in setting up the environment for the downlink. [14], [15], [16] were then used to generate the UW data required for the LTE downlink environment. The system was setup, run and the results were analyzed in the previous section. It came out that the two systems had very close and similar performances in terms of power density spectral. The system's constellation diagrams were also similar.

The third objective was to measure the performances of CP-OFDM and UW-OFDM in the LTE downlink environment using throughput and spectral efficiency. Data on the throughput and BER for the two systems were collected and analyzed. The throughput of UW and hence the spectral efficiency outperformed the CP systems by over 10%.

On the other hand, the BER performances were better with the CP-OFDM than with the UW-OFDM. The BER observation in our study conforms to [13] where a reduction in BER is also observed when the CP is used to transmit pilot signals. This is further explained by the fact that the number of bits in the UW is more than in CP for the same input bandwidth and power. The UW-OFDM performs comparably well against the CP-OFDM in respect of the power spectral density graphs. The UW-OFDM out-performs the CP-OFDM both in throughput and spectral efficiency.

VI. CONCLUSION

This paper investigated the possible benefits of changing Cyclic Prefix OFDM by Unique Word OFDM in the LTE downlink. A model of OFDM for a 2x2 MIMO was constructed and simulated under Matlab/Simulink. The UW was found to have a better power spectral density performance than CP OFDM. In addition, the spectral efficiency of the UW was 7% better than that of CP. However, the BER of the UW performs worse than the CP system. The throughput of the two systems were measured and compared with the same parameter settings. The UW was found to perform averagely 10% better than the CP. This implies that the UW could be suitable for applications that are resilient to BER degradations in favor of efficiency, throughput and power spectral density.

Based on the measurements discussed in this paper, it can be realized that, generally, the UW-OFDM performs better than the CP-OFDM in the LTE downlink environment.

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