EFFECT OF VARYING THE CYCLIC PREFIX LENGTH ON OFDM SYSTEM PERFORMANCE OVER DIFFERENT WIRELESS CHANNEL MODELS

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Abstract—Cyclic Prefix (CP) is a significant feature of an OFDM waveform. It is used to completely eliminate both Inter-Symbol Interference (ISI) and Inter-Carrier Interference (ICI) as long as the CP length is greater than the channel delay spread. By eliminating the ISI and ICI, the CP compensates for the effect of the multi-path dispersion; but it consumes a considerable amount of the scarce spectrum and the power. Conventional OFDM uses a fixed and large CP length to tolerate worst case channel condition. This technique, however, causes a loss in bandwidth efficiency as well as consumes relatively more transmitter energy. Therefore, there is a need to adopt the CP length according to instantaneous channel parameters. In this paper, we study the effect of varying the CP length on the OFDM system performance over different channel models, where the variable CP length is estimated based on the RMS delay spread of the channel. According to this method, the estimated CP length optimizes the system capacity and improves the overall system performance.

Keywords—Cyclic Prefix, OFDM, Power Delay ProfileS, System Capacity, RMS Delay Spread.

I. INTRODUCTION

There is an ever increasing demand to increase the data throughput and to make more efficient use of the available spectrum in wireless data communication systems. The Orthogonal Frequency Division Multiplexing (OFDM) modulation technique is one of the methods used to achieve these goals. Due to its robustness against multi-path fading the OFDM is becoming a modulation technique of choice for most commercial high-speed broadband wireless communication systems. The OFDM is a special form of multi-carrier modulation schemes that is capable of overcoming the frequency selectivity of the radio channels and providing high data rates without the ISI [1-3]. However, in multipath fading channels, the time variation of a fading channel over an OFDM symbol period destroys the orthogonality between the sub-channel and leads to the ICI [4, 5].

A circular extension known as the CP is added at the head of OFDM symbols in order to eliminate both ISI and ICI. To achieve this goal, the CP length must be greater than the delay spread of the multipath channel [6]. However the introduction of the CP reduces the bandwidth efficiency and decreases the data rate (capacity of the system) because it conveys no information.It also disperses the transmitter energy(the amount of consumed power relies on how large CP length), where the signal-to-noise (SNR) lost due to the CP introduction indicates the loss of transmission energy. Because of the loss of SNR and the bandwidth efficiency, the CP needs to be chosen optimally. Typically, it is chosen based on the multipath channel duration in a given operating environment [7, 8].

The CP is always appended to the head of the OFDM symbols. This result in loss of spectral efficiency of the system. For example, in IEEE 802.11a/g standard about 25% of the useful signal is utilized by the CP [9,10]. Therefore, it is essential to understand the CP adaptation scheme. The conventional OFDM uses a large and fixed CP length, which is selected to be several times more than the RMS delay spread of the operating environment. This CP selection mandates devices which experience smaller RMS delay spread to use an excessively longer CP. In this situation the scarce network resource is misused and the limited battery power is wasted from the device perspective [9,10]. This fact motivates the research into ways for making the CP length shorter and even adaptive. An adaptive CP length could introduce a significant enhancement in spectral efficiency. In 2004, Zhang [11] proposed a method to adopt the CP length based on the variation of the channel delay spread. His method suggested selection of the CP length which is twice the channel RMS delay spread. In 2005, Chiwoo, Youngbin,Panyuh, Hyeonwoo and Jaeweon [12] proposed another method to adopt the CP length via adjusting the sampling rate. The drawback of this

method is that it requires a wide OFDM spectrum; since the CP is extended by sampling up, the occupied bandwidth will also increase. In [11,12], the Power Delay Profile (PDP) of the channels is fitted into a Negative Exponentially Decaying Profile (NEDP). Based on the NEDP a mathematical formula is derived to estimate the variable CP length for the different channel models.

The evaluation of the CP length requirements for different mobile environments is the problem addressed in this

II. SYSTEM MODEL DESCRIPTION

Fig.1 shows a basic model of an OFDM system. First the input binary data are generated and converted to the data symbols by using different modulation schemes. Once the sequence of binary values is mapped to a data symbol form, the next step is to generate an OFDM waveform by converting the serial data symbol sequence into a number of shorter parallel symbol sequences. These modulated signals are processed by the IFFT block. Then, the CP is added to the signals. The CP extends the OFDM symbol by copying the last samples of the OFDM symbol and appending it in front of the transmitted OFDM symbol. The reason for that is to preserve the orthogonality between the sub-carriers. Also, the CP allows receiver to integrate over an integer number of sinusoid cycles for each of the multi-paths when it performs OFDM demodulation with the FFT. After adding the CP, the signals are converted to serial form and transmitted through the channel [13].At the receiver side, a reverse process is performed. The serial data is received and converted to the parallel form. Then cyclic prefix is removed. After removal of cyclic prefix, Fast Fourier Transform is performed. Then the signals are demodulated using different modulation schemes to get the original binary data [13].
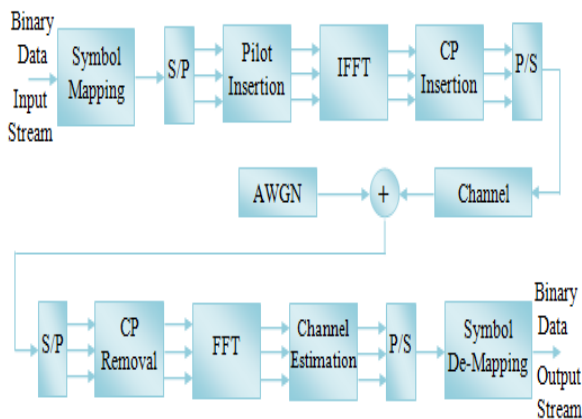

Fig. 1 Block diagram of OFDM system

Fig.2 shows the proposed OFDM system model. According to this model, at the transmitter end the signal is modulated and subsequently the CP controller attaches the CP length adaptively to mitigate both ISI and ICI introduced due to the channel. At the receiver end, the CP controller detaches the

research. In this paper, the variable CP length is estimated based on the RMS delay spread of the channel and the PDPs are not fitted into NEDP but it is scaled by a weighting function to ensure the synchronicity assumption. Furthermore, an analytical method for evaluating Signal to Interfere and Noise Ratio (SINR)in OFDM system is utilized in th (1) for the evaluation of the CP length over different channel model.

CP length before demodulator in order to recover the transmitted signal.
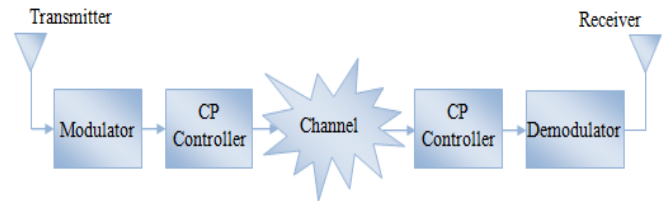

Fig. 2 Block diagram of proposed OFDM system

III. SINR CALCULATION MTHOD

An analytical method for evaluating SINR in OFDM system is taken from [14]. The SINR can be defined as:

$$SINR = \frac{p_s}{P_i + \sigma_\omega{}^2}$$

Where P_s is the useful signal power,P_i is the interference signal power and $\sigma_\omega{}^2$ is the variance of the additive white noise. The useful and the interference signal powers are both obtained from the PDP scaled by a weighting function called "bias function" given as:

$$C(\tau) = \begin{cases} 0, & \tau < 0 \\ 1, & 0 \leq \tau < T_g \\ 0, & T_{OFDM} \leq \tau \\ \frac{T_u - (\tau - T_g)}{T_u}, & T_g \leq \tau < T_g \end{cases} \quad (2)$$

Where T_g is the CP length, T_u is the useful OFDM symbol length and T_{OFDM} is total OFDM symbol length.
The channel PDP is assumed to have P taps with power $|\alpha_i|^2$ and i^{th} tap at delayτ_i. The channel is normalized such that $\sum_{i=1}^{p} a_i = 1$.
So, the useful signal power is given by:

$$P_s = \sum_{i=1}^{p} C(\tau)^2 |a_i|^2 \quad (3)$$

While the interference signals power is given by:

$$P_i = \sum_{i=1}^{p} (1 - C(\tau)^2)|a_i|^2 \quad (4)$$

IV. WIRELESS STANDARD AND CHANNEL MODELS

Several wireless channel models are used to simulate the radio wave propagation. These channels are currently utilized in industry where each model is convenient for a specific type of environment. Uses of standardized models allow researchers to provide 'apple to apple' comparisons of the obtained results. The considered channel models that are used for the performance evaluation tasks in this paper work are:

A. ITU CHANNEL MODELS

The ITU channel models consist of two types of the channels. Table.1 and Table.2 show the PDPs and the characteristic of

C. 3GPP CHANNEL MODELS

The 3GPP channel model consists of urban micro-cell and urban macro-cell channel model. Table.4 shows the tap delay, the average power and the RMS delay spread for these channel models.

Table 1 Power Delay Profiles of ITU-A Channel

Tap No.	Indoor A		Pedestrian A		Vehicular A	
	Delay (ns)	Power (dB)	Delay (ns)	Power (dB)	Delay (ns)	Power (dB)
1	0	0	0	0	0	0
2	50	-3.0	110	-9.7	310	-1.0
3	110	-10.0	190	-19.2	710	-9.0
4	170	-10.0	410	-22.8	1090	-10.0
5	290	-26.0	NA	NA	1730	-15.0
6	310	-32.0	NA	NA	2510	-20.0
	$\tau_{RMS} = 35\ ns$		$\tau_{RMS} = 45\ ns$		$\tau_{RMS} = 370\ ns$	

Table 2 Power Delay Profiles of ITU-B Channel

Tap No.	Indoor B		Pedestrian B		Vehicular B	
	Delay (ns)	Power (dB)	Delay (ns)	Power (dB)	Delay (ns)	Power (dB)
1	0	0	0	0	0	-2.5
2	100	-3.6	200	-0.9	300	0
3	200	-7.2	800	-4.9	8900	-12.8
4	300	-10.8	1200	-8.0	12900	-10.0
5	500	-18.0	2300	-7.8	17100	-25.2
6	700	-25.2	3700	-23.9	20000	-16.0
	$\tau_{RMS} = 100\ ns$		$\tau_{RMS} = 750\ ns$		$\tau_{RMS} = 4000\ ns$	

Table 3 Power Delay Profiles of EITU Channel

Tap No.	EPA		EVA		ETU	
	Delay (ns)	Power (dB)	Delay (ns)	Power (dB)	Delay (ns)	Power (dB)
1	0	0	0	0	0	-1.0
2	30	-1.0	30	-1.5	50	-1.0
3	70	-2.0	150	-1.4	120	-1.0
4	90	-3.0	310	-3.6	200	0.0

these channels. Theses Tables indicate the relative delay, the average power for the taps of the multi-path channel and the RMS delay spread based on the ITU recommendation.

B. EITU CHANNEL MODELS

The Extended ITU channel model for LTE was called Extended Pedestrian-A (EPA), Extended Vehicular-A (EVA), and Extended Typical Urban (ETU). Table.3 represents the PDPs of this channel. This Table shows the channel models parameters such as the excess delay, the average power and the RMS delay spread.

5	110	-8.0	370	-0.6	230	0.0
6	190	-17.2	710	-9.1	500	0.0
7	410	-20.8	1090	-7.0	1600	-3.0
8	NA	NA	1730	-12	2300	-5.0
9	NA	NA	2510	-16.9	5000	-7.0
	$\tau_{RMS} = 45\ ns$		$\tau_{RMS} = 357\ ns$		$\tau_{RMS} = 991\ ns$	

Table 4 Power Delay Profiles of 3GPP Channel

Tap No.	Urban Macro		Urban Micro	
	Delay (ns)	Power (dB)	Delay (ns)	Power (dB)
1	0	0	0	0
2	0.36	-2.22	0.28	-1.27
3	0.25	-1.72	0.20	-2.72
4	1.04	-5.72	0.66	-4.30
5	2.7	-9.05	0.81	-6.01
6	4.59	-12.50	0.92	-8.43
	$\tau_{RMS} = 850\ ns$		$\tau_{RMS} = 295\ ns$	

V. RESULTS AND DISCUSSION

The focus of this study is to give insight on the choice of an optimal CP length.

A. *Performance Evaluation of SINR for Different CP Length*

SINR expressed in Eq. (1) is used to evaluate some specific PDPs such as ITU-A, ITU-B, EITU, 3GPP and the exponential decaying PDP. Fig. 3, 4, 5 and 6 compare the effect of the CP length on the received SINR over ITU-A, ITU-B, EITU and 3GPP against exponential decaying PDPs with corresponding RMS delay spread. These figures indicate that SINR in dB is plotted as function of the CP length. It can be observed that SINR value increases as the CP length is increased. It can be seen clearly in these figures that SINR has different curves even though the RMS delay spreads are of equal value. For all the curves in these figures, the maximum SINR corresponding to the received SNR is occurred when the CP length exceeds the maximum excess delay spread of the

channel. Therefore; increasing the SNR will raise the SINR levels resulting in a larger CP length requirement.
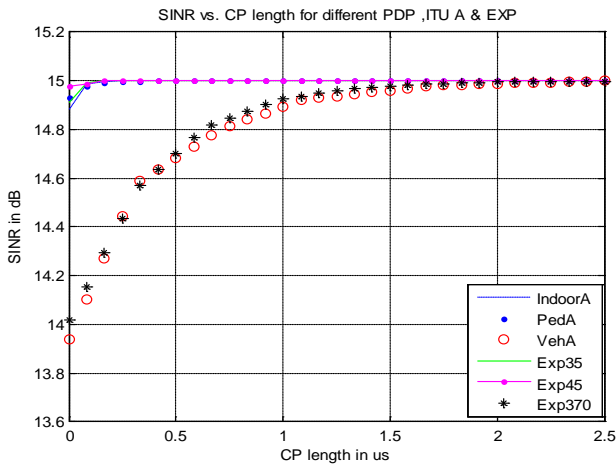

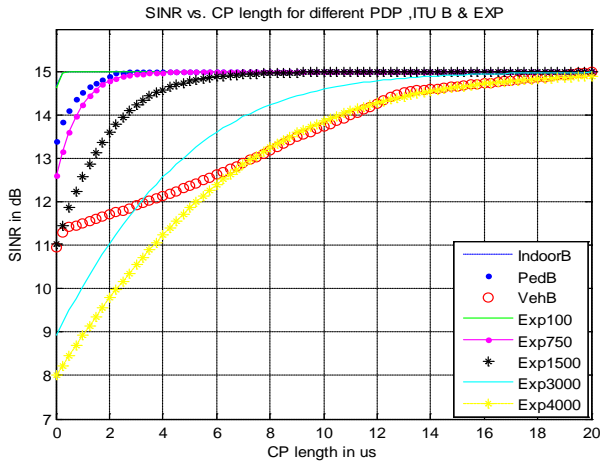Fig. 3 *SINR vs. CP length for different PDP {ITU-A & EXP}*

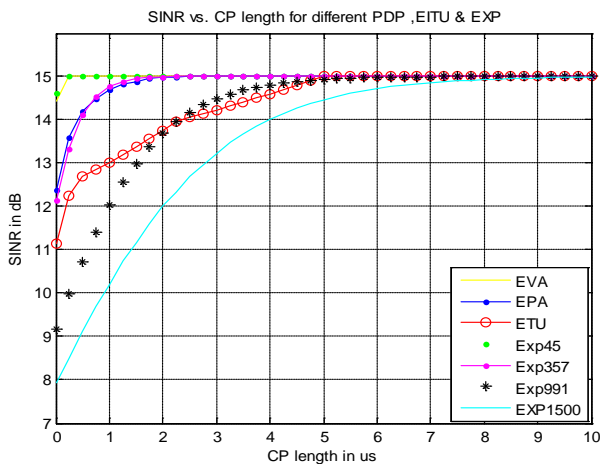Fig. 4SINR vs. CP length for different PDP {ITU-B & EXP}
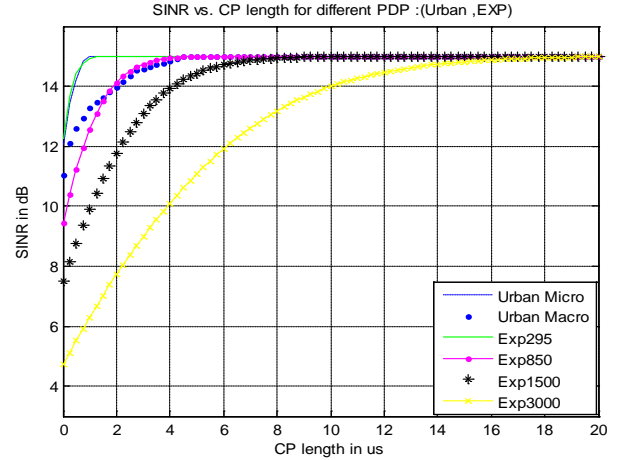

Fig. 5SINR vs. CP length for different PDP {EITU & EXP}

Fig. 6SINR vs. CP length for different PDP {3GPP & EXP}

B. Effect of CP Length on OFDM System Spectral Efficiency

In this sub-section, a conducted study giving insight on the impact of the CP length on the capacity of a base-band synchronized OFDM system. The capacity is used to evaluate the system and it is measured in bits per second per hertz. This study indicates how the CP length affects Spectral Efficiency Loss (SEL) and Signal to Interference and Noise Ratio (SINR) where SINR is mapped to capacity through Shannon's formula [14]. The optimum CP length maximizes the capacity for a given set of system parameters. The system parameter that considered in this section is the PDPs for the different channel models such as ITU-A, ITU-B, EITU and 3GPP.

As seen previously, maximizing SINR causes high BER at the receiver side, which requires a larger CP length, but utilizing a larger CP length extends the transmission time required. Therefore, an optimization of the SINR is required and can be obtained from Shannon's capacity theorem. In [14] system capacity modeling is proposed with adaptive modulation scheme and degradation factor (a link adaptation loss from the Shannon limit). It follows that capacity model is given by:

$$C(T_g) = (1 - SEL) * \min \left\{ \log_2 \left(1 + \alpha_{loss} \ SINR(T_g) \right), 6 \right\}$$

Where SELis the Spectral Efficiency Loss (CP length / Total OFDM symbol length) and$\propto_{loss}$ is the degradation factorwhich has a value of 0.4 for this study as it is used in [14].

- *Effect of the CP Length on the Different Power Delay Profiles:*
  Figures 7, 8, 9 and 10 show the effects of the CP length on the different PDPs. In these figures the CP length varies from one PDP to another based on the RMS delay spread. As seen from the figures, the indoor channel has the smallest CP length while the vehicular has the largest CP length. These figures

also indicate that the CP length increases as the RMS delay spread is increased. One of the methods used to estimate the CP length is based on the RMS delay spread; according to this method the CP length is estimated and it is given as: ($CP=\alpha*RMS$) where α is the constant in the range between (2.5to3.5). This conforms the findings of a previous study by Arslan who found that the ($CP=\beta*RMS$)) where β is the constant in the range between (2to4) [15]. It can also be observed that the estimated CP maximizes the system capacity, but increasing the CP length beyond this optimum CP results in decreasing the system capacity.
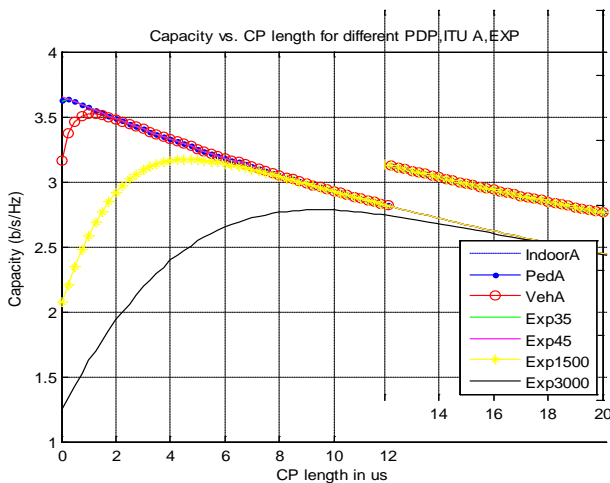

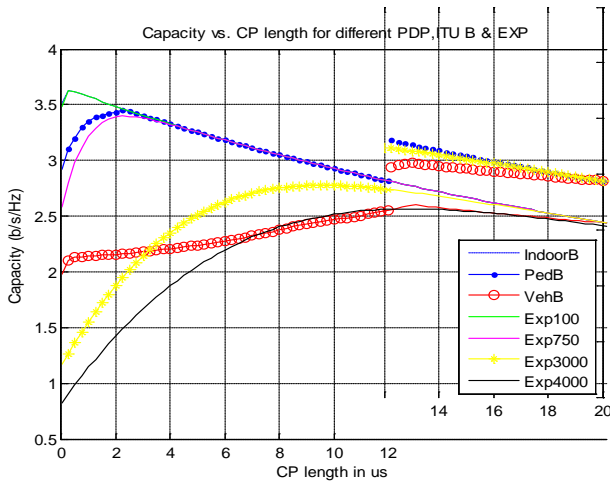
Fig. 8 Influence of the EITU PDP & EXP PDP on CP length

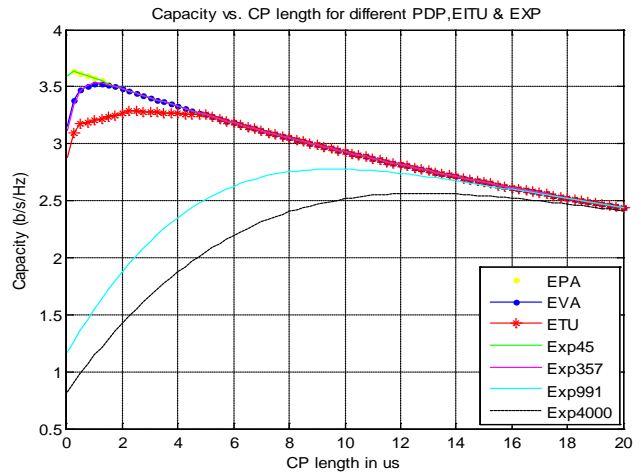Fig. 7 Influence of the ITU-A PDP & EXP PDP on CP length.

Fig. 9 Influence of the ITU-A PDP & EXP PDP on CP length.

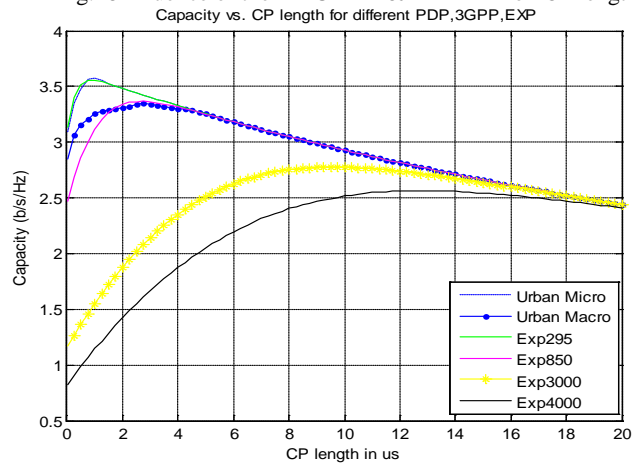

Fig. 7 Influence of the ITU-B PDP & EXP PDP on CP length.

C. Mathematical Relationship Between the CP &the RMS Delay Spread of the Channel.

As mentioned in one of the previous sections the CP can be estimated based on the RMS delay spread of the channel. In this study the SINR is applied to the PDP and the CP is calculated based on the RMS delay spread. It is found that $CP=\alpha*RMS$ where $\alpha$is the constant in the range between (2.5to3.5) optimizes the system's performance. Fig 10, 11 and 12 show the mathematical relationship between the CP and the RMS delay spread. It can be seen clearly from these figures that the CP length increases as the RMS delay spread of the channel is increased which indicates a linear relationship exists between them. Obviously the RMS delay spread is not fixed in the mobile wireless communication and its value changes depending on the terrain, clutter, antenna directivity and other factors related to propagation environment. The conventional OFDM system uses a fixed and large CP length which increases the overhead, but if one estimates the CP length based on the RMS delay spread the overhead will be reduced. Therefore; the CP length needs to be adjusted to the environment so that the mobile battery power and scarce spectrum can be conserved when the delay spread is small. Furthermore the system performance will be maintained by

reducing the ISI and ICI when the delay spread is large. From these figures it is evident that channels such as the Indoor A, B and EPA with smallRMS delay spread require small CP length, whereas the channel such as the vehicular B channel with large RMS delay spreadrequires large CP length.
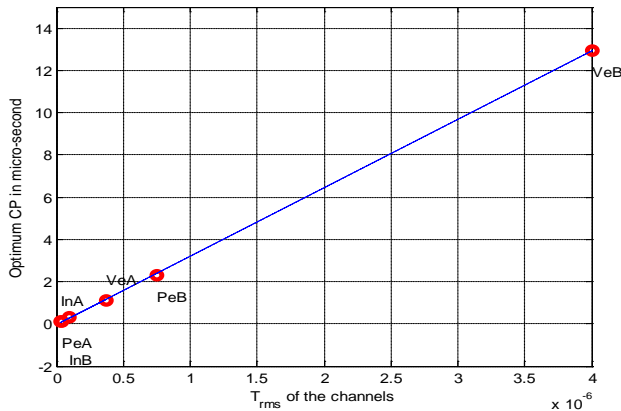

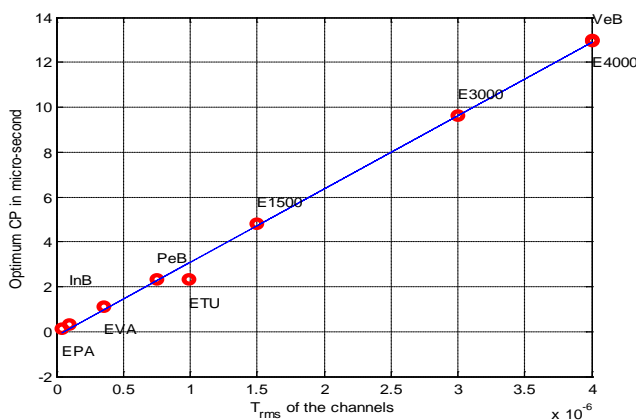Fig. 10 CP lengths vs. RMS delay spread for ITU-A, & ITU-B

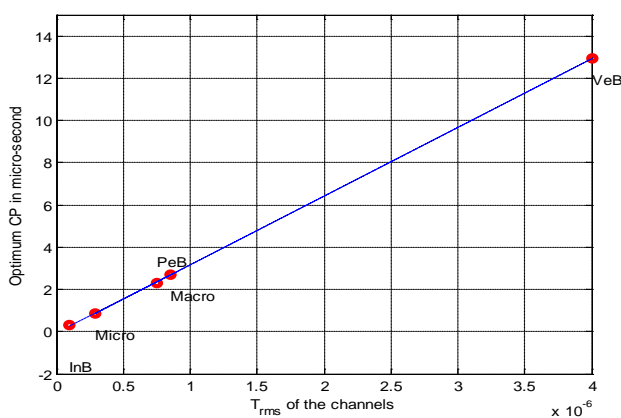Fig. 11 CP lengths vs. RMS delay spread for ITU-B, EITU & EXP

Fig. 12 CP lengths vs. RMS delay spread for ITU-B, & 3GPP

The optimal parameters associated with above analysis can be summarized in the Table 5:

Table 5The values of the CP length for different channel models according to the RMS delay spread method.

Channel Type	RMS delay	Beta value	$CP = \beta * \tau_{RMS}$
EXP	variable	3	variable
Indoor A	$\tau_{RMS} = 35$ ns	3.17	0.111 µs
Pedestrian A	$\tau_{RMS} = 45$ ns	2.7	0.121 µs
Vehicular A	$\tau_{RMS} = 370$ ns	3.04	1.127 µs
Indoor B	$\tau_{RMS} = 100$ ns	3	0.3 µs
Pedestrian B	$\tau_{RMS} = 750$ ns	3.1	2.3 µs
Vehicular B	$\tau_{RMS} = 4000$ ns	3.4	13.6 µs
EPA	$\tau_{RMS} = 45$ ns	2.7	0.121 µs
EVA	$\tau_{RMS} = 357$ ns	3.15	1.124 µs
ETU	$\tau_{RMS} = 991$ ns	2.52	2.5 µs
Urban Macro	$\tau_{RMS} = 850$ ns	3.05	2.4 µs
Urban Micro	$\tau_{RMS} = 295$ ns	2.88	0.8 µs

VI. CONCLUSIONS

An adaptive OFDM system with variable CP length over different channel models with different PDPs was described in this paper. It presented a method that is used to estimate the CP length based on the RMS delay spread of the channel. According to this method, the CP length is chosen to improve the system performance and to optimize the system capacity by mitigating both ISI and ICI. The results showed thatthe optimal CP length correlates very well with the RMS delay spread of thechannel. Thus, the choice of variable CP length is preferable to large and fixed CP length because it offers improved spectral efficiency. Furthermore, these results showed that increasing the CP length beyond the optimum length does not resultin further improvement of the system capacity and the system performance.

Finally, it may be concluded that the CP length is an essential aspect of the OFDM system. When the CP selected optimally based on the channel parameters, the overall system performance is improved. This is accomplished through

effectively mitigating the dominant problems (ISI and ICI) in the OFDM system.

References

[1] Kaur, Sandeep, and Gurpreet Bharti. "Orthogonal Frequency Division Multiplexing in Wireless Communication Systems: A Review." International Journal of Advanced Research in Computer Engineering & Technology (IJARCET) 1, no. 3 (2012): pp-125.

[2] Marchetti, Nicola, Muhammad Imadur Rahman, Sanjay Kumar, and Ramjee Prasad. "OFDM: Principles and Challenges." In New Directions in Wireless Communications Research, pp. 29-62. Springer US, 2009.

[3] Prasad, Ramjee. OFDM for wireless communications systems. Artech House, 2004.

[4] J. Li and M. Kavehrad, "Effects of time selective multipath fading on OFDM systems for broadband mobile applications," IEEE Commun. Lett., vol. 3, no. 12, pp. 332-334, 1999.

[5] Y. Zhang and H. Liu, "Impact of time selective fading on the performance of quasi-orthogonal space-time coded OFDM systems," IEEE Trans. Commun., vol. 54, no. 2, pp. 251-260, 2006.

[6] Shah, D. C., B. U. Rindhe, and S. K. Narayankhedkar. "Effects of cyclic prefix on OFDM system." In Proceedings of the International Conference and Workshop on Emerging Trends in Technology, pp. 420-424. ACM, 2010.

[7] Ness, Reto, Jean-Paul Linnartz, Liesbet Van der Perre, and Marc Engels. "The OFDM Principle." In Wireless OFDM Systems, pp. 33-51. Springer US, 2002.

[8] Pavaswini P. and Manjaiah D.H "Analysis of Effect of Cyclic Prefix on Data Rates in OFDM Modulation Techniques" International Journal of Advanced Research Computer and Mathemmatical Sciences (IJARCMS) , Vol. 3 ,2012, pp-465-470.

[9] Das, Suvra Sekhar, Frank HP Fitzek, F. D. Carvalho, and Ramjee Prasad. "Variable guard interval orthogonal frequency division multiplexing in presence of carrier frequency offset." In Global Telecommunications Conference, 2005. GLOBECOM'05. IEEE, vol. 5, pp. 5-pp. IEEE, 2005.

[10] Ghosh, Sayani. "Performance Study of WiMAX for Different QoS Parameters with Varying Cyclic Prefix." PhD diss., JADAVPUR UNIVERSITY KOLKATA, 2011.

[11] Zhang, Zhao-yang, and Li-feng Lai. "A novel OFDM transmission scheme with length-adaptive Cyclic Prefix." Journal of Zhejiang University SCIENCE 5, no. 11 (2004): 1336-1342.

[12] Lim, Chiwoo, Youngbin Chang, Jaeweon Cho, Panyuh Joo, and Hyeonwoo Lee. "Novel OFDM transmission scheme to overcome caused by multipath delay longer than cyclic prefix." In Vehicular Technology Conference, 2005. VTC 2005-Spring. 2005 IEEE 61st, vol. 3, pp. 1763-1767. IEEE, 2005.

[13] Nolan, Keith E. "Reconfigurable OFDM systems." PhD diss., Trinity College Dublin., 2005.

[14] Batariere, Mickael, Kevin Baum, and Thomas P. Krauss. "Cyclic prefix length analysis for 4G OFDM systems." In Vehicular Technology Conference, 2004. VTC2004-Fall. 2004 IEEE 60th, vol. 1, pp. 543-547. IEEE, 2004.

[15] Arslan, Hüseyin, and Tevfik Yucek. "Delay spread estimation for wireless communication systems." In Computers and Communication, 2003.(ISCC 2003). Proceedings. Eighth IEEE International Symposium on, pp. 282-287. IEEE, 2003