DOI: 10.21917/ijct.2019.0301

NEW ANALYSIS OF OPTIMAL GUARD INTERVAL FOR A MC-CDMA SYSTEM

Jong Sam Ri[1] and Yong Chan Ri[2]

[1]*Faculty of Communication, Kim Chaek University of Technology, Democratic People's Republic of Korea*

[2]*College of Information Engineering, Wonsan Jogunsil University of Technology, Democratic People's Republic of Korea*

Abstract

In MC-CDMA system, the guard interval (GI) generally is longer than the channel impulse response to mitigate inter symbol interference (ISI). But in this environment, SNR is decreased and BER is high. So, some approaches to determine the optimal GI length under SNR and BER constraints have been proposed. In this paper, we propose the new theoretical expression that can determine optimal guard interval based on modeling the channel uniform distributed exponential decay channel, when the system parameters such as RMS delay spread and the channel parameters as the number of sub-carriers are given for MC-CDMA system.

Keywords:

Optimum Guard Interval, Multicarrier Code Division Multiple Access, Inter Symbol Interference, Root-Mean-Square Delay Spread

1. INTRODUCTION

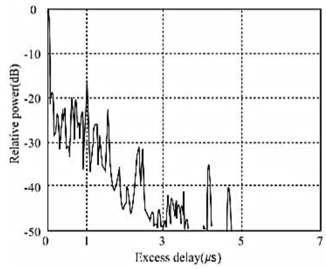
As in OFDM system, Inter symbol interference (ISI) due to time dispersion of the multi-path channel deteriorates the performance of the MC-CDMA system [1]. In order to reduce the effects of ISI, many approaches such as the iterative interference reduction techniques [2] and the pre-equalization at the transmitter and post-equalization at the receiver [3] were proposed, but these have higher computational complexity. To tackle this problem, a guard interval or a cyclic prefix is inserted into OFDM symbol [4]. It provides a periodic extension to the OFDM signal through which the "linear convolution" operation performed on the transmitted signal by the channel can be approximated by a "circular convolution" operation and simplifies the channel equalization.

Generally, a guard interval is longer than the channel impulse response [6]-[8], [18]-[19]. In this case, ISI can be mitigated completely, but SNR is decreased and BER is high, as the useful power is decreased. They referred that optimal GI minimizing BER and derived BER equation with respect to GI in M-ary DPSK Multicarrier modulation.

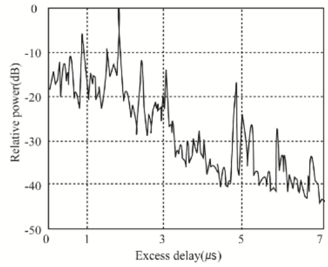
In preceding work, two hypothetical models were introduced for the optimization of guard intervals: one is an exponentially decaying profile with uniformly distributed multi-path arrivals [6], and the other is a 2-ray equal-power profile [11], [17]. The 2-ray equal-power profile which can represent the worst-case frequency selectivity is widely used in the optimization of the number of sub-carriers for multicarrier systems. In this case, there exist 2 options for the guard interval, the one is $0 < T_G < 2\tau_{RMS}$, where the second arriving ray contributes to ISI, and the other is $T_G > 2\tau_{RMS}$, where no multi-path components exceed the guard interval and there is hence no ISI. Because this model is not practical, it is not suitable for determining GI.

In [10], [12], the guard interval was set to be 4 times the τ_{RMS}, in [9], [13] to be 20% of the symbol period and in [14] to be 25% of the symbol period. In [15], they determined optimal GI by using three channel profiles based on real measurements. In [15], the propagation measurements were previously carried out in the center of Manchester, England, within the 2110-2170 MHz band using a chirp sounder. There are some parameters for characterizing the time dispersive properties of multi-path channels: average delay, RMS delay spread, and delay window and so on [16], [17]. The average delay is the first moment of the PDP. The RMS delay spread is the square root of the second central moment of the PDP. The delay window (W_q) is the duration of the middle portion of the PDP that contains q% of the total multi-path power.

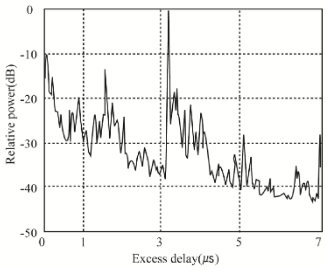
The total multi-path power ($p_{m,tot}$) is the sum of multi-path power above the noise threshold. The Fig.1 illustrates the PDPs for the 3 channels used in [5].



(a)



(b)



(c)

Fig.1. Power delay profiles for a) Ch1, b) Ch2, and c) Ch3 [5]

The value of the RMS delay spread was 0.22μs for Ch_1, 0.77μs for Ch_2, and 1.14μs for Ch_3. Based on the statistics presented in [17], Ch_1, Ch_2, and Ch_3 are representative of small, mild, and strong multi-path spreads for outdoor radio channels, respectively.

In [11], they confirmed that optimal GI exists and determined GI with respect to autocorrelation function of channel. In [5], they solved this problem, but they did not derive actual theoretical expression.

However, we cannot say that theoretical expression proposed in [5] is not completely theoretical, as they can determine optimal guard interval only when using this expression based on experiment results.

In this paper, we propose the theoretical expression that can determine optimal guard interval based on modeling the channel uniform distributed exponential decay channel, when the system parameters such as RMS delay and the channel parameters as the number of sub-carriers are given.

2. PROPOSED METHOD

Here, we derive an expression for the SNR with respect to GI and determine optimal GI based that PDP of multi-path channel CIR is modeled by uniformly distributed exponential decay random process.

For PDP, $p(t)$ is time distribution of power of received signal transmitting δ impulse.

$$p(t)=\sum_{k=0}^{L-1} a_k^2 \delta(t-\tau_k) \tag{1}$$

where a_k is real path gain and τ_k is path delay and L is the number of multi-paths.

PDP can be modeled by several models, but it is the most general to model by uniform distributed exponential decay random process. PDP is characterized by RMS delay, τ_{RMS} average delay, $\bar{\tau}$ and the length of CIR $\Delta\tau$.

$$\tau_{RMS}=\sqrt{\frac{\int_{-\infty}^{+\infty}(t-\tau)^2 p(t)dt}{\int_{-\infty}^{+\infty}p(t)dt}},\quad \bar{\tau}=\frac{\int_{-\infty}^{+\infty}t\cdot p(t)dt}{\int_{-\infty}^{+\infty}p(t)dt},\quad \Delta\tau\approx 4\tau_{RMS}$$

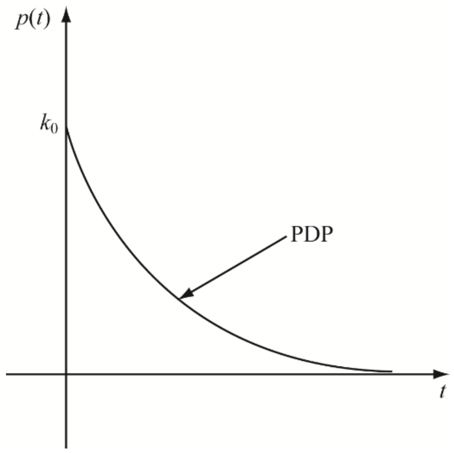


Fig.2. PDP

$$p(t)=k_0 e^{-kt}$$

In this case, $\int_{-\infty}^{+\infty}p(t)dt=1$ and we assume that the channel is causal, i.e. $p(t)=0,\ t<0$, the following relation can be satisfied.

$$k_0\int_{-\infty}^{+\infty}e^{-kt}dt=1\Leftrightarrow -\frac{k_0}{k}e^{-kt}\Big|_0^{+\infty}=1\Leftrightarrow k=k_0 \tag{2}$$

Average delay, RMS delay is as following.

$$\bar{\tau}=\int_{-\infty}^{+\infty}t\cdot p(t)dt=k_0\int_0^{+\infty}t\cdot e^{-k_0 t}dt=\frac{1}{k_0} \tag{3}$$

$$\tau_{RMS}^2=\int_0^{+\infty}(t-\bar{\tau})^2 p(t)dt$$

$$=k_0\int_0^{+\infty}\left(t-\frac{1}{k_0}\right)^2 e^{-k_0 t}dt=k_0^{-2}$$

$$\tau_{RMS}=\frac{1}{k_0}=\bar{\tau} \tag{4}$$

We analyze one MC-CDMA block consisting of μ OFDM symbols. We assume that the orthogonality is recovered by rake combination and ISI is mitigated by CP (GI). The length of CP is $G\cdot T_{spl}$. Considering the first chip in the first OFDM symbol adjacent to CP, chip energy is spread from $[0,T_{spl}]$ to $[0,\infty]$.

Total chip energy is T_c. As in Eq.(2) of Fig.4, considering one chip, the power of received chip with respect to time is as follows:

$$p_{receive,chip}(t)=\begin{cases}\int_0^t p(t-\tau)d\tau, & t\in[0,T_{spl}]\\ \int_0^{T_{spl}} p(t-\tau)d\tau, & t\in[T_{spl},+\infty]\end{cases} \tag{5}$$

$$p_{receive,chip}(t)=\int_0^t p(t-\tau)d\tau$$

$$=\int_0^t k_0 e^{-k_0(t-\tau)}d\tau=\int_0^t k_0 e^{-k_0 t}e^{k_0\tau}d\tau$$

$$=e^{-k_0 t}e^{k_0\tau}\Big|_0^t=e^{-k_0 t}(e^{k_0 t}-1)$$

$$=1-e^{-k_0 t}, 0\le t<T_{spl}$$

$$p_{receive,chip}(t)=\int_0^{T_{spl}}p(t-\tau)d\tau$$

$$=e^{-k_0 t}e^{k_0\tau}\Big|_0^{T_{spl}}=e^{-k_0 t}(e^{k_0 T_{spl}}-1)$$

$$=e^{-k_0(t-T_{spl})}-e^{-k_0 t}, t\ge T_{spl}$$

$$p_{receive,chip}(t)=\begin{cases}1-e^{-k_0 t}, & t\in[0,T_{spl}]\\ e^{-k_0 t}(e^{k_0 T_{spl}}-1), & t\in[T_{spl},+\infty]\end{cases} \tag{6}$$

The received energy in $T_{spl}\le t<T_{spl}+GT_{spl}$ of received energy in $t\ge T_{spl}$ is removed by CP and received energy in $t\ge T_{spl}+GT_{spl}$ will be IBI (Inter Block Interference). The received energy that is removed by CP in the first chip adjacent CP is as follows:

$$E_{cp,chip}^{(1)}=\int_{T_{spl}}^{T_{spl}+GT_{spl}}p_{receive,chip}(t)dt \tag{7}$$

Received energy that is not removed by CP and becomes IBI is as follows:

$$E_{IBI,chip}^{(1)} = \int_{T_{spl}+GT_{spl}}^{\infty} p_{receive,chip}(t)dt \tag{8}$$

As the chip affected by CP is spread over one MC symbol, received energy removed by CP is as follows.

$$E_{cp,MC} = \sum_{i=1}^{N_c} E_{cp,chip}^{(i)} \tag{9}$$

Received energy that is not removed by CP and becomes IBI is as follows:

$$E_{IBI,MC} = \sum_{i=1}^{N_c} E_{IBI,chip}^{(i)} \tag{10}$$

In Eq.(7) and Eq.(8), $E_{cp,chip}^{(i)}$, $E_{IBI,chip}^{(i)}$ is received energy removed by CP and energy that becomes IBI of received energy of chip apart $(i-1)T_{spl}$ from CP, respectively.

$$E_{cp,chip}^{(i)} = \int_{iT_{spl}}^{T_{spl}(i+G)} p_{receive,chip}(t)dt \tag{11}$$

$$E_{IBI,chip}^{(i)} = \int_{(i+G)T_{spl}}^{\infty} p_{receive,chip}(t)dt \tag{12}$$

$$E_{cp,chip}^{(i)} = \int_{iT_{spl}}^{T_{spl}(i+G)} p_{receive,chip}(t)dt$$
$$= \frac{1}{k_0} e^{-ik_0T_{spl}} (e^{k_0T_{spl}} - 1)(1 - e^{-Gk_0T_{spl}}) \tag{13}$$

$$E_{IBI,chip}^{(i)} = \int_{(i+G)T_{spl}}^{\infty} p_{receive,chip}(t)dt$$
$$= \frac{1}{k_0}(e^{k_0T_{spl}} - 1)e^{-k_0(i+G)T_{spl}} \tag{14}$$

Substituting Eq.(13) and Eq.(14) into Eq.(11) and Eq.(12),

$$E_{cp,MC} = \sum_{i=1}^{N_c} E_{cp,chip}^{(i)} \approx \sum_{i=1}^{\infty} E_{cp,chip}^{(i)}$$
$$= \frac{1}{k_0}(e^{k_0T_{spl}} - 1)(1 - e^{-Gk_0T_{spl}}) \sum_{i=1}^{\infty} e^{-ik_0T_{spl}}$$
$$= \frac{1}{k_0}(e^{k_0T_{spl}} - 1) \tag{15}$$

$$E_{IBI,MC} = \sum_{i=1}^{N_c} E_{IBI,chip}^{(i)} \approx \sum_{i=1}^{\infty} E_{IBI,chip}^{(i)}$$
$$= \frac{1}{k_0}(e^{k_0T_{spl}} - 1)e^{-Gk_0T_{spl}} \sum_{i=1}^{\infty} e^{-ik_0T_{spl}}$$
$$= \frac{1}{k_0} e^{-Gk_0T_{spl}} \tag{16}$$

Consequently, it needed (N_c+G) received energy, considering GI during one MC block symbol, however, the useful energy is decreased from $T_{spl}(N_c + G)$ to $T_{spl}N_c - E_{cp,MC}$ and IBI energy $E_{IBI,MC}$ causes. The power of noise is σ_n^2, SINR before remove CP with ignoring ISI except for IBI due to CP.

$$\Gamma_{rec} = \frac{1}{\sigma_n^2} \tag{17}$$

$$\Gamma_{rec,cp}(G) = \underbrace{\frac{1}{\sigma_n^2 + E_{IBI,MC}(G)/(N_cT_{spl})}}_{IBI\text{ power}} \underbrace{\frac{T_{spl}N_c - E_{cp,MC}(G)}{(N_c+G)T_{spl}}}_{\text{useful power decrease}} \tag{18}$$

The optimal GI, G_{opt}, is as follows.

$$G_{opt} = \arg\max_{g} \Gamma_{rec,cp}(G) \tag{19}$$

Considering that $k_0 = \frac{1}{\tau_{RMS}}$ and assuming that $E_{cp,MC}(G)$ =0, $E_{IBI,MC}(G) = 0$,

$$\Gamma_{rec,cp}(G) = \frac{N_c}{N_c + G}\frac{1}{\sigma_n^2} = \frac{N_c}{N_c + G}\Gamma_{rec}$$

In ideal case, Eq.(18) represents received power decrease due to remove CP in receiver.

$$\Gamma_{rec,cp}(G) = \frac{N_cT_{spl} - E_{cp,MC}(G)}{(N_c+G)T_{spl}} \frac{N_cT_{spl}}{N_cT_{spl}\sigma_n^2 + E_{IBI,MC}(G)}$$
$$= \frac{N_c}{N_c+G} \frac{N_cT_{spl} - \tau_{RMS}(1 - e^{-\frac{GT_{spl}}{\tau_{RMS}}})}{N_cT_{spl}\sigma_n^2 + \tau_{RMS}e^{-\frac{GT_{spl}}{\tau_{RMS}}}} \tag{20}$$

The Eq.(20) is theoretical expression of received SINR that can determine the optimal GI, G_{opt}.

As you can know, G_{opt} is determined by the number of subcarriers, *Nc*, RMS channel delay, τ_{RMS} , chip duration, T_{spl} and noise power of channel, σ_n^2 .

It is difficult to determine G_{opt} by differentiating Eq.(20). Because the equation obtained by differentiating Eq.(20) is closed expression with respect to *G*.

Therefore, there are two ways to determine G_{opt} by using Eq.(20). The first is to determine *G* that we calculate $\Gamma_{rec,cp}(G)$ with respect to *G* and received SINR is maximized. The second is to obtain approximate solution gradually.

The method to obtain approximate solution gradually is as following. Using the fact that

$$\left(\frac{B(x)}{A(x)}\right)' = 0 \Leftrightarrow \frac{B'(x)A(x) - B(x)A(x)}{A^2(x)} = 0$$
$$\Leftrightarrow B'(x)A(x) = B(x)A'(x)$$
$$\frac{\partial \Gamma_{rec,cp}(G)}{\partial G} = 0$$
$$\Leftrightarrow T_{spl}e^{-G\frac{T_{spl}}{\tau_{RMS}}}(N_c+G)\left(N_cT_{spl}\sigma_n^2 + \tau_{RMS}e^{-G\frac{T_{spl}}{\tau_{RMS}}}\right)$$
$$= \left(N_cT_{spl} - \tau_{RMS}(1 - e^{-G\frac{T_{spl}}{\tau_{RMS}}})\right)$$
$$\left((N_c+G)T_{spl}e^{-G\frac{T_{spl}}{\tau_{RMS}}} - \left(N_cT_{spl}\sigma_n^2 + \tau_{RMS}e^{-G\frac{T_{spl}}{\tau_{RMS}}}\right)\right)$$

$$\Leftrightarrow\left((N_c+G)T_{spl}e^{-G\frac{T_{spl}}{\tau_{RMS}}}+N_cT_{spl}-\tau_{RMS}(1-e^{-G\frac{T_{spl}}{\tau_{RMS}}})\right)\cdot$$

$$\left(N_cT_{spl}\sigma_n^2+\tau_{RMS}e^{-G\frac{T_{spl}}{\tau_{RMS}}}\right)$$

$$=\left(N_cT_{spl}-\tau_{RMS}(1-e^{-G\frac{T_{spl}}{\tau_{RMS}}})\right)(N_c+G)T_{spl}e^{-G\frac{T_{spl}}{\tau_{RMS}}}$$

Dividing two sides by $\left(N_cT_{spl}\right)^2$,

$$\Leftrightarrow\left((1+\frac{G}{N_c})e^{-G\frac{T_{spl}}{\tau_{RMS}}}+1-\frac{1}{N_c}\frac{\tau_{RMS}}{T_{spl}}-(1-e^{-G\frac{T_{spl}}{\tau_{RMS}}})\right)$$

$$\left(\sigma_n^2+\frac{1}{N_c}\frac{\tau_{RMS}}{T_{spl}}e^{-G\frac{T_{spl}}{\tau_{RMS}}}\right)$$

$$=\left(1-\frac{1}{N_c}\frac{\tau_{RMS}}{T_{spl}}(1-e^{-G\frac{T_{spl}}{\tau_{RMS}}})\right)(1+\frac{G}{N_c})e^{-G\frac{T_{spl}}{\tau_{RMS}}}$$

$$\Delta\tau=\frac{\tau_{RMS}}{T_{spl}}$$

$$\Leftrightarrow\left((1+\frac{G}{N_c})e^{-\frac{G}{\Delta\tau}}+1-\frac{1}{N_c}\Delta\tau-(1-e^{-\frac{G}{\Delta\tau}})\right)\left(\sigma_n^2+\frac{\Delta\tau}{N_c}e^{-\frac{G}{\Delta\tau}}\right)$$

$$=\left(1-\frac{\Delta\tau}{N_c}(1-e^{-\frac{G}{\Delta\tau}})\right)(1+\frac{G}{N_c})e^{-\frac{G}{\Delta\tau}}$$

Multiplying $e^{2\frac{G}{\Delta\tau}}$ by two sides,

$$\Leftrightarrow\left(1+\frac{G}{N_c}+e^{\frac{G}{\Delta\tau}}+\frac{\Delta\tau}{N_c}(e^{\frac{G}{\Delta\tau}}-1)\right)\left(\sigma_n^2e^{\frac{G}{\Delta\tau}}+\frac{\Delta\tau}{N_c}\right)$$

$$=\left(1+\frac{G}{N_c}\right)\left(e^{\frac{G}{\Delta\tau}}-\frac{\Delta\tau}{N_c}(e^{\frac{G}{\Delta\tau}}-1)\right)$$

$$\frac{G}{\Delta\tau}=g$$

$$\left(1+\frac{\Delta\tau}{N_c}g+e^g-\frac{\Delta\tau}{N_c}(e^g-1)\right)\left(\sigma_n^2e^g+\frac{\Delta\tau}{N_c}\right)$$

$$=\left(1+\frac{\Delta\tau}{N_c}g\right)\left(e^g-\frac{\Delta\tau}{N_c}(e^g-1)\right)$$

$$\frac{\Delta\tau}{N_c}=\tau$$

$$(1+\tau g+e^g-\tau(e^g-1))(\sigma_n^2e^g+\tau)$$

$$=(1+\tau g)(e^g-\tau(e^g-1))\Leftrightarrow(1+\tau g+e^g-\tau e^g-\tau)(\sigma_n^2e^g+\tau)$$

$$(1+\tau g)(e^g-\tau e^g-\tau)e^g=Q$$

$$(1+\tau\ln Q+Q(1-\tau)+\tau)(\sigma_n^2Q+\tau)$$

$$=(1+\tau lnQ)(Q(1-\tau)+\tau)$$

Expressing the above equation to quadratic equation with respect to Q,

$$(1-\tau)\sigma_n^2Q^2+\begin{bmatrix}\sigma_n^2(1+\tau\ln Q+\tau)-\\(1-\tau)^2-\tau\ln Q(1-\tau)\end{bmatrix}Q \qquad (21)$$
$$+(\tau+\tau^2\ln Q+\tau^2-\tau-\tau^2\ln Q)=0$$

The Eq.(21) is not quadratic equation with respect to Q completely, as there is $\ln Q$ in the coefficient of linear term. However, we can solve Eq.(21) gradually considering $\ln Q$ is constant with respect to Q change in small range, as $Q=e^g$ is much bigger than $g=\ln Q$ and the change velocity is more fast. Thus, we obtain $Q^{(1)}$ by selecting appropriate initial value, $Q^{(0)}>e$ and inserting $\ln Q^{(0)}$ into Eq.(21). In this way, we obtain the last value, Q_{end} and determine $\tilde{G}_{opt}$ from Q_{end} until $|Q^{(i)}-Q^{(i+1)}|\leq\eta$ is satisfied.

3. SIMULATION RESULTS

In order to compare the proposed method with experiment results about optimal GI obtained in [5], we used the same parameters as in [5] and simulated. (Table.1)

Table.1. System parameters and channel properties

Number of users	Single user
Uplink/Downlink	Downlink
Spreading code	Walsh-Hadamard OVSF
Code length, N	4
Gain combining	MRC
Transmission bandwidth, B	40MHz
Channel model	Uniform distributed exponential decay channel
Number of subcarriers	256
τ_{RMS}	0.22μs
Symbol period, T_{spl}	6.4μs
Received SNR	10, 20dB

For channel model, the effect of guard interval on received SNR gain is illustrated in Fig.3.

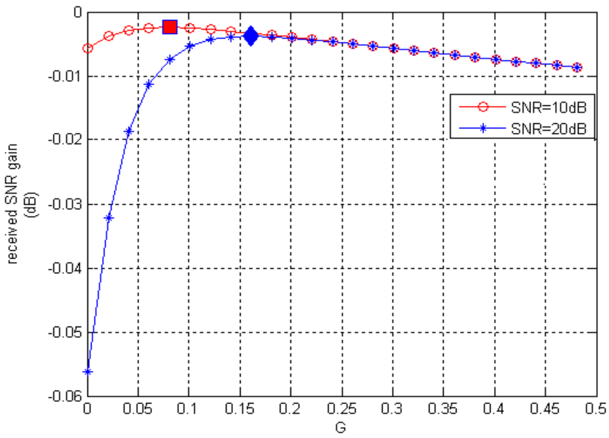


Fig.3. Received SNR gain versus guard interval for SNR = 10dB and SNR = 20dB

In Fig.3, a transverse axis is guard interval normalized T_{spl} and longitudinal axis is received SNR gain.

As shown in Fig.3, there exist optimal guard interval maximizing received SNR when SNR = 10, 20dB and this value is decreased as SNR decreases. Of course, it means that maximum useful power. The Table.2 shows the results compared theoretical optimal guard interval in paper with optimal guard interval obtained from experiment results [5].

Table.2. Comparison with experiment results [5]

Methods	SNR=10dB			SNR=20dB		
	G_{opt}	$\frac{G_{opt}}{\tau_{RMS}}$	$\frac{T_{spl}}{G_{opt}}$	G_{opt}	$\frac{G_{opt}}{\tau_{RMS}}$	$\frac{T_{spl}}{G_{opt}}$
Results [5]	0.6	2.7	10.7	1.4	6.4	4.6
Theoretical results	0.51	2.35	12.35	1.0	4.5	6.3

As shown in Table.2, there is some difference between theoretical optimal guard interval and experiment results, because we used uniform distributed exponential decay channel model, but they used real channel model [5].

The Fig.4 shows the effect of guard interval on received SNR gain for various SNR, when τ_{RMS} = 0.22µs and Table.3 shows optimal guard interval in this case.

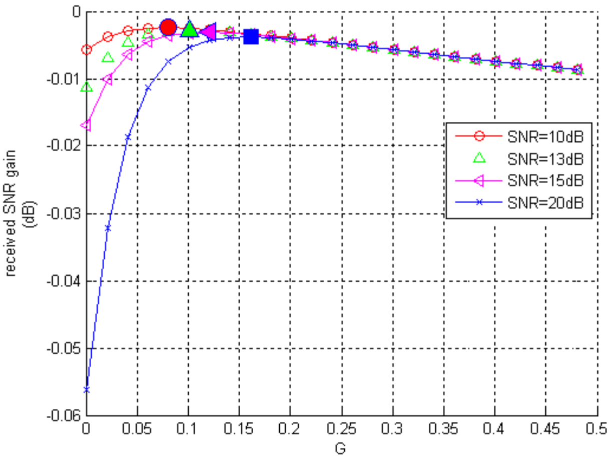


Fig.4. Received SNR gain versus guard interval for various SNR, when τ_{RMS} = 0.22µs

Table.3. Optimal guard interval for various SNR

SNR	Theoretical results		
	G_{opt}	$\frac{G_{opt}}{\tau_{RMS}}$	$\frac{T_s}{G_{opt}}$
10dB	0.51	2.35	12.35
13dB	0.64	2.93	9.9
15dB	0.77	3.52	8.26
20dB	1.01	4.59	6.32

The Fig.5 shows the effect of guard interval on received SNR gain for various τ_{RMS}, when SNR=10dB and Table.4 shows optimal guard interval in this case.

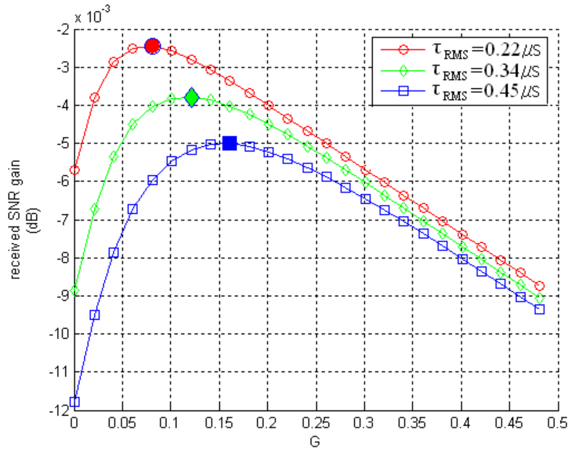


Fig.5. Received SNR gain versus guard interval for various τ_{RMS}, when SNR=10dB

Table.4. Optimal guard interval for the different τ_{RMS}

τ_{RMS}	Theoretical results		
	G_{opt}	$\frac{G_{opt}}{\tau_{RMS}}$	$\frac{T_{spl}}{G_{opt}}$
0.22µs	0.51	2.35	12.35
0.34µs	0.77	2.27	8.26
0.45µs	1.03	2.28	6.21

As shown in Fig.4, Fig.5 and Table.2, Table.3, optimal guard interval decreases with a decreasing SNR and optimal guard interval increases with an increasing τ_{RMS}.

4. CONCLUSIONS

In this paper, we obtained theoretical expression determining optimal length of guard interval or cyclic prefix used in OFDM and MC-CDMA system and compared through simulation. Simulation results show that theoretical expression coincides approximately with the experiment results of the prior method. The theoretical expression of optimal guard interval can make determine optimal guard interval without experiment for various SNR, τ_{RMS} and the number of subcarriers.

REFERENCES

[1] F. Fazel and S. Kaiser, "*Multi Carrier and Spread Spectrum System*", John Wiley and Sons, 2008

[2] P. Torres and A. Gusnao, "Iterative Receiver Technique for Reduced-CP, Reduced-PMEPR OFDM Transmission", *Proceedings of IEEE International Conference on Vehicular Technology*, pp. 1-8, 2007.

[3] B.M. Masini and F. Zabini, "On the Effect of Combined Equalization for MC-CDMA Systems in Correlated Fading Channels", *Proceedings of IEEE International Conference on Wireless Communications and Networking*, pp. 112-117, 2009.

[4] A.B. Djebbar and K. Abed Merain, "Blind and Semi-Blind Equalization of Downlink MC-CDMA System Exploiting

Guard Interval Redundancy and Excess Codes", *IEEE Transactions on Communication*, Vol. 51, No. 1, pp. 163-169, 2009.

[5] Centin Kurnaz and Hulya Gokalp, "Investigating the Relation between Optimum Guard Interval and Channel Delay Spread for a MC-CDMA System", *Turkish Journal of Electrical Engineering and Computer Sciences*, Vol. 20, No. 3, pp. 439-452, 2012.

[6] Luca Sanguinetti and Michele Morelli, "Channel Acquisition and Tracking for MC-CDMA Uplink Transmissions", *IEEE Transactions on Vehicular Technology*, Vol. 55, No. 3, pp. 956-967, 2006.

[7] Yong Chan Lee, Won Chol Jang and Yong Hak Sin, "Detection of Unknown FH Signals using Differential Spectrum Processing", *Journal of Theoretical Physics and Cryptography*, Vol. 11, pp. 1-4, 2016.

[8] Yong Chan Lee, Won Chol Jang and Yong Hak Sin, "A Method for RFO Estimation Using Phase Analysis of Pilot Symbols in OFDM Systems", *Journal of Theoretical Physics and Cryptography,* Vol. 12, pp. 1-11, 2016.

[9] E. Kannari and J. Iinatti, "Performance Analysis of Multirate MC-CDMA in Rayleigh-Fading with Delay Power Spectrum Exceeding the Guard Interval", *IEEE Journal on Selected Area in Communications*, Vol. 24, No. 3, pp. 542-553, 2006.

[10] R.V. Nee and R.Prasad, "*OFDM for Wireless Multimedia Communications*", Artech House Publisher, 2000

[11] S. Hara and R. Prasad, "Design and Performance of Multicarrier CDMA System in Frequency-Selective Rayleigh Fading Channels", *IEEE Transactions on Vehicular Technology*, Vol. 48, No. 5, pp. 1584-1595, 1999.

[12] B.S. Lee and S.C. Park, "Design and Performance analysis of the MC-CDMA", *Proceedings of 14th IEEE International Symposium on Personal Indoor and Mobile Radio Communication*, pp. 1-6, 2003.

[13] A.C. Mccormirk and E.A. Al Susa, "Multicarrier CDMA for Future Generation Mobile Communication", *Electronics and Communication Engineering Journal*, Vol. 14, No. 2, pp. 52-60, 2002.

[14] S. Le Nours, F. Nouvel and J.F. Helard, "Design and Implementation of MC-CDMA Systems for Future Wireless Networks", *EURASIP Journal on Applied Signal Processing*, Vol. 2004, No. 10, pp. 1604-1615, 2004.

[15] S.Salous and H. Gokalp, "Medium and Large-Scale Characterization of UMTS Allocated Frequency-Division Duplex Channels", *IEEE Transactions on Vehicular Technology*, Vol. 56, No. 5, pp. 2831-2843, 2007.

[16] J.D. Parsons, "*The Mobile Radio Propagation Channel*", John Wiley and Sons, 1992.

[17] E. Kunnari and J. Iinatti, "Performance Analysis of Multirate MC-CDMA in Rayleigh-Fading Channels with Delay Power Spectrum Exceeding the Guard Interval", *IEEE Journal on Selected Areas in Communications*, Vol. 24, No. 3, pp. 542-543, 2006.

[18] T.N. Vo, K. Amis, T. Chonalvel and P. Siohan, "Achievable Throughput Optimization in OFDM Systems in the Presence of Interference and its Application to Power Line Networks", *IEEE Transactions on Communications*, Vol.62, No. 5, pp. 1704-1715, 2014

[19] M. Atamanesh and F. Farzaneh, "A Proposed Equivalent Channel Power Delay Profile for a Millimeter Wave Wireless OFDM System and Optimum Guard Interval Evaluation in a Built-Up Area Propagation Scenario", *Wireless Personal Communication*, Vol. 69, No. 4, pp. 1223-1239, 2013.