論文
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Performance Analysis of Multicarrier DS-CDMA for Vehicular Sensor Communications and Networking (자동차 내부 센서간의 통신 및 네트워킹을 위한 다중 반송파 DS-CDMA의 성능 분석)

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ABSTRACT

The multicarrier direct sequence code-division (MC-DS/CDMA) is a well-known multiple access and data transmission scheme that is applicable for various mobile and wireless communications. Particularly for modern, smart vehicles equipped with multiple sensors, MC-DS/CDMA is one of the possible means for giving the sensors to get connected one another for sending and receiving messages and control information. For intra-vehicular communication and networking applications, we have proposed a novel MC-DS/CDMA multiple access and data transmission scheme incorporating a new idea of inserting sub-symbol based cyclic prefixes for compromising inter-symbol interference. In the performance investigation of our MC-DS/CDMA, we have looked into system performances related to bandwidth utilization, coding gain, and multiple number of sensors. Since the channel delay is comparatively shorter inside of vehicle than any other general mobile channels, the proposed scheme can be a successful candidate for networking wireless sensors simultaneously operating in an intelligent vehicle.

요약

다중 반송파 기반의 DS/CDMA 다중 접속 및 데이터 전송 기법은 여러 종류의 모바일 통신과 무선 통신 분야에 적용 가능한 것으로 알려지고 있다. 특히, 다양한 센서를 탑재한 차세대 지능형 자동차에서 이들 무선 센서 간의 통신 및 네트워킹을 수행함에 있어서 MC-DS/CDMA 기술은 가장 먼저 고려 될 수 있는 기법중의 하나이다. 본 논문에서는 자동차 내부의 센서간의 통신 및 네트워킹을 위해서 부심벌 단위로 순환 접두부를 삽입하는 새로운 방식의 MC-DS/CDMA 기법을 제안하고 우리가 제안한 기법의 간섭 잡음 제한 성능을 주파수 밴드 사용 효율, 코드화 이득 및 동시 접속 센서의 개수 등의 파라미터를 대상으로 비교 평가하였다. 차량의 내부는 일반적인 모바일 통신 환경에 비하여 채널 지연 확산이 매우 작은 경우이므로 본 논문에서 제안한 기법은 다수의 무선 센서가 동시에 작동하는 지능형 차량의 센서 간의 통신과 네트워킹에 효과적인 적용이 가능할 것으로 사료된다.

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1. INTRODUCTION

Recently, a lot of attention is given to developing intelligent vehicles. Since such vehicles are equipped with various sensors, providing them effective and robust communication means for connecting one another to send and receive vital data and control information stages hot research issues.

The communication medium can be another consideration, however, wireless devices are a trend and have a much higher applicability when considering a light weighted, energy saving vehicles. Now, considering wireless sensors provided for intelligent vehicles, in order to support communication and networking capability to those sensors, there several possible multiple access schemes for data transmission. Among them DS/CDMA and OFDM are the well-known choices.

While DS/CDMA can exploit a high coding gain, however, its limitations are found when high data rata applications are needed . On the other hand, OFDM scheme can exploit a number of lower rate sub-channels, however, considering an extension to inter- vehicular communication, its applicability is limited by inter-vehicular interferences and signal origin authenticity.

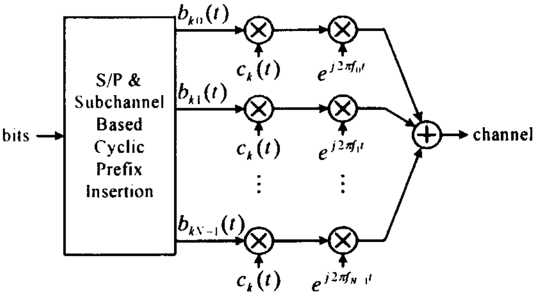
Here, we propose an alternative scheme that comes in the middle way between DS/CDMA and OFDM. The proposed scheme is called a multicarrier DS/CDMA or MC-DS/CDMA in short. The proposed MC-DS/CDMA multiple access and data transmission scheme for sensors inside of vehicle can exploit advantages of DS/CDMA and OFDM while it can circumvent shortcomings of those schemes. Of course, the performance of our proposed scheme should be compromised, however, we can obtain the data transmission performance equivalent to OFDM by incorporating our novel idea of inserting sub-symbol based cyclic prefixes considered for a relative short channel delay spread of a vehicle.

The paper is organized as follows. In Section 2, the proposed MC-DS/CDMA scheme is described along with signal transmission and reception mechanisms. In Section 3, the performance analysis is derived for our MC-DS/CDMA system assuming a channel that undergoes Rayleigh fading. And, in Section 4, numerical calculations with graphical illustrations are given to show the performances of our MC-DS/CDMA scheme in relation to bandwidth utilization, coding gain, and number of multiple sensors. Finally, conclusions are drawn in Section 5.

2. PROPOSED MC-DS/CDMA SCHEME

In this section, mechanisms for signal transmission and signal reception involving our MC-DS/CDMA system is described.

First, for the transmission of a sensor signal, our system utilizes N subchannels and a signature spreading code of length C, that is used to spread subchannel signals. Depending on requested data rate or applications, the information on each subchannel can be 1) totally same, 2) partly same, or 3) totally different.



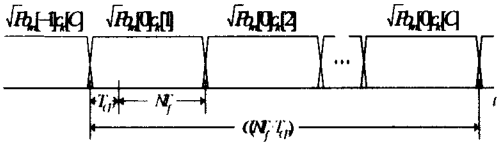
[Fig. 1 MC-DS/CDMA transmitter for k^{th} sensor

[Fig. 1] illustrates the transmitter for k^{th} sensor. The data bit to be transmitted are first serial-to-parallel converted, and processing rate for each subchannel reduces by N times. The subchannel processing rate decreases slightly more for subchannel (or subsymbol) insertion of cyclic prefixes. The subchannel symbol time gets extended as much as the time duration of cyclic prefix, and the signature spreading code multiplication and IDFT (inverse discrete Fourier transform) operations are immediately followed.

The transmission signal for k^{th} sensor is defined as follows:

$$s_k(t) = \sum_{n=0}^{N-1} \sqrt{P} b_{kn}(t) c_k(t) e^{j(2\pi f_n t + \phi_{kn})}, \quad f_n = \frac{n}{NT_f} \tag{1}$$

where $b_{kn}(t)$ is the input data signal that takes a logical value 1 or -1 during a symbol period T_s; $c_k(t)$ is the signature spreading code signal; N is the number of subchannel; $1/T_f$ is the total effective bandwidth of the system; and P is the average transmission power per subchannel.

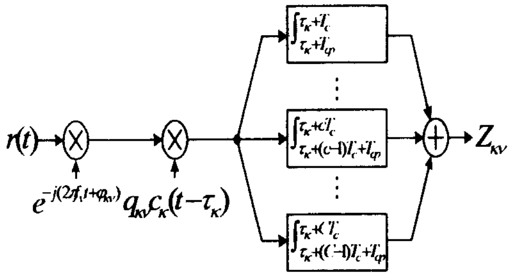


[Fig. 2 Timing diagram of the transmission symbol $b_{kn}[0]$ through n^{th} subchannel

[Fig. 2] represents the timing diagram of the transmission signal that is processed through n^{th} subchannel where $b_{kn}[0]$ is the 0^{th} symbol of k^{th} sensor transmitted on n^{th} subchannel; and $c_k[1]$ is the first chip of the spreading code for k^{th} sensor. In contrast to the guard time insertion method adopted in DS/CDMA or OFDM, where the guard time is normally added on transmission symbol bases, in our case, however, the guard times called cyclic prefixes are added on sub-symbol bases. In our system the durations of sub-symbol and spreading code chip are same, where the chip duration of a spreading code is $T_c = NT_f + T_{CP}$ instead of NT_f. NT_f is the duration of a IDFT (inverse discrete Fourier transform) block, and T_{CP} is the duration of the cyclic prefix included in each chip (or subsymbol) of the spreading code.

Therefore, the bit energy is $E_b = E_{b,NT_f} + E_{b,CP}$ where $E_{b,NT_f} = PGNT_f$ is the portion of energy included in NT_f time interval, and $E_{b,CP} = PGT_{CP}$ is the portion of energy included in T_{CP} time interval. Then, the efficiency of the bandwidth R_{eff}, or effective channel utilization can be expressed as follows:

$$R_{eff} = \frac{E_{b,NT_f}}{E_b} = \frac{NT_f}{NT_f + T_{CP}} \tag{2}$$



[Fig. 3] MC-DS/CDMA signal reception of symbol $b_{\kappa\nu}$ on νth subchannel

During signal propagation through a communication channel formed around the vehicle, we assume the signal experiences Rayleigh fading and undergoes amplitude and phase distortions. For our system, the communication channel is modelled as follows:

$$h_{kn}(t)=\sum_{l=1}^{D}a_{kn}^{(l)}\delta(t-\tau_k^{(l)})e^{-j\psi_{kn}^{(l)}} \tag{3}$$

where $\tau_k^{(l)}$ is the propagation delay of l^{th} path of a channel; $\alpha_{kn}^{(l)}$ is the attenuation factor on k^{th} sensor signal processed through n^{th} subchannel; and $\psi_{kn}^{(l)}$ is the phase distortion on the corresponding transmission signal. In this paper $\alpha_{kn}^{(l)}$ and $\psi_{kn}^{(l)}$ are assumed to have Rayleigh probability distribution and uniform probability distribution over $[-\pi,\pi]$, respectively.

For a special case where the maximum delay spread of the communication channel T_m is shorter than that of inserted cyclic prefix T_{CP}, the number of resolvable paths associated with each subchannel of our MC-DS/CDMA system becomes $D\approx\lfloor T_m/T_{CP}\rfloor+1=1$. And the corresponding time-varying impulse response of the wireless communication n^{th} subchannel of k^{th} sensor becomes as follows:

$$h_{kn}(t)=a_{kn}\delta(t-\tau_k)e^{-j\psi_{kn}} \tag{4}$$

On the other hand, the received signal $r(t)$ is represented as follows:

$$r(t)=\sum_{k=1}^{K}\sum_{n=0}^{N-1}\sqrt{P}\alpha_{kn}b_{kn}(t-\tau_k)c_k(t-\tau_k)e^{j(2\pi f_n t+\varphi_{kn})}+\eta(t) \tag{5}$$

where $\varphi_{kn}=\phi_{kn}-\psi_{kn}-2\pi f_n\tau_k$ is the total phase shift, and $\eta(t)$ is the additive white Gaussian noise that has a double sided power spectral density of $N_0/2$. The signal reception for χth sensor on νth subchannel is done by the receiver illustrated in [Fig. 3]. As shown in the figure, the received signal is first down converted followed by one-tap subchannel equalization and multiplication of the signature spreading code $c_\chi(t)$ on each subchannel, serially. Then, the outputs of signal dumping devices are added together before bit decision for that subchannel.

Assuming an accurate estimation of subchannel phase change, the decision variable $Z_{\chi\nu}$ can be expressed as follows:

$$\begin{aligned}Z_{\chi\nu}&=\sum_{c=1}^{C}\int_{\tau_\chi+(c-1)T_c+T_{cp}}^{\tau_\chi+cT_c}r(t)q_{\chi\nu}c_\chi(t-\tau_\chi)e^{-j(2\pi f_\nu t+\varphi_{\chi\nu})}dt\\&=\sum_{k=1}^{K}\sum_{n=0}^{N-1}\sum_{c=1}^{C}\int_{\tau_\chi+(c-1)T_c+T_{cp}}^{\tau_\chi+cT_c}\sqrt{P}\alpha_{kn}q_{\chi\nu}b_{kn}(t-\tau_k)\\&\quad\cdot c_k(t-\tau_k)c_\chi(t-\tau_\chi)e^{j(2\pi(f_n-f_\nu)t+\varphi_{kn}-\varphi_{\chi\nu})}dt+N_{\chi\nu}\end{aligned} \tag{6}$$

where $N_{\chi\nu}$ is the contribution from noise as follows:

$$\begin{aligned}N_{\chi\nu}&=\sum_{c=1}^{C}\int_{\tau_\chi+(c-1)T_c+T_{cp}}^{\tau_\chi+cT_c}n(t)q_{\chi\nu}c_\chi(t-\tau_\chi)e^{-j(2\pi f_\nu t+\varphi_{\chi\nu})}dt\\&=\sum_{c=1}^{C}q_{\chi\nu}c_\chi[c]\int_{\tau_\chi+(c-1)T_c+T_{cp}}^{\tau_\chi+cT_c}n(t)e^{-j(2\pi f_\nu t+\varphi_{\chi\nu})}dt\end{aligned} \tag{7}$$

3. PERFORMANCE ANALYSIS

In this section, the performance analysis of our MC-DS/CDMA system is derived to obtain an qualitative expression for performance measure in terms of average bit error rate vs. signal-to-noise ratio.

From Eq. (6), $Z_{x\nu}$ can be rewritten as follows:

$$Z_{x\nu}=D_{x\nu}+I_{x\nu}^{(s)}+I_{x\nu}^{(o)}+N_{x\nu} \tag{8}$$

The above equation basically divides the decision variable $Z_{x\nu}$ into four signal components. From right side of Eq. (8), $D_{x\nu}$ is the transmission signal component of the sensor when $k=x$ and $n=\nu$, and it can be expressed as follows:

$$\begin{aligned}D_{x\nu} &=\sum_{c=1}^{C}\int_{\tau_x+(c-1)T_c+T_{cp}}^{\tau_x+cT_c}\sqrt{P}a_{x\nu}q_{x\nu}b_{x\nu}(t-\tau_x)c_x^2(t-\tau_x)dt\\ &=\sqrt{P}a_{x\nu}q_{x\nu}\sum_{c=1}^{C}\int_{\tau_x+(c-1)T_c+T_{cp}}^{\tau_x+cT_c}b_{x\nu}(t-\tau_x)dt\end{aligned}$$

(9)

Under a channel conditions satisfying $T_m\leq T_{CP}$, Eq. (9) can be rewritten as follows:

$$\begin{aligned}D_{x\nu} &=\sqrt{P}a_{x\nu}q_{x\nu}\sum_{c=1}^{C}NT_f b_{x\nu}[0]\\ &=\sqrt{P}a_{x\nu}q_{x\nu}CNT_f b_{x\nu}[0]\end{aligned} \tag{10}$$

Furthermore, the second term $I_{x\nu}^{(s)}$ is one of two interference components in the case of $k=x$ and $n\neq\nu$. We call it self-interference, and it comes from other subchannels of the same user as follows:

$$\begin{aligned}I_{x\nu}^{(s)}= &\sum_{\substack{n=0\\ n\neq\nu}}^{N-1}\sum_{c=1}^{C}\int_{\tau_x+(c-1)T_c+T_{cp}}^{\tau_x+cT_c}\sqrt{P}a_{xn}q_{x\nu}b_{xn}(t-\tau_x)\\ &\cdot c_x^2(t-\tau_x)e^{j(2\pi(f_n-f_\nu)t+\varphi_{xn}-\varphi_{x\nu})}dt\end{aligned} \tag{11}$$

Similarly to Eq. (10), under a channel condition satisfying $T_m\leq T_{CP}$, Eq. (11) can be rewritten as follows:

$$\begin{aligned}I_{x\nu}^{(s)}= &\sum_{\substack{n=0\\ n\neq\nu}}^{N-1}\sum_{c=1}^{C}\sqrt{P}a_{xn}q_{x\nu}b_{xn}[0]\\ &\cdot\int_{\tau_x+(c-1)T_c+T_{cp}}^{\tau_x+cT_c}e^{j(2\pi(f_n-f_\nu)t+\varphi_{xn}-\varphi_{x\nu})}dt\\ = &\ 0\end{aligned} \tag{12}$$

Since the integration of a complex exponential term in Eq. (12) over NT_f period becomes zero, the self-interference $I_{x\nu}^{(s)}$ from all other subchannels becomes zero.

Moreover, $I_{x\nu}^{(o)}$ is the other interference component in the case of $k\neq x$. We call it inter-sensor interference, and it comes from all other sensors in operation as follows:

$$\begin{aligned}I^{(k)}= &\sum_{\substack{k=1\\ k\neq x}}^{K}\sum_{n=0}^{N-1}\sum_{c=1}^{C}\int_{\tau_x+(c-1)T_c+T_{cp}}^{\tau_x+cT_c}\sqrt{P}a_{kn}q_{x\nu}b_{kn}(t-\tau_k)\\ &\cdot c_k(t-\tau_k)c_x(t-\tau_x)e^{j(2\pi(f_n-f_\nu)t+\varphi_{kn}-\varphi_{x\nu})}dt\\ = &\sum_{\substack{k=1\\ k\neq x}}^{K}\sum_{n=0}^{N-1}\sqrt{P}a_{kn}q_{x\nu}b_{kn}[0]\sum_{c=1}^{C}c_k[c]c_x[c]\\ &\cdot\int_{\tau_x+(c-1)T_c+T_{cp}}^{\tau_x+cT_c}e^{j(2\pi(f_n-f_\nu)t+\varphi_{kn}-\varphi_{x\nu})}dt\\ = &\ 0\end{aligned}$$

(13)

As shown in Eq. (13), $I_{x\nu}^{(o)}$ comes out to be zero under the channel condition mentioned above, because in that case the orthogonality of signature spreading codes among the sensors can be hold.

From the results shown in Eqs. (12) and (13), the cyclic prefixes inserted on subsymbol bases can compromise the delay spread of the communication channel, and the qualitative expression for the performance measure of our MC-DS/CDMA system comes out as a simple, closed form. For the general cases of the channel, however, a closed form of analytic expression would be hardly possible.

Finally, $N_{x\nu}$ is the noise component contribution into the decision variable. Since the white noise $\eta(t)$ has a Gaussian distribution with zero mean and variance of $N_0/2$, $N_{x\nu}$ also follows the Gaussian distribution with zero mean and variance of $q_{x\nu}^2 N_0 CNT_f/2$.

From Eq. (8), the decision variable $Z_{x\nu}$ can be defined as a random variable following a Gaussian distribution with the expected value of $\sqrt{P}\alpha_{x\nu}q_{x\nu}CNT_f$ and the variance of $q_{x\nu}^2 N_0 CNT_f/2$.

With these first order and second order statistics obtained for the decision variable $Z_{x\nu}$, we now can further estimate the bit error probability involved in a bit decision process. First, the bit error probability with respect to channel fading parameter $\alpha_{x\nu}$ can be defined as follows:

$$\begin{aligned} P_b(\alpha_{x\nu}) &= Q\left(\sqrt{\frac{(E[Z_{x\nu}])^2}{\mathrm{Var}[Z_{x\nu}]}}\right) \\ &= Q\left(\sqrt{2\alpha_{x\nu}^2 E_b/N_0}\right) \\ &= \frac{1}{\pi}\int_0^{\pi/2} e^{-\frac{\alpha_{x\nu}^2 E_{b,IFT}/N_0}{\sin^2\theta}}\, d\theta \end{aligned} \tag{14}$$

where the Q-function is defined as follows:

$$Q(x) = \frac{1}{\pi}\int_0^{\pi/2} e^{-\frac{x^2}{2\sin^2\theta}}\, d\theta, \quad x \geq 0 \tag{15}$$

Since the channel attenuation parameter $\alpha_{x\nu}$ has a Rayleigh probability distribution, so it has a probability density function of the form as follows:

$$f(\alpha) = \frac{\alpha}{\sigma^2} e^{-\alpha^2/2\sigma^2} \tag{16}$$

where σ^2 is the average variance of the channel. Using Eqs. (14) and (16), the average bit error rate can be defined as follows:

$$\begin{aligned} P_b &= \int_0^{\infty} P_b(\alpha) f(\alpha)\, d\alpha \\ &= \frac{1}{\pi}\int_0^{\pi/2} \frac{\sin^2\theta}{2\sigma^2 E_{b,IFT}/N_0 + \sin^2\theta}\, d\theta \end{aligned} \tag{17}$$

Also, Eq. (17) can be rewritten using the relation $E_{b,IFT} = E_b R_{eff}$ as follows:

$$P_b = \frac{1}{\pi}\int_0^{\pi/2} \frac{\sin^2\theta}{2\sigma^2 R_{eff} E_b/N_0 + \sin^2\theta}\, d\theta \tag{18}$$

On the other hand, the average bit error rate of the general MC-DS/CDMA system that adopts a symbol based guard interval insertion method is defined as follows:

$$P_b = \frac{1}{\pi}\int_0^{\pi/2} \frac{\sin^2\theta}{\gamma_c + \sin^2\theta}\, d\theta$$

$$\text{where } \gamma_c = \left[\left(\frac{\sigma^2 E_b}{N_0}\right)^{-1} + 2(K-1)\left(\frac{1}{3C} + (N-1)\overline{I_M}\right)\right]^{-1}$$

$$\bar{I}_M = \frac{1}{N(N-1)} \sum_{\nu=0}^{N-1} \sum_{\substack{n=0 \\ n\neq\nu}}^{N-1} \frac{1-\operatorname{sin}c[2(n-\nu)]}{2\pi^2(n-\nu)^2 C}$$

(19)

4. NUMERICAL RESULTS

For the performance verification of the

proposed MC -DS/CDMA system, a numerical analysis on the average bit error rate (BER), and system comparisons are considered in this section.

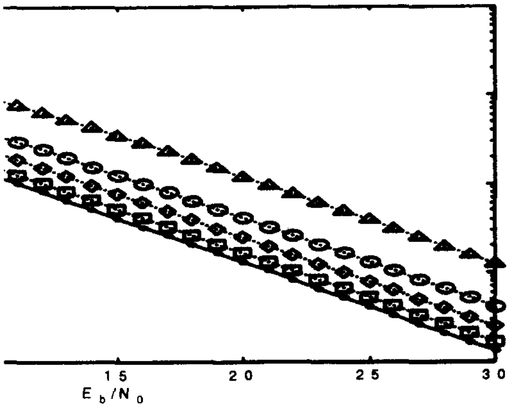
First, the relationship between the effective bandwidth utilization R_{eff} and the system performance is investigated using a numerical method. As illustrated in [Fig. 4], the figure shows the BER performance of our proposed MC-DS/CDMA scheme with respect to various R_{eff}, when the amplitude attenuation factor α_{xv} has a Rayleigh fading distribution with variance $\sigma^2=1$. Of course, for the longer CP inserted, one can only achieve a lower transmission efficiency. For example, $R_{eff}=0.75$ means 75 percent transmission efficiency, and the rest portion is wasted by CP transmission. As expected, in the result shown in Eq. (18), the BER performance gets degraded with respect to decreasing R_{eff}.

Second, the relationship between the number of sensors operating simultaneously and the system performance is investigated. [Fig. 5] shows the BER performance with R_{eff} fixed at $R_{eff}=0.75$, which is a conservative measure in a vehicular sensor communication channel environment. We also fixed the number of subchannels at $N=128$ and the number of chips in the sensor signature spreading code at $C=32$. As shown in figure, our proposed MC-DS/CDMA system has a same performance to that of OFDM scheme. As the analytical derivation result obtained in Eq. (13), the system performances are not affected by the number of sensors communicating simultaneously. For general cases, on the other hand, the system performance would normally get degraded with respect to increasing number of sensors as observed in the cases of general MC-DS/CDMA systems' shown in the figure.. As a note, furthermore, when the number of sensors operating simultaneously becomes more than two, the general MC-DS/CDMA schemes degrades rapidly and is no longer appropriate for high-speed transmission applications.

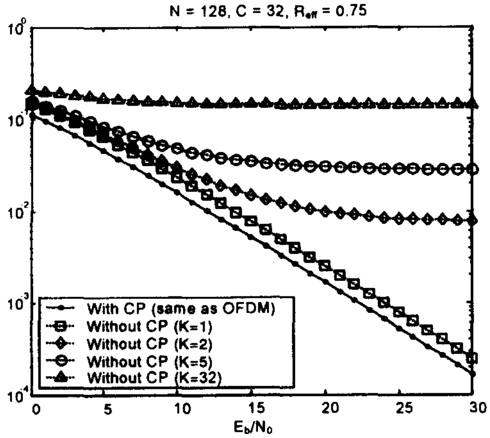
Finally, the relationship between the sensor signature spreading code length C and the system performance is investigated using a numerical method. As illustrated in [Fig. 6], the figure shows the BER performance of our proposed MC-DS/CDMA scheme with respect to various spreading code length C when the number of users is fixed at $K=5$ and the number of subchannels at N=128, and the transmission efficiency at $R_{eff}=0.75$. While the proposed system has an equivalent BER vs. SNR to that of the OFDM system, however, for the general MC-DS/CDMA systems, their performance cannot close the performance gap to that of our system or OFDM even when the coding length C increases exponentially.

5. CONCLUSIONS

In this paper, we have investigated a multicarrier DS/CDMA multiple access and data transmission scheme applicable for the communications and networking of vehicular sensors provided for the intelligent vehicles. Our MC-DS/CDMA scheme lies in the middle way between DS/CDMA and OFDM systems in the view points of exploiting spreading coding gain of DS/CDMA and frequency diversity of OFDM. By implementing a novel idea of inserting cyclic prefixes on subsymbol bases, instead of symbol bases that is typical in DS/CDMA, OFDM, or general a MC-DS/CDMA system, our system could effectively alleviate interference components, hence, enhance the system performance in term of BER vs SNR measures.



[Fig. 4] BER for the various R_{eff}.



[Fig. 5] Our system performance compared OFDM and general MC-DS/CDMA systems with respect to number of sensors.

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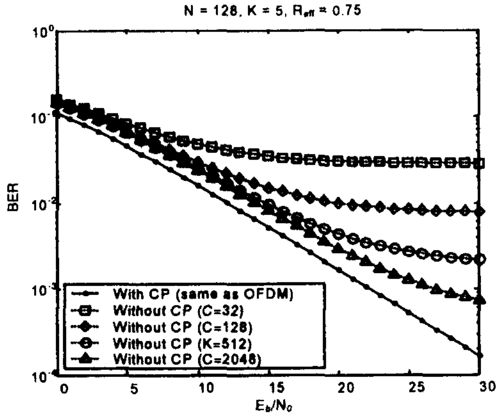

[Fig. 6] Our system performance compared to OFDM and general orthogonal MC-DS/CDMA systems for various coding gains with number of sensors fixed at 5.

Also, using analytical derivations and the numerical computations, we have verified that our proposed system has an equivalent performance to that of OFDM system, and it outperforms those of general MC-DS/CDMA systems. Since the delay spread profile of a vehicle is a very small scale, the proposed scheme pays comparatively minor penalty for inserting cyclic prefixes on subsymbol bases, and it can be a successful candidate for supporting vehicular sensor communications and networking of the future.

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