Efficient Interference Cancellation Scheme for Wireless Body Area Network

Jung Nam Bae, Young Hoon Choi, Jin Young Kim, Jang Woo Kwon, and Dong In Kim

Abstract: **In this paper, we propose and simulate an efficient interference cancellation scheme with an optimal ordering successive interference cancellation (SIC) algorithm for ultra wideband (UWB)/multiple-input-multiple-output (MIMO) systems in a wireless body area network (WBAN). When there are several wireless communication devices on a human body, multiple access interference (MAI) usually occurs. To mitigate the effect of MAI and achieve additional diversity gain, we utilize SIC with an optimal ordering algorithm. A zero correlation duration (ZCD) code with robust MAI capability is employed as a spread code for UWB systems in a multi-device WBAN environment. The performance of the proposed scheme is evaluated in terms of the bit error rate (BER). Simulation results confirm that the BER performance can be improved significantly if the proposed interference cancellation scheme and the ZCD code are jointly employed.**

Index Terms: **Body area network, interference cancellation, multiple input multiple output (MIMO), ultra wideband (UWB).**

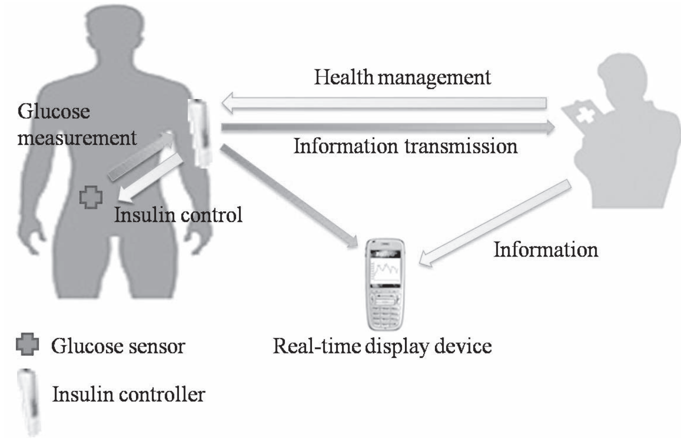

Fig. 1. U-health system.

I. INTRODUCTION

The rapid growth of wireless communication, sensors, and low-power integrated circuits has resulted in the development of a new generation of wireless sensor networks. Sensor networks are used in farm product, traffic volume, and health monitoring. In particular, sensor networks in the area of healthcare enable long-term health monitoring with real-time updates of medical records via the Internet. In addition, the development of sensor devices has made it possible to construct inexpensive and wearable wireless sensor networks in a wireless body area network (WBAN). A number of wearable or implanted sensors are used for the early detection of medical conditions and for availing of medical services in emergency situations. These are the key factors of ubiquitous These are the key factors of ubiquitous healthcare (u-health) systems, which can provide medical and healthcare services anytime, anywhere [1], [2] as depicted in Fig. 1.

Since the emergence of the WBAN in 2006, various studies have been performed to test the practical implementation of u-health systems. The WBAN is composed of a number of mobile units and compact intercommunicating wireless sensor nodes that can be worn on or implanted in the human body. The signals from a u-health system can radiate near the human body, and hence, the system should be operated at a low power. One of the promising solutions to this is the ultra wideband (UWB) system. The power level of a UWB system can be sufficiently lowered so that there are no harmful effects on the human body [3]–[7].

The UWB system employing a multiple-input-multiple-output (MIMO) scheme has been known to have various advantages, including spatial diversity and spatial multiplexing, which afford high system throughput. However, in UWB/MIMO systems, performance degradation may occur as a result of intersymbol interference (ISI), multiple access interference (MAI), and multipath fading. Efforts have been made to mitigate the effects of the abovementioned types of interference in WBAN systems and enhance the system performance [8]–[12]. Previous studies show that the successive interference cancellation (SIC) scheme is effective for interference cancellation in code division multiple access (CDMA) and other multimedia transmission systems. Therefore, the SIC scheme is a promising method for mitigating the effect of interference on the WBAN performance.

UWB systems based on the spread spectrum (SS) technique can be categorized into pulse amplitude modulation (PAM)/direct sequence (DS) systems and pulse position modulation (PPM)/time hopping (TH) systems, which utilize DS and TH codes, respectively. The effect of MAI can be mitigated substantially by using a spreading code with superior correlation performance. In a PAM/DS UWB system, the pseudo noise (PN) code is typically used as the spreading code. However, the

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Table 1. Classification of WBAN channel.

Criterion	WBAN channel mode
Field of applications	Non-medical, medical
Location	In-body, on-body, off-body
Speed	Low, middle, high

PN code is not perfectly orthogonal. Therefore, there is room for performance improvement by using a spreading code with better correlation.

Extensive studies have been carried out to reduce the combined effect of ISI and MAI. Among the well-known solutions are zero forcing (ZF), minimum mean-square error (MMSE), and ordered SIC (OSIC). The ZF algorithm can bring down the ISI to zero in a noise-free case, while the ZF algorithm amplifies noise and can degrade performance in a noisy channel. The MMSE scheme does not eliminate ISI completely, but it minimizes the total power of the noise and ISI components. However, when the channel state information (CSI) is imperfect, performance degradation usually occurs. The OSIC scheme successively decodes data streams through nulling and canceling.

In this paper, we propose and simulate an efficient interference cancellation scheme for UWB/MIMO systems with a WBAN. The nodes in a WBAN are connected through a wireless communication channel within a very close range. The decrease in the internode distance can induce the interference between devices. To mitigate the effect of this interference and achieve additional diversity gain, we utilize the SIC scheme with optimal ordering. In this scheme, enhanced bit error rate (BER) performance can be achieved by restoring the data stream based on the signal-to-interference-and-noise ratio (SINR) and successive interference cancellation. As a spread code of PAM/DS UWB systems, the zero correlation duration (ZCD) code with robust MAI capability is employed in a WBAN environment. The system performance is analyzed in terms of the BER. Through mathematical analysis and extensive simulation, we show that the interference can be effectively mitigated when using the proposed interference cancellation scheme.

The rest of the paper is organized as follows. The WBAN channel model is introduced in Section II. The UWB/MIMO system model considered is described in Section III. The performance of the proposed interference cancellation scheme is analyzed in Section IV. Simulation results are presented in Section V. Finally, concluding remarks are given in Section VI.

II. WBAN CHANNEL MODEL

The WBAN has promising applications in several fields, including medicine, military, sports, security, and multimedia. Table 1 shows a classification of the WBAN systems for several criteria. The WBAN technologies are divided into two categories in accordance with the application field.

The first category is a non-medical application in which multimedia services can be provided to the user in the form of a wireless connection between an MPEG Audio Layer-3 (MP3) player and a headset. The other category is in the healthcare domain. A patient can wear communication equipment with a WBAN made up of sensors that constantly measure specific biological parameters, including temperature, blood pressure, heart rate, respiration rate, and electrocardiogram (ECG) and electroencephalogram (EEG) findings. There are three choices for the location of the communication equipment: In-body, on-body, and off-body. In addition, there are three possible transmission speeds: Low speed, moderate speed, and high speed [12]. Fig. 2 shows the possible channel link models for WBAN. The distance between external devices is typically considered to be a maximum of 5 m.

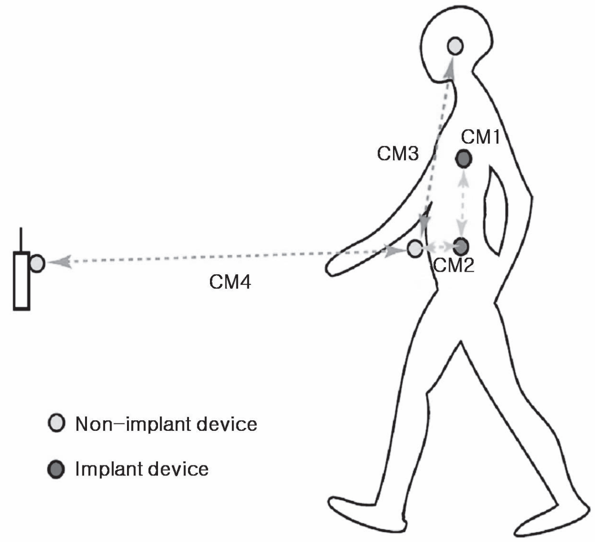

Fig. 2. Possible communication links for WBAN.

In the WBAN channel, the complex channel impulse response $h^i(t)$ for the ith device is given by [13]

$$h^i(t) = \sum_{l=0}^{L-1} \alpha_l^i \delta\left(t - \tau_l^i\right) \quad (1)$$

where L is the number of total arrival paths and modeled as Poisson random variables with a mean value of 400 and α_l^i is the magnitude of the lth path, which can be expressed as

$$\left|\alpha_l^i\right|^2 = \Omega_0 \exp\left(-\frac{\tau_l^i}{\Gamma} - F_k\left[1-\delta(l)\right]\right)\beta \quad (2)$$

where Ω_0 is the path loss, which can be assumed to be equal to the free space path loss. Γ is an exponential decay factor and β is a log-normal random variable with zero mean and variance σ^2. τ_l^i is the path arrival time that is modeled as Poisson random process with an arrival rate of $\lambda = 1/0.50125$ ns, d is the distance between the lth device and the receiver, and $c = 3 \times 10^8$ m/s is the velocity of light. F_k denotes the effect of the K-factor in non-line-of-sight (NLOS) environments and can be calculated as

$$F_k = \frac{\Delta k ln 10}{10} \quad (3)$$

where Δk is the difference between the magnitude of the first impulse response and the average value of the impulse responses. Table 2 shows the values of Γ, F_k, and σ for different orientations of a body [14].

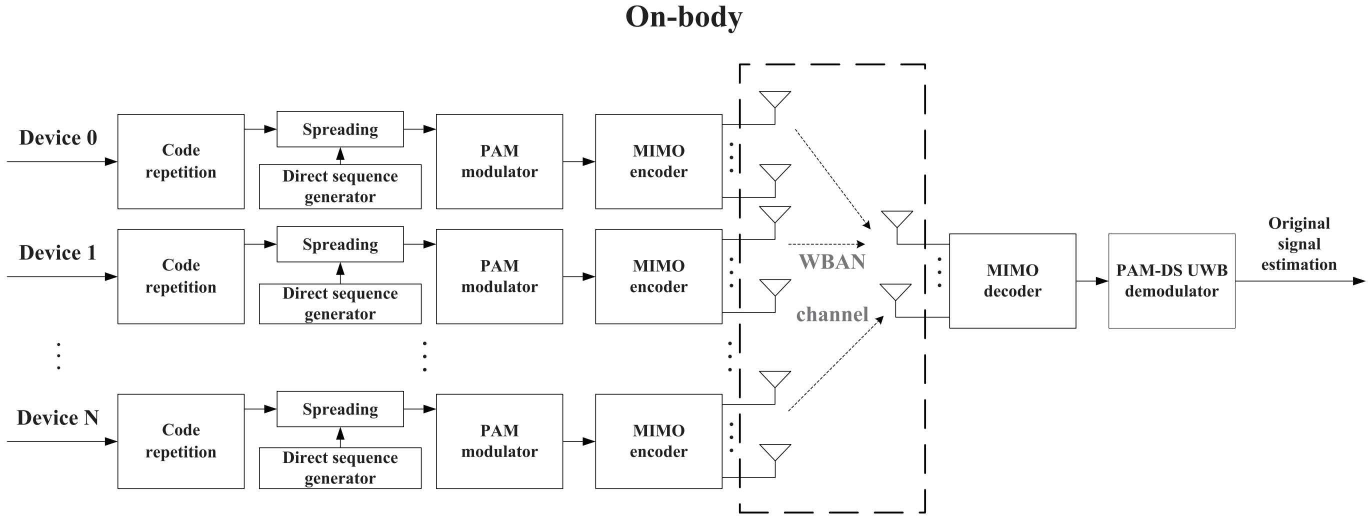

Fig. 3. Block diagram of proposed UWB/MIMO system.

Table 2. Parameters of WBAN channel for different orientations of a body.

Orientation of a body	Γ [ns]	F_k (Δk [dB])	σ [dB]
0	44.6346	5.111 (22.2)	7.30
90	54.2868	4..348 (18.8)	7.80
180	53.4186	3.638 (15.8)	7.03
270	83.9635	3.983 (17.3)	7.19

III. PROPOSED UWB/MIMO SYSTEM MODEL

Fig. 3 shows a block diagram of the proposed UWB/MIMO system. The UWB/MIMO system with N transmit and M receive antennas is considered in the WBAN environment. The transmitted PAM-DS UWB signal spread by a ZCD sequence from the nth transmit antenna is expressed as

$$x_n(t) = \sum_{i=-\infty}^{\infty} \sqrt{E_s} d_n(i) p(t - iT_s) \quad (4)$$

where $d_n(i)$ is the ith information symbol from the nth transmit antenna given by $d_n(i) = b_n(i)c_n$ ($b_n(i)$ is the data sequence of the nth transmit antenna and c_n is the ZCD sequence of the nth transmit sequence). E_s is the energy of basic pulse $p(t)$ which is the impulse response of the pulse shaper filter. And T_s is the average pulse repetition period. For the ZCD sequence, a periodic correlation function for two sequences of $C_k^{(x)} = [c_0^{(x)}, c_1^{(x)}, \cdots, c_{K-1}^{(x)}]$ and $C_k^{(y)} = [c_0^{(y)}, c_1^{(y)}, \cdots, c_{K-1}^{(y)}]$ can be defined as

$$C_{x,y}(\tau) = \sum_{k=0}^{K-1} c_k^{(x)} c_{k \bigoplus \tau}^{(y)} \quad (5)$$

where K is the period of the sequence and $\bigoplus$ represents modulo K addition. The ZCD refers to the time duration when the maximum levels of the side lobes of the autocorrelation function (ACF) and the cross-correlation function (CCF) are successively both zero.

The channel impulse response in the WBAN channel with multipath propagation can be expressed as

$$h(t) = \sum_{l=0}^{L-1} \alpha(l)\delta(t - lT_p) \quad (6)$$

where L is the total number of multipath components, $\alpha(l)$ is a fading coefficient of the lth path whose magnitude follows a log-normal distribution, $\delta(t)$ is the Dirac delta function, and T_p is the minimum multipath resolution.

The received signal $y_m(t)$ at the mth receive antenna can be expressed as

$$y_m(t) = \sum_{n=1}^{N} \sum_{l=0}^{L} h_{m,n}(l) x_n(t - lT_p) + n_m(t) \quad (7)$$

where $h_{m,n}(l)$ represents a fading coefficient of the lth path for the signal from the nth transmit antenna to the mth receive antenna and $n_m(t)$ is the additive white Gaussian noise (AWGN).

IV. INTERFERENCE CANCELLATION SCHEME

A. ZF Receiver

To nullify the interference, we consider the ZF linear detectors that satisfy the following condition.

$$\mathbf{W}_{\text{ZF}}\mathbf{H} = \mathbf{I} \quad (8)$$

where $\mathbf{W}_{\text{ZF}} = (\mathbf{H}^H\mathbf{H})^{-1}\mathbf{H}^H$ is the ZF decoding matrix and $(\cdot)^H$ is the Hermitian transpose. $\mathbf{H}$ is the channel matrix and $\mathbf{I}$ is the identity matrix. The receiver can obtain the estimated signal by using ZF equalization, which is given by

$$\hat{\mathbf{X}} = \mathbf{W}_{\text{ZF}}\mathbf{Y} \quad (9)$$

where $\hat{\mathbf{X}}$ is an estimate matrix of the transmitted signal. If the determinant of $\mathbf{H}$ is not zero and there is no inverse matrix of $\mathbf{H}$, the decoding matrix can be expressed as

$$\mathbf{W}_{\text{ZF}} = \mathbf{H}^{-1}. \quad (10)$$

The ZF algorithm is ideal when the channel is noiseless. However, when the channel is noisy, the ZF algorithm will amplify the noise greatly in the areas of the channel with small magnitude in an attempt to invert the channel completely.

B. MMSE Receiver

To minimize the power of the noise component, we employ the MMSE algorithm, which is given by

$$\mathbf{W}_{\text{MMSE}} = \underset{\mathbf{W}_{\text{MMSE}}}{\arg\min} E[\|\mathbf{W}_{\text{MMSE}}\mathbf{Y} - \mathbf{X}\|_F^2] \quad (11)$$

where $\mathbf{W}_{\text{MMSE}}$ is the MMSE decoding matrix and $\|\cdot\|_F$ represents the Frobenius norm. The following result is obtained from the orthogonality principle.

$$E[(\mathbf{W}_{\text{MMSE}}\mathbf{Y} - \mathbf{X})\mathbf{Y}^H] = \mathbf{0}_{2,2} \quad (12)$$

where $\mathbf{0}_{2,2}$ is a 2×2 zero matrix. By using (11) and (12), the decoding matrix can be expressed as

$$\mathbf{W}_{\text{MMSE}} = (\mathbf{H}^H\mathbf{H} + \frac{1}{\lambda}\mathbf{I})^{-1}\mathbf{H}^H \quad (13)$$

where λ is the signal-to-noise ratio (SNR). The MMSE algorithm can be used to counteract the interference by varying the decoding matrix in accordance with the SNR. It also prevents the noise component from being amplified.

C. SIC with Optimal Ordering

We can achieve additional diversity gain by adopting the interference cancellation technique after linear equalization. In conventional SIC, the estimated signal, whose effect needs to be eliminated from the received signals, is randomly selected. If the early decision is wrong and errors occur, the next decision also could be wrong [15].

To overcome the error propagation problem, an SIC scheme with optimal ordering is adopted. The SIC scheme operates simply by subtracting the contributions of MAI in the decreasing order of relative strength between the users. The strongest signal is cancelled out first, followed by the second strongest, etc. The steps involved in of the SIC scheme are as follows:

i) Recognize the strongest signal.
ii) Decode the strongest signal.
iii) Estimate the amplitude of the decoded user from the output of the correlator.
iv) Regenerate the strongest signal using its chip sequence and the estimate of its amplitude.
v) Cancel the strongest signal.
vi) Repeat (until all users' signals are decoded or a permissible number of cancellations are achieved).

After the decoding process, the received power at the receiver related to the transmitted signal x_1 and x_2 is given by

$$P_{x_1} = |h_{1,1}|^2 + |h_{2,1}|^2, \quad P_{x_2} = |h_{1,2}|^2 + |h_{2,2}|^2, \quad (14)$$

respectively. If P_{x_1} is greater than P_{x_2}, the receiver decides to eliminate the effect of $\hat{x}_1$ from the received signal vector $\mathbf{Y}$. Then, $\hat{x}_2$ is re-estimated as

$$r_2 = hx_2 + n \quad (15)$$

Table 3. Simulation parameters.

Modulation	PAM-DS
MIMO scheme	$2 \times 2, 4 \times 4$
Spreading code	PN, ZCD
Channel model	WBAN
Equalizer	ZF, MMSE
Interference cancellation scheme	SIC

where r is the re-estimated signal vector. We also estimate the transmitted signal x_2 by combining information from multiple copies of the received signals. In this study, the maximal ratio combining (MRC) scheme is adopted. Then, the final result for x_2 is expressed as follows.

$$\hat{x}_{2,\text{Final}} = \frac{h^H r_2}{h^H h}. \quad (16)$$

In a similar manner, if P_{x_1} is less than or equal to P_{x_2}, the receiver decides to remove the effect of $\hat{x}_2$ from the received signal vector $\mathbf{Y}$. Then, $\hat{x}_1$ is re-estimated as

$$r_1 = hx_1 + n. \quad (17)$$

We can estimate the transmitted signal x_1 by combining information from multiple copies of the received signals. Therefore, the final result for x_1 is given by

$$\hat{x}_{1,\text{Final}} = \frac{h^H r_1}{h^H h}. \quad (18)$$

The SIC scheme with optimal ordering guarantees the reliability of the signal decoded first, and hence, that signal has lower error probability than do the other signals.

V. PERFORMANCE ANALYSIS

The instantaneous SNR y_n of linear receiver output for the nth data stream can be written as

$$\gamma_n = 2\lambda \sum_{l=0}^{L-1} (\alpha_n^2)(l) = 2\lambda\gamma'_n. \quad (19)$$

The conditional BER expression conditioned on a fixed set of channel coefficients is given by

$$P(\gamma_n) = Q(\sqrt{\gamma_n}) = \left(1/\sqrt{2\pi}\right) \int_{\sqrt{\gamma_n}}^{\infty} e^{-y^2/2} dy \quad (20)$$

where $Q(\cdot)$ is the complementary error Q-function.

By following an analysis similar to that in [16], the quadratic form can be expressed as

$$\alpha_n^2 = H_n(l)^H G(l) H_n(l) \quad (21)$$

where $G(l)$ is an $M \times M$ positive Hermitian matrix formed by $h_1(l), \cdots, h_{n-1}(l), h_{n+1}(l), \cdots, h_n(l)$.

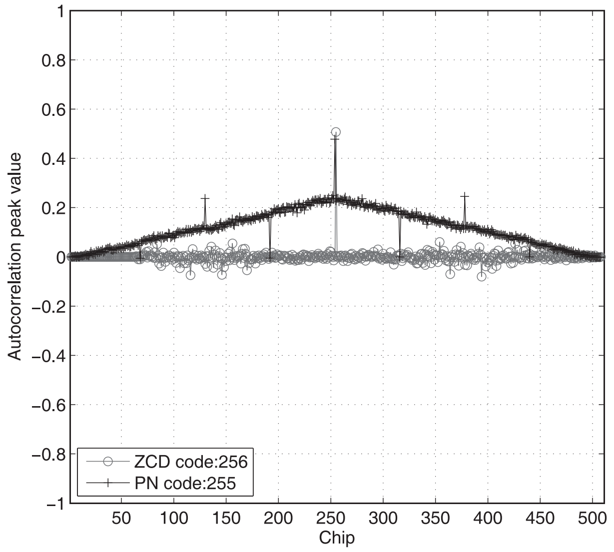

Fig. 4. Performance of autocorrelation function.

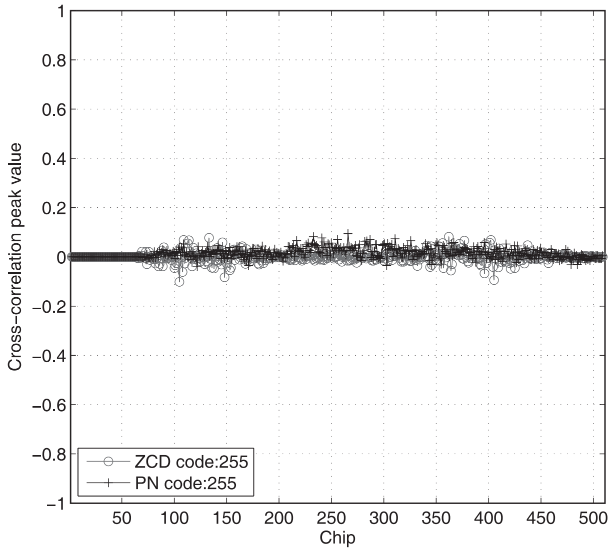

Fig. 5. Performance of cross-correlation function.

To derive the average BER, we need a probability density function (pdf) of γ_n'.

$$\gamma_n' = \sum_{l=0}^{LM-1} \lambda_i k_i^2 \tag{22}$$

where k_i is the zero mean unit-variance Gaussian random variables, and γ_i denotes the eigenvalue of the matrix $G_n = \text{diag}[G_n(0)\cdots G_n(L-1)]$ having LM eigenvalues, among which $L(M-N+1)$ eigenvalues are equal to 1 and the other $L(N-1)$ eigenvalues are equal to 0.

Since k_i is distributed as a Gaussian distribution with zero mean and unit variance, the variable γ_n' is a central Chi-square distributed random variable pdf given by [17]

$$f_{\gamma_n'}(y) = \left(\frac{1}{2^p\Gamma(p)}\right) y^{p-1} e^{-y/2} \tag{23}$$

where $p = (M-N+1)/2$ and $\Gamma(\cdot)$ is the gamma function defined as $\Gamma(a) = \int_0^\infty \tau^{a-1} e^{-\tau} d\tau$, $a > 0$. The average BER for a particular bit of the nth transmitted data stream over log-normal fading channels can be calculated as

$$P_{b,\text{OSIC}} = \int_0^\infty P(y) f_{\gamma_n'}(y) dy. \tag{24}$$

To derive the average BER in a closed form, a simple approximated expression can be obtained for $Q(\cdot)$ as [18]

$$Q(x) \cong \frac{1}{12} e^{\frac{-x^2}{2}} + \frac{1}{6} e^{\frac{-2x^2}{3}}. \tag{25}$$

The overall BER of the SIC with an optimal ordering receiver for a fading channel in closed form can be expressed as

$$\begin{aligned}\text{BER}_{\text{OSIC}} =& \frac{1}{M} \sum_{n=1}^{M} \frac{(p-1)!}{\Gamma(p)} \left[\left\{ 12 \left\{ \frac{\gamma_n}{\gamma_n'} + 1 \right\}^p \right\}^{-1} \right. \\ & \left. + \left\{ 6 \left\{ \frac{4\gamma_n}{3\gamma_n'} + 1 \right\}^p \right\}^{-1} \right]. \end{aligned} \tag{26}$$

VI. SIMULATION RESULTS

In this section, the performance of the proposed UWB/MIMO system with an interference cancellation scheme is simulated in the WBAN environment. Table 3 shows the simulation parameters. To verify the performance, the BER is tested when there are several devices in the WBAN channel. ZCD and PN codes are used as spreading codes. In the simulation, the interference cancellation performance of the ZF-SIC scheme is compared with that of MMSE-SIC. In addition, the performance of the conventional SIC scheme is compared with that of SIC with optimal ordering. Two different MIMO structures are considered: A 2×2 structure (two receive antennas and two transmit antennas) and a 4×4 structure (four transmit and four receive antennas).

The performance of the ZCD code is dependent on how perfect the synchronization is. When the synchronization is not perfect, the performance of the ZCD-based system is degraded because the autocorrelation peak of the ZCD code may appear at the wrong point [19]. In this study, perfect synchronization is assumed for the preliminary performance analysis. The ZCD code is robust to MAI and multipath fading because it has zero correlation periods. Therefore, the performance of the ZCD-code-based system is less affected by interference than is the PN-code-based system.

Figs. 4 and 5 show the performance of the correlation function in accordance with the spreading code. The performance is evaluated in terms of the correlation peak value. The ZCD code shows better performance than the PN code for the auto correlation function.

The energy of the side lobes is high in the case of the PN code and low in the case of the ZCD code. Fig. 5 shows that the cross-correlation performance is almost the same in the two codes. However, in the case of the ZCD code, there are successive zero-correlation sections that will minimize the effect of MAI. Thus, the ZCD code has slightly better performance than does the PN code, from the standpoint of correlation functions.

Fig. 6 depicts the BER performance of the PPM-TH system

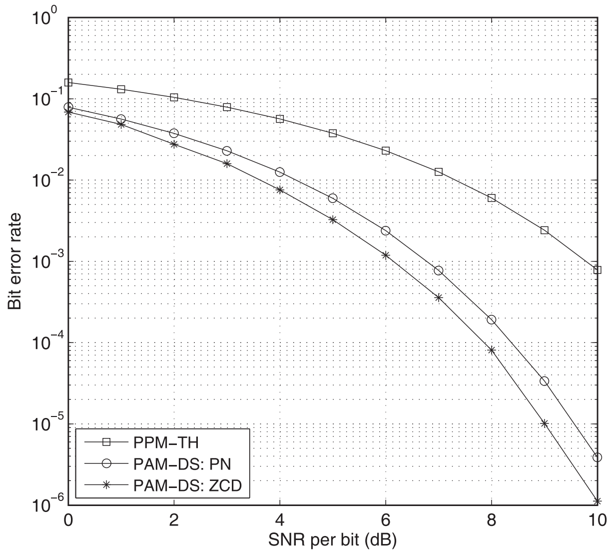

Fig. 6. Performance of UWB system for various modulation schemes.

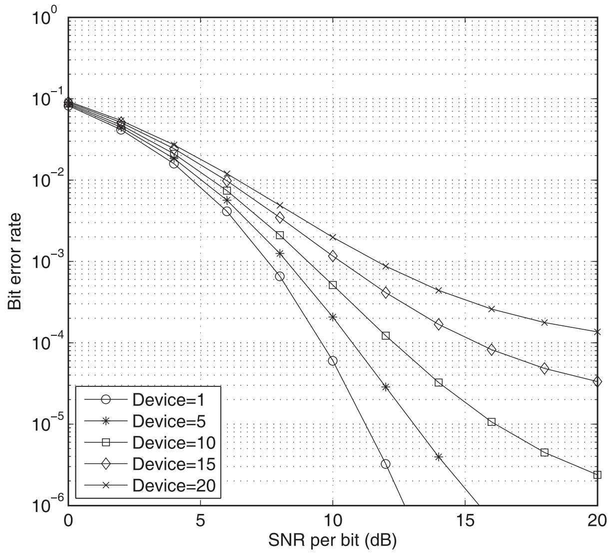

Fig. 7. Performance of PAM-DS UWB/MIMO (2×2) system for multidevice environments.

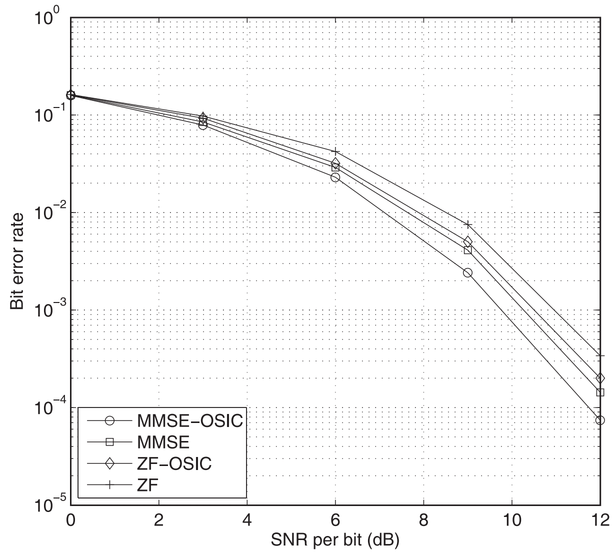

Fig. 8. Performance of UWB/MIMO (2×2) system employing SIC with optimal ordering.

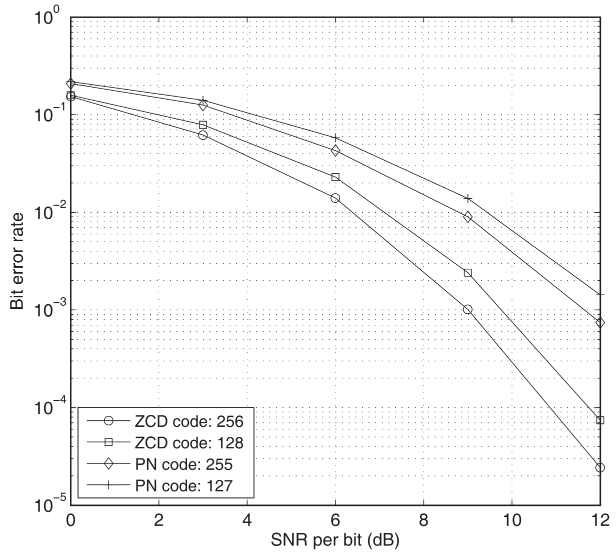

Fig. 9. Performance of UWB/MIMO (2×2) system employing SIC with optimal ordering for different sequence lengths.

and the PAM-DS system for PN and ZCD codes. The result shows that the system using PAM-DS has better BER performance than does the system using PPM-TH. In the PAM-DS system, the BER performance with the ZCD code is better than that with the PN code.

Fig. 7 shows the performance of the PAM-DS UWB/MIMO (2×2) system for a multidevice WBAN environment. The increase in the number of devices causes an increase in MAI power, which in turn results in an increase in distortion. Thus, the increase in the number of devices causes performance degradation of the system in a WBAN environment.

Fig. 8 shows the error performance of the UWB/MIMO $(2{\times}2)$ system employing SIC with optimal ordering for a ZCD code length of 256. The performance of the system with the SIC scheme is significantly improved over that of the system with the non-SIC scheme. It is also illustrated that the MMSE-SIC with optimal ordering achieves better performance than does the ZF-SIC with optimal ordering.

Fig. 9 compares the performance of the typically employed PN and the proposed ZCD code with different code lengths for the MMSE-SIC with optimal ordering. Owing to its robust MAI characteristics, the ZCD code shows better performance than does the PN code.

Fig. 10 shows the error performance of the UWB/MIMO (4×4) system employing SIC with optimal ordering for a ZCD code length of 256. The BER performance is improved with the number of antennas, and the MMSE-SIC scheme with optimal ordering shows the best performance owing to its advantageous characteristics. In addition, the BER performance of the system with the SIC scheme is better than that of the system with the non-SIC scheme.

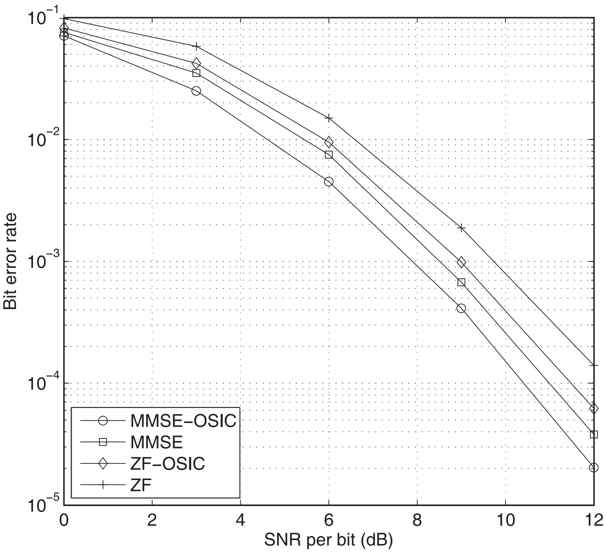

Fig. 10. Performance of UWB/MIMO (4×4) system employing SIC with optimal ordering.

VII. CONCLUSIONS

In this paper, we proposed an efficient interference cancellation scheme that helps mitigate the effect of MAI and fading for UWB/MIMO systems in a WBAN. From the simulation results, it is confirmed that the system performance can be improved significantly if the proposed interference cancellation scheme is used in conjunction with the ZCD code. The results of this paper can be used for the design and implementation of UWB systems in WBAN applications.

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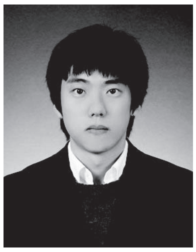

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