1-1-2013

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Abstract

This paper proposes a simple, but efficient, adaptive space-time-frequency coded (STFC) multiband orthogonal frequency division multiplexing ultra-wideband (MB-OFDM UWB) system to improve the average BER performance for body-to-external link wireless body area network (WBAN) applications. The novelty of this paper is the proposed body direction based adaptive algorithm that controls the set of modulation scheme, space-time-frequency code (STFC) coding rate, and power of signal constellations implemented in STFC MB-OFDM UWB WBAN. Simulation results show that the proposed system can provide a consistent 1-2 dB improvement in the case of 2I1O configuration, and 1-3 dB improvement in a medium-to-high SNR region in the case of 2I2O configuration, compared to the non-adaptive system. The improvement practically means a possible reduction of 12.5% - 50% of the total transmitted power to achieve the similar performance as the non-adaptive system. In other words, it can save significantly the power consumption and prolong the battery life of WBAN devices.

Keywords

applications, wban, system, stfc, uwb, mb, ofdm, simple, adaptive

Disciplines

Engineering | Science and Technology Studies

Publication Details

M. Sudjai, L. Chung. Tran & F. Safaei, "A Simple Adaptive STFC MB-OFDM UWB System for WBAN Applications," in IEEE International Symposium on Communications and Information Technologies (ISCIT 2013), 2013, pp. 60-65.

A Simple Adaptive STFC MB-OFDM UWB System for WBAN Applications

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***Abstract*— This paper proposes a simple, but efficient, adaptive space-time-frequency coded (STFC) multiband orthogonal frequency division multiplexing ultra-wideband (MB-OFDM UWB) system to improve the average BER performance for *body-to-external* link wireless body area network (WBAN) applications. The novelty of this paper is the proposed body direction based adaptive algorithm that controls the set of modulation scheme, space-time-frequency code (STFC) coding rate, and power of signal constellations implemented in STFC MB-OFDM UWB WBAN. Simulation results show that the proposed system can provide a consistent 1–2 dB improvement in the case of 2I1O configuration, and 1–3 dB improvement in a medium-to-high SNR region in the case of 2I2O configuration, compared to the non-adaptive system. The improvement practically means a possible reduction of 12.5% - 50% of the total transmitted power to achieve the similar performance as the non-adaptive system. In other words, it can save significantly the power consumption and prolong the battery life of WBAN devices.**

***Keywords*— Adaptive system, MIMO, UWB, WBAN**

I. INTRODUCTION

Wireless body area network (WBAN) has become the focal point of research during the last years. By utilizing tiny-low power and high data rate devices, it promises a wide range of applications, such as entertainment, sports and training, military, and health care [7]. In particular, WBAN alleviates the hurdle and inflexibility of cable-connected devices for monitoring health conditions via various implantable and wearable sensors.

The IEEE 802.15 TG6 has recently released the WBAN standard that includes the Impulse Radio Ultra Wideband (IR-UWB) as its physical layer [9]. Prior to this standard, IEEE also released the WBAN channel models [8] that defined four different channel conditions, i.e. CM1 – CM4, in which CM4 considers the *body-to-external* link.

Another competing technology for a short range, very high data rate communication is MB-OFDM UWB, endorsed by the WiMedia Alliance [6]. It combines the capability of OFDM to flatten the response of dispersive-frequency selective channels of UWB, while maintaining the benefit of high capacity of UWB. Thus, in [10], we proposed the use of MB-OFDM UWB as an alternative physical layer for WBAN, in combination with Space-Time-Frequency-Code Multi-Input Multi-Output (STFC MIMO) techniques. STFCs are the extended versions of the conventional Space-Time Block Codes (STBCs) to a three -dimensional space, namely space, time and frequency, to increase further the system diversity. Readers may refer to [5] for more details about STFCs. We demonstrated that the proposed system, referred to as STFC MB-OFDM UWB, could provide better performance, higher data rate, and greater range at the price of a modest increase in complexity [10]. Further, we evaluated the performance of the proposed system in the CM4 channel model. One important observation from the result in [10] (or Fig.3 in this paper) is that the system BER performance differs significantly in different body directions, i.e. the direction of the receiver placed on the surface of the body with respect to (w.r.t) the transmitter. This is due to the effects of LOS (Line-of-Sight), partial LOS, and body shadowing. The results are also consistent with the parameters of the IEEE WBAN CM4 channel [8].

Adaptive techniques have been employed for numerous systems and applications in order to enhance their performance. For instance, [2] examined a unified adaptive modulation scheme for a general communication system where the data rate, transmitted power, and instantaneous BER are varied to maximize spectral efficiency. A cross layer adaptive modulation to minimize the transmission energy in wireless sensor networks is proposed in [3]. However, an adaptive scheme for the WBAN physical layer has not been examined. The contribution of this paper is the proposal for the first time a body direction based adaptive algorithm implemented in STFC MB-OFDM UWB WBAN, in order to improve the average BER performance and/or reduce the power consumption of the body-to-external link for WBAN applications. The core idea is that a combination of different digital modulation schemes (BPSK, QPSK), powers of signal constellations, and STFC coding rates is adaptively selected, depending on the body direction w.r.t. the transmitter. The adaption is carried out by the measurement of angles of the body w.r.t. the transmitter. A simple direction sensor, e.g. a Giant Magneto Resistance (GMR) thin film sensor chips, can be used to accurately measure the angle [11]. The angle information is then feedback to the transmitter via a simple feedback loop to vary its modulation, STFC coding rate, and constellation power.

The paper is organized as follows. Section II analyzes the proposed system model, including a review of the CM4 IEEE WBAN channel model. Section III describes the algorithm of the adaptive scheme, including the decoding complexity. Simulation results and analyses are presented in Section IV. Section V concludes the paper.

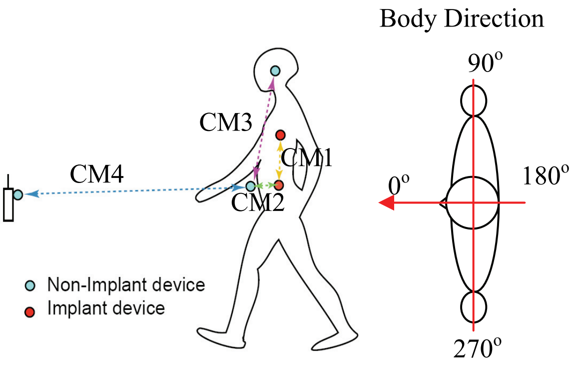


Fig.1. WBAN channel models and body directions of CM4 [8].

II. SYSTEM MODEL

A. Review of CM4 IEEE's WBAN Channel Model

IEEE WBAN CM4 channel model [8] will be used in this paper to create channel realizations for the *body surface-to-external* WBAN link as shown in Fig.1. It is applied to three different frequency bands, including the UWB band (3.1-10.6 GHz) and takes into account the effect of body directions [8].

The channel response is characterized by the following power decay profile

$$h(t) = \sum_{m=0}^{L-1} \alpha_m \delta(t - \tau_m) \quad (1)$$

where $|\alpha_m|^2 = \Omega_0 e^{-\frac{\tau_m}{\Gamma} - k[1-\delta(m)]}\beta$

$$k = \Delta k\left(\frac{ln10}{10}\right); \tau_o = d/c \text{ ; and } \beta \sim \log\text{normal}(0,\sigma) .$$

L is the number of arrival paths, modeled as a Poisson random variable with the mean value of 400; α_m is the amplitude of each path; τ_m, m =1,…, L-1, is timing of path arrivals and is modeled as a Poisson random process with the arrival rate λ= 1/0.501251 ns; Γ is an exponential decay factor with Ω_0 as the path loss; k is the K-factor (NLOS), d is the *Tx-Rx* distance, and c is the velocity of light.

The parameters of CM4 also depend on the direction of body toward the Tx antenna, and listed in the Table I [8].

TABLE I. PARAMETERS OF CM4 [8].

Body Direction	Γ *(ns)*	k *(Δk (dB))*	σ *(dB)*
0°	44.6364	5.111(22.2)	7.30
90°	54.2868	4.348(18.8)	7.08
180°	53.4186	3.638(15.8)	7.03
270°	83.9635	3.983(17.3)	7.19

From Table I, as opposed to our intuition, the worst link is corresponding to the 270° body direction, rather than 180° , and the channel behaviours of the 90° and 270° are significantly different. It might possibly be due to the asymmetrical radiation pattern of the antenna and different surrounding environments of the 90°, and 270° directions during the measurement. This observation will be reflected in our simulation results in this paper.

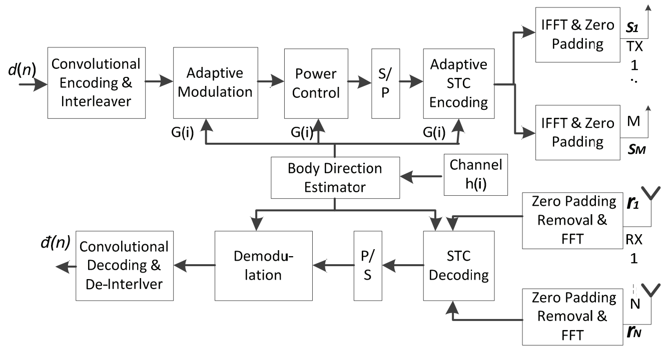


Fig. 2. Adaptive STFC MB-OFDM UWB system

B. Proposed Adaptive STFC MB-OFDM UWB System

Fig.2 depicts the proposed adaptive STFC MIMO-OFDM UWB system with M-Tx antennas and N-Rx antennas. The data stream *d(n)* undergoes convolutional coding and interleaving, before being mapped to symbols. The body direction estimator measures the orientation of the body w.r.t. the transmitter. The angular information is then feedback to the transmitter via a simple feedback loop in order to adjust its modulation, constellation power, and STFC coding rate accordingly. The adaptive modulation block selects either QPSK or BPSK, while the power control block adjusts the constellation power based on certain rules as detailed in the next section. Those parameters areadaptively varied in a way that the average total power and total data rate over all four body directions are exactly the same as that in a non-adaptive system for a fair comparison. The stream of modulated symbols is then converted by a Serial-to-Parallel (S/P) block into the symbol blocks (or vectors) $\bar{x} = \left[x_1, x_2, \dots, x_{N_{fft}}\right]^T$, where N_{fft} is the FFT/IFFT size.

The adaptive STFC block creates a space-time code with either full rate, or 3/2-rate. For the full rate, it uses the Alamouti code [1] to convert the two consecutive symbol blocks, denoted as $\bar{x}_1$ and $\bar{x}_2$, into a STFC block as follows

$$\mathbf{X} = \{\bar{x}_{t,m}\}_{T\times M} = \begin{bmatrix} \bar{x}_1 & \bar{x}_2 \\ -\bar{x}_2^* & \bar{x}_1^* \end{bmatrix} \quad (2)$$

where $\bar{x}_1$ and $\bar{x}_2$ are symbol vectors transmitted from the first and the second antenna at a given time slot, respectively. $(.)^*$ denotes complex conjugate. For 3/2-rate STFC, three symbol vectors are encoded following the Sezginer-Sari code [4]

$$\mathbf{X} = \{\bar{x}_{t,m}\}_{T\times M} = \begin{bmatrix} a\bar{x}_1 + \frac{b\bar{x}_3}{\sqrt{2}} & -\left(c\bar{x}_2^* + \frac{d\bar{x}_3^*}{\sqrt{2}}\right) \\ a\bar{x}_2 + \frac{b\bar{x}_3}{\sqrt{2}} & c\bar{x}_1^* + \frac{d\bar{x}_3^*}{\sqrt{2}} \end{bmatrix} \quad (3)$$

where *a, b, c,* and *d* are complex-valued design parameters. Here, we use the optimum parameters $a = c = \sqrt{2}$, and $b = d = (1 + j\sqrt{7})/4$ as determined in [4].

We denote the matrix **X** in the general form as $\mathbf{X} = \{\bar{\mathrm{x}}_{t,m}\}_{T\times M}$, where the index *t* indicates the time slot and *m* indicates the Tx antenna. Each of symbol vectors in the matrix **X** is then converted into an N_{fft}-point MB-OFDM symbol by the IFFT block, resulting in the STFC code matrix $\mathbf{X}_{OFDM}$ whose elements are the N_{fft}-point IFFT of the corresponding symbol vectors $\bar{\mathrm{x}}_{t,m}$ in **X**. Hence, the transmitted matrix of STFC MB-OFDM symbols is

$$\mathbf{X}_{OFDM} = \{\bar{\mathrm{x}}_{OFDM,t,m}\}_{T\times M} = \{\mathrm{IFFT}\{\bar{\mathrm{x}}_{t,m}\}\}_{T\times M} \tag{4}$$

The actual transmitted matrix is the matrix $\mathbf{X}_{ZP}$ whose elements are the N_{fft}-length vectors $\bar{\mathrm{x}}_{OFDM,t,m}$ in $\mathbf{X}_{OFDM}$ appended with the 37-samples zero padded suffix (ZPS), denoted as $\bar{\mathrm{x}}_{ZP,t,m}$, before being transmitted to the channel. This means

$$\mathbf{X}_{ZP} = \{\bar{\mathrm{x}}_{ZP,t,m}\}_{T\times M} \tag{5}$$

The channels between *M*-Tx antennas and *N*-Rx antennas are defined as the channel matrix **H**

$$\mathbf{H} = \begin{bmatrix} \bar{\mathrm{h}}_{1,1} & \cdots & \bar{\mathrm{h}}_{M,1} \\ \vdots & \ddots & \vdots \\ \bar{\mathrm{h}}_{1,N} & \cdots & \bar{\mathrm{h}}_{M,N} \end{bmatrix} \tag{6}$$

where $\bar{\mathrm{h}}_{m,n}$ is the channel coefficient vector between the *m-th* Tx antenna, for *m* = 1,2,…,*M*, and the *n*-th Rx antenna, *n* = 1,2,…,*N,* containing *L* multipath. The distribution and parameters of $\bar{\mathrm{h}}_{m,n}$ are determined by Eq. (1) and Table I.

The received signal at the *n-th* Rx antenna during the *t-th* transmitted OFDM symbol duration is computed as

$$\bar{\mathrm{r}}_{t,n} = \sum_{m=1}^{M} \left(\bar{\mathrm{x}}_{ZP,t,m} \otimes \bar{\mathrm{h}}_{m,n}\right) + \bar{\mathrm{n}}_{t,n} \tag{7}$$

where ⊗ denotes the *linear convolution*, $\bar{\mathrm{x}}_{ZP,t,m}$ is the MB-OFDM symbol including ZPS (Zero Padded Suffix) transmitted from the *m-th* Tx antenna, and $\bar{\mathrm{n}}_{t,n}$ is the zero mean additive white Gaussian noise (AWGN) vector. The ZPS is removed by an Overlap-And-Add-Operation (OAAO) prior to the FFT operation. After performing OAAO, the received signal can be written as [5, Eq.(8)]

$$\bar{\mathrm{r}}_{OFDM,t,n} = \sum_{m=1}^{M} \bar{\mathrm{x}}_{OFDM,t,m} * \bar{\mathrm{h}}_{m,n} + \bar{\mathrm{n}}_{t,n} \tag{8}$$

where (*) denotes *circular convolution*. After the FFT block, the input signals of the STFC decoder is calculated as [5, Eq.(12)]

$$\bar{\mathfrak{r}}_{t,n} = \sum_{m=1}^{M} \bar{\mathrm{x}}_{t,m} \bullet \bar{\mathfrak{h}}_{m,n} + \bar{\mathfrak{n}}_{t,n} \tag{9}$$

where (•) denotes the dot (Hardamard) product between the two vectors, $\bar{\mathfrak{r}}_{t,n} = \mathrm{FFT}(\bar{\mathrm{r}}_{OFDM,t,n}) = \left[\mathfrak{r}_{m,n,1}, \ldots, \mathfrak{r}_{m,n,N_{fft}}\right]^T$, $\bar{\mathrm{x}}_{t,m}$ is the original modulation symbols, $\bar{\mathfrak{h}}_{m,n} = \mathrm{FFT}(\bar{\mathrm{h}}_{mn}) = \left[\hbar_{m,n,1}, \ldots, \hbar_{m,n,N_{fft}}\right]^T$, and $\bar{\mathfrak{n}}_{t,n} = \mathrm{FFT}(\bar{\mathrm{n}}_{t,n})$. Denote $\mathcal{R} = \{\bar{\mathfrak{r}}_{t,n}\}_{T\times N}$ to be the matrix of the received signals after FFT, $\mathcal{H} = \{\bar{\mathfrak{h}}_{m,n}\}_{M\times N}$ to be the channel response matrix, and $\mathcal{N} = \{\bar{\mathfrak{n}}_{t,n}\}_{T\times N}$ the matrix of noise. Then we can re-write (9) as

$$\mathcal{R} = \mathbf{X} \circ \mathcal{H} + \mathcal{N} \tag{10}$$

where (◦) denotes the operation which is similar to the normal matrix multiplication, except that each element in $\mathcal{R}$ is determined by (9). Thus the detected vectors are decided by the following Maximum Likelihood (ML) rule

$$\{\tilde{\bar{\mathrm{x}}}_{t,m}\} = \arg\min_{\{\bar{\mathrm{x}}_{t,m}\}} \|\mathcal{R} - \mathbf{X} \circ \mathcal{H}\|_F^2 \tag{11}$$

Since the matrix **X** preserves its orthogonality in the similar manner as in a conventional STBC MIMO system, the STFC MB-OFDM UWB system can also employ a simple linear decoding process. For simplicity, we can omit the time index *t*. Hence in the 2I1O configuration with M-PSK modulation, we have the following decoding metrics

$$\begin{aligned} \bar{\mathrm{x}}_1 &= \arg\min_{\bar{\mathrm{x}}\in\mathcal{C}^{N_D}} \|(\bar{\mathfrak{h}}_1^* \bullet \bar{\mathfrak{r}}_1 + \bar{\mathfrak{h}}_2 \bullet \bar{\mathfrak{r}}_2^*) - \bar{\mathrm{x}}\|_F^2 \\ \bar{\mathrm{x}}_2 &= \arg\min_{\bar{\mathrm{x}}\in\mathcal{C}^{N_D}} \|(\bar{\mathfrak{h}}_2^* \bullet \bar{\mathfrak{r}}_1 - \bar{\mathfrak{h}}_1 \bullet \bar{\mathfrak{r}}_2^*) - \bar{\mathrm{x}}\|_F^2 \end{aligned} \tag{12}$$

where N_D is number of data subcarriers (N_D = 100, according to the standard [6]), and $\mathcal{C}^{N_D}$ denotes the N_D-dimensional complex space of the transmitted vector $\bar{\mathrm{x}}$. More importantly, each data point in an MB-OFDM symbol can be decoded separately rather than jointly [5], thus the decoding process is significantly simplified. In particular, the decoding metric of each data at the *k*-th subcarrier (*k*=1,…, N_D) in the MB-OFDM symbols for the 2I1O configuration are

$$\begin{aligned} \tilde{\mathrm{x}}_{1,k} &= \arg\min_{x_{1,k}\in\mathcal{C}} \left[\left|(\hbar_{1,k}^* \mathfrak{r}_{1,k} + \hbar_{2,k} \mathfrak{r}_{2,k}^*) - x_{1,k}\right|^2\right] \\ \tilde{\mathrm{x}}_{2,k} &= \arg\min_{x_{2,k}\in\mathcal{C}} \left[\left|(\hbar_{2,k}^* \mathfrak{r}_{1,k} - \hbar_{1,k} \mathfrak{r}_{2,k}^*) - x_{1,k}\right|^2\right] \end{aligned} \tag{13}$$

Similarly, for the 2I2O configuration , the decoding metrics are

$$\begin{aligned} \tilde{\mathrm{x}}_{1,k} &= \arg\min_{x_{1,k}\in\mathcal{C}} \left[\left|\sum_{n=1}^{2} (\hbar_{1,n,k}^* \mathfrak{r}_{1,n,k} + \hbar_{2,n,k} \mathfrak{r}_{2,n,k}^*) - x_{1,k}\right|^2\right] \\ \tilde{\mathrm{x}}_{2,k} &= \arg\min_{x_{2,k}\in\mathcal{C}} \left[\left|\sum_{n=1}^{2} (\hbar_{2,n,k}^* \mathfrak{r}_{1,n,k} - \hbar_{1,n,k} \mathfrak{r}_{2,n,k}^*) - x_{2,k}\right|^2\right] \end{aligned} \tag{14}$$

For the 3/2-rate STFC, we follow the decoding process as mentioned in [4]. Generalization for the case of *M*-Tx and

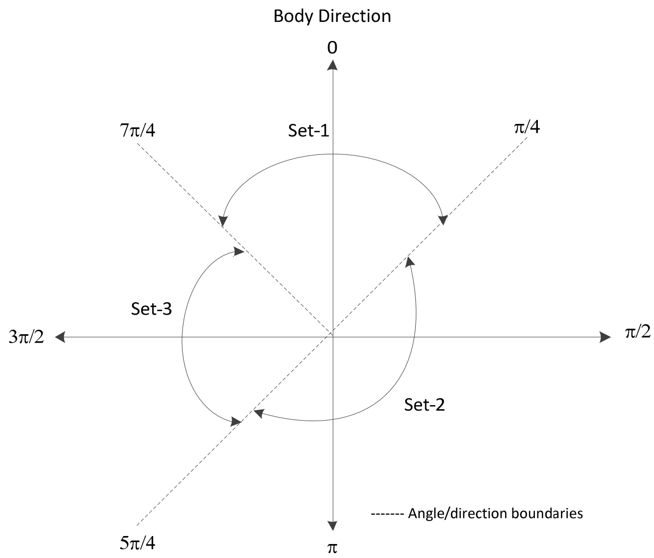


Fig.3. Angle direction boundaries for adaptive decision.

N-Rx antennas is straightforward.

III. ADAPTIVE SCHEME

A. Adaptive Selection Algorithm

As mentioned previously in Section I, adaptive modulation and coding schemes have not been examined for WBANs using MB-OFDM UWB technology, though they have been intensively researched for other systems. This section proposes for the first time a simple-but-efficient adaptive modulation and space-time-frequency coding scheme for such system. The proposed adaptive scheme is controlled by the measurement of the angular direction of the body. Depending on which region among three regions shown in Fig. 3 the current body direction belongs to, the corresponding 2-bit angular information is fed back to the transmitter to select a suitable combination of its modulation, STFC coding rate, and constellation power. It is noted that the three regions in Fig. 3 have been derived based on our observations that the best channel behaviour is corresponding to the 0^o direction, the 90^o and 180^o directions possess relatively close error performances, and the worst channel behaviour is the 270^o direction. These observations have been discussed in our previous publication [10], and can also be seen in Fig. 4 mentioned in Section IV of this paper.

Either QPSK or BPSK is used for modulation. We use two different STFC coding rates, namely coding rate-1 which uses an Alamouti full rate code, and coding rate-3/2 which uses a Sezginer-Sari 3/2 rate code. The normalized transmitted constellation power may take one of the three values 0.5, 1.0, and 1.5. The selection of the adaptive scheme is done in a way that the average data rate and total transmitted power over all main four directions of the body are maintained exactly equal to those in a non-adaptive system (rate-1.0 STFC, constellation power 1.0, and QPSK modulation for all four directions) for a fair comparison. This is done as follows.

1. Data rate constraint: the lowest density signal constellation (BPSK) is used for the worst link (270^o) in order to improve the system error performance over this direction. A higher density constellation (QPSK) is used for all other three directions. The highest rate STFC (rate-3/2) is selected for the best link (0^o) while the rate-1 STFC is selected for all three remaining directions. Thus the average spectrum efficiency over four main directions is maintained at 2 bits/s/Hz which is exactly the same as that in the non-adaptive system.

2. Power constraint: the normalized power of one is selected for the signal constellations (QPSK) for the 90^o and 180^o directions, similar to the non-adaptive system, while the highest power level (1.5) is selected for the best link (0^o) to compensate for the possible performance degradation caused by the highest STFC coding rate (3/2) chosen for this direction. The above power allocation leaves the power of 0.5 for the BPSK signal constellation in the 270^o direction. Thus the total transmitted power over all four main directions is exactly the same as that in the non-adaptive system.

The core idea behind the proposed algorithm is that the best channel conveys the most information with the most power allocated while the worse link carries the least information. Hence, we define three set of adaptive schemes. Set-1 is aimed to take advantage of best channel link by maximizing the capacity, i.e. by using QPSK modulation and STFC code rate 3/2 and normalized power TX as 1.5. Set-2 uses QPSK, STFC code rate 1.0, and power TX 1.0, and Set-3 uses BPSK, STFC code rate 1.0, and power TX 0.5.The proposed algorithm is summarized as follows:

```
Start
Detect_body_direction = bd;
If   bd ≤ π/4 or bd ≥ 7/4 π
   Set_Modulation = qpsk;
   Set_Power_Tx  = 1.5;
   Set_STFC_rate  = 1.5;
If   π/4 < bd < 5/4 π
   Set_Modulation = qpsk;
   Set_Power_Tx  = 1.0;
   Set_STFC_rate  = 1.0;
If   5/4 π < bd < 7/4 π
   Set_Modulation = bpsk;
   Set_Power_Tx  = 0.5;
   Set_STFC_rate  = 1.0;
End
```

B. Decoding Complexity

The decoding process of the 3/2 rate code has the complexity *O(4)* compared with the full rate code, since the decoder firstly has to decide $\tilde{x}_3$ from four possible symbols in QPSK, prior to decoding $\tilde{x}_1$and $\tilde{x}_2$symbols. Meanwhile, in the worst link, the complexity is reduced to *O(2)* due to BPSK (rather than QPSK) is used. The overall complexity of the decoding process increases by a factor of [*O*(4)–*O*(2)], beside the body direction estimation. It should be emphasized that, though the decoding complexity in the adaptive system increases, the decoding processes for both adaptive and non-adaptive system are relatively simple.

For body direction estimation, a simple direction sensor, e.g. by using a Giant magneto resistance (GMR) thin film sensor chips, can be used. It is a magnetic sensor, robust, and capable to provide 360° angular measurement [11]. As mentioned above, the measured body direction is not fed back directly to the transmitter. Instead, depending on which region among the three pre-defined regions shown in Fig. 3 this body direction belongs to, two bits are required to be fed back to the transmitter to indicate this region in order for the transmitter to select the corresponding combination of modulation, STFC structure, and constellation power. In other words, the proposed adaptive scheme could be implemented with a slightly increased system complexity.

IV. SIMULATION RESULTS

The Monte-Carlo simulations are carried out to compare the average BER performance of the adaptive system with that of the non-adaptive one, assuming perfect channel state estimations are available at the receiver. The non-adaptive system, as the benchmark, uses QPSK modulation, normalized power of 1.0, and the full rate STFC for all body directions. It is assumed that a person wearing the WBAN devices moves and turns the body clock-wisely against the transmitter. Channel coefficients are assumed to be constant during each

TABLE II. SIMULATION PARAMETERS.

Parameters	Value
FFT & IFFT size N_{fft}	128
Number of ZPS N_{ZPS}	37
Convolutional coder (K=7) rate	½
Conv. decoder and mode	Viterbi, Hard
Interleaver/De-interleaver	Column-wise written, row-wise read
Average number of paths in CM4	400

STFC block, but random between consecutive STFC blocks. The channel realizations are simulated by the Matlab^{TM} program enclosed in the appendix of IEEE 802.15.6 channel modeling subcommittee final document [8]. Other simulation parameters are listed in Table II.

Fig.4 shows the performance of a *non-adaptive* system for both 2I1O and 2I2O configurations. It reveals a significant degradation in the BER performance within almost the whole range of SNR when the receiver (on the body) turns away from the transmitter. The front body has a LOS component, resulting in the best performance compared to other directions of the body. The back of the body (180° direction) suffers from a body shadowing effect and only receives NLOS multipath signals. The performance is still reasonably good in the very dispersive channel, particularly with the 2I2O configuration. Its performance degrades 6 dB for BER = 10^{-4}, compared to the front body.

Fig. 4 also shows that, the 270° direction experiences a significant performance degradation, compared to the 90° direction. This is possibly due to the difference of side lobes of the Rx antenna when it turns 90° and 270° and/or the

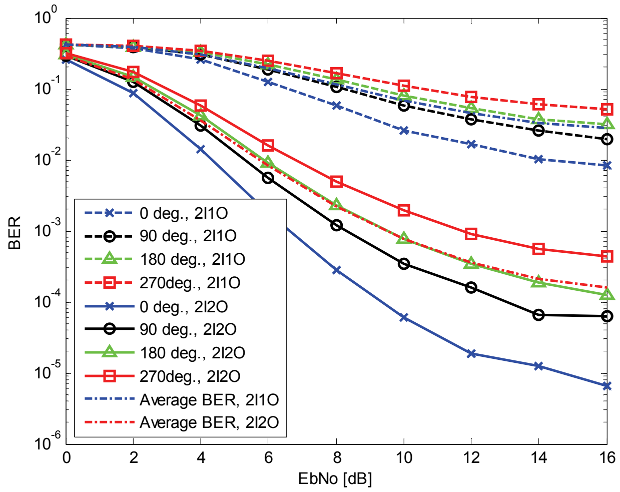
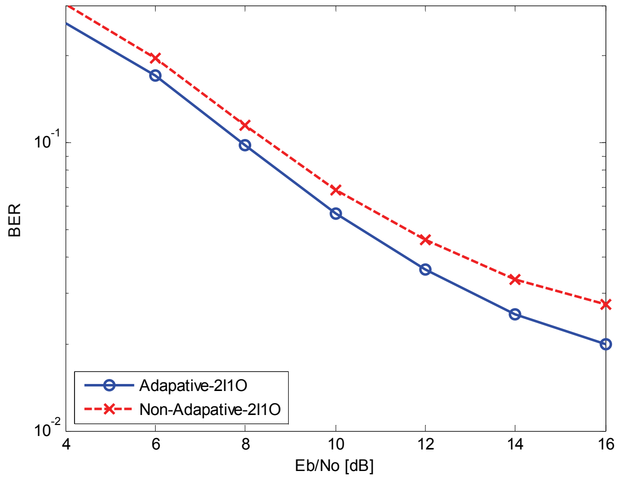
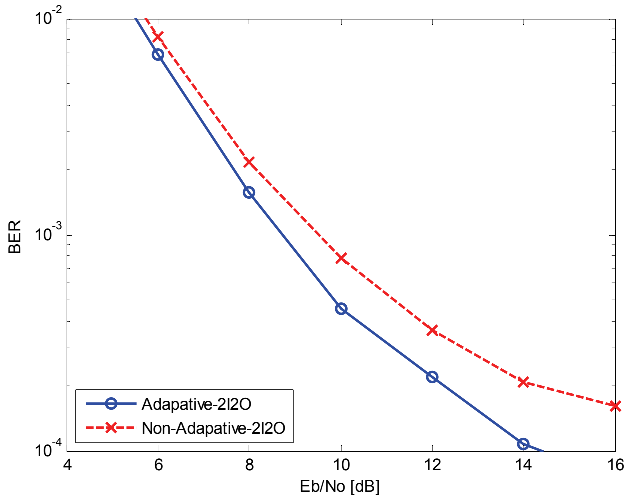


Fig.4. Performance of non-adaptive scheme in CM4.



(a)



(b)

Fig.5. Performances of adaptive scheme in CM4, (a) 2I1O, (b) 2I2O.

propagation environment surrounding these directions. This observation is consistent with parameters of CM4 as mentioned in Table I. The average BER performance for each MIMO configuration is then calculated over four body directions and used as the benchmark for comparison with the adaptive system. This average BER performance is shown by dotted curves in Fig.4 for the ease of comparison with the proposed adaptive algorithm.

Fig.5 shows the improvement of the *adaptive* scheme compared to the non-adaptive one in 2I1O and 2I2O configurations. The BER averaged over all four directions in the adaptive scheme shown by a circled-continuous line is consistently better than that of the non-adaptive one in a 2I1O configuration by about 1–2 dB in the whole SNR region, and by about 1–3 dB in the medium-to-high SNR region in a 2I2O configuration. If we compare the average BER of the adaptive scheme with the BER of the worst scenario (270^o direction) in the non-adaptive one (cf. Square-marked curves in Fig.4), the improvement is significantly high, i.e. 5.5 dB at BER $5{\cdot}10^{-2}$ in the 2I1O configuration and 6 dB at BER $4{\cdot}10^{-4}$ in the 2I2O case. (Comparing to the BER of the best link (0^o direction, cross-marked curves in Fig.4) of the non-adaptive system in both MIMO configurations, as expected, the averaged BER of the adaptive scheme is slightly worse due to the fact that, the adaptive system selects the highest STFC coding rate (3/2) for the 0^o direction in order to maximize the capacity, with a price of minor performance degradation). It is noted that the aforementioned average BER improvements are achieved without any increase of the total transmitted power or any sacrifice of the data rate. Due to the fact that power is the main constraint in WBAN applications [7], [9], an improvement in the order of 1–3 dB means a reduction of 12.5% - 50% of the total transmitted power, while maintaining the same BER performance as in the non-adaptive system.

V. CONCLUSION

We have presented a novel body direction based adaptive STFC MB-OFDM UWB WBAN system, in order to improve the average BER performance and/or reduce the power consumption. Simulation results confirm that the proposed system can achieve a consistent 1–2 dB improvement in the case of 211O, and approximate 1–3 dB in the medium-to-high SNR range in the 2I2O configuration compared to the non-adaptive system. Those improvements practically mean a possible reduction of 12.5% - 50% of the total transmitted power. In other words, it can save and prolong significant battery life of WBAN devices. We conclude that, with the price of slightly increased complexity, the proposed system can provide a power saving and better average BER performance for WBAN applications without sacrificing the data rate. Our future work will focus on the adaptive scheme driven by the measured BER in the receiver.

ACKNOWLEDGMENT

The first author is grateful for the funding support from AusAID through Australian Development Scholarship.

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