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Optimal adaptive wireless body area networks for high speed in Health Services

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Abstract

Adaptive ultra-wideband wireless body area networks have been proposed as one of feasible mHealth platforms offering a high-speed, robust mobile health service. The error performance of such sytems outperforms non-adaptive systems by up to 4 dB. To further improve the error performance, the optimization of adaptive parameters is investigated in this paper. Simulation results show that the proposed optimal adaptive systems achieves a 2 dB gain with respect to bit error rate (BER). This improvement is equivalent to extra reduction of the power consumption up to 37% in these networks, thus increasing the longevity and reliability of mHealth services.

Keywords

speed, optimal, adaptive, services, wireless, body, area, networks, high, health

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Optimal Adaptive Wireless Body Area Networks for High Speed mHealth Services

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Abstract

Adaptive ultra-wideband wireless body area networks have been proposed as one of feasible mHealth platforms offering a high-speed, robust mobile health service. The error performance of such sytems outperforms non-adaptive systems by up to 4 dB. To further improve the error performance, the optimization of adaptive parameters is investigated in this paper. Simulation results show that the proposed optimal adaptive systems achieves a 2 dB gain with respect to bit error rate (BER). This improvement is equivalent to extra reduction of the power consumption up to 37% in these networks, thus increasing the longevity and reliability of mHealth services.

1 Introduction

Mobile health (mHealth) fosters the advancement of personal and mobile healthcare services. It promises an effective health monitoring system which is potentially capable of reducing the ever-increasing healthcare cost of the ageing society [1]. A reliable array of tiny, lightweight medical sensors and a robust energy-efficient communication system are keys for the success of mHealth delivery [1]. Therefore mHealth services could be promoted by the development of advanced Wireless Body Area Networks (WBAN). A WBAN consists of wearable and implantable sensors to continuously monitor physiological conditions and feedback real time data wirelessly to the doctor and/or the patient [3]. These WBAN features give rise to some challenges. First, the monitoring and communication systems have to be reliable and accurate. Second, the devices have to be small, light, and highly power efficient to ensure their suitability and longevity. Third, the systems also have to provide high capacity to support many sensors and to cater for future bandwidth-hungry services.

To address these issues, we proposed a Space-Time-Frequency Coded Multi-Band Orthogonal Frequency Division Multiplexing Ultra-Wideband (STFC MB-OFDM UWB) system as an alternative high data rate physical layer for a WBAN system, which can achieve significantly better BER performance, compared to the conventional MB-OFDM system [4]. The system improvements by adaptive approaches for WBAN are hardly found in the literature [1]. Hence, we proposed for the first time in [5] a novel BER-based *adaptive* STFC MB-OFDM UWB systems. This proposed adaptive algorithm selects a suitable set among three possible sets of modulation, STFC coding rate, and Tx signal power. Each set of adaptive schemes is determined by two BER thresholds, namely the lower and upper thresholds. This adaptive scheme results in a performance improvement by up to 4 dB, meaning a possible 60% reduction of the total transmitted power, hence reducing the dimension of WBAN devices and prolonging their battery life. However, parameters of the adaptive algorithm in [5] have not been optimized. To pursue maximum performance and power reduction, further refinement is needed. Hence, this paper aims to optimize the aforementioned adaptive WBAN system to gain extra performance impro-vement and power saving for mHealth services.

2 Methods

We consider a WBAN employing the MB-OFDM UWB technology, which allows the data rate up to 1 Gbps [2]. This rate is far higher than an Impulse Radio (IR) UWB WBAN system proposed in [3], where the maximum data rate is 15.6 Mbps. Due to the severely dispersive body area propagation channel [6], we utilize the Multiple-Input Multiple-Output (MIMO) technique [7,8] to increase the diversity order and enhance the performance against channel fading. In particular, we have proposed the STFC MB-OFDM UWB system for a high speed WBAN physical layer [4]. Readers are recommended to refer to [4,9] for a thorough description of the system. The adaptive scheme is later added to the system in order to improve the BER performance and power efficiency while keeping high throughput in *body-to-external* links of a WBAN [5]. This paper mainly focuses on the optimization of adaptive parameters to further improve the performance and power saving.

2.1 System model

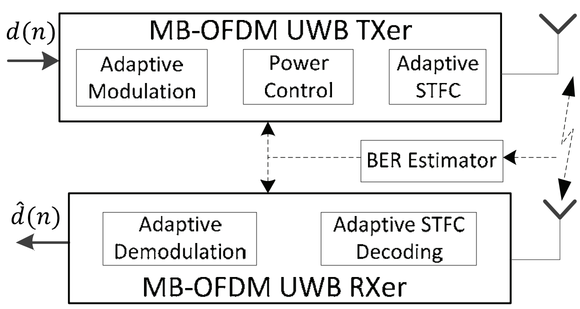

Figure 1 Adaptive STFC MB-OFDM UWB WBAN.

The system model with *M*-Tx antennas and *N*-Rx antennas is depicted in Figure 1. The transmitter consists of an adaptive block that controls three possible sets of modulation, signal power, and STFC coding, refered to as *Set-l* (l = 1, 2, and 3) [5]. The channel quality is measured by a BER estimator. The measured BER is not fed back directly to the transmitter, but is compared to the preset upper and lower thresholds, resulting in one out of three possible sets of adaptive schemes to be selected. Hence, to indicate which set of adaptive schemes should be used in the next transmission, only two bits are required to be fed back to the transmitter. Assuming that the non-adaptive system employs QPSK, STFC rate 1.0, and normalized power 1.0, thus providing a 2 bps/Hz spectral efficiency. In the adaptive system, *Set-1*, is designed to take advantage of the best channel by maximizing the throughput, i.e. by using QPSK, STFC rate 3/2 and power 1.5, providing a 3 bps/Hz spectral efficiency. *Set-2* is used for the average quality channel, hence employing the same scheme as the non-adaptive system. *Set-3* is aimed to tackle the worst channel by employing more powerful BPSK modulation, STFC rate 1.0, and power 0.5, providing a spectral efficiency of 1 bps/Hz. Assuming that the three sets are equiprobable and signal powers are selected as above, the average spectral density and total transmitted power in the adaptive system is equal to those in a non-adaptive system, resulting in a fair comparison.

Let $\bar{\mathrm{x}} = \left[x_1, x_2, \ldots, x_{N_{fft}}\right]^T$ be the symbol vector, where N_{fft} is the FFT/IFFT size. The adaptive STFC block in Figure 1 creates a space-time code either with full rate or 3/2-rate. The full rate code, i.e. the Alamouti code [7], converts two consecutive symbol vectors into a STFC block

$$\mathbf{X} = \{\bar{\mathrm{x}}_{t,m}\}_{T\times M} = \begin{bmatrix} \bar{\mathrm{x}}_1 & \bar{\mathrm{x}}_2 \\ -\bar{\mathrm{x}}_2^* & \bar{\mathrm{x}}_1^* \end{bmatrix} \quad (1)$$

For a 3/2-rate STFC, three symbol vectors are encoded following the Sezginer-Sari code [10]

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

where $\bar{\mathrm{x}}_1$ and $\bar{\mathrm{x}}_2$ are symbol vectors transmitted from the first and the second antenna at a given time slot, respectively. Here, $(\cdot)^*$ denotes complex conjugate, t indicates time slot and m indicates the m^{th} Tx antenna. $a, b, c,$ and d are complex-valued design parameters. We use the optimal parameters $a = c = \sqrt{2}$, and $b = d = (1 + j\sqrt{7})/4$ as determined in [10]. The received signals can be written in a matrix form as [5,8]

$$\mathcal{R} = \mathbf{X} \circ \mathcal{H} + \mathcal{N} \quad (3)$$

where $\mathcal{H}$ is the FFT transform of the channel matrix, and the operation $(\circ)$ denotes the matrix multiplication similar to the conventional matrix multiplication, except that each entry in $\mathcal{R}$ and $\mathcal{H}$ is not a single number, but a vector [4, 5,9]. The detected vectors are decided by the following Maximum Likelihood (ML) rule

$$\{\tilde{\bar{\mathrm{x}}}_{t,m}\} = \arg\min_{\{\bar{\mathrm{x}}_{t,m}\}} \|\mathcal{R} - \mathbf{X} \circ \mathcal{H}\|_F^2 \quad (4)$$

Readers may refer to [5] for a more comprehensive analysis of the system model.

2.2 Transmission model

For clarity, it is assumed that a person wearing WBAN devices makes a clockwise angular movement with respect to a fixed external transceiver. Different angles of the body direction experience dissimilar radio propagation characteristics, leading to different channel fading [6]. During each frame transmission, the BER is measured in the portion f of the frame, ($0 < f < 1$), where *Set-2* is selected as the default modulation and STFC coding scheme.

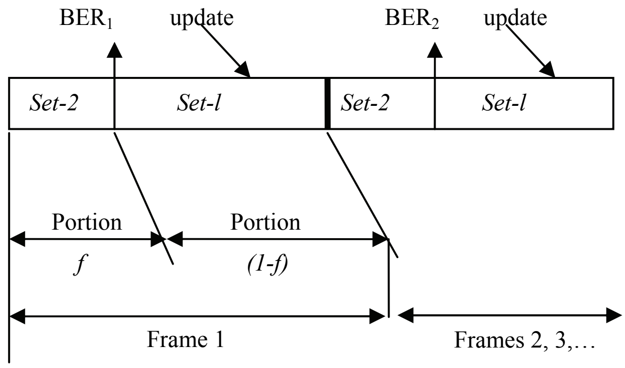

Figure 2 Adaptive frame transmission models.

The receiver measures the quality of the channel, i.e. BER, for this portion, compares it to the preset thresholds, and then decides which *Set-l* to be suggested to the transmitter via a two-bit feedback link to update the modulation and STFC coding scheme for the remaining portion $(1 - f)$ of that frame. Note that this *Set-l* is known to the receiver.

2.3 Adaptive algorithm

The adaptive scheme is controlled by the measured BER and BER thresholds [5]. Two BER thresholds, i.e. upper and lower thresholds, are defined that determine the selection of one among three possible *Set-l*. The upper and lower thresholds are derived from the average non-adaptive BER performance as the benchmark. The thresholds are linearly defined to reflect a constant deviation in the whole range of SNR w.r.t. to the non-adaptive average BER performance as the reference point. The lower and upper linear thresholds are defined as

$$BER_L^{(g)} = BER_{NA}^{(g)} - k \times BER_{NA}^{(g)} \quad (5)$$

$$BER_U^{(g)} = BER_{NA}^{(g)} + k \times BER_{NA}^{(g)} \quad (6)$$

where $BER_L^{(g)}$ is the lower threshold, $BER_U^{(g)}$ the upper threshold, and $BER_{NA}^{(g)}$ is the non-adaptive average BER performance for the g-th SNR value. k is a constant, whose value will be optimized later in this paper.

The algorithm for each frame transmission is as follows:

```
Start
Measure BER in the initial portion;
If  BER < BER_L
  Set_Modulation = qpsk;        } Use Set-1
  Set_Power_Tx  = 1.5;          } for next
  Set_STFC_rate  = 1.5;         } portion of the frame
else if BER ≥ BER_L and BER ≤ BER_U
  Set_Modulation = qpsk;        }
  Set_Power_Tx  = 1.0;          } Use Set-2
  Set_STFC_rate  = 1.0;         }
else
  Set_Modulation = bpsk;        }
  Set_Power_Tx  = 0.5;          } Use Set-3
  Set_STFC_rate  = 1.0;         }
End
```

2.4 Optimization of parameters

Performance of the adaptive system depends on the selected *Set-l* on a frame-to-frame basis. During *q-th* frame transmission, where $q = 0, 1, 2, \ldots, Q-1$, and Q is the number of frames, the measurement of BER and adaptation occurs during the f portion of the frame, as defined in Section 2.2. Hence, BER of the system is affected by the selected value of the f-factor. At the same time, BER is also affected by the selection of *Set-l*, which is done by comparing the measured BER of the current received frame with the thresholds, which are, in turn defined by the k-factor. Hence the system performance depends on both $f$and k. It is obvious that $0 < f < 1$ and $0 < k < 1$. For simplicity, but without loss of generality, we consider a set of limited discrete values of f and k as detailed in (7) and (8). Note that f and k are independent from each other.

$$f_i = 0.1i, \qquad i = 1,2,\ldots,9 \tag{7}$$

$$k_{\mathrm{j}} = 0.1\mathrm{j}, \qquad \mathrm{j} = 1,2,\ldots,9 \tag{8}$$

We denote a variable u_i^q where $u_i^q = 1$ if a certain portion of the frame f_i is selected to measure the BER, and $u_i^q = 0$ otherwise. We define a variable v_j^q where $v_j^q = 1$ if a certain value of k_j is selected to determine the upper and lower BER thresholds as mentioned in (5) and (6), and $v_j^q = 0$ otherwise.

We also denote z_i^q to be the cost associated with the selected f_i, and w_j^q is to be the cost associated with the selected k_j. The costs here mean the BER performance. Since the maximum likelihood decoding is used, the cost could be expressed as $\arg\min_{\{\bar{x}_{t,m}\}} \|\mathcal{R} - \mathbf{X} \circ \mathcal{H}\|_F^2$. The throughput is fixed to 1.8 bps/Hz or 90% of maximum capacity, since this is sufficient to support the curent and foreseeable future mHealth monitoring applications.

Our objective is to optimize the overall average BER of all Q frames. Hence, The total cost function is defined by

$$cost = \sum_{q=0}^{Q-1} \sum_{i=1}^{9} \sum_{j=1}^{9} \left(z_i^q \cdot u_i^q + w_j^q \cdot v_j^q\right) \tag{9}$$

The first term of (9) represents the average BER performance associated with given value of f, provided that a value of k is arbitrarily chosen. While the second term is likewise for given value of k, provided f is arbitrarily selected.

Note that only a single pair of values of f and k is chosen during each frame transmission. This is equivalent to selecting a single optimum value of u_i^q and v_j^q from their possible values. Thus, the constraints are determined by

$$\sum_{i=1}^{9} u_i^q = 1, \forall i = 1,2,\ldots,9 \tag{10}$$

$$\sum_{j=1}^{9} v_j^q = 1, \forall j = 1,2,\ldots,9 \tag{11}$$

and
$$u_i^q \geq 0, v_j^q \geq 0 \tag{12}$$

It is clear that the above optimization problem is equivalent to minimization of the total cost function (9) subject to the constraints (10)-(12).

Denote vector $\mathbf{u} = (u_1^0,.,u_9^0,u_1^1,.,u_9^1,.,u_1^{Q-1},.,u_9^{Q-1})^T \in \{0,1\}^{9Q\times 1}$, $\mathbf{v} = (v_1^0,.,v_9^0,v_1^1,.,v_9^1,.,v_1^{Q-1},.,v_9^{Q-1})^T \in \{0,1\}^{9Q\times 1}$, $\mathbf{z} = (z_1^0,.,z_9^0,z_1^1,.,z_9^1,.,z_1^{Q-1},.,z_9^{Q-1})^T \in \mathbb{R}^{9Q\times 1}$, $\mathbf{w} = (w_1^0,.,w_9^0,w_1^1,.,w_9^1,.,w_1^{Q-1},.,w_9^{Q-1})^T \in \mathbb{R}^{9Q\times 1}$, where $\mathbb{R}$ denotes a field of positive real numbers. Then, the cost function (9) can be expressed mathematically as

$$\mathbf{cost} = \mathbf{z}^T\mathbf{u} + \mathbf{w}^T\mathbf{v} \tag{13}$$

The first constraint (10) can be written as

$$\mathbf{Au} = \mathbf{1}_Q \tag{14}$$

where $\mathbf{A} = \mathbf{I}_Q \otimes \mathbf{1}_9^T \in \{0,1\}^{Q\times 9Q}$, $\mathbf{I}_Q$ is a $Q \times Q$ identity matrix , $\otimes$ denotes Kronecker product, and $\mathbf{1}_9$ is an all one 9×1 vector. Similarly, (11) becomes

$$\mathbf{Av} = \mathbf{1}_Q \tag{15}$$

Thus the optimization problem can be formulated as

$$\min_{u,v \in \{1,0\}^{9Q\times 1}} \mathbf{z}^T\mathbf{u} + \mathbf{w}^T\mathbf{v} \tag{16}$$

$$\text{s.t. } \mathbf{Au} = \mathbf{1}_Q, \mathbf{Av} = \mathbf{1}_Q$$

Clearly, (16) is a standard linear optimization problem with binary elements, since vectors **u** and **v** only consist of 0 and 1 entries [11]. To solve the optimization problem, we exploit the unique characteristic of the matrix **A** by using the totally unimodularity concept. **A** is totally unimodular (TUM) if the determinant of every square submatrix of **A** has value $-1, 0,$ or 1 [11]. It can be shown that the constraint matrix **A** is indeed TUM. The proof is not provided here owing to the limited space and it is out of the focus of this investigation.

From the integer optimization theory, if **A** is TUM and both **u** and **v** are integer vectors, the extreme points of possible solutions (polyhedron) are integral [11]. Hence, the optimization problem can be solved using linear programming, for instance, using a well known Simplex or Interior point method [11].

3 Results

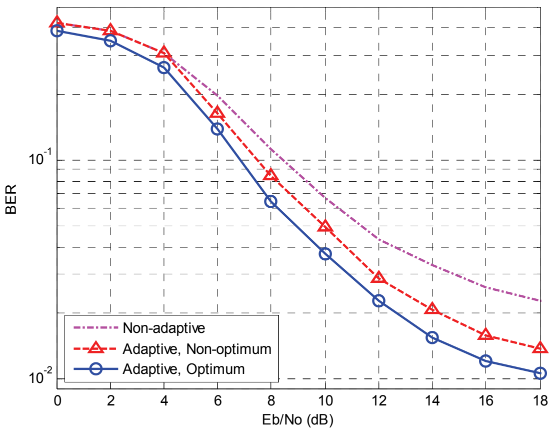

Figure 3 Optimal adaptive and non-optimal adaptive performances in a 2×1 MIMO configuration.

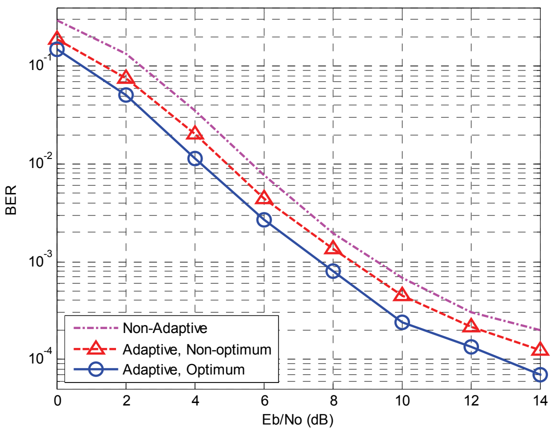

Figure 4 Optimal adaptive and non-optimal adaptive performances in a 2×2 MIMO configuration.

This section compares system BER performance of the non-adaptive system, the non-optimal adaptive system, and the optimal adaptive system. It is assumed that a perfect channel state estimation is available at the receiver. We use the IEEE's WBAN channel model 4 (CM4) that takes into account the effect of angular body movements [6]. CM4 represents links between body-worn devices and fixed external transceivers such as wireless access points. MB-OFDM UWB employs 128 subcarriers with a 37-zero padding, and bandwidth of 528 MHz. The STFCs are implemented in the 2×1 and 2×2 MIMO configurations.

Figure 3 shows the performance comparison in the 2×1 MIMO, while Figure 4 is for the 2×2 MIMO. In the medium to high SNR range, the non-optimal adaptive 2×1 MIMO system provides a 1–4 dB gain over the non-adaptive counterpart. The optimal adaptive system enhances the performance further by 1–2 dB in the whole SNR range. Meanwhile, the non-optimal adaptive 2×2 MIMO WBAN provides a near constant 1-2 dB gain in the whole range of SNR, compared to the non-adaptive WBAN as shown in Figure 4. Again, optimizing the adaptive parameters provides an additional 1-2 dB improvement.

Therefore, in these two MIMO configurations, the optimal adaptive WBAN result in a gain of up to 2 dB over the non-optimal adaptive WBAN, and up to 6 dB over the non-adaptive WBAN. Translating to the power saving, the optimal adaptive approach provides a power consumption reduction by up to 37% and 75%, compared to the two counterparts respectively.

4 Conclusion

The proposed adaptive STFC MB-OFDM UWB WBAN is one of feasible effective mHealth platforms. By the optimization of its adaptive parameters as shown in this paper, the performance of the system is improved considerably. The improvements provide critical power reduction of WBAN devices, thus extending the battery life and enhancing the reliability of mHealth services significantly.

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