Temporal Diversity Coding for Improving the Performance of Wireless Body Area Networks

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ABSTRACT

Wireless Body Area Networks (WBANs) promise a significant improvement in the reliability of monitoring and treating people's health. A WBAN comprises a number of intelligent biosensors and actuators that may either be implanted *in vivo* or mounted on the surface of the human body, and that are capable of wireless communication to one or more external nodes that are in close proximity to the human body. In this paper, we propose a new and efficient feedforward error-control technology, *Temporal Diversity Coding* (TDC), to increase the robustness and reliability of Wireless Body Area networks. *Temporal Diversity Coding* applies Diversity Coding in time and space to improve the WBAN's performance. We demonstrate that by implementing this novel technique, we can achieve significant improvement ($\sim$ 50%) in throughput compared to extant WBANs.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Network communications, Wireless Communication*; C.4 [**Performance of Systems**]: Performance attributes, Reliability, availability, and serviceability.

General Terms

Performance, Reliability.

Keywords

Wireless Body Area Networks, Diversity Coding, Performance, Probability of Success, Reliability.

1. INTRODUCTION

A Wireless Body Area Network (WBAN) is a collection of low-power, intelligent devices, such as sensors or actuators, which are located in, on, or in close proximity to, the human body and are wirelessly interconnected [1]. As is shown in [2], typically, the information collected by the sensor (implanted or body surface node) has to be transmitted over a two-hop network to reach the external node via a body surface node.

In this paper, we discuss and analyze the application and effect of Diversity Coding [3] on the performance of WBANs, and propose the *Temporal Diversity Coding* scheme (TDC), a novel technique that applies Diversity Coding in time and uses multiple paths to enhance the performance of WBANs, especially for emerging real-time *in vivo* traffic such as (1) streaming real-time video during surgery, and (2) measurement-response applications. The latter application requires feedback on a small time-scale, such as cardio-feedback applications, where the remote control system needs to react to fast changes in the biological/physiological parameters and actuate an *in vivo* mechanism. Because of the nature of these time-sensitive applications and the fact that some sensors may be able to transmit but not to receive, retransmissions may not be possible. Moreover, the throughput is often reduced because the tissues and organs within the human body affect the signal propagation and integrity from the *in vivo* sensor to the destination/gateway. This was demonstrated in [4] where the channel impulse response and the attenuation change with the location of the receiver. An example of an implementation of *in vivo* real-time application, where TDC can improve the communications performance, is the MARVEL (Miniature Anchored Robotic Videoscope for Expedited Laparoscopy) [5] research platform developed at USF. MARVEL decreases the surgical-tool bottleneck experienced by surgeons in state-of-the-art Laparoscopic Endoscopic Single-Site procedures for minimally invasive abdominal surgery.

The paper is organized as follows. In section 2, we present a summary of Diversity Coding, and an overview of our approach. The *Temporal Diversity Coding* scheme (TDC) to increase the performance of WBANs is presented in Section 3. Section 4 presents simulation results of the performance of TDC in WBANs. Finally, in Section 5 we present our conclusions.

2. RELATED WORK

Diversity Coding [3] (DC) is an established feedforward spatial diversity technology that enables near-instant self-healing and fault-tolerance in the presence of link and node failures. The protection paths (c_i) carry information that is the combination of the uncoded data lines (d_j). For example, in a DC system with N data lines ($j = 1, 2, \dots, N$) and one protection line ($i = 1$), if any of the data lines fails (e.g., d_3), the failure detector detects the problem (e.g., loss of signal) and informs the receiver about the failure of d_3. The destination (receiver), through the protection line (c_1), can recover the information of the data line that was lost (d_3) by taking the mod 2 sum of all of the received signals ($\widehat{d_3} = d_1 \oplus d_2 \oplus \dots \oplus d_N \oplus c_1$). This model can be generalized as a $M-$ for $-N$ Diversity Coding system as shown in [3]. As we will show later in this paper, Diversity Coding may also be used to provide time diversity. More generally, we can say that the M protection packets are the combination of data packets $\{d_1, d_2, \dots, d_N\}$, where each protection packet is calculated as [3]:

$$c_i = \textstyle\sum_{j=1}^{N} \beta_{ij} d_j \quad i \in \{1, 2, \dots, M\} \tag{1}$$

where c_i and d_j are protection (diversity coded) and data (uncoded) packets, respectively. As in [3], the β coefficients are given by $\beta_{ij} = \alpha^{(i-1)(j-1)}$ and α is a primitive element of a Galois Field GF(2^q). All the operations in Diversity Coding are performed over a Galois Field GF(2^q), where $q \geq \lceil log_2(N + M + 1) \rceil$. The total number of transmitted packets is equal to the number of data packets plus the number of protection packets ($N + M$), where the number of protection packets is typically less than the number of data packets ($M \leq N$). So, the β matrix for $i = \{1, 2, \dots, M\}$ and $j = \{1, 2, \dots, N\}$ is:

$$[\beta_{ij}] = \begin{bmatrix} 1 & 1 & 1 & \dots & 1 \\ 1 & \alpha & \alpha^2 & \dots & \alpha^{(N-1)} \\ 1 & \alpha^2 & \alpha^4 & \dots & \alpha^{2(N-1)} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & \alpha^{M-1} & \alpha^{(M-1)2} & \dots & \alpha^{(M-1)(N-1)} \end{bmatrix} \tag{2}$$

Notice that (2) represents the Discrete Fourier Transform matrix on a Galois Field with respect to the primitive element α.

3. TEMPORAL DIVERSITY CODING FOR INCREASING THE PERFORMANCE OF *IN VIVO* WIRELESS COMMUNICATIONS

Without some form of coding, if a sensor incurs a packet loss, the throughput is always reduced. Moreover, because of the real-time nature of these applications, retransmission is not always feasible. To overcome the effects of packet loss, one can use several schemes. For example: one can use spatial diversity with multiple paths, so the same information is transmitted to the destination through different nodes (links. Alternatively, one can transmit additional (extra) redundant copies of the original (uncoded) packets. However, since there is no *a priori* knowledge about which packets will be lost during the transmission, as with classical communications, a coded scheme, such as Diversity Coding, applied to the additional (extra) packets could be beneficial.

With this in mind, we take as a frame of reference the WBAN topology proposed by the IEEE P802.15 Working Group in [2], and we investigate the proposed *Temporal Diversity Coding* ($TDC-2$) model of Fig. 1, where “2” represents the number of relays that help to transmit the source packets towards the destination. Each sensor transmits independently, but may use the same relays.

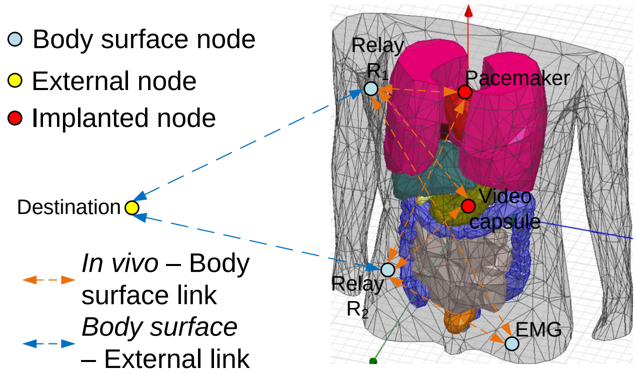

Figure 1: Temporal Diversity Coding: Network Topology.

The system model, as depicted in Fig. 1, applies Diversity Coding only in the time mode. It transmits the same packets through multiple paths with the aim of enhancing the throughput and reliability of real-time *in vivo* applications such as medical imaging and capsule endoscope. The scheme also increases the energy efficiency of transmitting a message, while minimizing the delay. Since coding is applied at the packet level, Diversity Coding provides time diversity instead of spatial diversity as in [3]. Reliability is increased by using multiple relays (paths). Because of the complexity and energy constraints of these *in vivo* sensors, the reliability should be maximized while the sensor's energy to transmit the message should be minimized. *Temporal Diversity Coding* promises improvement in these two parameters, including improved reliability in the presence of link and node failures. The throughput is calculated as the sum of all received packets that add new information at the destination. Additionally, Diversity Coding is a feed-forward technology where protection packets are transmitted and no retransmission is required for the destination to be able to decode the information.

In $TDC-K$, the source node (e.g., an implanted node) has a block of information (e.g., N data packets) to transmit to the destination through each of the K relays. So, the source (S) starts to transmit the N data packets to the R_k relays[1], where $k \in \{1, 2, \dots, K\}$, and simultaneously uses those data packets to create the M protection packets that are transmitted to the relays after the N data packets have been transmitted. The c_i protection packets are created using Eq. (1). The computational complexity needed to create the protection packets is low since the β coefficients in Eq. (2) are known by the source and the destination nodes, and no randomness is required for choosing the coefficients. This is in contrast with the case of Network Coding (Random Linear Network Coding [6]). Moreover, the protection packets length is the same as the data packets and no extra information such as the β coefficients needs to be included in the packet's header. However, it is necessary to include properly include a sequence number in the identification field (packet header) for the destination to reassemble the packets into the original block of information.

The R_k relays regenerate the received signal and transmit

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[1] Because of physical and practical constraints, K should be kept low.

to the destination only the data and protection packets that are error free. The packets include a cyclic redundancy check (CRC) to detect bit errors, and erroneous packets are discarded. Diversity Coding operations, such as decoding and/or encoding, are not performed at the relays. However, the relays detect and compute the CRC to determine which packets are in error and should be discarded. Error correction techniques at the bit level can be combined with $TDC-K$ to improve the network's performance. However, we have not included any bit level error correction technique in this study because of the computational complexity, energy consumption, and processing time required to code and decode the bits at the source, the relay, and the destination nodes. For instance, each relay would need to decode the received bits (including deinterleave them), correct any bit errors (according to its error correction capability), check the CRC and, if the packet has no errors, code the bits (including interleave them) and transmit the packet.

To reassemble the original information, the destination (D) receives data and protection packets from the R_k relays and accepts all the error-free packets. The number of correctly received data and protection packets depends on the probability $p_{(SR_k)}$ of link transmission loss between source S and relay R_k and the probability $p_{(R_kD)}$ of link transmission loss between the relay R_k and the destination node D. The probability of link transmission loss p is a function of the transmission power, channel conditions, modulation scheme, and packet's length.

Let $\tilde{N}$ and $\tilde{M}$ denote the number of correctly received data and protection packets, respectively, where $\tilde{N} \leq N$ and $\tilde{M} \leq M$. To be able to decode the entire block of information (N), the destination needs to correctly receive at least N data and/or protection packets, where $N \leq \tilde{N} + \tilde{M}$; otherwise only $\tilde{N}$ information packets can be recovered. That is, the useful information is given by:

$$I = \begin{cases} N & N \leq \tilde{N} + \tilde{M} \\ \tilde{N} & o.w. \end{cases} \tag{3}$$

Although the destination receives data and protection packets, the protection packets provide useful information if and only if $N \leq \tilde{N} + \tilde{M}$. Thus, we define another metric, called utilization, to find the percentage of useful information that can be recovered from the correctly received packets. The utilization can be calculated as:

$$\rho = \frac{I}{\tilde{N} + \tilde{M}} \tag{4}$$

The probability of successful reception at the destination is given by the total number of useful data packets received at the destination to the total number of information packets transmitted by the source ($N+M$) ratio. We have mathematically characterized in Eq. (5) the probability of successful reception at the destination (Ps), for the $TDC-1$ scheme, as a function of the probability of link transmission loss, where p_k is the probability of transmission loss of path k between the source and the destination nodes and for a two-hop communication path:

$$\begin{aligned} P_s &= \sum_{t=1}^{N-1} \left(\frac{t}{N+M}\right) \binom{N+M}{t} {p_k}^t (1-p_k)^{N+M-t} \\ &+ \sum_{t=N}^{N+M} \binom{N+M}{t} {p_k}^t (1-p_k)^{N+M-t} \end{aligned} \tag{5}$$

where p_k is equal to $(1-p_{SR_k})(1-p_{R_kD})$.

As we can see, this probability distribution is characterized by the binomial probability distribution function. The generalization of the probability of successful reception at the destination for the $TDC-K$ scheme is given by the multivariate binomial distribution, where K is the number of variables in the multivariate binomial distribution.

The expected number of correctly received information packets at the destination, which is calculated as the product of the number of original packets (N) and the probability of successful reception at the destination, along with the utilization and DC coding rate metrics, can be used to optimize the performance of the network.We define the "DC code rate" as the ratio of data packets to the number of transmitted packets (data plus protection packets) i.e., $DCcoderate = \frac{N}{(N+M)}$. As it is well known, any coding technique adds overhead into the system and therefore, reduces the maximum efficiency that a coding technique can achieve, while increasing the goodput of the network. That is, the DC code rate is also the maximum efficiency of the $TDC-K$ scheme because it indicates how much overhead has been added to the system.

In the following section, we present the simulation results for a range of network parameters, such as: the number of coded packets, the number of relays, the modulation scheme, and the ratio of the energy per bit to noise power spectral density.

4. RESULTS

The results presented here were obtained through averaging 1,000 simulation runs. We used the MATLAB communications toolbox for the modulation schemes (4-PSK and 16-QAM), the additive white Gaussian noise channel model (AWGN), and the Galois Field operations in our simulations. The topologies presented in [2] and Fig. 1 (single path and multiple paths topologies, respectively) were considered for comparing network performance. We assumed that the source node transmits blocks of information of 10 packets ($N=10$) and the diversity coding operations were performed over a Galois field GF(2^8). Also, we assumed that all the links have the same average performance (E_b/N_0).

We compared the performance of the *Temporal Diversity Coding* ($TDC-2$) scheme with the following other communication models: i) The single path uncoded model, where the information is transmitted uncoded with the assistance of only one relay. The information is transmitted from the source node (e.g., implant) to the destination (e.g., external node) via a relay (e.g., body surface node). This communication mode incurs no additional overhead because no extra redundant packets (coded packets) are transmitted. We refer to this model as "$U-1$"; ii) The single path Diversity Coded model where the source node uses Diversity Coding to code the packets (as explained in section 2), and transmits the data (uncoded) and protection (coded) packets to the destination via a relay. This communication mode incurs overhead of $\frac{N}{N+M}$. We refer to this model as "$TDC-1$"; and iii) The multiple relay paths uncoded model is where the source transmits its information (uncoded) to the destination through spatially different paths with the help of two relays as is shown in Fig. 2. No information is coded in this scheme. We refer to this model as "$U-2$", where 2 is

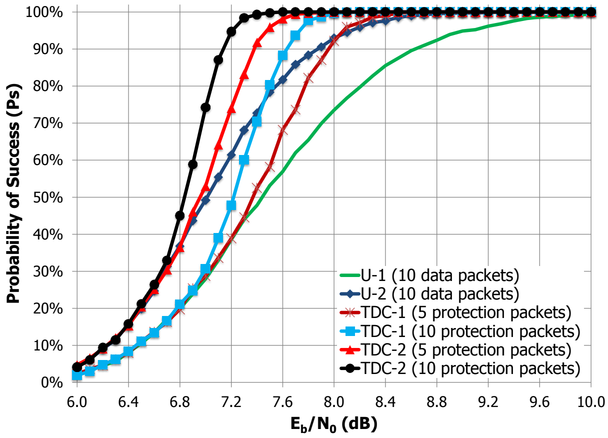

Figure 2: Comparison of the Probability of success for Temporal Diversity Coding ($TDC-2$) and the other 3 schemes ($U-1$, $U-2$, $TDC-1$).

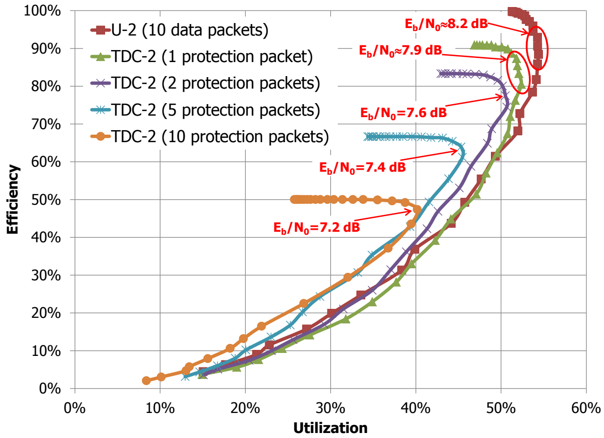

Figure 3: Efficiency vs. Utilization for an uncoded (U) and Temporal Diversity Coding (TDC) schemes for a 2-path system.

the number of relays that help to transmit the information towards the destination.

First, we compare the performance of the 4 schemes ($U-1$, $U-2$, $TDC-1$, $TDC-2$) as a function of the E_b/N_0 (Fig. 2). Temporal Diversity Coding ($TDC-2$) outperforms the other three schemes. $TDC-2$ requires about 3.6 dB less E_b/N_0 than the single path uncoded scheme to receive the entire message. In other words, with the same E_b/N_0, e.g., 7.6 dB, $TDC-2$ achieves full throughput and maximum efficiency at a $1/2$ DC code rate. Also, we can see that by transmitting the packets through multiple paths about 12% improvement in throughput is achieved, Temporal Diversity Coding $TDC-1$ ($1/2$ DC code rate) provides about 18% improvement in throughput, and the combination of these two techniques [$TDC-2$ ($1/2$ DC code rate)] provides a 43% improvement in throughput. As expected, we can see in Fig. 2 that there are regions where $TDC-1$ outperforms $U-2$. That is the case when the E_b/N_0 is greater than 7.5 dB. Therefore, it is preferable to use Temporal Diversity Coding ($TDC-1$) instead of two paths ($U-2$). Figure 3 shows the performance, in terms of efficiency and utilization, of $U-2$ and $TDC-2$ schemes. As we can see, the efficiency of both schemes ($U-2$ and $TDC-2$) increases with the energy per bit to noise power spectral density (E_b/N_0). However, for E_b/N_0 larger than a certain value, the efficiency of $TDC-2$ remains constant. For example, for E_b/N_0 of 7.2 dB or larger, $TDC-2$ $1/2$ achieves its maximum efficiency (50%). For the $U-2$ scheme, 100% efficiency can be achieved for E_b/N_0 of 9 dB or larger because all the packets transmitted by the source contain useful information (data packets). However, the $U-2$ scheme requires larger E_b/N_0 than $TDC-2$ to improve the performance of the system.

5. CONCLUSIONS

In this paper, we proposed the Temporal Diversity Coding ($TDC-K$) scheme, a novel technique that utilizes Diversity Coding in time through K spatially independent paths to achieve improved network performance by increasing the network's reliability and minimizing the delay. Wireless body area networks (WBANs) are an attractive application for *Temporal Network Coding* because of the requirement for low complexity, limited power, and high reliability that this type of networks in real-time applications such as capsule endoscopy and video/medical imaging where retransmissions are not a good alternative.

The *Temporal Diversity Coding* scheme features: 1) low complexity because the Diversity Coding coefficients implicitly known to the source and destination nodes; 2) limited power consumption because smaller E_b/N_0 is required to recover the entire message; 3) better reliability because of the use of a cooperative relays that help to transmit the packets from the source to the destination node; and 4) real-time transmission because of the reduced complexity of the scheme, allowing processing on low-power nodes.

6. REFERENCES

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