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

BODYNETS 2012

September 24-26, 2012

Oslo, Norway

Gabriel E. Arrobo[1], Zygmunt J. Haas[2], and Richard D. Gitlin[1]

[1] Department of Electrical Engineering, University of South Florida, USA

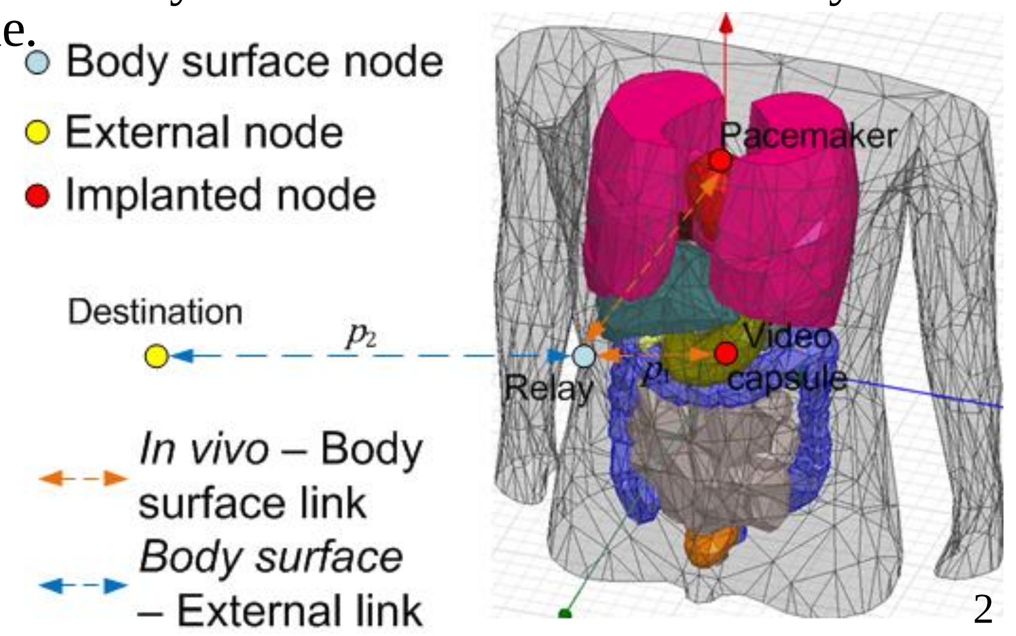
[2] School of Electrical and Computer Engineering, Cornell University, USA

Cornell University
School of Electrical and Computer Engineering

USF UNIVERSITY OF SOUTH FLORIDA
COLLEGE OF ENGINEERING

Wireless Body Area Networks

- 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.
- The probability *Ps* that a packet transmitted from the implanted node is correctly received by the external node is given by: $Ps = (1 - p_1)(1 - p_2)$, where p_1 is the probability of link error between the implanted node and the body surface node and p_2 is the probability of link error between the body surface node and the external node.
- The probability of link error (p_i) depends on different parameters such as modulation scheme, transmission power, interference, channel conditions, etc.

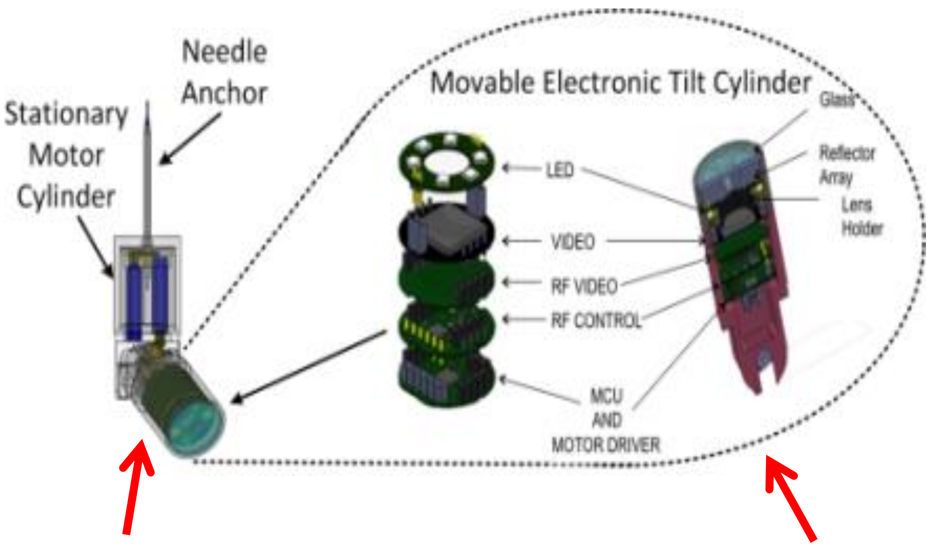


Temporal Diversity Coding (*TDC*)

- 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.

Applications for TDC

- 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.



MARVEL CAD model and exploded circuit board stack

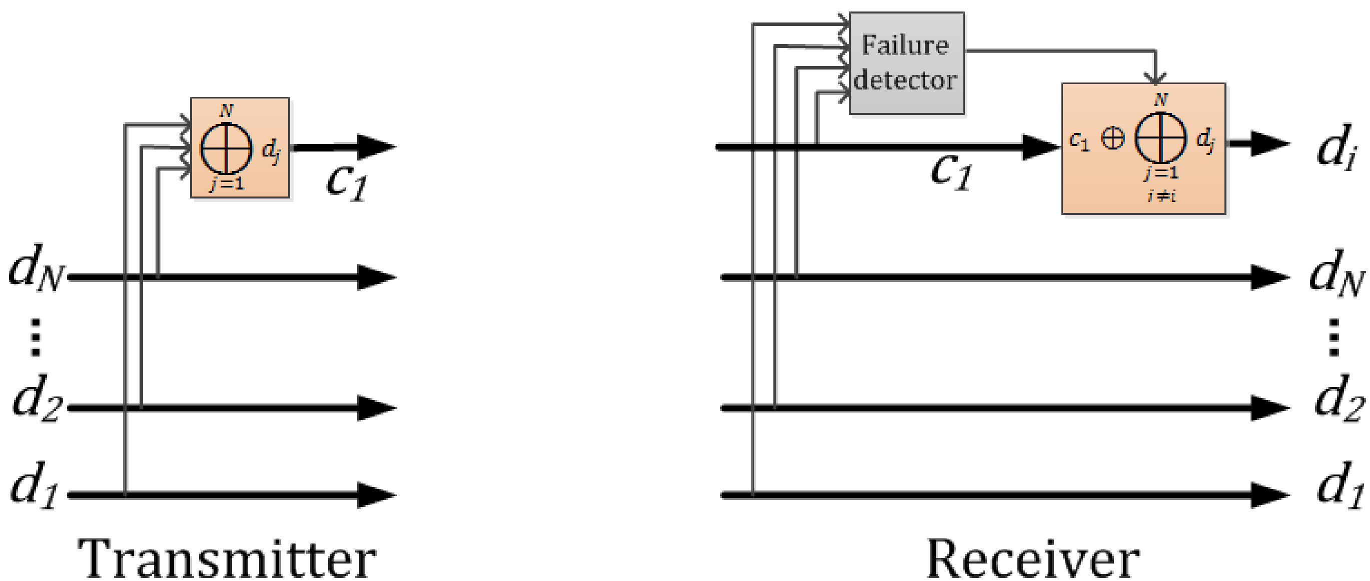
MARVEL research model

Image of internal organs captured by MARVEL unit

MARVEL units in a porcine abdominal cavity

Diversity Coding -- Overview

- Diversity Coding (DC) is an established feed-forward spatial diversity technology that enables near instant self-healing and fault-tolerance in the presence of wireless link failures.
- The protection paths (c_i) carry information that is the combination of the uncoded data lines (d_j).
- The figure below shows a Diversity Coding system that uses a spatial parity check code for a point-to-point system with N data lines and 1 protection line.
  - If any of the data lines fail (e.g. d_3), through the protection line (c_1), the destination (receiver) 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.



Diversity Coding (DC) - Details

- Diversity Coding improves network reliability because if a link or node fails, the information can often be recovered since it is transmitted through spatially different paths.
- In diversity coding, only the redundant (protection) packets are coded using (1) and the data (original) packets are transmitted uncoded. In other words, *M* data plus *N* protection packets are transmitted.
- In diversity coding, the coding coefficients (β_{ij}) are calculated as:

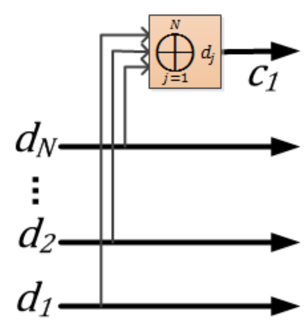
$$\beta_{ij} = \alpha^{(i-1)(j-1)} \quad i = 1, 2, \ldots, N; \qquad j = 1, 2, \ldots, M$$

where α is a primitive element of $GF(2^q)$ and q should be at least $\lceil \log_2(M+N+1) \rceil$.

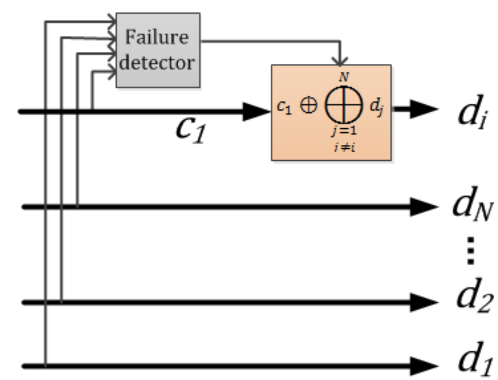
- Additionally, since the coding coefficients are known by the source and destination nodes, there is no need to transmit the β_{ij} coefficients in the packet header.

$$\boldsymbol{\beta} = \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \\ 1 & \alpha & \alpha^2 & \cdots & \alpha^{N-1} \\ 1 & \alpha^2 & \alpha^4 & \cdots & \alpha^{2(N-1)} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & \alpha^{M-1} & \alpha^{(M-1)2} & \cdots & \alpha^{(M-1)(N-1)} \end{bmatrix}$$

$$c_i = \sum_{j=1}^{N} \beta_{ij} d_j \quad i = 1, 2, \ldots, M \qquad (1)$$



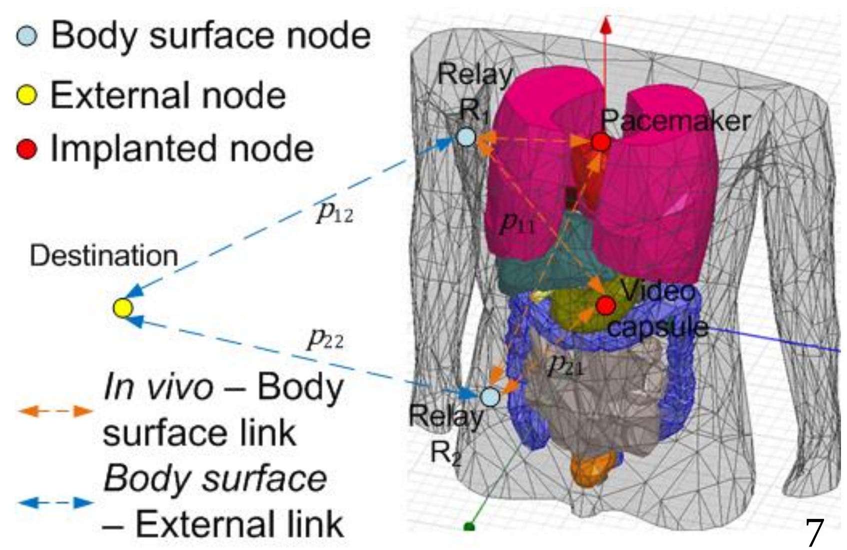
Transmitter



Receiver

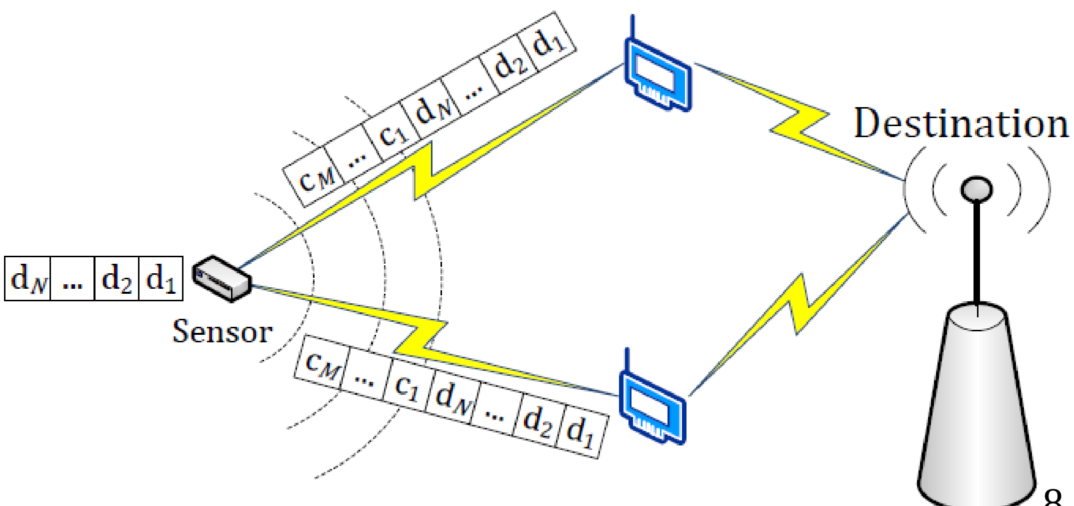
TDC for *In Vivo* Wireless Communications

- 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-*K*) model, where "*K*" represents the number of relays that help to transmit the source packets towards the destination.



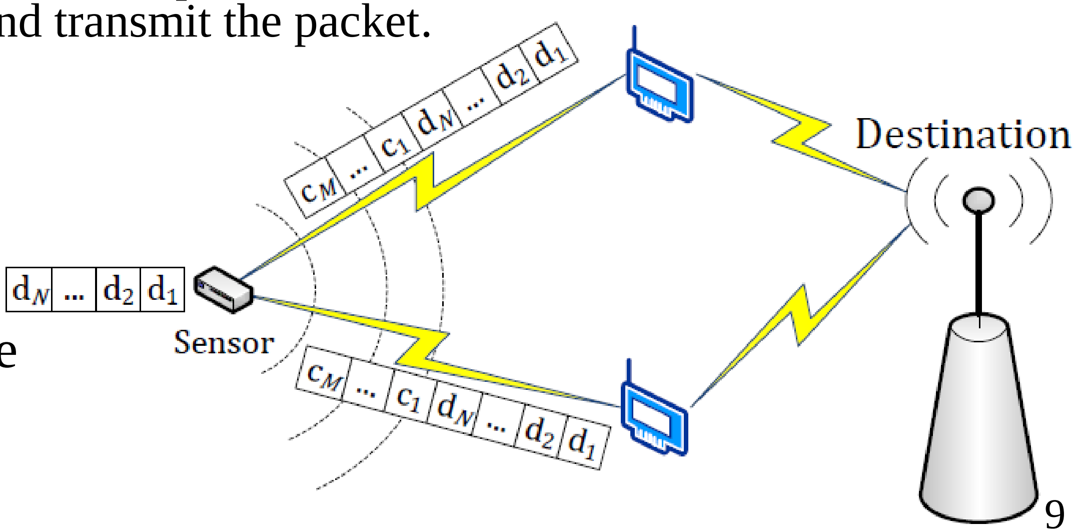
How TDC works at the Source Node?

- The source node (e.g., an implanted node) has a block of information (e.g., N data packets) to transmit to the destination through the K relays.
- The source (S) starts to transmit the N data packets to the R_k relays and simultaneously uses those data packets to create the M protection packets that are transmitted to the relays after the N data packets.
- The c_i protection packets are created using Eq. (1).
  - The computational complexity needed to create the protection packets is low since the coefficients (β_{ij}) are known by the source and the destination nodes.
  - 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 coefficients needs to be included in the packet header.
  - However, it is necessary to include a sequence number in the identification field (packet header) for the destination to reassemble the packets into the original block of information.



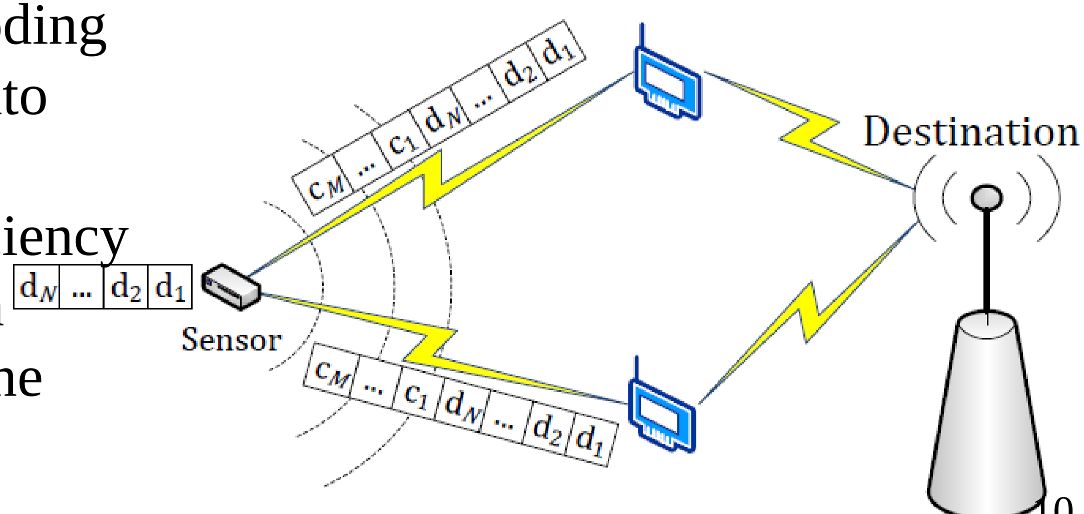
How TDC works at the Relays?

- The R_k relays regenerate the received signal and transmit 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.
- Error correction techniques at the bit level can be combined with TDC-*K* to improve the network's performance.
  - 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 deinterleaving 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.
- However, it is necessary to include a sequence number in the identification field (packet header) for the destination to reassemble the packets into the original block of information.



How TDC works at the Destination?

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



TDC – Performance Metrics

- **Probability of successful reception:**

$$Ps_{TDC-1} = \sum_{i=1}^{N-1} p(x = i \mid x\ data) + \sum_{i=N}^{N+M} p(x = i)$$

$$Ps_{TDC-2} = 1 - \left[\sum_{i+j=0}^{N-1} p(x = i,\ y = j) + \sum_{\substack{i+j \geq N \\ i,j<N \\ rank(header)<N}} p(x = i,\ y = j) \right]$$

- The destination needs to correctly receive at least *N* data and/or protection packets, where $N \leq \tilde{N} + \tilde{M}$, to be able to decode the entire block of information (*N* packets), otherwise only $\tilde{N}$ information packets can be recovered.

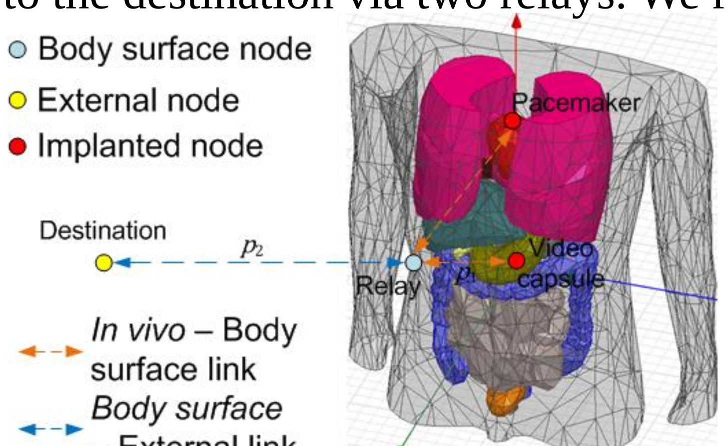
- That is, the **useful information** is given by: $I = \begin{cases} N & N \leq \tilde{N} + \tilde{M} \\ \tilde{N} & o.w. \end{cases}$

- Since the destination can receive data and protection packets, and the protection packets can provide information if and only if $N \leq \tilde{N} + \tilde{M}$, there would be cases where correctly received protection packets provide no information because not enough packets have been correctly received and it is not possible to decode them.
- So, we define another metric, called utilization, to find the percentage of useful information that can be recovered from the correctly received packets.

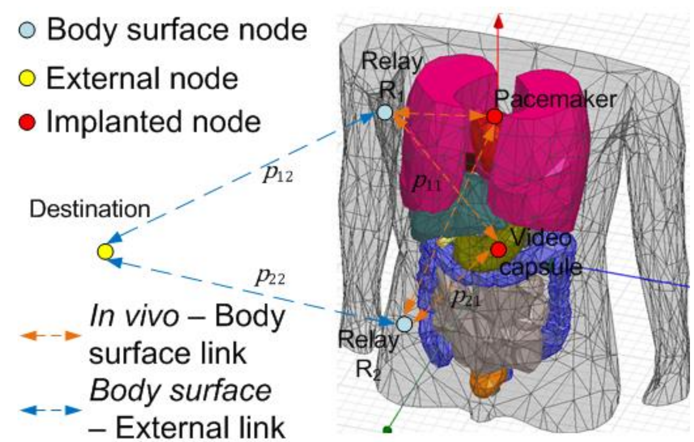
- The **utilization** can be calculated as: $\rho = \dfrac{I}{\tilde{N} + \tilde{M}}$

Comparison Models

- The single path uncoded model where the information is transmitted uncoded and 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). We refer to this model as **"U-1"**;
- The single path Diversity Coded model where the source uses Diversity Coding to code the packets, and transmits the data (uncoded) and protection (coded) packets to the destination via a relay. We refer to this model as **"TDC-1"**;
- 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. No information is coded in this scheme. We refer to this model as **"U-2"**, where 2 is the number of relays that help to transmit the information towards the destination; and
- The two-path Diversity Coded model where the source uses Diversity Coding to code the packets, and transmits the data (uncoded) and protection (coded) packets to the destination via two relays. We refer to this model as **"TDC-2"**.



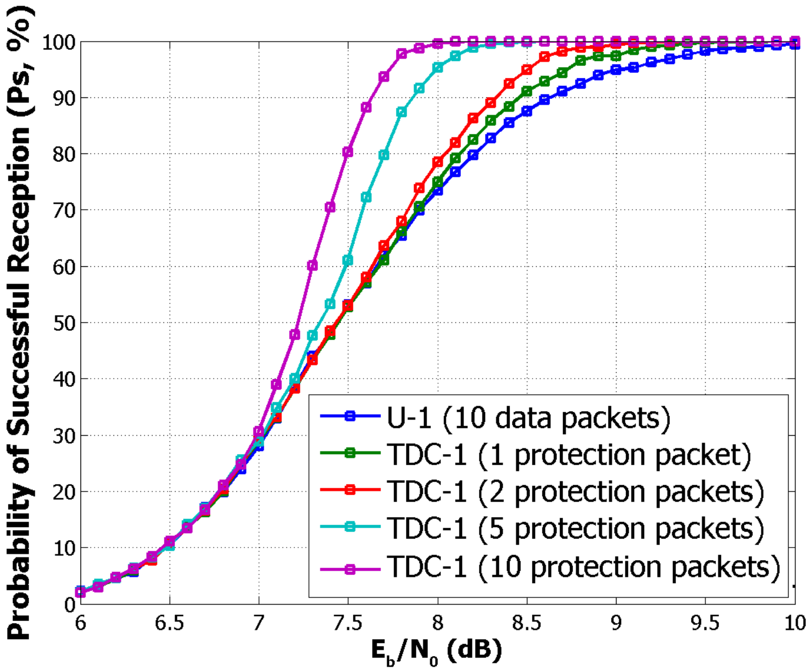
Model for **U-1** and **TDC-1**

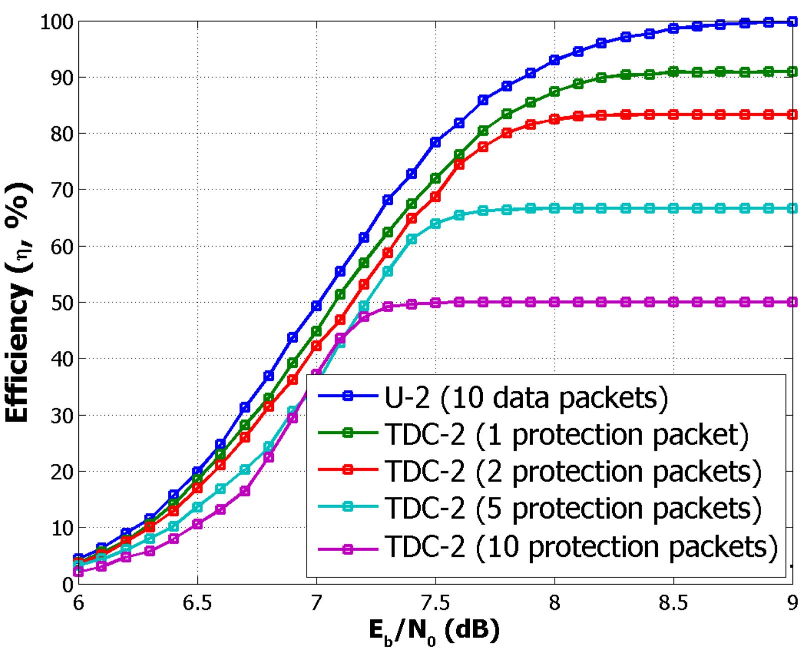


Model for **U-2** and **TDC-2**

Results

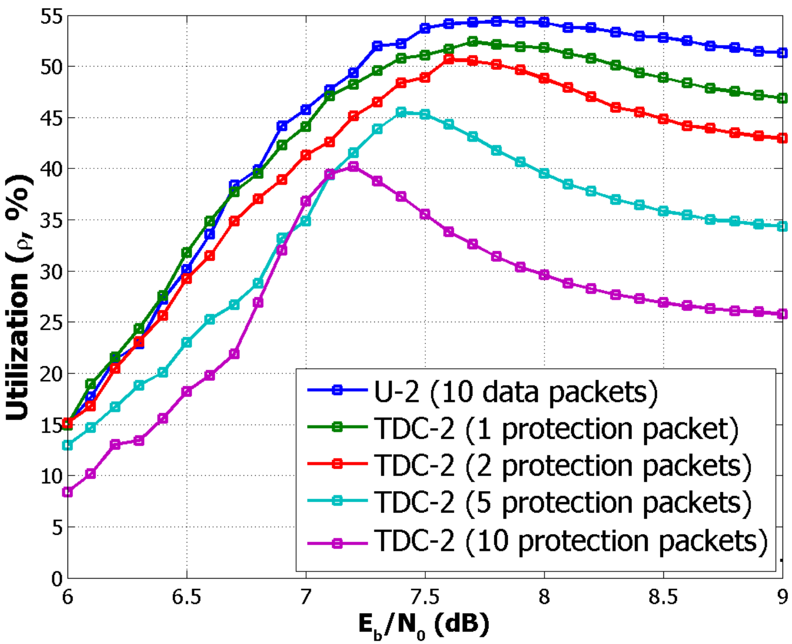
- In the left figure, we show the probability of successfully receiving useful information as a function of the E_b/N_0 for the uncoded scheme (**U-1**) and Temporal Diversity Coding scheme (**TDC-1**).
- As we can see, for ½ and ⅔ DC code rates , the TDC-1 scheme considerably improves (decreases) the E_b/N_0 from about 2.9 and 2.6 dB.
- Similar results are obtained when 16-QAM is used. However, the curves are shifted to the right because of the increased E_b/N_0 required for higher order modulations.
- In the right figure, the performance, in terms of efficiency, of **U-2** and **TDC-2** schemes is shown.
- The efficiency of both schemes increases with the E_b/N_0. However, for E_b/N_0 higher of certain value, the efficiency for **TDC-2** maintains constant.

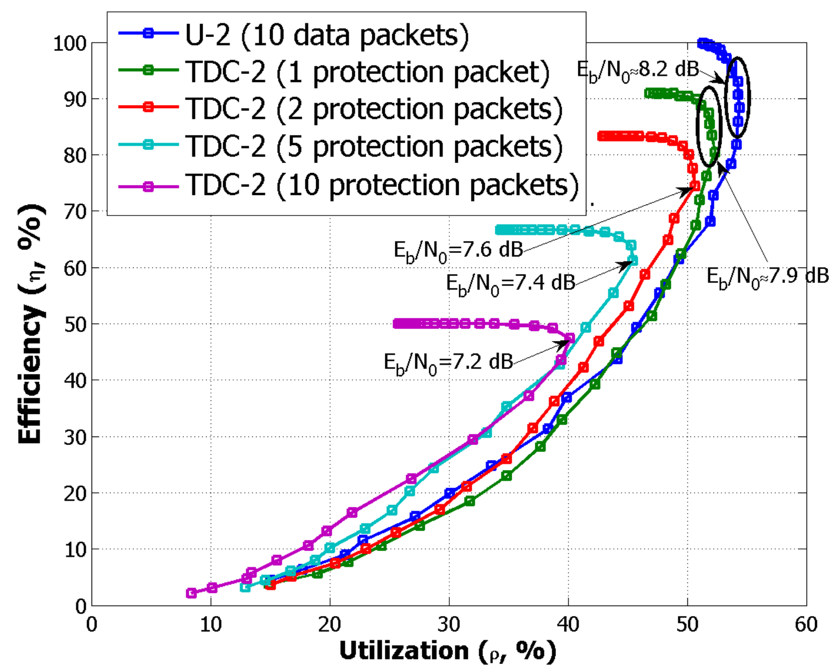




Results – contd.

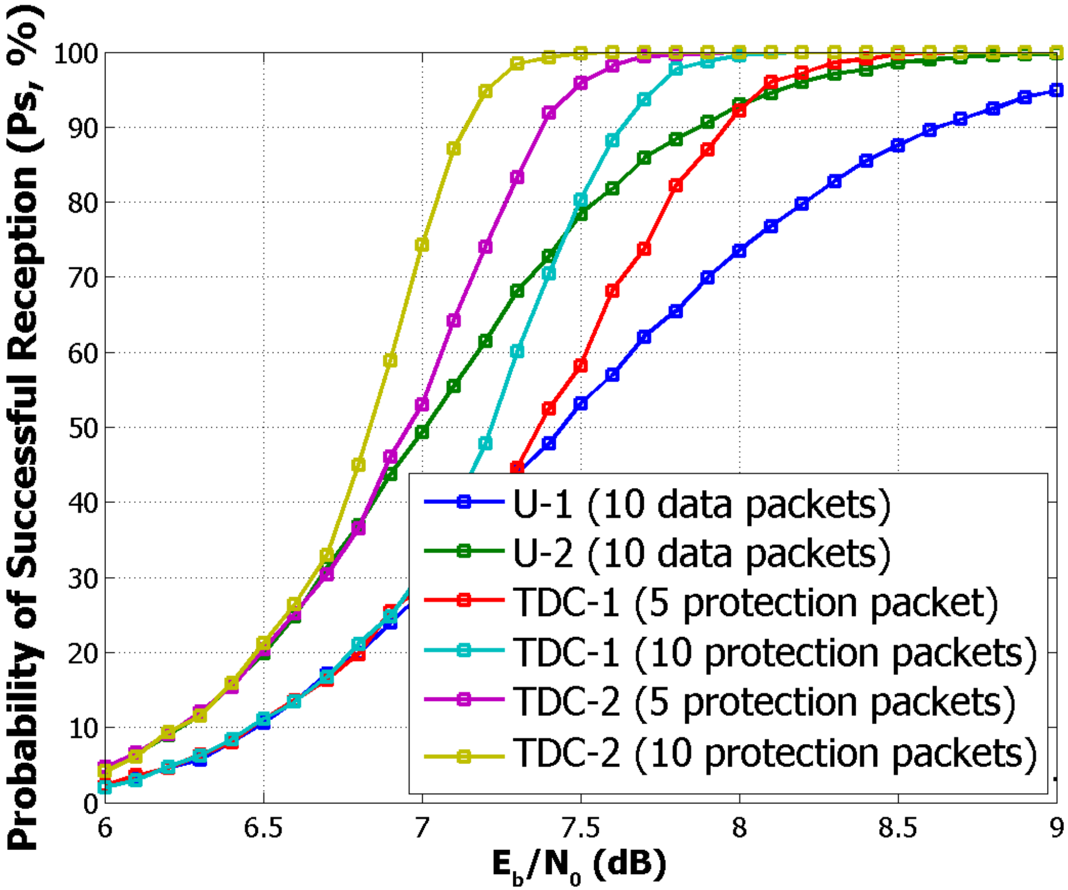
- Utilization, which is the ratio of the number of useful information to the number of correctly received packets, as a function of the E_b/N_0 is shown in the left figure.
- As we can see, the utilization increases with the E_b/N_0 , reaches a peak and then decreases with higher values of E_b/N_0.
- For instance, TDC-2 ½ and TDC-2 ⅔ reach their maximum utilization (ρ) when E_b/N_0=7.2 dB and 7.4 dB, respectively.
- The left figure 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 E_b/N_0.





Results – contd.

- The figure below shows the performance comparison of the 4 schemes (**U-1**, **U-2**, **TDC-1**, **TDC-2**) as a function of the E_b/N_0.
- Time Diversity Coding 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** (10 protection packets) outperforms **U-1**, **U-2**, and **TDC-1** (10 protection packets) by 43%, 18%, and 12%, respectively.
- As expected, we can see 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 preferred to use Temporal Diversity Coding (**TDC-1**) instead of two paths (**U-2**).



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.
- We demonstrate that by implementing this novel technique, we can achieve significant improvement (~50%) in throughput compared to extant WBANs.
- 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

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