IEEE International Conference on Microwaves, Communications, Antennas and Electronics Systems (COMCAS 2011)
Tel Aviv, Israel
November 7-9, 2012

New Approaches to Reliable Wireless Body Area Networks

Gabriel E. Arrobo and Richard D. Gitlin

University of South Florida, Tampa, FL, 33637, USA

***Abstract* — In this paper we present and contrast two approaches, Cooperative Network Coding (CNC) and Cooperative Diversity Coding (CDC) to achieving reliable wireless body area networks. CNC combines cooperative communications and network coding, while CDC combines cooperative communication and diversity coding. These approaches also provide enhanced throughput and transparent self-healing which are desirable features that Wireless Body Area Networks should offer. Additionally, these feed-forward techniques are especially suitable for real-time applications, where retransmissions are not an appropriate alternative. Although, these techniques provide similar benefits, simulation results show that CDC provides higher throughput than CNC because of the fact that the network topology is known and few hops between the source and destination. Moreover, CDC has lower complexity, since the source and destination nodes know the coding coefficients.**

***Index Terms* — Cooperative communications, diversity coding, network coding, throughput, wireless body area networks.**

I. INTRODUCTION

Wireless Body Area Networks (WBANs) are receiving considerable attention because they can provide ubiquitous real-time monitoring, often without restricting the person's regular activities [1] - [2]. A WBAN, Fig. 1, is a network formed by low power and limited-energy networked nodes (often referred to as sensors) that monitor vital human signs and are located in, on or around the human body [3]. WBANs can be used in several applications such as healthcare, fitness, gaming and entertainment, military, etc. However, the most promising application is in healthcare, where the WBANs could lead to proactive monitoring and treatment of a person's health. For example, a proactive release of insulin to a patient with diabetes can occur when the level of sugar drops under a certain level. WBANs have certain characteristics such as low-complexity nodes, limited transmission and processing power, reduced latency, high reliability, mobility, and operating in a highly lossy and dispersive radio frequency (RF) channel [4] – [5] that make WBANs unique compared to other networks. The sensor nodes are restricted in complexity and processing power because of their size and battery limitations. The transmission power is limited to avoid hazardous RF radiation to the human body, as well as to extend the node's battery lifetime. Since the patient's vital signs are continuously monitored, the latency should be negligible or at least very small, especially for real-time applications, such as *in vivo* video monitoring. The radio channel is continuously changing because the dielectric characteristics of the human tissues and organs are themselves in continuous variation. Moreover, the movements of the body such as arms, legs, and the movement of internal fluids such blood make the channel time varying. Because of these channel variations, it is a challenge to realize a WBAN with reliable communications among the nodes [6].

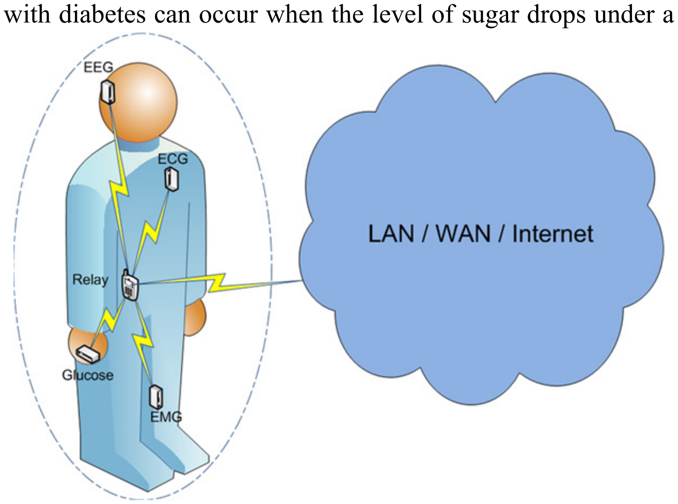


Fig. 1. Wireless Body Area Network (WBAN)

In summary, WBANs must satisfy some stringent technical requirements, especially, when the network is monitoring life-saving related signals such as indicators of a heart attack. WBANs face several design challenges including that they are expected to (1) be extremely reliable by avoiding single points of failure and provide self-healing capabilities if nodes or links are not operating properly, (2) transmit at low power to extend the network's lifetime and preclude any harmful effects in the human body, and (3) allow enhanced throughput under a dynamic and challenging channel. A frequent constraint is that it is often neither possible nor desirable to retransmit the sensor data.

With these challenges in mind, we explore novel feed-forward approaches to creating reliable WBANS called Cooperative Network Coding (CNC) [7] and Cooperative Diversity Coding [8]. Cooperative Network Coding combines

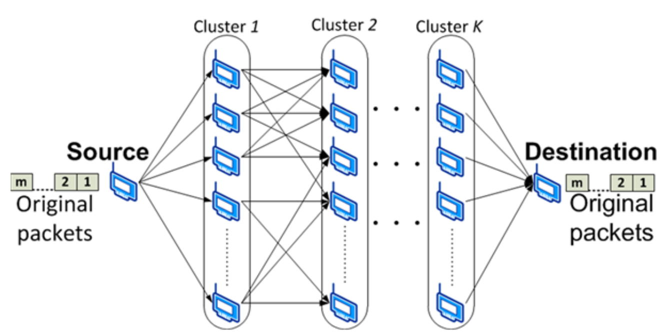


Fig. 2. Cooperative Network Coding Model

Network Coding [9] (more precisely Random Linear Network Coding [10]) and Cluster-based Cooperative Communications [11] to improve the performance of wireless *ad-hoc* networks, such as WBANs. CNC increases reliability by transmitting information through spatially separate paths, as shown in Fig. 2, where the solid lines represent logical wireless channels. Additionally, CNC is especially suitable for real-time applications, where retransmissions are not an appropriate alternative. Further, the system incorporates self-healing characteristics, which allows automatic recovery from failures.

Before any message is transmitted, the route between the source and the destination is established using protocols such as Ad hoc On-demand Distance-Vector routing (AODV) [12], and the nodes that will be forwarding the packets recruit, or are pre-assigned (as might be the case in a WBAN), other geographically close nodes to form clusters. The nodes in a cluster cooperate to transmit the source's information towards the destination.

After the clusters are formed, the source creates coded packets by linearly combining a block of information (e.g. m packets) and transmits those coded packets to the nodes in the first cluster (cluster 1). Then, nodes in cluster 1 create coded packets from the received packets and transmit them to the next cluster. From cluster 2 through K, the nodes receive coded packets from nodes of the preceding cluster, create new coded packets and transmit those coded packets towards the destination. All the coding operations are performed over a Galois Field, $GF(2^q)$. Finally, the destination node needs to receive at least m linearly independent coded packets from nodes in cluster K to recover the original information.

Network reliability is increased because if any of the nodes (relays) fail, the coded packets can still be transmitted by the other relays towards the destination. Also, if any of the links fail, the information can reach the destination through other paths without the need of retransmissions. In the case of a node failure, a background mechanism, as in [13], communicates the failure among the other nodes in a cluster. The nodes then can compensate by transmitting additional linearly independent coded packets to the destination, so it is able to decode the original information.

The paper is organized as follows. In section II, we describe the general concept of network coding, diversity coding, and cooperative communications. New approaches to improving the performance of WBANs using cooperative network coding and cooperative diversity coding are analyzed in Section III. Section IV presents simulation results of the effect of cooperative network coding and cooperative diversity coding in wireless body area networks. Also, a comparison between CNC and CDC is shown in this section. Finally, in Section V we present our conclusions.

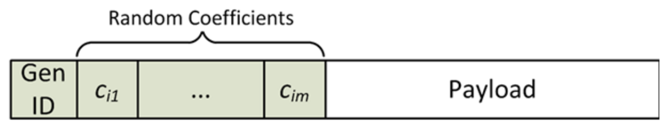


Fig. 3. Network Coding packet format

II. Related Work

A. Network Coding

Network Coding [9], an extensively studied technique, provides throughput gain by combining the packets received at intermediate nodes and transmitting coded packets towards the destination. A (randomly) coded packet contains information of all the source packets and is computed as the sum of the products of each of the m original packets with a random coefficient c_{il}:

$$y_i = \sum_{j=1}^{m} c_{ij} x_j \qquad i = 1,2,\dots,m' \tag{1}$$

where y_i and x_j are the coded and original packets, respectively, m' is the number of coded packets and at least equal to the number of original packets $(m' \geq m)$. The coefficients c_{il} are randomly chosen from a Galois Field $GF(2^q)$, where the $GF(2^q)$ elements are $\{0, 1, 2, \dots, 2^q - 1\}$, and all the operations in (1) are performed over a Galois Field $GF(2^q)$.

The random coefficients $\{c_{il}\}$ comprise the encoding vector and are embedded into the coded packet's header, as shown in Fig. 3. The coded packet will also include a cyclic redundancy check (CRC, error detecting) field, so that packets in error can be identified. The generator ID field (Gen ID) is used to identify combination packets from different sources.

As long as the destination receives at least m original packets, it is able to recover the original information; otherwise, the received packets are discarded. The decoding could be performed through block decoding or earliest decoding, the latter being preferred because of its smaller decoding delay [14].

In a point-to-point architecture with a probability p of link transmission loss, the probability of successful reception, Ps, can be calculated as:

$$Ps = P(i \geq m)$$

$$Ps = \sum_{i=m}^{m\prime} \binom{m'}{i} (1-p)^i p^{m'-i} \tag{2}$$

The throughput can be calculated as the product of the number of original packets and the probability of successful reception $(T = m * Ps)$.

B. Diversity Coding

Diversity Coding [15], a forerunner of Network Coding, is a feed-forward technique that provides self-healing in several types of networks using spatial diversity to transmit information through different links. Moreover, Diversity

$$Ps = \sum_{i=m}^{m\prime} \binom{m'}{i} (1-p)^i p^{m'-i} + \sum_{i=1}^{m-1} \binom{m'}{i} (1-p)^i p^{m'-i} \left(\frac{i}{m'}\right) \quad (4)$$

Coding improves the network reliability, since the information 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, where $m + n = m'$. In contrast to network coding where the β_{ij} coefficients are randomly selected, in diversity coding, the β_{ij} coefficients are calculated as:

$$\beta_{ij} = \alpha^{(i-1)(j-1)} \qquad i = 1,2, \dots, n; j = 1, 2, \dots, m \qquad (3)$$

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 into the packets header.

Considering the same topology as in the previous subsection (*II.A*), the probability of successful reception, Ps, can be calculated as in (4), where the first component correspond to the probability that at least any m (data and/or protection) packets have been received and the second component is the probability that i data packets were received, where $i < m$. The throughput can be calculated as in network coding as ($T = m * Ps$).

C. Cooperative Communications

Cooperative Communications [16] is a well-known technique that improves the probability of reception of the information by transmitting it through multiple paths/links with the help of relays. Thus, the receiver attains data from multiple relays and by properly combining this data; the receiver can make more reliable decisions about the transmitted information. In other words, cooperative communication allows single-receiver devices to act as Multiple-Input-Multiple-Output (MIMO) systems by the use of cooperation [17].

III. Approaches to Reliable Wireless Body Area Networks

As discussed above, we will contrast two approaches to attaining reliable wireless body area networks (WBANs), namely Cooperative Network Coding and Cooperative Diversity Coding. These feed-forward techniques increase the reliability of WBANs by using spatial diversity through cooperation and time diversity through either Network Coding or Diversity Coding, respectively.

A. Cooperative Network Coding

For typical WBANs that have two hops (Source-Relay-Sink), the generalized Cooperative Network Coding model of Fig. 2 [7] is simplified to have only one cluster of R relays that help to transmit the coded packets from the sources to the sink, as shown in Fig. 4 (a). Each source transmits independently and a MAC protocol, such as TDMA, controls the access to the channel. In practice, the number of relays (R) should be kept small (e.g. $R = 2$) because of physical and practical constraints. Fig. 4(b) depicts the situation as seen by each source.

At the relays, the CRC of each packet is verified to detect error(s) in a packet. So, a packet with error is discarded. For the coded packets that have no errors, there are three options to transmit them to the destination:

1) The relays forward the correctly received coded packets,
2) Each of the R relays creates new coded packets from the correctly received coded packets and forwards those coded packets to the destination. Since the number of linearly independent coded packets that can be created at each relay is given by the number of correctly received packets, each relay can create only as many linearly independent coded packets as the number of correctly received coded packets. Any additional new (created) coded packet will be linearly dependent on the other new coded packets (and thus useless).
3) Some of the R relays create new coded packets from the correctly received packets while the other relays only forward the correctly received coded packets. For the case where there are only 2 relays helping to transmit the packets to the destination, either relay 1 or relay 2 can forward the coded packet while the other relays create new coded packets and forward them to the destination.

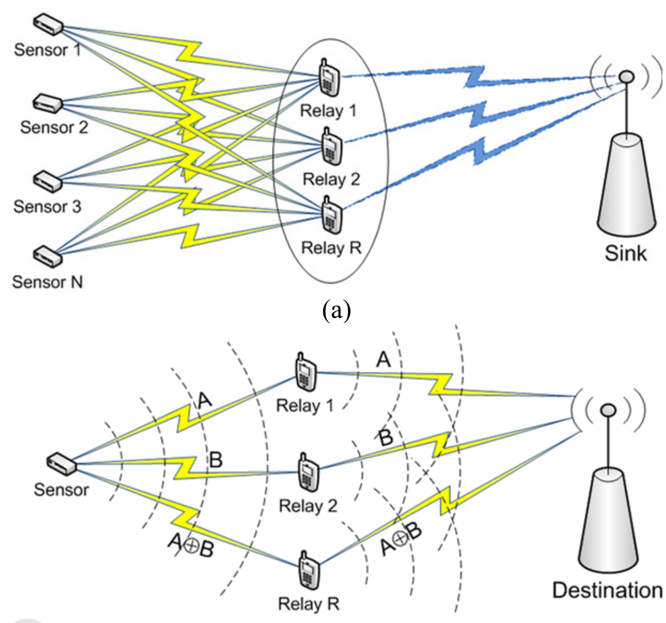


Fig. 4. Cooperative Network Coding Model for WBANs (R=3) (a) network viewpoint, and (b) source viewpoint.

As in the previous alternative, a relay can create new linear independent coded packets that do not exceed the number of correctly received coded packets.

As it was mentioned in the previous sections, the destination needs to receive at least m linearly independent coded packets to be able to decode the original information.

Note that the network topology for Fig. 4 (a) and Fig. 4 (b) is the same and the only difference between them is that since the source nodes operate independently from each other, the destination can view the network (Fig. 4 (a)) as one source node network (Fig. 4 (b)).

B. Cooperative Diversity Coding

Cooperative Diversity Coding operates similarly to Cooperative Network Coding but uses Diversity Coding [15] instead of Network Coding (Random Linear Network Coding) [18].

The source creates the protection packets that are transmitted to the relays along with the data packets. The relays regenerate the signal, verify which packets have error(s) using the CRC, and transmit towards the destination only the packets that have no error. The destination receives data and protection packets, and based on those packets, it can recover, from the protection packets, the data packets that were lost during transmission. The network topology for this technique is similar to the topology presented in Figs. 4 (a) and 4 (b).

C. Cooperative Network Coding and Cooperative Diversity Coding for WBANs

Since the relays are located around the human body, for practical and physical constraints, it may be desirable to reduce the number of relays, e.g. 2, as shown in Fig 5. Under this circumstance, instead of using Network Coding and Diversity Coding in a space diversity mode, we can use these two techniques in a time domain mode, with coding at the packet level, where the source (sensor) transmits (broadcasts) data (uncoded) and protection (coded) packets when using diversity coding and only coded packets when using Network Coding to the relays. Fig. 5 shows the case for Cooperative Diversity Coding where data (uncoded) and protection (coded) packets are transmitted. The relays forward the correctly received packets to the destination, and the destination attempts to recover the original message from the received packets. Also, note that since the source node transmits (broadcasts) a group of packets, under ideal conditions (no packet is lost), all the relays receive the same packets, and in case of relay or link failure, the information can be received through the other relay/path.

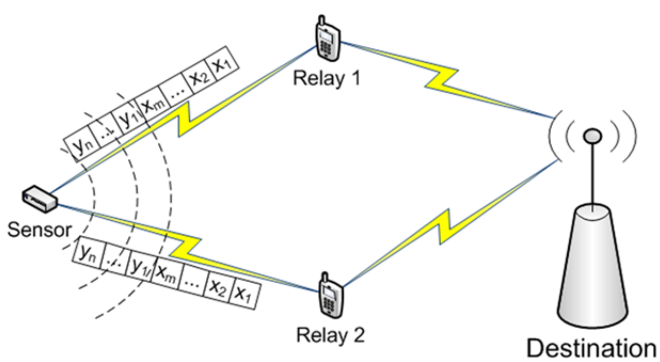
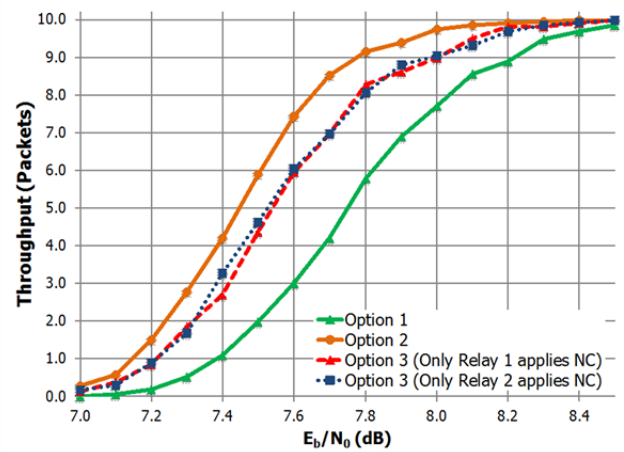


Fig. 5. Cooperative Diversity Coding Model for WBANs for only one source and 2 relays ($R = 2$).

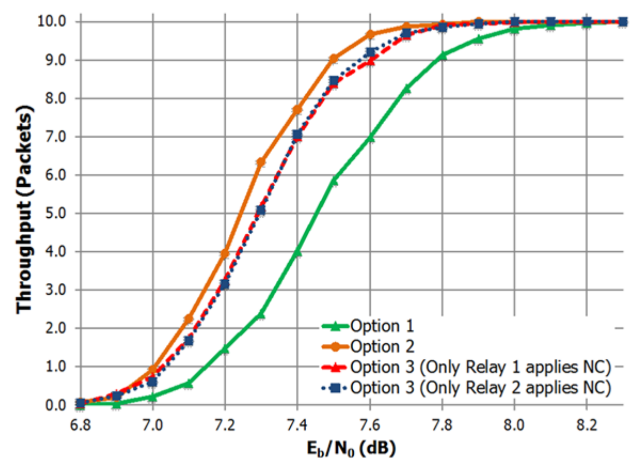
In the following section, we present the simulation results for cooperative network coding and cooperative diversity coding techniques. Also, a throughput comparison of these two technologies is shown.

IV. RESULTS

In this section the simulation results of the throughput for CDC and CNC in WBANs are presented. The results were obtained by running 1,000 trials and averaging the results. The assumptions for the network were that a source has 10 original packets to transmit to the destination through two relays, the probability of link transmission loss is the same for all the links and is uniformly distributed, the channels (AWGN) are



(a)



(b)

Fig. 6. Throughput as a function of the energy per bit to noise power spectral density ratio (E_b/N_0) for Cooperative Network Coding (three options at relays) given (a) $m' = 11$ coded packets, and (b) $m' = 13$ coded packets.

independent of each other, the modulation scheme is 4-PSK, and all the operations are performed over a Galois Field $GF(2^8)$.

Figure 6 shows throughput as a function of the energy per bit to noise power spectral density ratio (E_b/N_0) for Cooperative Network Coding for the three options at the relays given that 11 and 13 coded packets were transmitted. We can see that CNC option 2 (network coding at both relays) achieves the highest throughput for cooperative network coding. Moreover, CNC option 2 requires about 2 coded packets less than CNC option 1 to achieve similar throughput as shown in Fig. 7.

Also, it can be shown that when the ratio of the number of coded packets to the number of original packets increases, option 3 tends to achieve similar performance as option 2. The advantage of option three is that only one of the two relays has to spend extra energy in creating new coded packets. This suggests an adaptive approach for the relays, when the ratio of the number of coded packets to the number of original packets is high (e.g. ≥2) the relays can alternate the creation of new coded packets by block. In other words, during the transmission of the first block of information, relay 1 can create new coded packets and forward them to the destination while relay 2 only forward the correctly received coded packets (no network coding operations), during the transmision of the next block of information, relay 2 can create new coded packets while relay 1 only forwards the correctly received packets. In this way, both relays can achieve a balance in the comsnption energy due to the network coding operations.

Figure 8 shows a comparison of throughput between cooperative diversity coding (CDC) and (a) cooperative network coding (CNC) option 1, and (b) cooperative network coding (CNC) option 2. In Fig. 8 (a), the relays only forward the correctly received packets and no coding operations are performed. Because of the transmission of uncoded (data) and coded (protection) packets, CDC achieves higher throughput. From a different viewpoint, CNC requires higher energy per bit to noise power spectral density ratio to achieve similar perform as to CDC. Fig. 8 (b) shows similar results but there is a (very) small region where CNC outperforms CDC but at the expense of using extra processing power at the relays for coding operations.

The superior performance of CDC over CNC is becauase with Network Coding (Random Linear Network Coding) all the packets are coded and the destination needs to receive at least a number of coded packet equal to the number of original packets (e.g. m original packets) and if less than m coded packets are received, those packets are, in effect, wasted because no information can be recovered from them. On the other hand, since with Diversity Coding, the destination can received uncoded and coded packets and if the destination receives less than m (uncoded and/or coded) packets, it still is able to obtain some of the original information from the uncoded packets. This can also be mathematically explained using (4) and (2), since the probability of success for Diversity Coding equals the probability of success of Network Coding (first component of (4) is equal to (2)) plus an additional probability of success that is given by the uncoded packets (second component of (4)).

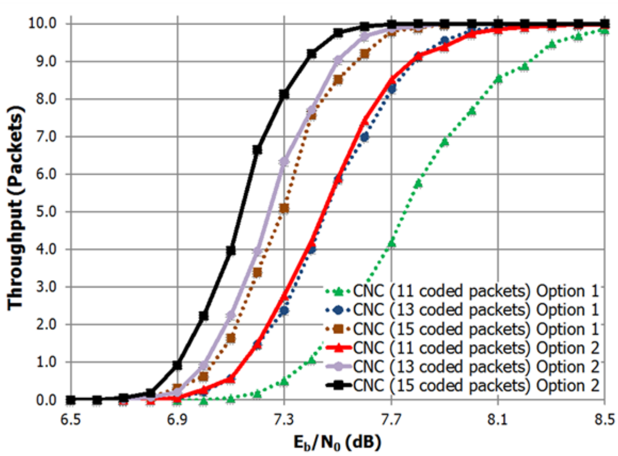
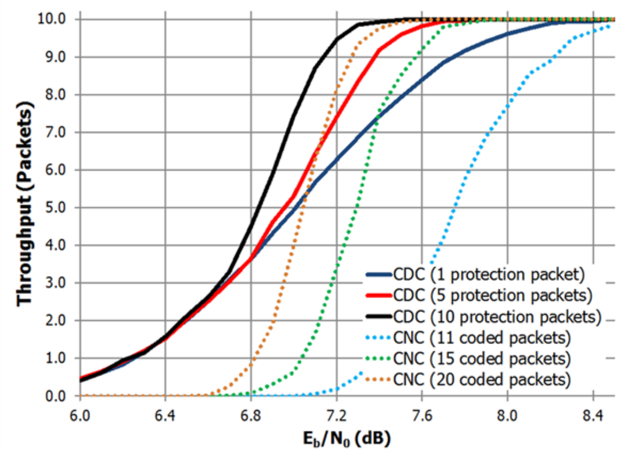
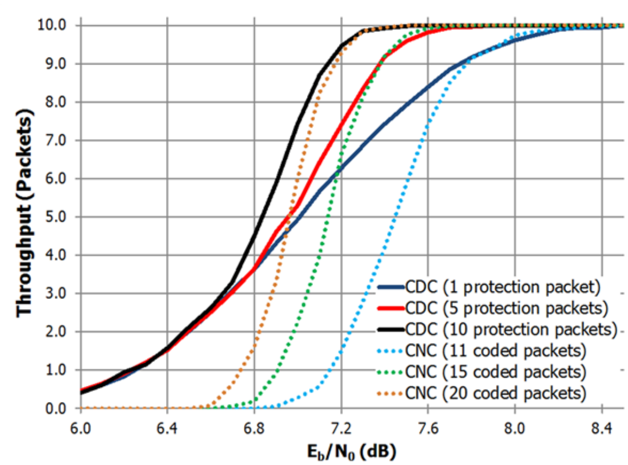


Fig. 7. Throughput as a function of the E_b/N_0 for Cooperative Network Coding (Options 1 and 2) for different number of coded packets.



(a)



(b)

Fig. 8. Comparison of throughput as a function of the E_b/N_0 for (a) CDC and CNC Option 1, and (b) CDC and CNC Option 2.

V. CONCLUSION

In this paper we contrasted novel approaches, cooperative network coding and cooperative diversity coding that provide enhanced throughput, increased reliability and transparent self-healing for Wireless Body Area Networks. Cooperation provides increased reliability while coding (network coding or diversity coding) provide increased throughput by using spatial and time diversity. Additionally, latency, which is an important metric in some WBANs applications, is decreased because of the feed-forward nature of these approaches.

Also, since the topology of these networks (few hops) is known, Cooperative Diversity Coding provides higher throughput when compared to the other networks that we have considered in this paper including Cooperative Network coding, Cooperative Communications without coding and Diversity Coding without cooperation.

Although, these approaches provide similar benefits, CDC provides higher throughput than CNC because since in CDC both data (uncoded) and protection (coded) packets are transmitted, it is possible to obtain some or all of the original information from the uncoded packets; while since in CNC only coded packets are transmitted, it is required that the destination receives at least equal number of coded packets as to the original packets to be able to decode the original information. Moreover, CDC requires lower complexity because the coding coefficients are known by the source and destination nodes. Additionally, since the packet length in not increased (no need to embed the coding coefficients into the packet's header), the probability of packet error is smaller.

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