Improving the Reliability of Wireless Body Area Networks

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Abstract—**In this paper we propose a highly reliable wireless body area network (WBAN) that provides increased throughput and avoids single points of failure. Such networks improve upon current WBANs by taking advantage of a new technology, Cooperative Network Coding (CNC). Using CNC in wireless body area network to support real-time applications is an attractive solution to combat packet loss, reduce latency due to retransmissions, avoid single points of failure, and improve the probability of successful recovery of the information at the destination. In this paper, we have extended Cooperative Network Coding, from its original configuration (one-to-one) to many-to-many as in multiple-input-multiple-output (MIMO) systems.**

Cooperative Network Coding results in increased throughput and network reliability because of the cooperation of the nodes in transmitting coded combination packets across spatially distinct paths to the information sinks.

I. INTRODUCTION

A wireless body area network, WBAN, is a network formed by low-power devices that are located on, in or around the human body and are used to monitor physiological signals and motion for medical, personal entertainment and other applications and purposes [1], Fig. 1. Healthcare applications have attracted researchers' attention because of the increasingly aging population prone to age-related diseases and could often benefit from continuous monitoring of physiological signals [2]. The use of WBANs may enable ubiquitous healthcare and could lead to proactive, and even remote, diagnostic of diseases in an early stage. Moreover, a WBAN may contain an actuator, which based on measurements and settings, can automatically release medicine or other agents. An example being an actuator to supply insulin to a patient with diabetes under the appropriate conditions. Additionally, WBANs provide health monitoring without interfering the patient's everyday activities.

For real-time applications where the caregiver needs to receive information about the patient's health on a continuous basis, the WBANs should provide, among other characteristics, reliable communications that are relatively insensitive to link or node failures [3]. However, patient mobility increases the probability of packet loss, and it is preferred that the packet error rate should be kept less than 1% [4]. Moreover, the WBANs must transmit at low power to protect the patients against harmful health effects

associated with the radiofrequency (RF) emissions. Thus, the specific absorption rate (SAR) should be low [5]. SAR is the rate at which the RF energy is absorbed by a body volume or mass. Due to this limitation on the specific absorption rate, it is not possible to increase the transmission power beyond a certain level to overcome the transmission loss of the packets.
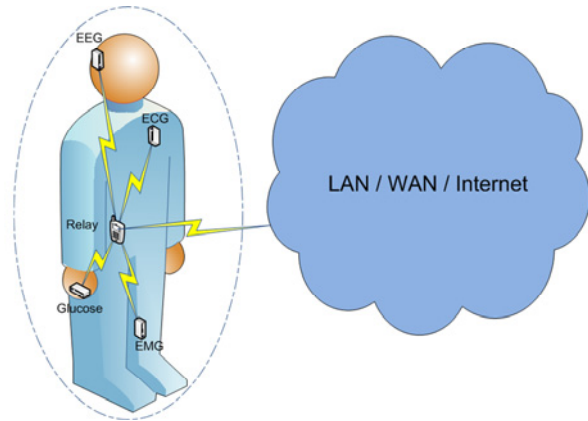

Figure 1. Wireless Body Area Network

To increase the network's throughput and reliability in the presence of packet losses and avoid single points of node or link failures, we extend *Cooperative Network Coding* (CNC) as proposed in [6] to networks where there are many sources, many relay nodes and many sinks/destinations. The relays and sinks act as multiple-input-multiple-output (MIMO) nodes. A relay is a wireless node that helps to transmit the received packets towards the destination, and a sink is a node with high processing capability that receives the packets transmitted by the relays. There is communication, via wired or wireless communications, among the sinks to combine the received packets and decode the information.

The very attractive feature of *Cooperative Network Coding* is that it synergistically combines *Cooperative Communications* and *Network Coding*, in a *feed-forward architecture that creates combination packets of the source information and transmits these over spatially distinct paths*, to improve network performance by providing high throughput and overcoming packet losses.

The paper is organized as follows. In section II, we briefly summarize the prior work on network coding, cooperative communications, cooperative network coding and multiple-input-multiple-output systems. Also, we present some prior work done on WBANs by applying network coding. Our approach to improve the performance of WBANs using cooperative network coding is presented in Section III.

Section IV presents simulation results of the effect of cooperative network coding in wireless body area networks. In Section V we present our conclusions.

II. RELATED WORK

A. Network Coding

Network Coding [7] is a networking technology that achieves capacity gain by combining the packets received at intermediate nodes and transmitting a linearly independent "combination" packet that contains information about all the original (source) packets. A combination packet is obtained by multiplying each of the m original packets with a random coefficient and then the results are summed:

$$y_i = \sum_{l=1}^{m} c_{il} x_l , \quad i = 1,2,\dots,m' \tag{1}$$

where y_i and x_l are the combination, also known as coded, packets and original packets, respectively, $m' (\geq m)$ is the number of combination packets, the coefficients c_{il} are randomly chosen from a Galois Field $GF(2^q)$ and all the operations are performed over a Galois Field $GF(2^q)$, where the $GF(2^q)$ elements are $\{0, 1, 2, \dots, 2^q - 1\}$. The random coefficients $\{c_{il}\}$ are embedded into the packet's header.

As with *Diversity Coding* [8], an early instantiation of Network Coding, this feed-forward approach enables rapid self-healing and fault-tolerance in the presence of link and node failures.

B. Cooperative Communications

Cooperative Communications [9] is a communications technology that improves the reliability of wireless links because the receiver obtains data from multiple relays and by properly combining this data, the receiver can make more reliable decisions about the transmitted information. In effect, cooperative communication allows single-receiver devices to obtain the considerable advantages of Multiple-Input-Multiple-Output (MIMO) systems [10].

C. Cooperative Network Coding

Cooperative Network Coding synergistically combines Network Coding and Cooperative Communications to increase network reliability. In the Cooperative Network Coding model shown in Fig. 2, the source creates combination packets using Eq. (1) and transmits these packets towards the nodes in cluster 1. A cluster is formed by a group of nodes located close to each other. Then, nodes in cluster 1 create a combination packet from the received packets and transmit it towards the next cluster.

Nodes, in clusters 2 through K, receive the combination packets and transmit new combination packets. Node j in the cluster i creates and transmits to nodes in cluster $i + 1$ combination packets from the received combination packets as follows:

$$y_{ij} = \sum_{l=1}^{m_j} c_{ijl} y_{i-1,l}, \quad j = 1,2,\dots,n_i \tag{2}$$

where y_{ij} and $y_{i-1,l}$ are the transmitted combination packets and received combination packets, respectively, n_i is the number of nodes in cluster i, m_j is the number of combination packets received by node j in cluster i from nodes in cluster $i - 1$ and the coefficients c_{ijl} are randomly chosen from $GF(2^q)$. In order to increase the probability that the destination will receive a sufficient number of linearly independent packets to recover the source packets, each node in a cluster should transmit at least the smallest integer greater than or equal to the ratio of the number of original packets (m) and the number of nodes per cluster (n).
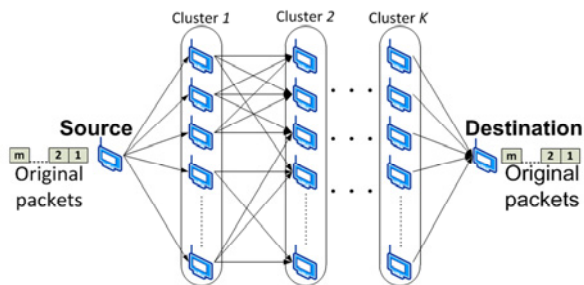

Figure 2.   Single-Destination Cooperative Network Coding Model

At the destination, the destination node needs to receive at least m linearly independent combination packets from nodes in cluster K to be able to recover the original information

D. Multiple-Input-Multiple-Output Systems

A Multiple-Input-Multiple-Output (MIMO) system is a system that uses multiple transmitters and multiple receivers to improve communication performance. Traditionally, a transmitter and receiver, with multiple antennas are viewed as a MIMO system. However, because small-size devices form a WBAN, it is often not possible to implement more than one antenna for each network device. Thus, cooperation among the sources and among the relays, as in a MIMO system, is preferred. Due to the multiple links between the transmitter and receiver nodes, and the cooperation between the receiver nodes, the probability that at least one receiver node correctly receives the message is greatly increased because, in MIMO systems, the probability that all the links fail at the same instant is very low.

E. Network Coding for wireless body area networks

Several papers have considered the use of network coding for wireless body area networks. In [11] and [12], the authors demonstrated that by using network coding in wireless body area networks, a network throughput gain is achieved or the packet loss rate is reduced. The sources transmit 'uncoded' packets to the relays and the relays code the received packets via network coding and transmit the 'coded' packets to the destination. However, a drawback of this approach is that the sources are not taking advantage of network coding because only the relays code the packets.

In the following section, we discuss using Cooperative Network Coding to improve the reliability of WBANs in the presence of node or links failures.

III. IMPROVING RELIABILITY

In this paper, we consider using Cooperative Network Coding for a *multiple source – multiple destination* network, as is the case for wireless body area networks, where there may be several sensors (i.e., sources) that, for example, *in vivo* video, measure heart rate, blood pressure, oxygen level, motion sensors and transmit this information to a receiving devices (sinks) through relays. Through a highly reliable background, wired or wireless, communication, the sinks combine the received packets, decode the information and send it to servers. The model presented in [6] is the point of departure for our analysis.

Figure 3 shows an example network that uses cooperative network coding where 4 sensors/sources transmit information to 2 sinks via 2 relays. In this model, we avoid single points of failure by having multiple relays and, thus, provide multiple paths to transmit a message.
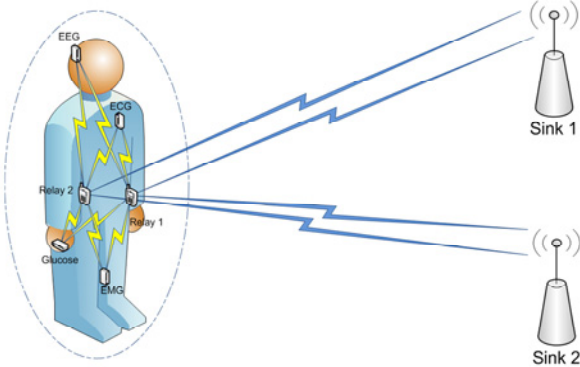

Figure 3.   Cooperative Network Coding for Wireless Body Area Networks

As discussed above, with CNC each source creates m'_s combination packets by using Eq. (1), where i is the index of each source node, $s = \{1, 2, ..., N\}$. The combination packets are transmitted to the R relays and assuming that no packet is lost during transmission, each relay can receive r_r combination packets from the N sources:

$$r_r = \sum_{s=1}^{N} m'_s \qquad (3)$$

Then, by using Eq. (2), the relays create new combination packets, from the received combination packets, by combining packets only from the same source. That is, relay 1 creates combination packets of the received packets from source 1 and transmits those packets to the sinks; next, relay 1 creates combination packets of the received packets from source 2 and transmits those packets to the sinks, and so on. Therefore, the minimum number of combination packets that each relay should create for each source is given by the smallest integer greater than or equal to the ratio of original packets (m_s) to the number of relays (R):

$$r_{t_{min}} = \left\lceil \frac{m_s}{R} \right\rceil \qquad (4)$$

When one or more relays fail, $r_{t_{min}}$ must be increased so that the available relays can receive, create and transmit the appropriate number of combination packets for the sinks to

be able to decode the information of all the sources. In the case of a relay failure, a background mechanism communicates the failure among the other relays. The relays then compensate by transmitting more combination packets to the sinks, so it is able to decode the original information.

Recall that the sinks, in the aggregate, need to receive at least m_i *linearly independent* combination packets for each source to be able to decode the original information of all the sources. Fig. 4 shows our proposed WBAN system that uses CNC with N sources, one cluster of R relays and S sinks. This architecture avoids single point node failures because of the multiple relays and sinks.
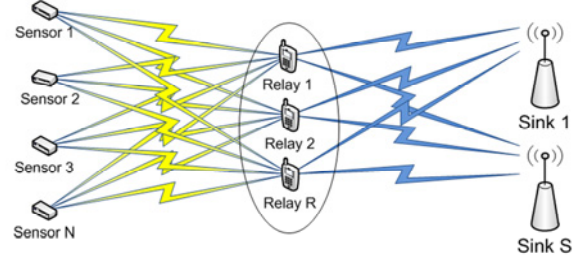

Figure 4.   Cooperative Network Coding model for WBANs

The above example can be generalized to a multihop network of $(K + 1)\ hops$ by having K clusters of relays, between the sources and the sinks, helping to transmit the combination packets towards the destination node.

IV. SIMULATION RESULTS

We have analyzed the effect of different parameters, such as number of transmitted packets by the sources and number of transmitted packets by the relays, number of relays, as well as number of sinks, in order to optimize the network throughput for different probabilities of transmission loss of a link. Using the cyclic redundancy check (CRC), the receiver can determine if the packet is correctly received.

An experiment is considered successful when, after the sinks interchange the received packets, at least one sink can correctly decode the information of all the sources. The interchange process by the sinks of the received packets is performed through highly reliable communication links (no packet is lost during this process). Therefore, all the sinks will have each others packets. Additionally, we assumed that the network consists of 5 sources, each source has a block of information of 10 packets ($m_s = m = 10$) and the probability of link transmission loss is the same for all the links. The network coding operations were performed over a Galois field $GF(2^8)$ with packets size of 100 bytes.

Figure 5 shows throughput as a function of the probability of link transmission loss for different numbers of transmitted packets per source (m') and per relay (r_t) when the network has two relays. Note that m and m' are the number of original and combination packets, respectively; r_t is the number of packets that a relay creates and transmits by each source; and $r_{t_{min}}$ is the minimum number of combination packets that a relay needs to create and transmit to the sinks. As expected, the network offers higher throughput for a

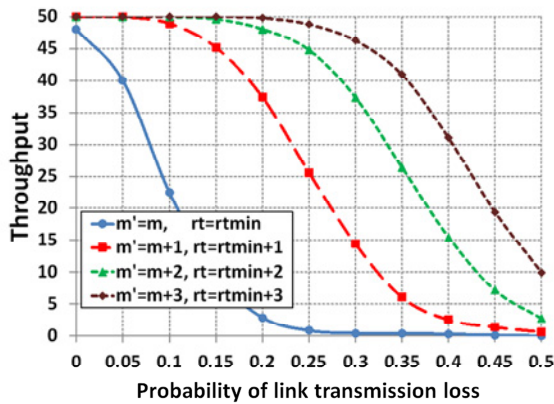given transmission loss as the number of extra packets increases.

Figure 5. Throughput vs. probability of link transmission loss for two relays ($R = 2$) and different numbers of transmitted packets per source (m') and per relay (r_t)
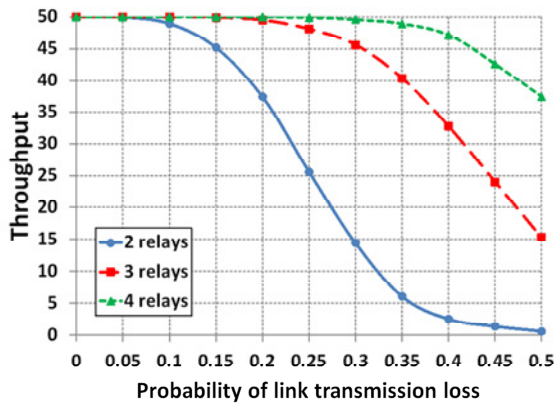

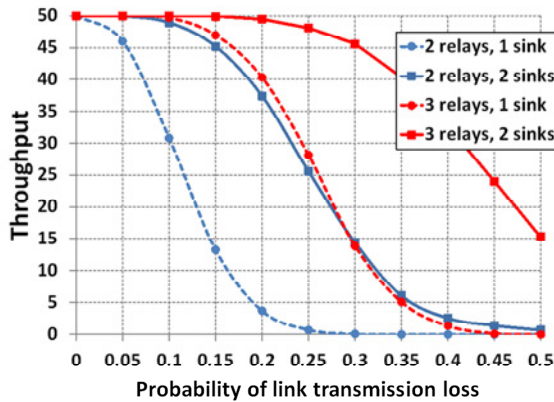Figure 6. Throughput vs. probability of link transmission loss as a function of the number of relays

Figure 7. Throughput vs. probability of link transmission loss as a function of the number of relays and the number of sinks

Figure 6 shows the throughput vs. the probability of link transmission loss for different numbers of relays given that the number of combination packets transmitted by each source and by each relay are $m + 1$ and $r_{t_{min}} + 1$, respectively. As we can see, increasing the number of relays results in increasing the throughput of the network. Fig. 7 shows a comparison of throughput using Cooperative

Network Coding with multiple sinks for different probabilities of link transmission loss. Cooperative Network Coding with a single sink is plotted in dashed lines and Cooperative Network Coding with two sinks is shown in solid lines. It is clear that Cooperative Network Coding with two sinks significantly outperforms Cooperative Network Coding with a single sink because of the multiple paths between the relays and the sinks.

V. CONCLUSION

In this paper, we proposed and evaluated the performance of a highly reliable wireless body area network that uses Cooperative Network Coding combined with multiple-input-multiple-output cooperative techniques at the sinks to achieve high throughput and avoid single points of failure compared to extant wireless body area technologies. Since, real-time applications for wireless body area network are sensitive to packet loss; Cooperative Network Coding offers an attractive solution against packet loss and improved probability of successfully recovering the information at the sink/destination. Cooperative Network Coding in a wireless body area network avoids single points of failure and provides a more reliable network.

In conclusion, Cooperative Network Coding with multiple sinks enables substantially increased throughput and network reliability in Wireless Body Area Networks.

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