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An Energy Efficient Network Coding Approach for Wireless Body Area Networks

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***Abstract*—In this paper, we propose a practical network coding approach for wireless body are networks (WBANs) using decode-and-forward relays. In this scheme, namely decode and forward-network coding (DF-NC), each relay linearly combines different messages from different sources to generate one message, and then transmits that message to the destination. Each relay node in DF-NC requires only one transmission time slot to forward its message. Thus, in this approach, energy usage at each relay is minimized compared to existing cooperative schemes without network coding, which require N_s time slots per relay for relay transmissions; where N_s is the number of source nodes. Simulation results show that the proposed DF-NC scheme can achieve near optimal outage probability while minimizing the number of transmissions per node, maximizing the energy efficiency of WBANs, and minimizing the delay.**

***Index Terms*—Wireless Body Area Networks, Cooperative Communication, Energy Efficiency, IEEE 802.15.6, Network Coding**

I. INTRODUCTION

Recent technological advancements in wireless communication, Micro-Electro-Mechanical Systems (MEMS) technology and integrated circuits has enabled low-power, intelligent, miniaturized, invasive/non-invasive micro and nano-technology sensor nodes strategically placed in or around the human body to be used in monitoring body function and its surrounding environment. This exciting new area of research is called Wireless Body Area Networks and leverages the emerging IEEE 802.15.6 and IEEE 802.15.4j standards-specifically standardized for medical WBANs [1]. The aim of these networks is to simplify and improve the speed and accuracy of data collection from sensors, offer low energy and reliable communication. Sensors in a WBAN are capable of monitoring vital signals, providing real-time feedback and information on the recovery process. Further, WBANs may also control actuators for timely release of medication. They may also enable data logging of a patient's normal environment, allowing doctors to have a clear view of the patient's status and the potential environmental issues. All in all, WBANs promise to revolutionize health monitoring by allowing continuous, non-invasive, inexpensive and ambulatory health monitoring using the Internet to provide real-time updates of medical information.

Nodes in WBANs are usually battery-driven sensory devices which are placed either in or on the human body. As frequent charging can be quite uncomfortable, the practical deployment of WBANs requires novel solutions towards energy-efficient communication. Additionally, as electromagnetic radiation has negative impacts on the human body, significant reduction of the transmit power could be considered as a potential approach. However, due to the large path loss in WBANs, if the transmit power is not sufficient, the severe attenuation on wireless signals will degrade link quality.

One of the most promising solutions to the unique requirements and challenges in WBANs is the deployment of cooperative communications, which is declared as an option in the IEEE 802.15.6 standard [1]. The major advantages of cooperative communication lies within but are not limited to lower interference, extended coverage and reduced power consumption (low transmitted power) that leads to better frequency reuse in wireless networks, higher spatial diversity that provides resistance to small scale and shadow fading and adaptability to network conditions that enables opportunistic use and redistribution of bandwidth and network energy [2, 3]. However, there is a significant tradeoff between the spatial multiplexing gain and the diversity gain in multiple-antenna channels which needs to be considered in the use of cooperative networks for WBANs [4].

Recent work on cooperative communication in WBANs has been provided in literature and has been shown to provide major improvements in terms of outage probability and delay [2, 5–8]. Cooperative communication has been shown great interest in the recent years as it uses the available user terminals as relays that cooperate together to enhance overall system performance. In fact, cooperative strategies use the broadcast nature of wireless channels to be overheard by the neighboring nodes of a source signal intended for a particular destination. The neighboring nodes named relays, helpers or partners process the overheard signal and transmit it to the destination. Signals received from the relays and the source are combined at the destination enabling robustness against channel variations, due to fading, noise, and other channel impairments. More specifically, cooperative communication has

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been shown to satisfy the major requirements of WBANs in terms of high reliability and QoS requirements, high path loss, lower energy consumption, automatic and self organization, ultra low transmission power, prolonged network lifetime and coordinating mission tasks.

In this paper, we first present an overview of the existing cooperative solutions for WBANs. In these schemes, relay nodes normally perform the decoding process on the received signal from each source node, and then re-encode and forward it to the destinations. Then, the destination combines multiple signals from different paths and decodes the original source message. However, once the number of source nodes increases, each relay node needs to forward several messages which belong to several source nodes, leading to severe power usage at the relay nodes as well as a huge delay in the entire network. For instance, when there are N_s source nodes and N_r relays, $N_s(N_r+1)$ time slots (or orthogonal channels) are required for transmission. This means that relay node requires at least N_s time slots to forward N_s messages. Clearly, with the increase in N_s, the relay node requires to send more messages, leading to early depletion of the relay nodes.

To overcome this problem, we present a novel cooperative scheme based on network coding to minimize the number of transmissions of each relay as well as the overall delay, while achieving a reasonable performance in terms of outage probability. In the recent years, the use of network coding in wireless networks has gained a lot of interest, and has shown to significantly reduce power usage in WBANs [9]. In this paper, we present a practical network coding scheme for WBANs with decode-and-forward relays, namely Decode and Forward-Network Coding (DF-NC). In DF-NC, messages received at each relay are linearly combined to generate only one message, which is then transmitted to the destination. Thus, each relay requires only one time slot to forward its message. We further formulate the outage probability of the proposed network coding scheme and compare it with the existing cooperative schemes in WBANs. Results show that the outage probability of DF-NC is close to the optimal strategy (maximum ratio combining without network coding), while it requires far less time slots and achieves higher energy efficiency.

The rest of the paper is organized as follows. In Section II, some background on WBANs is presented. Different cooperative schemes based on decode-and-forward relays are summarized in Section III. We then propose our network coding scheme for WBANs in Section IV. Simulation results are presented in Section V, followed by some concluding remarks in Section VI.

II. BACKGROUND

A. System Model

We consider a two hop configuration shown in Fig. 1 as the general system model used in this paper, where N_s sources want to communicate towards the destination (D) via N_r relays. Each source is assumed to have k information symbols for transmission and uses a channel code of rate R to generate a codeword of length n ($= k/R$). The relays are considered to operate in the half-duplex mode; i.e., a node cannot transmit and receive at the same time as the analog amplifier of the receive chain of relays is forced into saturation in the full-duplex mode due to the large difference in the power of transmitted and received signals.

On the other hand, data transmission in the half-duplex mode is accomplished over different time slots which interprets as loss of data rate. At first, the source node broadcasts a packet to the destination node. A copy of the packet will also be sent in a further slot if the relay is capable of decoding it. Thus, the sink can decode the message from the two copies it has received. A simple Time Division Multiple Access (TDMA) setup is mainly used to avoid idle listening and decrease interference, where each node is only allowed to transmit in its allocated time slot. In TDMA each nodes is assigned with a time slot, and can only send its message during that time slot. It remains silent and overhears other nodes transmissions in other time slots.

B. WBAN Specific Channel Model

As different types of nodes coexist in WBANs that are scattered in and on the human body, multiple transmission channels are developed between the nodes based on their location. The major goal of a channel model is to evaluate the performance of several physical layer proposals as well as providing a fair comparison amongst them. However, they do not intend to provide information regarding absolute performance in different body postures and environments. Most scenarios are established based on the distance of the communication nodes which are body surface, implant and external; and are grouped in classes represented by the channel model. External devices are considered to reach a maximum distance of up to 5 meters.

Another important setup is to differentiate electromagnetic wave propagation from devices in or around the body. However, due to the complex structure of the body shape and the human tissue, a simple path loss model cannot be easily modeled for WBANs. Moreover, as the body antennas are either placed in or on the body, the influence of the body on radio propagation also needs to be considered [5].

Additionally, WBANs experience high path loss due to body absorption that must be supported through heterogenous and multi-hop links with different types of sensors at various locations. Changes in operational conditions may also lead to error-prone and incomplete sensory data relative to inherent sensor limitation, human postures and motions, sensor breakdown and interference. Hence, their is a huge demand for specific solutions that reduce the radiated and consumed power of electromagnetic fields by the user or via interference [10]. Moreover, since health-care facilities and human subjects have specific regulations, the design of implants and wearable devices becomes crucial. Further, channels models in WBANs are far more complex due to mobility, multi-path and running.

In order to model the channel between each pair of nodes, we use the same model as in [11], where Gamma distribution

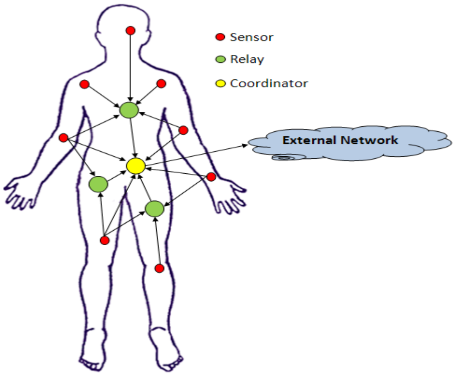

Fig. 1. A cooperative network consisting of N_s source nodes and N_r relays and one common destination

is used to model a slow fading process dominated by shadowing. This channel model is quite helpful for WBANs as the shadowing and pathloss effects are quite severe in WBANs and deep fading can be introduced at a slow rate with a change in body positioning [11]. The probability distribution function of Gamma distribution is as follows:

$$p(x|a,b) = \frac{1}{b^a \Gamma(a)} x^{a-1} e^{-\frac{x}{b}},$$

where $\Gamma(.)$ is the gamma function. During this paper we consider that $a = 1.77$ and $b = 0.454$ [11].

C. Cooperative Mechanisms

In this part, we review the four common relaying techniques used in wireless networks.

1) Amplify-and-Forward: In the amplify-and-forward approach, the cooperative relay simply amplifies the received signal and then transmit it to the destination in its allocated time slot. However, this approach has major deficiencies in low signal to noise ratios as the noise at the relay will be amplified as well as the signal; thus, it is inconvenient for use in WBANs due to their requirements. Despite the simplicity of the amplify-and-forward relaying scheme, this approach leads to a huge performance loss when the user-relay channels are weak. Therefore, this approach is not applicable for WBANs which experience high path-loss due to body absorption and the moving nature of the body.

2) Compress-and-Forward (CAF): The compress-and-forward strategy is an extension of the amplify-and-forward approach as the analogue signal is sampled, quantized, compressed and retransmitted. With this approach, the signal can be temporarily stored or even relayed via a different communication standard. A relay using the CAF approach estimates the signal observed during the 1^{st} time slot. In the 2^{nd} time slot, it sends a compressed version of this signal. The compression employs the fact that the observations at the relay and destination during the 1^{st} time slot are correlated. More specifically, the relay employs source coding using side information at the destination.

3) Decode-and-Forward: In the decode-and-forward approach, normally a single or multi-relay scenario is considered where a user attempts to detect the received bits from another user and retransmits the detected bits. More specifically, the received signal is decoded and re-encoded via a different codebook before retransmission. This approach has high complexity and power usage of nodes involved in the coding process which leads to early depletion of nodes in WBANs with scarce limitation of resources. Additionally, as accuracy is of vital importance in different WBAN applications, issues with bad source-relay links need to be resolved.

4) Coded Cooperation: In the coded cooperation approach, cooperation is integrated in channel coding where different segments of each user's code word are sent through two independent coding paths. The main idea in this technique is that each user transmits incremental redundancy to nodes in its coverage and switches to a noncooperative mode when such transmissions are not feasible. However, this redundancy in transmissions depletes the energy level of the nodes in a short time which is inappropriate for use in WBANs such as implant WBANs deployed in medical applications.

Since most work on cooperative communication in WBANs have focused on decode-and-forward relaying, we also focus on this simple scheme.

III. DECODE-AND-FORWARD COOPERATION IN BANS

In decode-and-forward communication, the i^{th} sender node S_i transmits packets to a destination D via the assistance of one or multiple relays. In fact, the sensor broadcasts the packet to the destination and relay nodes in the i^{th} time slot t_i. The relays then try to decode the received signal in t_i. Normally, a Cyclic Redundancy Check (CRC) is performed at the relays to ensure the accuracy of the decoded packets. The packet is then decoded at relay j and then re-encodes and forwarded to the destination in $t_{(j-1)N_s+i}$. In the end, based on one of the following combining schemes the packets are combined at the destination, after which S_i's message is decoded.

The three combining schemes in decode-and-forward techniques shown in Fig. 2 are as follows:

1) Maximum Ratio Combining (MRC): In this technique, the received signal from each node at the destination is multiplied by a weight value which is proportional to the amplitude of the signal; i.e., weak signals are attenuated and strong signals are amplified. The combined signal is then decoded to recover the original signal sent by the source node. As shown in [12], the overall SNR at the destination can be calculated as follows:

$$\gamma_{i,MRC} = \gamma_{S_i D} + \sum_{j \in \mathcal{C}_i} \gamma_{R_j D}, \tag{1}$$

where $\gamma_{S_i D}$ and $\gamma_{R_j D}$ are the instantaneous SNR of the channel between S_i and D and the channel between R_j and D, respectively, and $\mathcal{C}_i$ is the decoding set for S_i, which is the set of all relay nodes that have successfully decoded S_i's message. Outage probability for S_i can then be calculated as follows:

$$P_{i,out} = p(\gamma_{i,MRC} < \gamma_{Th}), \tag{2}$$

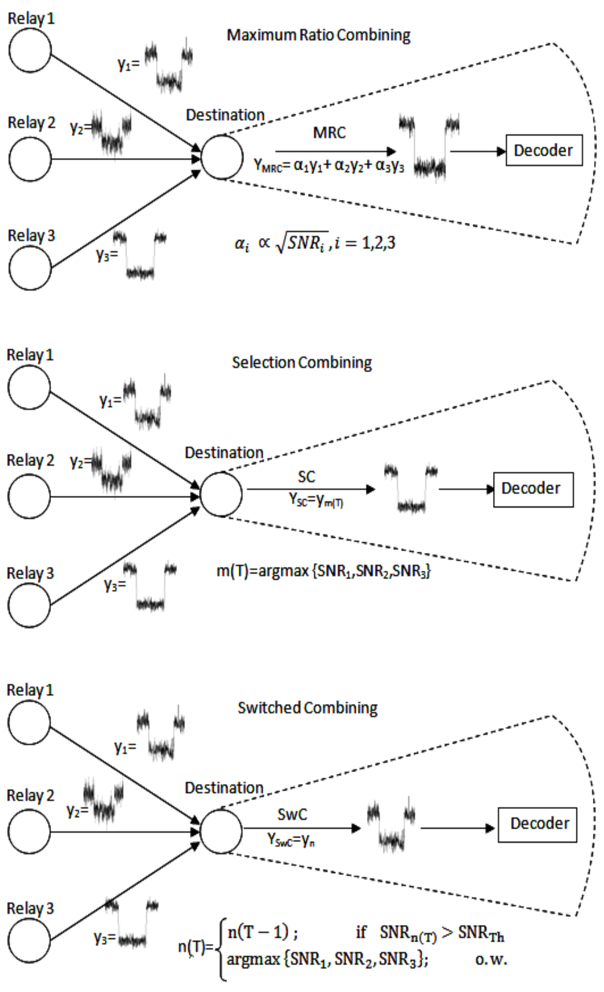

Fig. 2. Three different combining schemes at the destination for decode-and-forward relaying.

where γ_{Th} is the threshold value of the SNR based on which a signal with SNR higher than this value can be decoded. According to the law of total probability we have the following:

$$P_{i,out} = \sum_{\mathcal{C}_i} p_{\mathcal{C}_i} p(\gamma_{S_iD} + \sum_{j\in\mathcal{C}_i} \gamma_{R_jD} < \gamma_{Th}), \tag{3}$$

where $p_{\mathcal{C}_i}$ is the probability that the decoding set is $\mathcal{C}_i$. Since we assume that all source-relay and rely-destination channels have the same statistics in this paper, we can further simplify (3) as follows:

$$P_{i,out} = \sum_{k=0}^{N_i} \binom{N_i}{k} q_i^k (1-q_i)^{N_i-k} p(\gamma_{S_iD} + \sum_{j=1}^{k} \gamma_{R_jD} < \gamma_{Th}), \tag{4}$$

where N_i is the number of relays that have successfully decode S_i's message and q_i is the probability that a relay node can decoded S_i's message; which can be calculated as $q_i = p(\gamma_{S_iR_j} \geq \gamma_{Th})$.

In this scheme, each relay needs to send N_s messages in N_s different time slots. Thus, the entire system requires at least $T_{MRC} = N_s(N_r + 1)$ time slots.

2) Selection Combining: This technique requires channel estimations for all its links; after which the branch with the highest signal amplitude is selected. Therefore, in each transmission the destination may choose to switch amongst the different branches. This leads to unnecessary switching at the destination due to the variant characteristics of the channel in WBANs. In fact, frequent relay switchings lead to issues with synchronization as the initialization process has to start from scratch each time a relay changes. Further, the readjustments in frequency synchronization increases the overall system complexity, outages and delays [6].

In this scheme, we can define parameter γ_j for relay j as follows:

$$\gamma_{i,j} = \min\{\gamma_{S_iR_j}, \gamma_{R_jD}\}. \tag{5}$$

The selected link at the destination has the largest value amongst $\gamma_{i,j}$'s and γ_{S_iD} [13]:

$$\gamma_{i,SC} = \max_j\{\gamma_i, \gamma_{SD}\}, \tag{6}$$

and the outage probability for S_i can be simply calculated as follows:

$$P_{i,out} = p(\gamma_{SC} < \gamma_{Th}) \tag{7}$$

In this scheme, for each source message transmission we require at least two time slots; one for source node transmission and one for relay forwarding. Thus we require at least $T_{SC} = 2N_s$ time slots transmission of whole users' messages.

3) Switched Combining: In order to minimize the issue with unnecessary switching and to eliminate the switching rate, a novel switched combining approach has been proposed in [6]. The switching rate is defined as the rate at which the selection of branches occurs at the destination. This approach has less complexity compared to the selection combining technique as it only requires a single end-to-end channel estimation for each transmission. Switching occurs only in cases where both the channel gain of a current branch becomes lower than the threshold value and the channel gain of at least one other branch exceeds the channel gain of the current branch. In [6], a switch and examine combining method has been proposed for WBANs. For instance, in the case of a three-branch configuration, switching occurs once the channel gain of the current branch becomes lower than a certain threshold. However, in cases where the alternate branch has a channel gain below the defined threshold, the current branch remains as the switched branch.

In order to calculate the outage probability of this scheme, we first consider that the m^{th} path has been selected in the previous transmission. Hence, outage probability in the next time slot can also be calculated as follows:

$$P_{i,out|m} = p(\gamma_m < \gamma_{Th}) p(\gamma_{i,SC} < \gamma_{Th}), \tag{8}$$

and according to the law of total probability we have the following:

$$P_{i,out} = \sum_{m=1}^{N_r+1} P_{i,out|m} c_m, \tag{9}$$

where c_m is the probability that the m^{th} branch has been selected in the previous transmission. We can find c_i by solving the following equation [14]:

$$c_m = c_i p(\gamma_m \geq \gamma_{Th}) + \sum_{j \neq m} c_j p(\gamma_j < \gamma_{Th}) p(\gamma_m = \gamma_{SC}). \tag{10}$$

Since we assume that all source-relay and relay-destination channels have the same statistics, it is reasonable to assume that c_m is similar for $m = 1, ..., N_r$. Thus, in cases where the SNR of the Source-Destination channels is very low, we can assume that $q_i = 1/N_r$; as the source-destination is not selected with high probability. The number of time slots for transmission of all source nodes' messages is the same as that in selection combining, so $T_{SwC} = 2N_s$.

In cases where complexity is not an issue, more than one relay can be used which significantly increases the performance gains. However, the placement of a sensor node in alignment with its coordinator is of utmost importance as 6 dB performance differences for selection combining approach and 2 dB performance difference has been shown to exist with variations in placement of the relay, the coordinator and the sensor-to-relay channel gain thresholds. Additionally, the use of more relays increases the packet successful transmission rate which is because the average fade durations of combined signals for decode-and-forward are much smaller than direct-link communication. Due to the low switching rates and the simplicity of switched combining, this approach is the most appropriate decode-and-forward technique in WBANs [6].

IV. DECODE-AND-FORWARD RELAYING WITH NETWORK CODING

In all cooperation schemes based on decode-and-forward proposed for WBANs, relay nodes are required to fully decode the message of the source node and then re-encode it and transmit it to the destination. These schemes can only be convenient for WBANs in cases with few source nodes. Simply put, by increasing the number of source nodes the relays have to do a lot more decoding, which means a lot more transmissions. For instance, in a network with five source nodes, one relay receives five messages which it has to decode and later send them in five independent time (frequency) slots towards the destination. However, as WBANs have scarce limitation of resources in terms of bandwidth and power, these methods are not convenient for practical deployment in WBANs and lead to early depletion of the relay nodes.

Two potential solutions can be considered to avoid the aforementioned issue. One approach is to decrease the complexity of decoding at the relay. In this approach, the relay only decodes a number of the received signals instead of all of them and then transmits them. Obviously, this leads to a lower decoding complexity and the relay will require fewer time slots for transmission towards the destination. However, the major drawback of this technique is that the network performance will degrade compared to the other proposed schemes. In fact, there is a trade off between the performance and complexity as the increase in the number of messages that have to be processed at the relay, improves the overall performance whilst increasing complexity as well. On the other hand, with fewer number of processing messages at the relay the complexity will decrease at the cost of performance degradation.

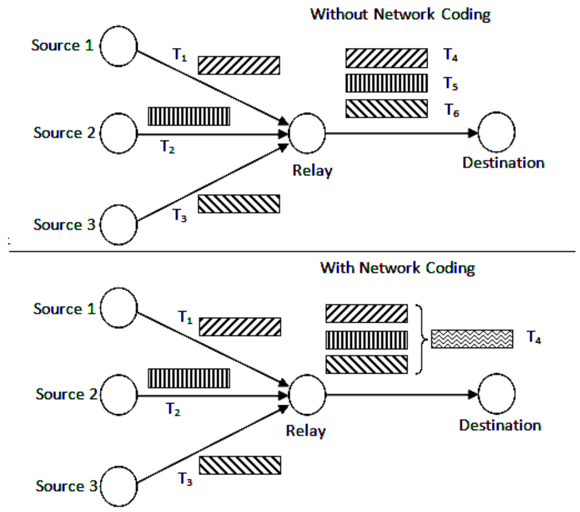

Fig. 3. Cooperative networks with and without Network coding.

One other approach to reduce the complexity and specifically reduce the number of time slots required for transmission towards the destination is to use network coding. Generally, in this approach the relay is still required to decode all or a predefined number of the received messages, and then jointly re-encode them and transmit them to the destination. To further reduce the complexity, we consider a simple bitwise XOR operation for network coding. This way, the relay only requires one time slot to send the network coded message to the destination.

Fig. 3 shows a network with three source nodes and one relay. Without network coding, the relay requires three time slots to forward the messages from the sources to the destination. But, by using network coding the three decoded packets at the relay are linearly combined and a network coded packet is generated and sent to the destination which only requires one time slot.

As sensors in WBANs are required to operate for prolonged periods without heat dissipation, energy efficiency is of vital importance in these networks. Thus, the proposed communication methods must deploy algorithms to avoid excessive and unnecessary usage of the limited resources in WBANs. We have proposed a cooperative scheme based on decode-and-forward and network coding to enhance the energy efficiency and network lifetime in WBANs. This way we reduce the number of time slots required for the transmission. In this

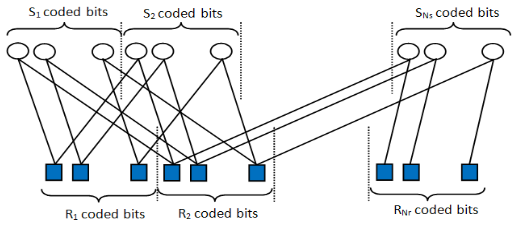

Fig. 4. Bipartite graph of the SNR-Aware random XOR network-coded scheme when two coded bits are connected to each network coded symbol ($d = 2$).

scheme, each relay decodes the received message from each source node and includes them in the network coding process in cases where the decoding process has been successful. Then, the relay node re-encodes the messages, permutes them, then XORs them and transmits to the destination.

A. The DF-NC Scheme

As mentioned before we consider that each source node has k information symbols to send which it encodes to generate n coded symbols. Let us consider that R_j has decoded set $\mathcal{C}_j$ of source nodes with cardinality N_j. For simplicity we assume that $\mathcal{C}_j = \{A_1, A_2, ..., A_{N_j}\}$, where $A_m \in \{S_1, S_2, ..., S_{N_s}\}$. Each network coded symbols at relay j is then calculated as follows. We randomly choose a coded symbol from each source node in $\mathcal{C}_j$ and then XOR them. the l^{th} symbol of the network coded message at relay j can be calculated as follows:

$$r_{j,l} = \left(\sum_{i=1}^{N_j} a_{i,l}\right) \mod 2, \quad l = 1, 2, ..., n, \tag{11}$$

where $a_{i,l}$ is randomly selected from coded symbols of A_i.

We consider network coded symbols check nodes and coded symbols of each users as variable nodes. Then we can show the connection between variable and check node by a bipartite graph. Fig. 4, shows the bipartite graph for for the proposed network coding schemes. As shown in this figure, R_1 has only decoded S_1 and S_2, so network coded symbols of R_1 are only connected to S_1 and S_2 coded symbols.

B. Decoding at the Destination

The detection algorithm initiates at the destination once all nodes have broadcasted their messages throughout the network. As stated earlier, the first N_s time slots are allocated to the symbols from the source nodes. The signal received from the i^{th} source node at the destination is as follows:

$$r_{iD} = h_{iD}x_i + n_{iD}, \tag{12}$$

where h_{iD} and n_{iD} are the channel gain between the source i and the destination and the additive white Gaussian noise, respectively. The last N_r time slots are allocated to symbols from the relays. Therefore, the signal received from the j^{th} relay at the destination is as follows:

$$r_{jD} = h_{jD}\tilde{x}_j + n_{jD}. \tag{13}$$

We have used the message-passing algorithm (MPA) based on belief propagation to decode the signal for the i^{th} source [15]. In MPA, messages are sent iteratively from check to variable nodes and then from variable to check nodes in each iteration. This procedure continues until a predefined number of iterations are performed or all variable nodes are decoded. In MPA, messages are normally LLRs or conditional probabilities. For simplicity, we denote variable nodes by v_i where, $i = 1, 2, ..., N_s k$, and check nodes by c_j, where $j = 1, 2, ..., N_r k$. The message passing decoder is described as follows:

$$q_{ij}^{(0)} = L(c_{iD}), \tag{14}$$

$$m_{ji}^{(l)} = 2\tanh^{-1}\left(\tanh\frac{L(c_{jD})}{2} \cdot \prod_{i' \in \mathcal{N}(j)\backslash i} \tanh\frac{q_{i'j}^{(l-1)}}{2}\right), \tag{15}$$

$$q_{ij}^{(l)} = L(c_{iD}) + \sum_{j' \in \mathcal{M}(i)\backslash j}^{kN_r} m_{j'i}^{(l)}, \tag{16}$$

where, $q_{ij}^{(l)}$ is the message transmitted from variable node i to check node j in the l^{th} iteration, and $m_{ji}^{(l)}$ is the message sent from check node j to variable node i in the l^{th} iteration. $\mathcal{N}(j)\backslash i$ is the set of all variable nodes connected to check node j except variable node i, and $\mathcal{M}(i)\backslash j$ is the set of all check nodes connected to variable node i except check node j. Note that $L(c_{jD})$ and $L(c_{iD})$ are log-likelihood ratios that can be estimated as follows:

$$L(c) = \ln\frac{p(c=0|y)}{p(c=1|y)} \tag{17}$$

The final LLRs at variable nodes after a fixed number of iterations M will be as follows:

$$L_{c_i} = L(c_{iD}) + \sum_{j \in \mathcal{M}(i)} m_{ji}^{(M)}. \tag{18}$$

Finally, in order to decode each source node's message these LLRs are fed to the maximum *a posteriori* (MAP) decoder.

C. Analysis of outage Probability

In order to calculate the outage probability for DF-NC, we first consider that each source node transmits n coded symbols in its allocated time slot. Thus, the mutual information between S_i and the destination is $n\log_2(1 + \gamma_{S_i D})$. If relay i has already decoded the source message, it includes this source message into the network coding process. Thus, relay j transmits n network coded symbols, and the destination will receive at most $n\log_2(1 + \gamma_{R_j D})$ information from relay j; where $\frac{n}{N_j}\log_2(1 + \gamma_{R_j D})$ information belongs to the source. Hence, the mutual information between S_i and the destination will be:

$$I_i = n\log_2(1 + \gamma_{S_i D}) + \sum_{j=1}^{N_r} \text{Ind}_{j,i}\frac{n}{N_j}\log_2(1 + \gamma_{R_j D}), \tag{19}$$

where $\text{Ind}_{j,i}$ is an indicator function that is defined as follows:

$$\mathrm{Ind}_{j,i} = \begin{cases} 1, & \text{if } R_j \text{ has decoded } S_i \\ 0, & \text{if } R_j \text{ has not decoded } S_i \end{cases}$$

The outage probability can then be calculated as follows:

$$P_{i,out} = p(I_i < k), \qquad (20)$$

where $k = n\log_2(1+\gamma_{Th})$ and by performing some simple mathematical calculations, we have

$$P_{i,out} = p\left((1+\gamma_{S_iD})\prod_{j=1}^{N_r}(1+\gamma_{R_jD})^{\frac{\mathrm{Ind}_{j,i}}{N_j}} < 1+\gamma_{Th}\right). \qquad (21)$$

As each relay node requires only one time slot to forward its messages, then the total number of time slots requires to transmit all source nodes' messages in DF-NC is $T_{DF-NC} = N_s + N_r$.

V. SIMULATION RESULTS

For simulation purposes, we have considered that each source node has $k = 60$ bits for transmission. Each source node uses a rate-(1/2) convolutional code with a generator polynomial $G = (7,5)_8$ as a mother code. Thus, each source node generates $n = 120$ coded symbols which are then BPSK-modulated to generate n modulated symbols. These symbols are sent to the relays and the destination.

Fig. 5, shows the outage probability versus the average SNR when the average SNR of all channels are the same. As can be clearly seen in this figure, when the number of source nodes is $N_s = 5$, the DF-NC scheme has the outage probability very close to the optimal one which belongs to DF scheme with maximal ratio combining (MRC). It is important to note that in terms of outage probability, the MRC scheme is optimum as it uses all the branches to maximize the received SNR and thus minimizing the error probability. The SC scheme performs worse than MRC as it only selects the best path amongst all available paths. The performance of the SwC scheme is very close to the SC scheme and the small gap between them is because the SwC scheme does not select the optimum path at all times; hence, its outage probability is slightly higher than the SC scheme. By increasing the number of source nodes and relay nodes, the performance of the DF-NC scheme is still close to the optimum one but with a huger gap. This is because increasing the number of source nodes decreases the effective amount of information that each relay transmits per source node; thus, outage probability is increased.

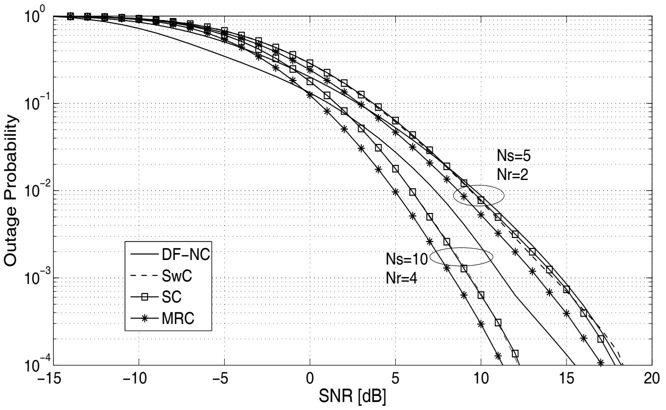

Fig. 5. Outage probability versus SNR when the average SNR of all channels are the same.

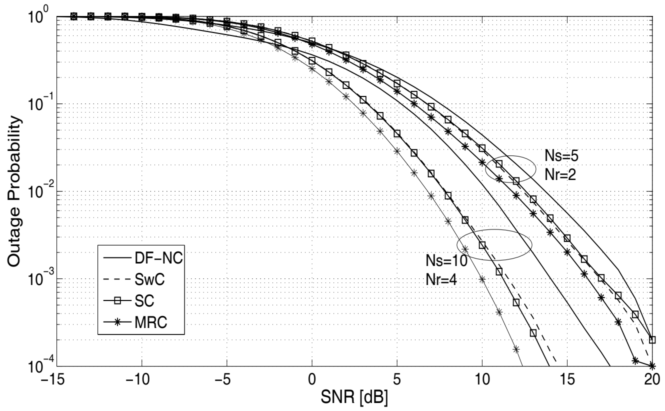

Fig. 6. Outage probability versus SNR when the average SNR of source-relay and relay-destination are 10 dB higher than source-destination channels.

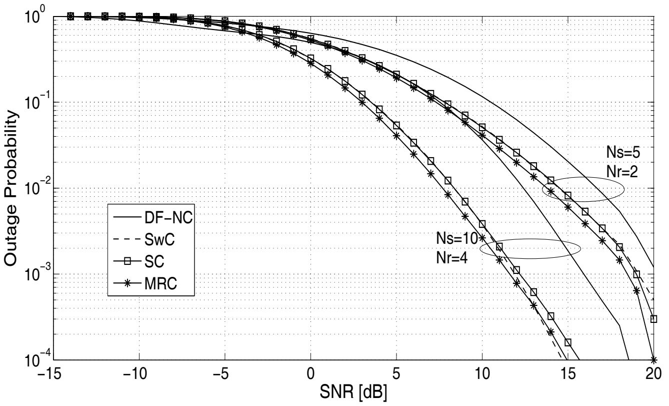

Fig. 7. Outage probability versus SNR when the average SNR of source-relay and relay-destination are 20 dB higher than source-destination channels.

Fig. 6 and Fig. 7 show the outage probability for different SNRs when the source-destination channel has respectively 10 dB and 20 dB lower average SNR than that of relay channels. As it is clearly shown in these figures, the DF-NC scheme has an outage probability close to the conventional cooperative schemes without network coding. However, by increasing the number of source nodes the performance of the DF-NC scheme will degrade. As can be seen in Fig. 6, the gap between DF-NC and the optimal curve is about 2 dB when $N_s = 5$ and the gap will be 10 dB when $N_s = 10$. The same thing happens in Fig. 5 and Fig. 7. In fact by increasing the number of source nodes, the outage probability of the DF-NC scheme degrades. However, compared to conventional cooperative schemes without network coding; its energy efficiency is increased as each relay node requires to transmit only once. Therefore, there is a tradeoff between outage probability and energy efficiency where a higher outage probability interprets as lower energy efficiency and vice versa.

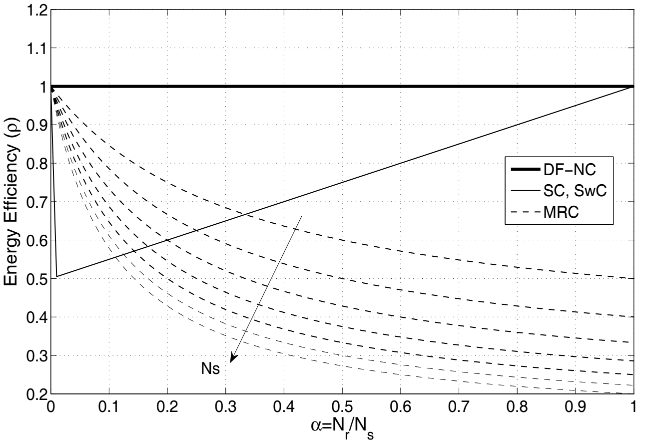

Fig. 8. Energy efficiency versus the number of relays for different cooperative schemes.

Table I shows the energy efficiency as a function of α, where α is the ratio of the number of relay nodes and the number of source nodes. Here we assume that nodes in the network use the same transmission power, thus the total transmission energy can be characterized by the number of transmissions. So we define the energy efficiency as the inverse of the average number of transmission per node. As can be seen in Fig. 8, the DF-NC scheme has the highest energy efficiency compared to other schemes and its efficiency is independent of α. Also the energy efficiency of the MRC scheme is very low due to the large number of transmissions of each relay, and by increasing the number of source nodes, the energy efficiency will degrade. It is important to note that as in SC and SwC schemes only two transmissions are performed for each source's message, then the energy efficiency in these schemes which increases when α increases. More specifically, when $\alpha = 1$, i.e., the number of source and relay nodes are equal, the energy efficiency of SC and SwC schemes will be the same as the DF-NC scheme. However, since the number of relay nodes is usually lower than the number of source nodes, then we can conclude that the proposed DF-NC scheme has the best energy efficiency compared to other schemes.

VI. CONCLUDING REMARKS

In summary, cooperative communications has shown to provide major advantages in energy-efficiency, reliability and delay compared to direct transmission for WBANs. In this paper we proposed a network coding approach for wireless body area networks with decode-and-forward relays to maximize the energy efficiency in WBANs while achieving a reasonable outage probability performance. In the proposed scheme, each relay combines multiple messages received from different sources and generates a network coded message and then transmits it to the destination. Compared to conventional cooperative strategies such as Maximum ratio combining, Selection combining, and Switched combining, each relay in the proposed DF-NC scheme requires only one time slot to transmit the network coded message. Simulation results have shown that the DF-NC scheme achieves a near optimal outage probability performance while maximizing the energy efficiency of WBANs by fixing the average number of transmission per node.

TABLE I
ENERGY EFFICIENCY FOR DIFFERENT COOPERATIVE SCHEMES AS A FUNCTION OF THE NUMBER OF SOURCE NODES, N_s, AND $\alpha = \frac{N_r}{N_s}$.

Scheme	MRC	SC	SwC	DF-NC
No. Transmissions	$N_s(N_r + 1)$	$2N_s$	$2N_s$	$N_s + N_r$
Energy Efficiency (ρ)	$\frac{N_s\alpha+1}{1+\alpha}$	$\frac{2}{1+\alpha}$	$\frac{2}{1+\alpha}$	1

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