When Both Transmitting and Receiving Energies Matter: An Application of Network Coding in Wireless Body Area Networks

Xiaomeng Shi*, Muriel Médard*, and Daniel E. Lucani†

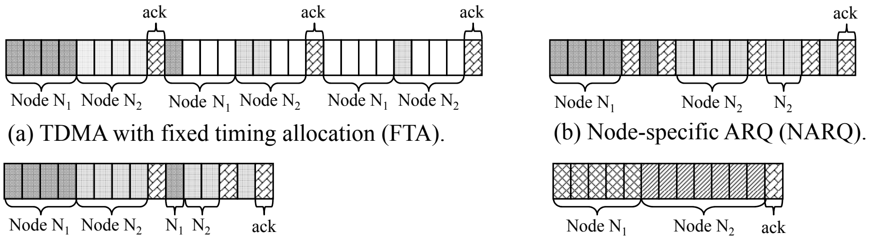
*Massachusetts Institute of Technology, Cambridge, MA 02139, USA
†Instituto de Telecomunicações, DEEC Faculdade de Engenharia, Universidade do Porto, Portugal
{xshi, medard}@mit.edu, dlucani@fe.up.pt

Abstract. A network coding scheme for practical implementations of wireless body area networks is presented, with the objective of providing reliability under low-energy constraints. We propose a simple network layer protocol for star networks, adapting redundancy based on both transmission and reception energies for data and control packets, as well as channel conditions. Our numerical results show that even for small networks, the amount of energy reduction achievable can range from 29% to 87%, as the receiving energy per control packet increases from equal to much larger than the transmitting energy per data packet. The achievable gains increase as a) more nodes are added to the network, and/or b) the channels seen by different sensor nodes become more asymmetric.

Keywords: wireless body area networks, network coding, medium access control, energy efficiency

1 Introduction

Body Area Networks (BAN) present numerous application opportunities in areas where measured personal information is to be stored and shared with another individual or a central database. One example is wearable medical monitors which can relay patients' vital information to physicians or paramedics in real time. A wireless body area network (WBAN) is composed of sensors attached to the human body. The sensors also function as transceivers to relay measurements to a personal server (base station); this central receiver then communicates with remote servers or databases. In this paper we consider such WBANs where the central communication problem is to ensure reliable and secure transmission of the measured data to the base station (BS) in a timely and robust fashion. Here the amount of data uploaded from the sensors to the BS much outweighs the amount of control signals downloaded from the BS, but energy used to receive control signals can still be high depending on the specific physical layer implementation and the network layer control protocol used. We develop a protocol to incorporate network coding into the system architecture, and show for a star network with multiple sensor nodes, using network coding can reduce the number of times sensors wake up to receive control signals, thus reducing the overall energy consumption and lengthen the system depletion time.



(a) TDMA with fixed timing allocation (FTA).
(b) Node-specific ARQ (NARQ).
(c) Combined ARQ (CARQ).
(d) CARQ and network coding (CARQ, NC).

Fig. 1. Example comparing overall completion energy for 2 nodes, each with 4 packets to upload; the erasure probabilities are $p_1 = 0.2$, $p_2 = 0.4$.

In the remaining part of the introduction, we show through a simple example the potential energy gains of applying network coding to transmissions in a WBAN. We also discuss briefly past works related to energy efficient WBAN design. The rest of this paper is organized as follows. Section 2 describes the network and energy model, and the network coded algorithm. Section 3 provides a Markov chain model to analyze the optimal number of packets to transmit by each sensor node. Numerical results are presented in Section 4, comparing the network coded scheme with uncoded scheme in terms of completion energy. Section 5 concludes the paper.

1.1 Example: Network Coding Benefits in WBAN

Before discussing other past work related to energy efficient WBAN design, we first show through a simple example why network coding can be beneficial. One category of energy use often overlooked in wireless networks is the reception energy spent on listening to control signals from the base station. In a WBAN, however, such reception energies can have more significant effects on node depletion time since data rate is much lower, but control signals need to be transmitted frequently for medium access purposes. Let us consider a two-sensor star network with nodes N_1 and N_2, each trying to directly upload 4 packets to a BS through the same frequency band. In the link layer, assume the packet erasure probabilities are time invariant, at 0.2 and 0.4 respectively. Figure 1 shows instances of four different possible communication schemes, all based on time division multiple access (TDMA) with automatic repeat requests (ARQ). Shaded blocks represent data packets in transmission and ack packets in reception; white blocks represent time during which nodes are idle. Some packets are lost during transmission according to the different erasure probabilities. Define a transmission round to be the transmission of data packets by one or more sensor nodes, followed by a broadcasted ack packet. Both nodes wake up at the end of a transmission round to listen to the ack, which contains retransmission requests and schedules for the next round.

(a) *Fixed Timing Allocation (FTA)*: each node is allocated 4 slots per round, and both wake up at the end of each round to receive the broadcasted ack.
(b) *Node-specific ARQ (NARQ)*: each node transmits until all of its packets are received successfully. The ack packet contains retransmission requests for the actively transmitting node and scheduling information for both nodes.
(c) *Combined ARQ (CARQ)*: both nodes are allocated specific transmission periods each round, with a combined ack packet broadcasted at the end.

Table 1. Comparison of completion energy per accepted data packet; there are 2 nodes in the star each with 4 packets to upload. E_{TX} = total transmission energy; E_A = energy spent on listening to acknowledgement packets; E_{tot} = total completion energy per accepted data packet, η = throughput.

	E_{TX}	E_A	E_{tot}	η
(a) FTA	$12E$	$6E$	$9E/4$	$8/27$
(b) NARQ	$12E$	$10E$	$11E/4$	$8/17$
(c) CARQ	$12E$	$6E$	$9E/4$	$8/15$
(d) CARQ-NC	$12E$	$2E$	$7E/4$	$8/13$

(d) *Combined ARQ and network coding (CARQ-NC)*: each node linearly combines its 4 data packets before transmission. Since each coded packet represents an additional degree of freedom (dof) rather than a distinct data packet, more than 4 coded packets can be sent to compensate for anticipated losses.

To evaluate energy use, assume every data packet transmission and every ack packet reception consumes an equal amount of E units of energy. Table 1 compares the total energy required for the schemes shown in Figure 1. Also shown is the throughput of each scheme, defined as the total number of accepted data packets divided by the total transmission time in units of packet slots. Excluding ack periods and time during which nodes are sleeping, all schemes require $12E$ in data transmission. On the other hand, the energy used for ack reception varies significantly across the different schemes. CARQ-NC (hereafter referred to as 'NC') is the most energy efficient. FTA requires less or the same amount of total energy than NARQ and CARQ, but is throughput inefficient. As the number of nodes in the network increases, this inefficiency will become increasingly severe. CARQ outperforms NARQ, and NC introduces further gains. It is not necessarily true that NC always transmits the same total number of data packets as CARQ. In fact, NC sends *more* packets than the required number of dofs. Nonetheless, the added transmission energy is offset by reduced reception energy to give a smaller overall completion energy. This specific example is extremely simple, but very similar results can be expected as more sensor nodes are added. In the remaining parts of this paper, we will consider only the CARQ and the NC scheme. Our goal is to determine analytically the optimal network coding and transmission scheme such that the expected completion energy for the overall transmission is minimized.

1.2 Related Work

To make WBANs practical, one approach is to modify existing wireless sensor networks (WSN) to suite the need of WBAN systems. References [1,2] compare WBAN with traditional WSNs and give comprehensive overviews of recent research efforts in the design of WBAN systems, particularly in terms of sensor devices, physical layer schemes and data link layer protocols. In WSNs, energy is often wasted in medium access collisions, idle listening, and protocol overheads when the desired data rate is low. Low power MAC protocols such as T-MAC, S-MAC and Wise-MAC have therefore been proposed to introduce various degrees of synchronization into the transmission schedule, but these schemes are not throughput efficient. Recently a WBAN specific MAC protocol has been proposed to adjust parameters of the IEEE 802.15.4 parameter in an

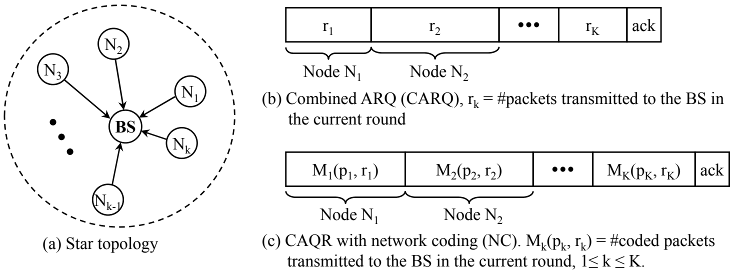


Fig. 2. Uplink transmissions using combined ARQ and network coding.

adaptive fashion to achieve energy efficiency [4], but direct modification of this existing standard also introduces redundant communication modes. Unlike WSNs, a WBAN contains only a limited number of nodes, all positioned close to the BS. A single-hop master-slave architecture with TDMA suffices to remove much of the energy wastage seen in a WSN. Reference [9] implements such an architecture, with adjustable wakeup fallback times to mitigate possible slot overlaps. We use a similar TDMA setup in the current paper. What we aim to achieve is to introduce network coding into the system architecture, such that overall data transmission completion energy can be reduced by reducing the number of times sensor nodes wake up to listen to control signals. Recent works by Lucani et al. consider the use of network coding in time division duplex systems to minimize packet completion time, energy use, and queue length in unicast and broadcast settings [5–7]. The current study extends the unicast TDD case to that of a simple star network, with single-hop links between the BS and the sensors.

2 Linear Network Coding for Energy Efficiency

2.1 System Model

We model a WBAN with a star topology as shown in Figure 2(a): each of K sensor nodes communicates with the BS directly to upload M data packets. Nodes and the BS are assumed to operate in half-duplex mode, either transmitting or receiving, but not at the same time. A WBAN occupies a single frequency band, with the BS centrally coordinating a TDMA scheme. Exact synchronization among the nodes and the BS is assumed, and nodes return to sleep when not transceiving. Computation of the transmission schedule is relegated to the BS, with start and stop times allocated through the ack signal. We assume ack packets are transmitted reliably, and propagation delays from BS to nodes are negligible. The channel between an individual sensor N_k, $1 \leq k \leq K$, and the BS are assumed to be memoryless, with packet erasure probability p_k, which is invariant during the time when the M packets are uploaded.

The above system model may seem over-simplified, but is sufficiently accurate for the current study. As already discussed in Section 1.2, the small physical size of a WBAN enables the use of a star topology with TDMA scheduling controlled centrally by a BS. Compared to sensor nodes, the BS is relatively unconstrained in power. Ack packets can therefore be piggybacked on a periodic synchronization signal transmitted at high power, or protected through error correction codes to ensure reliability. In an actual implementation, additional headers or beacon periods will be needed for synchronization, but such details can be safely omitted here in analyzing the data transmission energy efficiency and system throughput. An additional difficulty in WBAN design is channel modeling for physical layer designs. Unlike cellular networks or WSNs, a WBAN is in close proximity to the human body. Absorption of emitted power and body movement can easily and frequently alter the channel response. Reference [11] provides a summary of channel modeling studies conducted and submitted to the IEEE 802.15.6 body area network task group. In the current paper, we only consider an erasure channel abstraction for the network layer model. The time-invariance assumption is a reasonable first step, since data in WBAN come in very small bursts periodically and the channel can be assumed to fade slowly over each such small periods.

In the CARQ scheme, nodes take turns to transmit data packets before waiting for a combined ack, which contains repeat requests and scheduling information. Figure 2(b) illustrates one round of transmission, where r_k represents the number of packets requested by the BS for retransmission. In the NC scheme, each node linearly combines its M packets before taking turns to transmit the ensuing mixtures. The coefficients can be generated on the fly and attached to the data payload, or tabulated a priori. Assume the field size is large enough such that accepted coded packets are independent from each other with very high probability. Since coded packets represent degrees of freedom (dof) rather than distinct data packets, each node can transmit more than the required number of dof to compensate for packet losses. Figure 2(b) illustrates one round of transmission. M_k represents the number of coded packets for (re)transmission. M_k is a function of p_k, the erasure probability, and r_k, the remaining number of dof needed at the BS to decode successfully. Note $M_k \geq r_k$. Since all nodes within the network need to wakeup from sleep modes to listen to the ack, reducing the number of ack packets effectively reduces the total energy consumption. M_k should also be kept small to minimize redundant transmissions. We want to show that an optimal number, M_k, $1 \leq k \leq K$, of coded packets exists to minimize the mean completion energy.

2.2 Energy Consumption

We assume sensor nodes operate in two modes: transceive and sleep. Denote the processing and transmission energy per data packet by $E_{p,CARQ}$ and $E_{p,NC}$ for the uncoded and coded cases respectively; also denote the reception and processing energy per ack packet by $E_{a,CARQ}$ and $E_{a,NC}$. When in sleep mode, most circuit components are assumed to be turned off such that energy consumption is negligible. Let $E_{a,CARQ} = \alpha E_{p,CARQ}$, $E_{a,NC} = \alpha E_{p,NC}$, where the parameter α can take on different positive values depending on the circuit and protocol designs. For example, in narrow-band systems where transmission power is approximately the same as receiving power, α is the ratio between lengths of ack and data packets. For short range ultra-wide band systems where transmission energy per bit is much smaller than the reception energy per bit, α can take on large values in the range of tens to the hundreds [3, 8, 10]. Moreover, assume $E_{p,NC} = (1 + \beta)E_{p,CARQ}$, where the non-negative factor β represents the additional energy needed to perform network coding. In later sections, we will study the effect α and β have on overall completion energy.

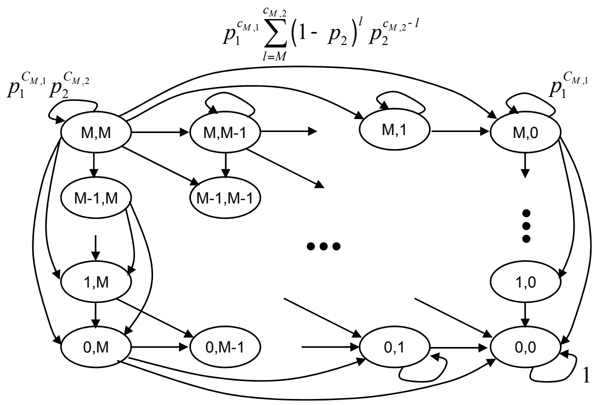


Fig. 3. Markov chain representation of the network coded scheme, number of nodes is $K = 2$.

3 Expected Energy for Completing Transmission

To study the expected completion energy of uploading data from sensor nodes to the BS in a WBAN, we model the communication process using a Markov chain. Let state $I = (i_1, \ldots, i_K)$ represent the dof requested by the BS from nodes $(N_1, \ldots, N_K)$ for the next round of transmission, where $0 \leq i_k \leq M$, $1 \leq k \leq K$. The overall communication process initializes in state $\mathbf{M} = (M, \ldots, M)$ and terminates in state $\mathbf{0} = (0, \ldots, 0)$. Assume packet losses occur independently across nodes, the transition probability from state $I = (i_1, \ldots, i_K)$ to state $J = (j_1, \ldots, j_K)$ is $P_{IJ} = P_{(i_1,\ldots,i_K)(j_1,\ldots,j_K)} = \prod_{l=1}^{K} P_{(i_k,j_k)}$, where $P_{(i_k,j_k)} = P_{i_k j_k}$ and

$$P_{ij} = \begin{cases} \binom{c_{i,k}}{i-j} (1-p_k)^{i-j} p_k^{c_{i,k}-i+j} & 0 < j \leq i \\ \sum_{l=i}^{c_{i,k}} \binom{c_{i,k}}{l} (1-p_k)^{l} p_k^{c_{i,k}-l} & j = 0 \end{cases} . \tag{1}$$

$c_{i,k} = M_k(p_k, i)$ denotes the number of coded packets node N_k transmits when it sees a packet erasure probability of p_k and the BS requires i additional dof for decoding; $c_{0,k} = 0$. The value of $c_{i,k}$ is computed by the BS. This Markov chain has $(M+1)^K - 1$ transient states and one recurrent state, $\mathbf{0}$, which signals completion of the transmission. Figure 3 illustrates the case where there are $K = 2$ sensor nodes within the WBAN.

Let E_I denote the expected system completion energy when nodes $(N_1, \ldots, N_K)$ have $(i_1, \ldots, i_K)$ dof to upload to the BS respectively, then E_I is the expected absorption time of this Markov chain. Let $\mathcal{Q} = \{0, \ldots, i_1\} \times \ldots \times \{0, \ldots, i_K\}$. The following recursion holds $E_I = \frac{1}{1-\prod_{k=1}^{K} p_k^{c_{i_k,k}}} \left\{ E_p \sum_{k=1}^{K} c_{i_k,k} + E_a K + \sum_{J \in \mathcal{Q} \setminus I} P_{IJ} E_J \right\}$. Unlike the erasure probabilities P_{IJ}, this expected completion energy can not be separated into node-specific energy terms. To minimize the expected completion energy $E_{\mathbf{M}}$, let $C = \{c_{i,k} | 1 \leq i \leq M, 1 \leq k \leq K\}$, $c_{0,k} = 0, 1 \leq k \leq K$, we then have $C^* = \underset{C}{\operatorname{argmin}}\, E_{\mathbf{M}}$, $E^*_{\mathbf{M}} = \min_C E_{\mathbf{M}}$, and the following recursion, where

$\mathbb{Z}_{M+1} = \{0, \ldots, M\}$.

$$E^*_{\mathbf{M}} = \min_{c_{M,1} \ldots, c_{M,K}} \frac{1}{1 - \prod_{k=1}^{K} p_k^{c_{M,k}}} \left\{ E_p \sum_{k=1}^{K} c_{M,k} + E_a K + \sum_{J \in (\mathbb{Z}_{M+1})^K \setminus \mathbf{M}} P_{\mathbf{M}J} E^*_J \right\} . \tag{2}$$

One approach to this optimization is to ignore the integer constraints, and solve for $c_{i,k}$ iteratively by finding values that set the partial derivatives of the objective function to zero. However, it can be shown that no closed-form solution exists. Also since there are $(M+1)^K$ states in the Markov chain. As M and K increase, the computational complexity becomes prohibitive for a practical system. An alternative is to perform exhaustive numerical searches for the optimal values C^* on an integer grid. For given values of $\{p_k | 1 \leq k \leq K\}$, E_p, and E_a, we can recursively search on an M dimensional space of non-negative integers to find C^*. We will show numerical examples in the next section for such an optimal scheme. In a practical implementation, the computation task is imposed on the BS, not individual sensor nodes. Neither do the results need to be computed in real time. Instead, pre-computed values can be stored in a look-up table according to different packet erasure probabilities. The exact quantization required to balance the accuracy and required memory is a topic for future studies.

4 Numerical Examples

In this section, we provide numerical examples for the CARQ and NC schemes to study the amount of energy reduction offered by network coding as system parameters vary.

Table 2 lists explicitly the solution to the optimization problem stated in Section 3 when there are $K = 2$ nodes within the network, each having $M = 4$ data packets to upload, $p_1 = 0.2, p_2 = 0.4$. Assume $\alpha = 1$ and $\beta = 0$. The first column(row) states the remaining number of dof required by the BS from node $N_1(N_2)$. Transmission initiates at $(i_1, i_2) = (4, 4)$, and terminates at $(0, 0)$. Since N_2 sees a more challenging channel, it sends more coded packets than N_1, when the same number of dof is requested. Observe that the number of coded packets sent by N_2 actually increases from 6 to 7 when $i_2 = 4$, and i_1 is decremented from 4 to 0. This is because N_1 is expected to complete its data transmission in a small number of rounds, thus N_2 would want to send more data packets such that it also completes its data transmission in a small number of rounds, to reduce the total number of times both wake up to listen to ack signals. The optimal solution minimizes the sum of all energy terms, taking into account of future rounds of retransmissions, and tries to reduce possible energy wastes. The optimal expected total completion energy is found to be $16.46E$, larger than $14E$ shown in Table 1, which illustrates only one possible channel realization.

Figure 4 extends the example in Table 2 to summarize the percentage reduction in expected completion energy per accepted data packet achieved by the NC scheme when packet erasure probabilities vary. A packet is said to be accepted by the BS if it is received successfully, and the percentage reduction is computed with respect to the CARQ scheme. Again, we assume $\alpha = 1$, i.e., $E_{p,NC} = E_{a,NC}$, $E_{p,CARQ} = E_{a,CARQ}$, and $\beta = 0$, i.e., $E_{p,NC} = E_{p,CARQ}$. The horizontal axis represents variations in the packet

Table 2. Optimal numbers of coded packets to transmit by each node when dof requested by the base station is i_1 from node N_1 and i_2 from node N_2; $M = 4$, $K = 2$, $p_1 = 0.2$, $p_2 = 0.4$, $\alpha = 1$, $\beta = 0$.

$i_1 \backslash i_2$	4	3	2	1	0
4	$(5, 6)$	$(5, 5)$	$(5, 3)$	$(5, 2)$	$(5, 0)$
3	$(3, 6)$	$(4, 5)$	$(4, 3)$	$(4, 2)$	$(4, 0)$
2	$(2, 6)$	$(2, 5)$	$(2, 3)$	$(2, 1)$	$(3, 0)$
1	$(1, 6)$	$(1, 5)$	$(1, 3)$	$(1, 2)$	$(1, 0)$
0	$(0, 7)$	$(0, 5)$	$(0, 3)$	$(0, 2)$	$(0, 0)$

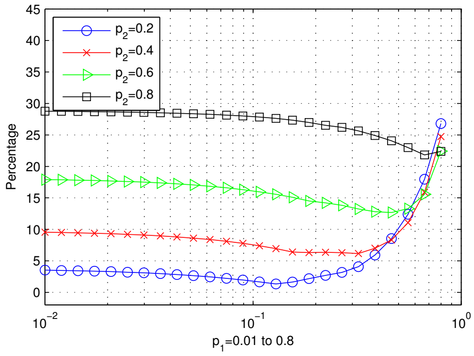


Fig. 4. Percentage reduction in expected completion energy per accepted data packet as p_2 varies; $M = 4$, $K = 2$, $\alpha = 1$, $\beta = 0$.

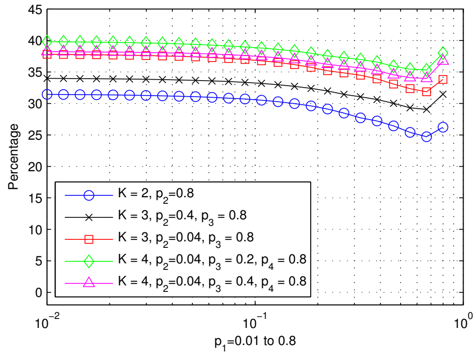


Fig. 5. Percentage reduction in expected completion energy as K is varied, $M = 2$, $\alpha = 1$, $\beta = 0$.

erasure probability of node N_1. When the erasure probability of N_2 increases from 0.2 to 0.8, the amount of reduction in expected completion energy per accepted data packet increases from 3.5% to about 29%. Although not shown explicitly in this graph, the energy gain is derived from reduced number of transmission rounds. As p_2 degrades, the actual amount of energy spent for each accepted data packet increases, because more retransmissions are expected. Since depletion occurs more quickly when the channel condition worsens, the increased amount of saving is beneficial in extending the lifetime of sensor nodes. Another observation from Figure 4 is that the curves take a dip at different values of p_1. The locations of these minima correspond approximately to the values of p_2 in each case. This is because the NC scheme achieves higher energy reduction when nodes experience more asymmetric channel conditions. When packet losses occur asymmetrically, nodes with more reliable channels complete data transmission quickly; yet they are forced to wake up for the ack signal repeatedly until other nodes with less reliable channels complete their transmissions. When nodes see similar channel conditions, with high probability, all nodes have non-zero number of packets to send each round, hence not as much energy is wasted in listening to the ack signals.

Figure 5 considers the more general case when the number of sensors within the network is increased, and M is set to 2 for simplicity. More gains can be achieved when more nodes are included, especially under asymmetric channel conditions. Although not shown explicitly here, we also compared numerical results under different network coding parameters. When the generation size M is varied, the amount of energy gain

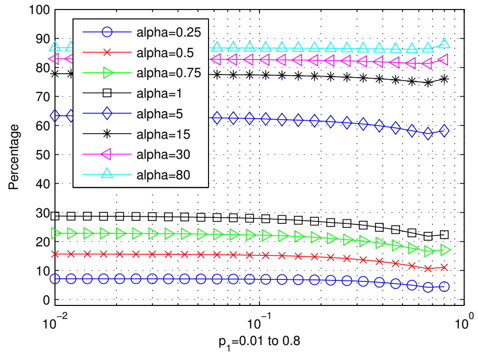


Fig. 6. Percentage reduction in expected completion energy when α is varied, $M = 4$, $K = 2$, $\beta = 0$, $p_2 = 0.8$.

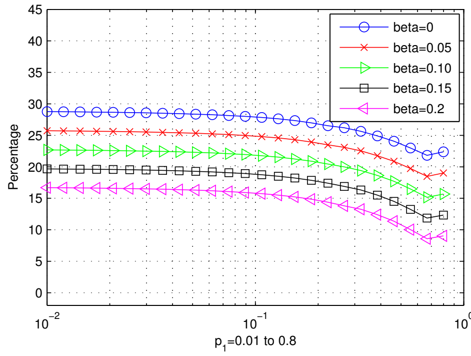


Fig. 7. Percentage reduction in expected completion energy when β is varied, $M = 4$, $K = 2$, $\alpha = 1$, $p_2 = 0.8$.

over CARQ is higher if M is smaller, with a decrease of approximately 10% as M increases from 2 to 10. This is because reception energy is amortized over more data packets. The NC scheme can also be shown to improve the throughput of the system.

So far we have examined reduction in completion energy achievable through NC when the reception energy E_a per ack packet is the same as the transmission energy E_p per data packet, i.e., $\alpha = 1$. The actual value of α is dependent on the circuit architectures of the transmitter and receiver, and the data and ack packet payload design. For example, α can be on the order of 1 for a narrow band system, but can be one or two orders of magnitude larger for an ultra-wide band system [3, 8, 10]. Figure 6 shows the reduction in completion energy in using NC over CARQ when α is varied, where $E_a = \alpha E_p$, $E_p = E_{p,NC} = E_{p,CARQ}$ and $E_a = E_{a,NC} = E_{a,CARQ}$. Again, the computation is conducted over a 2-node network for simplicity. The observed gain is not as significant as 29% when α decreases from 1, for data transmission energy much outweighs ack reception energy. However, as α increases to values higher than 15, we can achieve up to 87% in energy reduction, i.e., 5 times less energy. This is equivalent to extending the lifetime of a sensor node by a factor of 5.

Another assumption we have made explicitly in previous examples is that the average transmission energy E_p is the same for both NC and CARQ. In an actual implementation, the NC scheme may require non-negligible energy overheads for coding. Figure 7 compares the completion energy of the two schemes when $E_{p,NC} = (1+\beta)E_{p,CARQ} = (1+\beta)\alpha E_{a,CARQ}$, $\alpha = 1$, and $E_{a,NC} = E_{a,CARQ}$. Here the energy advantage is lessened because of the added cost of coding. Nonetheless, even with a 20% overhead in coding, we can still achieve an energy reduction of about 17%.

5 Conclusion

We proposed a network coded scheme to help improve energy efficiency of wireless body area networks. Assuming that the different channel conditions experienced by individual nodes are known at the base station, the base station can request each sensor node to send an optimal number of coded packets, taking into account anticipated packet losses during transmission, and energy needed for receiving control signals. We show with numerical examples that in a two-node star, when transmitting a data packet and receiving an ack packet cost approximately the same amount of energy, the network coded scheme can achieve up to 29% percent reduction in expected completion energy per accepted data packet compared to the CARQ scheme. When receiving costs a lot more than transmitting, network coding can reduce energy use by up to 87%. We also shown with numerical examples that the amount of energy gain achievable through coding increases as more nodes are added to the network, and when nodes see more asymmetric channel conditions.

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