Cross-Layer Energy Efficiency of FEC Coding in UWB Sensor Networks

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Abstract - **In this paper, energy efficiency of forward error correction (FEC) coding in ultra wideband (UWB) wireless sensor networks (WSNs) is studied taking into account the characteristics of the physical (PHY) and medium access control (MAC) layers. The underlying goal has been to develop a cross-layer framework that allows the design of energy efficient FEC coding in UWB WSNs. This study is carried out using analytical derivations and simulations. A cross-layer approach, such as the one described here, provides a deeper understanding of the various factors that affect the energy consumption in WSNs, and how FEC coding can improve it. Results clearly show that coding improves the energy efficiency in UWB transceivers. By using the framework introduced here, UWB network designers can analyze the network energy efficiency already in the design phase.**

I. INTRODUCTION

In wireless sensor networks a traditional network layer design is not efficient [1,2]. Usually there is an underlying feature, e.g., energy consumption, which spans across several layers. If the goal is to optimize a certain value directly related to this feature, separate designs for each layer leads to suboptimal performance. It is reasonable to expect that in order to have near optimum performance, the different layers should be able to coordinate their behavior beyond what is traditionally allowed in a layered network [1,3]. As an example of such coordination, let us consider the case of Rayleigh fading channels, where the received signal can go to deep fades. The PHY layer can try to use a stronger code (lower data rate) and inform the upper layer about this event. The upper layer can, in response, adjust its transmitting schedules (and associated timers) according to the new data rate. In the case of sensor networks, this adjustment translates into a change of awake/sleep periods which have a direct impact on each node's energy consumption. The first goal of this study is to develop a cross-layer framework that can be used to analyze cross-layer interactions in ultra wideband sensor networks.

UWB technology has several features that are well suited for sensor network applications. In particular, UWB based systems have potentially low complexity and low cost; have noise-like signals; are resistant to severe multipath and jamming; and have very good time domain resolution, allowing for location and tracking applications [4]. The radio technique used in this paper is a direct sequence (DS) UWB which has been a candidate for 802.15.4a [5] type low date rate networks. DS-UWB has a good performance in multipath channel and also in the presence of interference [4]. DS-UWB meets all the WSN requirements, and it can also be used in military applications. Its signal bandwidth, which can be even giga-Hertz wide, allows precise positioning, and the use of short pulses leads inherently to fine time resolution. In addition, DS technique makes user separation and simultaneous transmissions possible. In high data rate applications, DS-UWB is a PHY-layer option that can be used instead of competing multiband approach. The second goal of this paper is to develop a network model suitable for UWB WSNs.

Coding has an important role when the energy efficiency is being optimized. Sensor networks usually have very limited power resources and therefore error control coding is the preferred way to improve the link reliability. However, coding must be done properly to get the expected energy gains. In this paper, Bose-Chaudhuri-Hocquenhem (BCH) and Reed-Solomon (RS) codes are studied. These codes are very popular in wireless communication applications [6,7] because their complexity is low. Simpler versions of these codes can be implemented and decoded in real-time by software, and therefore they are good candidates for sensor networks. This leads to the third goal of the paper, which is to analyze the energy efficiency of the proposed codes.

In summary, the contributions of this paper are to introduce a unique framework for cross-layer design of PHY and MAC layers, and to show new results about the energy efficiency of coding in UWB low data rate networks.

II. CROSS LAYER INTERACTIONS

There are several factors in the PHY and MAC layers that can be used to optimize the energy consumption. These factors affect each other, and the challenge in this study is to find a compromise which maximizes the overall energy efficiency.

In a noisy channel, increasing coding will normally require more energy for the transmission of each message, but the number of retransmissions at MAC layer level will decrease. The smaller is the needed number of retransmissions, the sooner a node can go to sleep mode. At each node, the energy consumption in a sleep mode is much lower than in a transmit mode (Tx), a receive mode (Rx), or in an idle mode, i.e., the longer the sleep period is, the more energy is saved [2,8]. If the amount of coding decreases, less energy is used for message transmission. On the contrary, in a noisy channel with less coding, the number of retransmissions will increase, which requires longer awake periods, and therefore more energy consumption. In this scenario, coding in the PHY layer directly affects the MAC layer energy performance. The awake/sleep periods can be set more efficiently if the design is made jointly between these two layers. The level of coding must be set so that the messages can successfully, and as energy efficiently as possible, be transmitted and received during the waking periods. The goal is to have the awake periods as short as possible so that the sleep periods can be relatively long.

The MAC layer can affect the level of coding which is needed at the PHY layer. The MAC layer controls the number of users contending for the channel, and is directly related to multi-user interference. If a complex channel assignment mechanism is used, multi-user interference can be very low, and there is no need for coding beyond what is needed to mitigate other sources of noise in the channel. However, in most WSN applications the use of a complex channel assignment mechanism is not practical or feasible, and therefore multi-user interference can be significant. Extra coding at the PHY layer will be needed to deal with this kind of interference.

The scheduling of awake/sleep periods has an effect on the level of multi-user interference at the PHY layer. At any given time, different groups of nodes are scheduled for Tx, others for Rx, and others for sleep. This type of scheduling requires some degree of synchronization among the all participating nodes. If the schedule is not properly designed, multi-user interference will increase.

An analysis that takes into account all the mutual interactions between the different layers is deemed to be extremely complex. This complexity is exacerbated due to the difference in order of magnitude of the time constants at which each layer operates [9]. For the study presented in this paper, the goal is to minimize the energy consumption at each transceiver node. A cross-layer approach for the simultaneous design of the PHY and MAC layers is used. The transmission power of each node is assumed to be fixed because code control is preferable than power control in low data rate UWB networks [1,2]. An appropriate routing protocol for WSNs is also assumed and the channel assignment is assumed to been carried out during the network initialization phase.

By assuming these network characteristics, analytical derivations, as well as simulations, have been carried out. The results can be used to explore how coding can improve the energy efficiency in UWB sensor networks. The network model is kept quite general so that it can be used in a variety of scenarios. In this paper, a network model is especially introduced for DS-UWB networks. In [10], the authors propose corresponding model to be adopted for narrowband networks.

III. Network Model

For this study, the developed model for DS-UWB sensor network aims to facilitate the energy consumption analysis. The network is divided into concentric rings or sensing zones, as shown in Fig. 1. Within each ring, groups of M transmitters send data to a node in a downstream zone (inner ring), all the nodes are also sharing the same channel. DS-UWB is used as a physical layer technique between the communicating nodes due to the inherent noise like feature that this technology offers. Different dedicated spreading sequences are used to separate transmissions of different groups. Each node knows which spreading code to use, i.e., a perfect code assignment through the network is assumed. The following analysis does not take into account any specific channel model but instead of that, it assumes a fixed bit error rate at the receiver.

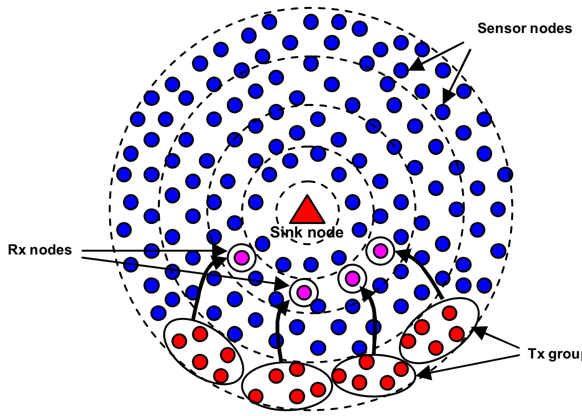

Fig. 1. UWB network divided into rings. The data flow from Tx groups towards the sink node.

In the model, the fact that there are multiple (M) Tx nodes for each Rx node takes into account that the farther from the sink node an outer ring is, the larger is its physical area. Therefore it has also more nodes (assuming a uniform spatial distribution for the sensor nodes). Because multiple transmissions are allowed, nodes from the different upstream Tx groups can transmit simultaneously using different spreading codes. However, within the same group, the nodes have to compete for the channel. Otherwise, the code assignment for the whole network would be too complex.

In the model used, within each group, the nodes utilize slotted time periods and random access protocol with acknowledgement (ACK) packets. There are no ready-to-send (RTS) or clear-to-send (CTS) messages to minimize the transmissions, and enable sleep periods to be as long as possible. This protocol is illustrated in Fig. 2, where SIFS and DIFS stand for short inter-frame space and distributed coordination function (DCF) inter-frame space, respectively.

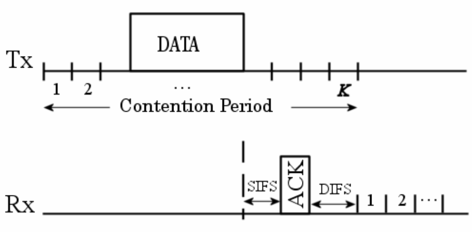

Fig. 2. DATA-ACK sequence.

The main features of this protocol are:

- The Tx nodes compete for the access to the channel by randomly choosing a mini-slot out of a maximum of K mini-slots,
- If the channel becomes busy before the start of its chosen mini-slot, the Tx node keeps sensing the channel to process the progress of the transaction between another Tx node, who gained access to the channel, and the Rx node,
- If the ongoing transaction between Tx and Rx nodes is successful, DATA and ACK packets are exchanged between them,
- Right after the transmission of the ACK packet, the remaining Tx nodes (with packets to transmit) contend for the channel on a new contention interval.

IV. Markov Chain Model

The states of the nodes in a Tx group can be modeled using Markov Chains (MC). Assume the network from Fig. 1, where a single Tx group has M competing nodes. The state of the Tx group, just before the start of a contention period, can be presented as a multidimensional vector as

$$S(t_i) = [n_0(t_i) \; \dots \; n_j(t_i) \; \dots \; n_{Q_{\max}}(t_i)], \quad (1)$$

where each component $n_j(t_j)$ is the number of sensor nodes with j packets in their transmitting queue at time t_i. Q_{max} is the maximum number of packets that the buffer queue of a sensor node's transmitter can hold. The total number of sensor nodes at time t_i is then

$$M(t_i) = \sum_{j=0}^{Q_{\max}} n_j(t_i). \quad (2)$$

During a contention period, the number of contending nodes is

$$M_c(t_i) = M(t_i) - n_0(t_i). \quad (3)$$

When a state is defined as (1), it is apparent that the Markov property holds since the probabilistic nature of the next state depends only on the current state. After a successful transmission during the interval $\Delta(t_i)$, one of the nonzero components of $S(t_i)$ can decrease by one, i.e., the one corresponding to the successful node. In UWB case, a duty (or burst) cycle is low, and Tx period is very short. Therefore, it can be assumed that any event that is sensed during a Tx period could be transmitted in the next Tx period. Therefore, the transmit queue cannot be increased during the Tx period.

A value of interest is the expected time to empty all the transmitters' queues. That value can be used to determine a value for the duration of the awake Tx period. The worst-case scenario is when every node has a full queue at the beginning of a Tx period. In the study, the following assumptions are made to reduce the size of the MC model:

- The Tx nodes transmit all their packets when they gain access to the channel,
- The size of the DATA packets is the same regardless of the queue size, i.e., the queue is emptied once the node gains access to the channel, and all its contents are combined or fused together into one DATA packet having a fixed size.

For this case, the vector $S(t_i)$ has two elements

$$S(t_i) = [n_0(t_i) \;\; n_1(t_i)], \quad (4)$$

where $n_0(t_i)$ denotes the number of nodes with zero packets in their Tx queues and $n_1(t_i)$ gives the number of nodes with one or more packets in their Tx queues. [0 M] can be assumed as the initial state, i.e., all the nodes have a nonempty queue. [M 0] is an absorbing state, i.e., all the nodes have emptied their transmitting queues. Because of the constraint $n_0(t_0) + n_1(t_0) = M$, all the states of this Markov chain model lie on a line in a 2-D space as illustrated in Fig. 3.

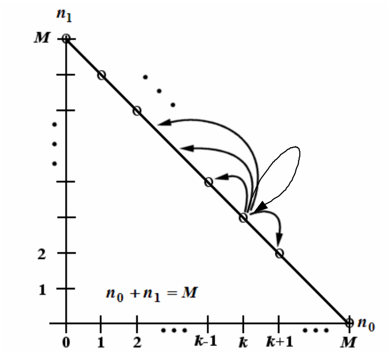

Fig. 3. 2-D representation of the Markov chain model.

For this reduced model, a state s can then be defined as a value of n_0, i.e., $s = i$, for $i = 0, 1, 2, \dots, M$; the absorbing state being $s = M$. Using this model, the expected time to empty all the Tx queues is the same as the time to absorption, i.e., the expected time to reach the absorbing state. In [10], the authors have derived the model which can be used to calculate the time to absorption analytically. Similar analysis can be made for UWB case, as is considered here. However, in this study, MATLAB simulations instead of analytical derivations are used to make the results more general. In [10], it is also shown that the simulation results follow very closely the corresponding analytical results.

V. Energy Consumption Model

This section introduces the energy consumption model which can be used to analyze the cross-layer energy efficiency. This model uses results from the time to absorption simulations explained in the previous section.

When a node transmits, the success probability of DATA and ACK packets depends on the conditions of the channel. If the bit error probability of the channel is p_{be}, the bit success probability can be calculated as p_{bs} = 1- p_{be}. The success probability p_{succ}^{unc} for the DATA and ACK packets (uncoded case) with total length N, can be calculated as

$$p_{succ}^{unc} = (p_{bs})^N . \quad (5)$$

The bit error probability of the transmission can be reduced by using coding. The code word error probability for block codes of the form (n,k,t) can be calculated as [11]

$$P_e(\varepsilon) \approx \sum_{h=t+1}^{n} \binom{n}{h} \varepsilon^h (1-\varepsilon)^{n-h} , \quad (6)$$

where ε is bit error probability, p_{be} is binary BCH code case. In the non-binary RS code case, ε is a symbol error probability P_s. n and k are the length of the code word and the number of input information bits, respectively. t is the number of errors that the code can correct. The symbol error probability can be calculated as

$$P_s = 1-(1-p_{be})^s , \quad (7)$$

where s is the symbol length in bits for the RS code. The packet error probability at the receiver can be calculated as

$$P_e = 1-(1-P_e(\varepsilon))^L , \quad (8)$$

where L is the number of code words in a packet. The success probability of the packet is then calculated as

$$P_{succ} = (1-P_e) . \quad (9)$$

The success probability of the communication between the source and destination (DATA packet and ACK message) can then be calculated as

$$p_{succ}^{comm} = P_{succ}^{DATA} P_{succ}^{ACK} . \quad (10)$$

The probabilities (5)-(10) can be used in the simulations to determine if the transmission is successful or not.

Next, let's assume the network model introduced earlier. When one ring in Fig. 1 starts a Tx period, all its Tx groups will attempt to send their data to the Rx nodes within the period by using DS-UWB signals. Within one Tx group, all the nodes have to compete for the channel access. They use slotted time periods and random access with ACK packets. As discussed earlier, with the proposed MC model, the expected time to absorption can be calculated using analysis [10] and simulation. Simulations can be done by using different channel BER values, different numbers of nodes and different codes. From the simulations, the time to absorption can be determined, and also the number of successful and unsuccessful transmissions. These parameters can then be used in energy consumption calculations.

The energy consumption of the transceivers in the Tx groups and receivers at the Rx end for one Tx period can be calculated as

$$\begin{aligned} E_{groups}^{TX\&RX} &= (P_{TX} t_{TX}) u \\ &+ \sum_{i=1}^{N} \left[P_{el-TX} t_{i-TX} + P_{Sleep} t_{i-TX-Sleep} \right] \\ &+ (P_{RX} t_{RX}) u + P_{el-RX} t_{i-RX} + P_{Sleep} t_{i-RX-Sleep} , \end{aligned} \quad (11)$$

which equals to

$$\begin{aligned} E_{groups}^{TX\&RX} &= (P_{TX} t_{TX} + P_{RX} t_{RX}) u \\ &+ \sum_{i=1}^{N} \left[P_{el-TX} t_{i-TX} + P_{Sleep} t_{i-TX-Sleep} \right], \\ &+ P_{el-RX} t_{i-RX} + P_{Sleep} t_{i-RX-Sleep} , \end{aligned} \quad (12)$$

where P_{TX} and P_{RX} are transmit and receive power consumptions, respectively. t_{TX} is the transmission time of a single packet, t_{RX} is the receive time of a single packet, u is the total number of successful and unsuccessful transmissions (obtained from the simulation), P_{el-TX} is the power consumption in the transmitter electronics, P_{el-RX} is the power consumption in the receiver electronics, t_{i-TX} is the time that the ith node stays in the transmit mode (obtained from the simulation), t_{i-RX} is the time that the ith node stays in the receive mode (obtained from the simulation), P_{Sleep} is the transmitter power consumption in the sleep mode, $t_{i-TX-Sleep}$ is the time that the ith node (within one Tx group) stays in the sleep mode, $t_{i-RX-Sleep}$ is the time that the ith node (within one Rx group) stays in the sleep mode, and $N = G{\cdot}M$ is the total number of Tx nodes (where G is the number of Tx groups in one ring, and M is the number of nodes in one Tx group). The sleep time for the ith node can be calculated as

$$t_{i-TX-Sleep} = t_{TX-period} - t_{i-TX} , \quad (13)$$

where $t_{TX-period}$ has been set to be as long as the time to absorption from the worst case in the simulations. The MAC layer sets the Tx/Rx period lengths so that every node has enough time to clear its transmission queue.

By calculating the energy consumption ($E_{groups}^{TX\&RX}$) as derived above in (12), the energy efficiency of different types of coding can be compared.

VI. RESULTS

The proposed cross-layer framework can be used to calculate the results using various parameters and network settings. The results shown here are for one generic setting to illustrate the usefulness of this model.

Simulations have been done for five upstream nodes (*M*) in a Tx group and one downstream node at the Rx end. The number of upstream groups (*G*) in one ring is 10. The total number of Tx nodes is therefore 50. The number of Rx nodes is 10 because there is only one Rx node for one Tx group. The number of information bits in a packet is 5000. The coding overhead is taken into account so that it increases the packet length. Table 1 shows the parameters for the FEC codes which were used in the simulations to code the DATA packets. The symbol length $s = 6$ is used for RS codes. The ACK packets are 128 bits long, and they consists of two BCH (63,51,2) code words. The data rate is assumed to be 200 kbps which is appropriate for low data rate WSNs [5]. The number of possible contention slots in a channel competition period is assumed to be 20. The UWB radio's power consumption parameters are normalized and therefore the results can be generalized to various systems. Transmit power P_{TX} = 1 unit, receive power P_{RX} = 5 units, sleeping power P_{Sleep} = 0.01 units, and power consumption in the electronics $P_{el\text{-}TX} = P_{el\text{-}RX} = 0.5$ units are used. Simulations could be done with many different power consumption value pairs, and their results naturally depend on them. To save space, only selected figures have been chosen to illustrate our results.

TABLE 1.
CODE PARAMETERS USED IN THE STUDY.

Code	*n*	*k*	*t*	*r*
BCH	511	457	6	0.89
BCH	511	403	12	0.79
RS	63	53	5	0.84
RS	63	47	8	0.75

Fig. 4 shows the normalized energy consumption values for the described system using the parameters assumed. The figure shows that when the codes from Table 1 are used for a channel with BER values between 10^{-5} – 10^{-3}, their performance is constant. However, Fig. 4 clearly indicates that coding is useful (when the shown codes are used) after the channel BER is higher than $3 \cdot 10^{-5}$. In low BER values, some other codes could be more energy efficient than the uncoded transmission. This has also been studied and, as an example, RS(63,61,1) code consumes less energy than the uncoded transmission with BER values higher than $2 \cdot 10^{-5}$. Energy consumption for the uncoded case starts to increase very fast as BER increases. For the coded case in Fig. 4, the cross-layer design approach is not critical for choosing the proper level of coding since the performance stays constant for those channel conditions, and for all the codes used.

Simulations with different power consumption values have shown that the results are slightly different than the ones shown in Fig. 4. As an example, if the transmit power consumption value is higher than in the previous case, total energy consumption of uncoded transmission increases because retransmissions costs more energy. Another simulated example shows that, if all the power consumption values are the same, the uncoded transmission consumes more energy than the coded transmission in the whole range of BER values shown in Fig. 4.

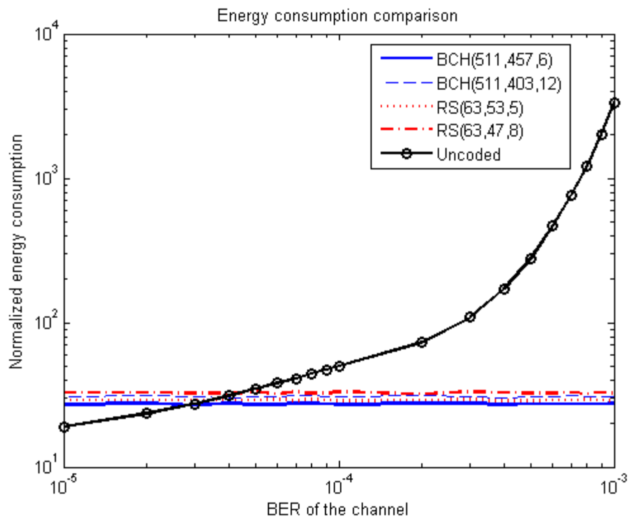

Fig. 4. Energy consumption; uncoded and coded cases.

Fig. 5 shows the relative energy consumption for the studied codes when the channel BER is between 10^{-3} – 10^{-2}. From the figure, it can be observed that the performances of the codes are not constant anymore if BER values are higher than the ones employed in Fig. 4. That is due to the longer time to absorption which increases if the number of retransmissions increases, i.e., the awake periods for both Tx and Rx become longer. Performances of the weaker BCH(511,457,6) and RS(63,53,5) codes start to decrease when the channel BER is higher than $4 \cdot 10^{-3}$. Performance of the stronger BCH(511,403,12) and RS(63,47,8) codes stays constant until the channel BER is higher than $9 \cdot 10^{-3}$. Fig. 5 also shows that stronger codes consume more energy when the BER is below $5 \cdot 10^{-3}$, but for larger values, their reliability is useful and they consume less energy than the weaker codes.

Simulations for the Fig. 5 case have been done also with other power consumption value pairs. Naturally results are slightly different but do not change drastically. However, as an example, if the transmit power consumption is higher than in the Fig. 5 case, the energy consumption of weaker codes increases faster because the retransmissions costs more energy.

From the results shown, one can observe that RS codes are good choices for UWB WSNs. In addition, they are good for burst error correction which makes them better than BCH codes to be used in WSN. The results highlight the importance of using the right code, which depends on the channel conditions. The results in Fig. 5 illustrate the importance of cross-layer information exchange. One can imagine a situation where channel conditions get worse, and the PHY layer does not have a chance to switch to a stronger code. Then the PHY layer should inform the MAC layer about the current situation. The MAC layer could then increase the Tx period length due to the longer time to absorption. Alternatively the MAC layer could try to improve the channel conditions by using better channel access methods. One can easily imagine that the effect on the network latency is also large. If cross-layer information is not exchanged, it is possible that the MAC layer sets the TX/RX periods too short. Then the nodes do not have enough time to transmit their data, and they have to send any remaining data in the next TX period. In that way, the nodes' transmit queues will eventually overflow, and some data will be lost. On the other hand, if the channel conditions are good, and the MAC layer does not know that fact, it will set the TX periods too long. This is not optimal from the energy consumption and the latency point of view.

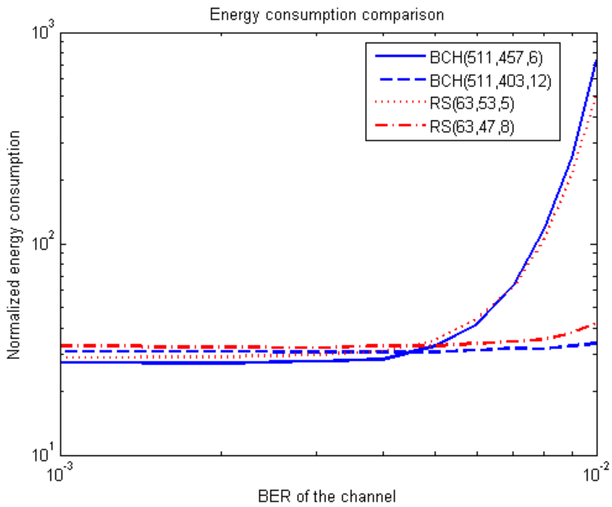

Fig. 5. Energy consumption for the different codes.

VII. Conclusions and Future Work

In this paper, cross-layer design issues for sensor networks are discussed. Markov chain and energy consumption analyses are developed and introduced for UWB wireless sensor networks. These analyses take into account characteristics of both physical and medium access layers in a WSN transceiver.

Simulations results clearly show that coding can decrease the energy consumption of UWB sensor networks. The energy consumption results show in this paper are generic and can be generalized to other UWB sensor network applications. The results show that the performance of BCH and RS codes are close to each other. Due to the RS codes' burst error correction capabilities, they are preferred in UWB transceivers.

In addition, the results clearly show the importance of cross-layer information exchange. Moreover, the introduced models and results shown in this paper can be used in the design of energy efficient UWB sensor networks. As an example, if the designer knows the probabilistic nature of the channel condition, it is possible to optimize the code and sleep/awake periods using the approach presented here.

The approach developed in this paper can be used to calculate results with various parameters and network settings. It can also be easily extended to include different types of coding and channel access protocols. In the future research, e.g., convolutional, turbo and RS codes performance could be compared. Also, the multi-hop scenario's energy consumption can be explored by developing the presented model. The impact of different channel models needs also to be included in the future model.

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