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An analytical model for energy efficiency of error control schemes in sensor networks

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Abstract - **This paper analyzes the energy efficiency of wireless sensor networks using different error control schemes. An analytical model is presented to evaluate the energy efficiency in Nakagami-*m* fading channels. The model is applied to error control schemes of Bluetooth technology. Some custom error control schemes and adaptive techniques using different FEC and ARQ strategies are analyzed. Performance results are obtained through analysis for networks with different number of hops and fading channel conditions.**

I. INTRODUCTION

The recent advances in wireless communications and digital electronics led to the implementation of low power and low cost wireless sensors. These devices can be grouped to form a sensor network [1]. Energy constraints are the driving factors in the design of wireless sensor networks. The wireless radio channel is time varying and can have high bit error rates. In order to improve the reliability of the data sent in the wireless channel, some techniques can be employed, such as automatic repeat request (ARQ) and forward error correction (FEC). Although an error control strategy improves the reliability of a packet, the energy consumed due to the transmission of the additional bits in these coded schemes contributes to increase the energy consumption.

Some authors have studied the problem of energy consumption for some error control schemes in wireless sensor networks [2], [3], [4], [5], [6]. In [2] and [3] the energy efficiency of different error control techniques was evaluated for sensor networks with a commercial radio transceiver using an analytical model. The reliability and energy consumption were analyzed in [4] using simulation for sensor networks without any specific technology or channel model. In [5] and [6] the energy consumption and reliability of Bluetooth error control strategies were studied in a Rayleigh fading channel using simulation.

This paper presents an analytical model to evaluate the energy efficiency of error control schemes of wireless sensor networks in Nakagami-*m* fading channels. This model can be used in different sensor network technologies, such as the IEEE 802.15 standards. In this work it is applied to Bluetooth technology using the different error control schemes of the specification and the custom and adaptive error control schemes presented in [5] and [6]. The performance results are obtained for various sensor networks scenarios with different number of hops and channel conditions.

Some techniques of error control for wireless sensor networks are discussed in Section II. In Section III the analytical model to evaluate the energy efficiency is described and Section IV shows the Bluetooth error control schemes and the adaptation of the analytical model for Bluetooth technology. Section V presents performance results obtained for different scenarios of Bluetooth-based sensor networks. Finally, Section VI gives the final considerations and conclusions.

II. ERROR CONTROL SCHEMES FOR WIRELESS SENSOR NETWORKS

In order to improve the reliability of the data sent in the wireless channel, techniques such as automatic repeat request (ARQ) and forward error correction (FEC) can be employed [7]. FEC employs error correcting codes to combat bit errors by adding redundancy (parity bits) to information packets. The receiver uses the parity bits to detect and correct errors. FEC techniques are associated with unnecessary overhead that increases energy consumption when the channel is relatively error free.

In ARQ techniques only error detection capability is provided; the receiver requests to the transmitter the retransmission of the packets received in error. Usually an ARQ scheme uses Cyclic Redundancy Check (CRC) codes for error detection. At the receiver, the CRC code verifies the packet. If it detects errors, the node asks a retransmission for the transmitter (negative acknowledgement). If the reception is correct, a positive acknowledgement is sent to the transmitter node. Hybrid ARQ schemes can be developed using the combination of FEC and ARQ schemes. Some typical error control techniques for wireless networks are discussed in [6]. The energy consumption of these schemes is very important. Although a strong error control can correct many errors, the energy consumed may be too high for an energy constrained sensor network.

Using the same error control scheme for the whole network could be a good choice in some cases, but not always. Sometimes it is needed to apply the best error control available, while in other cases less error control should be used. Thus, an adaptive scheme that changes the error control technique may be developed. In order to apply an adaptive scheme in a sensor network it was used an approach similar to the proposed in [4] and [5]. To use and adaptive error control

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scheme, a mechanism has to be designed to judge the importance of a packet and then choosing an appropriate error control scheme.

The importance of a packet is evaluated using the multihop principle, as shown in Fig. 1. The choice of error control technique shall be based on the number of hops the packet traveled within the sensor network. If a sensor node has to send a data packet to the sink node, before the packet reaches its destination it may travel through some other nodes of the network.

If the packet gets lost at the first hop, only the energy to send the packet from a sensor to a specific node is lost. If the packet is corrupted after few more hops, much more energy will be spent to transmit the packet through the network. In this sense, a packet is more important if it travels through more nodes in the network, and consequently, more energy is being consumed. An adaptive scheme might use stronger error control techniques for packets that travel more hops and weaker error control for packets with fewer hops. Some adaptive schemes are presented in Section IV.

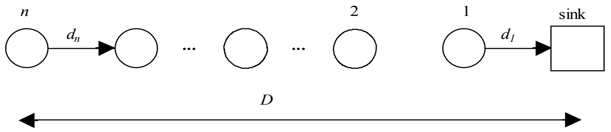

Figure 1. Multihop sensor network

III. ANALYTICAL MODEL

In this section it is presented an analytical model to evaluate the energy efficiency of different error control schemes in multihop wireless sensor networks. A received packet is not accepted whenever any of the bits of a packet is received with error (in non-coded systems). Thus, the packet error probability of the forward channel, PER_f, and reverse, PER_r (for ARQ systems) can be defined as:

$$PER_f = 1-\int_0^\infty f(\gamma_f)\left[1-p(\gamma_f)\right]^b d\gamma_f \tag{1}$$

$$PER_r = 1-\int_0^\infty f(\gamma_r)\left[1-p(\gamma_r)\right]^b d\gamma_r \tag{2}$$

where b is the size of the packet in bits, $f(\gamma_f)$ and $f(\gamma_r)$ are the probability density functions and γ_f and γ_r are the signal-to-noise ratio (SNR) of the forward and reverse channels, respectively. The variable $p(\gamma_f)$ is the bit error probability of the forward channel and $p(\gamma_r)$ is the bit error probability of the reverse channel.

The forward channel is used to send data packets and the reverse channel indicates the success or not of a packet transmission (for ARQ systems). The bit error probabilities $p(\gamma_f)$ and $p(\gamma_r)$ can be evaluated using an expression of symbol error probability of the modulation used in the sensor network. The modulation type used in a sensor network depends on the wireless technology (Bluetooth, IEEE 802.15.4, etc.). When channel coding is used, such as block or convolutional codes, the packet error rates PER_f and PER_r are evaluated in a different manner. Some examples are given in Section IV.

The wireless channel is modeled using the Nakagami fading. When $m \to \infty$, it converges to the AWGN channel and for $m=1$ is the Rayleigh fading. Using $m<1$ or $m>1$ fading intensities more and less severe than Rayleigh are obtained, respectively. The Nakagami probability density function is given by:

$$f(\gamma)=\frac{m^m\gamma^{m-1}}{\Gamma(m)\bar{\gamma}^m}\exp\left(-\frac{\gamma}{\bar{\gamma}}\right),\quad \text{for } \gamma\ge 0 \tag{3}$$

where $\bar{\gamma}$ is the average received SNR and γ is the instantaneous SNR. The packet error probabilities can be evaluated using equation (3) in (1) and (2). It is being assumed that the propagation conditions between the transmitter and the receiver are the same in both directions.

The probability of a packet being successfully received at the receiver node is the probability of success of the packet at forward and reverse channels:

$$PA = (1-PER_f)(1-PER_r) \tag{4}$$

Thus, the packet error probability for ARQ packets is:

$$PER = 1-[(1-PER_f)(1-PER_r)] \tag{5}$$

The probability of a packet being successfully received at the sink node for packets without ARQ is:

$$P_{narq} = (1-PER_f)^H \tag{6}$$

where H is the total number of hops. Let n be the number of retransmissions of ARQ packets. Assuming perfect error detection of a CRC code and infinite retransmissions, the probability that a packet arrives correctly at the sink node is:

$$P_{arq} = \sum_{n=0}^{\infty}\left[(1-PER_f)(1-PER_r)\right]^{H+n} = 1 \tag{7}$$

The probability of n retransmissions is the product of failure in the $n-1$ transmissions and the probability of success at the nth transmission:

$$p_N[n] = (1-PER)(PER)^{n-1} \tag{8}$$

Thus, equation (9) is used to evaluate the average number of retransmissions $\overline{N}$ in one hop:

$$\overline{N} = \sum_{n=1}^{\infty} p_N[n]\times n \tag{9}$$

The number of packets that arrive with error at the sink node can be defined for the packets without ARQ as the product of the total number of transmitted packets n_{pac} and the probability that the packet arrives with error at the sink node:

$$n_{error} = (1-P_{narq})\times n_{pac} \tag{10}$$

Considering the same assumptions of equation (7), none of the ARQ packets is received with errors and thus $n_{error} = 0$:

$$n_{error} = (1-P_{arq})\times n_{pac} = 0 \tag{11}$$

The reliability R is given by the percentage of the sent packets that arrive correctly at the sink node and it may be evaluated as:

$$R = [(n_{pac} - n_{error})/n_{pac}] \tag{12}$$

Since no specific hardware is being used, the energy consumption is expressed only in normalized terms. The energy considered are the energies spent in the communication (transmission and reception) and the decoding process. The encoding energies are assumed to be negligible. This assumption is reasonable for asynchronous codes, where the decoding process is more complex than coding.

It is considered the same model of [4] and [5], where the reception of a determined number of bits consumes approximately 75 per cent of the energy spent to transmit the same number of bits. The minimum energy consumed E_{min} for H hops is evaluated for packets without error control:

$$E_{\min} = H \times n_{pac} \times (n_{bits} + n_{bits} \times 0.75) \qquad (13)$$

where n_{bits} is the total number of bits of a packet. The total energy consumed E in a sensor network for packets without ARQ and without CRC is the total number of bits transmitted and received and the decoding energy per packet E_{dec}:

$$E = H \times n_{pac} \times (n_{bits} + n_{bits} \times 0.75 + E_{dec}) \qquad (14)$$

where n_{bits} is the total number of bits of a packet, including the parity bits of the code used in the packet. If no channel code is used, E_{dec}=0.

For the packets with ARQ, the energy E is the total number of bits transmitted and received, including retransmissions:

$$E = H \times n_{pac} \times \overline{N} \times [n_{bits} + n_{ack} + (n_{bits} + n_{ack})0.75 + E_{dec}] \qquad (15)$$

where n_{ack} is the total number of bits of the return packet.

In order to evaluate the energy E for packets without ARQ and with CRC the average number of hops has to be computed. The probability that a packet achieves h hops is the product of success in the *h-1* hops and the probability of failure in the hth hop, if $h<H$. If $h=H$ the probability of a packet achieving H hops is the product of success in the *h-1* hops and the probability of failure in the hth hop added to the probability of success in the H hops:

$$\begin{aligned} p_H[h] &= [(1-PER_f)^{h-1}(PER_f)], \text{if h} < \text{H} \\ p_H[h] &= [(1-PER_f)^{h-1}(PER_f) + (1-PER_f)^{h}], \text{if h} = \text{H} \end{aligned} \qquad (16)$$

Therefore, the average number of hops $\overline{H}$ can be evaluated as:

$$\overline{H} = \sum_{h=1}^{H} p_H[h] \times h \qquad (17)$$

Then the total energy consumed E for the packets with CRC and without ARQ is:

$$E = \overline{H} \times n_{pac} \times (n_{bits} + n_{bits} \times 0.75 + E_{dec}) \qquad (18)$$

For a sensor network to be considered energy efficient, the maximum amount of data bits has to be transmitted with the minimum energy consumption. An energy efficiency parameter η may be defined as:

$$\eta = \frac{E_{\min}}{E} \times R \qquad (19)$$

IV. ERROR CONTROL STRATEGIES FOR BLUETOOTH SENSOR NETWORKS

A. Error control of the Bluetooth specification

Bluetooth [9] is a low cost wireless technology designed to facilitate the formation of ad hoc networks. This characteristic makes the Bluetooth technology attractive also for sensor networks, together with its low cost, multihop capabilities, device discovery process and energy saving modes [10], [11], [12]. The Bluetooth specification version 1.2 defines seven asynchronous data packets. Each packet has three fields: the access code (72 bits), header (54 bits) and payload (0-2745 bits). The access code is used for synchronization and the header has information such as packet type, flow control and acknowledgement. The header contains a (n,k)=(3,1) repetition code for error verification. The payload carries the data bytes that are usually protected by an ARQ stop-and-wait strategy based in a CRC code (DMx and DHx packets). The receiver indicates in the next return packet whether the transmission was successful or not. The DMx packets have the data protected by a Hamming code (15,10) with rate 2/3. This code corrects all single bit errors and detects all two bits errors in a code word.

B. Custom error control

Whereas the packets defined by the Bluetooth standard have fixed error control schemes, custom coding can be implemented by making use of the AUX1 packet [5], [13]. In [13] was proposed the use of BCH codes with the CRC code for error detection. The coder is implemented inserting a (232, k) BCH code in the payload of the AUX1 packet. The inputs of the BCH coder are the data and two CRC bytes, resulting in a packet with $K=k-16$ data bits. The code then considered was a (232, 156) binary BCH code with a correction capability of up to t=10 errors.

In [5] and [6] some novel modifications in the AUX1 packet were proposed. The same BCH code can be applied, but without retransmission (BCH2 and BCH3 packets). The BCH2 packet utilizes the CRC code for error detection, without asking retransmission. A packet is discarded if the CRC detects any errors. The BCH3 packet does not use either retransmission or CRC. The difference between BCH2 and BCH3 is that in the latter the packets are transmitted to the next node even if it contains errors. The BCH2 packet has additional 16 bits for the CRC implementation and the packet is discarded if the CRC detects errors. Another modification is to use the same Hamming code of the DMx packets in the AUX1 payload, but without retransmission, with and without CRC (HAM and HAM2 packets, respectively). Other new packet is the AUX2, which is an AUX1 packet with CRC code. Table I shows the error control information for these new packet types.

TABLE I. PACKETS WITH CUSTOM ERROR CONTROL

Packet	Time-slots	Data (bytes)	FEC	ARQ	CRC
AUX2	1	0-27	No	No	Yes
HAM	1	0-18	Hamming (15,10)	No	No
HAM2	1	0-18	Hamming (15,10)	No	Yes
BCH	1	0-17	BCH(232,156)	Yes	Yes
BCH2	1	0-17	BCH (232,156)	No	Yes
BCH3	1	0-17	BCH (232,156)	No	No

C. Adaptive error control

Two different adaptive schemes were used, called ADP1 and ADP2. A packet with weaker error control is used for the initial hops and a packet with more powerful coding for the remaining hops throughout the sensor network. In the adaptive error control scheme, each packet must have a counter with the number of hops the packet had in the network. This can be implemented as a field in the payload of the packet. Table II shows the packet types proposed in these schemes. Although only two schemes are being presented here, other adaptive strategies with different packet types might be proposed.

TABLE II. ADAPTIVE SCHEMES

Scheme	1st and 2nd Hops	3rd, 4th and 5th Hops	Other Hops
ADP1	AUX2	HAM2	DH1
ADP2	AUX2	BCH2	DH1

D. Energy efficiency evaluation of Bluetooth error control schemes

In order to evaluate the energy efficiency of Bluetooth error control schemes, the packet error probabilities have to be computed. It is used a method based on [5] and [8]. A received packet is not accepted when any of the five events happens: (A) the destination fails to synchronize with the access code of the received packet; (B) the header of the received packet is corrupted; (C) the data of the received packet are corrupted after the channel code is decoded; (D) the source is unable to synchronize with the access code of the return packet and (E) the header of the return packet is corrupted.

A packet is synchronized if the correlator output exceeds a given threshold *T*. The frame is synchronized if at least *T* of the 72 bits of the access code were properly demodulated (*T = 65* in this work):

$$P[\overline{A}] = \sum_{k=0}^{72-T} \binom{72}{k} \cdot [p(\gamma_f)]^k \cdot [1-p(\gamma_f)]^{72-k}, \qquad (20)$$

Since the return packet also has an access code of 72 bits, the probability for the event D has the same form of event A,

$$P[\overline{D}] = \sum_{k=0}^{72-T} \binom{72}{k} \cdot [p(\gamma_r)]^k \cdot [1-p(\gamma_r)]^{72-k}, \qquad (21)$$

The events B or E occur if any of the eight triples of the repetition code (3,1) were incorrectly decoded,

$$P[\overline{B}] = \left\{3p(\gamma_f)[1-p(\gamma_f)]^2 + [1-p(\gamma_f)]^3\right\}^{18} \qquad (22)$$

$$P[\overline{E}] = \left\{3p(\gamma_r)[1-p(\gamma_r)]^2 + [1-p(\gamma_r)]^3\right\}^{18} \qquad (23)$$

The most probable error is that defined by event C. For DHx, AUX1 and AUX2 packets it occurs when any of the data bytes were received with error:

$$P[\overline{C}] = [1-p(\gamma_f)]^b, \qquad (24)$$

where *b* is the size of the payload in bits. For DMx and HAMx packets the data are protected by a Hamming code, where B is the number of blocks with 10 bits. The probability of event C for the DMx and HAMx packets is:

$$P[\overline{C}] = \left[15p(\gamma_f)[1-p(\gamma_f)]^{14} + [1-p(\gamma_f)]^{15}\right]^B \qquad (25)$$

The BCHx packets contain a (232, 156) binary BCH code that can correct up to *t*=10 errors. Then, for BCHx packets the probability of event C is:

$$P[\overline{C}] = \sum_{k=0}^{t} \binom{232}{k} \cdot [p(\gamma_f)]^k \cdot [1-p(\gamma_f)]^{232-k} \qquad (26)$$

Bluetooth uses GFSK modulation with time-bandwidth product *BT=0.5* and modulation index *i* between 0.28 and 0.35. In this work *i=0.32*, the same value used in [5] and [8]. The error symbol probability $p(\gamma)$ for the GFSK modulation is given by:

$$p(\gamma) = Q_1(a,b) - \frac{1}{2} e^{(a^2+b^2)/2} I_o(ab) \qquad (27)$$

where $Q_1\ (a,b)$ is the Q-Marcum function, I_o is the modified Bessel function of first kind and *a* e *b* are constants that depend on the signal-to-noise ratio and the correlation [8]. Thus, equations (1) and (2) can be rewritten for the Bluetooth system as:

$$PER_f = 1 - \int_0^\infty f(\gamma_f) P[\overline{A}] P[\overline{B}] P[\overline{C}]\, d\gamma_f \qquad (28)$$

$$PER_r = 1 - \int_0^\infty f(\gamma_r) P[\overline{D}] P[\overline{E}]\, d\gamma_r \qquad (29)$$

Thus, the energy efficiency is evaluated using equation (19). The energy efficiency for an adaptive scheme is evaluated using equation (19), but the energy *E* and the reliability *R* have to be evaluated in a different manner.

For the ADP1 scheme the AUX2 packet is used for the first and second hops, the HAM2 packet for the third, fourth and fifth hops and DH1 packet for the remaining hops of the sensor network. The total energy E is the energy consumed by the different packets:

$$E = E_{aux2} + E_{ham2} + E_{dh1} \qquad (30)$$

The energy consumed by the AUX2 packets is:

$$E_{aux2} = \overline{H} \times n_{pac} [n_{bits} + n_{bits} \times 0.75] \qquad (31)$$

where the average number of hops $\overline{H}$ can be evaluated using equation (17) with *H=2* and n_{bits} is the number of bits of the AUX2 packet. The energy consumed by the HAM2 packets is:

$$E_{ham2} = \overline{H} \times n_{pac} [n_{bits} + n_{bits} \times 0.75] \times p_{h2} \qquad (32)$$

where $\overline{H}$ can be evaluated by equation (17) with *H=3*, n_{bits} is the number of bits of the HAM2 packet and p_{h2} is the probability that the AUX2 packet arrives correctly at the receiver after the second hop (because the packet will be discarded if the CRC detects errors):

$$p_{h2} = (1 - PER_f)^2 \qquad (33)$$

The total energy consumed by DH1 packets is

$$E_{dh1} = H \times n_{pac} \times \overline{N} \times [n_{bits} + n_{bits} \times 0.75] \times p_{h5} \qquad (34)$$

where *H* is the number of the remaining hops of the network, n_{bits} is the number of bits of the DH1 packet and p_{h5} is the probability that the HAM2 packet arrives correctly at the receiver after the fifth hop, given by:

$$p_{h5} = (1 - PER_f)^3 \times p_{h2} \qquad (35)$$

The number of transmitted packets with error is the sum of errors occurred in the transmissions of the AUX2 and HAM2 packets, as the DH1 packet will always be retransmitted until it is correctly received:

$$n_{error} = n_{error\_aux2} + n_{error\_ham2} \qquad (36)$$

The number of errors of the AUX2 packet is the product of the total number of transmitted packets n_{pac} and the probability of error of the AUX2 packet in two hops:

$$n_{error\_aux2} = [1 - (1 - PER_f)^2] \times n_{pac} \qquad (37)$$

The number of errors of the HAM2 packet has the same form, but the number of errors occurred in the first and second hops using the AUX2 packet have to be subtracted from the total number of transmitted packets n_{pac}:

$$n_{error\_ham2} = [1-(1-PER_f)^3] \times (n_{pac} - n_{error\_aux2}) \qquad (38)$$

Then the reliability can be evaluated using equation (12) and finally, the energy efficiency using equation (19). For the ADP2 scheme, the energy efficiency may be evaluated using the same equations of ADP1 scheme, replacing the HAM2 packet by the BCH2 packet.

V. ANALYTICAL RESULTS

In the evaluation of energy efficiency a sensor sends 100000 packets to the sink (n_{pac}=100000), considering different number of hops. While in [3], [4] and [5] the energies spent in coding and decoding processes were not considered at all, in [2] these energies were considered, but their effect on energy efficiency is considered to be negligible compared to the energy consumed in the transmission of additional parity bits. In [14] it is stated that the energy consumed in transmitting 1 bit is many times higher of the energy consumed for executing one instruction. For instance, a sensor node developed by Rockwell Inc. consumes between 1500 and 2700 times more energy to transmit a bit than for executing one instruction [14]. Thus, only the parity bits of the error control schemes are considered in the evaluation of the results (E_{dec}=0). The data size to be transmitted was chosen to be 17 bytes. Although other data sizes could be used, this value may indicate a tendency of the packet behavior. The value of 17 bytes was chosen because is the maximum number of data bytes that the DM1 and BCH packets can transmit [5].

The energy efficiency of BCH and AUX1 packets for different number of hops and fading parameter m=1 are shown in Fig. 2. When the signal-to-noise ratio decreases, the energy efficiency also decreases for both packets, as expected. When the number of hops increases, the energy efficiency decreases for the AUX1 packet, but it remains constant for the BCH packet. In Fig. 3 the DH1 packet has the same behavior of the BCH packet. The energy efficiency of these packets is independent of the number of hops. This behavior is valid only for packets with retransmission (ARQ). The DH1 packet is better than the BCH packet for high values of SNR and worse for low values of SNR. The energy efficiency of ADP1 scheme, as shown in Fig. 3, decreases with the SNR and tends to converge to the DH1 packet when the number of hops increases, because it uses the DH1 packet after the fifth hop. From Figures 2 and 3 it can be observed that the relative performance among the packets begins to stabilize with approximately 25 hops.

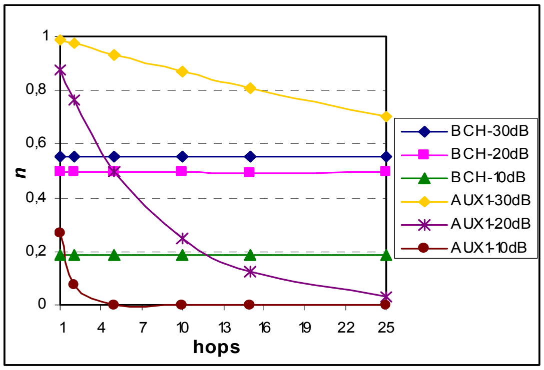

Figure 2. Energy efficiency for BCH and AUX1 packets

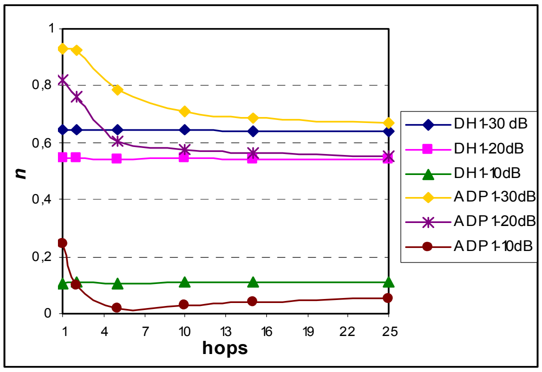

Figure 3. Energy efficiency for DH1 packet and ADP1 scheme

Fig. 4 shows the results obtained for the energy efficiency of each packet as a function of signal-to-noise ratio for 25 hops and m=1. The AUX1 packet only has the higher efficiency for channel conditions above 35 dB. Below this value the AUX2 packet becomes the best. The adaptive scheme ADP2 has the best efficiency when the SNR is close to 20 dB and the BCH packet is the best for SNR below 15 dB. It can be noted that when the channel quality is good, it is not necessary a very powerful error correction and the AUX1 and AUX2 packets can be utilized. If the channel conditions are very bad, a code able to correct many errors has to be used, so the BCH packet is the most recommended in such situations. For intermediary conditions, the adaptive schemes ADP1 and ADP2 have the best energy efficiency degree.

The effect of the number of hops in the packets without ARQ and the adaptive schemes can be better observed in Figures 5 and 6. It is shown the energy efficiency for the BCH2 packet and the ADP2 scheme. The energy efficiency of the BCH2 packet is greatly affected with the increase of hops when the SNR is below 30 dB (Fig. 5). For the ADP2 scheme (Fig. 6) the difference on energy efficiency is high for few hops (between 2 and 5 hops). But the difference between 15 and 25 hops is low, because the ADP1 scheme tends to converge to DH1 packet with many hops and become independent of the number of hops.

Fig. 7 shows the energy efficiency of the BCH packet and the ADP1 scheme for different values of m. When the parameter m is low, the fading is more severe and the energy efficiency is bad. For higher values of m the energy efficiency increases for all packets. The channel conditions greatly affect the performance of error control schemes. But it can be noted from Fig. 7 that when the channel quality is good, it is not necessary a powerful error correcting scheme. Only if the channel conditions are bad the BCH packet is the most energy efficient.

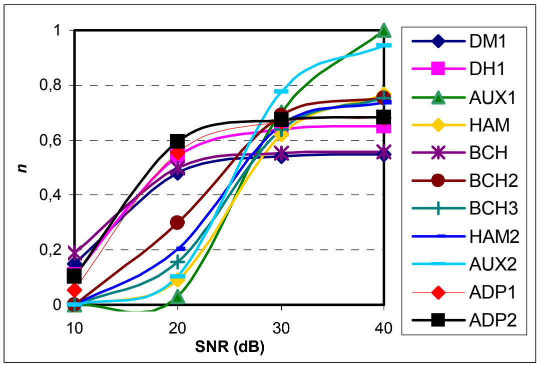

Figure 4. Energy efficiency for 25 hops

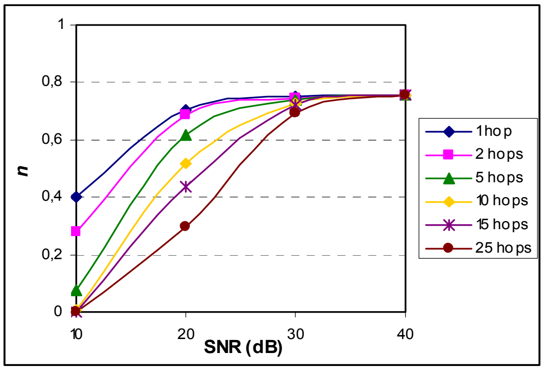

Figure 5. Energy efficiency for BCH2 packet

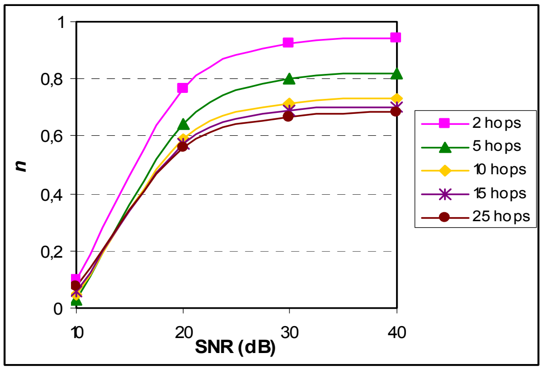

Figure 6. Energy efficiency for ADP2 scheme

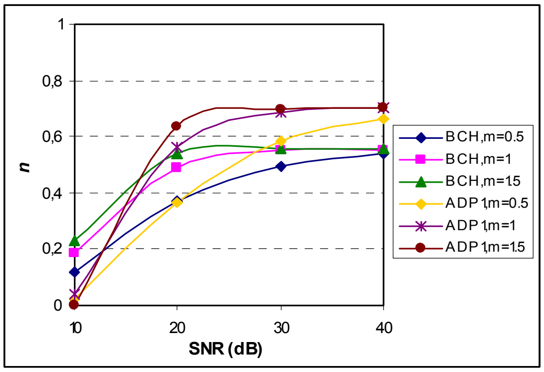

Figure 7. Energy efficiency for BCH packet and ADP1 scheme for different values of *m*

VI. CONCLUSION

In this paper the energy efficiency of error control schemes for wireless sensor networks in Nakagami-*m* fading channels was analyzed. A novel analytical model was presented and applied to error control strategies for Bluetooth sensor networks. The results have shown that the channel conditions and the number of hops of the network affect the energy efficiency. Nevertheless, the energy efficiency of Bluetooth packets with ARQ remains constant with the increase of hops. For good channel conditions the packets with little or no error protection present the best energy efficiency. For low values of SNR and *m* the BCH packet is the most efficient, because of its ability to correct more errors. In intermediary situations the adaptive schemes have the best performance. The analytical model presented in this paper, as well as the error control schemes, may be adapted to other technologies for wireless sensor networks.

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