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An energy efficiency model for adaptive and custom error control schemes in Bluetooth sensor networks

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Abstract

This paper analyzes the effect of custom error control schemes on the energy efficiency in Bluetooth sensor networks. An analytical model is presented to evaluate the energy efficiency metric, which considers in just one parameter the energy and reliability constraints of wireless sensor networks. New packet types are introduced using some error control strategies in the AUX1 packet, where custom coding can be implemented. Two adaptive techniques are proposed that change the error control strategy based on the number of hops traversed by a packet through the network. A packet selection strategy based on channel state is proposed for sensor networks with different channel conditions. Performance results are obtained through analysis and simulation in Nakagami-*m* fading channels for networks with different number of hops and channel conditions.

Keywords: Bluetooth; Error control; Sensor networks; Energy efficiency

1. 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. In a wireless sensor node the tasks that are the main energy consumers are the sensing unit, the computation unit and the communication unit. Actually, the most energy consuming component is the communication unit. The energy consumed to transmit 1 bit is many times higher than that 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 [2].

Efficient energy management involves all levels of the sensor system hierarchy, from hardware to software architecture and communication protocols. The network protocols, such as formation algorithms, routing and management, must have self-organizing capabilities. Bluetooth [3] 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. The devices can communicate with each other forming a network, called piconet, with up to eight nodes. Devices in different piconets can communicate using a structure called scatternet. In [4,5] sensor networks were analyzed using Bluetooth technology.

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Some protocols for scatternet formation and routing in Bluetooth sensor networks were proposed in [6–9].

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, many techniques can be employed, such as automatic repeat request (ARQ), forward error correction (FEC) or transmission power control. 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 [10–13]. In [10,11] the energy efficiency of different error control techniques was evaluated for sensor networks with a commercial radio transceiver using an analytical model. In [10] the energy efficiency was used as the metric for packet size optimization. In [11] the energy efficiency of some balanced channel codes was analyzed for different bit error probabilities. While in [12] the reliability and energy consumption were analyzed using simulation for sensor networks without any specific technology or channel model, in [13] the energy consumption and reliability of Bluetooth error control strategies were studied in a Rayleigh fading channel.

This paper presents an analytical model to evaluate the energy efficiency of error control schemes of Bluetooth data packets in Nakagami-m fading channels. The energy efficiency metric considers jointly the energy and reliability constraints of sensor networks. New Bluetooth packet types are proposed using custom coding in the AUX1 packet. The paper introduces two novel adaptive error control schemes that change the error control strategy accordingly to the number of hops traversed by a packet through the sensor network. A packet selection strategy based on channel state is proposed for sensor networks with different channel conditions. A simulation model is also presented for comparison and corroboration of the analytical model. The performance results were obtained for various sensor networks scenarios with different number of hops and channel conditions.

The techniques for error control of data packets, custom coding and adaptive schemes are presented in Section 2. In Section 3 the analytical model to evaluate the energy efficiency is described and Section 4 shows the performance results obtained for networks with different number of hops. Section 5 presents a simulation model and the comparison results between the simulation and analytical models. In Section 6 results are presented for different fading conditions and a packet selection strategy based on channel conditions is proposed. Finally, Section 7 gives the final considerations and conclusions.

2. Error control strategies for Bluetooth sensor networks

2.1. Error control of the Bluetooth specification

Bluetooth operates on the 2.4 GHz ISM (Industrial, Scientific and Medical) band employing a frequency-hopping spread spectrum (FHSS) technique. The transmission rate is up to 1 Mbps, using Gaussian frequency shift keying (GFSK) modulation. The channel is divided in time slots of 625 µs, using a time-division duplex (TDD) scheme for full-duplex operation.

The Bluetooth specification version 1.2 defines seven asynchronous data packets, as shown in Table 1. 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 access code is error robust, because the coded synchronization words have a large Hamming distance ($d_{\min} = 14$). 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. The receiver indicates in the next return packet (a Bluetooth NULL 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-bit errors in a code word. Table 1 shows this information for each asynchronous packet.

2.2. Custom error control

Whereas the packets defined by the Bluetooth standard (Table 1) have fixed error control schemes, a custom coding can be implemented by making use of the AUX1 packet [13,14]. With the AUX1 packet the Bluetooth device delivers the received bits independently whether they are correct or not. While the former asynchronous packets with ARQ maintain a reliable link with random delay (which approaches infinity for low values of signal-to-noise ratio (SNR), the AUX1 packet may alternatively provide an unreliable link with delay of only one time slot.

Valenti and Robert [14] have proposed the use of BCH codes with the CRC code for error detection. As the ARQ is turned off, it must be implemented at the application layer. The coder is implemented by 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 this paper five novel modifications in the AUX1 packet are proposed: (1) BCH code without ARQ; (2) BCH code without ARQ and CRC; (3) Hamming code without ARQ;

Table 1. Asynchronous packet types

Packet	Time-slots	Payload (bytes)	FEC	CRC and ARQ
DM1	1	0–17	Hamming (15,10)	Yes
DH1	1	0–27	No	Yes
DM3	3	0–121	Hamming (15,10)	Yes
DH3	3	0–183	No	Yes
DM5	5	0–224	Hamming (15,10)	Yes
DH5	5	0–339	No	Yes
AUX1	1	0–29	No	No

Table 2. Packet types 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

(4) Hamming code without ARQ and CRC; (5) AUX1 packet with CRC.

The same BCH code of [14] can be applied, but without retransmission (BCH2 and BCH3 packets). Although this strategy can decrease the reliability of transmitted packets, in terms of energy consumption it may be very useful, for it is not necessary to send a return packet to indicate the success of the transmission. 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 (in a multihop network) even if it contains errors, so wasting energy. In the BCH2 packet this fact does not happen, but the packet has additional 16 bits for the CRC implementation.

Another modification proposed in this work 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 2 shows the error control information for the new introduced packet types.

2.3. Adaptive error control

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. To use an adaptive error control scheme, a mechanism has to be designed to judge the importance of a packet and

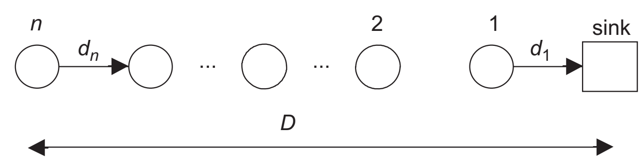

Fig. 1. Multi-hop sensor network.

then choosing the most efficient error control scheme for that particular packet. In Bluetooth case, to change the error correction scheme means to change the packet type to be transmitted. In order to apply an adaptive scheme in a sensor network, where the most important factor is to reduce the energy consumption, an approach similar to [12,13] was used.

The importance of a packet is evaluated using the multihop principle, as shown in Fig. 1. The choice of the packet type and the respective error control technique shall be based on the number of hops the packet traveled within the sensor network. For instance, a sensor node sends a data packet containing the information of the temperature of a region to the sink node, which collects the data of all the sensors of the network.

However, before the packet reaches the sink node, it may travel through some other nodes of the network that can be sensors or another type of node with routing capacity. 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

Table 3. Adaptive schemes

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

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.

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. Two different adaptive schemes were used: 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. Table 3 shows the packet types proposed in these schemes. Although only two schemes are being presented here, other adaptive strategies with different packet types might also be proposed.

3. Analytical model

In this section it is presented an analytical model to evaluate the energy efficiency of the Bluetooth packets in multi-hop sensor networks. In order to investigate expressions for energy efficiency, a method is used based on [13,15] to evaluate the packet error probabilities. A received packet is not accepted when any of the five events happens: (A) the destiny fails to synchronize with the access code of the received packet; (B) the header of the received packet is corrupted (after the repetition code is decoded); (C) the data of the received packet are corrupted after the channel code, if any, is decoded, causing the CRC check to fail; (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.

The synchronization is made correlating the demodulator output with a stored copy of the access code. 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, the same value used in [15]). The errors are assumed to be independently distributed. The synchronization with the received packet occurs if there are no more than ($72–T$) errors in the received access code:

$$P[\overline{A}] = \sum_{k=0}^{72-T} \binom{72}{k} [p(\gamma_{\mathrm{f}})]^k [1-p(\gamma_{\mathrm{f}})]^{72-k}, \tag{1}$$

where $p(\gamma_{\mathrm{f}})$ is the symbol error probability of the forward channel. 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,

$$P[\overline{D}] = \sum_{k=0}^{72-T} \binom{72}{k} [p(\gamma_{\mathrm{r}})]^k [1-p(\gamma_{\mathrm{r}})]^{72-k}, \tag{2}$$

where $p(\gamma_{\mathrm{r}})$ is the symbol 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 the transmission of a packet (for unidirectional transmission). The events B or E occur if any of the eight triples of the repetition code (3, 1) were incorrectly decoded,

$$P[\overline{B}] = \{3p(\gamma_{\mathrm{f}})[1-p(\gamma_{\mathrm{f}})]^2 + [1-p(\gamma_{\mathrm{f}})]^3\}^{18}, \tag{3}$$

$$P[\overline{E}] = \{3p(\gamma_{\mathrm{r}})[1-p(\gamma_{\mathrm{r}})]^2 + [1-p(\gamma_{\mathrm{r}})]^3\}^{18}. \tag{4}$$

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:

$$P[\overline{C}] = [1-p(\gamma_{\mathrm{f}})]^b, \tag{5}$$

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

$$P[\overline{C}] = [15p(\gamma_{\mathrm{f}})[1-p(\gamma_{\mathrm{f}})]^{14} + [1-p(\gamma_{\mathrm{f}})]^{15}]^B. \tag{6}$$

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

$$P[\overline{C}] = \sum_{k=0}^{t} \binom{232}{k} [p(\gamma_{\mathrm{f}})]^k [1-p(\gamma_{\mathrm{f}})]^{232-k}. \tag{7}$$

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 [15]. When the modulation index i is less than 0.5, the signal correlation ρ is given by

$$\rho = \frac{\sin(2\pi i)}{2\pi i}. \tag{8}$$

Two constants a and b can be defined:

$$a = \sqrt{\frac{\gamma}{2}\left(1-\sqrt{1-\rho^2}\right)}, \quad b = \sqrt{\frac{\gamma}{2}\left(1+\sqrt{1-\rho^2}\right)}, \tag{9}$$

where γ is the instantaneous signal-to-noise ratio (SNR). The error symbol probability $p(\gamma)$ for the GFSK modulation must be applied in Eqs. (1) and (6) and is given by

$$p(\gamma) = Q_1(a,b) - \tfrac{1}{2}\mathrm{e}^{(a^2+b^2)/2} I_o(ab), \tag{10}$$

where $Q_1(a,b)$ is the Q-Marcum function and I_o is the modified Bessel function of first kind. Thus, the packet error probability of the forward channel, $\mathrm{PER_f}$, and reverse, $\mathrm{PER_r}$, can be defined as

$$\mathrm{PER_f} = 1 - \int_0^{\infty} f(\gamma_\mathrm{f}) P[\overline{A}] P[\overline{B}] P[\overline{C}]\, \mathrm{d}\gamma_\mathrm{f}, \quad (11)$$

$$\mathrm{PER_r} = 1 - \int_0^{\infty} f(\gamma_\mathrm{r}) P[\overline{D}] P[\overline{E}]\, \mathrm{d}\gamma_\mathrm{r}, \quad (12)$$

where $f(\gamma_\mathrm{f})$ and $f(\gamma_\mathrm{r})$ are the probability density functions and γ_f and γ_r are SNR of the forward and reverse channels, respectively.

The wireless channel is modeled using the Nakagami fading. This distribution spans, via the fading parameter m, the widest range of multipath distributions. 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

$$f(\gamma) = \frac{m^m \gamma^{m-1}}{\Gamma(m)\bar{\gamma}^m} \exp\left(-\frac{\gamma}{\bar{\gamma}}\right) \quad \text{for } \gamma \geqslant 0, \quad (13)$$

where $\bar{\gamma}$ is the average received SNR. The error probabilities of each packet can be evaluated using Eq. (13) in (11) and (12). It is 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:

$$\mathrm{PA} = (1 - \mathrm{PER_f})(1 - \mathrm{PER_r}). \quad (14)$$

Thus, the packet error probability for ARQ packets is

$$\mathrm{PER} = 1 - [(1 - \mathrm{PER_f})(1 - \mathrm{PER_r})]. \quad (15)$$

This expression can be rewritten as

$$\mathrm{PER} = \mathrm{PER_f} + \mathrm{PER_r} - (\mathrm{PER_f})(\mathrm{PER_r}). \quad (16)$$

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

$$P_\mathrm{narq} = (1 - \mathrm{PER_f})^H, \quad (17)$$

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

$$P_\mathrm{arq} = \sum_{n=0}^{\infty} [(1 - \mathrm{PER_f})(1 - \mathrm{PER_r})]^{H+n} = 1. \quad (18)$$

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

$$p_N[n] = (1 - \mathrm{PER})(\mathrm{PER})^{n-1}. \quad (19)$$

Thus, Eq. (20) is used to evaluate the average number of retransmissions $\overline{N}$ in one hop:

$$\overline{N} = \sum_{n=1}^{\infty} p_N[n] \times n. \quad (20)$$

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:

$$n_\mathrm{error} = (1 - P_\mathrm{narq}) \times n_\mathrm{pac}. \quad (21)$$

Considering the same assumptions of Eq. (18), perfect error detection of the CRC code and infinite retransmissions, none of the ARQ packets is received with errors and thus $n_\mathrm{error}=0$:

$$n_\mathrm{error} = (1 - P_\mathrm{arq}) \times n_\mathrm{pac} = 0. \quad (22)$$

The reliability R is given by the percentage of the sent packets being delivered correctly to the sink node and it may be evaluated as:

$$R = [(n_\mathrm{pac} - n_\mathrm{error})/n_\mathrm{pac}]. \quad (23)$$

Since no specific hardware is being used, the energy consumption in the transmission and reception of the packets is expressed only in normalized terms. While the energies spent in coding and decoding processes were not considered in [11–13], in [10] their effect on energy efficiency were shown to be negligible compared to the energy consumed in the transmission of additional parity bits. Thus, only the parity bits of the error control schemes are considered in this work.

The same model of [12,13] is considered, where the energy consumed per bit is constant and the reception of a determined number of bits consumes approximately 75% of the energy spent to transmit the same number of bits.

The minimum energy consumed E_min for H hops is evaluated for a packet without error control:

$$E_\mathrm{min} = H \times n_\mathrm{pac} \times (n_\mathrm{aux1} + n_\mathrm{aux1} \times 0.75), \quad (24)$$

where n_aux1 is the total number of bits of the AUX1 packet. The total energy consumed E in a sensor network for a packet without ARQ and without CRC corresponds to the total number of bits transmitted and received, where each transmitted bit consumes 1 unit of energy and each received bit consumes 0.75 units of energy:

$$E = H \times n_\mathrm{pac} \times (n_\mathrm{bits} + n_\mathrm{bits} \times 0.75), \quad (25)$$

where n_bits is the total number of bits of a packet, including the access code, header and payload.

On the other hand, for the packets with ARQ and CRC and average number of retransmissions $\overline{N}$, the energy E is

$$E = H \times n_\mathrm{pac} \times \overline{N} \times (n_\mathrm{bits} + n_\mathrm{bits} \times 0.75 + n_\mathrm{ack} + n_\mathrm{ack} \times 0.75), \quad (26)$$

where n_{ack} is the total number of bits of the return packet. In order to evaluate the energy E for the packets without ARQ and with CRC (AUX2, BCH3 and HAM2 packets) 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:

$$p_H[h] = [(1 - \mathrm{PER_f})^{h-1}(\mathrm{PER_f})] \quad \text{if } h < H$$

$$p_H[h] = [(1 - \mathrm{PER_f})^{h-1}(\mathrm{PER_f}) + (1 - \mathrm{PER_f})^{h}] \quad \text{if } h = H. \tag{27}$$

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

$$\overline{H} = \sum_{h=1}^{H} p_H[h] \times h. \tag{28}$$

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

$$E = \overline{H} \times n_{pac} \times (n_{bits} + n_{bits} \times 0.75). \tag{29}$$

For a Bluetooth based 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

$$\eta = \frac{E_{min}}{E} \times R. \tag{30}$$

The energy efficiency for an adaptive scheme is evaluated using Eq. (30), 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:

$$E = E_{aux2} + E_{ham2} + E_{dh1}. \tag{31}$$

The energy consumed by the AUX2 packet is

$$E_{aux2} = \overline{H} \times n_{pac}[n_{bits} + n_{bits} \times 0.75], \tag{32}$$

where the average number of hops $\overline{H}$ can be evaluated using Eq. (28) with $H = 2$ and n_{bits} is the number of bits of the AUX2 packet. The energy consumed by the HAM2 packet is:

$$E_{ham2} = \overline{H} \times n_{pac}[n_{bits} + n_{bits} \times 0.75] \times p_{h2}, \tag{33}$$

where $\overline{H}$ can be evaluated by Eq. (28) 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):

$$p_{h2} = (1 - \mathrm{PER_f})^2. \tag{34}$$

The total energy consumed by DH1 packet is

$$E_{dh1} = H \times n_{pac} \times \overline{N} \times [n_{bits} + n_{bits} \times 0.75] \times p_{h5}, \tag{35}$$

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

$$p_{h5} = (1 - \mathrm{PER_f})^3 \times p_{h2}. \tag{36}$$

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:

$$n_{error} = n_{error\_aux2} + n_{error\_ham2}. \tag{37}$$

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:

$$n_{error\_aux2} = [1 - (1 - \mathrm{PER_f})^2] \times n_{pac}. \tag{38}$$

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}:

$$n_{error\_ham2} = [1 - (1 - \mathrm{PER_f})^3] \times (n_{pac} - n_{error\_aux2}). \tag{39}$$

Then the reliability can be evaluated using Eq. (23) and finally, the energy efficiency using Eq. (30). 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.

4. Analytical results

In the evaluation of energy efficiency a sensor sends 100,000 packets to the sink (n_{pac}=100,000), considering different number of hops. Higher values of n_{pac} would give the same results. In the results of this section, the value of the Nakagami fading parameter is $m = 1$. The data may indicate the temperature of an environment or some other variable that could be transmitted with few bytes of data. 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 performance. The value of 17 bytes was chosen because it is the maximum number of data bytes that the DM1 and BCH packets can transmit. In the analysis with 17 bytes the packets DM3, DH3, DM5 and DH5 are not used because these packets with fewer bytes would be equal to DM1 or DH1.

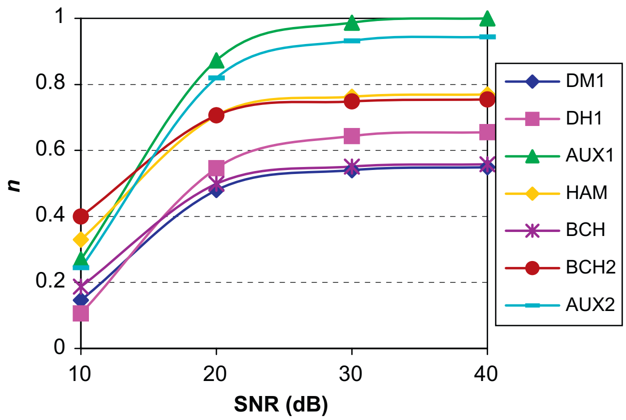

Fig. 2. Energy efficiency for 1 hop.

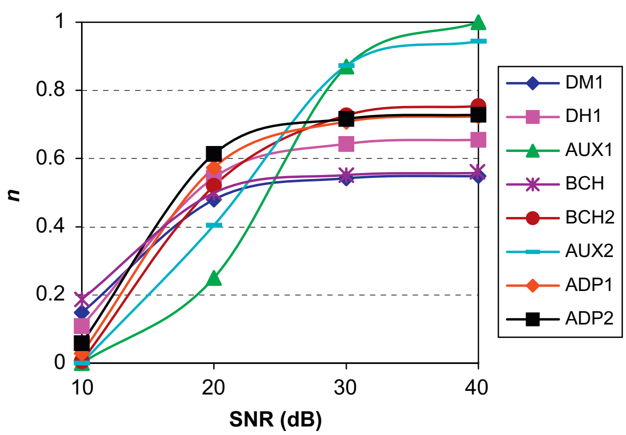

Fig. 3. Energy efficiency for 10 hops.

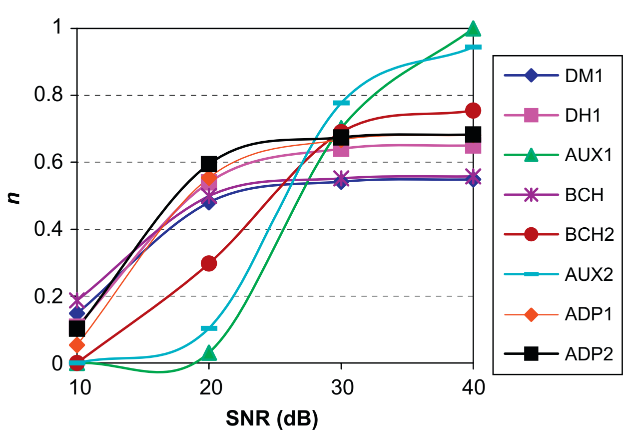

Fig. 4. Energy efficiency for 25 hops.

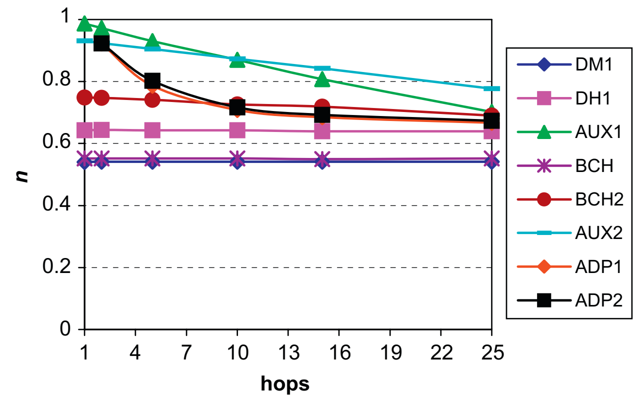

Fig. 5. Energy efficiency for 30 dB.

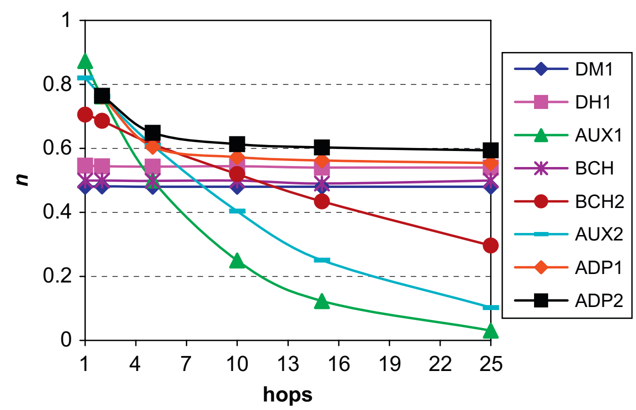

Fig. 6. Energy efficiency for 20 dB.

Figs. 2–4 show the results obtained for the energy efficiency of some packets as a function of SNR, for different number of hops (1, 10 and 25). Only the main packets are shown in the graphs. Although other figures with different number of hops and other packets could be shown, these figures illustrate well the behavior of the energy efficiency of different error control schemes. For a single hop network (Fig. 2) the AUX1 packet has the best efficiency for SNR values higher than 15 dB, approximately. When the SNR is below this value, the BCH3 packet is the best.

With 10 hops (Fig. 3) the relative performance among the packets begins to stabilize. The AUX1 packet only has the higher efficiency for channel conditions above 30 dB. For approximately 30 dB 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. This behavior of the different error control strategies is approximately the same for 25 hops (Fig. 4).

Figs. 5–7 show the efficiency η as a function of the number of hops for SNR values of 10, 20 and 30 dB. From these

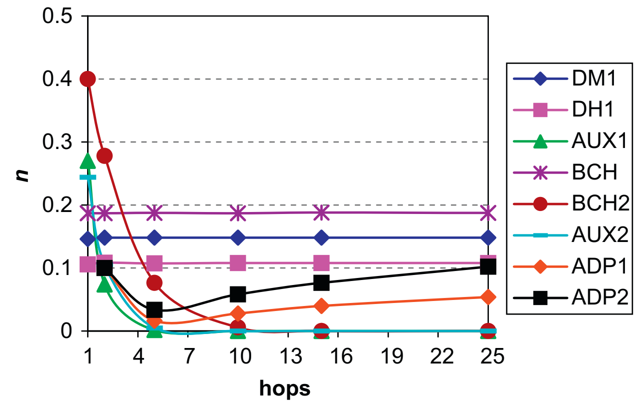

Fig. 7. Energy efficiency for 10 dB.

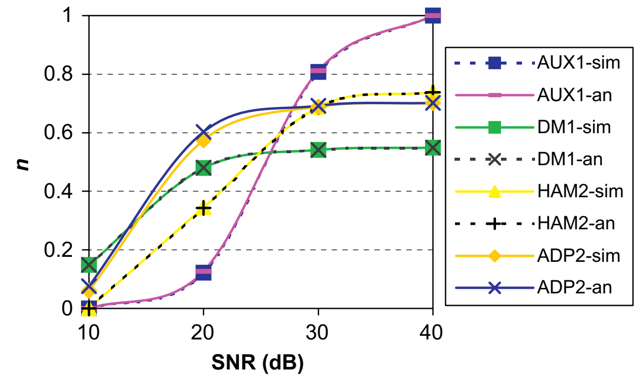

Fig. 9. Energy efficiency for simulation and analytical model.

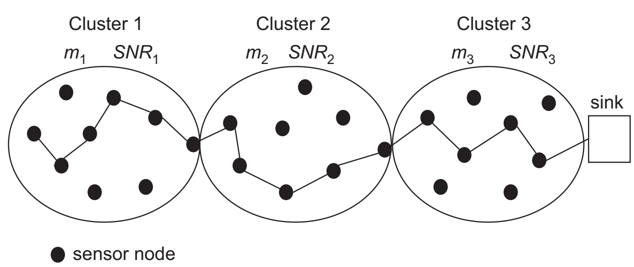

Fig. 8. Sensor network route with 15 hops.

graphs some conclusions taken from Figs. 2–4 can be better observed. The packets with best energy efficiency for about 30 dB are the AUX1 and AUX2 packets (Fig. 5), for 20 dB the adaptive schemes (Fig. 6) and about 10 dB the BCH packet (Fig. 7). The most interesting observation is that the energy efficiency of the packets with retransmission is independent of the number of hops. While the efficiency for the packets without ARQ varies with the SNR and the number of hops, the efficiency of DM1, DH1 and BCH varies only with the SNR. This is an important characteristic of the ARQ Bluetooth packets. Other observation is that the adaptive schemes tend to converge to the DH1 packet when the number of hops increases, because they use the DH1 packet after the fifth hop.

5. Simulation model

In order to validate the analytical model, simulations were implemented using the Matlab® software and are described in this section. The network considered is shown in Fig. 8, where a sensor must send data to the sink node. This is only one of many possible structures within the sensor network, which can have different topologies.

Each cluster of Fig. 8 may be considered as an environment with different channel conditions and consequently, with different values of m and SNR for the links. The network has 15 hops from a sensor node to the sink. In Section 4 it was shown that with 15 hops the relative performance between the packets begins to stabilize. Although with more hops the performance of the packets can be different, the packet with best energy efficiency remains the same. The results are average values obtained with several simulations.

It is being assumed that the Bluetooth scatternet was formed and that the scheduling policy and the routes are also defined, using protocols as the proposed in [6–9]. It is also considered that the Bluetooth device is in the connected state. The packet data is generated by a sensor node, that sends it to the next node, and so on, until it reaches the sink node. In the simulations a sensor sends 100,000 packets to the sink (n_{pac}=100,000).

Using Eqs. (11) and (12) the error probabilities for each packet may be evaluated. These probabilities are given as a function of the SNR. When a node receives a packet it is verified whether errors have occurred in the reception. If there were no errors the packet is sent to the next node. In packets with ARQ, an acknowledgement is sent to the transmitter indicating the success of the transmission. On the other hand, if errors are detected, three actions can occur, depending of the packet type. In packets with ARQ a packet indicating unsuccessful transmission (negative acknowledgement) is sent to the transmitter, so the packet will be sent again. In packets without ARQ, the packet is discarded (with CRC) or sent to the next node (no CRC). It is important to note that the NULL packet used to acknowledge or not a transmission can also be corrupted, although it does not carry any data except the access code and header field. If the NULL packet is corrupted the node has to send the data packet again.

The energy consumed E is updated on each transmission and reception of a packet, using the total number of bits transmitted/received. When a packet is received with errors and the error control scheme of the packet cannot correct it or ask a retransmission, the variable n_{error} is updated. At the end of simulation the reliability and the energy efficiency are evaluated.

Fig. 9 shows the results obtained for the simulation and analytical models for some packets in a sensor network with 15 hops and fading parameter $m = 1$. The simulation results

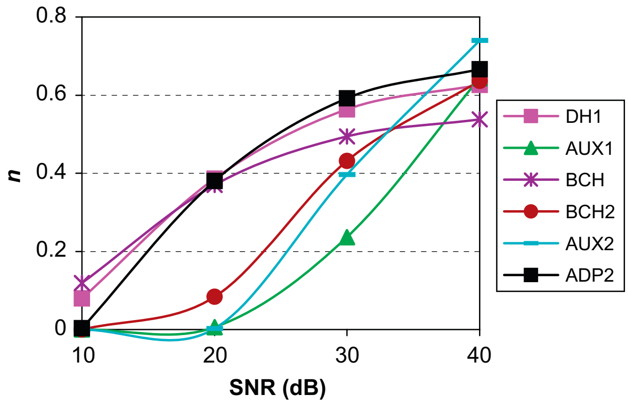

Fig. 10. Energy efficiency for $m_1 = m_2 = m_3 = 0.5$.

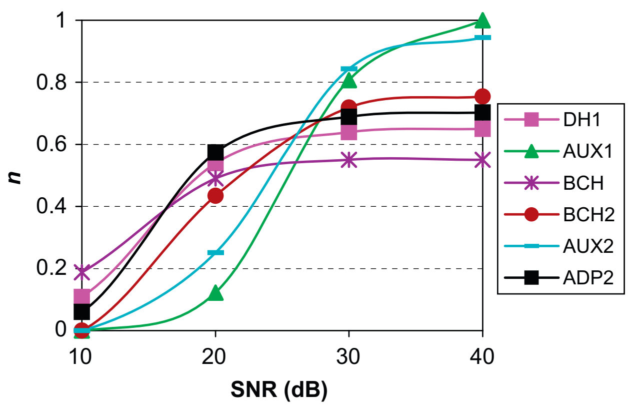

Fig. 11. Energy efficiency for $m_1 = m_2 = m_3 = 1$.

validate the analytical model, as the energy efficiency is almost the same for all packets. Only the adaptive scheme has a little difference due to the packet changes.

6. Results for different channel conditions

6.1. Results for different values of *m*

Figs. 10 and 11 show the energy efficiency of the packets for the network of Fig. 8 for different values of m using simulation. Only the main packets are shown in the graphs. When the parameter m is low (Fig. 10), the fading is more severe and the energy efficiency of the packets is bad. For higher values of m (Fig. 11) the energy efficiency increase for all packets. However, the relative performance of the packets is not the same. For instance, the AUX1 packet is the best packet for $m = 1$ and SNR > 35 dB, approximately. For $m = 0.5$ the AUX1 packet never is the best energy efficient packet. But it can be noted from Figs. 10 and 11 that when the channel quality is good, a powerful error correcting scheme is not necessary and the AUX1 or AUX2 packets can be utilized. For intermediary conditions, the adaptive scheme

Table 4. Adaptive packet selection scheme

SNR/*m*	0.5	1	1.5
10	BCH	BCH	BCH
20	DH1	DH1	DH1
30	DH1	AUX2	AUX1
40	AUX2	AUX1	AUX1

ADP2 and the DH1 packet have the best energy efficiency. If the channel conditions are bad the BCH is the most energy efficient packet.

6.2. Adaptive packet selection using channel state information

The results of previous sections indicate that for each different channel condition a specific packet has the best energy efficiency. For sensor networks deployed in large areas the channel conditions will be different for sensor nodes in different areas. Thus, it is proposed an adaptive packet selection scheme based on channel state (ADPC). For each value of m and SNR a different packet (and error control) will be applied.

In order to estimate the values of SNR and m, a method as the proposed in [16,17] has to be used. In a sensor network with low data rate this is not an easy task, because there are few samples of bits that are used in the estimation methods. But after some data transmissions, the estimated value tends to converge to the real value. The sensor node must have this feature, which is suitable only for some applications of sensor networks. The energy spent by the estimators to evaluate the values of m and SNR has to be considered for a real application. In this work, the results may serve only as a benchmark if the packet selection strategy is adopted. If great gains can be achieved with the ADPC scheme, it can be useful even if the energy spent by the estimators are considered, as the energy consumed in the execution of one instruction is many times higher than the energy used to transmit one bit [2].

The packet selection for each channel condition is based on Figs. 10 and 11. For instance, for $m = 1$ (Fig. 11) the best packet for SNR = 40 dB is the AUX1, for 30 dB is the AUX2 packet, for 20 dB the DH1 packet and for 10 dB BCH packet. Actually, for 20 dB the ADP2 scheme has the best energy efficiency. But for the adaptive packet selection scheme it is needed a single packet to be used for each value of m and SNR. Table 4 shows the packet selection for each case. Four values of SNR (40, 30, 20 and 10 dB) and three values of m (0.5, 1 and 1.5) were chosen to evaluate the ADPC scheme, ranging from bad channel quality to good channel quality. For instance, if the measured channel state is approximately $m = 1$ and SNR = 30 dB the AUX2 packet will be selected.

Fig. 12 shows the energy efficiency for the network of Fig. 8 for different values of m_1, m_2 and m_3. All the results

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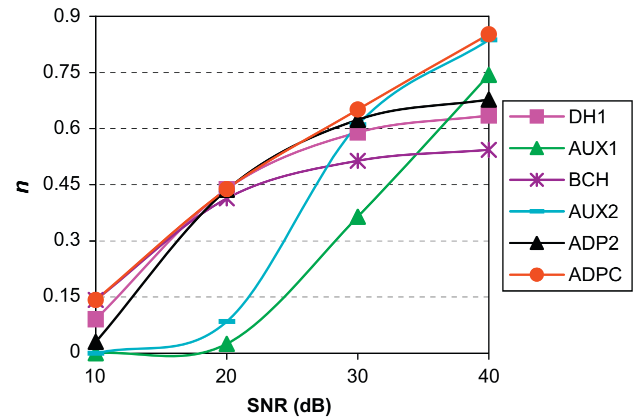

Fig. 12. Energy efficiency for $m_1 = 0.5$, $m_2 = 0.5$ and $m_3 = 1.5$.

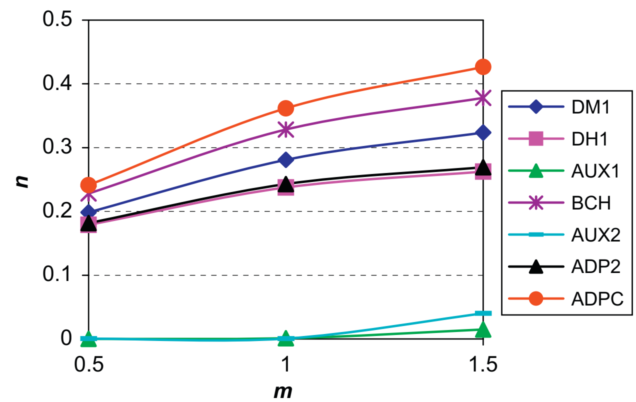

Fig. 13. Energy efficiency for $\mathrm{SNR}_1 = 30$, $\mathrm{SNR}_2 = 10$ and $\mathrm{SNR}_3 = 20$ dB.

in this section were obtained through simulations. The analytical model could be used, but additional equations would have to be derived for the ADPC scheme. The SNR is considered to be the same for all links ($\mathrm{SNR}_1 = \mathrm{SNR}_2 = \mathrm{SNR}_3$). The adaptive channel (ADPC) scheme has the best energy efficiency for all cases. For some channel conditions its performance is very close to the other packets, but in other cases the difference is higher. Actually, the ADPC scheme is better when more packet changes have to be made. For instance, in scenario of Fig. 12, the ADPC scheme always selects the BCH packet for 10 dB and the DH1 packet for 20 dB. In this case its performance is equal to BCH and DH1 packets. For 30 dB the ADP scheme selects the DH1 packet for $m = 0.5$ and the AUX1 packet for $m = 1.5$, so the gain in energy efficiency is greater.

Fig. 13 shows the energy efficiency for different values of SNR_1, SNR_2 and SNR_3 and fixed m values ($m_1 = m_2 = m_3$) and Fig. 14 for different values of m and SNR, according to Table 5 . The ADPC scheme also has the best energy efficiency for all these cases. Its energy efficiency is at least equal to the best packet for determined channel condition.

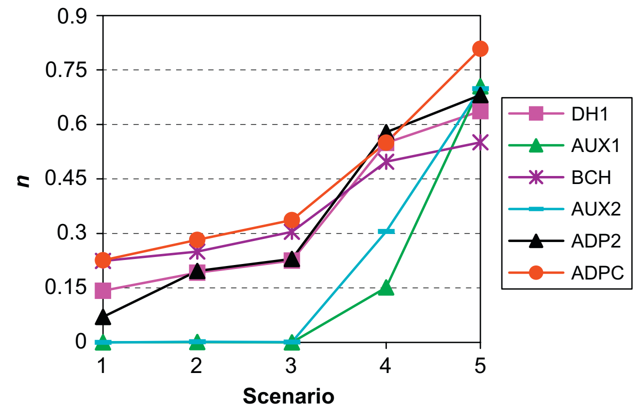

Fig. 14. Energy efficiency for different network scenarios.

The gain in energy efficiency of the ADPC scheme is higher when the difference of the channel condition between the links is high. If the channel state is the same for all links, as in the results of Section 4, the ADPC scheme will have energy efficiency equal to the best packet for that specific m and SNR.

The other packets have good energy efficiency for specific channel conditions. For instance, the BCH packet is the best packet for low values of m and/or SNR, whilst the AUX1 packet has the best energy efficiency for high values of m and SNR. In scenario 1 of Fig. 14 the BCH packet and the ADPC scheme have almost the same energy efficiency. This is because in this scenario the wireless channel is almost the same for each link (the packet error rates $\mathrm{PER_f}$ and $\mathrm{PER_r}$ for $m = 1$, $\mathrm{SNR} = 10$ and $m = 0.5$, $\mathrm{SNR} = 20$ are very close). The channel in scenario 1 can be considered in bad conditions, so the BCH packet has energy efficiency higher than the other packets. As in scenario 1, in the scenario 4 the $\mathrm{PER_f}$ and $\mathrm{PER_r}$ are almost the same for all links. In scenario 4 the ADP2 scheme achieved energy efficiency a little higher than of the ADPC scheme. In this scenario the wireless channel also has few variations in the links. In scenarios 2, 3 and 5 the ADPC scheme is superior to the other packets.

7. Conclusion

This paper presented an analytical and a simulation model to evaluate the energy efficiency of Bluetooth data packets in Nakagami-m fading channels. New Bluetooth packet types were introduced using custom error control schemes in the AUX1 packet. These modifications include a CRC for error detection (without ARQ), BCH code with and without CRC and Hamming code with and without CRC. Two adaptive error control schemes that change the error control strategy according to the number of hops a packet traveled through the sensor network were proposed. The results have shown that for good channel conditions the packets with little or no error protection (AUX1 and AUX2) present the best energy

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Table 5. Network scenarios

Scenario	m_1	m_3	m_3	SNR_1	SNR_2	SNR_3
1	1	0.5	1	10	20	10
2	1.5	0.5	0.5	30	10	30
3	1.5	1	0.5	30	10	20
4	1	0.5	1	20	30	20
5	1.5	1	1.5	30	40	20

efficiency. For low values of SNR and the fading parameter m, the BCH packet is the most efficient, because of its ability to correct more errors, despite more energy consumption. In intermediary situations the adaptive schemes ADP1 and ADP2 have the best performance. If the channel conditions in the network have great variations, the adaptive packet selection scheme based on channel state (ADPC) is the best choice. In the case of a network designer who has information about the channel conditions, these considerations may help in what scheme to use for each situation. The analytical and simulation models presented in this paper and the error control schemes proposed, may well be adapted to other wireless technologies for sensor networks.

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