Link Adaptation in IEEE 802.15.4-Based Wireless Body Area Networks

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***Abstract*—In this paper we consider an IEEE 802.15.4-based Wireless Body Area Network, where wearable sensor devices are distributed on a body and have to send the measured data to a coordinator. The Carrier Sense Multiple Access with Collision Avoidance algorithm defined by the standard is used as Medium Access Control protocol, whereas different modulation schemes are assumed to be available at the physical layer. We propose a novel Link Adaptation (LA) strategy, where nodes select the modulation scheme according to the experienced channel quality and level of interference. The novelty lays in the fact that in case of large Signal-to-Noise Ratio and low Signal-to-Interference Ratio nodes increase the bit rate, instead of reducing it, as largely done in the works present in the literature. The reduction of the bit rate, in fact, allows to decrease the time the channel is occupied and, therefore, the collision probability. Performance is evaluated in terms of packet error rate and results achieved with and without LA are compared. Results show that the proposed strategy improves performance.**

I. Introduction

Wireless Body Area Networks (WBANs) have lately gained increasing attention and are being widely researched. There are many potential applications where WBAN technology can be exploited, including medical sensing and control, fitness monitoring, personal audio or video, wearable computing, location awareness and identification [1], [2].

Nowadays, there is no standard developed especially for WBANs. In 2007, IEEE 802.15 Task Group 6 (TG6) was established and it is still working to develop an international communication standard optimized for low power devices and operation on, in or around the human body to serve a variety of applications, either medical or non-medical, such as consumer electronics, personal entertainment and others [3], [4].

Several MAC protocols have been proposed for WBANs, see for example [5]–[8]. The proposals in [7], [8] are based on IEEE 802.15.4 [9], a well known short-range wireless communication standard, which was specifically devised to support low power, low cost, and low data rate networks.

In this paper we consider a WBAN, where wearable sensor devices, hereafter denoted as *nodes*, are distributed on a human body with the aim of reporting the measured data to a coordinator which is located on the body, as well. We assume that nodes use the Medium Access Control (MAC) protocol defined by the IEEE 802.15.4 and can choose among different modulation schemes at the physical layer (PHY). A novel Link Adaptation (LA) strategy is proposed to improve performance. The possibility of selecting different bit rates in IEEE 802.11 networks has been significantly investigating, see for example [10], [11]; whereas only few papers are devoted to LA in 802.15.4 networks, for example [12], where a variable data rate scheme is proposed with the aim of reducing the average power consumption. However in all the above cited papers, as in the large amount of literature devoted to LA in cellular networks [13], the general idea is to change modulation and/or coding scheme so that lower bit rates (i.e., more robust modulation/coding when the overall bandwidth is set) are used in case of ”bad” channel conditions, and higher bit rates when the channel is ”good”. The channel is considered as ”bad” in case of low Signal-to-Noise Ratio (SNR), due to path loss, shadowing or fading problems, or when the Signal-to-Interference Ratio (SIR) is low. In both cases, the use of a more robust modulation/coding is supposed to reduce the error probability. The novelty in our work lays in the idea that, in case of large SNR but low SIR, owing to the use of a random MAC schema, it is better to use a higher bit rate. Larger bit rates, in fact, reduce the time needed to send a packet and consequently the interference caused by it. After showing that in some circumstances the use of a modulation scheme characterised by larger bit rates improves performance, we compare performance in terms of packet error rate (PER) when the LA strategy proposed is used and not. Results show that our proposal improves performance in many cases. Performance is evaluated in a very realistic scenario where radio channel characteristics are modelled according to the 3GPP proposal [14].

The rest of the paper is organized as follows. Section II describes the considered scenario, whereas Sections III and IV are devoted to the PHY and MAC layer protocols, respectively. Section V illustrates our proposal on the link adaptation and, finally, Section VI shows numerical results and section VII concludes the paper.

II. The Reference Scenario

We consider a WBAN composed of a set of nodes, which monitor body parameters, like heartbeat, body temperature, and movements. We consider up to ten nodes, deployed in different parts of the body as shown in Fig. 1. Small movements of the body are accounted for in our simulations. Results are, in fact, achieved by averaging over slightly different positions of the nodes in the body (without changing the considered parts of the body listed in Fig. 1).

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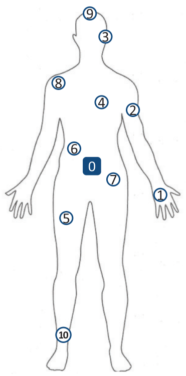

Fig. 1. Position of the nodes in the considered WBAN.

We consider a star topology: the coordinator, which is placed in the center of the body, periodically sends a query to all the nodes asking for data and, upon reception of this query, the WBAN nodes transmit their packets to the coordinator through direct links. One packet per query is generated by nodes and we assume that nodes have to transmit data having the same size.

The channel loss, denoted as A, is modeled according to the 3GPP proposal [14] for WBANs:

$$A(d)[dB] = A_0 + 10\,n\,\log(d/d_0) + s, \tag{1}$$

where d is the distance between transmitter and receiver, A_0 is the path loss in dB at a reference distance d_0 ($A_0 = 35.2$ dB for $d_0 = 0.1$ m), n is the path loss exponent ($n = 3.11$), and s is a random Gaussian variable, having zero mean and standard deviation $\sigma = 6.1$ dB.

For what concerns the packet capture model, a threshold model is accounted for. We assume that a packet is correctly received when the two following conditions are both satisfied:

- $P_{\text{R}} > P_{\text{R}_{\text{min}}}$, where P_{R} is the received power given by: $P_{\text{R}}[dBm] = P_{\text{tx}}[dBm] - A[dB]$, where P_{tx} is transmit power and A is given by eq. (1). $P_{\text{R}_{\text{min}}}$ is the receiver sensitivity;
- $$\frac{C}{I} \geq C/I\mid_{min} \tag{2}$$
  where C is the power received from the useful transmitter and I is the total power received from the interfering nodes. $C/I\mid_{min}$ is the minimum SIR ensuring the correct reception of a packet.

The values of $P_{\text{R}_{\text{min}}}$ and $C/I\mid_{min}$ depend on the modulation scheme used by the transmitter and are evaluated in the following Section.

III. Physical Layer

IEEE 802.15.4 standard provides specifications for operating in three different frequency bands: the 868 MHz band, available in Europe, the 915 MHz band, available in the US, and the 2.45 GHz ISM band, available worldwide. Each of these bands is divided into several channels.

We consider the 2.45 GHz band, where the bandwidth allocated to each channel is $B = 5$ MHz and the bit rate $R_b = 250$ kbit/s. The modulation used is Offset Quadrature Phase Shift Keying (O-QPSK) with half-sine pulse shaping, and direct sequence spread spectrum (DSSS) as spreading technique, with a spreading factor $f = 8$.

Beside the IEEE 802.15.4 O-QPSK we consider the modulation used in one of the IEEE 802.15 TG6 PHY proposals [15], that is Differential Phase Shift Keying with L modulation levels (L-DPSK), with $L = \{2, 4, 8\}$.

We assume that LA is performed by varying the bit rate, once we fix a common bandwidth, that is the bandwidth of the IEEE 805.15.4. We also assume that in the case of L-DPSK modulation a square root raised cosine (SRRC) filter for equalization, with roll-off factor $\alpha = 0.2$, is used and that a DSSS technique with spreading factor, f, equal to 8 (as in the case of 802.15.4) is applied. In such conditions the bandwidth is given by:

$$B = \frac{R_b}{log_2(L)} f(1+\alpha). \tag{3}$$

By setting $B = 5$ MHz we can derive the bit rates, R_b, achievable in the case of L-DPSK modulations (see Table I).

The performance of O-QPSK with half-sine pulse shaping in terms of the bit error probability P_{eb} in an additive white gaussian noise (AWGN) channel can be expressed as:

$$P_{eb} = \frac{1}{2} erfc\sqrt{W} \tag{4}$$

where W is the conventional SNR, given by: $W = \frac{P_{\text{R}}}{2N_0 R_b}$, where P_{R} is the received power, N_0 is the bilateral power spectral density of the gaussian noise, and *erfc* is the complementary error function, defined as:

$$erfc(x) = 1 - erf(x), \qquad erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-y^2} dy. \tag{5}$$

The bit error probability for L-DPSK modulation in AWGN channel with SRRC equalization, can be expressed as:

$$P_{\text{eb}} = \frac{1}{2} e^{-\frac{W}{b}}, \tag{6}$$

in the case $L = 2$ and

$$P_{\text{eb}} = \frac{1}{log_2(L)} erfc\left[\sqrt{\frac{W}{2b} log_2(L)} \frac{\pi}{L}\right], \tag{7}$$

in the case $L > 2$. b is the normalized equivalent noise bandwidth, that is set equal to 1.2.

We assume that a packet composed of N_{bit} bits is successfully received if all its bits are correct, which happens with probability $(1 - P_{\text{eb}})^{N_{\text{bit}}}$. The receiver sensitivity is defined as the received power so that the latter probability is equal to 0.99 [9].

The value $C/I\mid_{min} = 1.3$ dB for O-QPSK has been derived experimentally [16]. Table I summarizes the bit rates and the values of $C/I\mid_{min}$ for the different modulation schemes. The values of $C/I\mid_{min}$ for L-DPSK are estimated from the one measured for O-QPSK, by adding the same amount that also shifts the P_{eb} curves over the SNR axis.

TABLE I
MODULATIONS

Modulation	Bit rate [Mbit/s]	$\frac{C}{I}\|_{min}$ [dB]
O-QPSK	0.25	1.3
2-DPSK	0.5	2.0
4-DPSK	1	3.4
8-DPSK	1.5	7.4

IV. MEDIUM ACCESS CONTROL LAYER

The beacon-enabled mode of the IEEE 802.15.4 is considered.

According to the standard [9], the access to the channel is managed through a superframe, starting with a packet, called beacon, transmitted by the coordinator. The superframe is divided into two parts: a Contention Access Period (CAP), during which nodes use a slotted CSMA/CA, and a Contention Free Period (CFP), composed of slots, called Guaranteed Time Slots (GTSs), allocated by the coordinator to specific nodes. The use of GTSs is optional and they are not allocated in this paper. The superframe duration depends on the value of an integer parameter ranging from 0 to 14, called superframe order, denoted as SO, and is equal to: $15.36 \cdot 2^{SO}$ $[ms]$.

The CSMA/CA algorithm is implemented using units of time called backoff periods.

Each node maintains two variables for each transmission: NB and BE. NB is the number of times the CSMA/CA algorithm was required to backoff while attempting the current transmission; its initial value is 0 and its maximum value is NB_{max}. BE is the backoff exponent related to the maximum number of backoff periods a node will wait before attempting to assess the channel; its initial value is BE_{min}, and its maximum value is BE_{max}. In CSMA/CA first, NB and BE are set to the initial values. Then, the node enters in backoff for a random number of backoff periods in the range (0, $2^{BE}-1$) [step (1)]. After this delay, the node performs sensing for two subsequent backoff periods. If the channel is found free in both the backoff periods, the transmission starts. Otherwise, if it is found busy (during the first or the second backoff period), NB and BE are increased by 1, ensuring that BE is not larger than BE_{max}. If the value of NB is lower or equal to NB_{max}, the algorithm returns to step (1); otherwise the algorithm will unsuccessfully terminate, meaning that the node does not succeed in accessing the channel.

An acknowledge mechanism is performed: each node, after the transmission of a packet, waits for the acknowledge packet (ACK) for an interval of time equal to 0.86 $[ms]$. In case the acknowledge is not received the packet is retransmitted till the maximum number of retries is reached, or the superframe ends. A maximum number of three retries is allowed here.

V. THE LINK ADAPTATION

We propose a LA strategy based on the following considerations. When the SNR is low, meaning that the node is far from the coordinator or a deep shadowing occurs, the bit rate is decreased, so that a lower value of $P_{\mathrm{R_{min}}}$ is required and the probability to correctly receive the packet increases. When, instead, the SNR is high it can happen that packets are not successfully received because they collide with packets coming from other nodes. In this case, higher bit rates, which lead to packets transmitted in a shorter time, can be more suitable to reduce the probability that a collision happens.

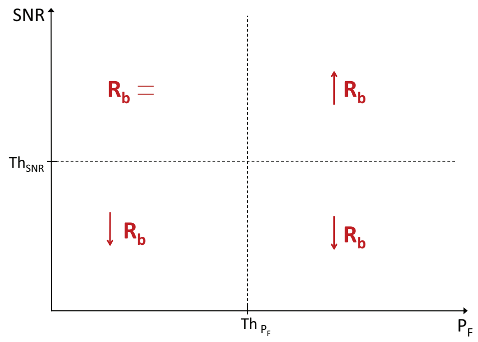

Fig. 2. Scheme of the proposed Link Adaptation algorithm.

Fig. 2 summarizes our LA algorithm. We assume that at the beginning, all nodes start with IEEE 802.15.4 O-QPSK modulation. As stated above, we are considering a beacon-enabled network, therefore the nodes wait for the beacon (which corresponds to the query) coming from the coordinator, before sending their data. From the measure of the received beacon power each node estimates the SNR which characterizes the channel between the coordinator and itself: if the estimated SNR is below the threshold Th_{SNR} the node decrements its bit rate. Otherwise it estimates the SIR (i.e., the level of interference on the channel) through the evaluation of a failure probability, denoted as P_F, that is the probability that a packet sent is not received by the coordinator. This probability is given by the ratio between the number of unacknowledged packets (i.e., packets for which the ACK is not received) and the number of packets which are sent on the channel (including retransmissions):

$$P_F = \frac{\sharp \textit{not received ACKs}}{\sharp \textit{sent packets}}. \tag{8}$$

P_F is evaluated counting the unacknowledged and sent packets over a window of 20 superframes. If P_F is above the threshold Th_{P_F}, the node is in a situation where many of its packets are lost and, since the channel quality is good (high SNR), these losses are due to interference. Thus, in this case the bit rate is incremented, in order to reduce the packet transmission time and the probability of collision. If $P_F < Th_{P_F}$ the node does not change the bit rate it is using.

VI. NUMERICAL RESULTS

In this Section we report results achieved through a simulator written in C. Results are achieved by simulating 25.000

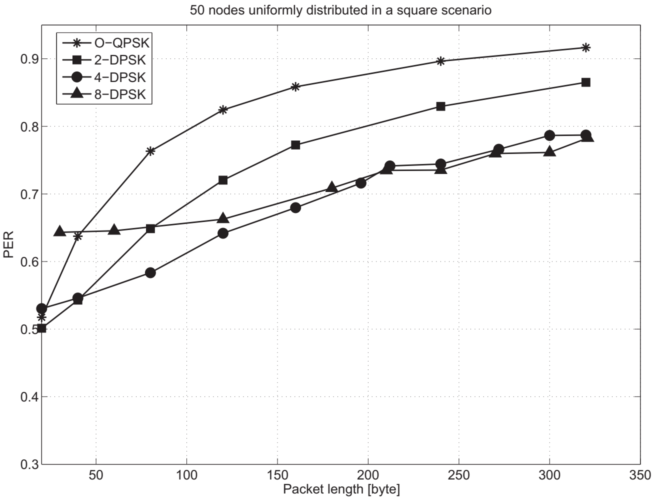

Fig. 3. PER for $N = 50$ nodes uniformly distributed in a square scenario.

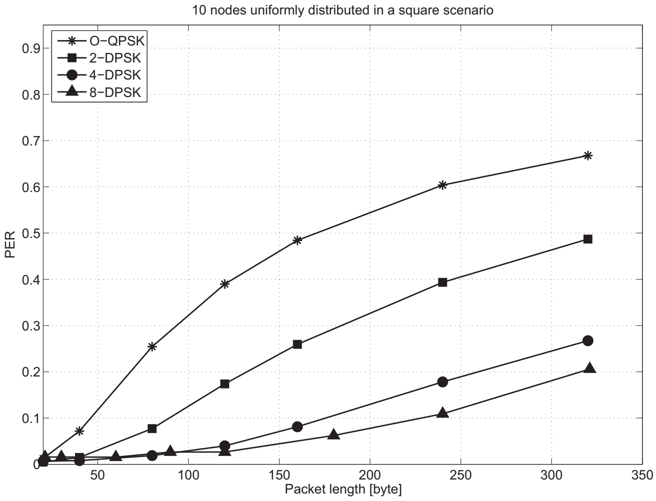

Fig. 4. PER for $N = 10$ nodes uniformly distributed in a square scenario.

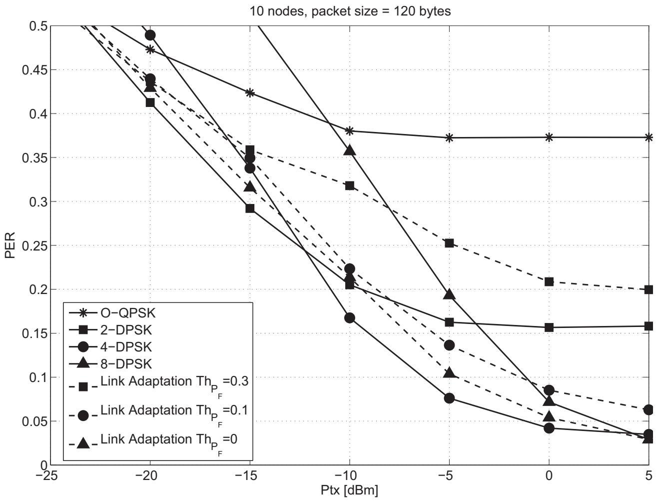

Fig. 5. PER for a WBAN with $N = 10$ nodes.

superframes, meaning 25.000 transmissions from the nodes to the coordinator. We set $NB_{max} = 4$, $BE_{min} = 3$, $BE_{max} = 5$, $SO = 4$, and consider a noise bilateral power spectral density $N_0 = 7.2 \cdot 10^{-19}$ W/Hz.

Performance is evaluated in terms of average PER, which is the probability that a packet generated by a node is not received by the coordinator. This can happen because the node cannot access the channel (the number of times the node tries to access the channel exceeds NB_{max}), or because it cannot transmit the packet correctly within the three retries ($P_{\mathrm{R}} \leq P_{\mathrm{R_{min}}}$ or $\frac{C}{I} < \frac{C}{I}\mid_{min}$).

First, we run simulations for N uniformly distributed nodes in a square scenario. In this scenario, the side of the square and the transmit power of the nodes are set so that no problems due to connectivity for any of the considered modulations occur, that is the received power at the coordinator is always higher than $P_{\mathrm{R_{min}}}$. The side of the square is equal to 7 m and the transmit power is set to 0 dBm. In this way we can evaluate how the use of the different considered modulations affects the performance when packets are lost only because of interference. Fig. 3 and 4 show the PER as a function of the packet length in such a scenario with $N = 50$ and $N = 10$ nodes, respectively. It can be noticed that, among the considered modulation schemes, there is not one single modulation which outperforms the others for every traffic load. In fact, for short packets, O-QPSK and 2-DPSK achieve a lower PER than 4-DPSK and 8-DPSK, while for longer packets the situation is the opposite. The advantage of the shorter channel occupancy of packets transmitted at a higher bit rate is increasingly relevant when the packets length increases, while for packets composed of a small number of bytes O-QPSK performs better. This is due to the higher $\frac{C}{I}\mid_{min}$ requested by the modulations with a higher number of levels.

Fig.s 5 and 6 show the PER as a function of the transmit power, P_{tx}, in the WBAN scenario described in Section II, for a fixed packet length of 120 bytes, considering $N = 10$ and $N = 5$ nodes, respectively. Continuous curves show the performance achieved when all the nodes in the WBAN use the same modulation, while dotted curves represents the cases where our LA algorithm is applied. The LA curves are achieved by fixing $Th_{SNR} = 11$ dB and by varying Th_{P_F}. As we can see the optimum value of Th_{P_F} varies by changing P_{tx}: it assumes a large value when P_{tx} is low and it is low (equal to zero, meaning that the bit rate is simply increased when $SNR > Th_{SNR}$), when P_{tx} is high. This can be clearly seen in the case $N = 5$. This is due to the fact that when P_{tx} is low the network is limited by connectivity problems, whereas for large values of P_{tx} the main problem are interferences.

VII. Conclusion

In the paper we consider a WBAN composed of nodes transmitting data to a coordinator located on the body. Nodes are assumed to use the MAC protocol defined by the

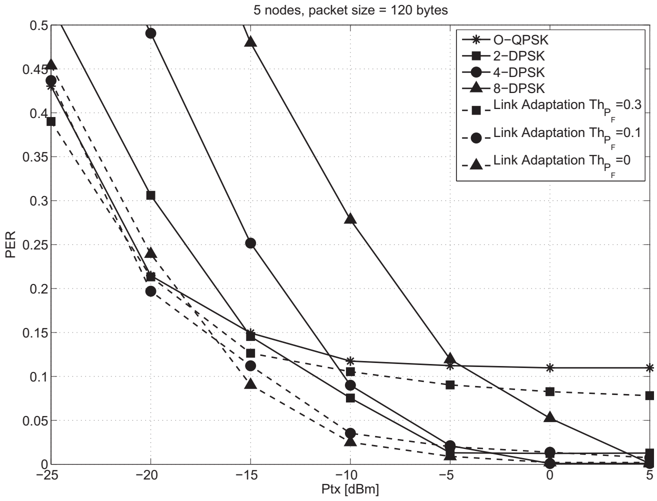

Fig. 6. PER for a WBAN with $N = 5$ nodes.

IEEE 802.15.4 standard and different modulation schemes are available. A link adaptation strategy, allowing nodes to change the modulation scheme according to the channel quality estimated and the level of interference present, is applied. Results in terms of PER show that the strategy proposed allows to improve performance in many scenarios.

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