Design and Performance of Contention Based MAC Protocols in WBAN for Medical ICT Using IR-UWB

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Abstract—**This paper focuses on wireless body area networks (WBAN) targeted for medical ICT applications. The studied network follows a typical IEEE 802.15.4 beacon-enabled star topology. We simulate the collection of medical data from patients using wireless sensors. Impulse radio ultra wideband (IR-UWB) is chosen as a physical layer technology, in compliance with the IEEE 802.15.4a standard. Two random access methods, slotted Aloha (S-Aloha) and preamble sense multiple access (PSMA) are studied in terms of throughput and energy consumption. This paper has two main objectives: 1) to address realistic performance of the two selected MAC protocols, accounting for false alarm, miss-detection and capture effect, when using IR-UWB; 2) to obtain feedback information on the design of medical networks that use the IEEE 802.15.4 beacon-enabled star topology. Therefore, the performances are obtained increasing the number of active sensors, varying in parallel typical superframe parameters as beacon order and superframe order to test the reaction of the network at the introduction of an inactive period.**

I. INTRODUCTION

Aging of the population and increasing demands for health care are pushing medical ICT towards the use of wireless technologies in order to reduce hospitalizations and costs. Nowadays, technology improvements and cost effective chipsets make the concept of wireless body area network (WBAN) feasible [1], although several challenges are still open. The task group IEEE 802.15 TG6 is currently aimed at developing a standard specific for WBANs. As new standards are likely to appear soon, some of the existing technologies are already appealing for health care assistance.

As people need to monitor a different number of vital parameters, a large number of sensors may be deployed on the human body. Therefore, a stringent requirement for wireless medical networks is to emit radio signals at power levels that are non harmful for human tissues. In addition, reliable data communication is essential for enabling doctors to produce diagnosis. Furthermore, easy to use and wear, long lifetime and low costs are the key aspects that can determine the success of wireless health monitoring. In such scenario, impulse radio ultra wideband (IR-UWB) can play a great role as a candidate physical layer technology. IR-UWB, already standardized by the Federal Communications Commission (FCC) in 2002 [2], is a technology that attracted great attention in the past few years and that is nowadays regulated in different parts of the world, though differently. This paper focuses on WBAN using IR-UWB as a physical layer technology and the typical IEEE 802.15.4 beacon-enabled star topology for network organization. UWB is compliant with the recent standard IEEE 802.15.4a [3] that can also enable accurate location and tracking systems. In the beacon-enabled star topology, data exchange can be done either during a contention access period (CAP) or during a contention free period (CFP). This paper addresses data transactions that occur during the CAP by means of random access protocols.

The chosen target use scenario is a waiting room (e.g., in a hospital), in which patients wearing wireless sensors enter in a serialized fashion. For each person, the same vital parameters are monitored, and data are transmitted to the coordinator (sink) of the network without advanced routing. Two medium access control protocols (MAC) are used: the slotted Aloha (S-Aloha) and the preamble sense multiple access (PSMA) proposed in [4]. Given the carrier-less nature of the IR-UWB signal, specific events as false alarm and miss-detection have been taken into account in the case of sensors using a non-coherent energy detector (ED) receiver. The simulations have been carried out with and without capture effect at the sink. Performances are evaluated in terms of average channel throughput and energy consumption when increasing the number of active sensors, and changing typical superframe parameters, as beacon order (BO) and superframe order (SO). In fact, both are used to define the network duty cycle (δ) by the ratio between the superframe duration and the beacon interval. As δ results to be less than one, an inactive period is introduced in the network. The impact of the inactive period on network performance is addressed. The remainder of the paper is organized as follows: Section II defines the system concept; Section III introduces the MAC protocols; Section IV and Section V show results and conclusions, respectively.

II. SYSTEM CONCEPT

A. Wireless medical applications

WBAN is a short range wireless network that can be fruitfully exploited in medical related systems. Medical WBAN devices can be divided into wearable and implantable ones. This paper considers wearable sensors located on or close to the body. Effective and reliable data transmissions must be ensured all the time. In this paper, typical vital parameters such as electrocardiogram (ECG), electroencephalogram (EEG), body temperature, heart rate and blood oxygenation are included. Payload values for those applications are given in [5]. A number of sensors can participate in collecting a single vital parameter, although here we assume that each simulated node generates the aggregated payload for each of them. Patients' vital signals are constantly monitored, thus yielding to a worst case. However, it is not necessary for a sensor to send data constantly.

B. *Impulse radio UWB and the IEEE 802.15.4a standard*

IR-UWB is chosen as a physical layer technology due to its potential low implementation costs and strict power emission limits. By definition, UWB signals have fractional bandwidth greater than 20%, or a bandwidth W of at least 500 MHz [2]. The UWB signal consists of the transmission of a number of disjoint pulses which are extremely short in time. The main characteristics are noise-like power emissions and very accurate time resolution of multipath components (which make it particularly appropriate for indoor environments). Furthermore, IR-UWB signals do not require the use of a carrier, hence not requiring upper and down frequency conversions. Non-coherent receivers based on energy detection (ED) result to be appealing since they allow for simplicity and low costs. The reference structure of a non-coherent ED receiver is shown in Figure 1. A common modulation scheme is binary pulse position modulation (BPPM). The integration time determines the amount of energy and noise captured by the receiver. The non-coherent decision is based on the collected energy within a specific time slot or chip. The decision variable Y is compared with a predefined threshold ε to determine the bit sent.

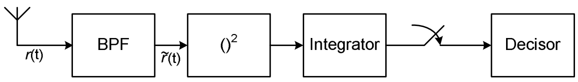

Figure 1. Reference architecture of the non-coherent energy detector.

C. *IEEE 802.15.4a*

The IEEE 802.15.4a is a physical layer standard amendment for IR-UWB to add location capability and improve performance in terms of data rate, range and power consumption [3]. Burst position modulation (BPM) is used to support usage of a common signalling scheme, where the symbol interval is divided in two subintervals, enabling binary position modulation. A burst of chips, located in either of those intervals, indicates the information bit [3]. A known preamble pattern, in the form of ternary sequence of pulses, is added at the beginning of a packet, to enable synchronization, channel estimation and clear channel assessment (CCA).

D. *False alarm and miss-detection*

A device that is either doing CCA, prior transmitting a frame, or is waiting for reception, must be able to asses the status of the radio channel. Given the carrier-less nature of the IR-UWB signal, both operations are less reliable than in narrowband communications. CCA for IR-UWB signals is done on the preamble, which is a sequence with known pattern. Two erroneous events might happen in preamble reception: false alarm and miss-detection. In our study, the statistical hypothesis H_0 describes the event of an idle channel (no preamble) and H_1 of a busy channel (preamble is present). The event of false alarm occurs when the channel is assessed busy upon H_0, and the event of miss-detection when the channel is assessed idle upon H_1. The probabilities corresponding to those events are referred to as probability of false alarm (P_{fa}) and probability of miss-detection (P_{md}), respectively.

Assuming the Additive White Gaussian Noise (AWGN) channel, the decision variable Y in input of a decision stage is a random variable following Chi-square distribution with $k=L_s N_p 2q$ degrees of freedom, where L_s is the number of symbols in the preamble, N_p is the number of pulses in a preamble symbol and $q=T_{\mathrm{int}}W$ is the time-bandwidth product, and T_{int} is the integration time. In the presence of hypothesis H_0, the Chi-square distribution is central, whereas with H_1 it is non-central. In the case that k is large enough (k >40), the Chi-square distribution can be approximated by the Gaussian distribution. The former approximation is especially valid in indoor environment which is rich of scattering, since the time-bandwidth product returns the number of multipath components. The probabilities of false alarm and miss-detection with Gaussian assumption are

$$\begin{cases} P_{\mathrm{fa}} = \Pr\{Y > \varepsilon | H_0\} = Q\left(\frac{\varepsilon'}{\sqrt{4L_s N_p q}}\right) \\ P_{\mathrm{md}} = \Pr\{Y < \varepsilon | H_1\} = 1 - Q\left(\frac{\varepsilon' - L_s \gamma}{\sqrt{4L_s N_p q + 4L_s \gamma}}\right) \end{cases} \tag{1}$$

where $\varepsilon' = \varepsilon - \mu_a$, γ is the received E_b/N_0 and μ_a is the mean of the decision variable Y under the hypothesis H_0 [4].

E. *Capture effect*

The classical analysis of radio packet switched networks using single packet reception assumes that collision of packets causes complete loss of information. However, in real networks, transmitters can be located at different distances from the sink or packets can experience different levels of fading [6]. Thus, even in the presence of simultaneous transmissions, a packet may be correctly received. Traditional concepts of capture effect do not directly apply to IR-UWB, due to the different nature of its transmission if compared to narrowband communications. In this work, we assume a presence of tagged station, while all other devices contribute to the interference. We analyze the capture probability when the transmission of the tagged station is burdened by only one interferer. In [3], the use of the Reed-Solomon code RS(63,55) is suggested. The capture probability P_c is defined as a function of the number of packet arrivals a as

$$P_c(a) = \begin{cases} P_d, \; a = 1 \\ \sum_{i=0}^{t} \binom{n}{i} P_e^i (1 - P_e)^{n-i}, \; a = 2 \\ 0, \; a > 2 \end{cases} \tag{2}$$

The symbol error probability is P_e=1- (1- P_b)^m, where m is the number of bits at the encoder, n=2^m -1, t is the error correction capability of the RS code, and P_b is the bit error probability in the presence of one interferer [4]

$$P_b = Q\left(\sqrt{\frac{\frac{2(E_{sb} - E_{i0})^2}{N_0}}{4(E_{sb} + E_{i0}) + 4qN_0}}\right). \tag{3}$$

In the equation above, E_{sb} and E_{i0} are the integrated energy for the symbol transmitted by the tagged user and the integrated energy of the symbol transmitted by the interferer, respectively. The probability of detection P_d is calculated as $P_d = 1 - P_{md}$.

III. MAC PROTOCOLS

F. The IEEE 802.15.4 standard

The IEEE 802.15.4 WPAN is based on the classification of full and reduced function devices [7]. The WPAN coordinator is a full function device able to choose between beacon-enabled and non-beacon enabled mode. In beacon-enabled mode (star topology), all network traffic converges to the coordinator in one hop and reduced function devices associate with the coordinator. The coordinator periodically broadcasts beacon frames with information of identification, synchronization and superframe structure. The superframe is bounded by two consecutive beacon transmissions, consisting of an active and an optionally inactive period. The time between two consecutive beacon transmissions is referred to as beacon interval (BI). On the other hand, the active period is defined as superframe duration (SD). Devices communicate during the active period which is divided into contention access period (CAP) and contention free period (CFP). During the CAP, devices are communicating using a carrier sense multiple access with collision avoidance (CSMA-CA). During the CFP, the coordinator can assign guaranteed time slots (GTS) to certain devices. In the superframe, the CFP is placed after the CAP period. During inactive periods, devices are turned into a low-power mode and no communication happens.

G. S-Aloha and PSMA random access

The IEEE 802.15.4a defines the use of slotted Aloha (S-Aloha) and an optional CCA mode (OCM) to access the channel. The OCM is based on the interleaving of preamble segments into the data packet to facilitate the detection. In this paper, the use of a preamble sense multiple access (PSMA) instead of OCM is proposed. PSMA has extensively been studied in [4], and it is based on transmitting the full preamble only once on top of the data packet. A successful data transmission must follow the positive acknowledgment scheme. Before transmission, a station applies the binary exponential backoff rules (BEB) first, keeping the transceiver in low-power mode. The backoff counter is then decremented by one as the backoff slot duration elapses. When the counter reaches zero the station addresses the status of the channel (busy/idle) by making one CCA only. If the channel is sensed busy, the station will defer the transmission to a later time, following again the BEB rules. In case of idle channel, the station will defer the transmission by one backoff slot. Thus, the station prevents colliding with an ongoing transmission that might not have been detected, as the preamble is transmitted only once. In fact, PSMA allows a transmission to last at most two consecutive backoff slots. If the channel is sensed at the boundary of the second slot it will be assessed erroneously idle. Within this sense, the PSMA allows to assess the status of the channel with much less overhead if compared to OCM. It is important to remark that in PSMA, the duration of a backoff slot is assumed to be a half of the packet transaction (including the time to receive the acknowledgment).

IV. RESULTS

H. Simulation scenario and parameters

The simulated scenario is a room having dimensions of 10 m x 10 m. Patients are wearing five active medical sensors, which are forming a WBAN. Each sensor collects patient's medical data and sends them to the coordinator through the wireless channel. The number of patients is not fixed: they can enter one by one (e.g., in a waiting room environment), thus increasing the channel contention. The monitored vital signals are summarized in Table I [5] in terms of sample rate, resolution and information rate per application, being the latter the product of the first two. The use of data compression is not assumed. Although a number of different sensors can participate in collecting a single vital signal, in this paper we consider only the aggregated effect. Therefore, each application generates the amount of bits corresponding to a specific vital signal, which are then queued at the MAC layer. Once the MAC receives the application message, it will make fragmentation if needed, using the value of the MAC protocol data unit (MPDU) as the fragmentation threshold. The MPDU length is 127 bytes, the PHY overhead is 11 bytes, the bit rate is 850 kbit/s including forward error correction (FEC), and transmit power is 0.37 µW [2] [3].

TABLE I. BIOMEDICAL MEASUREMENT PARAMETERS

Biomedical measurements	**Sample rate (samples/s)**	**Resolution (bit/samples)**	**Information rate (bit/s)**
ECG	1250	12	15000
EEG	350	12	4200
Blood oxygenation	50	16	800
Heart rate	25	24	600
Temperature of the body	5	16	80

Throughput S, energy consumption E and expected battery lifetime B_{life} are the metrics of interest. The average results have been collected by means of simulations, using the parameters from Table II [4]. The results are obtained varying the number of nodes and the superframe parameters, such as a beacon order (BO) and a superframe order (SO), which have a consequent change of the duty cycle $\delta \triangleq 2^{SO}/2^{BO}$ of the network. In fact, the superframe order contributes to the SD portion of the beacon interval, while the beacon order contributes to the BI. Therefore, the above mentioned metrics are calculated as

$$\begin{cases} S = \frac{N_{\text{pkt\_rx}} \cdot N_{\text{bits\_per\_pkt}}}{T_{\text{sim}}}, \\ E = \frac{E_{\text{Data}} + E_{\text{Ack}}}{N_{\text{bits\_rx}}}, \\ B_{\text{life}} = \frac{B}{E} T_{\text{sim}}, \end{cases} \qquad (4)$$

where $N_{\text{pkt\_rx}}$ is the total number of received packets per application, $N_{\text{bits\_per\_pkt}}$ is the size of a data packet in bits, T_{sim} is the simulation time, $N_{\text{bits\_rx}}$ is the total number of useful bits correctly received at the MAC layer, E_{Data} and E_{Ack} are the total energies spent for data transmission and acknowledgement reception, respectively. E_{Ack} is the same for both PSMA and S-Aloha, but E_{Data} accounts for different effects depending on the protocol (e.g., CCA). However, additional sources of energy consumption that can shorten battery life (e.g., display consumption) are not included.

TABLE II. PARAMETERS FOR ENERGY CONSUMPTION CALCULATIONS

Parameter	Comments	Value
M_{tx}	TX power consumption (including electronics)	20 mW
M_{rx}	RX power consumption (including electronics)	116 mW
M_{sleep}	Low-power mode consumption	0.2 mW
I	Battery current (typical commercial value)	1100 mA
V	Battery voltage (typical commercial value)	1.2 V
B	Battery power during the observation time	$I \cdot V$

I. Simulation results

The simulations have been carried out to account for the influence of false alarm, miss-detection and capture in different duty cycles δ = 100% and δ = 25%. Since temperature, heart rate and blood oxygenation showed not to be significantly affected by the channel contention and duty cycle, the throughput results are shown only for ECG and EEG in both S-Aloha and PSMA case. On the other hand, results for the energy consumption and expected battery lifetime are shown for all applications but only in the PSMA case, being the most sophisticated protocol for WBAN. S-Aloha does not use binary exponential backoff when retransmitting a packet but it uses a uniform backoff. The backoff duration is a uniform random value drawn from a fixed size contention window (CW). Within this work, it has been assumed a CW size corresponding to 32 backoff slots, being that 5 is the default standard defined backoff exponent [7]. In fact, we have experimentally noticed that after this value the backlog traffic begins to approach a Poisson process with good approximation. The number of simulated active nodes ranges from 5 up to 50. A data packet is retransmitted up to 4 times before being discarded, as defined in [7]. For each application a maximum of 10 nodes is simulated. It is also assumed that an increase in the number of nodes corresponds to higher offered traffic load to the wireless channel. The simulation results have been validated against the theoretical analysis exploited in [4]. However, this comparison is out of the scope of this paper.

In Figure 2, throughput for BO=SO=7 (δ=100%) shows a linear increasing behaviour as the number of active nodes increases. Figure 3 shows the worst case results for BO=6 and SO=4 (δ=25%), as the throughput assumes the classical cusp behaviour of random access protocols. The improvement given by the capture is evident, especially in the latter case. In fact, S-Aloha shows higher peak throughput, while PSMA is more stable as the number of nodes increases. The fact that reduction of the duty cycle worsens the throughput performance can be intuitively explained by observing that as the active portion of the beacon interval reduces, less time is available during the CAP for data transmission. Therefore collisions have higher probability to happen.

Figure 4 and Figure 5 show the energy consumption per useful bit in the case of δ=100% and δ=25%, respectively. The application showing the highest energy consumptions is the temperature, whereas the best values are provided by ECG and EEG. This effect denotes that the latter applications that require fragmentation have the attitude of capturing the channel in terms of utilization. Also for the energy consumption, the effect of reducing the active period within the beacon interval yields to higher energy consumptions in all the applications.

Figure 6 shows the qualitative behaviour of the expected battery lifetime in days for a fixed duty cycle δ=100% and increasing traffic load. The change of δ did not show a significant impact on the result. Obviously, applications requiring transmission of more packets (ECG and EEG) have the shortest lifetime, while heart rate and temperature have the longest one.

V. CONCLUSIONS

In this paper we have investigated the use of WBAN in medical applications for monitoring vital signals, such as ECG, EEG, heart rate, temperature of the body and blood oxygenation. Simulations have been carried out for different network duty cycles (δ = 100% and 25%) and number of active sensors. The network uses IEEE 802.15.4 compliant beacon-enabled star topology. IR-UWB which is compliant with the IEEE 802.15.4a is used as a physical layer technology for a non-coherent ED receiver. S-Aloha and PSMA are the studied MAC protocols, whose performances include false alarm, miss-detection and capture.

False alarm and miss-detection showed to have negligible impact on the results simulated in a 10 m x 10 m room scenario, while capture significantly improves the results. Simulations clearly show that imposing a synchronized inactive period, the performance of the network worsens in terms of throughput and energy consumption. Therefore, such a typical feature of IEEE 802.15.4 sensor networks does not apply to the design of medical networks. As a consequence, when designing a medical WBAN based on the considered technology, the use of an inactive period should be avoided. On the other hand, a long enough CAP can enable reliable delivery of the medical data regardless of the number of nodes that are deployed. Furthermore, in the realistic case of considering capture effect in the radio channel, the most sophisticated protocol (PSMA) does not always exhibit the best performance, mostly due to the discontinuous nature of IR-UWB transmission. Therefore, the MAC design can be simplified not only in terms of superframe structure but also in terms of the channel access mechanism.

The qualitative behaviour of the expected battery lifetime shows that as soon as the size of the application message becomes relevant (ECG and EEG), battery might require frequent changes in a relatively high contention environment. Transmitted and received power consumptions, as defined in Table II, are to be considered as relative values for comparison amongst the different applications. Their absolute value is clearly high, as they are referred to a prototype system other than an optimised device for commercial use [4]. In conclusion, a medical network for monitoring the life parameters such as considered in this paper and using the technology under investigation can particularly well suit for the home healthcare scenarios.

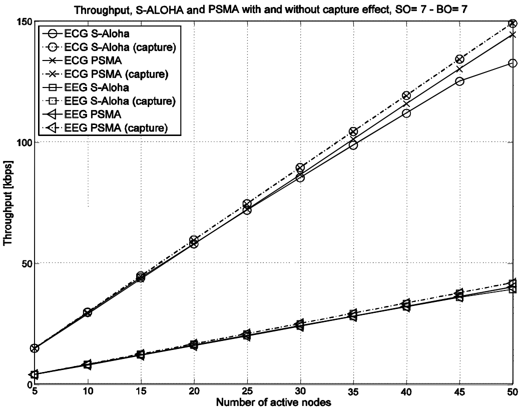

Figure 2. S-Aloha and PSMA throughput for ECG and EEG, with and without capture effect for *SO*=7, *BO*=7 (δ=100%).

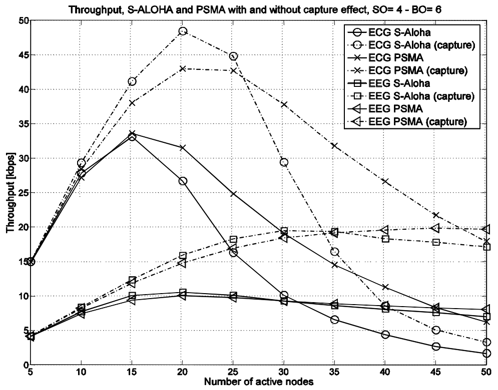

Figure 3. S-Aloha and PSMA throughput with and without capture for SO=4, BO=6 (δ=25%).

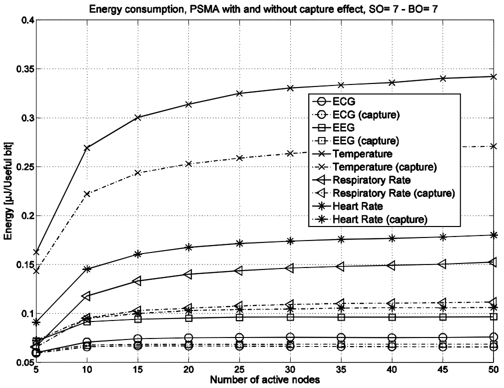

Figure 4. PSMA energy consumption with and without capture effect for SO=7, BO=7 (δ=100%).

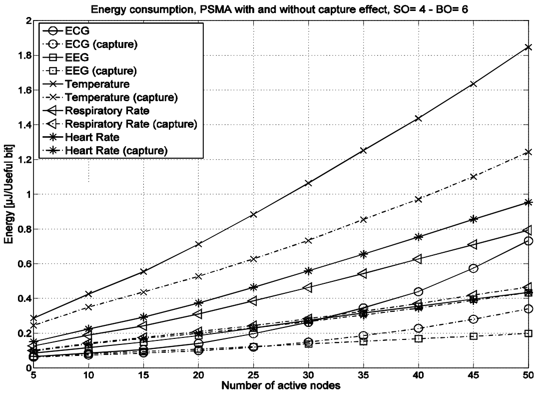

Figure 5. PSMA energy consumption with and without capture effect for SO=4, BO=6 (δ=25%).

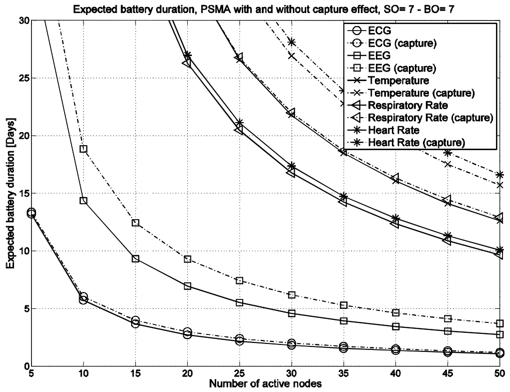

Figure 6. PSMA expected battery duration with and without capture effect for SO=7, BO=7 (δ=100%).

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