PERFORMANCE OF SENSOR MAC PROTOCOLS FOR MEDICAL ICT USING IR-UWB TECHNOLOGY

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Abstract: In this paper the feasibility of contention-based medium access control (MAC) protocols using impulse radio technology for medical ICT scenarios is shown. The particular scenario refers to a hospital waiting room in which people enter wearing a number of sensors for continuous monitoring of health status. The evaluation of the feasibility is founded on the implementation of slotted Aloha (S-Aloha) and preamble sense multiple access (PSMA) MAC protocols, the physical layer characteristics and the non-coherent receiver scheme for impulse radio ultra wideband (IR-UWB) in the network simulator Opnet. Simulated throughput and delay performance under Poisson traffic assumption are compared with analytical results for validation purposes. The simulation of the medical scenario, not easily tractable by analysis, accounts for important characteristics like capture effect and different bit rates of the sensors that monitor various vital functions. The results show that the used MAC protocols are scalable within the scenario constraints and PSMA exhibits a better delay performance than S-Aloha.

1 INTRODUCTION

Medical information and communication technology (ICT) applications have been gaining increasing importance in recent years (Arnon et al., 2003; Istepanian et al., 2004). The need of continuous monitoring of ill or elderly people is increasing, together with the requirement of low costs for healthcare systems. Wireless technologies enable non-invasive and ubiquitous solutions, but the choice of the proper physical layer (PHY) is required.

Due to its low power spectral density, ultra wideband (UWB) is suitable for transmissions near to the human body in the hospital environment, without causing harmful impact to patients or interfering with other medical equipment. Therefore, UWB is a promising PHY technology for these kinds of applications (Hämäläinen et al., 2008).

UWB received great attention from academy and industry in latter years, though this technology was already used in military applications. The development of new types of wireless networks, as wireless personal area networks (WPANs), led to the possibility of exploiting UWB also for civilian applications, especially after 2002, when the Federal Communications Commission (FCC) gave the first regulatory on the power emitted by hand-held devices using UWB transmissions (FCC, 2002).

Among the different possible technical implementations for UWB, only impulse radio UWB (IR-UWB) is considered in this work. The IR-UWB offers a high time resolution of multipath components, making it an appealing technology for indoor applications, and it has been chosen as alternative PHY for the IEEE 802.15.4a Amendment (IEEE-802.15.4a, 2007) of the IEEE 802.15.4 Standard (IEEE-802.15.4, 2006). The IEEE 802.15.4 focuses on low-rate WPANs (LR-WPANs), characterized by low costs and low power consumption.

According to (IEEE-802.15.4a, 2007), both coherent and non-coherent receiver solutions are possible. Even if the coherent approach can lead to optimal performance, we consider a simple non-coherent receiver based on energy detection (ED) since our target is an extremely simple, cheap, though efficient implementation solution for sensor devices.

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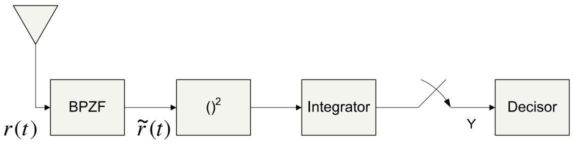

Figure 1: Reference architecture of the energy detection receiver.

In this paper we focus on evaluating a medical ICT scenario through simulations using multiple sensors with different service requirements. First, the IR-UWB PHY is modeled to a degree where the peculiarities of the technology are captured in sufficient detail. Second, the model is then fed to the Opnet network simulator and it is included in the analytical framework developed in (Haapola et al., 2009). Third, two different MAC protocols, tailored for IR-UWB, are implemented in the simulator: slotted Aloha (S-Aloha) and preamble sense multiple access (PSMA). The simulation results are compared with the ones of the analytical framework. Finally, the medical ICT scenario is developed and simulated.

The paper is organised as follows. Section 2 describes the characteristics of IR-UWB physical layer, whereas Section 3 illustrates the S-Aloha and the PSMA MAC protocols. The simulation scenario and the applications are presented in Section 4. Performance evaluation in terms of throughput and delay in the described scenario is carried out in Section 5, and Section 6 concludes the paper.

2 IR-UWB PHYSICAL LAYER

IR-UWB is based on the transmission of a series of, temporally extremely short, pulses with very low emitted power. The main features of UWB are noise-like power emission and very accurate time resolution of multipath components. The basics of IR-UWB signal are described in the pioneer work of (Win and Scholtz, 1998). Due to its carrier-less nature, IR-UWB enables simple transceiver implementations. In this work we refer to the non-coherent receiver based on energy detection (ED) shown in Fig. 1. The energy of the received signal, $r(t)$, which arrives at the receiving antenna, is filtered by the bandpass zonal filter (BPZF) and integrated for a certain time duration, T_{int}, and based on that the decision variable, Y, is made. The amount of integrated energy depends on the integration time, which has to set a trade-off between integration of noise and of the useful signal. The ED approach is simple and has a low power consumption, but it can be strongly influenced by multiuser interference.

IR-UWB uses several modulation schemes for transmission. One of the most used is the pulse position modulation (PPM). The IEEE 802.15.4a defines a variation of the standard PPM that is summarized in the next section. Furthermore, IR-UWB uses time hopping (TH) codes to address the problem of multi-user capability.

2.1 IEEE 802.15.4a

The IEEE 802.15.4a (IEEE-802.15.4a, 2007) is an amendment to IEEE 802.15.4 Standard (IEEE-802.15.4, 2006), where two alternative physical layers (PHYs) are defined to add location capability and to improve performance in terms of rates, range, and power consumption. In this paper we will consider only the UWB PHY. According to the amendment, data is transmitted as a burst of pulses with Burst Position Modulation (BPM). BPM modulation scheme is similar to the PPM but with the difference that the symbol interval is divided into two slots. One slot is for bit zero and the other one is for bit one. The preamble sequence, added before the physical service data unit (PSDU), provides packet synchronization and enables channel estimation. The preamble uses Ternary sequences with perfect periodic autocorrelation properties.

2.2 False Alarm and Miss-detection

A device assessing the status of the channel (idle/busy) can encounter into two erroneous events: false alarm and miss-detection. Let H_0 be the statistical hypothesis of no preamble in the channel, and let H_1 be the hypothesis of presence of a preamble. The false alarm refers to the event that the preamble is found, under hypothesis H_0, and the probability of this event is indicated with P_{fa}. Miss-detection refers to the event in which the preamble is missed under hypothesis H_1 and the probability of this event is indicated with P_{md}. Both events can affect MAC performance (Ramachandran and Roy., 2006), when performing clear channel assessment (CCA) before transmission or in the reception of a packet.

Considering an additive white Gaussian noise (AWGN) channel and conditioning on a multipath realization, the decision variable Y after the integrator follows a Chi-square distribution with $k = L_s N_p 2q$ degrees of freedom, where L_s is the number of symbols in a preamble, N_p is the number of pulses in a symbol, and q is the time-bandwidth product. Under hypothesis H_0 the decision variable is central Chi-square distributed, while under hypothesis H_1 it has a non-centrality parameter given by $\lambda = L_s SNR$, with SNR being the received Signal to Noise Ratio. When k is large enough, the Chi-square distribution can be approximated by a Gaussian distribution, and P_{fa} and P_{md} can be expressed as:

$$P_{fa} = Pr\{Y > \varepsilon | H_0\} = Q\left(\frac{\varepsilon}{\sqrt{L_s N_p 4q}}\right), \quad (1)$$

$$P_{md} = Pr\{Y < \varepsilon | H_1\} = 1 - Q\left(\frac{\varepsilon - L_s SNR}{\sqrt{L_s N_p 4q + 4 L_s SNR}}\right),$$

where ε is the threshold of energy on the channel for deciding the presence of a preamble.

2.3 Capture Effect for IR-UWB Techology

MAC protocol performance is classically analyzed by assuming that when a collision occurs none of the packets involved can be successfully received. The phenomenon of one packet prevailing at the receiver with respect to others is well known in the literature as capture effect. For narrowband systems, several works (e.g. (Zhang and Pahlavan, 1992)) have shown how taking this realistic effect into account affects MAC performance. The capture probability, P_c, can be generally defined for different n (number of packets arriving at the receiver) as

$$P_c(n) = \begin{cases} 1, & \text{if } n = 1 \\ 0, & \text{if } n \to \infty \\ \in (0,1), & \text{otherwise.} \end{cases} \quad (2)$$

For IR-UWB systems, a capture effect model has to consider how the pulses of the transmitted packets overlap in time as well as the received powers. By assuming the point of view of a reference packet, in the ED receiver, packets coming from other transmitters will interfere with the reference transmission if their pulses fall into the integration time of the receiver. Simultaneous transmissions do not necessary lead to complete information loss. This depends on the amount of integrated energy in both BPM positions corresponding to different bits. In the current study the capture effect in the presence of intra-piconet interference is considered, assuming that all the users use the same preamble sequence and the same TH code for the BPM transmission, and the data pulse structure of the IEEE 802.15.4a. To simplify the problem, the capture effect is considered only in the presence of two simultaneous transmissions, such that

$$P_c(n) = \begin{cases} P_d = 1 - P_{md}, & \text{if } n = 1 \\ \in (0,1), & n = 2 \\ 0, & \text{if } n > 2. \end{cases} \quad (3)$$

With $n = 1$ the probability of capture is just the probability of detecting the packet P_d. The exact value of $P_c(2)$ depends on the bit error probability (BEP) of the channel:

$$BEP = Q\left(\sqrt{\frac{\frac{2(E_{sb}-E_{io})^2}{N_0}}{4(E_{sb}+E_{io}) + 4qN_0}}\right), \quad (4)$$

with E_{sb} and E_{io} the integrated energy of the reference and the interfering signal, respectively, and N_0 the power spectral density of the thermal noise. The fully analytical model is given in (Haapola et al., 2009).

According to (IEEE-802.15.4a, 2007), we consider a Reed-Solomon $RS_6(63, 55)$ code, with a correction capability of $t = 4$ symbols. Let L_c be the length of a coded packet, and $b_c = 63$ symbols the length of a block of the coded packet. The probability of accepting one of the $x = \lceil \frac{L_c}{b_c} \rceil$ blocks of the packet is:

$$P'_c = \sum_{i=0}^{t} \binom{b_c}{i} SEP^i (1 - SEP)^{b_c - i}, \quad (5)$$

where $SEP = 1 - (1 - BEP)^6$ is the symbol error probability. A packet is correct if all the blocks are correct, therefore $P_c(2) = (P'_c)^x$.

3 MAC PROTOCOLS

According to (IEEE-802.15.4, 2006), a WPAN shall always include a coordinator, which is responsible of setting up and maintaining the WPAN. Among its tasks, the coordinator controls the access to the medium, choosing between a beacon-enabled mode or a non beacon-enabled mode. In the beacon-enabled mode, the coordinator broadcasts a periodic beacon frame, containing information about the WPAN. The period between two consecutive beacons defines a superframe structure. The superframe consists of an active and an optional inactive period; devices communicate only during the active period and should enter a low-power mode during the inactive one. The active part can be further split into a Contention Access Period (CAP), and an optional Contention Free Period (CFP). During the CAP data is transferred using Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) algorithm, while the CFP is composed of reserved slots, the Guaranteed Time Slots (GTSs), that the coordinator can assign to devices running applications with quality of service (QoS) constraints.

According to the CSMA-CA, when a device has data to send, it performs CCA after a random initial backoff delay. If the channel is found idle during two consecutive CCAs, the device transmits the data; otherwise it will repeat the procedure after another random backoff obeying the binary exponential backoff

(BEB) rules. Full description of the algorithm can be found from (IEEE-802.15.4, 2006).

Since the IR-UWB is a carrier-less technology, traditional CCA methods valid for narrowband systems are not suitable. The IEEE 802.15.4a (IEEE-802.15.4a, 2007) introduces Aloha as default channel access strategy, because it is suitable for lightly loaded networks where the probability of collision is reasonably small. Given the high processing gain of the IR-UWB the transmission can have high interference resilience. Alternative CCA methods based on the sensing of the preamble are defined. The standard defines an optional modified frame structure, in which preamble symbols are multiplexed with data symbols in the frame. The multiplexed preamble enables CCA at any time during frame transmission, but at a cost of significant overhead and according to (Haapola et al., 2009) it attains the worst performance for the traffic loads targeted in this paper and it will not be considered further.

In this paper we will investigate slotted Aloha (S-Aloha) and preamble sense multiple access (PSMA) (Haapola et al., 2006), which proposes an alternative channel access method to utilise the CCA in IR-UWB environment and it is compatible with the IEEE 802.15.4a PHY. We will consider a typical IEEE 802.15.4 star topology network in beacon-enabled mode. The access protocols analysed will thus refer to the CAP of the superframe; no GTSs are present.

The analysis of the average throughput is carried out using renewal theory, with the classical formula

$$S \triangleq \frac{U}{B+I}, \tag{6}$$

where U is the average useful period, B is the average busy period, I is the average idle period, and $B+I$ is referred to as the average cycle. For the theoretical analysis and for the validation of the simulator, the overall traffic is considered Poisson distributed with mean arrival rate g. The probability of generating n packets in a time slot T_s can be expressed as

$$p(n) = \frac{(gT_s)^n e^{-gT_s}}{n!}. \tag{7}$$

The duration of T_s is protocol dependent. The throughput is studied as a function of the normalized offered traffic G, with normalization interval related to T_s and thus protocol dependent.

3.1 S-Aloha

In a beacon-enabled network the S-Aloha protocol can be implemented as the synchronization is provided by the coordinator. The events of false alarm and miss-detection as described in section 2.2 for the

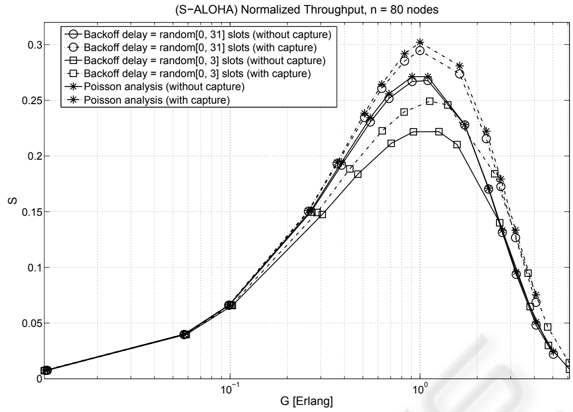

Figure 2: S-Aloha normalized throughput as a function of the normalized offered traffic $G = gT_s$.

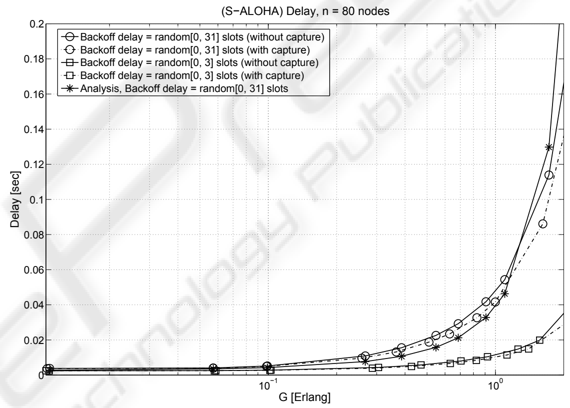

Figure 3: S-Aloha delay as a function of the normalized offered traffic $G = gT_s$.

CCA do not have a direct impact on the B for S-Aloha, because the status of the channel is not assessed before the transmission of a packet. However, the P_{md} affects also the reception of a frame: the receiver can actually receive a packet only after detecting the corresponding preamble. Considering this, the useful period can be expressed as $U = BP_sP_d$, where P_s represents the probability of success. We take into account the overhead introduced by the standard, which yields a decrease of 26% with respect to the maximum throughput achievable for S-Aloha (0.368).

When capture effect is taken into account, the useful period can be calculated as follows:

$$U = B\sum_{n=1}^{\infty}\frac{P_c(n)}{P_b}p(n) = B\sum_{n=1}^{2}\frac{P_c(n)}{P_b}\frac{(gT_s)^n e^{-gT_s}}{n!}, \tag{8}$$

where P_b is the probability to be in a busy period.

According to the Aloha protocol, in case of collision the packet is retransmitted after a random delay. We have considered a backoff delay uniformly distributed between 0 and N time slots. The choice of N

has a strong impact on the performance. The lower is N, the lower the throughput will be, since when a collision occurs, two or more nodes will schedule a retransmission within a shorter fixed period, leading to possible repeated collisions. On the other hand, a high value of N means higher delay in the reception of the packets. This effect can be seen from Fig. 2 and 3, where throughput and delay for S-Aloha are shown. Simulations were run with Opnet Modeler, considering 80 nodes, which proved to be a good approximation of the infinite case. Results for $N = 3$ and $N = 31$ illustrate how both throughput and delay are higher for the higher value of N. Throughput obtained for $N = 31$ is very close to the classical infinite population Poisson analysis. The dotted curves are obtained considering the capture effect on the channel, and show an improvement for both backoff windows. The analytical curve of throughput with capture has been obtained considering the interferer relative distance equal to 2.02 meters and SINR of 2 dB. The matching of simulation results and theory depends in fact on the relative distance between the reference user and the interferer, since different relative distances cause different overlapping during the receiver integration window leading to different performances.

3.2 Preamble Sense Multiple Access

The PSMA protocol has been described and analyzed by (Haapola et al., 2009; Haapola et al., 2006). When a node has a data frame to transmit, it chooses an initial random backoff according to the BEB value range. When the backoff timer expires, the node performs a CCA in terms of a preamble detection at the beginning of a backoff boundary. If no preamble is detected, the node transmits at the beginning of the next backoff boundary with a preamble sequence followed by the data. The data transmission and the corresponding acknowledgment must be completed within two time slots. If the CCA indicated “channel busy”, the node performs a backoff according to the BEB rules and re-attempts. The mechanism ensures that once a transmission has started, it can continue for two consecutive time slots without a collision. A collision can occur only if two or more nodes perform a “channel free” CCA simultaneously. With the above characteristics, PSMA classical, average Idle, Busy, and Useful periods are

$$I = \frac{T_s}{1 - e^{-gT_s}}, \qquad B = \frac{2T_s}{e^{-gT_s}}, \qquad (9)$$
$$U = \frac{CB}{2T_s}P_s, \qquad P_s = \frac{gT_s e^{-gT_s}}{1 - e^{-gT_s}},$$

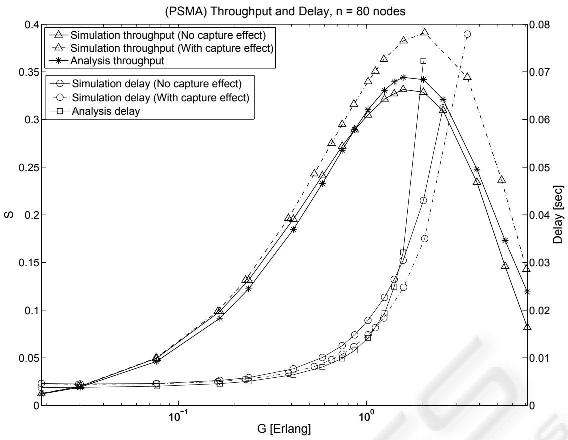

Figure 4: PSMA normalized throughput and delay as a function of the normalized offered traffic $G = 2gT_s$.

where P_s is the probability of success and C represents the fraction of useful data due to protocol overhead.

As the effects of BEB, P_{md}, and P_{fa} are taken into account, the following consequences can be perceived for the classical throughput equations of Eq. (9). The P_{md} has no effect on the length of the idle period, but the P_{fa} may increases it. If only one node performs CCA during a slot, with a constant probability P_{fa} it performs a backoff. When the BEB is taken into account, the P_{fa} can further increase the Idle period.

In the Busy period P_{md} can increase the B if a node performs the CCA during the first slot of an existing transmission and has a miss-detection. The B is extended by a T_s for every P_{md}, and it occurs if an arrival, with proper scheduling in the next, 2nd, 3rd, and 4th slot following the initial transmission, occurs. Multiple P_{md} are required to extend B by more than one T_s. With P_{fa}, a node performs a backoff, which reduces the length of the busy period.

For the Useful period, the P_d only affects the P_s of Eq. (9), and the $P_s \propto P_d$. There can be a successful transmission if and only if all but one of multile CCAs have a P_{fa} in a slot. The mathematical derivation of the above has been carried out by (Haapola et al., 2009).

Fig. 4 illustrates PSMA throughput and delay results. A good matching is shown between simulation and the analysis described in (Haapola et al., 2009). The dotted curves show the improvement obtained when considering the capture effect. For offered traffic values up to 0.6 the performance of S-Aloha and PSMA in terms of throughput are equivalent. For higher values PSMA performs better. The delay of PSMA is always lower than that of S-Aloha.

Table 1: Parameters of biomedical applications (Arnon et al., 2003).

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

4 SIMULATION SCENARIO FOR VITAL SIGNALS MONITORING

Aging of the population determines the need for reducing the costs and the number of the hospitalizations that will otherwise burden the healthcare systems. On the contrary, there is an increased demand for more accurate monitoring of vital signals of a large variety of customers (e.g., in sports and for chronically diseased people). Those two opposite trends pose the demand for new technologies able to fulfill both scenarios. Wireless technology can have the requisites of low costs, ease of use and ease of replacement, without being invasive. Energy consumption and reliability of the transmissions are the main issues.

The target scenario is given by a number of people wearing wireless sensors deployed on their body, thus forming a WPAN. The IR-UWB technology suits particularly well for transmissions near the body because of the low emitted power. The scenario under investigation resembles at home or inside the hospital monitoring of the vital signals summarized in Table 1 (Arnon et al., 2003). The study considers the aggregated traffic coming from different sensors that monitor the same set of parameters. For each of the monitored parameters samples are collected at a sampling frequency of five times higher than the maximum frequency (Arnon et al., 2003). Depending on the resolution, for every parameter the information rate is obtained as: *Information rate* = *Sample rate* · *Resolution*. Furthermore, a deterministic traffic pattern is assumed such that every second the aggregated traffic for each of the monitored parameters is generated. This way of modeling the application has significance for example when patients need to be constantly monitored. The MAC protocol encapsulates the generated traffic into PHY protocol data units (PPDU), also link-level fragmentation is used when needed.

This study assumes the beacon-enabled star topology defined in (IEEE-802.15.4, 2006) and the UWB PHY of IEEE 802.15.4a, focusing on the performance inside the WPAN. The coordinator, that maintains the synchronization issuing the beacon, can be mains powered. The wireless sensors transmit data to the coordinator (multipoint-to-point communications) and they are battery operated. The coordinator can act as a gateway to connect to the Internet or the backbone network. The scenario under investigation is a ward of 10x10 m in which patients wear wireless sensors and communication is initiated in a serialized manner. Realistically, a number of patients up to ten has been considered. As the number of patients increases, the traffic contending for the channel correspondingly increases. The scenario is assumed to be realistic also because the IR-UWB signal is not likely to interfere with other adjacent rooms due to absorption and signal attenuation through the walls. This can be concluded by considering the wavelength (smaller than 10 cm) of the UWB transmission and the wall attenuation as well as intentional lack of synchronization between adjacent wards. Moreover, the use of different preamble sequences (c.f. (IEEE-802.15.4a, 2007)) in adjacent rooms decreases the interference even further.

Given that the reliability of the data is crucial when monitoring vital signals the metrics under investigation are the throughput and the delay. Energy consumption is essential but the main target of this work is to prove that the use of IR-UWB technology and random access can provide sufficient data reliability in realistic conditions. Random access is in fact the default access in the IEEE Std 802.15.4. However, as it is shown in (Haapola et al., 2009) the energy consumption for PSMA per useful transmitted bit is less than 100 nJ up to the channel capacity of offered traffic. The average throughput and delay are investigated in a scenario with an increasing number of sensors and including realistic capture effect at receiver side. The monitored data are sent to the coordinator, which acknowledges the correct reception of a PPDU packet. In the case of large payloads, as for the ECG, several PPDUs have to be sent to the coordinator, but in the case that even a single PPDU is lost the entire message is discarded.

5 SIMULATION RESULTS

MAC and PHY parameters assumed in the paper are summarized in Table 2.

The transmitted power of 0.37 μW is compliant

Table 2: IEEE 802.15.4a PHY and MAC parameters.

Parameter	**Value**
Max data MPDU length	127 bytes
Preamble length	64 preamble symbols
Max ack waiting time	140 bits
Slot duration	1426 bits
PHY Bit rate	850 kbit/s
Center frequency	4492.8 MHz
Bandwidth	499.2 MHz
Transmitted power	0.37 μW
Transmitter power consumption	20 mW
Receiver power consumption	120 mW
Sleep power consumption	0.2 mW

with FCC ruling (FCC, 2002). The power consumption values are taken from (Stoica et al., 2005).

The metrics under investigation, the throughput S, in terms of bits per second correctly received, and the average delay D, can be expressed as follows:

$$S^{(j)} = \frac{M_{Rx}^{(j)} N_{Bits}^{(j)}}{T_{Sim}}, \quad D^{(j)} = \frac{\sum_{i=1}^{M_{Rx}^{(j)}} (T_{Rx}^{i} - T_{Enq}^{i})}{M_{Rx}^{(j)}}, \quad (10)$$

where the index j refers to the different applications, $M_{Rx}^{(j)}$ is the total number of application messages received per application, $N_{Bits}^{(j)}$ represents the message size in bits, T_{Sim} is the duration of a simulation, T_{Rx} indicates the instant at which the acknowledgment for the last packet of a message is received, and T_{Enq} is the time when the application message is enqueued at the MAC layer. These metrics have been studied as a function of the number of active nodes in the scenario.

Fig. 5 shows throughput results for applications with higher data rates. The PSMA and the S-Aloha achieve the same performance in the simulated scenario when the capture effect is considered. The PSMA curve without capture effect is not plotted because it practically overlaps with the one obtained considering capture. For S-Aloha, instead, an improvement can be seen when the capture effect is introduced in case of ECG and EEG. All curves exhibit a linearly increasing behaviour as the number of patients increases. The behavior is due to the fact that for the simulated traffic the protocol is working in the stability region and below the channel capacity.

The delay results are shown in Fig. 6 for the S-Aloha and in Fig. 7 for the PSMA. For both of the protocols, ECG and EEG achieve the highest delay values, and this is due to their higher information rate, which yields a higher number of MAC packets to be transmitted. The other three applications achieve lower delay, with very similar behavior, since their messages fit into one MAC frame. The impact of the capture effect on the delay is quite relevant. The PSMA delay appears to be lower than that of S-Aloha for all applications. This concludes that the PSMA performs better also in this case. Moreover, for the PSMA the delay stays almost constant and predictable while the number of active nodes are varied. We have not found a suitable comparison from the literature. The values obtained for the delay stay under the 125

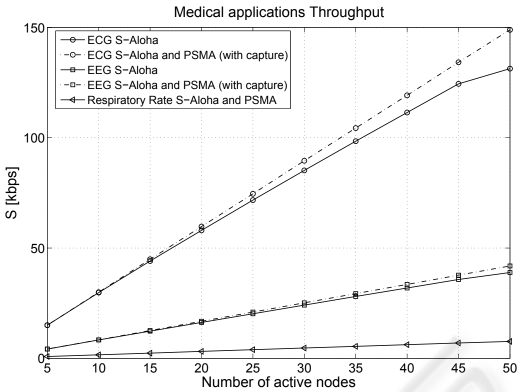

Figure 5: Throughput for medical applications.

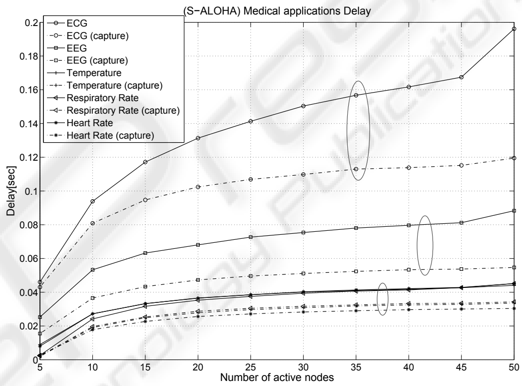

Figure 6: S-Aloha delay for medical applications.

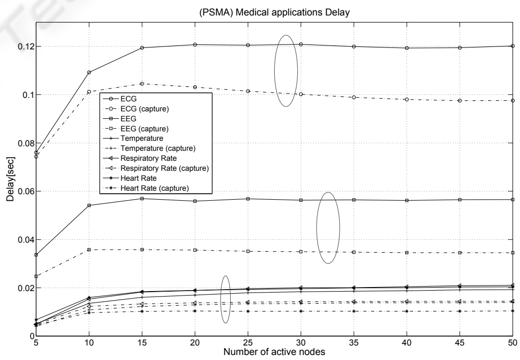

Figure 7: PSMA delay for medical applications.

ms threshold indicated in (Zhen et al., 2008) as a generic maximum latency for medical applications in body area networks (BANs), showing the feasibility of the protocols under study in the scenario. In particular, a constant delay is an important feature of a protocol to use for transmitting health related data. The proposed PHY/MAC solution, even in the presence of interference (more patients in the room), exhibits a stable behaviour, hence guaranteeing the mandatory reliability of the transmitted information that doctors use for diagnosis. Clearly, further work is required to evaluate not only the average delay but also the jitter, to meet the requirements of some critical real-time application.

6 CONCLUSIONS

This paper has investigated average throughput and delay performance of contention-based MAC protocols in a realistic medical ICT scenario when considering different applications used for health monitoring as: ECG, EEG, heart rate, respiratory rate and temperature of the body. The performance has been evaluated using the network simulator Opnet, after validation with theoretical analysis.

The scenario addresses a wireless sensor network for vital signal monitoring, in which the physical layer technology is IR-UWB, as defined in IEEE 802.15.4a standard. The network architecture is the star topology defined by the IEEE 802.15.4 standard. Given that the study targets cheap sensors implementations, the considered receiver scheme is the non-coherent energy detector. The MAC protocols investigated are S-Aloha and PSMA, whose performance has been obtained by varying the number of nodes in the scenario. The events of false alarm and miss detection in the sensing of the preamble, and the possibility of the receiver capturing a packet subjected to collision are the realistic effects that have been included in both analysis and simulations.

The results show good performance in terms of throughput for both protocols, but for the delay, PSMA performs better. In addition, the results enlighten the importance of accounting for realistic PHY effects and accurate modelling of the application. The study showed that the average delay is below the indicative maximum latency of 125 ms and that the capture improves the performances. Given the lack of explicit reference delay for these kinds of applications, we can conclude that in a realistic environment the network architecture used and the MAC protocols investigated satisfy the requirements for enabling the concept of wireless health monitoring.

REFERENCES

Arnon, S., Bhastekar, D., Kedar, D., and Tauber, A. (2003). A comparative study of wireless communication network configurations for medical applications. *IEEE Wireless Communications*.

FCC (2002). Revision of part 15: First report and order. Recommendation, Federal Communications Commission.

Haapola, J., Goratti, L., Oppermann, I., and Rabbachin, A. (2006). Preamble sense multiple access (psma) for impulse radio ultra wideband sensor networks. In *Embedded Computer Systems: Architectures, Modeling, and Simulation*. Springer Berlin / Heidelberg.

Haapola, J., Rabbachin, A., Goratti, L., Pomalaza-Ráez, C., and Oppermann, I. (2009). Effect of impulse radio-ultra wideband based on energy collection on mac protocol performance. *IEEE Transaction on Vehicular Technology*, To appear, 58(9).

Hämäläinen, M., Pirinen, P., Iinatti, J., and Taparugssanagorn, A. (2008). Uwb supporting medical ict applications. In *IEEE International Conference on Ultra-Wideband (ICUWB 2008)*.

IEEE-802.15.4 (2006). Part 15.4: Wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (LR-WPANs). Standard, The Institute of Electrical and Electronics Engineers, Inc.

IEEE-802.15.4a (2007). Part 15.4:wireless medium access control (mac) and physical layer (phy) specifications for low-rate wireless personal area networks (lr-wpans): Amendment to add alternate phy. Standard, The Institute of Electrical and Electronics Engineers, Inc.

Istepanian, R., Jovanov, E., and Zhang, Y. (2004). Guest editorial introduction to the special section on m-health: Beyond seamless mobility and global wireless health-care connectivity. *Information Technology in Biomedicine, IEEE Transactions on*.

Ramachandran, I. and Roy., S. (2006). On the impact of clear channel assessment on mac performance. In *IEEE Global Telecommunications Conference (GLOBECOM '06)*.

Stoica, L., Tiuraniemi, S., Oppermann, I., and Repo, H. (2005). An ultra wideband impulse radio low complexity transceiver architecture for sensor networks. In *IEEE International Conference on Ultra-Wideband (ICU), 2005*.

Win, M. and Scholtz, R. (1998). Impulse radio: how it works. *Communications Letters, IEEE*.

Zhang, K. and Pahlavan, K. (1992). Relation between transmission and throughput of slotted aloha local packet radio networks. *Communications, IEEE Transactions on*.

Zhen, B., Patel, M., Lee, S., Won, E., and Astrin, A. (2008). Tg6 technical requirements document (trd). Technical report, IEEE P802.15.