

Highly Reliable Energy-Saving MAC for Wireless Body Sensor Networks in Healthcare Systems

Begonya Otal, Luis Alonso, *Member, IEEE*, Christos Verikoukis, *Senior Member, IEEE*

Abstract—Wireless Body Sensor Networks (BSNs) in healthcare systems operate under conflicting requirements. These are the maintenance of the desired reliability and message latency of data transmissions, while simultaneously maximizing battery lifetime of individual body sensors. In doing so, the characteristics of the entire system, including physical, medium access control (MAC), and application layers have to be considered. The aim of this paper is to develop a new MAC model for BSNs to fulfill all these specific rigorous requirements under realistic medical settings. For that purpose, a novel cross-layer fuzzy-rule scheduling algorithm and energy-aware radio activation policies are introduced. The main idea is to integrate a fuzzy-logic system in each body sensor to deal with multiple cross-layer input variables of diverse nature in an independent manner. By being autonomously aware of their current condition, body sensors are able to demand a “collision-free” time slot, whenever they consider it strictly required (e.g. high system packet delay or low body sensor residual battery lifetime). Similarly, they may refuse to transmit, if there is a bad channel link, thus permitting another body sensor to do so. This results in improving the system overall performance. The proposed MAC model is evaluated by computer simulations in terms of quality of service and energy consumption under specific healthcare scenarios.

Index Terms—Body sensor networks, Energy consumption, Fuzzy logic, Healthcare, Medical applications, Medium access control, Quality of service, Scheduling.

I. INTRODUCTION

WHILST Wireless Sensor Networks (WSNs) continue to evolve for a broad range of applications from environmental to industrial monitoring, they do not specifically tackle the challenges associated with human body monitoring. Human body monitoring using a WSN may be achieved by attaching sensors to the body’s surface as well as implanting them into tissues for a more accurate clinical practice. The realization that proprietary designed WSNs are not ideally suited to monitoring the human body and its internal environment has led to the development of wireless Body Sensor Networks (BSNs) [1].

In healthcare systems, the scale of demand for human body monitoring can only be appreciated once the magnitude of patient early diagnosis and treatment is considered. Several

Manuscript received 30 July 2008; revised 5 December 2008. This work was supported in part by COOLNESS (218163-FP7-PEOPLE-2007-3-1-IAAPP) and TEC2006-10459/TCM.

B. Otal and C. Verikoukis are with the Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), Castelldefels, Barcelona, Spain (e-mails: begonya.otal@cttc.es, cveri@cttc.es).

L. Alonso is with the Signal Theory & Communications Department from the Universitat Politècnica de Catalunya (UPC), Barcelona Spain (e-mail: luisg@tsc.upc.edu).

Digital Object Identifier 10.1109/JSAC.2009.090516.

examples illustrate this need, but none as dramatically as chronic cardiovascular related illnesses. In this context, regular patient monitoring using electrocardiography (ECG) is required, along with other investigations, to aid diagnosis so that prompt treatment can be initiated to prevent long-term related complications. Apart from ECG, patient monitoring is normally in the form of further vital sign measurements (blood pressure, heart rate, respiratory rate, temperature). In hospitals, where a large number of patients are treated every year, BSNs offer a special benefit. Patients receive monitoring of various levels of intensity, ranging from intermittent (four to six times a day), to intensive (every hour), and to continuous invasive or non-invasive monitoring, such as that seen in the intensive care unit. Aside from being restrictive and “wired”, ward-based patient monitoring systems tend to be very labor intensive, requiring manual measurement and are prone to human error. Automation of this process, along with the ability to pervasively monitor patients wherever they are in the hospital (not just at their bedside), is desirable not only to the healthcare provider, but also to the patient [1].

Although the challenges faced by BSNs in healthcare environments are in a certain way similar to those already existing in WSN applications, there are intrinsic differences, which require special attention. The purpose of Section II is to provide a brief description of these special requirements that characterize BSNs, while analyzing the standard de facto for WSNs, the low-rate IEEE 802.15.4 MAC/PHY standard (802.15.4) [2]. Section III introduces a new Medium Access Control (MAC) protocol model with an energy-aware radio activation policy that pursues the idea to satisfy these specific medical requirements under BSNs in realistic hospital care scenarios. For that purpose, a novel cross-layer fuzzy-based scheduling algorithm is also presented in Section IV. Section V characterizes a case study of the overall designed system and Section VI shows the simulation results used to evaluate the whole system performance under specific hospital settings. The last section concludes the paper.

II. PROBLEM STATEMENT

The MAC layer is responsible for coordinating channel accesses, by avoiding collisions and scheduling data transmissions, to maximize throughput efficiency at an acceptable packet delay and minimal energy consumption. The 802.15.4 MAC [2] is intended to serve a set of applications with very low power consumption and cost requirements, though with relaxed demands for data rate and Quality of Service (QoS). In the literature, it is already possible to find some publications in relation to wireless BSNs in healthcare systems, such as

[3], [4], where the authors performed an evaluation analysis of 802.15.4 [2] under medical settings. It was pointed out that the scalability of 802.15.4 is not a given feature, since the current 802.15.4 MAC design does not support a high sensor density area and its use is extremely restricted under interference scenarios. Simulation results in [5] confirm that the 802.15.4 MAC is energy efficient in controlled environments, (i.e. without interference), but it fails in supporting QoS in co-existing scenarios, which is a serious issue for medical applications. Human monitoring BSNs must support high degrees of reliability under specific message latency requirements, without endangering sensor power consumption to avoid frequent battery replacements. The fact that the 802.15.4 MAC does not fully satisfy BSN requirements highlights the need for the design of new scalable MAC solutions. These guarantee low-power consumption to all different sorts of body sensors while ensuring rigorous QoS under co-existent scenarios in healthcare systems.

III. A DISTRIBUTED QUEUING MAC FOR BSNs

A. A Distributed Queuing MAC Overview

The use of the Distributed Queuing Random Access Protocol (DQRAP) for local wireless communications was already proposed in 1993 [6]. The authors demonstrated the ideal performance of the protocol in a multiple access voice packet environment. DQRAP divides the TDMA slot into an “access subslot” that is further divided into access *minislots*, and a “data subslot”. The basic idea is to concentrate user access requests in the access *minislots*, while the “data subslot” is devoted to collision-free data transmission. As explained in detail in [7], every station in the system joins one of the two common logical distributed queues; the Collision Resolution Queue (CRQ) or the Data Transmission Queue (DTQ). The CRQ controls station accesses requests into the access *minislots*, while the DTQ is engaged of scheduling station packets into the “data subslot” following a first-come-first-served discipline. This provides a collision resolution tree algorithm that proves to be stable for every traffic load even over the system transmission capacity when three or more *minislots* are utilized. DQRAP analytical model approaches the delay and throughput performance of the theoretical optimum queuing systems M/M/1, M/D/1 or G/D/1, depending on traffic distribution and packet length, as the authors showed in [6], [7]. Another interesting feature of DQRAP is its capacity to behave like an ALOHA-type protocol for light traffic load and to smoothly switch to a reservation system as the traffic load increases, thus reducing collisions automatically.

Despite the need of a central node to handle system information, every station in the system individually tackles four integer counters, which denote the distributed nature of DQRAP protocol; two station-dependant integers that represent their occupied position in each queue CRQ and DTQ; and two other integers shared among all stations in the system that visualize the total number of stations in each queue. DQRAP consists of several strategic rules performed independently by each station in the system, while managing appropriately the four integers counters [7]. These strategic rules give answer to:

- i) ‘who’ transmits in the “data subslot” and ‘when’,
- ii) ‘who’ sends an access request in the access *minislots* and ‘when’, and
- iii) ‘how’ to actualize their positions in the queues.

Recent publications based on DQRAP under Wireless Local Area Networks (WLAN) analyze and evaluate the protocol throughput performance in infrastructure mode [8] and in ad hoc mode [9] while comparing it to the IEEE 802.11 MAC standard based on Carrier Sense Multiple Access (CSMA). The obtained results show that the proposed schemes outperform the throughput bounds achieved when using a legacy 802.11 MAC protocol.

The promising behavior of [8], [9] adapted schemes under WLAN scenarios evokes the idea to further explore this MAC protocol in terms of energy consumption and application related QoS under BSNs to satisfy realistic healthcare requirements in the medical domain (e.g. in a hospital scenario).

B. DQBAN Protocol in Hospital Scenarios

This article proposes the Distributed Queuing Body Area Network (DQBAN) protocol as an alternative enhancement to 802.15.4 MAC [2] in all BSN possible scenarios. DQBAN corresponds to a new MAC model specially modified by means of a novel cross-layer fuzzy-logic scheduling mechanism and energy-aware radio activation policies to satisfy energy-efficient and stringent QoS demands in healthcare scenarios. DQBAN supports high application-dependant performance requirements in terms of reliability, message latency and power consumption, while being adaptable to changing conditions, such as heterogeneous traffic load, interferences, and the number of sensors in a hospital BSN. Most archetypal hospital care scenarios conform to a centralized infrastructure with heterogeneous traffic as for instance the one portrayed in Fig. 1.

Fig. 1 represents an example where the vital signs data of several hospitalized real-time monitoring patients (wearing different on-body sensors on bed or walking) and doctors’ notes (working on a PDAs or Laptops) are transmitted to a hospital Care Unit for controlling. In a hospital environment, a centralized architecture is appropriate as the Body Area Network (BAN) coordinator (e.g. the Care Unit in Fig. 1) is superior to the rest of the body sensors (e.g. ECGs, Respiratory-rate, Blood Pressure, Oxygen Saturation (SpO_2)) in terms of processing memory and power resources. Note that if the traffic load (or number of sensors) in the BAN notably increases beyond saturation limits, a cluster-tree architecture with several BAN coordinators can be adopted, as also allowed in 802.15.4 [2]. This article analyses the DQBAN behavioral bounds within a star-based BAN with a single coordinator close to saturation limits.

C. DQBAN Logic System Model

Like DQRAP, DQBAN utilizes the two common logical distributed queues CRQ and DTQ, for serving access requests (via the “access minislots”) and data packets (via the “data slot”) respectively. However, instead of keeping a first-come-first-served discipline in DTQ, a cross-layer fuzzy-rule based scheduler is introduced in the DQBAN logic system model as

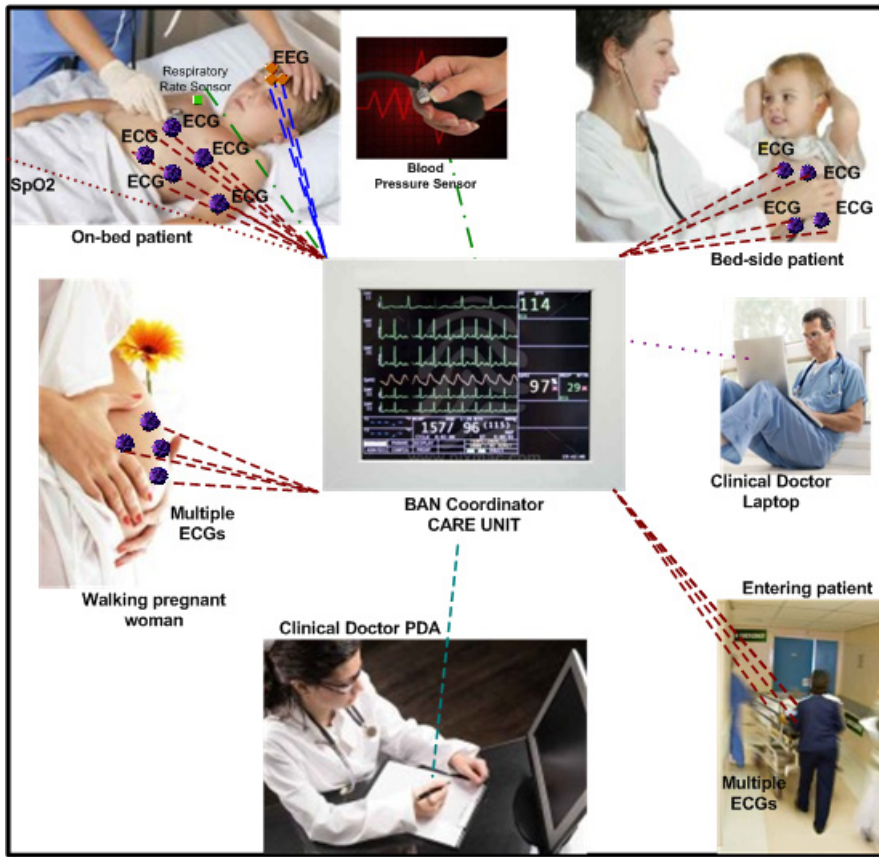


Fig. 1. A star-based BAN in a hospital scenario

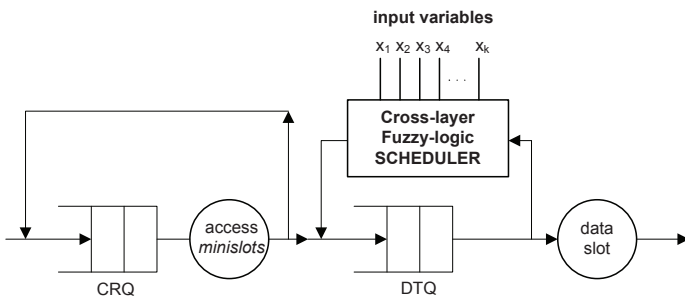


Fig. 2. DQBAN logic system model

depicted in Fig. 2. The use of the scheduler permits a body sensor, though not occupying the first position in DTQ, to transmit its data in the next frame collision-free “data slot” in order to achieve a far more reliable system performance. Practically speaking, this is obtained by integrating a fuzzy-logic system in each body sensor in the BSN. As explained later in Section IV, a fuzzy-logic approach allows each particular body sensor to individually deal with multiple cross-layer inputs of diverse nature (i.e. x_1, x_2, \dots, x_k in Fig. 2) and react accordingly to demand or refuse the next frame “data slot”.

D. DQBAN Body Sensor Flow Chart

As illustrated in the DQBAN flow chart of Fig. 3, a body sensor willing to transmit a packet must first synchronize with the BSN through the Feedback Packet (FBP) broadcasted by the BAN coordinator to update the state of the system queues (CRQ & DTQ) (see Fig. 3,(a)). Note that when both queues are empty, the protocol uses an exception of slotted-Aloha (see [7]). However, if CRQ is empty — but DTQ is not —, the body sensor sends an access request — randomly selecting one of the “access minislots” —, to grant its access into DTQ (see Fig. 3,(b)). If its access request collides with any of another body sensor in the selected “access minislots”, these body sensors involved therein occupy the same position in CRQ (following the order of the selected minislots position), and wait for a future frame to compete for a free “access minislots” again to grant its access into a DTQ exclusive position. New body sensors, with a packet to send, are not allowed to enter the system until CRQ is empty (i.e. all current collisions are resolved) (see Fig. 3,(c)). When a body sensor selects successfully a free “access minislots” (known at the reception of the FBP), it takes immediately a place in DTQ up. If DTQ is now empty, it may be in the first position of DTQ, thus transmitting directly in the next DQBAN superframe “data slot” (see Fig. 3,(d), DTQ Empty Case). If this is not the case, each body sensor applies its fuzzy-logic algorithm in order to demand a collision-free “data slot” (i.e. to be forwarded) or

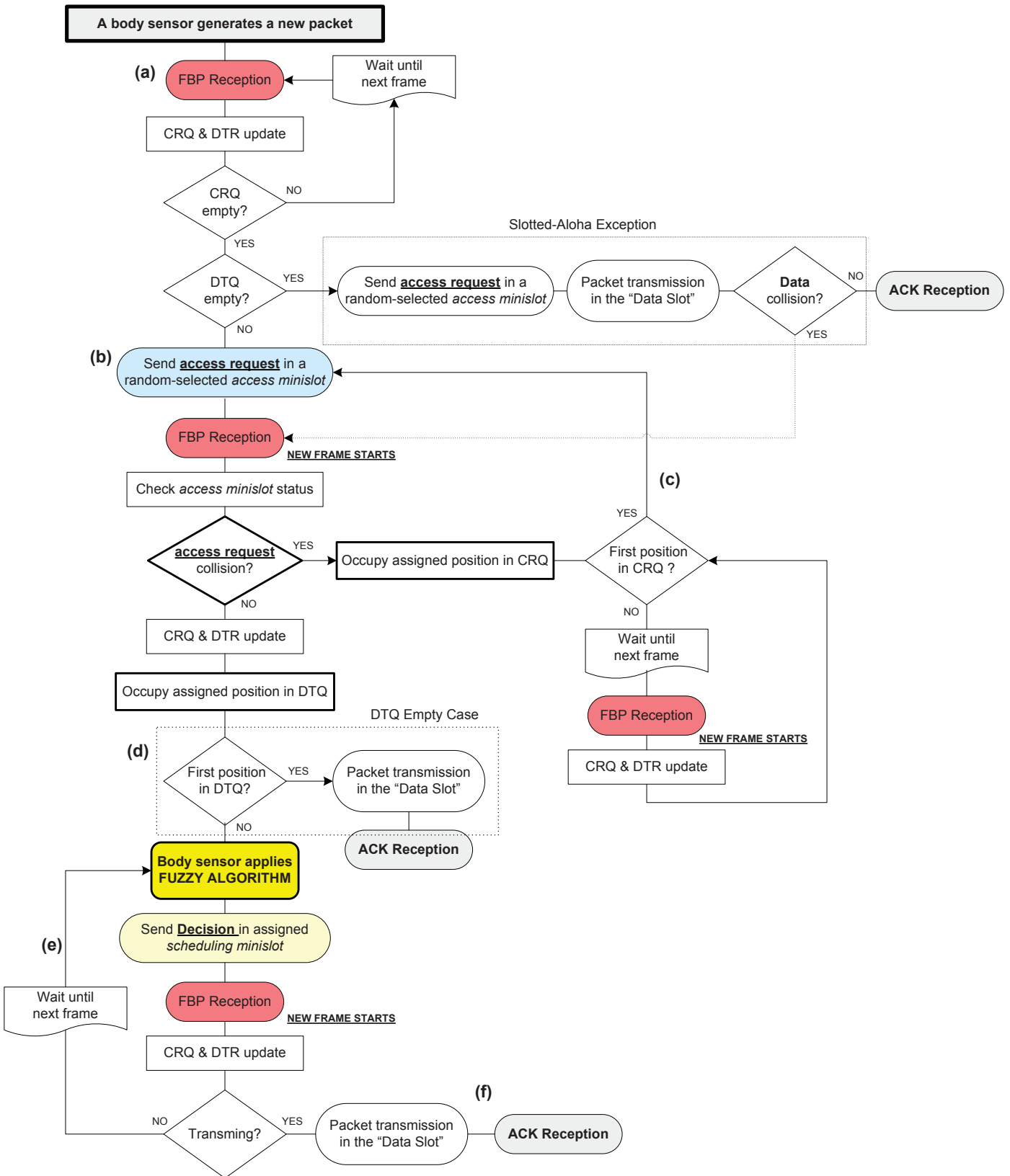


Fig. 3. DQBAN body sensor flow chart

to refuse the next "data slot" (i.e. to be delayed) whenever it is required. As explained in the next section, this algorithm consists of a number of fuzzy-logic rules, which permit body sensors to find out 'how favorable' or 'how critical' their specific situation is, in a particular time-frame.

Every body sensor in DTQ has the chance to individually send its **Decision** (i.e. *forward* or *delay*) to the BAN coordinator via the "scheduling minislots". Otherwise it remains in the same position and no decision is sent to the BAN coordinator. When having all different results, the BAN coordinator notifies

— through the broadcasted FBP — about the specific changes to improve the system overall performance: i) if a body sensor requires the next collision-free “data slot”, or ii) if a body sensor in the position to transmit indicated its refusal to do it (see Fig. 3,(e)). At the reception of the FBP, each body sensor knows whether it may transmit in the next “data slot” accordingly to its own demands, and is able to distributedly update the queue states consequently (see Section III.A). Finally, the turn comes for the body sensor to transmit and wait for the reception of an acknowledgement (ACK) of the BAN coordinator (see Fig. 3,(f)).

E. DQBAN Superframe Structure

Fig. 4 illustrates the new conditioned DQBAN superframe structure to satisfy the aforementioned medical specific requirements. Body sensors use the next frame format to communicate with the BAN coordinator:

- m “access *minislots*” of duration T_{access} for access requests,
- n “scheduling *minislots*” of duration $T_{scheduling}$ for exceptional body sensor warnings, and
- the collision-free “data slot” of variable duration T_{DATA} to send body sensor packets.

Similarly, the BAN coordinator communicates to the body sensors via the following fields:

- an ACK of duration T_{ACK} to acknowledge the packet of the transmitting body sensor that must arrive before T_{aw} elapses as explained in 802.15.4 [2],
- a synchronization preamble (pre) of duration T_{pre} , which permits energy-aware radio activation policies, and
- the FBP of fixed duration T_{FBP} , which is broadcasted by the BAN coordinator.

Following the illustration in Fig. 4, DQBAN superframe structure ends with inter-frame-space (T_{IFS}), as defined in 802.15.4 [2]. We decided to express field durations in time instead of in bytes to facilitate nomenclature along the article. The FBP is here of fixed duration and includes the packet length (Lgth) and the Modulation-Coding-Scheme (MCS) of the following data packet to allow body sensors to autonomously regulate their own power management activity, as explained later in this section. Please refer to DQRAP specifications in [7] for more details about the Queuing Discipline Rules (QDR field), which allow body sensors to independently update their four integer counters representing the logical queues states in CRQ and DTQ. Note that the scheduling *minislots*, the strategic FBP subfields — F (*Forward*) and D (*Delay*) — and the synchronization preamble are all brand-new fields especially designed to fulfill the above-mentioned BSN requirements in healthcare systems. A detailed description follows.

1) *DQBAN scheduling minislots*: Those body sensors occupying the n first positions in DTQ — with the exemption of the one transmitting in the “data slot” of the current superframe — may send a warning in the assigned scheduling minislot to demand or refuse the next “data slot” in case of danger (see Fig. 4). This situation can happen i) if a non-transmitting body sensor requires urgently to send its packet sooner as indicated in its current position in DTQ (for example due to

excessive packet system delay or not enough residual battery lifetime), or ii) whenever a body sensor occupying the second position in DTQ does not find it convenient to transmit in the next frame (for example due to interferences). Since all active body sensors in the BAN are constantly aware of the state of the queues via the FBP, the number of scheduling *minislots* (n) might be configurable from DQBAN superframe to superframe, though always equal or smaller than the total number of occupied positions in DTQ. Thus, now DQBAN behaves as an intelligent MAC protocol adapting itself to traffic load, channel link quality (i.e. interferences) and QoS requirements. That is, DQBAN operates as

- i) a slotted-ALOHA protocol for light traffic load;
- ii) a reservation protocol for high traffic load; and,
- iii) a “polling” protocol to guarantee — “on demand” — a collision-free “data slot”.

Notice that to for iii), apart from the new “scheduling *minislots*” the strategic subfields in FBP (F and D) are essentially required.

2) *DQBAN F and D subfields in FBP*: The FBP contains the new strategic fields F (*Forward*) and D (*Delay*), which are used by the BAN coordinator to inform body sensors about the overall result of their own decisions (i.e. after their having applied the fuzzy-logic algorithm). That is, the F field refers to “the position occupied by the body sensor in DTQ” which requires to be forwarded to transmit in the next collision-free “data slot”. Should more than one body sensor demand simultaneously to be forwarded, the BAN coordinator selects the one occupying the first relative position in DTQ. That is fair, since that body sensor has been waiting longer in the DQBAN system. Further, the D field is active if “the body sensor occupying the current first position in DTQ” indicated its refusal to transmit in the next “data slot”. If the F field is empty, the body sensor in the second position in DTQ transmits. Bear in mind that both fields are implementation dependant. The F field is an integer counter and the D field might be a flag (e.g. 1 byte for both fields).

3) *DQBAN synchronization preamble*: Apart from the transmit and receive modes, each body sensor supports two further states as defined in [10]: *shutdown*, when the clock is switched off and the chip is completely deactivated waiting for a start-up strobe; and *idle*, when the clock is turned on and the chip can receive commands (for example, to turn on the radio circuitry). In [11], we showed different power management scenarios of sensors using an energy-aware radio activation policy. In the DQBAN context, every body sensor in *idle* mode synchronizes to the BSN through a preamble sequence of duration T_{pre} (see Fig. 4). Thereafter, it receives all related information of the state of the queues CRQ and DTQ via the FBP. Thanks to the preamble, each body sensor in the BAN uses energy-aware radio activation policies in order to maximize its battery lifetime and minimize its overall energy consumption.

IV. CROSS-LAYER FUZZY-LOGIC SCHEDULING ALGORITHM

As previously mentioned in Section III.C, the cross-layer fuzzy-rule based scheduler main goal is to optimize MAC

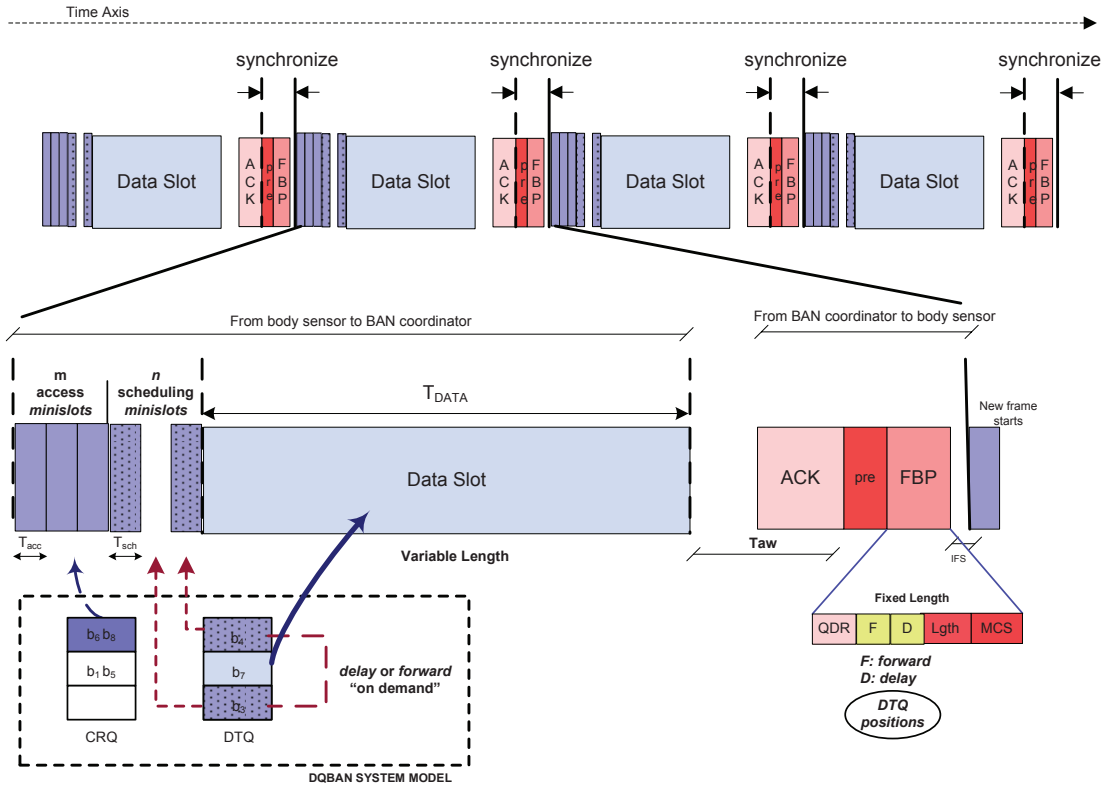


Fig. 4. DQBAN superframe structure

layer overall performance in terms of QoS and energy consumption by applying fuzzy-logic decision techniques that take multiple input variables of diverse nature into account (i.e. x_1, x_2, \dots, x_k in Figure 2). The basic idea is that body sensors consider relevant cross-layer system constraints, such as physical layer signal quality (due to time-variant interferences in the channel link to the BAN coordinator), packet system waiting time, and residual battery lifetime, to demand or refuse the next frame collision-free “data slot” via the scheduling *minislots*, as explained before. In order to do so, a fuzzy-logic system is integrated in each body sensor in the BAN. Bearing in mind the dynamic and unpredictable states of these input variables, the use of fuzzy-logic theory is considered appropriate for the implementation design of the DQBAN system. The advantage of a fuzzy-logic approach is its simplicity of implementation and scalability when dealing with non-linear systems with multiple inputs of diverse nature [12]. That is, the cost of introducing a new input variable in a fuzzy-logic system is much lower than re-designing a predetermined cost function as in [13]. In our current implementation design, the fuzzy-logic system integrated in each body sensor employs three cross-layer specific sensor-dependant (i) time-variant (t_i) input variables to satisfy the above-mentioned requirements. These are;

- i) the Signal-to-Noise Ratio in dB — $SNR_i(t_i)$ — derived at the reception of the FBP, assuming symmetry within uplink and downlink — to and from the BAN coordinator — given a certain coherence time;
- ii) the Waiting Time in the system in seconds — $WT_i(t_i)$ — calculated from an inherent clock; and,

- iii) the residual Battery Lifetime in mAh — $BL_i(t_i)$ — derived from an inner hardware indicator.

In general, a fuzzy-logic system is a nonlinear mapping of an input data vector into a scalar output and is widely used in fuzzy-logic controllers [14]. Fuzzy set theory establishes the specifics of the nonlinear mapping. A fuzzy logic controller contains four components: *fuzzifier*, *fuzzy rules*, *fuzzy inference process*, and *defuzzifier*. The *fuzzifier* turns the input real values (also called crisp values) into linguistic variables. The *fuzzy rules* are the linguistic rules, which make up the fuzzy logic controller decision behavior. The *fuzzy inference process* matches the linguistic input variables with the linguistic rules. The result of the *fuzzy inference process* is that the linguistic values are assigned to a set of linguistic output variables.

Note that in our fuzzy-logic system implementation, the use of the *defuzzifier* is not required, since body sensors make use of a unique *output linguistic variable (Decision)*, whose linguistic values remain invariable independently of the number of input real variables.

A. Fuzzifier

To facilitate the implementation design at the entrance of the fuzzy-logic system, we use normalized values with respect to each body sensor specific constraints: SNR_i^{min} , derived from its particular Bit-Error-Rate (BER_i); WT_i^{max} and BL_i^{min} , application-related maximal message latency and body sensor minimal battery lifetime to send a packet of a specified length. Thus, at the entrance of the *fuzzifier* there are the following normalized input crisp variables: i) $SNR_i^*(t_i) = SNR_i(t_i) -$

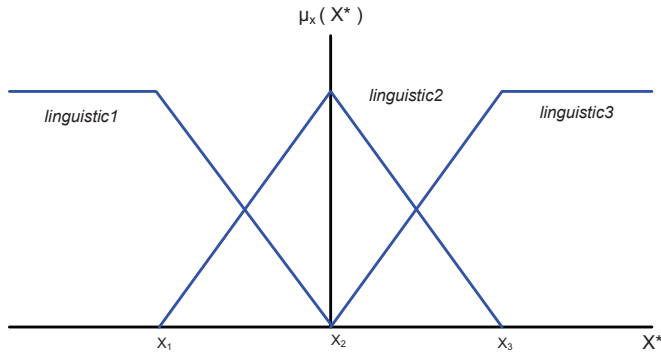


Fig. 5. Membership function example for antecedents and consequents

SNR_i^{\min} [dB]; ii) $WT_i^*(t_i) = WT_i(t_i) - WT_i^{\max}$ [s]; and, iii) $BL_i^*(t_i) = BL_i(t_i) - BL_i^{\min}$ [mAh].

These input normalized crisp variables in the *fuzzifier* are associated to the fuzzy sets with the following linguistic terms:

$$\begin{aligned} SNR &\subset \{dangerous, poor, superior\}; \\ WT &\subset \{acceptable, boundary, excessive\}; \\ BL &\subset \{critical, balanced, substantial\}. \end{aligned} \quad (1)$$

The input linguistic values $\{dangerous, poor, superior\}$ constitute the antecedents of the linguistic rules for the associated input fuzzy variable SNR. The set of linguistic values $\{acceptable, boundary, excessive\}$ and $\{critical, balanced, substantial\}$ are associated to the input fuzzy variables WT and BL, respectively.

Fig. 5 portrays an illustrative example of the membership functions used in our fuzzy-logic system for all the same sort of antecedents and consequents. The representation of *linguistic2* is an isosceles triangle and the corresponding $\{X_1, X_2, X_3\}$ figures are implementation dependant for each input fuzzy variable and adjusted as a function of the known values SNR_i^{\min} , WT_i^{\max} and BL_i^{\min} . We choose the triangular membership function for its simple expression (i.e. low implementation cost and processing power) as explained in [12].

B. Fuzzy-logic Rules and Fuzzy Inference Process

Since the linguistic input variables SNR, WT, and BL have each three different states, the total number of possible ordered triplets of these states is 27 (3x3x3). For each of these ordered triplets of states, we have to determine an appropriate state of the *output linguistic variable Decision*. That is,

$$\mathbf{Decision} \subset \{delay, onschedule, forward\}. \quad (2)$$

The output linguistic variable **Decision** is associated to the fuzzy set $\{delay, onschedule, forward\}$, which form the consequents of our fuzzy rules. A body sensor **Decision** can be to *delay* its transmission to a future DQBAN superframe, to keep its current position in DTQ (*onschedule*), or to demand the next frame “data slot” by indicating *forward*. A convenient way of defining all required *fuzzy-logic rules*, that play a role in the *fuzzy inference process* to determine the output linguistic values of **Decision**, is with a decision table as the one shown in Table I.

TABLE I
OUTPUT LINGUISTIC VALUES OF **Decision** (*fuzzy inference process*)

WT	SNR			BL
	<i>dangerous</i>	<i>poor</i>	<i>superior</i>	
<i>acceptable</i>	<i>delay</i>	<i>delay</i>	<i>onschedule</i>	<i>substantial</i>
<i>acceptable</i>	<i>delay</i>	<i>delay</i>	<i>onschedule</i>	<i>balanced</i>
<i>acceptable</i>	<i>delay</i>	<i>delay</i>	<i>delay</i>	<i>critical</i>
<i>boundary</i>	<i>delay</i>	<i>onschedule</i>	<i>onschedule</i>	<i>substantial</i>
<i>boundary</i>	<i>delay</i>	<i>onschedule</i>	<i>onschedule</i>	<i>balanced</i>
<i>boundary</i>	<i>forward</i>	<i>forward</i>	<i>forward</i>	<i>critical</i>
<i>excessive</i>	<i>forward</i>	<i>forward</i>	<i>forward</i>	<i>substantial</i>
<i>excessive</i>	<i>forward</i>	<i>forward</i>	<i>forward</i>	<i>balanced</i>
<i>excessive</i>	<i>forward</i>	<i>forward</i>	<i>forward</i>	<i>critical</i>

Next we provide seven high level *fuzzy rules* for the *output linguistic variable (Decision)* with their antecedents and consequent as a result of the combination of the states in Table I. The first three rules indicate when data transmission requires to be delayed. $R_i^{(1)}$ is used to detect a bad link channel before transmitting. If there is still enough time and battery lifetime left, the aim is to defer data transmissions; otherwise it may not be possible to guarantee a particular (BER_i) for the lowest power transmission state. $R_i^{(2)}$ claims to wait until batteries have been replaced, so that enough battery lifetime can be guaranteed during a packet transmission interval. In the same line, $R_i^{(3)}$ delays a transmission waiting for a better link channel following Table I solution.

- $R_i^{(1)}$: IF SNR is *dangerous* and WT is not *excessive* and BL is not *critical* THEN **Decision** is *delay*.
- $R_i^{(2)}$: IF BL is *critical* and WT is *acceptable* THEN **Decision** is *delay*. (3)
- $R_i^{(3)}$: IF SNR is not *superior* and WT is *acceptable* THEN **Decision** is *delay*.

Both $R_i^{(4)}$ and $R_i^{(5)}$ show when a body sensor can remain in the same position in DTQ since its situation is not *critical*.

- $R_i^{(4)}$: IF SNR is *superior* and WT is *acceptable* and BL is not *critical* THEN **Decision** is *onschedule*.
- $R_i^{(5)}$: IF SNR is not *dangerous* and WT is *boundary* and BL is not *critical* THEN **Decision** is *onschedule*. (4)

On the contrary, the last two rules warn body sensors about a critical situation to demand the next possible collision-free “data slot” to guarantee QoS. $R_i^{(6)}$ is used when a packet system waiting time is too close to its maximum latency. Note that if SNR were *dangerous*, a body sensor in that situation could even increase its power transmission to compensate the bad quality link, assuming the implementation design allows that. $R_i^{(7)}$ warns each body sensor about its critical residual battery lifetime. The idea is to let the sensor send its packet

in the next frame before batteries are replaced due to time constraints.

$R_i^{(6)}$: IF WT is *excessive*
 THEN **Decision** is *forward*.
 $R_i^{(7)}$: IF BL is *critical* and WT is not *acceptable*
 THEN **Decision** is *forward*. (5)

Body sensors are allowed to send the value of its *output linguistic variable Decision* in the corresponding scheduling *minislot* (see Section V.B).

V. CASE STUDY

In this section, we describe how to analytically model the three sensor-dependant time-variant input variables; $SNR_i(t_i)$, $WT_i(t_i)$, and $BL_i(t_i)$ used by the fuzzy-logic system, integrated in each body sensor. Further, a new way of implementing the output variable **Decision** is introduced in order to have a comparable relative reference for the evaluation results in the next section. Thereafter, we describe how to evaluate the performance of the overall proposed techniques.

A. The Cross-layer Input Variables Model

1) *Signal-to-Noise Ratio*: Every active body sensor (i) obtains its current $SNR_i(t_i)$, in dB, of the link to the BAN coordinator — separated at a random distance (d_i) — upon reception of the FBP at the instant (t_i) (see Fig. 4). Like the authors in [15], we define here the received signal as $P_i^R(t_i, d_i) = P_i^R(d_i) + X_{\sigma_s}(t_i)$, in dBm, where $X_{\sigma_s}(t_i)$ is a zero mean log-normal distributed random variable with a particular standard deviation 12 dB (i.e. to model interference scenarios). The time-variant received signal model $P_i^R(t_i, d_i)$ includes Additive White Gaussian Noise (AWGN) and the effect of log-normal shadowing assuming the channel is coherent within the transmission of a DQBAN superframe in indoor environments. The calculations are based on the path loss model from the 802.15.4 standard [2], where the average received power $P_i^R(d_i)$ is expressed as a function of an arbitrary T-R separation distance $d_i < 8$ meters (i.e. within a hospital setting). Here we compute $SNR_i(t_i)$ by generalizing the formula in [15] as,

$$SNR_i(t_i) = SNR_i^{\min} + (P_i^R(t_i, d_i) - P_i^{sens}), \quad (6)$$

where the power sensitivity P_i^{sens} and the current received power $P_i^R(t_i, d_i)$ are sensor-dependant and expressed in dBm. Further, as indicated in Section IV.A, SNR_i^{\min} depends on a predefined BER_i .

2) *System Waiting Time*: An active body sensor calculates its current system Waiting Time $WT_i(t_i)$, in seconds, at the end of each DQBAN superframe at instant (t_i), every time it has a packet pending to transmit in the queuing system (i.e. CRQ or DTQ). Analytically, $WT_i(t_i)$ is computed as the sum of all different time superframes $T_{FRAME}(t)$ (see Fig. 4), counting from the body sensor first access request at instant ($t = 0$) until the current time ($t = t_i$) for a particular packet in the DQBAN system. That is,

$$WT_i(t_i) = WT_i(t_{i-1}) + T_{FRAME}(t_i) = \sum_{t=0}^{t_i} T_{FRAME}(t), \quad (7)$$

where

$$T_{FRAME}(t) = m \cdot T_{access} + n(t) \cdot T_{scheduling} + T_{DATA}(t) + T_{aw} + T_{pre} + T_{FBP} + T_{IFS}. \quad (8)$$

Please refer to Section III.E for the specific time definitions, and bear in mind that the number of scheduling *minislots* $n(t)$ might be configurable from DQBAN superframe to DQBAN superframe.

3) *Residual Battery Lifetime*: Body sensor residual Battery Lifetime $BL_i(t_i)$, in mAh, is obtained as the difference from its *initial* charged battery B_i^{ini} at the time the body sensor sends its first access request ($t = 0$) and the *consumed* battery $B_i^{cons}(t_i)$ at the end of each time frame ($t = t_i$) for a particular packet in the DQBAN queuing system. That is,

$$BL_i(t_i) = B_i^{ini} - B_i^{cons}(t_i) = B_i^{ini} - \sum_{t=0}^{t_i} (B_i^{tx}(t) + B_i^{rx} + B_i^{idle}(t)), \quad (9)$$

where $B_i^{cons}(t_i)$ has been calculated following the power management scenario described in [11]. Thus, for a body sensor waiting in the DQBAN system,

$$\begin{aligned} B_i^{tx}(t) &= (T_{access}(t) + T_{scheduling}(t)) \cdot I_{tx}, \\ B_i^{rx} &= (T_{pre} + T_{FBP}) \cdot I_{rx}, \\ B_i^{idle}(t) &= (m \cdot T_{access} + n(t) \cdot T_{scheduling} + T_{DATA}(t) + T_{aw} + T_{IFS}) \cdot I_{idle}, \end{aligned} \quad (10)$$

where I_{tx} , I_{rx} and I_{idle} are the minimum consumption values in *transmit*, *receive* and *idle* modes corresponding to Chipcon specification data sheet for CC2420 transceiver [16] in mAh. Note that all other time values have been defined in Section III.E.

B. The Output Variable Model

In our fuzzy-logic system, each body sensor occupying the n first positions in DTQ is allowed to use the corresponding scheduling *minislot* to send — to the BAN coordinator — the value of its output linguistic variable **Decision**. A body sensor only transmits the warning linguistic values. That is, the ones corresponding to *forward* or *delay*, which are supposed to denote a case of urgency within the particular constraints of that body sensor. The way of transmitting those values is implementation dependant (see Section VI.A). In order to better analyze the benefits of our fuzzy-logic system, we decide to compare it with a decision cost function based on [13]. This cost function employs here the same cross-layer input variables and is implemented in each body sensor imitating the fuzzy-logic system approach. This decision cost function is defined as,

$$Decision_i(t_i) = a \cdot WT_i^*(t_i) + b \cdot SNR_i^*(t_i) - c \cdot BL_i^*(t_i). \quad (11)$$

The output variable $Decision_i(t_i)$ represents the body sensor (i) “decision weight” (= decision value) at the instant time (t_i); and the parameters a , b and c have to be configured every time a new input variable is introduced. In this case study, we consider $a = 1000$, $b = 1$ and $c = 1/2000$. A body

TABLE II
 MEDICAL BODY SENSOR SPECIFICATIONS

BODY SENSORS	ECG	Clinical Doctor PDA	Blood Pressure	Respiratory Rate	Endoscope Imaging
<i>BER</i>	10^{-6}	10^{-6}	10^{-8}	10^{-7}	10^{-4}
<i>Latency</i>	0.3 s	1 s	0.75 s	0.6 s	0.5 s
<i>Traffic generation distribution</i>	constant	Poisson	constant	constant	Poisson
<i>Message generation rate</i>	500 byte/s	1000 byte/s	512 byte/s	1024 byte/s	1538.46 bytes/s
<i>Inter-arrival packet time</i>	0.20 s	0.10 s	0.195 s	0.097 s	0.065 s

sensor transmits its “decision weight” into its corresponding scheduling *minislot*. The highest the values of $Decision_i(t_i)$, the more urgent it is for a body sensor to send its packet in the next “data slot”. On the contrary, very low $Decision_i(t_i)$ values indicate that a body sensor prefers to defer its transmission. Therefore, the BAN coordinator establishes a threshold to decide which body sensors require to be forwarded or delayed, and which ones can still remain in their positions in DTQ.

C. Performance Evaluation Metrics

The performance of the proposed techniques is evaluated in a star-based topology BSN where different body sensors with their specific medical requirements communicate with the BAN coordinator in a hospital care scenario through a shared wireless indoor radio channel (see Fig. 1). For scalability reasons, the proposed techniques have been assessed in two specific scenarios,

- i) a *homogenous* scenario characterized by a BSN with only wireless ECG body sensors; and,
- ii) a *heterogeneous* scenario characterized by a BSN with a number of ECG body sensors and other different medical sensors with their own specific QoS demands (see Table II).

Without losing generality, the PHY layer follows the 802.15.4 standard [2] and the here introduced DQBAN system is used to model the MAC layer. The performance evaluation metrics are defined as following.

1) “*Delivery Ratio*”: The authors in [10] performed an energy-saving study about WSNs and estimated the bit error probability on a test bench composed of a CC2420 transmitter wired to a second CC2420 in receiving mode, through a set of calibrated attenuators. Let’s consider here their estimated bit error probability — for a body sensor at a distance (d_i) from the BAN coordinator and at instant (t_i) —, as the exponential regression equation $\rho_i^{bit}(t_i) = 2.35 \cdot 10^{-30} \cdot e^{-0.659 \cdot P_i^R(t_i, d_i)}$. Thereby, we define the probability of success as $\rho_i^{success}(t_i) = (1 - \rho_i^{bit}(t_i))^{L_i}$, where L_i corresponds to the total amount of payload data in the DQBAN superframe expressed in bits. From the previous $P_i^R(t_i, d_i)$ and $SNR_i(t_i)$ expressions in (6), we define numerically the probability of success $\rho_i^{success}$ as a function of $SNR_i(t_i)$ values (see Table III). Further, $\rho_i^{success}$ is grouped in several interval values to ease the fuzzy-logic representation of the SNR membership function, which is used in our simulation scenario.

Thus, the “*Delivery Ratio*” for each particular body sensor is here computed as the percentage of packets that is transmitted successfully, considering:

 TABLE III
 PROBABILITY OF SUCCESS

$\Delta = SNR_i^*(t_i)$ $= SNR_i(t_i) - SNR_i^{\min}$	$\rho = \rho_i^{success}(t_i)$
$\Delta > 12.8$ dB	$0.9824 < \rho < 1$
6.8 dB $< \Delta < 12.8$ dB	$0.9359 < \rho < 0.9824$
4.8 dB $< \Delta < 6.8$ dB	$0.7881 < \rho < 0.9359$
2.8 dB $< \Delta < 4.8$ dB	$0.6199 < \rho < 0.7881$
1.8 dB $< \Delta < 2.8$ dB	$0.3967 < \rho < 0.6199$
0.8 dB $< \Delta < 1.8$ dB	$0.0314 < \rho < 0.3967$
$\Delta < 0.8$ dB	$0 < \rho < 0.0314$

- i) the probability of success $\rho_i^{success}$ in the wireless channel, as defined in Table III;
- ii) the packet timeout due to latency limits specified for every body sensor in Table II; and,
- iii) the battery lifetime limitations for each body sensor, as defined in the next section.

2) “*Mean Packet Delay*” and “*Average Energy Consumption per Utile Bit*”: The “*Mean Packet Delay*” is computed for every packet in the system based on (7). The purpose is to prove that the fact of using the fuzzy-logic scheduling algorithm does not affect the overall delay system performance. Each body sensor shall satisfy its own latency limits as previously defined in Table II.

Similarly, to obtain the “*Average Energy Consumption per Utile Bit*”, we compute the average time each body sensor is in *transmit*, *receive* and *idle* modes (see Section III.E) and multiply these calculated times by the corresponding reference power consumption, following Chipcon specification data sheet for CC2420 transceiver [16]. Note that this computation derives from formulas (9) and (10). Thereafter, we divide by the total average number of information (*utile*) bits per frame. Every sensor transmits with the lowest possible power transmission from those specified in the standard 802.15.4 [2], (i.e. -25 dBm).

VI. DQBAN PERFORMANCE EVALUATION RESULTS

By means of MATLAB computer simulations, we evaluate the aforementioned metrics — “*Delivery Ratio*”, “*Mean Packet Delay*” and “*Average Energy Consumption per Utile Bit*” — to assess the scalability of the DQBAN system performance while the traffic load raises until saturation conditions in a star-based BSN with a single BAN coordinator. For that purpose, the number of body sensors increases in both *homogenous* and *heterogeneous* scenarios as follows,

TABLE IV
DQBAN SYSTEM PARAMETERS BASED ON IEEE 802.15.4 VALUES

PHY header	6 bytes	ACK	11 bytes
MAC header	9 bytes	Preamble	4 bytes
Data Payload	100 bytes	FBP	11 bytes
T_{aw}	864 μ s	T_{IFS}	192 μ s

- i) from 5 to 35 in a *homogenous* scenario with — 1-lead — ECG body sensors with different initial amount of battery; and,
- ii) from 10 to 35 in a *heterogeneous* scenario characterized by 4 different medical sensors as defined in Table II (i.e. Clinical doctor PDA, Blood Pressure, Respiratory Rate, Endoscope Imaging) and a growing number of — 1-lead — ECG sensors.

Be aware that all body sensors are randomly placed from 1-meter to 8-meter distance away from the BAN coordinator in order to symbolize different channel link qualities, as previously detailed in Section V.A. In order to define the particular characteristics of the medical sensors, we have considered a similar approach as authors in [3], [4]. Medical sensors specifications in Table II typify each body sensor requirements in terms of BER, latency, traffic generation distribution and message generation rate or inter-arrival packet time at 250 Kb/s as in 802.15.4 [2]. The selected medical sensors are just a mere example of possible applications in hospital settings. For the sake of simplicity, all body sensors in the *heterogeneous* scenario are initially charged with the same amount of battery, i.e. 5500 mAh in our simulations. In our system implementation, whenever a body sensor runs out of battery its replacement is supposed to be automatically, since the number of body sensors just increases from iteration to iteration and, it never decreases.

A. System Parameters

Following DQBAN superframe structure (see Fig. 4), the chosen reference scenario is defined by the set of system parameters provided in Table IV, whose fields correspond to 802.15.4 MAC default values in the upper frequency band at 2.4 GHz and at the unique standardized data rate 250 Kb/s [2].

We use one of the longest possible data packet payload lengths — 100 bytes — in order to minimize PHY and MAC overhead per utile (i.e. *information*) bit. Observe that DQBAN preamble and FBP lengths have been based on the 802.15.4 PHY preamble and MAC beacon frame, respectively. For each of the four FBP subfields shown in Fig. 4 though, just 1 byte is required (i.e. 4 bytes). Here the DQBAN m access *minislots* occupy each the equivalent of 1 byte. That is a conservative estimate, since theoretically a single bit could do the job, and practically speaking, each body sensor access request could be a separate modulated signal transmission [6], [7]. Similarly, for the DQBAN novel n scheduling *minislots*, the same length of 1 byte is reserved to indicate either *forward* or *delay* (i.e. in the fuzzy-logic implementation for **Decision** output linguistic values); or the “decision weigh” values (i.e. in the cost function implementation $Decision_i(t_i)$, see Section V.B). In our current DQBAN simulations, there are $m = 3$

access *minislots* (as in the original DQRAP [7]); and $n = 5$ scheduling *minislots*, even though n could be configurable from DQBAN superframe to DQBAN superframe, depending on the number of body sensors in DTQ.

To simulate the fuzzy-logic system integrated in each body sensor, we utilize a MATLAB fuzz-logic toolbox. The aforementioned values (X_1, X_3) for each membership function (see Fig. 5) are derived by computer simulations as:

- i) (X_1, X_3) = (1.8, 12.8) dB for SNR (following Table III);
- ii) (X_1, X_3) = (−0.108, 0.012) seconds for WT; and,
- iii) (X_1, X_3) = (1000, 2000) mAh for BL.

B. Simulation Results

For the overall evaluation of the DQBAN MAC system performance, we carried out the following comparisons with a DQRAP-alike protocol (DQ) (see Section III.A) in both *homogenous* and *heterogeneous* depicted hospital care scenarios,

- A. DQBAN model (i.e. with the fuzzy-logic system scheduler and energy-aware radio activation policies),
- B. DQ model as defined in Section V.B (i.e. with a cost function scheduler and energy-aware radio activation policies),
- C. DQ without any scheduler implementation as in [11] (i.e. though with energy-aware radio activation policies),
- D. DQ with neither any energy-aware radio activation policy nor any scheduling algorithm implementation as in [6], [8].

The results of the “Delivery Ratio”, “Mean Packet Delay” and “Average Energy Consumption per Utile Bit” metrics are portrayed in Figs. 6–7 after long iterating and achieving the permanent regime of the DQBAN system.

1) *Homogenous scenario*: Figs. 6(a)–6(d) depict the DQBAN MAC performance in a *homogenous* BSN with an increasing number of — 1-lead — ECG body sensors, whose characteristics are specified in Table II. Note that 20% of the ECG sensors involved in each simulation are initially charged with much less amount of battery. The idea is to evaluate the energy-saving behavior of the DQBAN system as the traffic load raises until saturation conditions. The “Average Energy Consumption per Utile Bit” in Fig. 6(a) illustrates the requirement of an energy-aware radio activation policy. In a typical DQ protocol (see Section III.A), no energy-saving techniques are utilized. Therefore, as the traffic load increases in the BSN, body sensors remaining longer in the system may run out of battery. As a result, the average energy-consumption per delivered information bit increases. Fig. 6(b) emphasizes that by using energy-aware radio activation policies plus a scheduling algorithm, the MAC layer improves in terms of average energy consumption per utile bit. DQBAN outperforms the aforementioned B. and C. implementations. Notice that it was already proved by the same authors in [11] that the energy-consumption of the DQ protocol (implementation C.) outperforms 802.15.4 in WSNs scenarios.

The “Delivery Ratio” graphic Fig. 6(c) proves that the fact of scheduling data packets taking cross-layer constraints into account outperforms the first-come-first-served discipline of

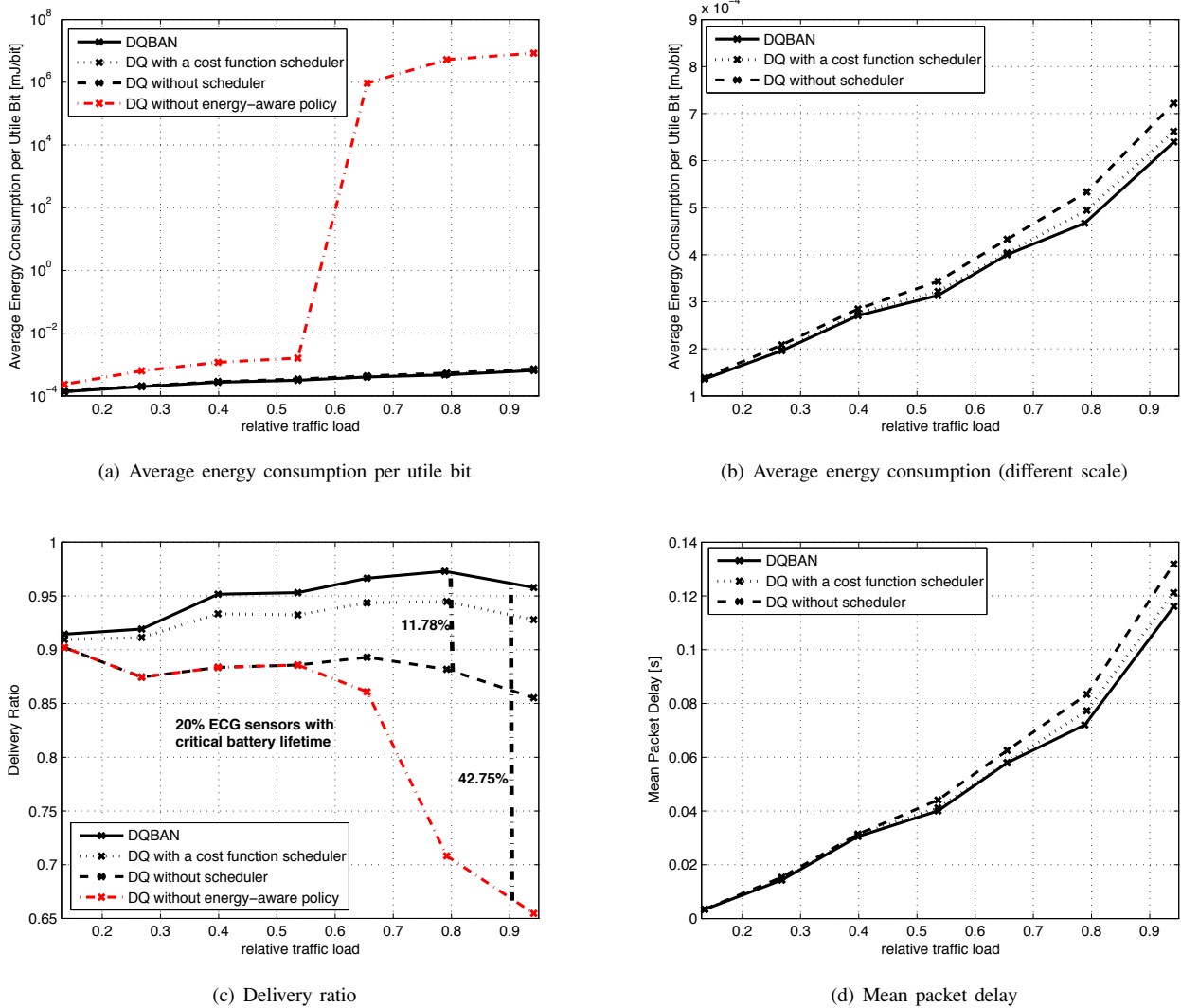


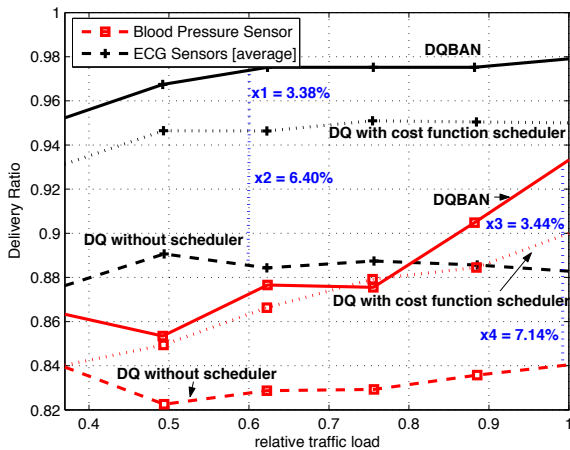
Fig. 6. Homogenous scenario

the original DQ protocol by guaranteeing the QoS requirements of high reliability, right message latency and enough battery lifetime to all body sensors transmissions in the BSN (as described in Section V.C). The use of DQBAN with the proposed cross-layer fuzzy-rule base scheduling algorithm reaches more than 95% of transmission successes, even though 20% of the ECG sensors have critical battery constraints. Close to saturation limits, DQBAN achievement is specifically 42.75% superior to the original DQ protocol without the energy-aware radio activation policy (i.e. implementation D.) and 11.78% superior compared to implementation C. The slight raise in the “Delivery Ratio”, in implementations A. and B., results from the growing number of body sensors in DTQ. That is, it is easier to find a body sensor with the appropriate environmental conditions to be scheduled in the first place, while others are reluctant to transmit. Further, Fig. 6(d) confirms that the use of DQBAN is also appropriate in terms of “Mean Packet Delay” and still outperforms implementation B., as in all previous studied scenarios.

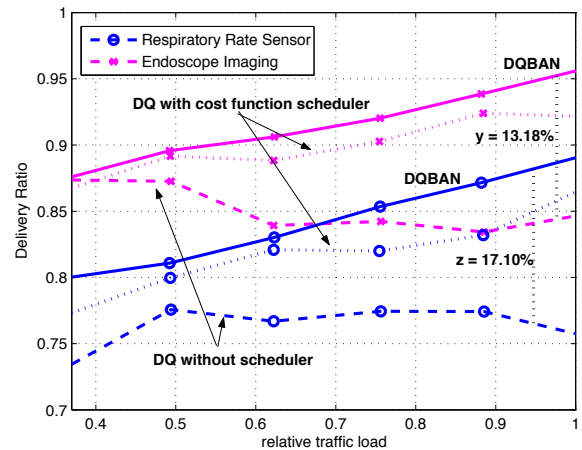
2) *Heterogeneous scenario*: Figs. 7(a)–7(d) illustrate the DQBAN MAC performance in a hospital scenario with *heterogeneous* traffic. The *heterogeneous* BSN is characterized by the four specific medical body/portable sensors defined in

Table II, and an increasing number of ECG body sensors from simulated iteration to iteration.

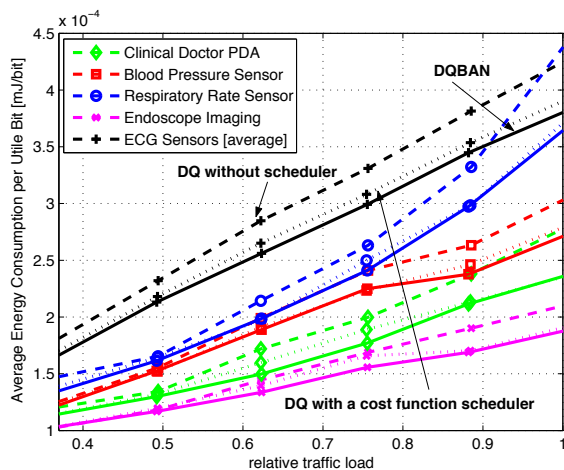
In order to facilitate the evaluation of the “Delivery Ratio” metric of the implementations A., B. and C., Fig. 7(a) portrays the performance of the Blood Pressure body sensor and the average performance of the total number of ECG sensors in the *heterogeneous* BSN, separately. When it comes to evaluate the “Delivery Ratio” of the Blood Pressure body sensor, DQBAN is specifically 3.44% and 10% higher than that of implementations B. and C., respectively. In the average ECG case, DQBAN is 3.38% and 10.83% better than implementations B. and C., respectively, while reaching more than 96% of transmission successes. Similarly, Fig. 7(b) depicts the DQBAN achievements for the Respiratory Rate body sensor (17.10%) and the Endoscope Imaging (13.18%) with respect to implementation C. As aforementioned, the slight raise in the “Delivery Ratio” in implementations A. and B., results from the growing number of body sensors in DTQ, and thereby the possibility of scheduling a more suitable candidate to transmit in the current data slot. In saturation conditions, DQBAN reaches nearly 90% (Respiratory Rate sensor) and 95% (Endoscope Imaging) of transmission successes. Like in the previous studied homogenous scenario, Figs. 7(c) and 7(d)



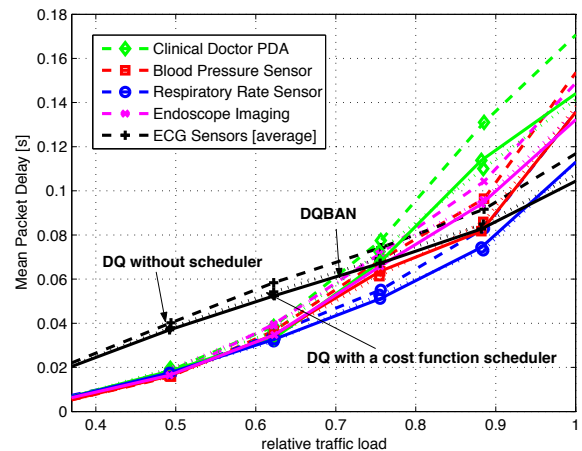
(a) Delivery ratio



(b) Delivery ratio



(c) Average energy consumption per utile bit



(d) Mean packet delay

Fig. 7. Heterogeneous scenario

show the “Average Energy Consumption per Utile Bit” and the “Mean Packet Delay” of all medical body sensors involved therein, confirming again the good inherent performance of the DQBAN model. In general, DQBAN outperforms B. and C. implementations in all analyzed scenarios, while even being more appropriate in terms of scalability and ease of implementation for healthcare applications (see Section IV).

VII. CONCLUSION

The new Distributed Queuing Body Area Network (DQBAN) MAC protocol commitment is to guarantee that all packet transmissions are served with their particular application-dependant quality of service (QoS) requirements (i.e. reliability and message latency), without endangering body sensors battery lifetime in Body Sensor Networks (BSNs). By being autonomously aware of their current condition, body sensors are able to demand or deny the next “collision-free” time slot according to their own limits. For that purpose, instead of keeping a first-come-first-served transmitting discipline, a cross-layer fuzzy-rule scheduling algorithm has been introduced. This scheduling mechanism permits a body sensor, though not occupying the first position in the new MAC queuing model, to send its packet in the

next frame in order to achieve a far more reliable system performance. Further, energy-aware radio activation policies are utilized to minimize the overall energy consumption in BSNs. The proposed DQBAN MAC model has been evaluated in a star-based BSN under two different realistic hospital scenarios with diverse medical body sensor characterizations. The evaluation metric results are in terms of “delivery ratio”, “average energy consumption per utile bit” and “mean packet delay”, as the traffic load in the BSN raises to saturation limits. By means of computer simulations, the DQBAN MAC model has shown to achieve higher reliabilities than other possible MAC implementations, while fulfilling body sensor specific latency demands and battery limits. Thus, the use of DQBAN MAC reaches high transmission successes even in saturation conditions while keeping the good inherent energy-saving protocol behavior. This proves to scale for future BSNs in healthcare scenarios.

ACKNOWLEDGMENT

The author expresses her thanks to Philips Research Europe colleagues and the MDs M.L. Ruiz and J.J. Otal for the motivation and inspiration given towards the medical field.

REFERENCES

- [1] G.-Z. Yang, Ed., *Body Sensor Networks*. Springer-Verlag London Limited, 2006.
- [2] *Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)*, IEEE 802.15.4-2003 Std.
- [3] N. Golmie, D. Cypher, and O. Rebala, "Performance analysis of low-rate wireless technologies for medical applications," *Elsevier Computer Communications*, vol. 28, no. 10, pp. 1266–1275, Jun. 2005.
- [4] N. Chevrollier and N. Golmie, "On the use of wireless network technologies in healthcare environments," in *Proc. IEEE 5th Workshop on Applications and Services in Wireless Networks (ASWN 2005)*, Paris, France, Jun. 2005, pp. 147–152.
- [5] D. Cavalcanti, R. Schmitt, and A. Soomro, "Performance analysis of 802.15.4 and 802.11e for body sensor network applications," in *Proc. IFMBE 4th International Workshop on Wearable and Implantable Body Sensor Networks (BSN 2007)*, Aachen, Germany, Mar. 2007, pp. 9–14.
- [6] H. Lin and G. Campbell, "Using DQRAP (Distributed Queuing Random Access Protocol) for local wireless communications," in *Proc. of Wireless '93*, Calgary, Canada, Jul. 1993, pp. 625–635.
- [7] X. Xu and G. Campbell, "A near perfect stable random access protocol for a broadcast channel," in *Proc. IEEE Communications, Discovering a New World of Communications (SUPERCOMM/ICC'92)*, vol. 1, Chicago, USA, Jun. 1992, pp. 370–374.
- [8] L. Alonso, R. Ferrús, and R. Agustí, "WLAN throughput improvement via Distributed Queuing MAC," *IEEE Communications Letters*, vol. 9, no. 4, pp. 310–312, 2005.
- [9] J. Alonso, E. Kartsakli, A. Cateura, C. Verikoukis, and L. Alonso, "Enhanced operation of DQMAN-based wireless ad hoc networks," in *Proc. IEEE 4th International Symposium on Wireless Communications Systems (ISWCS 2007)*, Trondheim, Norway, Oct. 2007, pp. 632–636.
- [10] B. Bourgard, F. Cathoor, D. C. Daly, A. Chandrakasam, and W. Dehaene, "Energy efficiency of the IEEE 802.15.4 standard in dense wireless microsensor networks: Modeling and improvement perspectives," in *Proc. IEEE Design, Automation and Test in Europe Conference and Exhibition, 2005*, Calgary, Canada, Mar. 2005, pp. 196–201.
- [11] B. Otal, C. Verikoukis, and L. Alonso, "Efficient power management based on a Distributed Queuing MAC for wireless sensor networks," in *Proc. IEEE 65th Vehicular Technology Conference (VTC 2007-Spring)*, Dublin, Ireland, 2007, pp. 105–109.
- [12] P. Srinoui, E. Shayan, and F. Ghotb, "Scheduling of flexible manufacturing systems using fuzzy logic," *International Journal of Production Research*, vol. 44, no. 11, pp. 1–21.
- [13] J.-L. Chen, Y.-C. Chang, and M.-C. Chen, "Enhancing WLAN/UMTS dual-mode services using a novel distributed multi-agent scheduling scheme," in *Proc. IEEE 11th Symposium on Computers and Communications (ISCC 2006)*, Pula-Cagliari, Sardinia, Italy, Jun. 26–29 2006.
- [14] J. M. Mendel, "Fuzzy logic systems for engineering: A tutorial," *Proceedings of the IEEE*, vol. 83, no. 3, pp. 345–377, Mar. 1995.
- [15] I. Howitt and J. Wang, "Energy efficient power control policies for the low rate WPAN," in *Proc. IEEE Sensor and Ad Hoc Communications and Networks (SECON 2004)*, Santa Clara, California, USA, Oct. 4–7 2004, pp. 527–536.
- [16] *SmartRF CC2420: 2.4 GHz IEEE802.15.4/Zigbee RF Transceiver*, Data Sheet, Chipcon.



Begonya Otal received the M.S. degree in telecommunications engineering from the Technical University of Catalonia, Spain, in 2001. From 2001 to 2006, she was full-time employed as a Research Scientist by Philips Research Laboratories (Aachen, Germany). She was formal PHILIPS representative in standardization bodies for 3G mobile systems 3GPP (RAN WG2), and for the standardization consortium (Tn Sync) in WLAN IEEE 802.11 MAC Task Group N "High Throughput". She collaborated in "MultiHop" and "WIGWAM", two German-national funded projects. She was also involved in projects related to personal healthcare applications for Philips Medical Systems. Part of her work supported "MyHeart", an European Commission IST/FP6 eHealth Project. Within Philips Research Labs., she collaborated in nearly 20 invention disclosures. In 2006, she joined CTTC in order to pursue her Ph.D. in the area of wireless Body Sensor Networks (BSNs) for medical applications. She has been devoted to the analysis of healthcare requirements and the optimization of MAC protocol solutions, fuzzy-logic scheduling algorithms and energy-saving techniques for the overall efficiency of BSNs in medical settings.



Luis Alonso received the Engineer of Telecommunications degree from the Universitat Politècnica de Catalunya (UPC), Spain, in 1997. He developed his PhD thesis in the Department of Signal Theory and Communications of the UPC and he reached the PhD degree in 2001. The same year, he moved to the Escola Politècnica Superior de Castelldefels (EPSC), Spain, where he obtained a permanent tenured position in the University, becoming an Associate Professor within the Radio Communications Research Group. He has participated in several research programs, networks of excellence, COST actions and integrated projects funded by the European Union and the Spanish Government, always working on the design and analysis of different mechanisms and techniques to improve wireless communications systems. He has also collaborated with some telecommunications companies as Telefónica, Alcatel and Sener, working as a consultant for several research projects. He also collaborates teaching within the Vodafone's Master in Mobile Communications, carried out in the UPC and directed by Professor Ramon Agustí in collaboration with Vodafone. He has been the Project Coordinator of a Marie Curie Transfer of Knowledge Action (funded by the European Union) and he is currently the Scientific in Charge of two more Marie Curie Actions and also of a three-year Research Project funded by the Spanish Ministry of Science and Technology. His current research interests are still within the field of medium access protocols, radio resource management, cross-layer optimization and QoS features for all kind of wireless communications systems.



Christos Verikoukis received degree in Physics and M.Sc. in Telecommunications Engineering from the Aristotle University of Thessaloniki in 1994 and 1997, respectively. He got his PhD from the Technical University of Catalonia in 2000. Since February 2004, he is senior research associate in Telecommunications Technological Centre of Catalonia (CTTC). Before joining CTTC, he was research associate and projects coordinator in the Southeastern Europe Telecommunications & Informatics Research Institute in Greece. He has been involved in several European (FP5 IST, FP6 IST & Marie-Curie, FP7 ICT & People, EUREKA) and national (in Spain and in Greece) research funded projects, while in some of them he has served at the Project or the Technical Manager. Dr. Verikoukis has served as a reviewer in several IEEE Magazines and Conferences. Since January 2007, he is a Senior Member of the IEEE. His research interests include MAC protocols, RRM algorithms, cross-layer techniques, cooperative and cognitive communications for wireless systems.