Research Article

Design and Analysis of an Energy-Saving Distributed MAC Mechanism for Wireless Body Sensor Networks

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The fact that the IEEE 802.15.4 MAC does not fully satisfy the strict wireless body sensor network (BSN) requirements in healthcare systems highlights the need for the design and analysis of new scalable MAC solutions, which guarantee low power consumption to all specific sorts of body sensors and traffic loads. While taking the challenging healthcare requirements into account, this paper aims for the study of energy consumption in BSN scenarios. For that purpose, the IEEE 802.15.4 MAC limitations are first examined, and other potential MAC layer alternatives are further explored. Our intent is to introduce energy-aware radio activation polices into a high-performance distributed queuing medium access control (DQ-MAC) protocol and evaluate its energy-saving achievements, as a function of the network load and the packet length. To do so, a fundamental energy-efficiency theoretical analysis for DQ-MAC protocols is hereby for the first time provided. By means of computer simulations, its performance is validated using IEEE 802.15.4 MAC system parameters.

1. Introduction and Related Work

Although the challenges faced by wireless body sensor networks (BSNs) in healthcare environments are in a certain way similar to those already existing in current wireless sensor networks (WSNs), there are intrinsic differences which require special attention [1]. For instance, human body monitoring may be achieved by attaching sensors to the body's surface as well as implanting them into tissues for a more accurate clinical practice. Some of these newly emerged challenges, due to healthcare requirements, range from low latency and high reliability (i.e., quality of service), to low power consumption in order to protect human tissue. Hence, one of the major concerns in BSNs is that of extreme energy efficiency, which is also the key to extend the lifetime of battery-powered body sensors, reduce maintenance costs, and avoid invasive procedures to replace battery in the case of implantable devices. While taking healthcare requirements into consideration, in this paper, we concentrate on the evaluation of energy consumption in the Medium Access Control (MAC) layer. For that purpose, we introduce a new energy-efficiency theoretical analysis of a Distributed Queuing MAC (DQ-MAC) protocol and evaluate its performance under BSN scenarios. Please note that the optimization design and evaluation of the here characterized DQ-MAC protocol in terms of quality of service was presented in [2] under BSN scenarios considering specific medical settings. The resulted protocol with integrated cross-layer fuzzy-logic scheduling techniques was renamed to Distributed Queuing Body Area Network (DQBAN) MAC protocol. Generally speaking, 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. In this context, among all IEEE 802 standards available today, the IEEE 802.15.4 (802.15.4) [3] is regarded as the technology of choice for most BSN research studies [1, 4–7]. However, even though the 802.15.4 MAC consumes very low power, the figures may not reach the levels required in BSNs [4, 5]. This is the reason why there exists the need to explore

other MAC potential candidates for future BSNs [2, 6–18], which might be potential candidates for other BSN-targeted standardization bodies, such as the IEEE 802.15.6 task group.

A lot of work has been done on reducing the power consumption since the first standardization of the 802.15.4 MAC in 2003 [3]. Most of the proposed low-powered MAC layer protocols are contention based (CSMA) and can be put into either, one of the two classifications, synchronous or asynchronous. The basic idea behind a synchronous MAC is to let the sensors sleep periodically, and to have them somehow aware of each other's sleeping schedules. In order to work efficiently, a very basic requirement is to have sensors tightly coupled or synchronized to each other. Some synchronous protocols found in the literature are S-MAC [8] and T-MAC [9]. S-MAC introduces periodic coordinated sleep/wakeup duty cycles, and as a result, the battery lifetime for sensors is increased. One problem of S-MAC is that the duty cycle requires to be tuned to a specific traffic load. Thus, its performance suffers under varying traffic loads. The T-MAC sleeping technique [9] satisfies the varying traffic requirements. The T-MAC also uses an adaptive listening technique in neighbor's transmissions, and sensors are able to immediately pass the data, avoiding the timeout introduced in T-MAC. Therefore, as T-MAC duty cycle varies adaptively, this improves the energy and throughput performance under varying traffic loads.

The asynchronous techniques employ a completely different approach. They append a long enough preamble to the data packets that ensures that the destination became active at least once while the preamble was being transmitted. B-MAC [10] uses a technique that allows sensors to sleep without them having to be aware of each other's schedules or without being synchronized. It is a simple protocol which uses long preambles to eliminate the need of synchronization. However, B-MAC somehow suffers from energy inefficiency due to the new introduced overhead, since all nodes in the sphere of influence require listening to the long preambles. X-MAC [11] takes the concepts of B-MAC further and comes up with techniques to reduce the length of the preamble by putting useful information in the preamble. X-MAC avoids overhearing by putting the destination address in the preamble, that is, unconcerned sensors come to know just by listening to a part of the preamble that the data packet is not intended for them, and thus they go back to sleep. MFP-MAC's greatest achievement is the reduction of idle listening and overhearing avoidance in broadcast traffic [12]. Idle listening is reduced by having the preamble divided into sequence numbered microframes. This way each sensor knows when the current data will be put.

The BSN-MAC [6] is a dedicated ultra-low-power adaptive MAC protocol designed for star-based topology BSNs based on 802.15.4 MAC. By exploiting feedback information from distributed sensors in the BSN, the BSN-MAC protocol adjusts protocol parameters dynamically to achieve best energy conservation on energy-critical body sensors. The same authors of BSN-MAC published thereafter the H-MAC [7], which is a novel Time Division Multiple Access (TDMA) MAC protocol especially designed for biosensors in BSNs. It improves energy efficiency by exploiting human heartbeat rhythm information to perform time synchronization for TDMA. By following the heartbeat rhythm, wireless biosensors can achieve time synchronization without having to turn on their radio to receive periodic timing information from a central controller, so that energy cost for time synchronization can be completely avoided and the lifetime of the BSN can be prolonged. Another energy-efficient TDMA-based MAC protocol for wireless BSNs is the BodyMAC [13], which uses flexible and efficient bandwidth allocation schemes and sleep mode to meet the dynamic requirements of BSNs. In [13], the authors compared BodyMAC with 802.15.4 MAC. To reduce energy consumption in a BSN, the authors in [14] designed a collision-free protocol, where all communication is initiated by the central node and is addressed uniquely to a slave node.

All of these protocols try to reduce some of the commonly identified sources of energy loss: idle listening, collisions, overhearing, or protocol overhead. On the one hand, purely contention-based protocols such as S-MAC [8], T-MAC [9], B-MAC [10], X-MAC [11], and MFP-MAC [12] are not energy-efficient enough for real-time monitoring applications in BSNs. On the other hand, the problem with TDMA-based protocols might be the bandwidth under utilization whenever there is a BSN with heterogeneous traffic. This is the main reason why we suggested the use of the DQ-MAC family, which grants immediate access for light traffic loads and seamlessly moves to a reservation system for high traffic loads, eliminating collisions for all data transmissions. The optimisation introduced in [2] proves how DQBAN is able to cope with constant and heterogeneous traffic in two different medical scenarios under BSNs, assuming that the central node is unconstrained in energy (e.g., central care unit) and is always reachable (see Figure 1). DQBAN energy-efficiency performance remains the same as the one analyzed in this paper without the optimization introduced in [2]. Here, apart from providing a new theoretical energy-consumption analysis in nonsaturation conditions, an energy-efficiency comparison between DQ-MAC performance and that of the standard facto 802.15.4 MAC and the BSN-MAC is portrayed. BSN-MAC has been selected as a reference benchmark for its similarity in terms of design as well as structure, and studied scenarios in [6].

Current 802.15.4 MAC limitations for BSNs are formulated in Section 2. Section 3 follows with a brief overview of the most relevant specifications regarding DQ-MAC protocols. Section 4 introduces significant DQ-MAC protocol enhancements to minimize energy consumption in BSNs. The newly proposed energy-efficiency analysis in nonsaturation conditions and the adopted energy-aware radio activation policy are presented in Section 5. The model validation and the performance evaluation by means of computer simulations are shown in Section 6. The last section concludes the paper.

2. 802.15.4 MAC Limitations in Healthcare Scenarios

The 802.15.4 MAC accepts three network topologies: star, peer to peer, and cluster tree. Our focus is here on 1-hop

star-based BSNs, where a body area network (BAN) coordinator is elected. In a hospital BSN, the BAN coordinator can be a central care unit linked to a number of ward patients wearing several body sensors (see Figure 1). Communication from body sensors to BAN coordinator (*uplink*), from BAN coordinator to body sensors (*downlink*), or even from body sensor to body sensor (*ad hoc*) is possible. In the following, we study *uplink* and *downlink* communications, which occurs more often than *ad hoc* communication for regular patient monitoring BSNs. In a 802.15.4 star-based network, the beacon mode appears to allow for the greatest energy efficiency. Indeed, it allows the transceiver to be completely switched off up to 15/16 of the time when nothing is transmitted/received, while still allowing the transceiver to be synchronized to the network and able to transmit or receive a packet at any time [19]. The beacon mode introduces the so-called superframe structure. The inter-beacon period is partially or entirely occupied by the superframe, which is divided into 16 slots. Among them, there are at most 7 guaranteed time slots (GTS), (i.e., they are dedicated to specific nodes), which form the contention-free period (CFP) [3]. This functionality targets very low-latency applications, but it is not scalable in BSNs, since the number of dedicated slots is not sufficient [4]. Further, most of the time, a device uses only a small portion of the allocated GTS slots, and the major portion remains unused, resulting in empty holes within the CFP (i.e., bandwidth under utilization). In the medical field, where one illness usually boost up other illnesses, many body sensors should be able to reach the BAN coordinator via such guaranteed services [5].

In such conditions, the use of the contention access period (CAP) is required, where channel accesses in the *uplink* are coordinated by a slotted carrier sense multiple access mechanism with collision avoidance (CSMA/CA). Nevertheless, it has already been proved that the CSMA/CA mechanism, used within the CAP, has a significant negative impact on the overall energy consumption, as the traffic load in the network steadily increases [19–21]. In [19], the authors suggested that physical level improvements, such as energy-aware radio activation policies, should be combined with other MAC optimizations to allow for more energy-efficient wireless networks. Thus, the appraisal of other existing MAC protocols in terms of effective energy per information bit introduces important challenges in BSNs. This is the reason why we here introduce energy-aware radio activation policies into a high-performance MAC protocol different from CSMA/CA, while analyzing and evaluating its energy-saving performance in BSNs. In the literature, it is already possible to find some research work on reducing the power consumption of the standard de facto 802.15.4 MAC in BSN scenarios [6, 7]. The Body Sensor Network MAC (BSN-MAC) is based on 802.15.4 MAC supporting both star and peer-to-peer network topologies. The authors in [6, 7] concentrate also on a 1-hop star-based topology, since in their analyzed BSN, the number of sensors is limited and an external mobile device, such as PDA or cell phone, acts as a BAN coordinator. However, the promising accomplishment of the DQBAN protocol in terms of quality

of service under healthcare requirements in hospital settings [2], evokes the idea to further explore and analyze the energy-efficiency of this family of DQ-MAC protocols (i.e., [2, 15–18]) in general BSN scenarios. In [15–18], DQ-MAC favorable behavior (especially versus CSMA/CA) is achieved thanks to the inherent protocol performance at eliminating collisions in data transmissions and minimizing the overhead of contention procedures (i.e., carrier sensing and backoff periods). Based on that, we propose here a novel DQ-MAC energy-efficiency theoretical analysis for non-saturation conditions and evaluate its performance in front of 802.15.4 MAC and BSN-MAC in BSN scenarios, bearing medical applications in mind. Please note that in order to cope with healthcare stringent requirements of quality of service, the same authors introduced new cross-layer fuzzy-logic scheduling techniques into the here proposed DQ-MAC protocol and evaluate its performance in terms of reliability and maximum latency in different hospital settings [2]. The results proved to show the suitability of the here presented DQ-MAC protocol in more specific healthcare BSN scenarios.

3. Overview of Distributed Queuing MAC Protocols

This section highlights the basic features related to DQ-MAC protocols that are essential for the understanding of the new energy-saving enhancements and energy-efficient theoretical analysis proposed in this paper. The introduction of the Distributed Queuing Random Access Protocol (DQRAP) for local wireless communications was already presented in [15] and later in [16] under the name of Distributed Queuing Collision Avoidance (DQCA), as an adaptation to IEEE 802.11b MAC environments. It has already been shown that the throughput performance of a DQ-MAC protocol outperforms CSMA/CA in all studied scenarios. The main characteristic of a DQ-MAC protocol is that it behaves as a random access mechanism under low traffic conditions, and switches smoothly and automatically to a reservation scheme when the traffic load grows, that is, DQ-MAC protocols show a near-optimum performance independent of the amount of active terminals and traffic load.

Let us consider a star-based topology with several nodes and a network coordinator, following DQRAP original description [17], the time axis is divided into an "access subslot" that is further divided into access *minislots* (*m*) 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 transmissions (see Figures 2 and 3). The DQRAP analytical model approaches the delay, and throughput performance of the theoretical is in charge of the data server (the "data subslot"). This provides a collision resolution tree algorithm that optimum queuing systems M/M/1 or G/D/1, depending on the traffic distribution. Hence, DQ-MAC protocols can be modeled as if every station in the system maintains two common logical distributed queues—the collision resolution queue (CRQ) and the data transmission queue (DTQ)—physically implemented as four integers in each station; two

station-dependant integers that represent the occupied position in each queue; two further integers shared among all stations in the system that visualize the total number of stations in each queue, CRQ and DTQ (see Figure 4). The CRQ controls station accesses to the collision resolution server (the access *minislots*), while the DTQ proves to be stable for every traffic load even over the system transmission capacity. Note that the number of access *minislots* is implementation dependant, but we are formally using 3 access *minislots*, following the original DQRAP structure and argumentation for maximizing its throughput performance [17].

A DQ-MAC protocol consists of several strategic rules, independently performed by each station by managing the aforementioned four integers (i.e., corresponding to the two distributed queues, CRQ and DTQ) [17], which answer

(i) "who" transmits in the data slot and "when",

(ii) "who" sends an access request sequence in the *minislots* (*m*) and "when" and

(iii) "how" to actualize their positions in the queues.

4. DQ-MAC Energy-Saving Enhancements for BSNs

Figure 2 shows the superframe format of a DQ-MAC protocol proposal in a possible star-based BSN scenario. There might be several ward patients wearing a number of body sensors that communicate to a central care unit (i.e., BAN coordinator), as portrayed in Figure 1. The complete energy-saving superframe structure comprises two differential parts:

(i) from body sensors to BAN coordinator (*uplink*), with a CAP and a CFP. The CAP is further divided into *m* access *minislots*, whereas the CFP is devoted to collision-free data packet transmissions;

(ii) from BAN coordinator to body sensors (*downlink*) using the feedback frame, which contains several strategic fields.

In fact, the DQ-MAC superframe is bounded by the feedback packet (FBP) contained in the feedback frame as portrayed in Figures 2 and 3 which is broadcasted by the BAN coordinator.

Similar to the 802.15.4 MAC superframe format, one of the main uses of the FBP is to synchronize the attached body sensors to the BAN coordinator. The FBP always contains relevant MAC control information (i.e., corresponding also to the protocol rules), which is essential for the right functioning of all body sensors in the BSN. When a body sensor wishes to transfer data, it first waits for the FBP. After synchronization, it independently actualizes the integer counters, by applying a set of rules that determine its position in the protocol distributed queues, CRQ and DTQ (see Figure 4). At the appropriate time, the body sensor transmits either an access request sequence (ARS), of duration t_{ARS}, in one of the randomly selected access *minislots* (within the CAP), or its data packet in the contention-free data slot of duration t_{DATA} (within the CFP). The BAN coordinator may acknowledge the successful reception of the data packet by sending an optional acknowledgment frame (ACK). This

sequence is summarized in the energy-saving DQ-MAC superframe depicted in Figure 3.

All in all, the main differences of this energy-saving DQ-MAC superframe format in Figure 3 with respect to the previous DQ-MAC protocols [9–18] the following:

(1) A preamble (PRE) is newly introduced within the broadcasted feedback frame, concretely between the ACK and the FPB, to enable synchronization after power-sleep modus (i.e., either idle or shutdown, see [19, 22]). The intuitive reasoning is the following: (i) the feedback frame is an aggregation of an ACK and the FBP in order to save PHY header overhead and therefore energy consumption at reception, that is, the ACK is essential only to the body sensor, which transmitted in the previous contention-free data slot. Hence, body sensors can prolong their power-sleep modus until the immediate reception of the FBP; (ii) the precise position of the PRE between the ACK and the FBP is mainly due to scalability in terms of energy efficiency. This means that in a future system design, several ACKs may be aggregated just before the preamble (PRE). Body sensors within the DQ-MAC system not being addressed in this multicast/aggregated communication shall only receive the FBP. This is the reason why a preamble is suitable in this explicit position.

(2) FBP is here of fixed length (i.e., independent of the number of sensors in the BSN) and contains two new fields for specific energy-saving purposes, the modulation and coding scheme (MCS) and length of the packet being transmitted in the next contention-free data slot (i.e., in the next CFP). This facilitates independent energy-aware radio activation policies, so that body sensors can calculate the time they can remain in power-sleep modus (see [22]). Further, the MCS field is also thought for future multirate medical applications in BSNs (i.e., scalability in terms of application-oriented medical body sensors).

Note that the FBP always contains a specific field named QDR (Queuing Discipline Rules), which contains the updating information regarding the aforementioned ARS (see [15–18]). Additionally, there is the possibility to transmit data packets of variable length (t_{DATA}), using the same frame structure, at the same time that energy-saving benefits are maintained, which means a flexible CFP.

It must be pointed out that a similar DQ-MAC superframe format approach using the preamble and the above-depicted FBP have already been proposed by the same authors in [2, 23], though studied in totally different scenarios and conditions. In [2], the DQBAN protocol commitment is to guarantee that all packet transmissions are served within their particular application-dependant quality-of-service requirements (i.e., reliability and message latency), without endangering body sensors battery lifetime within BSNs in medical scenarios. For that purpose, the authors propose a cross-layer fuzzy-logic scheduling algorithm to deal with multiple cross-layer input variables
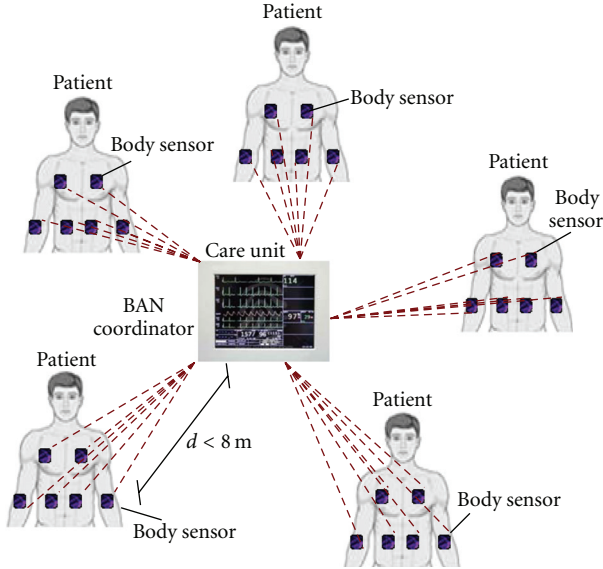
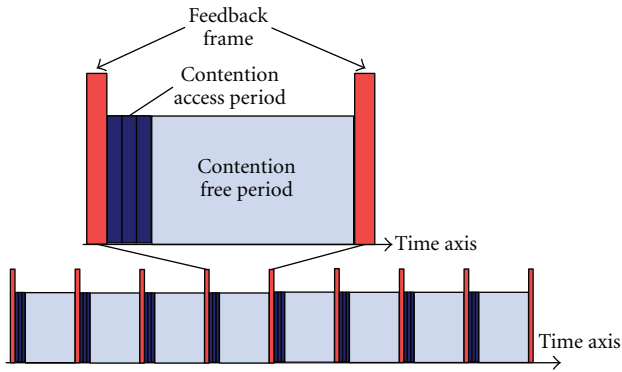FIGURE 1: A star-based BSN in a healthcare scenario.

FIGURE 2: DQ-MAC protocol frame format and time sequence.

of diverse nature in an independent manner. Note that the introduction of the fuzzy-logic techniques does not change the energy-consumption performance of the depicted protocol [2]. In [23], a preliminary analytical evaluation of the enhanced DQ-MAC protocol is presented under general WSN scenarios in saturation conditions. Though following the same line as [2, 23] in terms of DQ-MAC energy-saving superframe format, this paper aims to analyze the non-saturation DQ-MAC energy-efficiency performance in BSNs, mainly completing the work in [2] in a broadened scenario.

5. Non-Saturation DQ-MAC Energy-Efficiency Analysis

Without loss of generality, it is now considered that all body sensors in our studied scenario (see Figure 1) generate Poisson-distributed data messages, whose length is an exponential random variable with average $(1/\mu) \cdot L_{bit}$ bits. Recall from Figure 3 the DQ-MAC superframe structure,

and notice that L_{bit} is the payload length within the CFP expressed in bits. All body sensors generate here the same average traffic load, and the total packet arrival rate is λ (packets/superframe), where we define "packet" as the fraction of a message of length L_{bit} in bits. The average service rate of the system is further explained thereafter and denoted by μ (packets/superframe). For this theoretical analysis, we use the whole DQ-MAC superframe duration as the time unit, and we denote N by the number of DQ-MAC superframe units (see Figure 4).

As previously mentioned, a DQ-MAC statistical model approaches the delay and throughput performance of the theoretical optimum queuing systems M/M/1, or G/D/1, depending on the traffic distribution (i.e., M: exponential, G: general, and D: deterministic). DQ-MAC protocol can be modeled as if every body sensor in the system maintains two common logical distributed queues—CRQ and DTQ—as portrayed in Figure 4. The CRQ controls body sensor accesses to the collision resolution server (the access *minislots*) and is designed to resolve collisions among stations attempting to successfully obtain an access *minislot*. The DTQ, in charge of the data server (the "data subslot"), is used to buffer the data packets that have obtained permission to transmit and are awaiting their scheduled time of departure using a first-come-first-served (FCFS) discipline. The enable transmission interval (ETI), modeled with a nonqueuing infinite server system in Figure 4, is the time elapsed from the actual arrival time of a packet to the head of the CRQ subsystem at the beginning of the next DQ-MAC superframe, when the contention process can start. The first queuing system models the CRQ subsystem and the second represents the DTQ subsystem.

5.1. DQ-MAC Model (M/M/1). DQ-MAC energy-efficiency analysis applying Markov queuing theory can only be done in stable conditions, that is., when the input rate of a system denoted by λ (packets/superframe) is at most equal to the average service rate of the system denoted by μ (packets/superframe), that is, the stability condition can be expressed as $\lambda/\mu < 1$. Otherwise, the system becomes unstable and the queue might grow indefinitely, that is, not all arrivals are eventually served. The M/M/1 queuing model, with an interarrival and service-time distribution exponential, and an infinite queuing server, is considered as one of the simplest birth-death processes. As aforementioned, DQ-MAC can be modeled as a queuing system that consists of two statistical queuing subsystems. The CRQ subsystem is evaluated using M/M/1 Markov chain. The DTQ subsystem is modeled as a G/D/1 [15].

Here, the input rate λ is the ratio of the average number of newly arrived packets of L_{bit} bits—generated in messages—per DQ-MAC superframe unit (N). The average service rate μ is the ratio of served packets per DQ-MAC superframe unit and is computed as

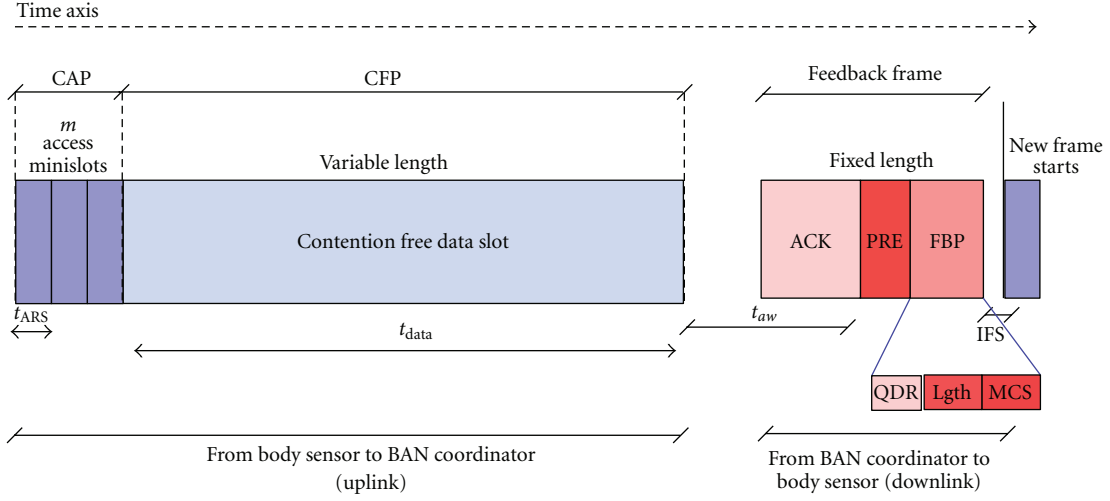$$\mu = \ln\left(\frac{1}{1 - p(\lambda)}\right), \tag{1}$$

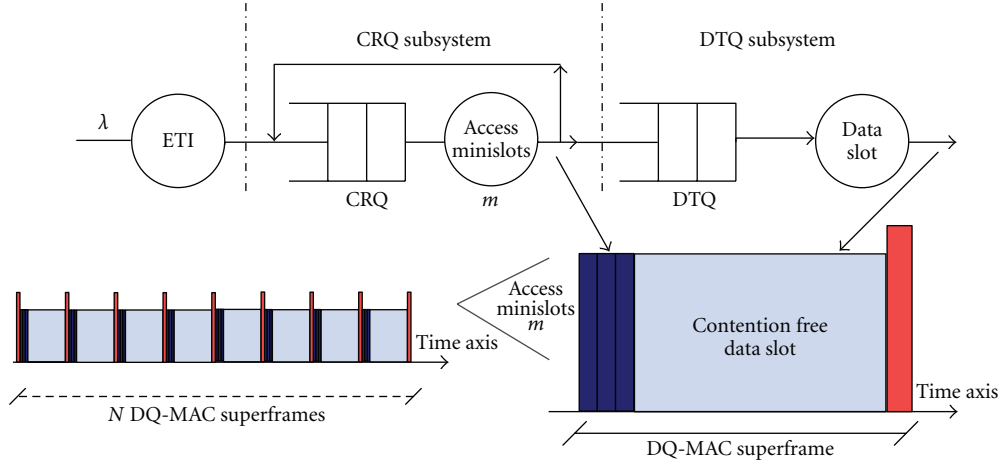FIGURE 3: Detailed new energy-saving DQ-MAC superframe for BSNs.

FIGURE 4: DQ-MAC system model and superframe relation.

where $p(\lambda)$ is the probability to find successfully an empty access *minislot*. We can with confidence make the assumption that the input traffic follows a Poisson process with input rate λ and that the CRQ service time for a packet follows an exponential distribution with average service rate μ, as shown in [18]. It is also possible to see that the input rate of the DTQ subsystem is $\lambda_{\text{DTQ}} = \lambda$, for m $\geq$ 3, and the average service rate $\mu_{\text{DTQ}} = 1$, that is, G/D/1.

Based on the delay analysis approach of [18], we define here the DQ-MAC system delay with the term N_{delay} as the total number of DQ-MAC superframes a body sensor remains in the DQ-MAC system for each specific packet it requires to transmit. First, let us consider a residual time in ETI N_{ETI} (expressed in number of DQ-MAC superframes), waiting for a new DQ-MAC superframe, where a body sensor may send an ARS within the access *minislots*. In case of collision, the body sensor remains in CRQ until it is the turn to transmit an ARS in another access *minislot*. Hence, N_{CRQ}, expressed in DQ-MAC superframes, is the CRQ waiting

plus the service time (CRQ subsystem). Similarly, N_{DTQ} represents the DTQ waiting time plus the DTQ service time in DQ-MAC superframes (DTQ subsystem). So, the average total delay $E[N_{\text{delay}}]$ a body sensor's packet remains in DQ-MAC system model can be computed as

$$E\left[N_{\text{delay}}\right] = E[N_{\text{ETI}}] + E\left[N_{\text{CRQ}_{\text{subsys}}}\right] + E\left[N_{\text{DTQ}_{\text{subsys}}}\right], \quad (2)$$

where for each packet,

 (i) $E[N_{\text{ETI}}]$ is the average residual DQ-MAC superframes in ETI (i.e., by default 0.5 units [18]),

 (ii) $E[N_{\text{CRQ}_{\text{subsys}}}]$ is the average number of DQ-MAC superframes in the CRQ subsystem, and

 (iii) $E[N_{\text{DTQ}_{\text{subsys}}}]$ is the average number of DQ-MAC superframes in the DTQ subsystem.

Further, based on the delay model of DQ-MAC protocol in [18], we can treat CRQ as an M/M/1 system. Thus,

applying the average service rate μ of (1) and the input rate λ to the M/M/1 queue, we achieve the average delay of the CRQ subsystem $E[N_{CRQ_{subsys}}]$ as

$$E\left[N_{CRQ_{subsys}}\right] = \frac{1}{\ln\left(1/(1-p(\lambda))\right) - \lambda}. \quad (3)$$

In [18], it is also proved that the input traffic process of DTQ, or say the output traffic of CRQ, is a Poisson process. It is also assumed that the corresponding size of the here depicted DQ-MAC superframe is 1. Hence, for DTQ, the service time for a packet is constant, one packet per DQ-MAC superframe. So, following M/D/1 queue analysis [18], we obtain $E[N_{DTQ_{subsys}}]$ immediately,

$$E\left[N_{DTQ_{subsys}}\right] = 1 + \frac{\lambda_{DTQ}}{2(1 - \lambda_{DTQ})} = 1 + \frac{\lambda}{2(1 - \lambda)}, \quad (4)$$

where the input rate of the DTQ subsystem is $\lambda_{DTQ} = \lambda$ for $m \geq 3$, as aforementioned.

5.2. Energy-Aware Radio Activation Policy. Figure 5 illustrates the energy-aware radio activation policy following DQ-MAC adapted energy-saving superframe format as in Figure 3. This allows different power management scenarios of body sensors using DQ-MAC under BSNs. Note that each body sensor synchronizes to the BSN thanks to the novel preamble sequence (PRE) of duration t_{PRE} after a period in idle mode. Thereafter, it receives the required system information via the FBP of duration t_{FBP} for updating its distributed queues, CRQ and DTQ [15]. After each FBP, a short interframe space t_{IFS} is left for processing purposes like in 802.15.4 [3]. Active body sensors involved in the access procedure like in scenarios (1) and (2) start by sending an ARS, here of duration length t_{ARS}, in one of the randomly selected access *minislots* [15]. Prior to that, these body sensors should have switched their radio from idle to transmit mode, which take them a transition time t_{ia} for body sensor radio wakeup (i.e., from idle to active modes [19]). Next, scenario (3) depicts the transmission of a previously granted packet of duration length t_{DATA} preceded by the transition time t_{ia}. If the packet is received correctly, an ACK of duration t_{ACK} is sent back to the transmitting body sensor together with the FBP after a maximum time $t_{aw} - t_{ACK}$, during which the receiver turns its radio to idle mode to save energy.

In [3], t_{aw} is characterized as the maximum time to wait for an ACK. Scenario (4) shows how an active body sensor waiting in idle mode synchronizes through the preamble sequence to receive the FBP. Finally, scenario (5) portrays how a body sensor in shutdown state wakes up and waits for some time in idle mode to synchronize through the preamble and get the FBP to update the state of its CRQ and DTQ queues [15].

5.3. Energy-Efficiency Theoretical Analysis. Let us first define P_{tx}, P_{rx} and P_{idle} as the power consumption (in W) in transmit, receive and idle modes respectively and, similarly $E[t_{tx}]$, $E[t_{rx}]$ and $E[t_{idle}]$ as the average time in seconds

a body sensor spends in each of the aforementioned modes within the queuing subsystems, CRQ and DTQ (see Figure 4). Further, we define $E[N_{waiting}]$ as the average total number of DQ-MAC superframes waiting in the whole queuing system (i.e., CRQ and DTQ), and $E[N_{ARS\_tx}]$ as the average number of DQ-MAC superframes required in the CRQ subsystem to transmit a successful ARS.

Thus, the average consumed energy per information bit (J/bit) $E[\varepsilon_{bit}]$ for every active body sensor in the BSN can be expressed as

$$E[\varepsilon_{bit}] = \frac{E\left[\varepsilon_{Superframe}\right]}{L_{bit}}, \quad (5)$$

where L_{bit} corresponds to the payload data length in bits, and $E[\varepsilon_{Superframe}]$ as

$$E\left[\varepsilon_{Superframe}\right] = P_{tx}E[t_{tx}] + P_{rx}E[t_{rx}] + P_{idle}E[t_{idle}], \quad (6)$$

where

$$E[t_{tx}] = E[N_{ARS\_tx}](t_{ARS} + t_{ia}) + E[T_{DATA}] + t_{ia},$$
$$\quad (7)$$
$$E[t_{rx}] = E\left[N_{waiting}\right](t_{PRE} + t_{FBP} + t_{ia}) + t_{ACK},$$

$$
\begin{aligned}
E[t_{idle}] = {} & E\left[N_{waiting}\right]\left(E\left[t_{Superframe}\right] - t_{PRE} + t_{FBP}\right) \\
& + E[N_{ARS\_tx}]\left(E\left[t_{Superframe}\right]\right. \\
& \left. - (t_{ARS} + t_{ia} + t_{PRE} + t_{FBP})\right) \\
& + \left(E\left[t_{Superframe}\right] - (E[t_{DATA}] + t_{PRE} + t_{FBP})\right).
\end{aligned}
\quad (8)
$$

Further, the duration of the time DQ-MAC superframe $t_{Superframe}$ in seconds derived from Figure 3 is characterized as

$$t_{Superframe} = mt_{ARS} + t_{DATA} + t_{aw} + t_{PRE} + t_{FBP} + t_{IFS}, \quad (9)$$

where m corresponds to the number of *minislots* used in the DQ-MAC protocol and t_{ARS}, t_{DATA}, t_{aw}, t_{ACK}, t_{PRE}, t_{FBP}, t_{IFS}, and t_{ia} have been previously described following the illustration example of power management scenarios in Figure 5.

Following the aforementioned assumption that the arriving traffic λ follows a Poisson distribution in both CRQ and DTQ subsystems, we have that the probability of finding an empty access *minislot* in the CRQ subsystem is

$$P(\lambda) = e^{-\lambda/m}, \quad (10)$$

where m corresponds to the number of access *minislots* used in the DQ-MAC protocol. This result can be explained intuitively; if the input rate to the CRQ system is λ, then the load to each access *minislot* is λ/m. So the probability of finding an empty access *minislot* is $e^{-\lambda/m}$. Now, considering

the previously-presented system delay analysis derived from [18], we define $E[N_{\text{waiting}}]$ as

$$E\left[N_{\text{waiting}}\right] = E[N_{\text{ETI}}] + E[N_{\text{CRQ}}] + E[N_{\text{DTQ}}], \qquad (11)$$

where

   (i) $E[N_{\text{ETI}}]$ here outlines the average number of residual DQ-MAC superframes waiting in idle mode, which is equivalent to the previously defined $E[N_{\text{ETI}}]$;

  (ii) $E[N_{\text{CRQ}}]$ denotes the average number of DQ-MAC superframes waiting in idle mode in the CRQ based on M/M/1 queuing model, which corresponds to the total number of DQ-MAC superframes in the CRQ subsystem, $E[N_{\text{CRQ}_{\text{subsys}}}]$, minus the number of DQ-MAC superframes required to transmit all ARS (see (3));

 (iii) $E[N_{\text{DTQ}}]$ represents the average number of DQ-MAC superframes waiting in the DTQ subsystem based on M/D/1 queuing model [18], which is the total number of DQ-MAC superframes in the DTQ subsystem, $E[N_{\text{DTQ}_{\text{subsys}}}]$, minus 1 DQ-MAC superframe used to transmit the data payload (see (4)).

Hence,

$$E[N_{\text{ETI}}] = 0.5,$$

$$E[N_{\text{ETI}}] = \frac{1}{\ln(1/(1 - p(\lambda))) - \lambda} - (E[N_{\text{ARS\_tx}}] - 1), \qquad (12)$$

$$E[N_{\text{DTQ}}] = \frac{\lambda}{2(1 - \lambda)}.$$

Eventually, $E[N_{\text{ARS\_tx}}]$ denotes the average number of time frames used to transmit all required ARS during the waiting time in the CRQ system, before a sensor grants its access into the DTQ system. Based on the CRQ subsystem represented in Figure 4, we characterize $E[N_{\text{ARS\_tx}}]$ here as,

$$
\begin{aligned}
E[N_{\text{ARS\_tx}}] &= 1p(\lambda) + 2(1 - p(\lambda))p\left(\frac{\lambda}{m}\right) \\
&\quad + 3(1 - p(\lambda))\left(1 - p\left(\frac{\lambda}{m}\right)\right)p\left(\frac{\lambda}{m^2}\right) \\
&\quad + 4(1 - p(\lambda))\left(1 - p\left(\frac{\lambda}{m}\right)\right) \\
&\quad \times \left(1 - p\left(\frac{\lambda}{m^2}\right)\right)p\left(\frac{\lambda}{m^3}\right) + \cdots \\
&= \sum_{i=1}^{\infty}\left[ip\left(\frac{\lambda}{m^{i-1}}\right)\prod_{k=1}^{i-1}\left(1 - p\left(\frac{\lambda}{m^{k-1}}\right)\right)\right] \\
&= \sum_{i=1}^{\infty}\left[ie^{\lambda/m^i}\prod_{k=1}^{i-1}\left(1 - e^{\lambda/m^k}\right)\right].
\end{aligned}
\qquad (13)
$$

Following (10), we defined $p(\lambda)$ as the probability of finding an empty access *minislot* assuming that the arriving traffic λ follows a Poisson distribution in the CRQ subsystem, that is, if a body sensor does not succeed in sending an ARS in an empty access *minislot* with probability $p(\lambda)$ the first time, the second time is with probability $p(\lambda/m)$, the third time with probability $p(\lambda/m^2)$ and so on. This is the inherent behavior of a DQ-MAC protocol, because only the body sensors occupying the same position in the CRQ subsystem compete for the one of the m access *minislots* at a time (see Figure 4) [17, 18].

6. Model Validation and Performance Evaluation

The performance of the previously studied DQ-MAC energy-efficiency analysis is validated first with an analytical representation of the proposed model and thereafter via MATLAB computer simulations as following

   (i) The energy-efficiency analytical DQ-MAC model in non-saturation conditions is compared to 802.15.4 MAC energy-consumption analysis presented by Bougard in [19] and a state-of-the-art energy-saving BSN-MAC [6].

  (ii) Computer simulations are further performed, by implementing DQ-MAC protocol strategic rules from [9], within a star-based BSN, as the one portrayed in Figure 1.

6.1. Scenario Description. The reference scenario is defined by the system parameters corresponding to the standardized 802.15.4 MAC default values in the upper frequency band 2.4 GHz at the fixed data rate 250 Kb/s [3]. Based on the illustration scenario in Figure 1, we study the following scenarios:

   (i) Scenario 1 is a comparison of the analytical results in a high density area (i.e., 80% traffic load). In this scenario, we study the energy consumption depending on the payload length.

  (ii) Scenario 2 portrays the analytical and simulation results under increasing relative traffic loads. In this scenario, we choose the longest data payload lengths (L) of 80, 100, and 120 bytes, to minimize the PHY (6 bytes) and MAC (8 bytes) headers overhead per information bit.

A body sensor waits for an ACK (11 bytes) for a maximum time of $t_{\text{aw}} - t_{\text{ACK}}$, where t_{aw} is limited to 864 μs, as defined in [3]. Thereafter, the synchronization preamble sequence (PRE) corresponding to 4 bytes is followed by the FBP of 11 bytes, similar to a beacon frame in [3]. We use $m = 3$ access *minislots*, like in [2, 15–18], and the ARS duration t_{ARS} is equivalent to the Preamble sequence in 802.15.4 MAC (see Table 1).

TABLE 1: IEEE 802.15.4 MAC parameter values.

Parameter	Value	Parameter	Value
PHY header	6 bytes	ACK	11 bytes
MAC header	9 bytes	Beacon	11 bytes
Data payload	20 to 120 bytes	t_{aw}	$864 \, \mu s$
Data rate	250 Kb/s	t_{IFS}	$192 \, \mu s$
DQ-MAC			
Preamble	4 bytes	m	3
FBP	11 bytes	t_{ARS}	$128 \, \mu s$

TABLE 2: IEEE 802.15.4 transceiver power consumption (-5 dBm).

P_{tx}	P_{rx}	P_{idle}
22.09 mW	35.23 mW	$712 \, \mu W$

In order to make a fair comparison, all used transceiver power consumption values are formalized as in [19, 22] (see Table 2). Note that the power consumption in transmission mode is for a transmit power of -5 dBm, which is the value used in [19] analytical results, which we use for our comparison with DQ-MAC energy-efficiency analysis.

6.2. Channel Modeling and Time-Coherence Assumption. Every active body sensor is supposedly located at a random distance d from the BAN coordinator, as portrayed in Figure 1. The channel link implementation is based on the path loss model of the 802.15.4 standard [3], where the average received power is expressed as a function of an arbitrary T-R separation distance $d < 8$ meters (i.e., within a hospital setting). In our simulations, the time-variant received signal also includes additive white Gaussian noise (AWGN) and the effect of log-normal shadowing, assuming that the channel is coherent within the transmission of a DQ-MAC superframe, like in indoor environments [24].

6.3. Scenario 1: Analytical Result Comparison (High-Density Area). Analytical results for a high-density area (80% traffic load) are here compared between the DQ-MAC energy consumption analytical model, the 802.15.4 MAC energy-consumption analysis presented by Bougard in [19], and the BSN-MAC protocol developed by the authors in [6]. This BSN-MAC protocol is used as a second reference benchmark besides the standard de facto 802.15.4 MAC, since it is a state-of-the-art energy-saving MAC proposal for BSN environments. In the energy-efficiency analysis, the authors of 802.15.4 MAC model [19] and BSN-MAC model [6] focus on a general1-hop star-based wireless sensor network under high traffic conditions. We have used the energy-efficiency model from [19] and the BSN-MAC model from [6], using adaptively beacon orders up to 12, in order

to be able to fairly compare 2 different models with our here proposed DQ-MAC model. Our aim is to evaluate the energy consumption per information bit, which is defined as the ratio of the average total energy-consumption per body sensor and per payload length (i.e., information bit). The results portrayed in Figure 6 follow the axis description: The x-axis represents the payload length which increases until 120 bytes (see Table 1). In the y-axis, we evaluate the energy consumption per information bit following DQ-MAC theoretical analysis (see (5)) in our BSN scenario. The energy consumption is computed considering each body sensor time and power consumption in each of these states in non-saturation conditions. Figure 6 portrays the analytical results of the energy consumption per information bit of the here presented DQ-MAC model (see (5)) versus the 802.15.4 MAC model analyzed in [19] and the BSN-MAC protocol developed by the authors in [6], as the packet payload load increases in the x-axis. Different curves are shown for a traffic load of 80% (i.e., high-density area). It can be seen that

(i) BSN-MAC outperforms IEEE 802.15.4 MAC in 19.09% for payload length packet of 50 bytes;

(ii) DQ-MAC outperforms IEEE 802.15.4 MAC in 43.31% for a payload length packet of 50 bytes;

(iii) BSN-MAC outperforms IEEE 802.15.4 MAC in 7.20% for payload length packet of 80 bytes;

(iv) DQ-MAC outperforms IEEE 802.15.4 MAC in 36.65% for a payload length packet of 80 bytes.

We conclude that DQ-MAC is superior to both the standard 802.15.4 and the BSN-MAC in terms of energy consumption for high traffic loads (i.e., 80% traffic load) and all packet lengths. This can be explained by understanding the inherent DQ-MAC behavior of avoiding collisions in data transmissions, idle listening, and overhearing, at the cost of some small protocol overhead, which remains invisible for high traffic loads. Thus, DQ-MAC reduces the most critical energy-consumption features of other state-of-the-art MAC protocols under hightraffic conditions, and for this reason it
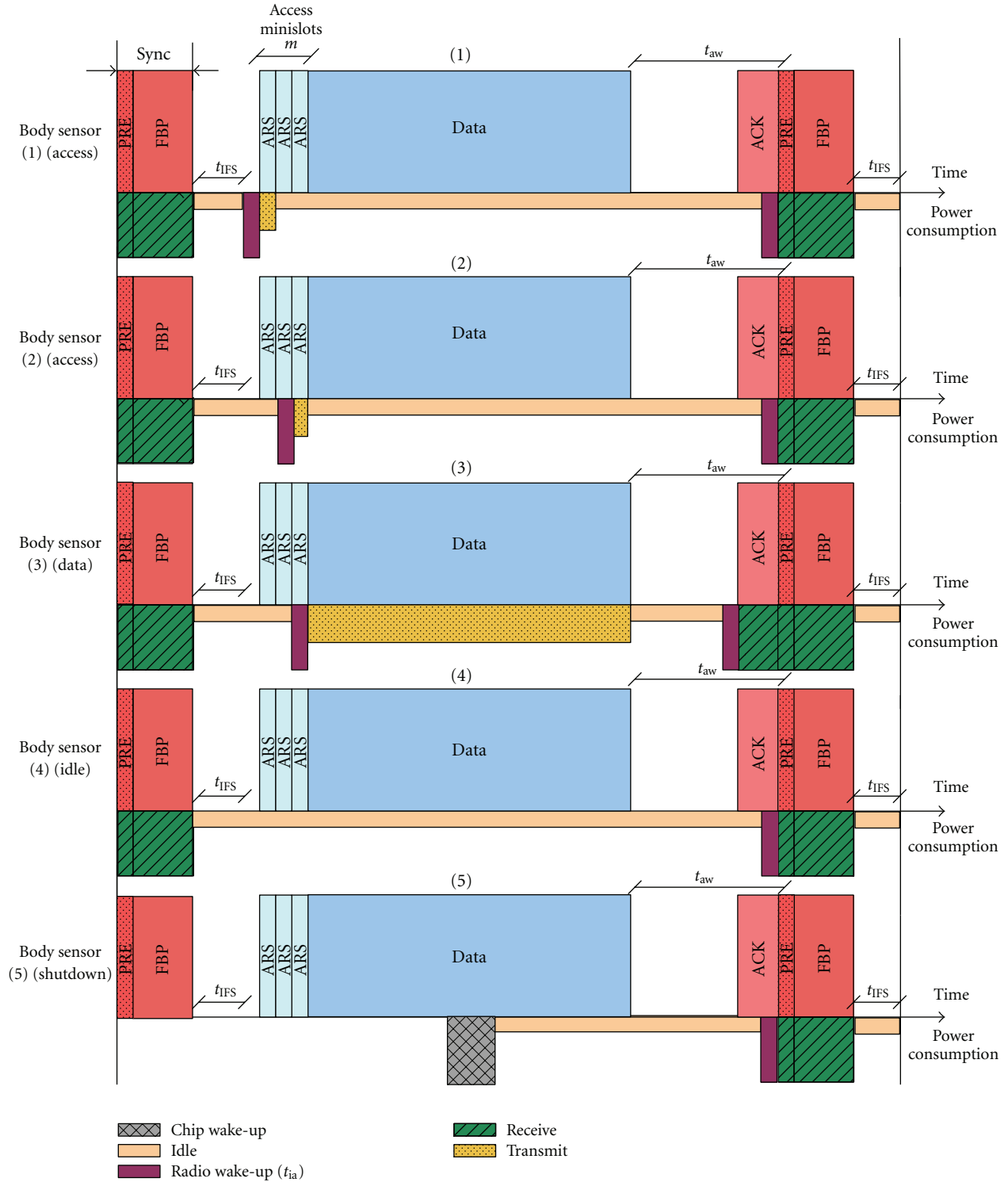
FIGURE 5: Power management scenarios for different body sensors using DQ-MAC.

might be a suitable candidate for star-based BSNs in medical settings, completing our work in [2].

6.4. Scenario 2: Analytical and Simulation Results. Analytical and simulation results are portrayed under increasing traffic loads. We compare first our here presented DQ-MAC energy-consumption analytical model with the 802.15.4 MAC energy-consumption analysis presented by Bougard in [19]. Thereafter, the DQ-MAC analytical model is evaluated by MATLAB computer simulations.
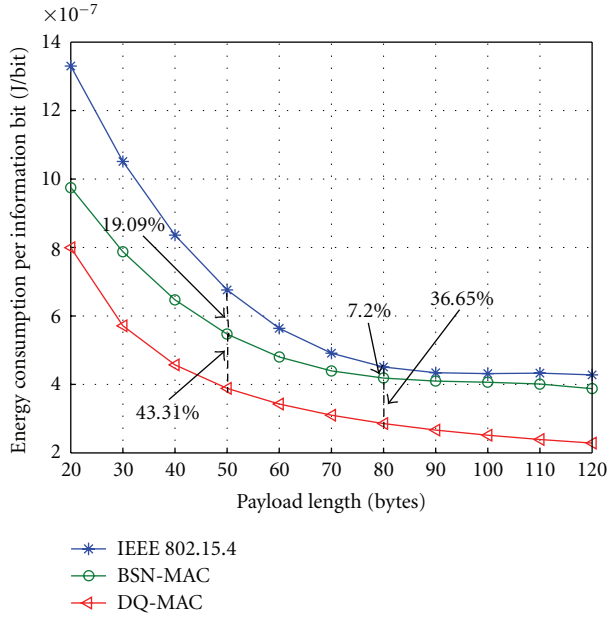
FIGURE 6: Analytical energy consumption per information bit (high-density area).

FIGURE 7: Analytical energy consumption per information bit: DQ versus IEEE 802.15.4 MAC.

The results portrayed in the succeeding figures follow the axis description hereafter.

   (i) The x-axis represents the relative traffic load, here defined, as the ratio of generated data packets per DQ-MAC superframe (i.e., MATLAB simulated iteration). As aforementioned, the traffic load follows a Poisson distribution, since we consider here a generalized case scenario. In our simulated scenario, the traffic load rises by increasing the number of active body sensors in the BSN in each simulation.

  (ii) As in the previous scenario, in the y-axis, we evaluate the energy consumption per information bit and the time spent in each of the aforementioned states (i.e., transmit, receive, and idle) following DQ-MAC procedure in our simulated BSN scenario. The energy consumption is computed considering each body sensor time and power consumption in each of these states. Thus, the energy consumption per information bit is defined as the ratio of the average total energy consumption per body sensor and per payload length (i.e., information bit).

Figure 7 portrays the analytical results of the energy consumption per information bit of the here presented DQ-MAC model (see (5)) versus the 802.15.4 MAC model analyzed in [19], as the relative traffic load in the system increases. Different curves are shown for data payload lengths (L) of 80, 100 and 120 bytes. It can be seen how the use of DQ-MAC outperforms 802.15.4 MAC reaching 36.65% of energy-efficiency improvement, when the relative traffic load is as high as 80%.
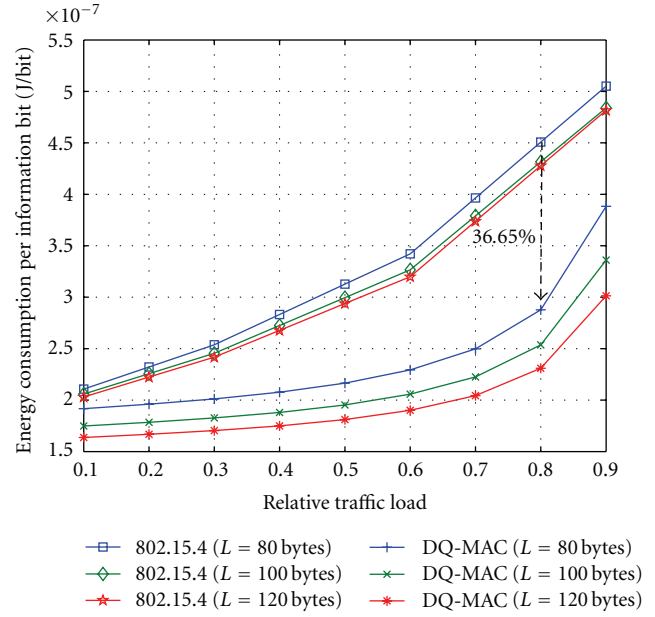
As previously analyzed, DQ-MAC achievement is most relevant for high traffic loads than for low traffic loads. Remember though that DQ-MAC may behave adaptively, that is, granting immediate access for light traffic loads and seamlessly moving to a reservation system (i.e., CRQ and DTQ) for high traffic loads. Again this shows the good inherent performance of the protocol also in terms of energy-consumption.

The same scenario of Figure 7 is now depicted in Figure 8 as a comparison between the aforementioned DQ-MAC analytical model (see (5)), and the simulated results from DQ-MAC energy consumption per information bit. As before, in the x-axis, the relative traffic load in the system increases, and different curves are shown for data payload lengths (L) of 80, 100 and 120 bytes. Here, the excellent protocol performance can be seen even for the highest traffic load between 80% and 90%, which remains under 350 nJ/bit. Further, simulation results prove the right theoretical analysis of the protocol performance in terms of energy efficiency. Needless to say, the energy consumption per information bit tends to be minimized by using the maximum packets lengths allowed in the standard. Simulations results corroborate also this fact.

In order to further evaluate the energy-consumption performance of the whole DQ-MAC queuing system, we study the time spent in each of the activity modes, that is, transmit, receive and idle modes, separately. Figure 9 shows that the transmit and receive time remains practically constant for all traffic loads, with the exception of the receive time for very high traffic loads (i.e., $\lambda \geq 85\%$). However, when the traffic load is higher than roughly 60%, the most critical time is while waiting in idle mode (idle time), since the packets remain waiting to be served either in the CRQ or DTQ subsystems. This might also be the reason why the
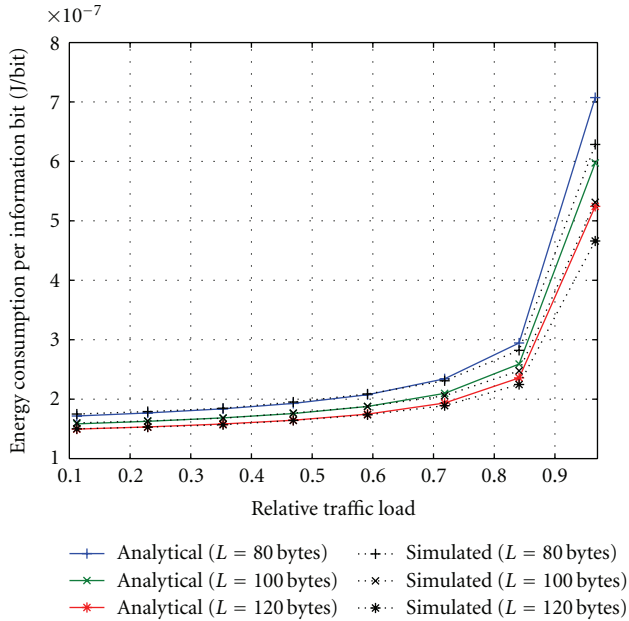
FIGURE 8: DQ-MAC energy consumption per information bit: Analytical versus Simulation.
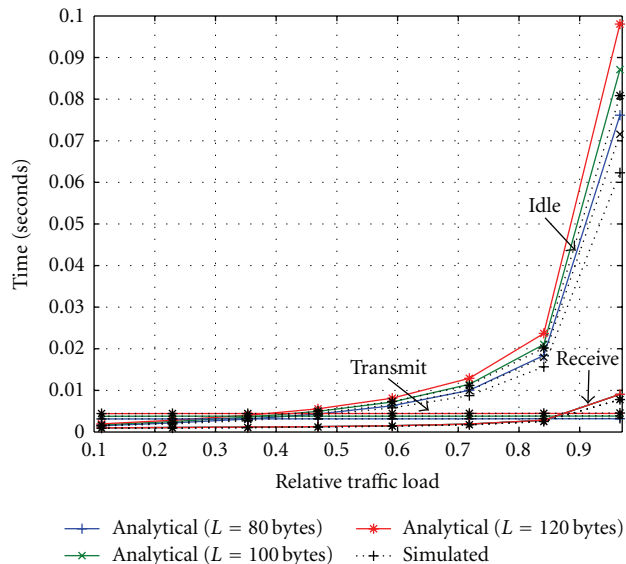

FIGURE 9: DQ-MAC time spent in transmit, receive and idle mode: Analytical versus Simulated curves.

receive time increases, and along with that the total energy-consumption per information bit. This means that the longer a body sensor remains in the DQ-MAC queuing system, the more FBPs have to receive for the same packet in the queue. In the end, the energy consumption per information bit increases because of the protocol control information. This corroborates the previous FBP assumption, in which it was discussed that FBP should be kept fixed in size and minimized in control information, that is, to reduce energy consumption for information bit, especially in high traffic loads.

Here, it must be pointed out that the time spent in transmission mode seems constant for all traffic loads, that is, independent of the traffic load. This is obvious for the DTQ subsystem, since there is just one packet duration to transmit. Now, analyzing (13), where $E[N_{ARS\_tx}]$ denotes the average number of time frames used to transmit all required ARS during the waiting time in the CRQ system, we observe a dependency on arriving traffic load λ into the CRQ subsystem, though this arriving rate becomes smaller (for a concrete body sensor waiting in the CRQ subsystem) with the time, that is, $\lambda/m, \lambda/m^2, \ldots$. Furthermore, the time spent in transmission mode is computed using expression (7) and t_{ARS} is substantially smaller than $E[t_{DATA}]$, derived from Table 1. This explains the constant behavior of the time spent in transmission mode.

7. Conclusions

In this paper, we have been evaluating IEEE 802.15.4 MAC limitations under new challenging healthcare requirements for wireless body sensor networks (BSNs). Further, a new energy-efficiency theoretical analysis for an enhanced distributed queuing medium access control (DQ-MAC) protocol has been introduced, as a potential candidate for future BSNs. For that purpose, an energy-saving DQ-MAC super-frame optimization has been presented taking energy-aware radio activation policies into account. This allows body sensors a power management regulation to minimize the energy consumption per information bit. The analytical study has been compared with a BSN state-of-the-art MAC protocol (BSN-MAC) and validated by simulation results, which have shown that the proposed mechanism outperforms IEEE 802.15.4 MAC and BSN-MAC energy-efficiency for all traffic loads in a generalized BSN scenario. This favorable energy-efficient behavior is especially achieved thanks to the inherent protocol performance at eliminating collisions in data transmissions, while minimizing the control overhead and hence the overall energy consumption per information bit.

References

[1] G.-Z. Yang, Ed., *Body Sensor Networks*, Springer, London, UK, 2006.

[2] B. Otal, L. Alonso, and C. Verikoukis, "Highly reliable energy-saving mac for wireless body sensor networks in healthcare systems," *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 4, pp. 553–565, 2009.

[3] IEEE Std. 802.15.4-2003, "IEEE Standards for Information Technology Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)," October 2003.

[4] B. Zhen, H.-B. Li, and R. Kohno, "IEEE body area networks for medical applications," in *Proceedings of the 4th IEEE International Symposium on Wireless Communication Systems (ISWCS '07)*, pp. 327–331, Trondheim, Norway, October 2007.

[5] P. Kumar, M. Günes, A. A. B. Almamou, and J. Schiller, "Real-time, bandwidth, and energy efficient IEEE 802.15.4 for medical applications," in *Proceedings of the 7th GI/ITG KuVS Fachgespräch "Drahtlose Sensornetze"*, FU, Berlin, Germany, September 2008.

[6] L. Huaming and T. Jindong, "An ultra-low-power medium access control protocol for body sensor network," in *Proceedings of the 27th Annual International Conference of the Engineering in Medicine and Biology Society (EMBS '05)*, pp. 2451–2454, September 2005.

[7] L. Huaming and T. Jindong, "Heartbeat-driven medium-access control for body sensor networks," *IEEE Transactions on Information Technology in Biomedicine*, vol. 14, no. 1, pp. 44–51, 2010.

[8] W. Ye, J. Heidemann, and D. Estrin, "Medium access control with coordinated adaptive sleeping for wireless sensor networks," *IEEE/ACM Transactions on Networking*, vol. 12, no. 3, pp. 493–506, 2004.

[9] T. van Dam and K. Langendoen, "An adaptive energy-efficient MAC protocol for wireless sensor networks," in *Proceedings of the 1st International Conference on Embedded Networked Sensor Systems (SenSys '03)*, pp. 171–180, November 2003.

[10] J. Polastre, J. Hill, and D. Culler, "Versatile low power media access for wireless sensor networks," in *Proceedings of the 2nd International Conference on Embedded Networked Sensor Systems (SenSys '04)*, pp. 95–107, November 2004.

[11] M. Buettner, G. V. Yee, E. Anderson, and R. Han, "X-MAC: a short preamble MAC protocol for duty-cycled wireless sensor networks," in *Proceedings of the 4th International Conference on Embedded Networked Sensor Systems (SenSys '06)*, pp. 307–320, Boulder, Colo, USA, November 2006.

[12] A. Bachir, D. Barthel, M. Heusse, and A. Duda, "Micro-frame preamble MAC for multihop wireless sensor networks," in *Proceedings of the IEEE International Conference on Communications (ICC '06)*, pp. 3365–3370, July 2006.

[13] G. Fang and E. Dutkiewicz, "BodyMAC: energy efficient TDMA-based MAC protocol for wireless body area networks," in *Proceedings of the 9th International Symposium on Communications and Information Technology (ISCIT '09)*, pp. 1455–1459, 2009.

[14] O. Omeni, A. C. W. Wong, A. J. Burdett, and C. Toumazou, "Energy efficient medium access protocol for wireless medical body area sensor networks," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 2, no. 4, pp. 251–259, 2008.

[15] H.J. Lin and G. Campbell, "Using DQRAP (Distributed Queuing Random Access Protocol) for local wireless communications," in *Proceedings of the Wireless*, pp. 625–635, Calgary, Canada, July 1993.

[16] L. Alonso, R. Ferrús, and R. Agusti, "WLAN throughput improvement via distributed queuing MAC," *IEEE Communications Letters*, vol. 9, no. 4, pp. 310–312, 2005.

[17] X. Xu and G. Campbell, "A near perfect stable random access protocol for a broadcast channel," in *Proceedings of the IEEE Communications, Discovering a New World of Communications (SUPERCOMM/ICC '92)*, vol. 1, pp. 0370–0374, Chicago, Ill, USA, June 1992.

[18] X. Zhang and G. Campbell, "Performance analysis of distributed queuing random access protocol—DQRAP," DQRAP Research Group Report 93-1, Computer Science Department, IIT, Chicago, Ill, USA, August 1993, http://citeseer.ist.psu.edu/article/zhang94performance.html.

[19] B. Bougard, F. Catthoor, D. C. Daly, A. Chandrakasan, and W. Dehaene, "Energy efficiency of the IEEE 802.15.4 standard in dense wireless microsensor networks: modeling and improvement perspectives," in *Proceedings of the IEEE Design Automation and Test in Europe Conference and Exhibition (DATE '05)*, vol. I, pp. 196–201, Calgary, Canada, March 2005.

[20] T. R. Park, T. H. Kim, J. Y. Choi, S. Choi, and W. H. Kwon, "Throughput and energy consumption analysis of IEEE 802.15.4 slotted CSMA/CA," *Electronics Letters*, vol. 41, no. 18, pp. 1017–1019, 2005.

[21] S. Pollin et al., "Performance analysis of slotted IEEE 802.15.4 medium access layer," Tech. Rep., September 2005, DAWN Project.

[22] Chipcon, "SmartRF CC2420: 2.4 GHz IEEE802.15.4/Zigbee RF Transceiver," Data Sheet.

[23] B. Otal, C. Verikoukis, and L. Alonso, "Efficient power management based on a distributed queuing MAC for wireless sensor networks," in *Proceedings of the 65th IEEE Vehicular Technology Conference (VTC '07)*, pp. 105–109, Dublin, Ireland, April 2007.

[24] S. Thoen, L. Van der Perre, and M. Engels, "Modeling the channel time-variance for fixed wireless communications," *IEEE Communications Letters*, vol. 6, no. 8, pp. 331–333, 2002.

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