Joint Power-QoS Control Scheme for Energy Harvesting Body Sensor Nodes

Ernesto Ibarra[a,b], Angelos Antonopoulos[b,c], Elli Kartsakli[c], Joel J. P. C. Rodrigues[d,e], and Christos Verikoukis[b]

[a] University of Barcelona (UB), Barcelona, Spain.
[b] Telecommunications Technological Centre of Catalonia (CTTC), Castelldefels, Barcelona, Spain.
[c] Signal Theory and Communications Department, Technical University of Catalonia (UPC), Barcelona, Spain.
[d] Instituto de Telecomunicações, University of Beira Interior, Covilhã, Portugal.
[e] National Research University of Information Technologies, Mechanics and Optics (ITMO), St. Petersburg, Russia
Emails: eibarra@cttc.es, aantonopoulos@cttc.es, ellik@tsc.upc.edu, joeljr@ieee.org, cveri@cttc.es

***Abstract*— In this paper, we aim at the optimal use of the scarce energy collected by a node powered by human energy harvesting in order to improve the provided Quality of Service (QoS). To achieve this goal, we have developed a Power-QoS control scheme, called PEH-QoS. PEH-QoS is composed of three sub-modules that interact with each other in order to make optimal use of energy and get the best possible QoS. The scheme intends to ensure that a node can both capture/detect the medical events and transmit the respective data packets efficiently. One of the main features of our mechanism is that only useful data sequences are transmitted, discarding data packets that have lost their clinical validity (i.e., out of date). Extensive simulations have been conducted in order to evaluate the behavior of PEH-QoS in a typical medical node under energy harvesting conditions.**

***Index Terms*— WBAN, Quality of Service, Energy Harvesting, Medium Access Control (MAC), Wireless Sensor Networks**

I. Introduction

A wireless body area network (WBAN) is composed of medical devices for clinical applications. These medical devices are commonly called body sensor nodes (BNs). In WBANs, each sensor performs important functions, intended either for the treatment, the diagnosis or the monitoring of the patient's health. Due to the space constraints of the human body, the functions performed by each node are unique and irreplaceable. BNs must be able to perform their tasks efficiently and interact with the human environment in a comfortable, unobtrusive and undetectable form for the patient. To achieve this goal, the BNs must be tiny and lightweight. These parameters are closely related to the battery size and the system power consumption [1]. The battery power not only restricts the node's weight and size, but also limits its lifetime, since it is a finite source of energy. Moreover, changing or recharging the battery of a node is not always feasible, since it could damage the node or put the patient's health at risk [2].

The most innovative and promising techniques to solve the power supply limitations in WBANs are the energy harvesting (EH) or energy scavenging from the human body. Using energy harvesters, a BN can convert various energy sources (heat, motion, vibration, light, etc.) into electrical energy [3]. EH is considered as an infinite source of energy, so that nodes may be able to operate perpetually, i.e., nodes remain in energy neutral operation (ENO) [4]. A node powered by EH is declared in ENO if it consumes less or equal energy compared to the energy captured from the environment, and if a desired performance level can be always supported [4]. EH process only delivers small amounts of energy and depends on the nature, the source's availability and the nodes location in the human body. According to the characteristics of the source to be harvested, we can consider that the energy is delivered in either a constant (e.g., heartbeat) or a random (e.g., human locomotion) manner. The energy that is usually collected through the harvesting processes is not sufficient for the node operation. Therefore, the captured energy must be stored in a rechargeable battery or a supercapacitor to reach the desired operational level. The energy storage unit also serves as a buffer to handle any changes in the power supply. The time required to store the amount of energy needed to detect or report (transmit) an event depends on the amount of energy collected in a given period of time. Based on the above, it becomes clear that the collected energy exploitation is a key factor that determines the smooth operation of a node.

The idea of a WBAN that works in synergy with the human body is indeed promising. However, certain considerations must be taken into account to maintain an acceptable level of Quality of Service (QoS) in WBANs operated by human EH. The QoS requirements are more stringent in WBANs compared to traditional Wireless Sensor Networks (WSNs) [5]. In WBANs, the QoS is a fundamental demand and, hence, the throughput maximization, the delay minimization and the extension of the network's lifetime are some of the main goals to be achieved [6]. In general, the QoS and working requirements of a BN depend on the patient's health conditions, the clinical application as well as the characteristics of the collected data. In a network operated by batteries, the main purpose of Medium Access Control (MAC) protocols is to prolong the network's lifetime. On the other hand, a network powered by EH is intended to maximize the performance using the available energy. Through EH, the life of a wireless network may be extended, but other QoS metrics may be degraded (e.g., throughput, delay, packet loss, etc.)[7].

In the field of WSNs, some authors have developed MAC protocols to reduce the effect of the energy gap of nodes due to EH [8-11]. This is because the choice of medium access mechanism is the main factor that determines the network consumption [9]. However, WBANs face different challenges than WSNs. One major challenge is the measurement accuracy of the nodes. In a WSN, the large number of nodes compensates the accuracy, but a WBAN usually consists of few nodes which, as a result, are required to be robust and accurate [12].

In this paper, we present a Power-QoS control scheme (PEH-QoS) designed for BNs operated by human EH. PEH-QoS is an ENO inspired algorithm, developed so that nodes can provide the best possible QoS in WBANs powered by human EH [13]. Our contribution is summarized in the following:

1. PEH-QoS balances the proper BN's operation, the QoS requirements and the EH rate of human environment. Specifically, our algorithm has the following traits: i) it promotes the BN's ability to detect events (normal or emergency) through power-aware management based on ENO, ii) it prevents the saturation of the data packet queue and maintains the clinical validity of the information stored by discarding odd packets and updating the data queue, and iii) it makes an optimum use of the energy dedicated for data communication through a packet aggregation system, in order to maximize the throughput under EH conditions.
2. We evaluate (via extensive simulations) the throughput and other QoS metrics in a typical BN with PEH-QoS and we compare them with a baseline scenario under the same EH conditions, where the PEH-QoS is not applied.

The rest of the paper is organized as follows. In Section II, we describe the related work on EH applied to WBANs. In Section III, we introduce the PEH-QoS. In Section IV, we evaluate the performance of PEH-QoS by extensive simulations and, finally, Section V concludes the paper.

II. Related Works

In the literature, there exist only few papers that address issues related to the application of the EH in the WBANs. In [14], Seyedi and Sikdar provide a unified Markov model that combines an EH model and a traffic model for a node in a WBAN. The results obtained in [14] express the probability of not detecting an event as a function of the average event rate, the average EH rate and the battery size. In [15], the same authors develop energy efficient transmission strategies for BNs powered by EH. These strategies are based on a tradeoff between the energy consumption and the packet error probability using Markov Decision Processes. Ventura and Chowdhury [16] propose MAKERS for multi-sources energy harvesting networks. MAKERS is a Markov based model for the prediction of the probability that a BN fails to detect an event due to lack of energy. He et al. propose analytical solutions for the optimal source rate [17] and resource allocation [18] for WBANs with energy harvesting. All these studies show that the EH rate greatly affects the performance of the nodes. Furthermore, these studies demonstrate the importance and the necessity of maintaining the sensing function in a BN operated by EH.

The main challenge to be faced by a BN powered by human EH is maintaining its functionality of detecting and transmitting correctly. Kansal et al. [4] explain that ENO is the method to achieve infinite lifetime, as soon as there are not any hardware failures. BNs powered by EH and working in ENO state represent an alternative to avoid the death of nodes due to depletion of their batteries. This goal becomes much more important when we refer to nodes confined within the human body.

III. Power-QoS aware management algorithm

The PEH-QoS algorithm is executed at each node in the WBAN. The main goal of our scheme is to adapt the BN's performance considering its particular features, power supply and QoS requirements. To achieve this goal, our mechanism combines three sub-modules that are: i) the Power-EH Aware Management (PHAM), ii) the Data Queue Aware Control (DQAC), and iii) the Packet Aggregator/Scheduling System (PASS). Figure 1 shows the interrelationship of these three sub-algorithms in the BN's operation.

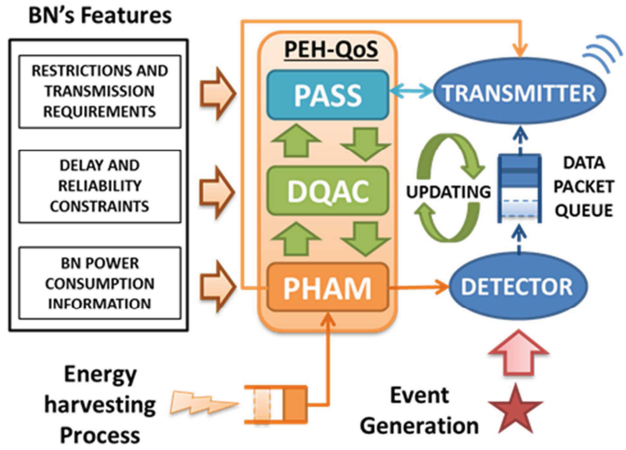

Figure 1 Illustration of the PEH-QoS operation.

A. PHAM: Power-EH Aware Management module.

PHAM handles the distribution and guarantees the optimal use of energy collected from the human environment. The energy management is a key to achieve acceptable performance in EH conditions. The sub-module performs power management using the BN's power consumption information. The operation of a BN mainly consists of two tasks: detection and transmission. BN's radio consumes much more energy compared to the detector ($E_{Tx} \gg E_{det}$). The EH process affects these two tasks, since the node must harvest enough energy to carry out its work properly. In WBANs, the BN's ability to detect events is as important as the transmission function. If an event is not detected, it is not possible to know whether this is a normal or abnormal event (i.e., alarm or critical event). The purpose of PHAM sub-module is to try to keep the node in ENO state and maintain good detection efficiency. The detector efficiency (D_{eff}) is given by:

$$D_{eff} = \frac{Total\ number\ of\ events\ detected(t)}{Total\ number\ of\ events\ occurred(t)} \quad (1)$$

In this paper, we consider that the BN's power consumption is divided into two main parts: the detection power consumption (P_{det}) and the transmission power consumption

(P_{Tx}) [17]. P_{det} includes all power consumption related to the correct BN's operation (i.e., microcontroller (MCU), analog-to-digital converter (ADC), sensor and read-out). On the other hand, P_{Tx} includes the power consumption related to the duty cycle of the transceiver (i.e., data communication process). The power management is carried out by the PHAM sub-module depending on the EH conditions. A BN is considered as a harvesting system with non-ideal energy buffer. To ensure that one node is in ENO state, the following criterion must be met [4]: $B_0 + n\int_0^T [P_s(t) - P_c(t)]^+ dt - \int_0^T [P_c(t) - P_s(t)]^+ dt - \int_0^T P_{leak}(t)dt \leq B \quad \forall T \in [0, \infty)$ (2)

where B_0 is the already stored energy, n is the charging efficiency (efficiency of the storage), $P_s(t)$ is the power obtained from the EH source at time t, $P_c(t)$ is the power being consumed at that time, $P_{leak}(t)$ is the leakage power for the energy buffer, and B is the size of the energy buffer. If after BN's operation $B \geq B_0$ then the node is in ENO and if $t \to \infty$ then the node will be forever in the ENO state.

In the PHAM sub-module (see ALGORITHM 1), we use the principles of ENO to try to maintain a good performance of the detector (BN's main function). The level of energy stored in the battery (B_{level}) depends on the energy harvested (E_{EH}) from the human environment (i.e., $\mathrm{B}_{level}(t) = \mathrm{B}_{level}(t-1) + E_{EH}$). In turn, E_{EH} depends on the energy harvesting rate $\mathrm{K_{EH}}$ (i.e., $E_{EH} = \int_0^T \mathrm{K_{EH}} = \mathrm{K_{EH}} * T$). In PHAM, the harvested energy is intended to keep the detector operating properly (i.e., BN's detector ON, when $\mathrm{B}_{level} \geq E_{det}$). To achieve this goal, the algorithm controls the BN's power consumption based on the stored energy level. The transmission may be performed when the battery's energy level reaches $\mathrm{B}_{level} \geq E_{det} + E_{Tx}$ (BN's transceiver ON), where E_{det} is the amount of energy required to maintain the function of detection at time t and E_{Tx} is the amount of energy required to perform the data communication process of D_{Load}. D_{Load} is the number of data packets to be transmitted for every data communication process. D_{Load} is calculated with the help of DQAC and PASS sub-modules. Moreover, E_{TX} is calculated with the help of PASS sub-module.

ALGORITHM 1: *Power-EH Aware Management*
1: **if** $\mathrm{B}_{level} \geq E_{det} + E_{Tx}$ **then**
2: *Keep BN's detector* ***ON***
3: **if** $D_{Queue} \geq D_{Load}$ **then**
4: *Keep BN's transceiver* ***ON***
5: *Make communication process of* D_{Load}
6: **else**
7: *Keep BN's transceiver* ***SLEEP mode***
8: **elseif** $\mathrm{B}_{level} < E_{det} + E_{Tx}$ ***do***:
9: **if** $\mathrm{B}_{level} \geq E_{det}$ **then**
10: *Keep BN's detector* ***ON***
11: *Keep BN's transceiver* ***OFF***
12: **else**
13: *Keep BN's detector* ***OFF***
14: *Keep BN's transceiver* ***OFF***
15: **end**
16: *Repeat step* 1

B. DQAC: Data Queue Aware Control module.

Since the amount of harvested energy depends on the magnitude and the availability of the EH source, data packets can remain stored for a long time until they can be transmitted. This raises two major issues; the first problem is related to the saturation of the data queue, since the node has a finite storage capacity. Once the node has reached its maximum capacity of data storage, it may not be able to store the next detected events and, consequently, these packets are lost. The second problem is related to the loss of validity of the stored data. In this condition, the stored data may lose their clinical importance because of the waiting time (e.g., in monitoring vital signs, in some cases, old data lose their value in the presence of most recent data). DQAC is a sub-module designed to control the data queue and deal with these problems. DQAC sub-module performs two main tasks: i) it prevents the saturation (overflow) of the queue with unimportant data, and ii) it allows all detected events to be stored. The sub-module performs the packet discard and update of the data queue (see ALGORITHM 2) using the information of maximum permitted end-to-end delay (D_{max}) and maximum storage capacity (SC_{max}). D_{max} depends on the BN's application requirements and SC_{max} is a physical restriction of the BN's hardware. DQAC constantly monitors the waiting times of each data packet in the data queue (T_{pkt}), and the number of stored packets (DQ_{level}). The value of T_{pkt} must not exceed the maximum waiting time in the queue (T_{Qmax}), otherwise the data packet is deleted to free up space in the queue. Deleted packets are data packets that either have lost their importance or have been deleted to make space for more recent packets. T_{Qmax} is calculated as: $T_{Qmax} = D_{max} - T_{TX}$, where T_{TX} is the time needed for the data communication process and it is calculated in PASS sub-module.

ALGORITHM 2: *Data Queue Aware Control*
1: **if** $DQ_{level} > 0$ **then**
2: ***Check*** T_{pkt} *of all data packets stored*
3: **if** $T_{pkt} \geq T_{Qmax}$
4: **Delete** *data packet*
5: **end**
6: **end**
7: **if** $DQ_{level} < SC_{max}$ **then**
8: **if** *event is detected* **then**
9: **Save** *Data packet in the Queue*
10: **end**
11: **elseif** $DQ_{level} == SC_{max}$ **then**
12: **if** *event is detected* **then**
13: **Delete** *packet with longer waiting time*
14: **Save** *new data packet in the Queue*
15: **end**
16: **end**
17: *Repeat step* 1

C. PASS: Packet Aggregator/Scheduling System module.

In BNs operated by battery, the data packets can be transmitted as soon as they are generated. On the other hand, in BNs operated by EH, data transmission can be realized when the node accumulates enough energy to do it. *PASS* is a sub-module that has been designed to optimize the data transmission in EH conditions (see ALGORITHM 3). The main objective of this algorithm is to send the maximum number of data packets (among the BN's transmission possibilities) for every transmission. *PASS* uses the MAC protocol information for the calculation of E_{Tx}. The MAC protocol defines the rules for the frame exchange (e.g., control and data frames) between the BN and the body node coordinator (BNC), which is the sink of the information. The sub-module applies an aggregation in the part of data payload of the data frame. Figure 2 shows the structure of the IEEE 802.15.6 data frame [19]. In this way, several packets can be transmitted using the same control frames (depending on the applied protocol). The aggregation packet number is variable (D_{Load}). An increase of the size of D_{Load} implies an increase of the amount of required E_{Tx}. D_{Load} depends on the BN's energetic conditions (i.e., B_{level}) and the status of the data queue (i.e., DQ_{level}). Thus, the value of D_{Load} is indirectly adapted to the K_{EH} and data arrival time in the node.

ALGORITHM 3: *Packet Aggregator/Scheduling System*

1: **Calculate** E_{Tx} *required to send a single packet.*
2: **Check** B_{level} *and* DQ_{level} *status*
3: **if** $\mathrm{DQ}_{level} = 1$ *and* $\mathrm{B}_{level} \geq E_{Tx} + E_{det}$ **then**
4:    **Make** $D_{Load} = 1$
5:    **Perform** *data communication process*
6: **elseif** $\mathrm{DQ}_{level} > 1$ **then**
7:    **Determine** D_{Load}
8:    **Calculate** E_{Tx} *required to send* D_{Load}
9:     **if** $\mathrm{DQ}_{level} \geq D_{Load}$ *and* $\mathrm{B}_{level} \geq E_{Tx} + E_{det}$ **then**
10:       **Make** *packet aggregation* D_{Load}
11:       **Perform** *data communication process*
12:     **elseif** $\mathrm{DQ}_{level} < D_{Load}$ *and* $\mathrm{B}_{level} \geq E_{Tx} + E_{det}$ **then**
13:       **Recalculate** D_{Load}
14:       **Calculate** E_{Tx} *required to send* D_{Load}
15:       **Make** *packet aggregation* D_{Load}
16:       **Perform** *data communication process*
17:     **else** *wait to accumulate* $\mathrm{B}_{level} \geq E_{Tx} + E_{det}$
18:       **Perform** *from Line* 13 *to Line* 16
19:     **end**
20: **end**
21: *Repeat step* 1

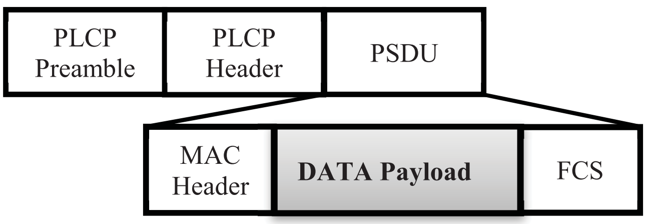

Figure 2 Illustration of IEEE 802.15.6 data frame structure

IV. Performance Evaluation

A. Simulation Considerations and Setup.

We have developed an event-driven MATLAB simulator that implements our algorithm in a simple WBAN. We consider a WBAN formed by one BNC and one BN. We assume that the BNC has no energy shortage restrictions (it has an external power supply), while the BN is connected to an energy harvester. Energy harvester supplies energy to the node at a constant rate K_{EH}. The BN stores the harvested energy in a rechargeable battery. The node we have chosen for our simulation is the electrocardiograph (ECG), which is a medical sensor whose function is the monitoring of electrical activity of the heart. Events detected by the ECG are converted into packets and then stored in a data buffer. The characteristics [20-23] and the QoS requirements [24] of the ECG are summarized in Table I. We assume that the process of communication between the ECG and the BNC can be done directly and without interference. The BNC provides medium access through the execution of the polling access of the IEEE 802.15.6 [19]. The network parameters have been selected according to the IEEE 802.15.6 PHY-MAC specifications [19]. The system parameters used in the simulation are summarized in Table II.

TABLE I. ECG BN CHARACTERISTICS

Data and Trafic Features	DATA ARRIVAL TIME		2 ms
	BUFFER SIZE		200 packets
	PACKET SIZE		12 bits
Power Consumption Distribution	SENSOR, READ – OUT AND ADC		30 μW
	MCU		19.25 μW
	TRANSCEIVER	Reception	3.8 mW
		Transmission	4.6 mW
		Sleep	4 μW
		Idle	0.712 mW
QoS Requirements	DELAY CONSTRAINT		250 ms
	PACKET LOSS CONSTRAINT		10 %

TABLE II. SYSTEM PARAMETERS

PARAMETER	VALUE	PARAMETER	VALUE
SIMULATION TIME	60000 ms	MAC HEADER	56 bits
pSIFS	0.05 ms	FCS	16 bits
pCSMA Slot	0.125 ms	PLCP PREAMBLE	90 bits
PLCP Tx RATE	91.9 kbps	PLCP HEADER	31 bits
DATA T_X RATE	485.7 kbps	ACK	72 bits
CONTROL T_X RATE	121.4 kbps	T. POLL	88 bits

To evaluate our approach, we study the performance of an ECG with and without PEH-QoS, respectively. In our simulation scenario, we consider only the packet loss due to the saturation of the data buffer, the non-detection of the events, and the non-transmission of the stored packets. For the delay calculation, we use the average packet end–to-end delay of all transmitted data packets. This delay is calculated as the time the packet is generated until it is received by the BNC (i.e., $T_{pkt} + T_{TX}$). In addition, we also measure the data storage efficiency, the normalized throughput and the energy efficiency of the BN. We calculate the efficiency of data storage as the total number of stored events divided by the total number of detected events. Energy efficiency is defined as the total amount of useful delivered data over the total energy consumption [25]. Finally, normalized throughput is defined as the number of bits successfully transmitted over the total number of generated bits, within the same period of time.

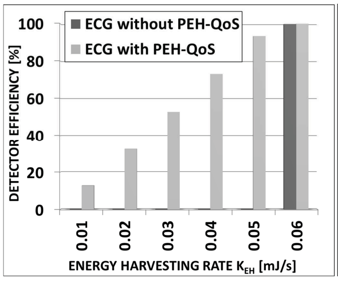

Figure 3 Detection Efficiency

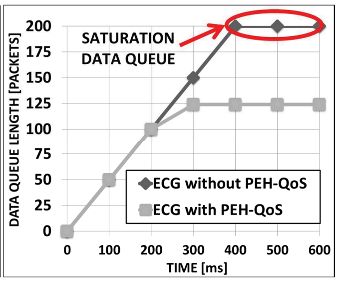

Figure 4 Data Queue Behavior

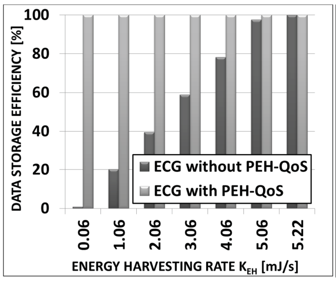

Figure 5 Storage Efficiency

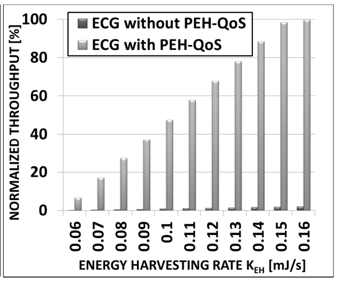

Figure 6 Normalized Throughput

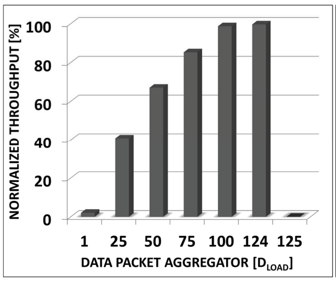

Figure 7 Packet Aggregator

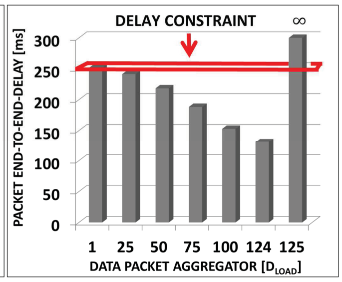

Figure 8 Average Packet Delay

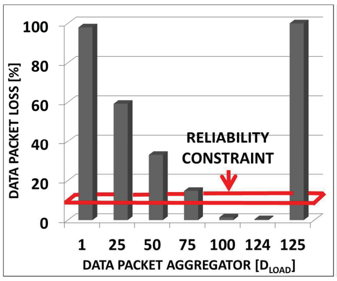

Figure 9 Data Packet Loss

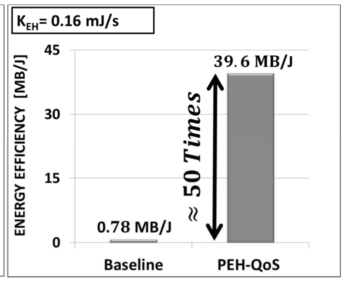

Figure 10 Energy Efficiency

B. Simulation Results.

Simulation results for the detection efficiency of ECG with and without PEH-QoS are shown in Figure 3. In this figure, we can see how the PEH-QoS improves the performance of the ECG in terms of detection efficiency. We observe that for very small values of $\mathrm{K_{EH}}$ (i.e., $\mathrm{K_{EH}} < \frac{E_{det}}{T}$), the ECG without the PEH-QoS cannot detect any event. This is because the node is not aware of the available energy and tries to detect events, although there is not enough energy for the detection, hence wasting the collected energy. In this range, our scheme enhances the performance by a 12.8% and 93.4% for $\mathrm{K_{EH}}$= 0.01 mJ/s and $\mathrm{K_{EH}}$= 0.05 mJ/s, respectively. In the case of $\mathrm{K_{EH}}$= 0.06 mJ/s ($\mathrm{K_{EH}} \geq \frac{E_{det}}{T}$), we can see that both systems achieve a detection efficiency of 100%, since there is sufficient energy for the detection of all the events.

Figure 4 shows the behavior of the data queue for the two systems when $\mathrm{K_{EH}}$= 0.06 mJ/s. In this graph, we can observe that the packets are continuously accumulated because the nodes do not have sufficient energy for the transmission. In these conditions, our algorithm manages to stabilize the data queue, unlike the baseline scenario where the data queue becomes saturated. In Figure 4, it can be also seen that the level of the queue is stabilized in 124 data packets (i.e., in this case D_{Load} = 124), where 100% of the stored information is valid, unlike the case that the algorithm is not applied and the queue is saturated with information that is no longer valid. Figure 5 demonstrates that PEH-QoS is able to maintain the efficiency of data storage at 100%, which allows all sensory data to be stored until they are transmitted or have lost their clinical validity. In order for the node without PEH-QoS to reach a good storage efficiency, a larger $\mathrm{K_{EH}}$ should be used but, unfortunately, high values of $\mathrm{K_{EH}}$ cannot be achieved with current EH technologies.

Figure 6 presents the system throughput behavior for different values of $\mathrm{K_{EH}}$ for both schemes. In this figure, we can see how our scheme, with data aggregation D_{Load} = 124, achieves much better performance than the baseline system. Our system in $\mathrm{K_{EH}}$= 0.16 mJ/s reaches 100% of the normalized throughput while the other system achieves only 2.06%. This is justified by the fact that our scheme sends 124 data packets for transmission, unlike the baseline that transmits only a single packet. Figure 7 shows the variation in the normalized throughput in our scheme when applying different D_{Load} when $\mathrm{K_{EH}}$= 0.16 mJ/s. For the same conditions, Figure 8 and Figure 9 show the relationship between D_{Load} and the restrictions of reliability and delay respectively. As can be corroborated in these two figures, the value of D_{Load} = 124 data packets achieves the best delay value and reliability. In Figure 10, we can see that our system is approximately 50 times more energy efficient than the benchmark. This fact can be rationally explained if we consider that the ECG with PEH-QoS, for the transmission of a sequence of 124 data packets of 12 bits, the node spends only E_{Tx} = 24.3 μJ. On the contrary, in the case of ECG without PEH-QoS, where no aggregation is applied (i.e., L= 1), the node needs E_{Tx} = 10.3 μJ for the transmission of a single data packet of 12 bits.

Furthermore, in terms of packet loss (Figure 11), our scheme fulfilled the reliability requirements of the application (i.e., maximum packet loss 10%), unlike the basic system which exceeded this threshold. In particular, the baseline reaches 97.94%, while our system achieved 0.39% packet loss (97.6% lower). Finally, in Figure 12, we can see that the average packet end-to-end delay experienced in our system is 130 ms (maximum delay permitted 250 ms), contrary to the baseline which obtained a much higher value (16.18 s) (i.e. ≈ 125 times).

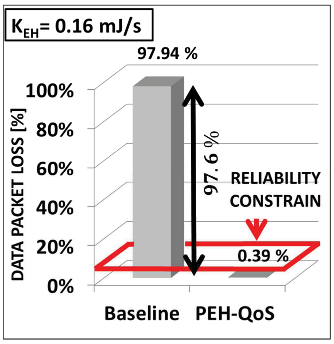

Figure 11 Data Packet Loss

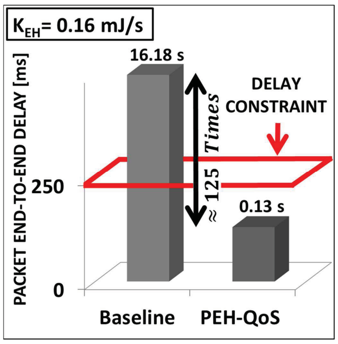

Figure 12 Average Packet Delay

V. CONCLUSION

In this paper, we have introduced *PEH-QoS*, a novel power and QoS aware management algorithm for BNs powered by human EH. Our proposal is aimed to be applied to all types of BNs, as it is adapted to the individual requirements of each node in order to improve the provided QoS under EH conditions. *PEH-QoS* substantially improves the BN's performance, achieving optimal management of the collectd energy, while keeping the node in ENO state. Our algorithm has been proven to outperform the BN without *PEH-QoS* in terms of normalized throughput, energy efficiency, packet loss and average packet end-to-end delay. In addition, BNs with *PEH-QoS* have higher detection and storage efficiency than the baseline approach, achieving a good performance both in transmission and detection. In our future work, we plan to extend our algorithm in more complex networks, taking into account different sources of energy and location of the BNs in/on the human body.

ACKNOWLEDGEMENTS

This work has been funded by the Research Projects ESEE (324284), Kinoptim (324491), WSN4QoL (286047), by SENACYT-IFARHU (Grant 270-2009-173), by the Government of Russian Federation (Grant 074-U01), by Instituto de Telecomunicações, Next Generation Networks and Applications Group (NetGNA), Portugal, and by National Funding from the FCT - Fundação para a Ciência e a Tecnologia through the PEst-OE/EEI/LA0008/2013 Project.

REFERENCES

[1] C. Bachmann, M. Ashouei, V. Pop, M. Vidojkovic, H. de Groot, and B. Gyselinckx, "Low-Power Wireless Sensor Nodes for Ubiquitous Long-Term Biomedical Signal Monitoring," In Proceedings of IEEE Communications Magazine, vol.50, no.1, pp.20-27, Jan. 2012.

[2] P. A. Gould, and A. D. Krahn, "Complications Associated With Implantable Cardioverter-Defibrillator Replacement in Response to Device Advisories," Journal of the American Medical Association, vol. 295, no.16, pp.529-551, Apr. 2006.

[3] J. A. Paradiso and T. Starner, "Energy scavenging for mobile and wireless electronics," In Proceedings of IEEE Pervasive Computing, vol.4, no.1, pp.18-27, Mar. 2005.

[4] A. Kansal, J. Hsu, S. Zahedi, and M. B. Srivastava, "Power management in energy harvesting sensor networks," Journal of ACM/IEEE Trans. On Embedded Computing Systems, vol.6, no.4, pp.651-656, Sept. 2007.

[5] M.A. Ameen, A. Nessa, and K.S. Kwak, "QoS Issues with Focus on Wireless Body Area Networks," In Proceedings of 3rd International Conference on Convergence and Hybrid Information Technology (ICCIT), pp.801-807, Nov. 2008.

[6] S. Ullah, B. Shen, S. M. R. Islam, P. Khan, S. Saleem, and K. S. Kwak, "A Study of Medium Access Control Protocols for Wireless Body Area Networks," In Proceedings of IEEE Global Telecommunication Conference (GLOBECOM), pp.1-13, Apr. 2010.

[7] W.S. Hortos, "Effects of energy harvesting on quality-of-service in transient wireless sensor networks," In Proceedings of Military Communications Conference (MILCOM), pp.1-9, Oct. 2012.

[8] Z. A. Eu, H.-P. Tan, and W. K. G. Seah, "Design and performance analysis of MAC Schemes for Wireless Sensor Networks Powered by Ambient Energy Harvesting," Journal of Ad Hoc Networks, vol.9, no.3, pp.300-323, May 2011.

[9] N. Tadayon, S. Khoshroo, E. Askari, H. Wang and H. Michel, "Power management in SMAC-based energy-harvesting wireless sensor networks using queuing analysis," Journal of Network and Computer Applications, pp.1-10, Apr. 2012.

[10] S. Sankpal and V. Bapat, "Performance Evaluation of Proposed SEHEE-MAC for wireless Sensor Network in Habitat Monitoring," International Journal of Scientific & Engineering Research, vol.2, no.10, pp.1-6, Oct. 2011.

[11] X. Faboutis and N. Dragoni, "ODMAC: An On-Demand MAC Protocol for Energy Harvesting - Wireless Sensor Networks," In Proceeding of 8th ACM International Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Network (PE-WASUN), pp.49-56, Nov. 2012.

[12] G-Z Yang, Body Sensor Networks, 1st ed., vol.1. Springer: Verlag London, 2006, pp.1-34.

[13] E. Ibarra, A. Antonopoulos, E. Kartsakli, and C. Verikoukis, "Energy Harvesting Aware Hybrid MAC Protocol for WBANs," In Proceedings of IEEE 15th International Conference on E-Health Networking, Application & Services (HEALTHCOM), Oct. 2013.

[14] A. Seyedi and B. Sikdar, "Modeling and analysis of energy harvesting nodes in body sensor networks," In Proceedings of Medical Devices and Biosensors (ISSS-MDBS), pp.175-178, June 2008.

[15] A. Seyedi and B. Sikdar , "Energy Efficient Transmission Strategies for Body Sensor Networks with Energy Harvesting," IEEE Transactions on Journal of Communications, vol.58, no.7, pp.2116-2126, July 2010.

[16] J. Ventura, and K. Chowdhury, "Markov modeling of energy harvesting Body Sensor Networks," In Proceedings of IEEE 22nd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), pp.2168-2172, Sept. 2011.

[17] Y. He, W. Zhu and L. Guan,, "Optimal Resource Allocation for Pervasive Health Monitoring Systems with Body Sensor Networks," Journal of IEEE Transactions on Mobile Computing, vol.10, no.11, pp.1558-1575, Nov. 2011.

[18] Y. He, W. Zhu, and L. Guan, "Optimal source rate allocation in Body Sensor Networks with energy harvesting," In Proceedings of IEEE International Conference on Multimedia and Expo (ICME), pp.1-6, July 2011.

[19] 802.15. 6™-2012 IEEE Stds. Standard for local and metropolitan area networks: Part 15.6: Wireless Body Area Networks, Feb. 2012.

[20] J. Khan, M. Yuce, and F. Karami, "Performance evaluation of a wireless body area sensor network for remote patient monitoring," In Proceedings of IEEE EMBS, pp.1266-1269, Aug. 2008.

[21] R.F. Yazicioglu, K. Sunyoung, T. Torfs, P. Merken, and C. Van Hoof, "A 30µW Analog Signal Processor ASIC for biomedical signal monitoring," In Proceedings of IEEE International Solid-State Circuits Conference Digest of Technical Papers (ISSCC), pp.124-125, Feb. 2010.

[22] L. Yao-Hong, H. Xiongchuan, M. Vidojkovic, A Ba, P. Harpe, G. Dolmans and H. de Groot, "A 1.9nJ/b 2.4GHz multistandard (Bluetooth Low Energy/Zigbee/IEEE802.15.6) transceiver for personal/body-area networks," In Proceedings of IEEE International Solid-State Circuits Conference Digest of Technical Papers (ISSCC), pp.446-447, Feb. 2013.

[23] C. Bachmann, M. Ashouei, V. Pop, M. Vidojkovic, H.D. Groot, B. Gyselinckx, "Low-power wireless sensor nodes for ubiquitous long-term biomedical signal monitoring," IEEE Communications Magazine, vol.50, no.1, pp.20-27, Jan. 2012.

[24] M.A. Razzaque, C.S. Hong and S. Lee, "Data-Centric Multiobjective QoS-Aware Routing Protocol for Body Sensor Networks," Journal of Sensors, vol.11, no.1, pp.917-937, Jan. 2011.

[25] V. Rodoplu, T.H. Meng, "Bits-per-joule capacity of energy-limited wireless networks", IEEE Transactions on Wireless Communications, vol.6, no. 3, pp.857-865, May 2007.