Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 151 (2019) 1040–1045

Procedia Computer Science

www.elsevier.com/locate/procedia

The International Workshop on Microwave Engineering, Communications Systems and Technologies (MECST'2019)
April 29 – May 2, 2019, Leuven, Belgium

Energy harvesting based WBANs: EH optimization methods

Marwa BOUMAIZ[a], M. EL GHAZI[a]*, S. MAZER[a], M. FATTAH[b], A. BOUAYAD[c], M. EL BEKKALI[a], Y. BALBOUL[a] ,

[a]*Transmission and Information Processing Laboratory, Sidi Mohamed Ben Abdellah University, Fez, Morocco*
[b]*ETTI Team, FPE, Moulay Ismail University, Meknes, Morocco*
[c]*Systems Engineering Laboratory, Ibn Tofail University, Kenitra, Morocco*

Abstract

Wireless Body Sensor Networks (WBAN) are a special case of wireless sensor networks (WSN), developed to operate at the human body scale. Thus, energy efficiency is one of the major aspects that must be taken into consideration before designing any WBAN solution, because the change of batteries could be very difficult, especially when sensors are implanted inside the human body. For this reason, several research projects have been carried out on the adoption of energy harvesting schemes, that aim to collect energy from several sources surrounding the human body (sun, body warmth, movements, heartbeat, RF radiation ...) and transform it into an electrical energy to power the nodes of a WBAN. Nevertheless, this harvested energy must also be better exploited, given the temporal variation nature of these alternative sources. The purpose of this paper is to present a general overview of energy harvesting schemes, as well as methods in literature focusing on optimizing the exploitation of the harvested energy in a WBAN, through Mac, routing or physical layer protocols.

Keywords: WBAN applications, Energy harvesting aware WBAN, Energy harvesting aware MAC protocols, Energy harvesting aware Routing protocols;

* Corresponding author. Tel.: +212-671-721-112; fax: +0-000-000-0000 .
E-mail address: mohamed.elghazi@usmba.ac.ma

10.1016/j.procs.2019.04.147

1. Introduction

The recent technological advances in electronics and short-range wireless communications have led to the development of miniaturized wireless sensors that can be worn on, or even implanted inside the human body to serve a multitude of applications operating at the human body scale[1], which can be categorized into medical and non-medical applications. Fig1. Shows a set of medical and non-medical WBAN applications.

In the medical area, WBANs can be adopted to serve several applications, including[2]:

- **Remote patient monitoring:** which aims to continuously monitor the vital signs of patients. The known patient monitoring devices include electrocardiography (ECG) and blood pressure sensors to monitor heart disease, electroencephalogram (EEG) to monitor cognitive abilities, respiration and temperature sensors to detect infections, or accelerometers to track patient mobility.
- **Patient rehabilitation**: which is dedicated to patients with mobility problems caused by traumatic brain injury or stroke. The importance of patient rehabilitation is manifested in avoiding inappropriate exercises, updating the complexity of the exercise and recovery monitoring to name a few.
- **Biofeedback:** means that the physiological activity is measured and transmitted "back" to the user to better control its activity and health.
- **Assisted living**: Is manifested by the appearance of smart homes, which introduce the use of several acoustic vibratory and visual sensors, installed in a house to monitor the activity and lifestyle of the patient.

In non-medical WBAN applications, users are the target population. And the biological information can be used for entertainment, security and self-quantization purposes[2] such as:

- **Fitness, performance and well-being monitoring:** this type of supervision is dedicated to athletes and military personnel whose goal is to optimize training methods, thus improving their endurance.
- **Cognitive biometrics:** vital signals such as ECG, EEG and electrodermal activity can be considered as unique biometric signatures that are difficult to be subjected to malicious operations (theft, falsification ...). thus, they can be used in biometric authentication schemes.
- **Serious Games:** is a set of games designed to promote behavioral changes, or educational purposes[3]

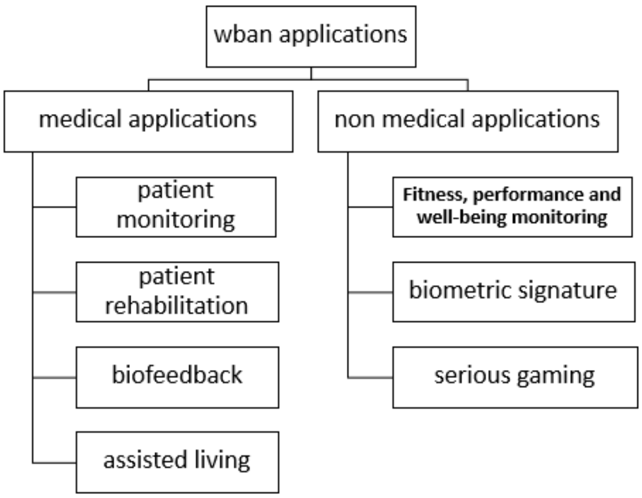

Fig. 1. A set of medical and non-medical applications of WBANs.

Nodes in wbans are generally self-powered with integrated batteries, which makes energy efficiency one of the major requirement in such networks[4]. Thus, shifting interest to energy harvesting schemes is highly recommended, in order to achieve an Energy Neutral Operation (ENO) WBAN, that can be powered only by clean and available energy sources, such as, body motion, warmth or sun light to name a few.

However, the variable and time depending nature of these ambient energy sources, must be taken into account in designing mac, physical layer and routing protocols, to better exploit the harvested energy in WBANs. To the best of our knowledge, a study of protocols optimizing the energy harvested in WBANs at the MAC, PHY and routing level, is not yet present in the literature. Therefore, the purpose of this paper is to present a state of the art of the important studies that have been carried out to optimize the exploitation of energy harvested in EH based WBANs, at the mac, physical and routing layers.

The remainder of this paper is organized as follows: in section 2, the main energy harvesting methods in WBANs are presented. We propose in section 3, a state of the art of research works optimizing the exploitation of the harvested energy in WBANs, and section 4 concludes the paper.

2. Energy harvesting methods in WBANs:

Energy harvesting techniques in WBANs consist of transforming the ambient energy sources into an electrical signal using energy harvesters [5,6] such as: piezoelectric transducers (transform mechanical activity into an electrical signal), thermoelectric elements (transform body heat into an electrical signal), photovoltaic cells (transform light into an electrical signal) , or antennas (transform radio frequency radiation into an electrical signal).

2.1. Ambient energy sources[7,8]:

- **Light energy (solar energy):**

Sun light is a clean source of energy that can be transformed into an electrical signal to power sensor nodes in a WBAN, it gathers a maximum of photons to create an alternative electrical energy. In outdoor conditions, sun light can produce up to 15 mW per square centimeter, however, in a full indoor environment, this value drops out to 10 mW [9].

- **Vibration energy:**

It is the energy produced by body vibration, due to physical movements, or physiological processes such as breathing. From [10], the walking scenario can produce up to 10 Mw, using a piezoelectric transducer.

- **Radio frequency energy:**

Radio frequency energy harvesting takes interest from many RF sources such as base stations, wireless networks, television towers…

- **Thermal energy:**

Human body warmth can also be a source of energy [11]. Thermoelectric transducer can then be used to convert thermal energy into an electrical energy, and can achieve a maximum power of 60 micro watt per cm square [12].

- **Blood Pressure Energy:**

Heart beat is another way to generate energy, according to [13] the heartbeat of a normal person can produce up to 0.93W.

3. Optimizing the exploitation of the harvested energy in WBANs:

The replacement of batteries when sensors are implanted inside the human body may involve surgical operations[14]. Thus, the energy harvesting in the human body's sensors can be performed through the integration of specific equipment called energy harvesters, which aim to convert many types of energy sources into an electrical energy. however, this method provides a small and time independent amount of energy. Therefore, several researchers are focused on proposing WBAN protocols at the MAC, Routing and physical layers, taking into account the energy harvesting constraints.

3.1. At the physical layer:

At the physical layer level, Mosavat-Jahromi et al.[15] studied the spectral efficiency of two communication links (one hop, two hop based on a decode and forward relay) in a WBAN based on TDMA. the maximization of spectral efficiency was therefore considered for the two links, taking into account the following constraints: the capacity of the data buffer, the harvested energy, the transmission power and the probability of failure. In the proposed scheme, the non-causal energy harvesting model is adopted (all energy values are known at the transmitter). therefore, the transmitter knows the instants and the quantities of energy as well as the gain of the channel in advance (at t = 0). from this work it has been shown that spectral efficiency maximization relies on the allocation of a power vector for all time slots.

In [16] a two phase resource allocation scheme has been proposed. the first phase optimizes both transmission power allocation and source rate to improve long-term QOS performance. Whilst the second phase dynamically adjusts allocation time slots to improve short-term performance of QoS of an energy harvesting based WBAN. The studied constraint in the proposed work is long-term QoS (the average PLR should be less than a threshold). Furthermore, the source rate and transmitted power are allocated based on the maximization of the throughput. the effectiveness of the proposed algorithms has been evaluated for two comparison schemes (offline and online scheme) in terms of long-term (PLR, delay and throughput) and short term QOS.

Table 1. a summarizing table of the proposed works in the physical layer.

Physical layer study	idea	Study constraints	Study metrics
Hamed et al[15]	Maximizing the spectral efficiency	-the capacity of the data buffer. -the harvested energy. -the transmission power. -the probability of failure.	-spectral efficiency -energy consumption per bit
Liu Z et al[16]	Optimizing transmission power and source rate.	the average PLR should be less than a threshold	long-term (PLR, delay and throughput) and short term QOS.

3.2. At the mac layer:

The work in [17] proposes a mechanism of energy management called PEH Qos (joint power-QoS) which takes into account some important QOS metrics in energy harvesting based wbans. according to this work, power consumption in WBAN nodes is divided into two parts: consumption power of detection and consumption power of transmission. the proposed mechanism is based on 3 interconnected modules (phases):

- **The Power-EH Aware Management (PHAM):** which deals with the calculation and management of harvested energy. That is to say that the energy harvested from the human body will be distributed between the two spots of a sensor node (the event detection and the transmission of packets).
- **The Data Queue Aware Control (DQAC):** which manages the queue of the packets, and ensures that only the useful data are transmitted.
- **The Packet Aggregator / Scheduling System (PASS):** which uses the PHAM and DQAC information to determine the optimal number of packets that can be transmitted in each communication process.

The performance of the proposed mechanism was studied on the basis of several metrics such as: the effectiveness of detection, the storage efficiency. The normalized throughput, the Packet loss, the end to end delay, and the energy efficiency.

HEH BMAC [18] is another MAC protocol that uses dynamic schedule algorithm to combine user-defined polling with probabilistic contention random access, while considering the variable nature of energy harvesting sources, and traffic prioritization. The used modes are:

- **ID polling access mode:** which is a contention-free access mode used for nodes with a predictable (heartbeat) or high priority energy source.
- **probabilistic contention random access mode:** this access mode is applicable to nodes with unpredictable energy source, or low priority.

The performance of the proposed protocol is compared to the non-beacon access mode without superframe boundaries proposed by the IEEE 802.15.6 standard and based on the CSMA / CA protocol (with its two cases: small CW, large CW), in terms of energy efficiency and throughput, however some important metrics have not been evaluated (latency, packet loss ...). the comparison between this protocol and that of the IEEE has shown an improvement in performance in terms of the cited metrics.

Based on a two-hop topology (cooperative topology introducing relays) the CEH-MAC [19] protocol (cooperative energy harvesting mac) allows relays of a WBAN network to switch to idle mode in order to be charged. this time is selected by the network hub based on the amount of available energy of the other nodes. two links are possible in the adopted topology (direct link: between source and destination. indirect link: source-relay-destination). the main idea of this protocol is the introduction of a charging time (T_{Charge}) which allows the relay nodes to recover enough energy to carry out the cooperation phase. The T_{charge} parameter is adjusted dynamically by the coordinator in each communication period, depending on the feedback information about the relay's energy levels and the expected duration of the cooperation phase (depending on the number of relays, channel conditions, etc.). the proposed protocol is compared with a basic cooperation scheme of IEEE 802.15.6 entitled Coop802.15.6 based on the CSMA / CA protocol. and that does not take into account the energy levels that can change over time in EH- based WBANS. the performance of the CEH protocol was evaluated in terms of throughput, latency and energy efficiency, and showed improving results in comparison with the COOP802.15.6 protocol, however no evaluation was made in terms of packet loss.

Table 2. A Comparative table of the proposed EH aware mac protocols

Mac protocols	Detection efficiency	Storage efficiency	Throughput	Packet loss	Energy efficiency	topology	Traffic priority	Latency
PEH-Qos [17]	✓	✓	✓	✓	✓	One hop		✓
HEH-BMac [18]			✓		✓	One hop	✓	
CEH-Mac[19]			✓		✓	Two hop		✓

3.3. At the routing level:

In [20] the proposed protocol dynamically modifies the routing trees taking into account the recovered energy available, based on an maximization of Dijkstra's shortest distance algorithm to address the dynamic nature of energy harvesting. the proposed protocol considers the dynamic link cost function which changes within every data gathering round. in this work, network sustainability was studied using the outage as a metric of evaluation in function of data packet size, thus it was proved that low data-rate applications can be implemented using the current energy harvesting technology that high data-rate applications warrant further improvements in harvesting methods.

In [21] a new routing algorithm was proposed (EHARA) for WSN based IOT applications that considers a new parameter called extra backoff which aims to extend the backoff period in the IEEE 802.15.4 CSMA/CA, thus allowing nodes to have more time to wait and harvest energy from the ambient energy sources. the evaluation of the proposed protocol is done in comparison with the existing Randomized Minimum Path Recovery Time (R-MPRT) and Energy Harvesting Aware Ad-hoc On-Demand Distance Vector Routing Protocol (AODV-EHA), in terms of energy efficiency, packet delivery ratio, packet losses ratio, throughput and goodput. and it was shown that the proposed protocol (EHARA) has a better performance, however it didn't study the feasibility to be adopted for IEEE 802.15.6 WBANs.

4. Conclusion

Energy efficiency is one of the major requirements that must be considered in WBANs. therefore, there is much research that has focused on providing mechanisms to improve the energy efficiency of WBANs, including energy harvesting from different sources around the human body.

In this paper energy harvesting methods in Wireless Body Area Networks have been reviewed, as alternative sources for powering WBAN nodes. However, these methods should be well exploited as they are variable and time dependent. Thus, the paper also presents an overview of the proposed EH aware mac, physical, and routing protocols in literature.

References

[1] Negra R, Jemili I, Belghith A. Wireless Body Area Networks: Applications and Technologies. Procedia Comput Sci. 2016;83(May):1274-1281. doi:10.1016/j.procs.2016.04.266

[2] Obón DIPT, Alk TIHF, Aier MAM. W I R E L E S S C O M M U N I C At I O N S F O R E -H E a Lt H a P P L I C At I O N S C Ontext a Wareness in Wban S : a S Urvey on M Edical and N on -M Edical a Pplications. 2013;(August):30-37.

[3] Connolly TM, Boyle EA, Macarthur E, Hainey T, Boyle JM. Computers & Education A systematic literature review of empirical evidence on computer games and serious games. Comput Educ. 2012;59(2):661-686. doi:10.1016/j.compedu.2012.03.004

[4] Shankar SK, Tomar AS. A survey on wireless body area network and electronic-healthcare. 2016 IEEE Int Conf Recent Trends Electron Inf Commun Technol RTEICT 2016 - Proc. 2017:598-603. doi:10.1109/RTEICT.2016.7807892

[5] Pasquale G De, Wei M, Somà A, Wang J. CAPACITIVE MEMS ENERGY HARVESTERS FOR STRUCTURAL MONITORING : DESIGN AND FABRICATION. :211-214.

[6] Sangha HS, Sohal H. Power challenges in wireless body area network for mobile health powered by human energy harvesting: A survey. Indian J Sci Technol. 2016;9(46). doi:10.17485/ijst/2016/v9i46/106912

[7] Ali H, Riaz M, Bilal A, Ullah K. Comparison of Energy Harvesting Techniques in Wireless Body Area Network. Int J Multidiscip Sci Eng. 2016;7(6):20-24.

[8] Xu X, Shu L, Guizani M, Liu M, Lu J. A Survey on Energy Harvesting and Integrated Data Sharing in Wireless Body Area Networks. Int J Distrib Sens Networks. 2015;2015. doi:10.1155/2015/438695

[9] Jain PC. Wireless Body Area Network for Medical Healthcare. 2011;28(4).

[10] Demir SM, Al-Turjman F, Muhtaroglu A. Energy Scavenging Methods for WBAN Applications: A Review. IEEE Sens J. 2018;18(16):6477-6488. doi:10.1109/JSEN.2018.2851187

[11] Hoang DC, Tan YK, Chng HB, Panda SK. Thermal energy harvesting from human warmth for wireless body area network in medical healthcare system. Proc Int Conf Power Electron Drive Syst. 2009;(December):1277-1282. doi:10.1109/PEDS.2009.5385814

[12] Hudak NS, Amatucci GG, Hudak NS, Amatucci GG. Small-scale energy harvesting through thermoelectric , vibration , and radiofrequency power conversion Small-scale energy harvesting through thermoelectric , vibration , and radiofrequency power conversion. 2008;101301. doi:10.1063/1.2918987

[13] Life F. Firefighter Fatalities and Injuries : The Role of Heat Stress and PPE.

[14] Waldo AL, Associated C, Implantable W. A. L. Waldo, MD Complications Associated With Implantable Cardioverter-Defibrillator Replacement in Response to Device Advisories. 2005;533:457-458.

[15] Mosavat-Jahromi H, Maham B, Tsiftsis TA. Maximizing Spectral Efficiency for Energy Harvesting-Aware WBAN. IEEE J Biomed Heal Informatics. 2017;21(3):732-742. doi:10.1109/JBHI.2016.2536642

[16] Liu Z, Member S, Liu B, Chen CW. Joint Power-Rate-Slot Resource Allocation in Energy Harvesting-Powered Wireless Body Area Networks. 2018;(October). doi:10.1109/TVT.2018.2872960

[17] Ibarra E, Antonopoulos A, Kartsakli E, Rodrigues JJPC, Verikoukis C. QoS-Aware Energy Management in Body Sensor Nodes Powered by Human Energy Harvesting. IEEE Sens J. 2016;16(2):542-549. doi:10.1109/JSEN.2015.2483064

[18] Ibarra E, Antonopoulos A, Kartsakli E, Verikoukis C. Energy harvesting aware hybrid MAC protocol for WBANs. 2013 IEEE 15th Int Conf e-Health Networking, Appl Serv Heal 2013. 2013:120-124. doi:10.1109/HealthCom.2013.6720651

[19] Esteves V, Antonopoulos A, Kartsakli E, Puig-Vidal M, Miribel-Català P, Verikoukis C. Cooperative energy harvesting-adaptive MAC protocol for WBANs. Sensors (Switzerland). 2015;15(6):12635-12650. doi:10.3390/s150612635

[20] Argade N, Tsouri GR. Dynamic Routing Trees with Energy Harvesting Constraints for Wireless Body Area Networks. ICST. 2013. doi:10.4108/icst.bodynets.2013.253911

[21] Nguyen TD, Khan JY, Ngo DT. An effective energy-harvesting-aware routing algorithm for WSN-based IoT applications. IEEE Int Conf Commun. 2017;(September). doi:10.1109/ICC.2017.7996888