Energy Harvested IEEE 802.15.4 Wireless Body Area Network

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ABSTRACT

With the increasing demand of wireless body area network (WBAN) for patient monitoring systems, it is necessary to develop efficient energy management systems to either prolong node battery replacement time or to develop battery-less WBAN nodes. In this paper, we introduce an energy harvesting WBAN architecture that combines the energy harvesting system and an adaptable duty cycle adjustment algorithm ABSD (*Adaptive Beacon Order, Superframe Order and Duty cycle*) to prolong a WBAN node battery lifetime. The paper presents an energy harvesting model to show the effectiveness of human body motion based energy harvester. The paper further analyses the performance of a multi-patient and energy harvested WBAN using our proposed adjustable duty algorithm known as ABSD. The paper also presents several initial simulation results.

Keywords

Energy harvesting, human body motion, WBAN, IEEE802.15.4, adjustable duty cycle

1. INTRODUCTION

Wireless Sensor Networks (WSNs) have attracted a wide range of disciplines where close interactions with the physical world objects are essential. The distributed sensing capabilities and ease of deployment provided by a wireless communication paradigm make WSNs an important component of our daily lives. WSNs are deployed in a variety applications ranging from medical to military, and from home to industry. The recent development of IEEE 802.15.4-based Wireless Body Area Networks (WBANs) is promising as a cost effective approach to a patient monitoring system.

Energy efficiency (EE) is a main critical issue for the mass deployment of WSNs and WBANs. One of the key problems for the mass deployment is powering the sensor and router nodes due to use of limited energy source such as the battery. Frequent replacement of batteries for WBAN nodes could cause severe patient inconvenience. Even though many research have been studied and developed in layers of Physical (PHY), Data Link and Network to minimize energy consumption of a battery-powered node to prolong the lifetime of sensor nodes, the lifetime is still bounded and finite, thus limiting deployment of WBAN nodes for mass deployment.

To address the problem of finite node lifetime, energy harvesting (EH) is an alternative approach for field deployable WSNs as well as WBANs. EH refers to the capability of extracting energy from the surrounding environment, such as: kinetic energy (human body motion, mechanical vibrations, wind and wave), thermal energy (solar power, temperature variations), wireless transfer energy, and RF radiation energy. Energy from diverse sources are converted into electrical energy which could be either used directly to power sensor nodes or stored for later use. The EH techniques allow sensor nodes to recharge during the network operation to reduce the operational cost, also avoiding network downtime. EH networks allow fixed battery-less operation [11], thus making it very important for a sustainable *"near-perpetual"* WSN operability [2, 11]. Therefore, Energy-Harvesting-based WSNs (EHWSNs) architecture has been attracting a significant attention.

In recent year, the potential for human-powered energy harvesting has been gaining attention and considered as an effective approach for powering sensor nodes or devices [6]. In principal, human-powered energy harvesters or microgenerators will harvest energy from human body motions/activities or body heat. These sources could provide unlimited energy over an infinite period of time, however, only very limited amount of energy can be obtained at any particular time. The generated levels of power from these motions are different. Experimentally, sprint walking and motion have been considered as a major source of energy [12, 3, 9, 16] when it can generate up to $1630(mW)$ compared to $81(\mu W)$ during a sleep period [3]. In [12], Buren et. al introduced a map of major body motions (as shown in Fig. 1) during walking that could be considered as potential energy sources, such as: leg motions (ankle, knee, and hip motions), shoulder and elbow joint motion during arm swings, heel strikes and center of mass motion. These locations are set into two groups, namely *"upper body"* (locations 2 - 6) and *"lower body"* (locations 7, 8, 9). Significantly, the lower body locations yield around four times more power than the upper body locations [12].

This paper aims to consider the issue of energy efficiency of an energy harvested IEEE 802.15.4-based WBAN under variable traffic conditions. Here, the source of energy harvesting is from human motion. Our main contribution is to

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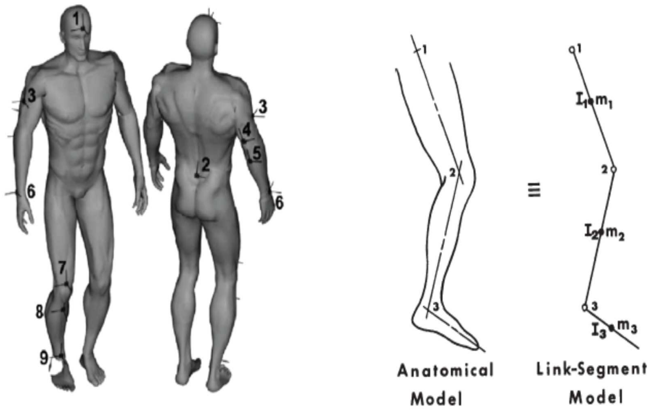

Figure 1: Major body locations for analyzing human movement [12, 13].

propose a combination between an adaptive packet transmission protocol and a human motion-based energy harvesting technique to enhance the EE. This paper also presents the battery lifetime performance for variable traffic load conditions for a multi-patient monitor scenario.

The rest of this paper is organized as follows. Section 2 provides an overview of the existing studies of human motion energy harvesting techniques. Section 3 introduces the IEEE 802.15.4-based WBAN and its traffic characteristics. The combination between an adaptive packet transmission protocol and a selected human motion energy harvesting technique is proposed in Section 4. Numerical results from OPNET and MATLAB based simulation models in terms of energy harvesting and battery lifetime performance will be presented in Section 5. Section 6 concludes the paper.

2. HUMAN MOTION AND RELATED WORKS

Biomechanical energy harvesting from human motion is emerging as a promising clean alternative to electrical power supplied by batteries for portable electronic devices. In principal, the idea of harvesting energy from human body motion is based on converting the mechanical energy (including positive and negative muscles work) that can be derived from the body within each motion to electrical energy [13, p.143].

To harvest energy from the human body motions, force-driven generators and inertial (or vibration-driven) generators can be used [12]. In the first generator, a mechanical energy will be converted by an direct application force. Meanwhile, the inertial generator is a mixed electromechanical system. Here, the mechanical energy will be transformed into electrical energy using the inertia of a moving mass within the generator frame combined with electric/magnetic field, or piezoelectric materials.

There are a number of research studies have investigated the human motion energy harvesting. In [14], based on the force-driven generator, Xie and Cai developed an in-shoe magnetic harvester that could be embedded in a shoe to scavenge mechanical energy from human foot strike during daily activity for conversion into electricity. In this work, a special trapezoidal sliding mechanism and gear train are used for transforming a low-speed linear motion into a high-speed rotation for a generator, which yields a relatively high power output for low-frequency footsteps. This motion then is sent to a microgenerator to produce electricity. By doing this, the harvester could generate an approximately 1W of output power during normal walking condition.

In [12], Buren et. al., compared the optimal performance of these different architectures including Velocity-damped resonant generator ($VDRG$), Coulomb-damped resonant generator ($CDRG$) and Coulomb-force parametric generator ($CFPG$), using actual measured acceleration waveforms from nine locations on the body of walking human subjects. Authors measured average harvested energy at different locations on the body when a person was walking on a treadmill for a given period of time. This is the first model which allowed to determine which body location could provide the most power as well as which generator architecture is best suited to which body location. However, the measured values of harvested energy are suitable for aconsistent walk. This is the main limitation in the work.

To overcome the above practical limitation, Zhang and Seyedi [16] consider the statistical characteristics of harvested energy as subject performs normal daily motions, develop stochastic models for human motion energy harvesting in human-worn wireless devices.

By combining the deployment of velocity-damped resonant generator ($VDRG$) structure and the use of wearable devices (at the four body locations: left ankle, left wrist, right wrist, and waist), named *Alive Heart and Activity Monitor*, human-motion accelerations are measured and then converted to electrical energy. Models provided in this study enable realistic analysis and simulation of wearable communication systems with human motion energy harvesting.

Different from [16], Merrett et. al, [6] consider the effect on harvestable power of generator location (five locations on the body, such as: elbow, wrist, waist, knee and ankle), human activities and take into account the effect of generator orientation and its relation with the other parameters. Authors also propose 2-DOF (Degree of Free) generators in order to examine whether these 2-DOF generators do increase the output power of energy harvested as well as do improve a generator's tolerance to orientation variation and different activities. Experiments and substantial analysis show that 2-DOF generators do not provide significantly greater output power. However, factors of rotation and misalignment which have significantly affected energy harvested, can be reduced using the 2-DOF generator.

3. OVERVIEW OF IEEE 802.15.4-BASED WBANS

3.1 Overview of IEEE 802.15.4 Standard

This standard defines the specifications of PHY and MAC layers for low-rate wireless personal area networks (LR-WPANs)[1]. The standard supports both star and peer-to-peer topologies, which can operate in both non-beacon-enabled and beacon-enabled modes.

Fig. 2 depicts the IEEE 802.15.4 superframe structure for the beacon-enabled mode. The frame is delimited by beacon slots sent by the coordinator, which divides the superframe into 16 slots of equal duration. The superframe is defined by the *Beacon Interval (BI)* and the *Superframe Duration (SD)* which are controlled by the *Beacon Order (BO)* and the *Superframe Order (SO)*, respectively. The *BI* refers to the time duration between two consecutive beacons, and it consists of an active and an inactive period. The active period is

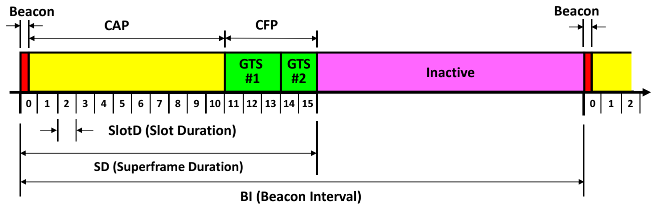

Figure 2: The IEEE 802.15.4 superframe structure for the beacon enabled mode.

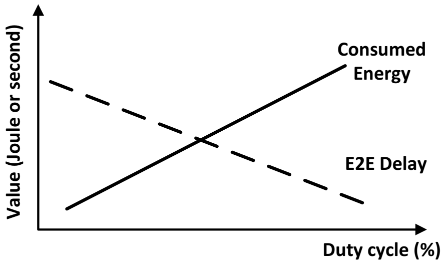

Figure 3: Consumed energy and E2E delay versus duty cycle [15].

further divided into a contention access period *(CAP)* and an optional contention free period *(CFP)*. Any sensor node intending to transmit a packet during the *CAP* must compete with others using the slotted CSMA/CA mechanism. After this period, nodes are able to enter the inactive mode to conserve their energy.

The values of *BI*, *SD* and duty cycle *(DC)* are determined by the following relations:

$$BI = aBaseSuperframeDuration \times 2^{BO}(symbols), \quad (1a)$$

$$SD = aBaseSuperframeDuration \times 2^{SO}(symbols), \quad (1b)$$

$$DC = SD/BI = 2^{SO-BO}, \quad (1c)$$

where $0 \leq SO \leq BO \leq 14$.

The duty cycle control has long been used in a wide variety of battery-operated devices and networks to save the energy and thus extend a network lifetime. Selecting an appropriate *DC* value is important because this does not only affect the energy consumption, but also the QoS parameters [15]. As seen from Fig. 3, with a lower *DC* value, sensor nodes spend more time in the inactive period to save their energy. And meanwhile, the costs for transmission (i.e, delay and packet losses) could sharply increase because of a higher contention level in the network. Therefore, a trade-off between the EE and QoS requirements needs to be maintained.

3.2 Overview of WBAN

An IEEE 802.15.4-based WBAN is a special purpose of WSN and it is composed of multi wireless body sensor nodes which are responsible for sensing physiological parameters on the patient body, such as electrocardiography (EKG), electroencephalogram (EEG), temperature, blood pressure or heart beat. These parameters are then transmitted to a Central Coordinator Unit (CCU) via wireless communication links before sending to remote monitoring stations (or health telemonitoring centers) to process and evaluate [4, 5]. The CCU also controls sensor node's data transmission.

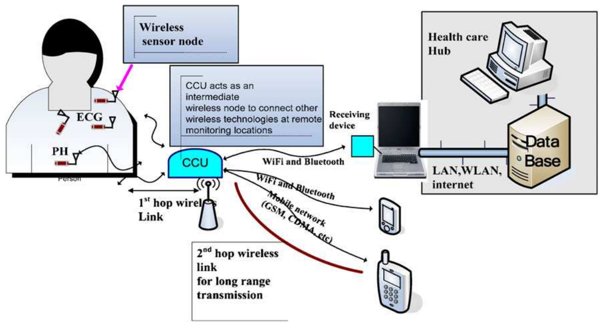

Figure 4: A typical model of WBAN [4]. Springer

Note that, due to the variations of practical physiological conditions of a patient, the data rate, sample rate and sample size at sensor nodes could be varied. This causes these signals to appear as a periodic or a random (non-periodic) signals. For instance, if a patient develops an abnormal heart condition, then the heartbeat sensor can generate a non-periodic signal [4]. Thus, effectively adapting with these changes is one of important requirements for WBAN protocols, particular the media access control (MAC) layer.

Basically, WBAN-communications follow the standard of IEEE 802.15.4 [1] which is originally designed to support wireless personal area networks (WPANs) operating in short range (on or in the human body area) and on low data rates. The main purpose of this is to provide an efficient low-power and low-complexity communication. A typical WBAN model is illustrated in Fig. 4.

The sensed physiological parameters from sensor nodes (as shown in Table 1) in a WBAN can be divided into two main categories of information, including: regular and emergency. In the emergency case, the information has to be transmitted immediately to the remote monitoring stations to produce an alert signal. In such the case, the value of transmission delay will be minimized. In practical, *reliability (i.e., packet losses rate, data throughput, jitter)* and *latency* are the utmost important requirements and they strictly depend on the design of physical (PHY) and Data Link (MAC sublayer) layers [4, 5].

4. ENERGY EFFICIENCY IN AN IEEE 802.15.4 WBAN

In this section, we will focus on the issue of energy efficiency in an IEEE 802.15.4 WBAN under the variable load conditions. To do that, there is a combination between an adaptive packet transmission algorithm and human motion energy harvesting technique using the inertial generator as described in [12, 16].

4.1 An Energy-Avare Packet Transmission Algorithm

From Fig. 3, the energy management is ineffective if the duty cycle remains in the high range for a longer period (*i.e.*, 50% - 100%). In practical, the duty cycle of 50% could allow a node to save up to 50% of consumed energy.

In our earlier work, we reported some preliminary results on enhancing energy efficiency in an IEEE 802.15.4 WSN using our preliminary algorithm, namely *ABSD (Adaptive Beacon Order, Superframe Order and Duty cycle)*[7]. This algorithm allows to adapt the value of *DC* according to the offered load conditions via simultaneously adjusting the BO and SO values. A more detailed description of this algorithm can be found in [7].

The total consumed energy at a node is given by [7]:

$$E = E_{listen} + E_{tx} + E_{rx} + E_{sleep}, \tag{2}$$

where E_{listen} is the energy consumed during the listening period, E_{tx} is the energy for transmitting a data packet and its associated control overhead, E_{rx} is the energy used for successfully receiving a transmitted data packet and its associated control overhead, and E_{sleep} is the energy consumed during the sleeping period.

From [7], E in (2) can be explicitly rewritten as (3):

where:

t_{CCA} is the CCA duration and t_{idle} is the idle time,

t_{tx} is the time for transmitting a packet of $L(bits)$ at a data rate of $R(Kbps)$,

t_{sleep} and I_{sleep} are the time required and the current drawn by the radio in the sleeping mode, respectively,

t_{rx} is the time required to receive successfully a packet at the coordinator at the rate of R,

I_{tx} is the current consumed in the transmitting mode, I_{rx} is the current in the receiving mode,

U is the battery voltage.

4.2 A Human Motion Energy Harvesting Technique

As mentioned in Section 1 and Section 2, *"lower body"* locations are the main sources of energy for energy harvesting. Thus, in this paper, we explore the option of generating energy during activities that are performed naturally throughout the day, with particular emphasis on walking and *"lower body"* locations (Hip, Knee and Ankle) as shown in Fig. 5.

With these assumptions, when a person walks, forces or moments at these three locations will be generated. In this case, the human motion (i.e., walking) can be considered as a kinetics model. Based on this model, we can determine the forces, total moment of force values of ankle, knee, and hip joint during a motion. Based on an anatomical model, a link segment model and a free body diagram as illustrated in Fig. 5, combined with the Newton's Third Law, Newton's equations and Euler's equations [13], values of vertical force (F_y), horizontal forces F_x and moments (M) at the Hip, Knee and Ankle are determined as follows:

For the Ankle:

$$F_{Ax} = m_3 a_x, \tag{4a}$$
$$F_{Ay} = m_3 g + m_3 a_y, \tag{4b}$$
$$M_A = I_3 \alpha + F_{Ax} d_y + F_{Ay} d_x. \tag{4c}$$

For the Knee:

$$F_{Kx} = m_2 a_x - F_{Ax}, \tag{5a}$$
$$F_{Ky} = m_2 g + m_2 a_y + F_{Ay}, \tag{5b}$$
$$M_K = I_2 \alpha + F_{Ax} d_y + F_{Ky} d_x + F_{Kx} d_y + F_{Ky} d_x + M_A. \tag{5c}$$

For the Hip:

$$F_{Hx} = m_1 a_x - F_{Kx}, \tag{6a}$$
$$F_{Hy} = m_1 g + m_1 a_y + F_{Ky}, \tag{6b}$$
$$M_H = I_1 \alpha + F_{Hx} d_y + F_{Hy} d_x + F_{Kx} d_y + F_{Ky} d_x + M_K. \tag{6c}$$

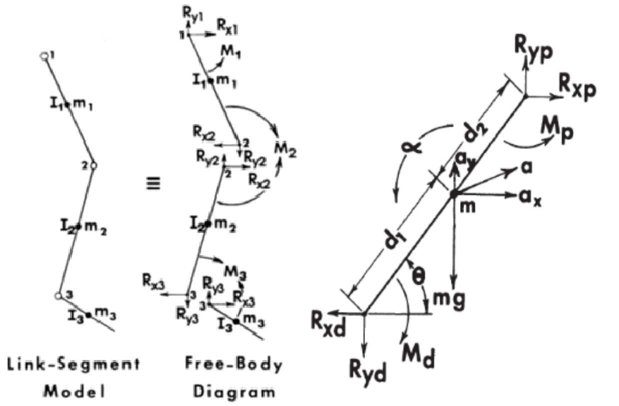

Figure 5: Link-segment and free-body model [13].

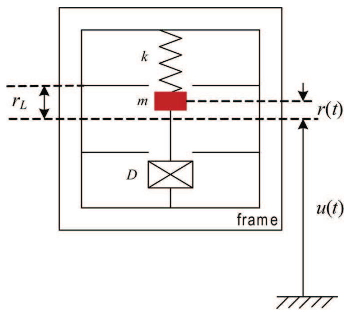

Figure 6: Model of vibration-driven power generator [12, 16].

where m is the mass, a is acceleration of segment, d is the distance, α is angular acceleration of segment and I is moment of inertia.

In this paper, we assume that a velocity damped resonant generator (VDRG) is used [12, 16]. The VDRG is a resonant generator with a magnetic internal mass moving inside a frame as illustrated in Fig. 6. The internal mass will be linked with the external frame by a spring and is damped by a force proportional to its velocity. The movement of the mass in an electromagnetic field will generate the harvestable power. Here, $u(t)$ is the absolute position of the external frame, and $u(t)$ is the second integral of $a(t)$. From [16], we have:

$$m\ddot{r}(t) = -kr(t) - D\dot{r}(t) - ma(t), \tag{7}$$

where k is the spring constant, D is the proportionality factor between the damping force and the velocity of the internal mass.

The Laplace transform between the mass-to-frame position $R(s)$ and the frame acceleration $A(s)$ is:

$$\frac{R(s)}{A(s)} = -\frac{1}{s^2 + \frac{D}{m}s + \frac{k}{m}}, \tag{8}$$

and the harvested power is given by:

$$p(t) = -f(t)\dot{r}(t) = D\dot{r}^2(t). \tag{9}$$

4.3 Battery Model for WBAN Sensor Node

$$E = \left\{((1+N)I_{tx} + I_{rx})\frac{L}{R} + (2^{BO} - 2^{SO})I_{sleep} + (2 \times t_{CCA} + t_{idle})I_{listen}\right\} U. \quad (3)$$

Table 1: Physiologic data characteristics [4].

Physiologic Parameter	Parameter range	Maximum frequency (Hz)	Inter-arrival time (sec)	Payload/Sample (bits)	Data (*Kbps)*
Blood flow	1-300 ml/s	20	0.025	12	0.48
ECG signal	0.5-4 mV	250	0.002	12	6
Respiratory rate	2-50 breaths/min	10	0.05	12	0.24
Blood pressure	10-400 mmHg	50	0.01	12	1.2
Blood pH	6.8-7.8 pH units	2	0.25	12	0.048
Body temperature	32-40 ^{o}C	0.1	5	12	0.0024

As mentioned in Section 1, extending the lifetime of nodes is known as an extremely important task in battery-powered systems, particular in WBAN and WSN. In practical, these battery-powered systems and devices always require an appropriate battery model. In this work, we utilize a battery model based on a Kinetic model, namely Kinetic Battery Model (KiBaM). KiBaM is an intuitive battery model, which was originally developed to model chemical processes of large lead-acid batteries by a kinetic process [8]. To use and deploy battery for sensor nodes in this work, we adopt the KiBaM for nickelmetal hydride (NiMH) battery as described in [8].

In this work, to store the harvested energy from the human motion, we use a rechargeable NiMH battery. In order to achieve a high recharging performance, state of charge (SOC) of batteries should be monitored. Depending on an actual SOC, the decision for battery recharging will be proposed to ensure there is enough energy to maintain normal operation of sensor nodes.

Table 2: Simulation parameters and QoS requirements.

	Parameter	Symbol	Value
Sensor Node MICAZ	Receive	$I_{rx}(mA)$	19.7
	Transmit (0dBm)	$I_{tx}(mA)$	17.4
	Idle Listening	$I_{listen}(mA)$	0.02
	Sleeping	$I_{sleep}(mA)$	0.001
	Voltage	$U(V)$	2.7-3.3
Traffic	Packet arrival time (s)	λ	0.3-10
	Traffic ($packet/s$)	$1/\lambda$	
	Distribution	$Poisson$	
	Packet size ($bits$)	L	1,024
	No. of ReTx	N_{max}	3
Human walking	Body weight (kg)	M	70
	Speed (m/s)	v	1
	Gravity (m/s^2)	g	9.8
No. of patient			6
Ni-MH battery	Voltage (V)		1.25

5. SIMULATION RESULTS

We develop a simulation model using MATLAB to determine the amounts of harvested energy from three different locations on the human leg (Hip, Knee and Ankle) during a walking. A set of data for a normal walking simulation is obtained from [13]. Also, the mathematical model of a energy consumption at a WBAN node as shown in (3) is performed in MATLAB environment. Simulation parameters are summarized in the Table 2.

Fig. 7 illustrates the generated values of forces and moment of force at three different locations on the human leg during his walking. According to the Dempster's Body Segment Parameters [10, p.65], the differences among the ratio of *segmental mass/total mass* at the segments of foot (ankle to ball of foot), leg (knee to ankle center) and thigh (hip to ankle center) (0.0145, 0.0465 and 0.1, respectively) are not significantly. During the period of 45-minute walking, the total harvested energy at the points of Hip, Knee and Ankle are approximately 1.1($Joule$), 0.3($Joule$) and 0.9($Joule$), respectively. As can be seen from this Figure, the generated values of forces, moments, particular the harvested energy at these points are quite the same and suitable with reported values in [12].

Later we use an OPNET model to simulate a bursty traffic source for different IEEE 802.15.4 WBAN sensor nodes that transmit packets to the CCU using the superframe structure. In the simulation, the variations of the incoming traffic load under three typical values of interval packet per node (i.e, 0.5, 2 and 3 $packet/s/node$) and their distributions are shown in Fig. 8(a). The simulated scenario represents a multi-patient monitoring system. This figure shows that for different packet interval time, the offered traffic load varies with time. In addition, the load variability increases with the increasing traffic load. For a multi-patient WBAN, the traffic rate could vary depending on the physiological parameters observed.

Fig. 8(b) describes the relationship between a remaining energy in the battery at sensor node and packet. As seen, the remaining energy decrease with an increase in incoming traffic load.

As mentioned earlier, managing the state of charge of battery is an important task. In Fig. 9(a), at the initial stage, the battery state of charge (SOC) is 100%. It means that battery is full-charged and there is no need a charging at battery. During the sensor node's operation, nodes will use this energy to transmit or receive data and communicate with the CCU. Thus, the energy in sensor node's battery decreases quickly. If there is no harvester, the remaining energy continuously declines. In the case when SOC value

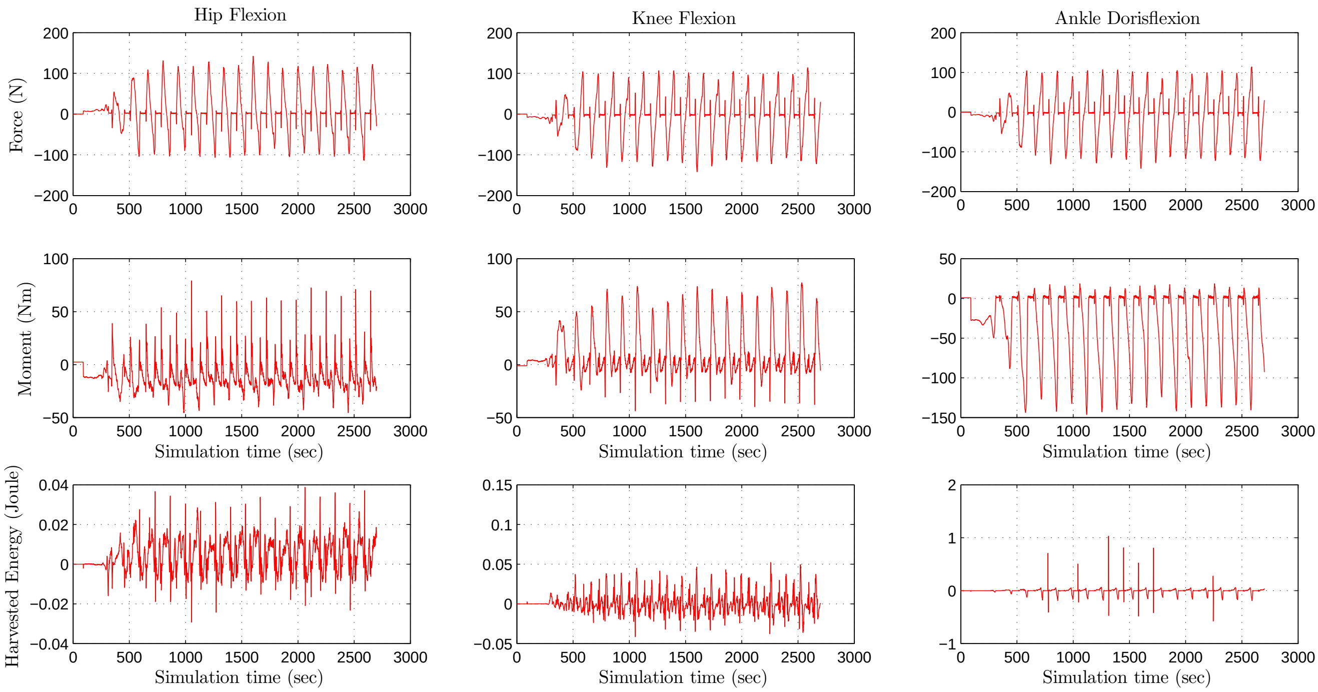

Figure 7: Force, Moment and Harvested energy at Hip, Knee and Ankle.

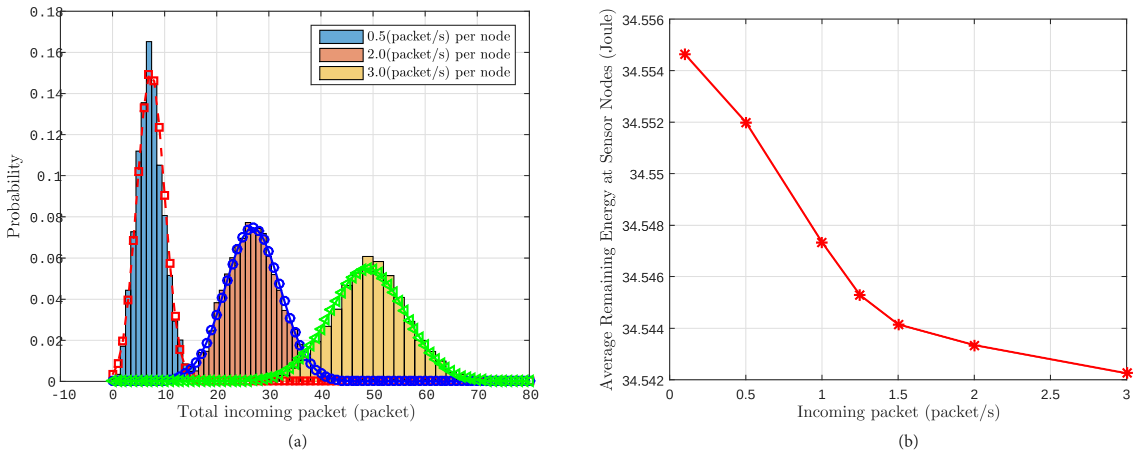

Figure 8: Incoming traffic at the CCU & Relationship of the Remaining Energy and Incoming traffic.

is equal or lower than 10%, the main operations of sensor nodes (transmitting, receiving) will be stopped and nodes will enter into the sleeping state and wait for batteries re-charging.

With an energy harvester, when the remaining level of energy in battery (or SOC value) reaches 50%, the battery will be re-charged. The amount of harvested energy will be charged into the battery and the remaining energy will start increasing. The more the amount of harvested energy is, more energy will be re-charged in battery. Fig. 9(b) shows that with the human motion energy harvester, the battery can extend their lifetime from the time of 1500(sec) to more than 2700(sec). Clearly, the energy harvester has a significant improvement on the lifetime of battery. This leads to an extension in the lifetime of sensor nodes.

Note that, in this simulation, battery charge level performance was obtained for the MATLAB by using the energy characteristics of IEEE 802.15.4 nodes obtained from an OPNET model when a patient monitoring system was simulated using 6 WBAN nodes. Also, for space limitation detail of the OPNET model is not provided.

6. CONCLUSION

The paper analyzed the performance of an energy harvested IEEE 802.15.4 WBAN using the proposed ABSD energy efficient packet transmission technique. The work used two simulation models to obtain the performance data of the WBAN. Initially, an OPNET based discrete event model was developed to measure the performance of the ABSD packet transmission technique. The OPNET model generated energy usage profiles of WBAN nodes for different traffic intensities. The energy usage profile was utilized

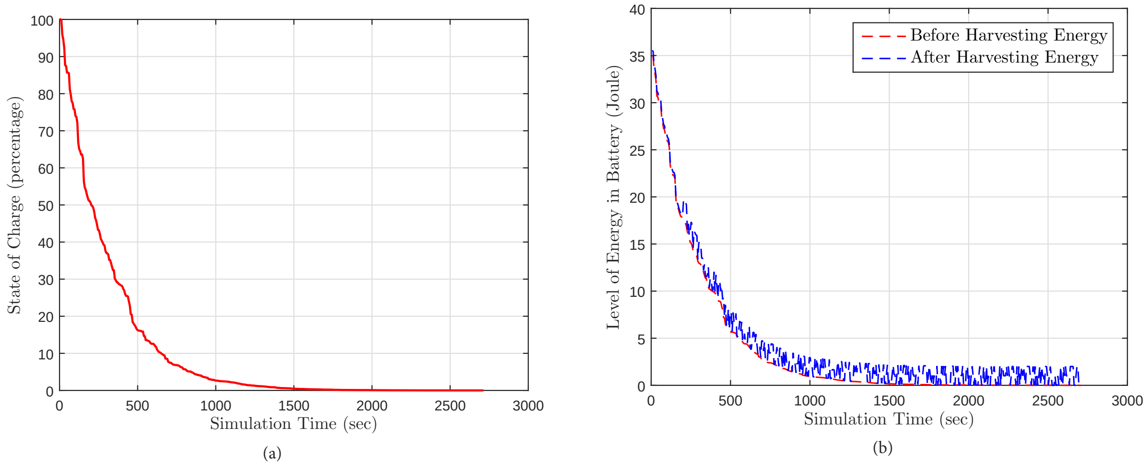

Figure 9: Battery state of charge and energy harvesting.

in the MATLAB model to compute the battery lifetime by linking the energy profile of WBAN nodes with the energy scavenging model. This a unique approach used in this work to measure energy efficiency with realistic network operating parameters and an energy scavenging model which takes account of human body movements and physiological traffic characteristics. As shown in the previous section that a body energy harvested network could significantly prolong a battery or energy source lifetime.

Energy efficient WBAN hardware can be designed by using other form energy storage devices such as the super capacitor which could act as an energy buffer and potentially provide WBAN support to patients or athletes without replacing the energy source at all. The energy scavenging model can be further extended to power up wearable devices either for standalone or for networking applications. This work will be further extended to develop a combined OPNET model by incorporating the MATLAB energy scavenging module. Such a combined model will allow us to analyze the performance a WBAN for different traffic and applications scenarios.

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