# Wireless Energy and Information Transfer in WBAN: An Overview

Fengye Hu, Xiaolan Liu, Meiqi Shao, Dan Sui, and Liheng Wang


## Abstract

Wireless body area networks (WBANs) aim to improve the speed, accuracy and reliability of communication of sensors/actuators that are energy-limited. Some significant physiological parameters need a higher transmission rate and a larger amount of energy. Since they harvest different amounts of energy from the surrounding environment of the human body, the advances in wireless energy transfer provide an attractive solution to supply continuous and stable energy for sensors. However, the additional energy dimension raises many new research problems and implementation issues in the dynamic and heterogeneous WBAN. It is important to perform a trade-off between wireless information and energy transmission. In this article, we provide an overview of the combination of wireless energy and information transmission in WBANs, and build three application models to highlight the key design challenges, solutions, and opportunities.


## Introduction

Wireless body area networks (WBANs) are dynamic heterogeneous networks that include sensors with different sizes, functions, energy demands, etc. By placing sensors in the body, below the skin tissue a few millimeters or implanted in the body, WBANs provide the human body with real-time monitoring and serves a variety of applications (e.g., military, sports, and entertainment) [1, 2]. WBANs interconnect many tiny sensors or actuators and achieve communication among them based on radio frequency. Some physiological parameters need continuous data transmission such as ECG and EEG (which are important to heart disease and brain injury patients). Others need higher data transmission rates, such as audio streaming (1Mb/s) and video streaming (1–10Mb/s) [3]. However, the performance of data transmission is heavily influenced by the limited energy of sensors. The recent advances in energy harvesting technologies enable sensors around the human body to harvest different kinds of energy, but the ability to harvest energy of each sensor is different. The sensor located on the knee can easily harvest a large amount of energy, while the ECG sensor can hardly harvest any energy.

Energy harvesting is a promising technology to supply sufficient energy for sensors. Recently, communication strategies under energy harvesting in wireless networks have drawn attention. Research has performed on the optimal resource allocation scheme to make full use of the harvested energy, since it can improve the communication performance of the wireless network, such as obtaining higher throughput, longer network lifetime, and less waste of the harvested energy [4]. A game-theoretic approach has been introduced to optimize energy management in WSN with energy harvesting technologies [5]. Stochastic optimal control strategy is designed for wireless powered communication networks [6]. Therefore, wireless energy transfer (WET) has become an indispensable technology to power the devices. WET is achieved by the energy transmitter transmitting energy to the energy receiver with the help of radio signals. However, it may cause interference on data transmission in the wireless network, so it is important to balance wireless energy and information transmission (WEIT) due to the additional energy dimension. Also, WET ensures reliable and efficient information transmission because it can provide the devices with continuous energy. In addition, energy and information can be transmitted to the receiver simultaneously over the same RF signal, which is called simultaneous wireless information and power transfer (SWIPT). In SWIPT systems, it is significantly important to choose a moderate switching scheme at the receiver to achieve a tradeoff between the information rate and the harvested energy [7]. Particularly, the optimal tradeoff is obtained between the information rate and the harvested energy by employing multi-antenna random beamforming at the transmitter [8].

In WBANs, almost all sensors can harvest different kinds of energy from the surrounding environment, such as thermal energy, biomedical energy, vibration energy, etc. The different characteristics (e.g., functions, locations) of sensors decide which energy harvesting technology to be used. The authors in [9] describe how to design low-power switched-inductor converters when harvesting ambient kinetic energy. An omnidirectional microelectromechanical system (MEMS)-based ultrasonic energy harvester is designed for implanted biosensors and actuators [10]. In [11], the authors present experimental results of thermal and vibration energy harvested from the human body using a thermoelectric generator and a piezo electric harvester, respectively. An electric circuit model and a dynamic analysis of enzymatic biofuel cells is presented, which can successfully power pacemakers [12]. However, the amount of energy harvested by each sensor and the energy conversion efficiency are different. RF-enabled WET provides an attractive solution to this, which helps reallocate the harvested energy, that is, the sensor with a larger amount of harvested energy can transmit its remaining energy to a sensor with less energy. This technology is effective since it has many practical advantag-

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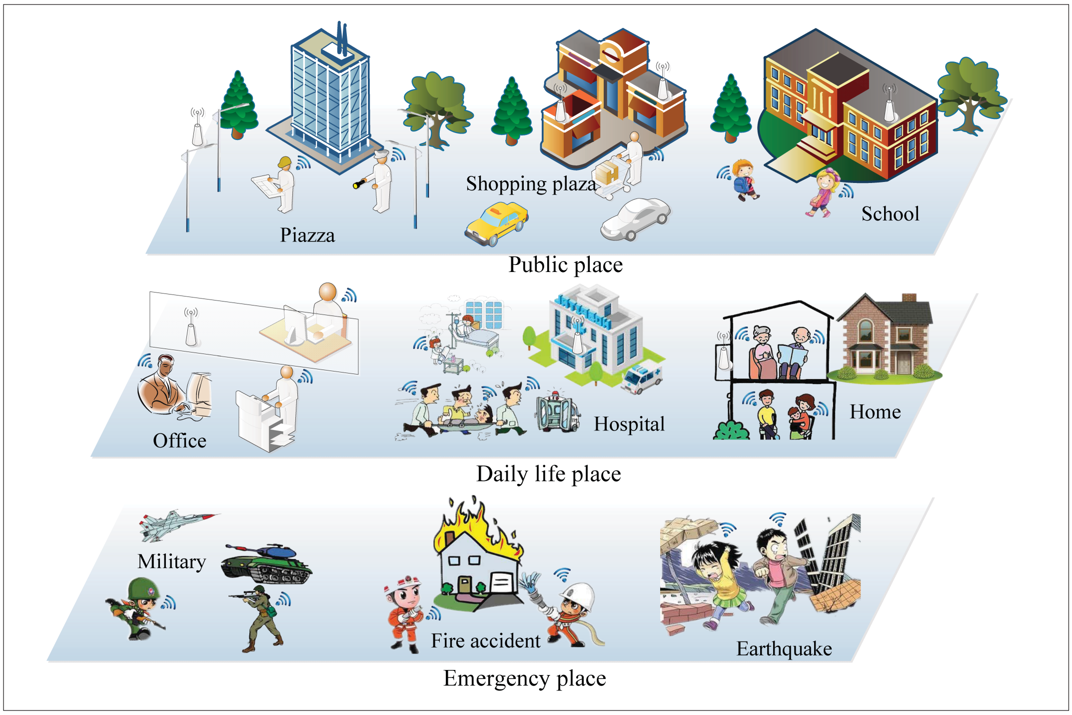


FIGURE 1. The scenarios of WEIT in WBAN.

es, such as low production cost, small receiver form factor, and efficient energy multicast due to the broadcast nature of EM waves. Also, radio frequency is a potential energy harvesting technology to supply energy for sensors by the AP in heterogeneous WBANs. As a result, research on WEIT should be performed in WBANs because the additional energy transmission will cause interference on the information transmission and put pressure on the hardware circuit of sensors. WBANs, which are low-power and near field communication networks, then face more challenges when performing WEIT.

Although RF-energy has been considered for power sensors, it is in fact a technology that faces many challenges in practical WBAN applications. On one hand, the differences in the human body structure (e.g., male or female, height, weight, etc.) and posture (e.g., reclining, sitting, walking, running, etc.) will result in emerging dynamic changes of network topology, so the energy level is instable and unpredictable at receiver sensors. On the other hand, joint design of wireless energy and information transmission is also a challenging problem in WBANs. First, the senor needs to harvest enough energy through wireless energy transfer (WET) or other energy harvesting technologies before transmitting information to the AP. At the same time, the information needs to be transmitted to the AP in a timely manner, so we need to find an optimal ratio of time slot allocation. Second, WET may cause interference to the concurrent information transmission, and the total transmission power of energy and information should be less than the maximum threshold, which avoids the influence of radio frequency waves on the human body.

In this article, we first provide an overview of the condition of WET in WBANs. Then we focus on introducing WEIT models applied to WBANs in the following three topics:

The new emerging energy harvesting technology can replace the battery to supply continuous energy for sensors. However, each sensor has a different ability to harvest energy, so the WET is an attractive technique to reallocate the harvested energy among sensors.

- The single point-to-point model for WEIT in WBANs.
- The analysis of WEIT in one WBAN or several WBANs.
- The design challenges and opportunities of WEIT in WBANs.

Finally, we provide conclusions for this article.

## Overview of WET in WBANs

WBANs provide a variety of services for daily life, such as physiological monitoring, medical treatment, entertainment and sports training, and for emergency cases such as early warning, military applications, automatic alarms and requesting help [13]. These sensors collect data about the human body and then transmit them to the AP. After that, the AP transmits processed information to the services, and it can send alarm signals when an exception occurs. In the conventional WBAN, devices are powered by batteries, which limit long-term applications of the operation due to their size and lifespan. The new emerging energy harvesting technology can replace the battery to supply continuous energy for sensors. However, each sensor has a different ability to harvest energy, so the WET is an attractive technique to reallocate the harvested energy among sensors. WET also can transfer predictable and dedicated energy from the AP to sensors.

WEIT plays an important role in WBANs in our daily life. As shown in Fig. 1, we assume that everyone carries a WBAN. Each sensor in the WBAN can normally harvest energy from the surrounding environment according to its position.

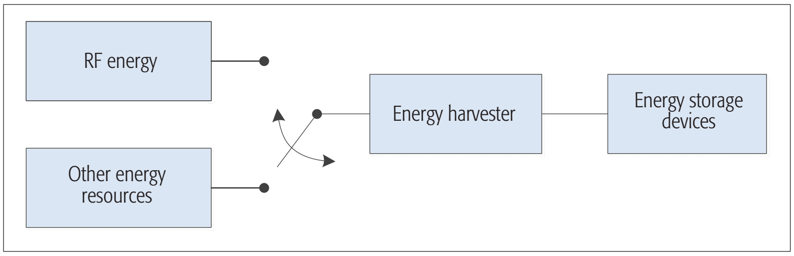


FIGURE 2. The scenarios of WEIT in WBAN.

A few normal life application scenarios are considered, such as school, shopping plaza, office, home, etc. The AP can harvest energy from the radio signals it receives from the base station in the public place. Obviously, WET in WBANs will have influence on each other in crowded places, but the interference can be harvested by sensors as useful energy. In daily life places, the AP harvests wireless energy from Wi-Fi hotspots. Patients and elderly people can use the AP to send injury information and ask for help. Finally, all the sensors transmit wireless energy to the AP together in emergency places, and it then can send a rescue signal to get in touch with other people.

There are three WET schemes: inductive coupling, strongly coupled magnetic resonance, and electromagnetic radiation. Currently, inductive coupling is used to provide energy for biomedical implanted devices. It is achieved by two coils mutually coupling at a short distance (within a range of several centimeters), where one coil is located externally on the human body and the other is located internally. Unfortunately, due to the adverse conditions in some biomedical applications, the transfer efficiencies are commonly poor. Similarly, strongly coupled magnetic resonance (SCMR) has been used for medical implant devices, which has relatively large operation distance (within a larger range of a few meters) [14]. However, it also suffers from transfer efficiency degradation due to the position changes of the receiver. For instance, the biomedical capsule endoscopy receiver is always moving through the gastrointestinal tract [15]. Actually, there is abundant electromagnetic radiation in our surrounding environment. We can exploit its far-field radiative properties to charge low-power biomedical devices. RF energy transfer technology has many advantages in practical applications, such as a small form factor, wider operation distance (within a maximum range of 12 m –14 m) and easier implementation. Nevertheless, it also suffers from low energy transfer efficiency due to the dynamic and shadowed propagation environment around the human body. The beamforming technique has been extensively studied to overcome these deficiencies. Therefore, low-power biosensors can benefit from dedicated RF sources to achieve continuous operations.

The challenge in WBANs is the incomplete battery life of sensors, and WET provides a useful solution to this with RF energy. Compared with other energy sources (e.g., solar, vibration, wind, temperature, etc.), RF energy is predictable and reliable as it does not depend on the environment. These sensors can harvest from a wide range of energy resources, so the energy harvesting circuit used in each sensor is different. In addition, the sensor may have more than one energy harvesting technology, so it is important to be able to freely switch among them. The block diagram of an energy harvesting circuit is shown in Fig. 2. The energy harvesting rate of these energy resources can be represented by different probability density functions (PDFs). Hence, an optimal switch scheme should be designed to provide the sensor with the maximum amount of power. Normally, the AP broadcasts the wireless energy and delivers dedicated energy to the sensor when it sends the AP energy request information. Dedicated wireless energy transmission can be achieved by beam steering at the transmitter, and redesigning the antenna at the receiver. If there is no non-line of sight (NLOS) transmission link between the sensor and the AP, the sensor can perform energy harvesting instead of information transmission. For instance, if the sensor is worn on the right wrist and the AP is located on the left side of the waist, the sensor can transmit information to the AP when the arm swings behind the body, while it can harvest energy when the arm swings in front of the body. Certainly, the information transmission between one sensor and the AP may cause interference on other sensors, but the interference can be collected by the RF energy harvester. Similarly, wireless energy transfer also influences information transmission, so we can propose an optimal power allocation scheme and time allocation scheme to avoid these influences. In the power allocation scheme, the information transmit power $\rho P$ should be lower than the energy transmit power, and the total transmit power $1 - \rho P$ should not exceed the threshold power (–16dBm). This is to avoid the harmful effects (e.g., absorption rate, heating effect, etc.) of electromagnetic radiation on the human body. We also have to present an optimal time allocation scheme to find a tradeoff between information transmission ($\tau T$) and wireless energy transfer ($1 - \tau T$), with $T$ being the total transmission cycle.

In this article, three WEIT application scenarios are considered for use around the human body. In the first scenario, a basic point-to-point WEIT model is introduced. We categorize it into two cases: one is the transmission process of the AP and sensors outside the body; the other is the transmission process between the AP and implanted sensors. In the second scenario, we assume that one person stays in an empty room alone, and biosensors are placed around the person's body, which forms a heterogeneous WBAN. In this case, wireless energy and information transmission is analyzed, and it is not affected by other networks. In the last scenario, we assume some people are in a party, and everyone carries a WBAN. Obviously, the WEIT of different WBANs will have influences on each other. Fortunately, we can power our own devices and forward our information with the help of devices in other WBANs.

## The Single Point-to-Point WEIT in WBANs

In this section, the single point-to-point model of WEIT in WBANs is considered. We categorize the model into two cases since some biosensors are located externally on the body and others are located internally. As shown in Fig. 3, we assume *A* denotes the sensor implanted in the body,

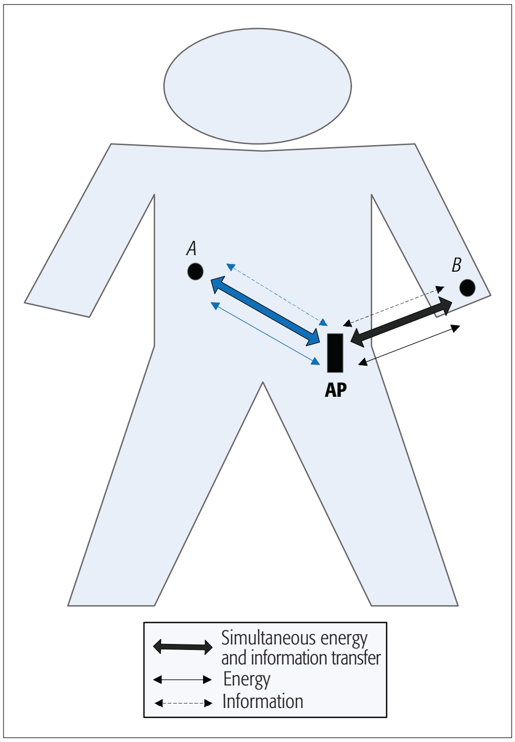


FIGURE 3. The single point-to-point WEIT in WBAN.

and $B$ denotes the sensor worn on the wrist. The point-to-point WEIT between the AP and sensor $B$ is detailed as an example. The other point-to-point WEIT between the AP and sensor $A$ is similar but with a different propagation environment. The AP contains three modules: the information gateway, the dedicated RF energy source, and the energy harvesting module. Sensor $B$ also contains three modules: the information module, the energy harvesting module, and the RF energy transmitter. Normally, sensor $B$ initially harvests enough dedicated RF energy from the AP and other energy resources from the surrounding environment, and then it sends sensory data to the AP. In order to pursue better spectrum efficiency, the SWIPT is performed. In this case, we should use a different receiver structure to perform information decoding (ID) and EH. Currently, research on the following receiver structures has drawn some attention: the time switching receiver, the power splitting receiver, and the integrated receiver. Generally, it is better to perform ID and EH in one integrated module to consider the cost and human comfort. Also, we can only perform wireless information (energy) transmission between the AP and sensor $B$ to maximize information (energy) transmission efficiency within a time period in extreme cases.

As shown in Fig. 3, the transmission process is categorized into three modes: simultaneous energy and information transmission, information transmission, and wireless energy transmission. Their application scenario is summarized as follows. Initially, the AP transmits energy to enable the sensor to sense data and harvest energy (e.g., RF energy, vibration energy, etc.). Then the sensor transmits the sensory data to the AP after harvesting enough energy. After that, the AP can perform SWIPT to pursue better spectrum efficiency, which needs to find a tradeoff between energy and data rate. However, the sum transmit power of the AP should be less than the maximum threshold (−16dBm) to avoid causing harm (e.g., the absorption rate, heating effect, etc.) to the human body. Similarly, the AP can harvest wireless energy from sensors when it has run out of its energy since those sensors can harvest energy through other energy resources (e.g., vibration, temperature, etc.) in WBANs. Another transmission process between the AP and sensor $A$ experiences a similar transmission procedure, but it suffers from a complicated propagation environment due to skin tissue, so it uses different WET technologies such as inductive coupling and strongly coupled magnetic resonance.

> The challenge in WBANs is the incomplete battery life of sensors, and WET provides a useful solution to this with RF energy. Compared with other energy sources, RF energy is predictable and reliable as it does not depend on the environment.

## The Analysis of WEIT in One WBAN or Several WBANs

### The Analysis of WEIT in One WBAN

The model of WEIT in one WBAN is analyzed in this section. We assume that a person stays in an empty room alone. Some sensors are placed around his body, which forms a WBAN, and we assume that the WBAN is not affected by other networks. In WBANs, biosensors sense the data and transmit it to the AP over the RF signals. Then the AP communicates with the Internet to provide people with different services. The WBAN model under the condition of WEIT is shown in Fig. 4. These devices are divided into three categories: the sensor denoted by $A$ which not only performs its own WEIT with the AP, but also relays information and energy of other sensors. For example, the EEG sensor denoted by $B_1$ which is far from the AP and it is non-line of sight signal transmission, so sensor $A$ is used to relay the information or energy between them; the sensor denoted by $B$ which only performs its own WEIT with other devices. For instance, the wristbands sensor $B_4$ can directly carry out WEIT with the AP; the last device denoted by $C$ which only relays information and energy of sensors suffering from severe channel fading. The communication channel between knee joint sensor $B_3$ and the AP suffers from serious shadow fading when the person is walking or running, so the device $C$ is used to achieve the same function as sensor $A$. But if sensor $A$ was used to monitor the ECG data, it also needs to transmit and receive its own information and energy.

The interference among sensors has been a challenging problem. In conventional WBANs, some methods, such as game theory and cooperative communication, are used to reduce the effect of interference on adjacent sensors. However, interference can be collected by RF energy harvesting circuits since it is a radio frequency wave. From Fig. 4, the interference is denoted by the dot-dash line, which exists among some sensors (such as sensor $A$ and sensor $B_4$, sensor $A$ and sensor $B_2$, etc.). Therefore, it is one of the abundant energy sources that can be collected by energy harvesting circuits.

WET between any two sensors, we need to design the same WET technology that suits different kinds of sensors in WBANs. The sensor can also harvest energy from other energy resources, so it is necessary to be able to freely switch among different energy harvesting technologies.

Recently, the advances in RF energy harvesting technology has enabled the wireless energy transmission between two adjacent sensors. This is a significant improvement for continuous energy demanded by WBANs. As shown in Fig. 4, we assume that the AP performs omnidirectional or directional energy radiation, and the other sensors perform directional energy radiation, so wireless energy transmission can be achieved between any two adjacent sensors. Also, sensors that need different amounts of energy can be divided into different priority levels that are based on the importance of the physiological parameters to the human body. Specifically, sensor *A* needs more energy because it performs two operations. Table 1 indicates the priority levels of different physiological parameters, their required data rates, and the potential harvested energy.

As shown in Table 1, we define three priority levels for different biosensors. The significant physiological parameters are defined with high priority, and other physiological parameters that are relatively not important are defined with a lower priority level. Specifically, sensor *A* needs a wide range of data rates due to its special applications. However, we can redefine the energy priority level according to the different requirements

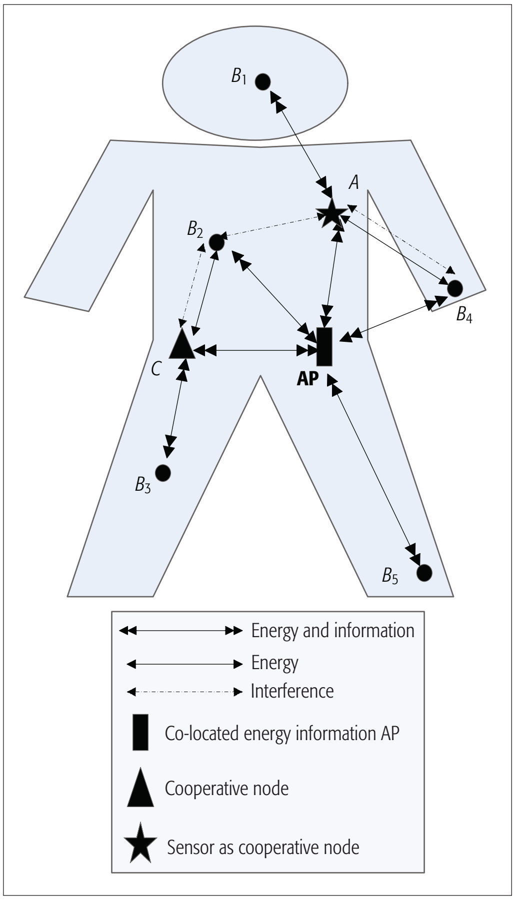


FIGURE 4. The WEIT model in one WBAN.

| Energy priority level | Sensor | Data rate | Harvested energy |
|---|---|---|---|
| 1 | ECG<br>Blood pressure<br>EEG | 3Kb/s<br>Few kb/s<br>Few kb/s | RF energy<br>0.1 μW/cm$^2$ |
| 2 | Music for headsets<br>Forgotten things monitor<br>Social networking | 1.4 Mb/s<br>256 kb/s<br>< 200 kb/s | Vibration<br>4 μW/cm$^2$ |
| 3 | Sensor *A* | Few kb/s–Mb/s | Thermal energy<br>30 μW/cm$^2$ |

TABLE 1. Characteristics of sensors with different energy priority levels.

of special patients (i.e., diabetes, heart disease, Alzheimer's, etc.). Also, there are many potential energy resources around the human body, and the amount of energy that can be harvested is presented in Table 1. RF energy is changeable with the distance from the energy transmitter to receiver, but it can be improved in transmission (e.g., by beam steering), receiving (with antenna redesign), and energy conversion efficiency. For instance, about 1.5 mW is obtained at 20 cm when the transmission power is 100 mW.

### The Analysis of WEIT Between Several WBANs

In our daily life, there are many crowded places and everyone can carry a WBAN. Obviously, the WEIT among WBANs will have influence on each other when the distance between them is less than approximately 2 m. The condition of WEIT between two WBANs is shown in Fig. 5. We assume that the $i^{th}$ WBAN is close to the $j^{th}$ WBAN. Wireless energy transmission is typically performed between the two WBANs. It is achieved among sensors that are the same or different categories (e.g., sensor $B_{i1}$ and sensor $B_{j1}$, sensor $A_i$ and sensor $B_{j2}$, sensor $B_{i4}$ and sensor $C_j$, etc.). Also, we can use the $AP_i$ in the $i^{th}$ WBAN to forward the information of the $j^{th}$ WBAN when $AP_j$ the suffers from lack of energy or malfunction. As an example, the $AP_j$ can use a low-power protocol (Bluetooth, ZigBee, etc.) to transmit the information to the $AP_i$ when the $AP_j$ only remains a small amount of energy. Also, sensor $C_j$ and $B_{j3}$ can transmit their information to the $AP_i$ directly when the $AP_j$ is suffering from malfunction. Certainly, there exists some interference which is indicated by the dot-dash line between the two WBANs in Fig. 5. It can also be collected by the RF energy harvester as useful energy for the sensor.

## The Design Challenges and Opportunities of WEIT in WBANs

### The Energy Information Table

There are a variety of energy resources that can be harvested by sensors in WBANs, e.g. the sensor worn on the wrist harvests vibration energy, the ECG sensor harvests thermal energy, the blood glucose sensor harvests biochemistry energy, etc. However, these sensors can harvest different amounts of energy due to their positions. Some important sensors that need to transmit data to the AP continuously cannot harvest enough energy, but others can still have energy remaining. In order to reallocate the harvested energy, we can build an energy information table at the AP. The table contains the consumed energy and the harvested energy of sensors. The AP decides to transmit energy and information to the sensor according to the table. It sends an instruction to the sensor to transmit its spare energy to other sensors that do not have enough energy. After one energy transmission, the table is updated. The AP also performs WET based on the energy-demand information from sensors.

### The Heterogeneity of WBAN

WBANs are sensor networks in which many sensors are located in a three dimensional space. The body posture is dynamic, which causes a complicated propagation environment around the human body. An energy-efficient medium access approach for WBANs based on body posture has been performed to explore the dynamic channel, but since the WET is analyzed in a WBAN, we can design a new dynamic protocol. For example, the sensor harvests energy when the wave of the arm causes NLOS propagation between the sensor and the AP, or the sensor transmits information. Also, the cooperative node can help forward information and energy when there are no LOS communication channels. There are two kinds of cooperative nodes, as shown in Fig.3. Sensor *C* only forwards energy and information of other sensors, while sensor *A* also needs to transmit its own energy and information. So sensor *A* needs two modules, one for cooperation and another for its own use.

### The Suitable WET Technology

We have introduced three technologies to perform wireless energy transfer among sensors. Although the RF-enabled WET technology has many advantages, inductive coupling is more suitable for charging the implanted sensor in some cases. In order to achieve WET between any two sensors, we need to design the same WET technology that suits different kinds of sensors in WBANs. The sensor can also harvest energy from other energy resources, so it is necessary to be able to freely switch among different energy harvesting technologies.

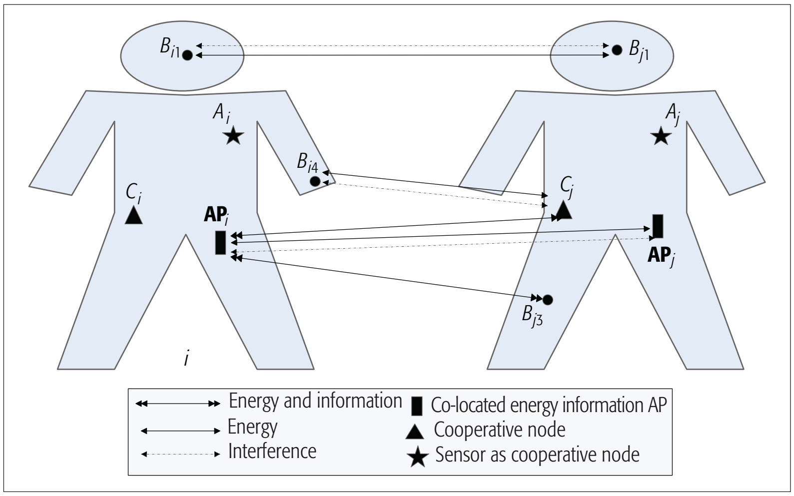


FIGURE 5. The WEIT model between two WBANs.

### Information Security

In order to reallocate harvested energy, we build an energy information table. Nevertheless, the table's disclosure will cause serious consequences for the security of WBANs, especially in military applications. In Fig. 4, the interference is collected by the energy harvesting circuit, but it also can be decoded by the information decoder, so it is better to encrypt the information to avoid decoding through interference. Also, the authorization should be performed when we need to transmit the information with the help of the AP in other WBANs.

### Improved Performance with WEIT

A variety of energy harvesting technologies are explored in WBANs, but the combination of these energy harvesting technologies and information

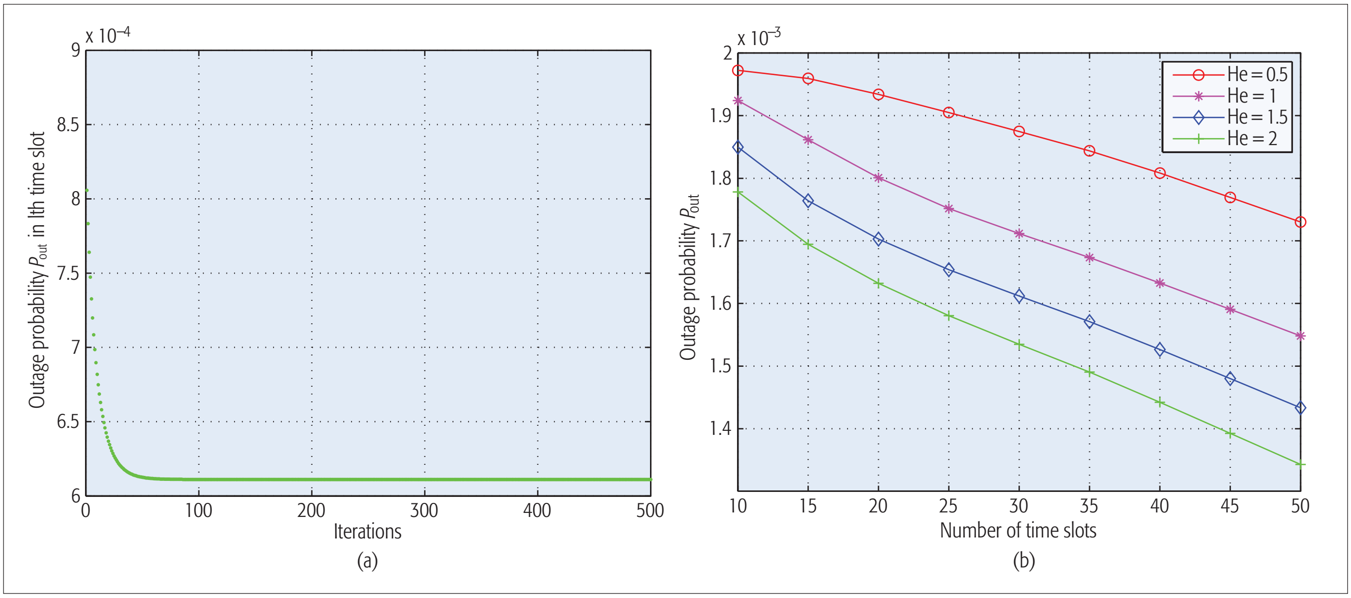


FIGURE 6. The performance of outage probability under energy harvesting: a) the characteristic curve of outage probability; b) the outage probability versus the number of time slots.

The network dynamics and heterogeneity are still the two hardest challenges; the application of different energy harvesting technologies provides energy resources for wireless energy transfer between two arbitrary sensors.

transmission at a device is also a challenging problem. All of these energy resources, especially RF energy, can provide the sensor with enough and continuous energy. As a result, it is not necessary to save energy when designing transmission strategies. The maximum transmit power is used as long as it does not exceed the threshold power that is permitted by IEEE 802.15.6. In Fig. 6, we give an example to illustrate the effects of energy harvesting on power allocation in WBANs with a point-to-point Rayleigh fading channel. We optimize the transmit power of the sensor under energy harvesting constraints, and then the minimum outage probability is obtained. After that, the average outage probability is discussed with $N$ time slots and the energy harvesting rate $H_e$. The outage probability decreases with an increasing number of time slots and $H_e$, as shown in Fig. 6b. The reason is that the transmit power of the sensor keeps the maximum value because the energy harvesting technology can provide the sensor with continuous energy.

## Conclusion

In this article, we have provided an overview of the WEIT and the basic application models for WBANs. We explored the reasons, importance, and technologies of WEIT when it is used in WBANs. Three application models were given to analyze the WEIT used in WBANs. In addition, challenges and opportunities were presented. The network dynamics and heterogeneity are still the two hardest challenges; the application of different energy harvesting technologies provides energy resources for wireless energy transfer between two arbitrary sensors. We foresee that the design of WEIT will be necessary and important for future WBANs to achieve energy self-sustainable and adaptive intelligent communications.

## Acknowledgement

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