sustainability

Article

A Cooperative Transmission Scheme in Radio Frequency Energy-Harvesting WBANs

Juncheng Hu, Gaochao Xu, Liang Hu and Shujing Li *

College of Computer Science and Technology, Jilin University, Changchun 130012, China; xugc@jlu.edu.cn (G.X.)
* Correspondence: lishujing@jlu.edu.cn

Abstract: Wireless Body Area Network (WBAN) plays an important role in e-health, sports training, and entertainment to monitor human bodies wirelessly and remotely. One critical challenge for WBAN is to guarantee the quality of user experience and improve the network performance within such a resource-constrained and dynamic network. In the proposed paper, we investigate a cooperative radio frequency energy harvesting-based WBAN. Herein, we primarily focus on improving the energy efficiency and network performance through intelligent cooperation among nodes, allowing sensors with sufficient energy to assist other sensors in data uploading. We propose a relay selection method that considers both energy demand and energy harvest efficiency. Each sensor calculates the transmission power threshold required for data uploading based on the perceived channel state and determines whether it can act as a potential relay node in conjunction with its own energy harvest efficiency. The coordinator is responsible for optimizing collaborative transmission plans based on real-time network status. Experimental results show that the cooperative scheme performs better than the common single-hop scheme in terms of packet reception rate and packet arrival rate. In a network consisting of 10 sensors, the increase in packet reception rate ranges from 4.9% to 7.8% when the sensors are placed in preset fixed positions. When the sensors are randomly placed, the increase in packet reception rate ranges from 0.9% to 7.9% and from 0.7% to 7.4%, corresponding to δ values of 0.7 and 0.9, respectively.

Keywords: wireless body area network; radio frequency; energy harvesting; cooperative transmission

check for updates

Citation: Hu, J.; Xu, G.; Hu, L.; Li, S. A Cooperative Transmission Scheme in Radio Frequency Energy-Harvesting WBANs. *Sustainability* **2023**, *15*, 8367. https://doi.org/10.3390/su15108367

Academic Editors: Ikram Ud Din, Hasan Ali Khattak and Ahmad Almogren

Received: 7 April 2023
Revised: 7 May 2023
Accepted: 17 May 2023
Published: 22 May 2023

1. Introduction

Chronic diseases like cancer and cardiovascular disease are the top health killers around the world. Studies demonstrate that these severe illnesses can be cured if diagnosed in the early stage [1]. Therefore, new medical concepts place greater emphasis on proactive prevention and early detection of diseases. Meanwhile, building an efficient and reliable e-health system is an important issue for ensuring sustainable development of humankind. For example, the spread of COVID-19 has greatly impacted the sustainable development of humanity. A well-functioning healthcare system and technology serve as the foundation for ensuring normal human life and work. Thanks to the development of the miniaturization of the integrated circuit, sensing technologies, and wireless communication, patient management such as remote monitoring, disease prevention, and disease diagnostics can be realized by the integrated e-health system. The wireless body area network (WBAN) is a key part of the e-health system, which enables efficient and long-term health monitoring and management. The development of the e-health system has played a positive role in promoting smart healthcare and sustainable development of humanity. WBAN, as a key technology of the e-health system, plays an important role in the sustainable development of the intelligent medical system.

A typical WBAN is a heterogeneous network consisting of a group of low-power, miniature, and lightweight wireless sensors designed to monitor various physiological parameters. It is important to improve the energy efficiency of WBANs, in addition to ensuring the quality of the service [2]. To enhance network performance and improve energy efficiency, several techniques, such as media access control (MAC) protocol [3–5], power adjustment scheme [6–8], sleep schedule [9], and the cooperative relay method [10,11] are commonly optimized and designed. However, most of the research studies in this area are focused on battery-powered WBANs, which may not be practical to replace or recharge batteries for sensor nodes in some cases [12].

Radio frequency (RF) energy harvesting, as a potential technology that can prolong the lifetime and usage lifespan of sensors, has drawn significant interest recently. The use of RF energy harvesting technology, which can recharge sensors without relying on external environments, provides a suitable solution for certain long-term, low-power medical monitoring applications. Consequently, the MAC protocol must be carefully designed to cater to the requirements of both energy harvesting and data transmission. Simultaneously, it is crucial to enhance energy efficiency since the available energy harvested from the received RF signal is restricted and limited. Researchers deploy dedicated relay nodes to forward packets generated by the sensors [13], where these nodes utilize all the harvested energy to forward packets generated by common sensors.

For RF energy harvesting-based WBANs, sensors located far from the coordinator harvest less energy but require more energy for data uploading, leading to poor transmission performance. Although the network performance can be improved when dedicated relays are deployed, the network size and complexity also increased, and it is also a complex issue to consider how many dedicated relays need to be deployed and where to deploy them. Improving network performance based on collaborative transmission among sensors is a potential solution. In an energy-heterogeneous network, nodes with sufficient energy can act as relays to forward packets generated by other nodes to reduce the packet loss rate.

To solve the above problems, in this paper, we present a novel cooperative-based relay scheme for RF energy harvesting-based WBANs. We provide a classification scheme which divides the sensors into two categories, relay nodes and common nodes, based on their energy harvesting efficiency and optimized transmission power. By jointly considering the wireless channel state and the sensors' energy distribution, the coordinator formulates and adjusts the cooperation strategy and selects appropriate relay nodes to forward packets transmitted by common nodes to enhance the packet reception rate. To the best of our knowledge, this study is the first to (1) present a classification method for relay identification and (2) determine a cooperative-based data uploading scheme in RF energy harvesting-powered WBANs such that network performances can be improved.

The rest of the paper is organized as follows. Section 2 presents the related works. Section 3 shows the network model. Section 4 explains the proposed work. Performance evaluations and results are discussed in Section 5. Finally, Section 6 concludes the paper.

2. Related Works

Unlike the flexible network topology of traditional wireless networks, WBANs typically use a single-hop or two-hop star network. When designing a relay selection scheme, it is necessary to select the appropriate relay node for the source node to forward the message to the coordinator. We can classify the existing routing protocols into five categories according to the following metrics: network structure, location, temperature, layer, and QoS [14]. A fitness function is proposed in [15] which can determine the placement of relay nodes, and a cuckoo-based scheme is presented using an adaptive step size proportion combined with a fitness function; energy efficiency can be improved and network load can also be balanced. A clustering-base routing scheme is proposed in [16]; a fuzzy function is used and reducing the radiation absorbed by the human body is considered. Both node temperature and the wireless link quality are considered when designing the routing protocol in [17]; potential routing paths are first discovered and then optimized based on the cost for data uploading using a prim's algorithm. To improve the energy consumption and network reliability, a routing scheme is designed aiming to optimize relay node selection in [18]; the distance estimated based on RSSI and the direction calculated according to the MUSIC algorithm are the main criteria considered when choosing the relay. Various network typologies are considered in [19]; different transmission powers are evaluated based on the energy efficiency and network lifetime performances, while two routing schemes are presented considering different strategies keeping SAR in consideration. To take into account more decision factors, a flexible relay candidate scheme is proposed in [20] which adopts an analytical hierarchy process; network performances can be improved under various situations. A clustering process is added in addition to relay selection in [21]; both cluster head and relay node can collect data from sensors and further forward these data to the sink. A routing tree is maintained to balance the energy consumption. Both the energy consumption rate and residual energy are considered when selecting relays in [22]; a heuristic solution is proposed to solve the optimization problem. Virtual MIMO is used to improve the network performances and different cooperative schemes are designed in [23]; network reliability can be effectively improved and fault tolerance can be reduced. A new mobile agent-based DA scheme for WBANs is presented in [24]; nodes in a WBAN form clusters and required data are collected by the base station through a generated mobile agent.

The above-mentioned protocols are specifically designed for battery-powered WBANs; potential relay nodes are selected from sensors according to the proposed algorithms, which consider different constraints, and no dedicated relay nodes are needed. By selecting appropriate relay nodes or routing paths, the network's lifetime and transmission performance can be effectively improved. The advantage of a battery-powered network is that, before the energy is exhausted, nodes are not heavily constrained by energy when transmitting data and can transmit larger packets when needed. However, once the battery energy is depleted, nodes are unable to transmit data, which leads to a rapid decline in network performance or even network failure. Battery reset operations can also reduce the quality of user experience.

Energy harvesting technology is a promising solution for prolonging the lifetime of communication networks by introducing self-sustainability to energy-constrained devices [25]. Considering the situation where sensors can harvest energy at any time, path cost is calculated in [26], which can be used for the relay selection; efficient data transmission and multi-hop routing can be achieved since multiple parameters are considered when designing the network. In RF energy harvesting-based WBANs, nodes must harvest energy first before transmitting data, making them highly constrained by available energy and having a higher demand for energy efficiency compared with battery-powered WBANs. Furthermore, different nodes exhibit varying energy demands and energy harvesting efficiencies; strategies must be formulated based on the differences in available energy among nodes and the characteristics of network topology when selecting relay nodes to optimize the collaborative transmission efficiency. Most protocols deployed dedicated relay nodes between sensors and the coordinator. A transmission power-chosen scheme which considers the energy harvesting efficiency and usage requirements is proposed in [27]; energy efficiency can be effectively improved in a one-hop star network. However, the proposed scheme does not consider collaborative transmission among nodes. Considering the requirement to maximize the spectral efficiency, transmission optimization methods are designed in [28] considering both single-hop and dual-hop scenarios; dedicated relays are needed in the dual-hop network. To improve the network performances of a network which contains only one source and one destination with multiple relays, a relay selection scheme is proposed in [29]; the proper relay can be chosen based to the status of the relays. A WBAN consisting of n sensors, a destination and a relay node, is considered in [30]; weights of sensors are considered when designing the network protocol. In these networks, dedicated relays need to be deployed to improve network performance, which increases the size and complexity of the network. Table 1 presents a summary of the related works.

Table 1. Characteristics of the related works.

References	Authors Contributions	Features			
		A	B	C	D
[15]	A fitness function is proposed, which can determine the placement of relay nodes; a cuckoo-based scheme is presented using an adaptive step size proportion combined with a fitness function.	Y	N	Y	N
[16]	A fuzzy-based routing protocol is presented which considers both the energy efficiency and the specific absorption rate.	Y	Y	N	N
[17]	Both node temperature and the wireless link quality are considered when designing the routing protocol; a prim's algorithm is adopted to select the proper route path.	Y	N	N	N
[18]	The proposed scheme takes into account the characteristics of the input signal. Two significant parameters, distance and direction, are considered for relay node selection.	Y	N	N	N
[19]	An incremental distance threshold-based routing scheme is proposed in addition to the fixed-distance threshold scheme.	Y	N	N	N
[20]	To take into account more decision factors, a flexible relay candidate scheme is proposed which adopts an analytical hierarchy process; network performances can be improved under various situations.	Y	N	N	N
[21]	The clustering process is used in addition to relay selection, and potential cluster heads are selected based on two metrics: Euclidean distance and residual energy.	Y	Y	N	N
[22]	To maximize the network lifetime of WBANs, energy consumption rate and residual energy are considered together when selecting relay nodes.	Y	N	N	N
[23]	A cooperative network coding approach is proposed which enables the cooperation among sensors; fault tolerance and reliability can be improved in the sepsis disease monitoring scenario.	Y	N	N	N
[24]	A new mobile agent-based DA scheme for WBANs is presented; nodes in a WBAN form clusters and required data are collected by the base station through a generated mobile agent.	Y	Y	N	N
[26]	Multiple parameters (e.g., energy of bio-sensors, network topology, congestion states of nodes, value of received SNR, and available network bandwidth) are considered when choosing relay nodes in an energy harvesting-based WBAN.	N	N	N	N
[27]	Sensors can adjust their transmission power dynamically according to the energy harvesting efficiency and the channel status to improve the network performances in an RF energy harvesting-based WBAN	N	N	N	Y
[28]	Both one-hop network and two-hop relay network are considered in an RF energy harvesting-based WBAN; meanwhile, both data buffer and energy buffer are considered as constraints for the data uploading.	N	N	Y	N
[29]	A cooperative transmission scheme is presented, and energy harvesting awareness is adopted; energy harvesting time can be adjusted according to the requirements.	N	N	Y	N
[30]	Because priorities of heterogeneous sensors are different, an analytic hierarchy process algorithm is proposed to determine the weight values of the sensors.	N	N	Y	N

Features: A: Battery-powered, B: Cluster-based, C: Dedicated relay, D: Power control. Values: Y: Yes, N: No.

3. Network Model

As shown in Figure 1, we consider a saturated WBAN that consists of a coordinator and several RF energy-harvesting sensors. All nodes are single-antenna devices that operate in a half-duplex scheme. Instead of batteries, each sensor is equipped with a super-capacitor and an EH circuit that can harvest energy from the radio signal. The coordinator's responsibilities include broadcasting RF energy to charge the sensors, managing and allocating wireless channel resources, and receiving health data sent by the sensors.

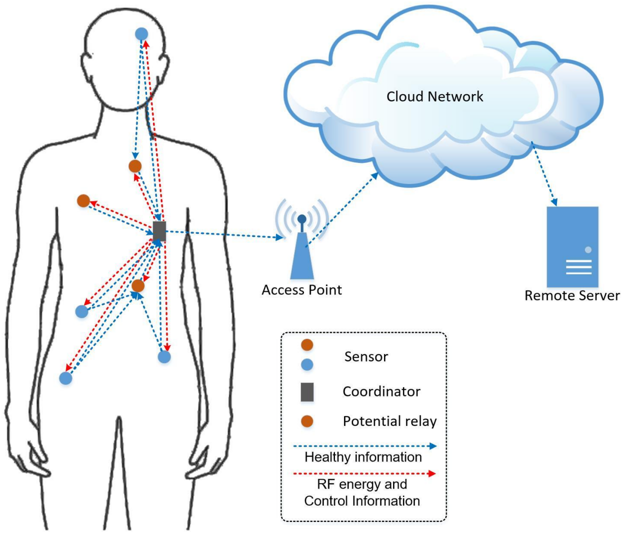

Figure 1. Network model.

Time is divided into periodic superframes, which consist of a download period and an upload period. During the download period, a power splitting scheme is used, and sensors receive command data while simultaneously harvesting energy from the RF signal broadcast by the coordinator. The upload period is divided into time slots, which are assigned to sensors according to the coordinator's schedule. Sensors upload packets in the assigned slots during the upload period. The network is assumed to operate under saturated conditions, with each sensor uploading one data packet per superframe.

The pass loss model considered in the WBAN is a combined distance and frequency dependency model similar to the classical wireless channel model [28]. According to the IEEE 802.15.6 standard, the path loss model with distance dependency can be described by the equation

$$PL(d) = PL(d_0) + 10nlog_{10}(\frac{d}{d_0}) + X_\sigma, \tag{1}$$

where d_0 denotes the reference distance, $PL(d_0)$ means the path loss at the reference distance d_0, n represents the path loss exponent, and X_σ denotes the shadowing component.

Sensors need to harvest energy before data transmission, and the harvested energy is limited. It is difficult for sensors to make cooperative decisions independently. The coordinator is chosen as the decider since it has a fixed power supply and enough computing power. During the initialization phase of the WBAN, a sensor estimates whether it can act as a relay node and reports related information to the coordinator. Then, the coordinator determines reasonable assistance plans to enable cooperative relay among sensors.

4. Cooperation Scheme

In this section, a cooperative method is designed to maximize the total network throughput with an efficient relay scheme. An initialization phase is required, during which sensors evaluate the optimal transmission powers based on the wireless channel state. Sensors that can harvest sufficient energy to support data transmission using the optimized powers are expected to work as relays. Then, the coordinator schedules the collaboration plan to facilitate cooperation among sensors during the cooperation phase.

Figure 2 is an example of the superframe structure and data upload process in a cooperative mechanism of a body area network (BAN) with five sensors. Figure 2b shows a superframe and data upload process in the initialization phase, where the coordinator assigns time slots to sensors without considering cooperative transmission among nodes.

Each sensor uploads its own data packet within the assigned time slot, and when one sensor is uploading a packet, other sensors enter a low-power state to save energy. At the same time, each sensor assesses the wireless channel and evaluates the threshold transmission power according to its own energy harvesting efficiency, to determine whether it can serve as a potential cooperative relay node. The potential relay nodes package their energy and channel state information in data packets and send them to the coordinator. In the cooperative transmission phase, the coordinator formulates and optimizes the cooperative transmission strategy based on the energy and channel state of the sensors. Figure 2c shows a superframe and data upload process in the cooperation phase, where sensors n_2 and n_5 enter a listening state while sensors n_3 and n_4 transmit their packets, and each uploads its own packet and received packets to the coordinator within its assigned time slot. By effectively utilizing the surplus energy of potential relay nodes, network throughput and energy efficiency can be improved.

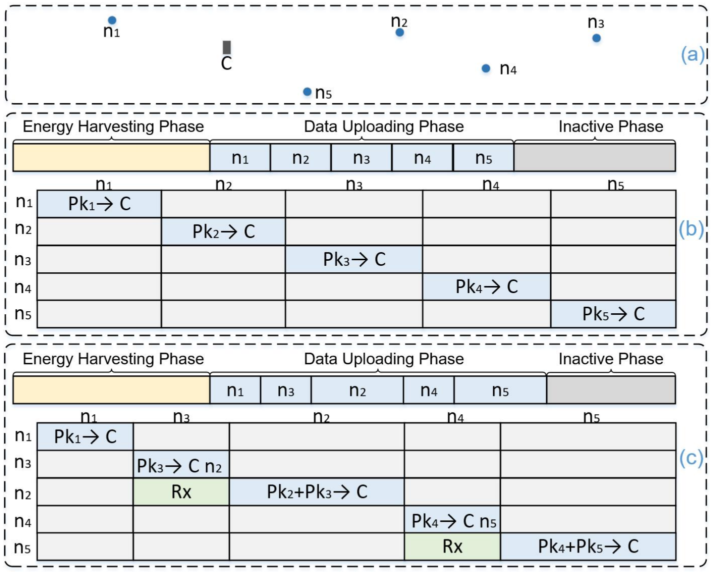

Figure 2. Illustration of the superframe, (**a**) Network, (**b**) Initialize phase, (**c**) Cooperation phase.

4.1. Initialization Phase

When a sensor transmits packets using limited energy, the probability of the packets being received by the coordinator increases, but the number of uploaded packets decreases when a higher transmission power is used. There is an optimized transmission power that can maximize the energy efficiency of a particular sensor. Typically, sensors that are farther from the coordinator can harvest less energy but need a higher transmission power when uploading packets to ensure a high packet reception ratio. The decision to determine whether a sensor can work as a relay node is based on whether the harvested energy can support the optimized power. The probability of a packet being received successfully is influenced by the signal-to-noise ratio (SNR). For example, in non-coherent FSK, the packet reception ratio can be expressed as

$$F(\gamma_{ic}) = (1 - f(\gamma_{ic}))^{L_i} = (1 - \frac{1}{2}exp^{-\frac{\gamma_{ic}B}{2R}})^{L_i}, \tag{2}$$

where $f(\gamma_{ic})$ denotes the bit error rate, and R, L_i, and B denote the transmission rate, the packet length in bits, and the noise bandwidth. γ_{ic} is the SNR at the coordinator, which is related to the transmission power p_i.

$$\gamma_{ic} = \frac{p_i |g_{ic}|^2}{\sigma^2}, \tag{3}$$

where σ^2 is the power of the noise signal and g_{ic} represents the channel gain. Then the energy efficiency can be expressed as

$$\mathbb{E}_i = \frac{F(\gamma_{ic})R}{p_i L_i} = \frac{R|g_{ic}|^2}{L_i \gamma_{ic} \sigma^2}(1 - \frac{1}{2}exp^{-\frac{\gamma_{ic}B}{2R}})^{L_i}. \tag{4}$$

The maximized energy efficiency problem can be resolved by calculating the derivative of $\mathbb{E}_i$ [27], and the optimized SNR $\gamma_{ic}^{\star}$ can be gained. Corresponding to $\gamma_{ic}^{\star}$, the transmission power required by the sensor is

$$p_i^{\star} = \frac{\gamma_{ic}^{\star}\sigma^2}{|g_{ic}|^2}. \tag{5}$$

When a sensor receives wireless signals broadcast by the coordinator, the received SNR is

$$\gamma_{ci} = \frac{p_c|h_{ci}|^2}{\sigma^2}, \tag{6}$$

where p_c and h_{ci} denote the transmission power of the coordinator and the channel gain. According to the reciprocity of the wireless channel, the receiver and the sender of the same wireless link can derive the same channel state if they observe the channel simultaneously [31]; the channel gains are modeled as $g_{ic} = h_{ci} = \sqrt{10^{PL(d_i)}}$. According to Equations (5) and (6), the value of $p_i^{\star}$ can be denoted as

$$p_i^{\star} = \frac{\gamma_{ic}^{\star}}{\gamma_{ci}} p_c. \tag{7}$$

Then, the energy needed to upload a packet using power $p_i^{\star}$ is

$$E_i^{\star} = \frac{L_i}{R} p_i^{\star}. \tag{8}$$

A sensor is identified as a potential relay if it can harvest more energy than $E_i^{\star}$. The harvested energy of sensor i during the energy harvesting phase is

$$E_i = \alpha\delta p_c |h_{ci}|^2 T_e, \tag{9}$$

where α and δ are the power split ratio and the energy conversion efficiency, and T_e denotes the length of the download period. Then, sensors can be divided into two groups, relay nodes (R = $\{r_1, r_2, \ldots, r_m\}$, the set of sensors with $E_i > E_i^{\star}$) and common nodes (N = $\{s_1, s_2, \ldots, s_n\}$, the set of sensors with $E_i \leqslant E_i^{\star}$). Relay nodes upload packets using power $p_i^{\star}$, and the residual energy is used for data relaying. Common nodes upload packets using all the harvested energy.

The coordinator needs to maintain some matrices which are used to optimize the relay selection, including metrics such as the correct reception rate when receiving messages from ordinary sensors and relay sensors, the probability that messages sent by ordinary nodes are correctly received by relay nodes, and the length of messages that relay nodes can forward, among others, such as

$$M_1 = \begin{bmatrix} c_{11} & c_{12} & \ldots & c_{1n} \\ & \ldots & & \\ c_{m1} & c_{m2} & \ldots & c_{mn} \end{bmatrix}$$
$$M_2 = \begin{bmatrix} a_1 & a_2 & \ldots & a_n \end{bmatrix}$$

$$M_3 = \begin{bmatrix} b_1 & b_2 & \ldots & b_m \end{bmatrix}$$
$$M_4 = \begin{bmatrix} l_1 & l_2 & \ldots & l_m \end{bmatrix}$$

Values $a_i(i \in [1,n])$ and $b_j(j \in [1,m])$ denote the probabilities that packets can be received by the coordinator correctly; these are uploaded by common node s_i or relay node r_j. The coordinator updates these values per superframe according to whether the packets of the corresponding nodes are received correctly.

Value l_i denotes the maximum data length that can be relayed by relay r_i, which is calculated as

$$l_i = R\frac{E_i - E_i^\star}{P_i^\star + p_r}, \tag{10}$$

where p_r denotes the power used when receiving signals. Value c_{ij} denotes the probability that packets can be received by relay r_i correctly when common node c_j broadcasts packets. During the initialization phase, each relay cyclically monitors the timeslots used by common nodes according to the guidance of the coordinator and obtains the initial values of c_{ij}. Relay node r_i packs related values l_i and c_{ij} into its packets, and the coordinator updates the corresponding data after receiving the packets.

4.2. Cooperation Phase

During the cooperation phase, the coordinator is responsible for selecting proper relays for common nodes. The coordinator calculates the optimal cooperation scheme and packs the related information in the command packets, which are broadcast during the download period. If relay r_i is selected as a cooperator to forward a packet uploaded by common node c_j, the probability that the packet can be correctly received by the coordinator is

$$\mathbb{P}_{ij} = a_j + b_i c_{ij} - a_j b_i c_{ij}. \tag{11}$$

Compared with uploading without the cooperating relay, the increment of the probability of the packet being successfully received is

$$\mathbb{P}_{ij}^{\Delta} = b_i c_{ij} - a_j b_i c_{ij}. \tag{12}$$

Common nodes are relatively far from the coordinator; these nodes harvest less energy but need more energy to ensure that the uploaded packets can be successfully received by the coordinator. Compared with relay nodes, common nodes have poor network performance, which is the short board of the network. The main goal of the cooperative transmission is to upgrade the performance of the common nodes with the help of the relay nodes. Maximization of the sum value of the increment of the packet reception probability is desired when the coordinator schedules the cooperation plan.

Let ξ_{ij} denote whether r_i acts as a relay node to forward packet transmitted by common node c_j. The value ξ_{ij} equals one when r_i is assigned to the relay packet uploaded by c_j; otherwise, ξ_{ij} is zero. Then, the problem can be formulated as

$$\begin{aligned} & max \sum_{i=1}^{m}\sum_{j=1}^{n} \xi_{ij}\mathbb{P}_{ij}^{\Delta} \\ & s.t. \sum_{i=1}^{m} \xi_{ij} \in \{0,1\}, j = 1,2,...,n \\ & \sum_{j=1}^{n} \xi_{ij} L_j \le l_i, i = 1,2,...,m \end{aligned} \tag{13}$$

The cooperation plan among sensors can be obtained by solving Equation (13), which is a 0–1 multiple knapsack problem. The problem can be solved by binary search algorithm [32] or greedy algorithm, and a set of ξ_{ij} can be gained. If relay node r_i is assigned to the relay packet transmitted by common node c_j, r_i will turn to receive mode during the time slot assigned to the common node c_j and forward the received packet to the coordinator.

5. Simulation Results

To evaluate the proposed scheme, a series of simulations were conducted in Matlab, and the results are presented in this section. The simulation considered a saturated WBAN that consists of one coordinator and several RF energy harvesting-based sensor nodes. The simulation parameters are listed in Table 2. The nodes were placed on the human torso and formed a 60 cm × 40 cm plane. A coordinate system was established where a long side and an adjacent short side were selected as the x-axis and y-axis, respectively. The coordinator was placed at the coordinate origin (0, 0). The length of each superframe was set to 0.1 s. When a potential relay node forwarded packets, the received power was set to be the same as the transmit power. The proposed scheme was compared with the single-hop scheme without cooperation in considered scenarios.

Table 2. Simulation parameter.

Parameter	Description	Value
P_c	transmission power of the coordinator	1 mW
R	transmission rate	100 kbps
$PL(d_0)$	path loss at the referent distance d_0	55
n	path loss exponent	2.4
d_0	the reference distance	1 m
σ^2	noise power	−104 dB
δ	energy conversion efficiency	0.9, 0.7
α	power split ratio	0.6
L_i	packet length	20∽100 bytes

In the first scenario, ten sensors are deployed in two columns; each column contains five nodes uniformly deployed within a distance of 40 cm. The abscissa of one column is fixed at 50 cm, and the abscissa of the other column is within the range of 10 cm to 50 cm. The length of the packets uploaded by the sensors is set to be 50 bytes at first, with the energy conversion efficiency set to be 0.7 or 0.9. The packet reception rate is mainly evaluated, which can be formulated as

$$Pr = N_r/N_s, \tag{14}$$

where N_r represents the number of non-duplicate packets received by the coordinator, and N_s represents the number of packets uploaded by the sensor.

Figure 3 illustrates the packet reception rates in the first scenario. With the distance of the sensors increasing, the packet reception rates demonstrate a downward trend. However, our proposed scheme performs better than the single-hop transmission scheme without cooperation. The sensors closer to the coordinator can use part of their energy for data forwarding to improve network performances. Sensors deployed with abscissa between 40 cm and 50 cm cannot harvest enough energy to ensure satisfactory packet reception rates. No potential relay exists when all sensors are deployed far from the coordinator, and the network performance of the two schemes is similar. When the distance of one column is within range from 10 cm to 35 cm, sensors in this column can harvest enough energy and act as potential relays. These sensors can forward packets uploaded by sensors far from the coordinator, which can improve the network performance through cooperation among nodes. Compared with the single-hop transmission scheme, our scheme increases the packet reception rate by 4.9% to 7.8% when the abscissa of one column is between 10 cm and 30 cm.

Subsequently, we evaluated the performance improvement of the proposed scheme under different load conditions. One column has a fixed abscissa of 50 cm, while the abscissa of the other column ranges from 10 cm to 35 cm. The packet size generated by the sensors is set from 20 bytes to 80 bytes, and the energy conversion efficiency is set to 0.7. The main metric evaluated is the improved packet arrival rate, which can be expressed as

$$Pi = (N_r^{'})/N_s, \quad (15)$$

where $N_r^{'}$ represents the number of packets uploaded by ordinary sensors that were not received by the coordinator but were successfully relayed to the coordinator through the relay nodes.

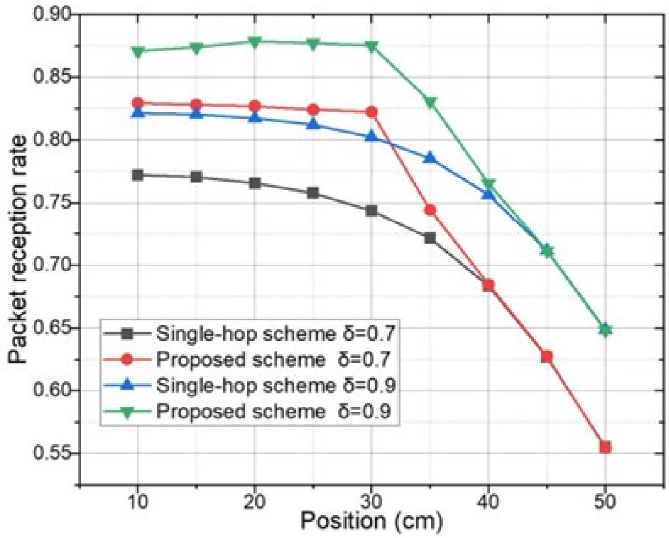

Figure 3. Analysis of packet reception rate in the first scenario.

Figure 4 shows the improved packet arrival rate under the proposed scheme. Since the network transmission performance of ordinary nodes far away from the coordinator is poor, the network performance is significantly improved with the cooperation of potential relay nodes. The larger the network load, the poorer the transmission performance of ordinary nodes themselves, and the more significant the performance improvement with the assistance of potential relay nodes. As the distance between potential relay nodes and the coordinator increases and the distance to ordinary nodes decreases, the probability of correctly receiving messages uploaded by ordinary nodes increases, and the probability of successfully forwarding these messages to the coordinator through potential relays after direct upload failure also increases. However, the energy collected by potential relay nodes decreases with the distance from the coordinator. When the harvested energy is insufficient to support the energy required for message forwarding, the improved network performance will decline sharply.

Finally, we evaluated the performance of the proposed scheme in a randomly deployed sensor scenario; the sensors are randomly deployed in the 60 cm × 40 cm plane. The sizes of packets generated by sensors are in the range of 20 bytes to 100 bytes. Figure 5 illustrates the packet reception rates. For the single-hop transmission scheme, the network density is not the main factor affecting the packet reception rate since no cooperation scheme is adopted. We can see that our scheme performs better when more sensors are deployed as the number of potential relay nodes will increase in a dense network. Packets uploaded by sensors far from the coordinator can be forwarded by potential relays under the guidance of the coordinator. The packet reception rates increase 0.9% and 7.9% when two or ten sensors are deployed if δ = 0.7. Correspondingly, the packet reception rates increase by 0.7% and 7.4% when δ = 0.9.

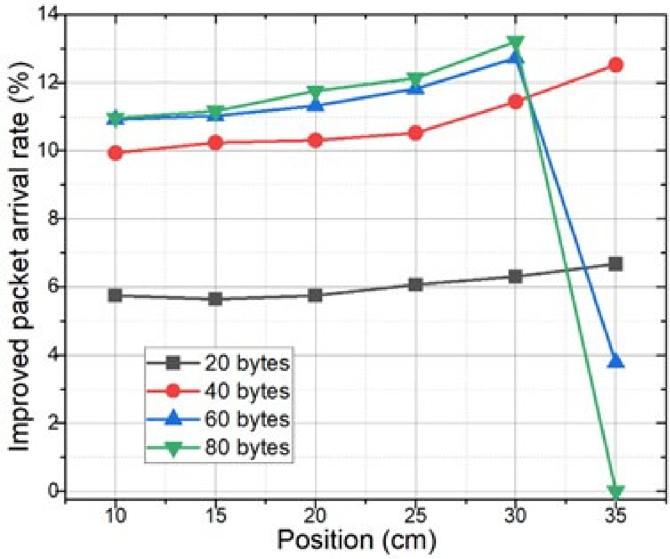

Figure 4. Analysis of improved packet arrival rate.

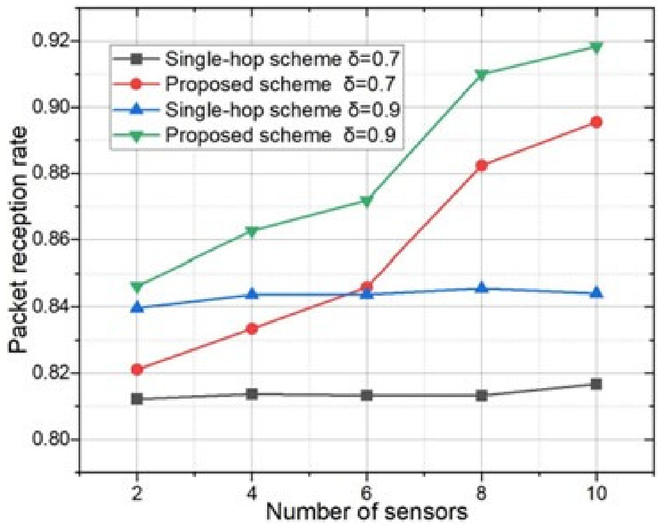

Figure 5. Analysis of packet reception rate in a random location scenario.

6. Conclusions

A cooperative RF energy harvesting-based WBAN is studied in this article, whereby sensors harvest energy before transmission and adaptively adjust transmission strategy to enhance network performance. We proposed a classification method to categorize sensors into potential relay nodes and common nodes. A centralized scheduling scheme is employed, and the coordinator is responsible for calculating the optimal cooperation scheme based on the real-time network status. Cooperative transmission can be realized among sensors, during which sensors with sufficient energy can forward packets received from common nodes. Numerical results show that the proposed scheme ensures maximum reliability of the data transmission. Compared with the common single-hop network, our proposed scheme achieves higher energy efficiency, larger network throughput, and better packet delivery ratio.

In our future work, we plan to extend this study to unsaturated networks where sensors upload packets only when necessary and the coordinator adjusts the superframe accordingly to satisfy sensors' energy charging and data transmission requirements. Additionally, we plan to explore the optimization of collaboration mechanisms among nodes using deep learning methods.

Author Contributions: Conceptualization, J.H. and S.L.; methodology, J.H.; software, S.L.; validation, J.H., G.X. and L.H.; formal analysis, S.L.; investigation, G.X. and L.H.; resources, L.H.; data curation, G.X.; writing—original draft preparation, S.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by the National Natural Science Foundation of China under Grants No. 61701190 and Project of Jilin Province Development and Reform Commission Grant No. 2019FGWTZC001.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. De la Rica, R.; Thompson, S.; Baldi, A.; Fernandez-Sanchez, C.; Drain, C.M.; Matsui, H. Label-Free Cancer Cell Detection with Impedimetric Transducers. *Anal. Chem.* **2009**, *81*, 10167–10171. [CrossRef]
2. Singh, S.; Chawla, M.; Prasad, D.; Anand, D.; Alharbi, A.; Alosaimi, W. An Improved Binomial Distribution-Based Trust Management Algorithm for Remote Patient Monitoring in WBANs. *Sustainability* **2022**, *14*, 2141. [CrossRef]
3. Misra, S.; Bishoyi, P.K.; Sarkar, S. i-MAC: In-Body Sensor MAC in Wireless Body Area Networks for Healthcare IoT. *IEEE Syst. J.* **2021**, *15*, 4413–4420. [CrossRef]
4. Mkongwa, K.G.; Zhang, C.; Liu, Q. A Reliable Data Transmission Mechanism in Coexisting IEEE 802.15. 4-Beacon Enabled Wireless Body Area Networks. *Wirel. Pers. Commun.* **2023**, *128*, 1019–1040. [CrossRef]
5. Das, K.; Moulik, S. Boss: Bargaining-based optimal slot sharing in ieee 802.15. 6-based wireless body area networks. *IEEE Internet Things J.* **2021**, *10*, 2945–2953. [CrossRef]
6. Liu, Z.; Liu, B.; Chen, C.W. Joint power-rate-slot resource allocation in energy harvesting-powered wireless body area networks. *IEEE Trans. Veh. Technol.* **2018**, *67*, 12152–12164. [CrossRef]
7. Archasantisuk, S.; Aoyagi, T. Transmission power control using human motion classification for reliable and energy-efficient communication in WBAN. *IEICE Trans. Commun.* **2019**, *102*, 1104–1112. [CrossRef]
8. Ayeesha Nasreen, M.; Ravindran, S. Energy Saving Mechanism Using Extensive Game Theory Technique in Wireless Body Area Network (ES-EG). In *Computational Vision and Bio-Inspired Computing: Proceedings of ICCVBIC 2021, Coimbatore, India, 25–26 November 2021*; Springer: Singapore, 2022; pp. 431–448.
9. Liu, J.; Al Ameen, M.; Kwak, K. Secure wake-up scheme for wbans. *IEICE Trans. Commun.* **2010**, *93*, 854–857. [CrossRef]
10. Moosavi, H.; Bui, F.M. Optimal relay selection and power control with quality-of-service provisioning in wireless body area networks. *IEEE Trans. Wirel. Commun.* **2016**, *15*, 5497–5510. [CrossRef]
11. Bilandi, N.; Verma, H.K.; Dhir, R. Energy-efficient relay node selection scheme for sustainable wireless body area networks. *Sustain. Comput. Informatics Syst.* **2021**, *30*, 100516. [CrossRef]
12. Abd-Elmagid, M.A.; Dhillon, H.S.; Pappas, N. A Reinforcement Learning Framework for Optimizing Age of Information in RF-Powered Communication Systems. *IEEE Trans. Commun.* **2020**, *68*, 4747–4760. [CrossRef]
13. Sui, D.; Hu, F.; Zhou, W.; Shao, M.; Chen, M. Relay Selection for Radio Frequency Energy-Harvesting Wireless Body Area Network With Buffer. *IEEE Internet Things J.* **2018**, *5*, 1100–1107. [CrossRef]
14. Movassaghi, S.; Abolhasan, M.; Lipman, J.; Smith, D.; Jamalipour, A. Wireless Body Area Networks: A Survey. *IEEE Commun. Surv. Tutorials* **2014**, *16*, 1658–1686. [CrossRef]
15. Samal, T.K.; Patra, S.C.; Kabat, M.R. An adaptive cuckoo search based algorithm for placement of relay nodes in wireless body area networks. *J. King Saud Univ. Comput. Inf. Sci.* **2022**, *34*, 1845–1856. [CrossRef]
16. Zadoo, M.; Sharma, M.; Choudhary, A. FEELS: Fuzzy based energy efficient and low SAR routing protocol for wireless body area networks. *Wirel. Networks* **2022**, *28*, 3593–3611. [CrossRef]
17. Bakkaiahgari, P.V.D.; Prasad, K.V. Prim based link quality and thermal aware adaptive routing protocol for IoMT using SigFox network in WBAN. *Evol. Syst.* **2022**, *14*, 533–544. [CrossRef]
18. Shunmugapriya, B.; Paramasivan, B. Fuzzy based relay node selection for achieving efficient energy and reliability in wireless body area network. *Wirel. Pers. Commun.* **2022**, *122*, 2723–2743. [CrossRef]
19. Saha, R.; Biswas, S.; Sarma, S.; Karmakar, S.; Das, P. Design and implementation of routing algorithm to enhance network lifetime in WBAN. *Wirel. Pers. Commun.* **2021**, *118*, 961–998. [CrossRef]
20. Kim, B.; Cho, J.; Jeon, S.; Lee, B. An AHP-based flexible relay node selection scheme for WBANs. *Wirel. Pers. Commun.* **2016**, *89*, 501–520. [CrossRef]
21. Ziaei, N.; Avokh, A. Relay selection, clustering, and data aggregation routing in wireless body area networks. *Int. J. Commun. Syst.* **2021**, *34*, e4837. [CrossRef]

22. Zhang, Y.; Zhang, B.; Zhang, S. A lifetime maximization relay selection scheme in wireless body area networks. *Sensors* **2017**, *17*, 1267. [CrossRef] [PubMed]
23. Mehmood, G.; Khan, M.Z.; Abbas, S.; Faisal, M.; Rahman, H.U. An energy-efficient and cooperative fault-tolerant communication approach for wireless body area network. *IEEE Access* **2020**, *8*, 69134–69147. [CrossRef]
24. Mehmood, G.; Khan, M.Z.; Fayaz, M.; Faisal, M.; Rahman, H.U.; Gwak, J. An energy-efficient mobile agent-based data aggregation scheme for wireless body area networks. *Comput. Mater. Contin.* **2022**, *70*, 5929–5948. [CrossRef]
25. Boshkovska, E. ; Ng, D.W.K.; Zlatanov, N.; Schober, R. Practical non-linear energy harvesting model and resource allocation for SWIPT systems. *IEEE Commun. Lett.* **2015**, *19*, 2082–2085. [CrossRef]
26. Khan, M.D.; Ullah, Z.; Ahmad, A.; Hayat, B.; Almogren, A.; Kim, K.H.; Ilyas, M.; Ali, M. Energy harvested and cooperative enabled efficient routing protocol (EHCRP) for IoT-WBAN. *Sensors* **2020**, *20*, 6267. [CrossRef] [PubMed]
27. Hu, J.; Xu, G.; Hu, L.; Li, S.; Xing, Y. An Adaptive Energy Efficient MAC Protocol for RF Energy Harvesting WBANs. *IEEE Trans. Commun.* **2023**, *71*, 473–484. [CrossRef]
28. Mosavat-Jahromi, H.; Maham, B.; Tsiftsis, T.A. Maximizing Spectral Efficiency for Energy Harvesting-Aware WBAN. *IEEE J. Biomed. Health Inform.* **2017**, *21*, 732–742. [CrossRef]
29. Esteves, V.; Antonopoulos, A.; Kartsakli, E.; Puig-Vidal, M.; Miribel-Cata, P.; Verikoukis, C. Cooperative energy harvesting-adaptive MAC protocol for WBANs. *Sensors* **2015**, *15*, 12635–12650. [CrossRef]
30. He, M.; Hu, F.; Ling, Z.; Mao, Z.; Huang, Z. A dynamic weights algorithm on information and energy transmission protocol based on WBAN. *IEEE Trans. Veh. Technol.* **2021**, *70*, 1528–1537. [CrossRef]
31. Wang, T.; Liu, Y.; Vasilakos, A.V. Survey on channel reciprocity based key establishment techniques for wireless systems. *Wirel. Netw.* **2015**, *21*, 1835–1846. [CrossRef]
32. He, C.; Leung, Y.T.; Lee, K.; Pinedo, M.L. An improved binary search algorithm for the Multiple-Choice Knapsack Problem. *RAIRO Oper. Res.* **2016**, *50*, 995–1001. [CrossRef]