IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676, p-ISSN: 2320-3331, Volume 18, Issue 6 Ser. I (Nov. – Dec. 2023), PP 45-56
www.iosrjournals.org

Efficient Energy Harvesting With Joint Information Transfer In Wireless Sensor Networks

Md. Faisal Ahmed, Ferdousi Mayoa
Noakhali Science And Technology University, Noakhali-3814, Bangladesh

Abstract
Energy harvesting technology is an ideal solution, which satisfies the energy needs of sensor networks in various applications. It is particularly suited for low-power sensor networks, which operate by collecting harvested energy from the surrounding environment and send information to the main node of the network. Usually, the harvested energy provided to the sensor nodes is not sufficient to satisfy their energy needs. In this paper, our main purpose is to increase the harvested energy provided to the sensor nodes using a directional beamforming technique in an appropriate direction. A system model is proposed, which is capable of generating a power signal of 1W. This signal is then transmitted by a 16-array directional antenna using the time-division multiplexing technique and a carrier frequency of 2.4 GHz. The maximum communication range between the sensor and the sink node is achieved at about 50 m, however, the optimum distance for communication is 20 m. The proposed model is composed of one sink node and multiple sensor nodes, whereas the sink node can transmit the harvested radio frequency (RF) energy signal to the sensor nodes. These nodes store the energy, process the data, and send them back to the sink node. This process is simulated using a time-domain power splitting method to achieve an ideal power splitting ratio value of 0.1. The average maximum value of power obtained in a specific direction is around 15 mW. The signal-to-noise ratio (SNR) defines the rate at which the transmission takes place, as the value of SNR depends on the power splitting ratio to achieve maximum results when the time and transmission rate utilize the condition of an equilibrium situation. In terms of energy transfer, RF-DC conversion is processed for charging the storage devices of the sensors. Also, appropriate impedance matching reduces system-power-conversion loss.
Index Terms: *Energy harvesting; time division multiplexing; beamforming; signal-to-noise ratio*

Date of Submission: 08-12-2023 Date of acceptance: 18-12-2023

I. INTRODUCTION

ENERGY harvesting (EH) has become a revolutionary technology for energy-constrained networks such as sensors, ad-hoc networks, etc. because of its outstanding capability of providing endless power supply. A vast number of sensors deployed today and in the near future will be a major part of our everyday life. A major concern for this huge number of sensors is their energy requirements and resource allocation [1] of different energy sources. To meet the energy requirements of wireless sensor nodes (WSNs), EH appears as one of the most promising technologies [2-4]. WSNs can collect energy and transmit information to locations, which are difficult to access, via wireless communication channels [5-7]. Therefore, innovative solutions could be produced by researching both EH and wireless power transfer (WPT) concerning sensor nodes communication [8-9]. A large amount of power can be transferred by magnetic resonance coupling [10] and inductive resonance coupling [11]. However, in both these methods, the range covered may be low. Power transfer using radio frequency (RF) could solve this problem [12]. Short-range wireless communications, such as Bluetooth low energy (BLE) or IEEE 802.15.4, and long-range low power wide area network communications are very popular technologies, which operate in specific frequency bands [13]. Some low-power stations transmit radio signals in the 5.86GHz frequency band (mainly used by Wi-Fi stations) to control the interference [14] between power and communication signals. In this case, the W^2 P-MAC protocol [15] has been proposed. The RF-based EH the scheme is mainly used in low-power sensor node devices in different applications, such as medical, military, environmental, homeland defence, transportation, crisis management, and also in smart homes. Cognitive radio-based sensor nodes (including EH) can achieve the simultaneous supply of energy and spectrum resources to cope with the shortcomings of conventional sensor nodes [16].

In low-power devices, smart sensors [17] need the energy to monitor the system's data, make them live, and send them to the receiver. A lot of energy sources are available to provide sufficient energy to these sensors. Among them, RF-based EH is an optimum and efficient technique [18] because of its availability anywhere, anytime. In this paper, an energy-harvesting-based directional beamforming [19-20] mechanism is designed to ensure sufficient energy transfer in a particular direction. The most conspicuous issue in WSNs is to achieve less power consumption and also to provide sufficient energy supply for sensing and collecting data, thus avoiding battery replacement. A directional antenna, which rotates at a fixed time, enables specific sensors to receive sufficient energy for their operation and also to store some of this energy. The rest of the sensors is used to perform their data processing utilizing the stored energy. When there is no energy transfer, this time is characterized as a dead zone in the time-division multiplexing diagram, where some time is dedicated to EH and the rest for data transfer. The channel path loss depends on some factors such as antenna radiation, RF imperfections, channel path loss, and noise variation. Also, Additive White Gaussian Noise (AWGN) affects the behaviour of the channel to a great extent.

In this paper, our main goal is to achieve the maximum amount of energy transmission and reception efficiently. To this purpose, beamforming is operated through the antenna so that a minimum number of wireless sensors consume the harvested RF energy from the sink node. Briefly, the contributions of this paper are described below:

1) The sensor nodes require a low amount of energy and the harvested RF energy is also very low. Therefore, to ensure efficient energy management, we propose a beamforming technique. The beamforming is applied to the sink node to operate a minimum number of sensor nodes at the maximum power so that the maximum energy transfer can be achieved in a short time.
2) Since the sink node provides limited beamforming, the antenna position changes simultaneously with the change in states of the sensors. A mathematical framework is developed to simulate the sink-node operations when it receives data from the sensor nodes.
3) A power splitter is proposed to divide the energy and command signals so that the sensor nodes will get notified early. A relay is also proposed to assist the antenna for the prospective information transfer.
4) Mathematical models are presented to explain the energy-conversion stages such as beamforming, power splitter, and amplification, and also to describe the reduction in energy before being reserved in the storage device.
5) A TDMA method is proposed to process energy and information simultaneously on an efficient basis.

The rest of the paper is organized as follows; in Section II, recent research studies relevant to the proposed work are discussed; in Section III, an overview of the proposed system design approach is presented; in Section IV, simulation results are presented; finally, in Section V, the conclusions of this work are discussed.

II. RELATED WORKS

In [20], a study on EH from an ambient RF signal for different frequency bands is presented. But using different frequencies the complex antenna needed that consume more energy. Also, the transmission of both information and energy requires sharing the same spectrum. This mainly affects the communication channel and co-channel interference may be created during the simultaneous information and energy transmission. In [21-22], an overview and performance analysis of a communication network is presented. The energy transfer phase and information transfer phase satisfy the energy causality constraint as well as the time duration. However, the quality of service constraint has achieved maximum throughput by balancing the time duration between these two phases. The output voltage of the storage depends on the incident signal, power sensitivity, both are crucial factor. At the 2.4 GHz ISM frequency band, the challenge is to cover an area, in which the harvested energy is sufficient to operate the charging/discharging capacitance in a simultaneous manner [23]. In [24-25], an overview of combining energy and information transfer in different aspects and various ways is presented. Following literature clearly describe the simultaneous information and power transfer, but the received power and the transmission distance was quite low. This problem can be solved by reducing the interference and loss, also proper management of time in both phases. In the rectifier circuit, impedance matching is the most crucial factor to increase efficiency [26]. Regarding point-to-point communication system energy transfer two different approaches may be employed; one is the time splitting approach and the other is the power splitting approach to optimize the power allocation in the sensor nodes. This short-range communication system is very popular in medical and healthcare, military, sports, and fitness applications. In these fields, EH can improve network efficiency and lifetime, and reduce the maintenance cost of communication [27]. The energy balancing technique can be used in a network to maintain joint power and mobile data allocation during a battery's charging process to reduce battery depletion [28].

La Rosa R. et al. [29] described the combining effect of both EH and WPT in the case of battery charging with a low power of 2.5 μW using a mixed-signal system on chip. Actually, for a green system design, EH is the best solution to achieve cooperation between the sensor nodes and the sink node. This is very effective in small battery sensor nodes [30]. MIMO systems can operate with large amounts of power. Thus, multi-antenna techniques are required in the receiver to improve energy efficiency and achieve high quality of service (QoS) using the energy beamforming method [31]. In [32], a random unitary beamforming technique was proposed for the determination of the maximum number of active beams to satisfy of EH requirements of the sensor nodes. An auxiliary or even distinct power source can be employed to achieve continuous monitoring and control of the sensors. However, in some cases, due to size constraints or design restrictions, this option may not be applicable [33]. In [34], "state of the art" schemes were proposed, which achieve optimum time allocation. When the energy transfers and the Wi-Fi signal both operate in the same channel allocation, interference may be created, which can reduce the system performance and possibly cause collapse of the network [15].

In short-range low power communication [35], Wi-Fi and Bluetooth both are used to transmit simultaneous information and power in 2.45 GHz frequency band and sub-gigahertz WPT. In that case, the transmitted power to a long-distance is challenging because in every stage of power transfer different types of loss have included. In circumstances, the output power in the receiver was very low due to increase in distance and transmission using a large array of antenna also needed high energy consumption. So proper power management is needed to reduce the loss and decreasing the interference may provide high power reception in the sensors node. In [36], an adaptive power management circuit is introduced, which capable of maximizing the delivery of the harvested energy. The circuit comprises an analog control to transfer power from the energy harvester to the storage capacitor as well as for controlling the energy flow from the capacitor to the load. In particular, the transceiver design is required for large antenna arrays in conventional digital beamforming schemes which may not be applicable because separate RF chains for each antenna element are required. This problem was solved by using hybrid beamforming techniques [37]. Further in multimode operation transceiver design has the complexity of power consumption in the transmitter on that case passive RF identification provides the solution for data transmission. The purpose of the receiver is to recover the data from the modulated RF signal using TDMA for the multiple node system [38]. Mobile off-loading computation during the energy transfer process can save energy and the channel state information aims at maximizing the probability of successful data computation [39]. In the dynamic power splitting mechanism [40], a relay node harvests the energy by forwarding the data in order to avoid energy depletion. To avoid low QoS, the harvested RF energy may originate from RF transmitter signals or interference signals as well as antenna noise. In most of the abovementioned literature, the harvested power and bit transmission is evaluated changing the communication distance. Here, efficient interference and energy management and information processing are very significant. Also, the performance of the network is constrained by the low efficiency and short range of transmission. Hence, our main goal is to solve the interference problem without much variation in power and efficient data transmission with the increasing distance.

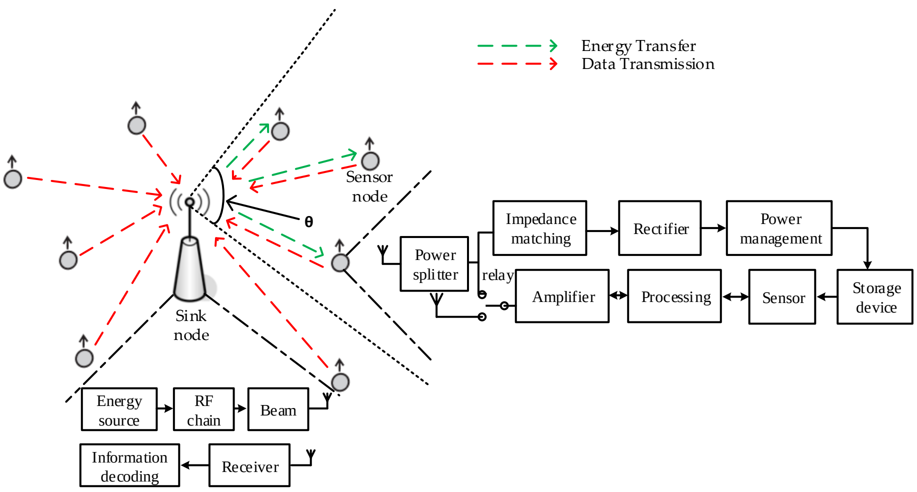

Fig. 1. Network model describing data transmission and energy transfer at a certain beamforming angle.

III. SYSTEM DESCRIPTION

The proposed system is composed of a sink node and several sensor nodes. The sensor nodes need energy for the purpose of data processing in every application. That energy is vital for the cooperation between the nodes so that information is transferred continuously. In the sensor nodes, the energy is stored in the storage devices and using that energy, sensor nodes send data to the sink node. Here, the storage devices operate both charging state and discharging state, due to temperature issue if it continuously charging and discharging at the same time then that causes the effect of battery performance. To overcome this a TDMA technique is proposed that will have described later. However, in the proposed system sink node is operated like a base station that is harvested the ambient RF energy and transmits through the antenna by using a beam. In the figure 1 we see that single sink node is operated to transfer energy using RF signal via antenna and number of sensor nodes surrounded it. Here, the energy source is taken energy from the ambient source, the amount of power is transmitted from the energy source is 1W after the conversion of the dBm unit, the signal integrated with RF signal send to the beam section. In that section, the signal is multiplied with the weights array, and in certain phase shift the RF signal pass through the power amplifier. Then the S-parameters antenna array combines the 16 arrays with the phase shift array. In this process, the input angle is taken 30° which is processed with the narrowband array in that section. The main signal process with a command and transmit in the wireless channel considering the AWGN in the channel. After receiving from the antenna, the power splitter divides the power signal and the command so that the command signal is amplified and directed to the sensor node for the processing to the next operation.

Then the impedance matching is processed in order to reduce loss, without proper matching a huge amount of energy can be lost. Then, the signal is rectified and transfer to the storage device for charging. Finally, the relay is switched and sends the information to the sink node via the antenna. The information is retrieved after further decoding in the sink node. This process is operated at 2.4 GHz ISM frequency band which is commonly used for Wi-Fi applications. The above network model represents the whole system structure for different time slots at a certain angle θ, which represents the normalized beam direction. The system employs a TDMA operation, where the time is divided into several time slots. Initially, in the downlink case, a sensor node consumes energy during the time t_{h0}. In the uplink case, it transmits information during the time $t_{hi}; i \in \{1,...,N\}$ at a certain beam angle. The sensor nodes, which are not in the operation of beamforming at time t_{h0}, are regarded as the dead mode. In the dead mode, energy is not being able to transfer but the information has been transferred.

Beamforming is a compensating technique for energy reduction in the process of RF signals propagation. Now the sink node assumed to serve the sensors in energy beamforming schemes at a normalized angle in a certain direction. Here, the beam p is expressed as

$$p = b(\theta), \qquad (1)$$

where the antenna array represents a uniform linear array of vector including k number of antennas,whereas the operating frequency must be greater than the total bandwidth of the system to make equal the signal wavelength in every subcarrier which is represented as

$$b(\theta) = \frac{1}{\sqrt{k}}\left[1, \exp(-i\pi\theta), ..., \exp(-i\pi(k-1)\theta)\right]^{tr}. \qquad (2)$$

In antenna design, the normalized angle θ is connected to the physical angle of departure $\Phi \in [-\pi/2, \pi/2]$ as $\theta = \frac{2d\sin(\Phi)}{\lambda}$, where λ and d are the wavelength and distance, respectively. The time allocated to transmit information is expressed as $t_{hi} \le T - t_{h0}$ where the total time of one cycle is defined as T. Now, the sink node transmits and receives signals to n^{th} sensor nodes via the number of antennas. The process of energy beamforming is mainly used to increase the efficiency η of energy transfer. Thus, we write the received power signal as

$$P_r = \eta P_t, \qquad (3)$$

where the transmit power P_t of the RF signal is attenuated by the wireless channel. Thus, we represent the harvested energy of the n^{th} sensor node as

$$E_n^H = \eta\beta_i P_t h_{in} l_n^{-m} t_{h0} + \sigma_k^2, \qquad (4)$$

where β_i denotes the power splitting ratio and h_{in} denotes the channel gain of the energy transfer situation of distance $l_n^{-m}; m \in \{1,...,N\}$. As the efficiency denoted $0 < \eta < 1$ remains constant, the sensor nodes convert the harvested energy to a storage device and transmit information to the sink node. The noise vector σ_k^2 is very small compared to the harvested energy and can be neglected. Therefore, the harvested energy is expressed as

$$E_n^H = \eta\beta_i P_t h_{in} l_n^{-m} t_{h0}. \qquad (5)$$

In the information transmission mode, the n^{th} sensors transfer their data to the sink node. Let's define W as the bandwidth of the system. The rate at which information is transmitted by the nodes are

$$R_n = \frac{t_{hi}}{T} W \log_2 \frac{P_n g_{in} l_n^{-m}(1-\beta_i)}{t_{hi}\sigma_a^2}, \qquad (6)$$

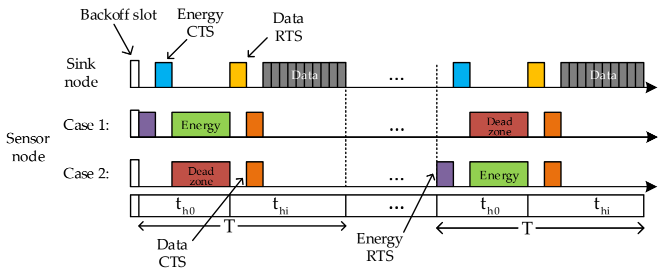

Fig. 2. Proposed TDMA protocol introducing the dead zone.

where σ_a^2 is the noise variance and g_{in} is the channel gain in the information transfer mode. An amplification coefficient α is used to describe the energy consumption which is represented as

$$\alpha = \frac{\eta\beta_i P_t h_{in}}{(1-\beta_i)P_n g_{in} + \sigma_a^2}. \quad (7)$$

It is worth noting that no energy has been transmitted to the dead zone and the harvested power, P_n is related to the information rate. In this case, the remained stored energy is utilized for the information processing in that zone. EH depends on the condition of the sensor nodes' storage device. Now, let us consider that the sensor nodes consume energy to maintain their operation. Furthermore, the consumed energy is used for information processing and data transmission and cannot exceed the harvested energy. In the case of EH, the dead zone is defined as

$$E_{ni}^H = \begin{cases} E_n^H, & \text{for fixed } p \\ 0, & \text{out of range } p \end{cases}. \quad (8)$$

Mainly, the harvested energy depends on the normalized angle, which is not fixed. This angle has been changed at a certain period of operation, at which the level of charging in the sensor's storage device goes below to the defined threshold. The whole process continues until the harvested energy becomes unable to fulfill the energy needs of the sensor nodes. As it is seen from the Figure 2 that the total time T is divided into two parts; one part corresponds to the energy transfer and the other corresponds to data transfer in the TDMA scheme. The n^{th}sensor in the network operates in two cases when it is in the range of the nominal direction angle; case 1 corresponds to energy transfer and case 2 corresponds to the sensor discharging mode. This process continues as long as the energy level of the device remain below the threshold. When the antenna is directed at the corresponding angle, the energy request-to-send (RTS) is dispatched from the sink node to enforce it to send energy. Therefore, the relay processes the signal and forward the energy clear-to-send (CTS) to the sink. In terms of data transmission, a specific time t_{hi} is referred to as data-transmission period for every sensor node. In this time, the sensor node transmits a data RTS, and sends the data after the operation of data CTS signal.

In the proposed model, simultaneous information and energy transfer via the wireless channel in WSNs is considered. In those sensor nodes, where the amount of harvested energy is not adequate for the proper operation of their low-power consumption devices, the beamforming technique is introduced to maximize the energy transfer at a particular angle. In this paper, two design models are proposed; one for data communication and the other for energy transfer.

Communication *Model*

In the communication model, the data are transmitted through the free space channel, where the channel gain is obtained by feedback from the sink node. Also, the information signal is corrupted by the AWGN, since the sink node operates at the same frequency as the sensor nodes, and therefore channel interference is aggregated. The channel capacity C and the data transmission rate are both utilized according to the Shannon's formula as follows

$$C = W\log_2(1 + P_n g_{in} l_n^{-m}\kappa), \quad (9)$$

where the constant $\kappa = \|h_{in}\|^2 / \sigma_a^2$ depends on the channel gain and noise vector. From Eq. (9) the capacity between sensor nodes and the sink node is calculated by taking different input power and bandwidth to find the optimum values. In this model, different types of sensors are used to monitor the surrounding conditions and ensure channel capacity and communication between the nodes. However, as the same frequency is used for signal transmission, interference may occur. Therefore, a TDMA scheme is introduced to avoid interference. The time t_{hi} is used for information processing as the data are transferred from the sensor nodes to the sink node. In that case, the relay is operated for the information processing and is connected to the antenna when it receives the data RTS that is mainly dispatched to the sink node. However, in the data communication perspective, the data and the message signal are generated using beaker code and matrix concentration, respectively. Then the signal is encoded, modulated, and transmitted through the AWGN channel. However, in the receiver section, the signal is synchronized using carrier synchronization. After detecting the signal using preamble detector, the final decoding process is performed.

A. Energy Harvesting Model

The sink node mainly transmits the harvested energy to the sensor nodes. Upon receiving this energy, the sensor nodes send their information to the sink node. According to the energy-conversion rule, the harvested energy must not be greater than the energy received by a sensor node. U_{Ri} denotes the received energy by the sensor node. Therefore, we can express the rule in mathematically as

$$E_n^H \geq U_{Ri}. \qquad (10)$$

In the power splitter section, the signal is divided into two parts where the signal-to-noise ratio (SNR) signifies that the received signal quality. As the information and power transfer is obtained in different time domains to continue this process. The power splitting ratio is denoted as β_i. The amount of energy is limited, therefore, minimizing the beam to a certain angle increase the SNR value. At the range of p certain time due to t_{h0} the sink node harvest energy E_n^H and the energy received by the sensor node is dependent on the SNR in harvesting energy.

$$SNR_{EH} = \min_{p} \eta P_t h_{in} l_n^{-m} t_{h0} \beta_i. \qquad (11)$$

Now, the energy conversion efficiency δ utilizes the energy signal that is used for the information processing and transferring purpose in the power splitter section. Due to the information transfer, the SNR is updated as follows

$$SNR_{IT} = \sum \delta P_n g_{in} l_n^{-m} t_{hi} h_{in} (1-\beta_i). \qquad (12)$$

When a sensor node receives energy, it can transmit both information and energy simultaneously. Therefore, the transmission rate, which depends on the end-to-end rate, would be

$$R_n \leq \frac{W}{T}\left\{ t_{h0}\log_2(1+SNR_{EH}), t_{hi}\log_2(1+SNR_{IT}) \right\}. \quad (13)$$

Due to the optimal condition, the SNR must be equal in both cases. To satisfy this condition the effective SNR must be determined and minimized. Combining Eq. (11) and Eq. (12) the effective SNR (SNR_E) can be written as,

$$\min_{p} \eta P_t h_{in} l_n^{-m} t_{h0} \beta_i = \sum \delta P_n g_{in} l_n^{-m} t_{hi} h_{in} (1-\beta_i) = SNR_E, \quad (14)$$

where the SNR_E remains constant. Solving Eq. (14) it is obtained,

$$SNR_E = \min_{p} \left\{ \frac{\sum \delta P_n g_{in} l_n^{-m} t_{hi} h_{in}}{1 + \frac{\sum \delta P_n g_{in} t_{hi}}{\eta P_t t_{h0}}} \right\}. \qquad (15)$$

Finally, the power splitting ratio in the i^{th} sensor node is obtained by considering Eq. (11) and using the value of SNR_E,

$$\beta_i = \frac{SNR_E}{\eta P_t h_{in} l_n^{-m} t_{h0}} = \frac{\min_{p} \left\{ \frac{\sum \delta P_n g_{in} l_n^{-m} t_{hi} h_{in}}{1 + \frac{\sum \delta P_n g_{in} t_{hi}}{\eta P_t t_{h0}}} \right\}}{\eta P_t h_{in} l_n^{-m} t_{h0}}. \, (16)$$

To obtain a case where $t_{h0} = t_{hi}$ and the received energy isused to transmit information $(P_r = \eta P_t \;\&\; P_r = P_n)$, as the harvested power to the sensor node must be equal to the received power. So, β_i can be expressed as

$$\beta_i = \min_{p} \left\{ \frac{\sum \delta g_{in}}{1 + \sum \delta g_{in}} \right\}. \qquad (17)$$

Solving Eq. (17) and Eq. (7) we found a relation between harvested power in the receiver and amplification coefficient which show the independence of power splitting ratio as

$$\alpha = \min_{p} \left\{ \frac{\left(\sum \delta g_{in}\right) P_n h_{in}}{P_n g_{in} + \sigma_a^2 \left(1 + \sum \delta g_{in}\right)} \right\}.$$

(18)

The above equation signifies that the power splitting factor only depends on the energy conversion efficiency, whereas the channel gain (apart from the amplification coefficient) does not depend on the splitting ratio. So from those equations, we saw that power spitting ratio does not depend on the channel gain of the energy harvesting section as a result the effective SNR value increases and show better performance. Again as much as the signal is amplified the power consumed to the sensor node's storage devices is more. In every time when the transmitter transfer energy to the receiver it produces a beam which is fixed at an angle. However, the angle increase that covers more sensors but divided its energy in many sensor nodes which cause to decrease the energy per sensor nodes. On the other hand, the energy conversion ratio depends on both splitter and amplifying purpose, if we control its value then the satisfying energy would be found in the receiver side as a result SNR rise up. Those mathematical equation signifies the operation of the different stages which is the reason for signal better performance and based on those equations the simulation model is designed.

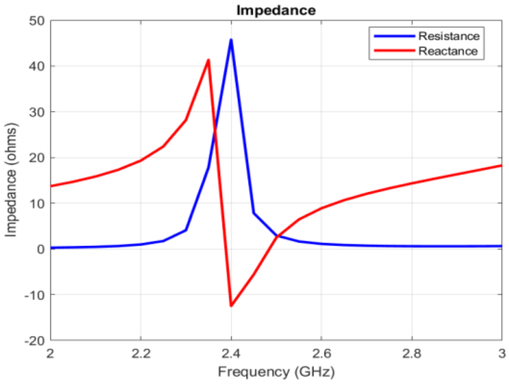

Fig. 3. Impedance of the antenna in RF-EH circuit.

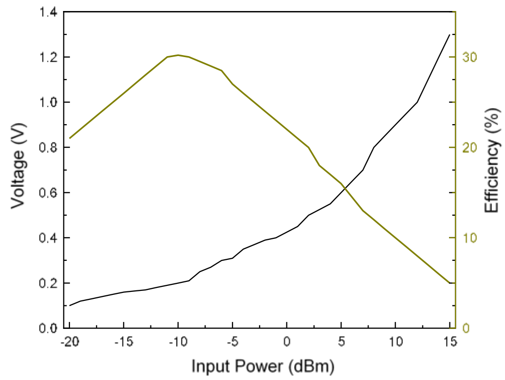

Fig. 4. Variation of input power including relative effect of efficiency and voltage.

IV. Simulation Results and Discussions

The results are divided into two parts such as energy harvesting and data communication. Both are connected to satisfying the energy sufficiency in the sensor nodes and information processing in a proper way. In the system, the signal generator generates a signal that contains the power of 1 W and converted into a dBm unit from the corresponding power. Afterward, the signal is processed in the RF chain with the command signal. Therefore, in the beamforming section, it is further driven at the normalized angle in a certain direction through the antenna. Then, the energy, combined with the command signal propagates in the wireless channel. By this time, several factors attenuate this signal. From Eq. (4), we saw that as the distance between a sensor node and the sink node increases, the transmitted harvested energy decreases. Thus, a planar inverted F-antenna should be used to focus the energy in a certain direction mainly in the 2.4 GHz Wi-Fi frequency band.

Table 1. Simulation Parameters.

Parameter	Value
Number of antenna array	16
Carrier frequency	2.4 GHz
Transmitted power from the sink	1 W
Bandwidth	8MHz
Information phase time	0.6 ms
Energy phase time	0.4 ms
Normalized angle	30°
Distance	20 m

The key parameter is the antenna gain that characterizes the antenna's capability and compensates for channel attenuation. When the receiver node receives the RF signal, it is converted into a DC signal, which is further directed to the storage device. In the receiver module, impedance matching is very significant due to the mismatch between the antenna and the rectifier seriously affects the RF-DC conversion efficiency. So an impedance matching circuit is designed with the characterized impedance of 50 ohms. Then the receiver captures the narrowband array and removes the noise after 4 dB noise figure and reshape the signal before the rectification. After rectifying the DC signal it properly converted for the battery after the DC-DC conversion. The simulation parameters are shown in Table 1.

B. Result Related to Energy Harvesting

In the receiver, the power splitter separates the power signal this cause the loss of energy. Further processing to the power signal is trying to match with the base impedance which is measured 50 ohms. Where the matching circuit is a combination of inductance and capacitance to form a filter. The resistance and reactance in the 2.4 GHz frequency band are shown in Figure 3 which shown the proper impedance matching in that frequency range. The signal's S-parameters obtained from the simulations were used for the evaluation of the impedance matching condition. In the simulation, a goal was set

for the parameter S_{11} (return loss) to remain below −35 dB for an incident power of about −15 dBm. Alternatively, when the antenna transmits the signal then the energy −15 to −10 dBm is obtained from the receiver antenna for this purpose then the rectifier converts the RF-DC conversion in the following stage we found the energy conversion efficiency around 50%. This stage the capacitor connected with the output resistance used to sharpen the DC signal. Then the signal is converted using boost converter for storage purposes in the batteries.

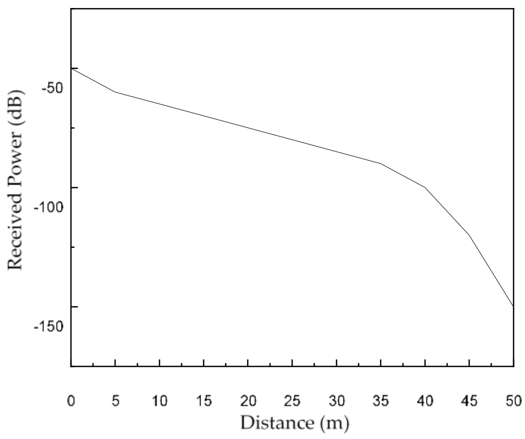

Fig. 7. Relationship between distance and system received power.

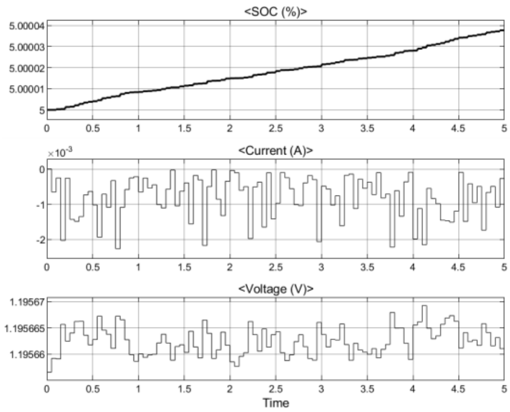

Fig. 6. The voltage, current, and the state of charge response of the battery with the variation of time.

At first when we gradually increasing the input power that is measured in dBm, then the voltage of the storage device changes due to the system loss after processing in different stages of operation. In the EH case, simulation results found after different stages of operation are presented to obtain the system's overall efficiency. If the input power is increased to a certain point, overall efficiency which has defined as η, is achieved, and its corresponding voltage increases as expected. The less amount of energy transmits from the source the lower amount of energy gets stored to the storage devices. From the given voltage level, we understand that the amount change in input power would harvest the energy of those sensors whose has voltage level is fixed on that value. If the input power of the system is increased, it is seen from Figure 4 that the efficiency rises up when the input power is around −10 dBm, and then it starts to fall due to path loss and signal noise. However, by increasing the input power, the voltage of the sensor is also increased. The input power of 5 dBm was determined as the optimum value for both cases.

Therefore, in the case of sensors' energy management, the change in transmit power is shown in Figure 5. It is observed that by increasing the number of sensors the energy harvested for an individual sensor is decreased. That means if we keep the transmit energy constant and change the angle then the number of sensors observed the energy rise up. But due to an increase of angle the strength of the signal which carries current decreases its value as a result low amount of energy consumed by one sensor. So we take the angle quite fixed and vary the angle in between 20° to 30° so that antenna rotates its position and every time new sensors would get the energy. During performing the simulation, the 2.4 GHz signal is sent from the transmitter. In the sensor model simulation is made by 12 number of sensors which make the model in an individual state of charge in different values. In the case of a particular direction of beamforming, we have taken three sensor nodes that are placed in the right angle of energy reception. Therefore, proper power management of the rectified DC signal is performed to charge the batteries where the voltage of a sensor node is 1.2 V. We have observed the incoming current when the distance between the sink node and sensor is 20 m. After several stages of calculation, we have found the average output power as 15 mW. Figure 6 provides the battery response of one sensor where we saw that the current, voltage, and state of charge response are given. So the sensor is operated at charging condition when the case 1 in the time diagram process.

Result Related to Data Communication

Data-communication the process depends on the priority of receiving specific information that is gathered from the surrounding and then sent to the sink node. For this, we use a random binary code integrated with massage and provide matrix concentration after multiplication. However, to send the information relay is switched to connect with the antenna array.when the data RTS is commanded. The data follow the path to the sink node before being decoded.This binary signal is received by a 16-element antenna for decoding, including the effect of antenna radiation, RF imperfections, channel path loss, and noise variation. The simulation for data transfer depend on the channel gain which is equal to the energy harvested path channel gain because both are on the same path to travel. Depending on the frequency and distance we see from Figure 7 that as the distance increases, the power received by the sensors is significantly affected the Wi-Fi maximum range is around 50 m.

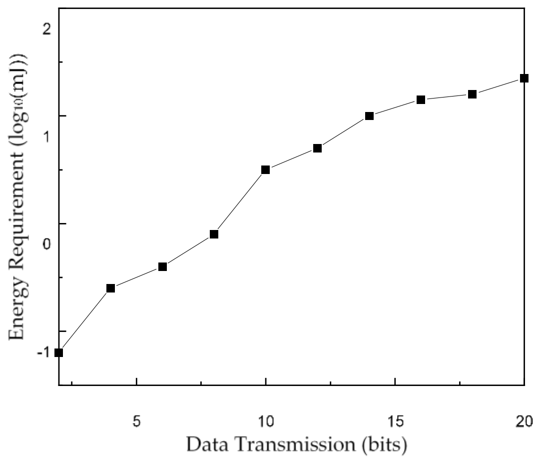

Fig. 8. Energy requirement of sensor node during data transmission with increasing number of bits.

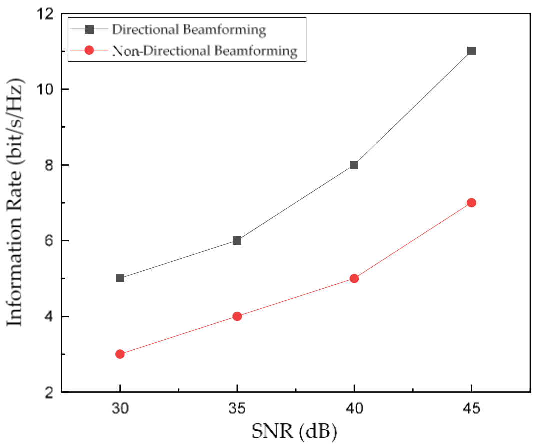

Fig. 9. SNR vs rate at different case of beamforming.

We see from the Eq. (5) that as long as the distance increase the consumption energy falls down as well. So from the simulation model, we transmit different types of messages and calculate the error. Therefore, continuous data monitor from the sink node when the distance has 20 m and very low error found. After the distance increases, the number of decoded error bits also increments.Therefore, in the data-communication case, if we increase the number of bits to transmit from the sensor nodes, more energy is required. For the ideal case, we take the distance of one sensor node to the sink node as 20 m and found the result that is shown in Figure 8.

The increase in energy requirement with the increasing number of bits is also shown in Figure 8.

Therefore, the harvested energy received by the sensors is quite low. As a result, to keep the sensor battery voltage constant the signal incident to the receiver as a property of the current. In the proposed model, from the results in Figure 9, it is observed that the rate of information transfer and harvested energy is higher in a particular direction than in the non-directional case. Thus, by increasing the SNR the strength of the signal increases, and the rate is also increased by 45 dB approximately compared to the non-directional case. According to the transmission rate Eq. (15), which utilizes both the EH case and the data transfer case, the SNR remains the same for both cases. Thus, the rate varies for different time conditions as obtained from the simulation for 0.4s and 0.6s. If we keep the time same from the simulation at 0.5s in both case, then the information transfer is not properly allocating all the sensor as total sensors are in operation at that time.

Comparison with Other Approaches

Both the energy and data communication is performed in either out of band or in-band in existing works. Interference cancellation and decreasing loss are the main issues, where the interference in previous work authors had used different frequency bands. However, several authors proposed different techniques to overcome this problem, but our proposed scheme is using the same frequencies operated at different time to eliminate the problem. Among other techniques, co-located half-duplex and full duplex with 80 dB SIC shown the most significant performance [21]. As shown in Figure 10, it can be seen that our results are superior than those models in terms of increasing distance. However, the full duplex, co-located, 80dB SIC model achieves better performance when the distance is less that 4m approx. It is also seen that the mathematical and the simulation results do not coincide well up to a distance of 5m, however, they are identical with excellent precision when the distance is more than or equal 5m.The simulation results are performed to a single sensor node when the angle is 30˚ and assuming the channel gain of 50 dB.

In particular, the key point is to apply proper time allocation between the two operating modes and to perform effective-energy-transmission strategies to minimize the energy drawn from the power source while satisfying the communication performance. According to the power splitting ratio Eq. (16) in the time domain, this ratio depends on the energy that is properly utilized to keep the channel gain constant as well as the distance between the sink node and the sensor nodes to about 20 m. In Figure 11 the ideal value for the maximum energy are shown. This value is obtained for a time of 0.4s and SNR=30dB. This means that at a low signal level the average value of the power is around 15 mW. The cases presented in the Figure 11 show different values for the power splitting ratio as the distance increases and the energy decreases. Even if the SNR is increased, the energy decreases. Therefore, by decreasing β_i, more harvested energy is transmitted, whereas the rest of the time is used for information processing and transmission. Also, the increasing channel gain causes the loss of the signal that results in the reduction of the energy value.

From Eq. (18) it is observed that the amplification factor used to increase the signal strength. By increasing the value of the amplification factor, the power is also increased, as the energy conversion efficiency remains unchanged and not significantly affected by the incident power. The average output power depends on the amplification coefficient and energy conversion efficiency as the Figure 12 indicates that power is increasing as much as the receiver incident the power and we found the average received power of the sensor is 9 mW when the distance of the sensor is kept constant. The variation shows the dependence on the energy conversion efficiency and amplification factor both increase found the efficient results as energy.

We discussed earlier, after observing the EH performance against the SNR, it is concluded that the communication requirements can be fulfilled by augmenting the harvested power. Also, from the mathematical analysis, we have observed that the power splitting ratio signifies the performance of the transmission process. We also conclude that the variation in distance has a great impact on information decoding than the EH process. In addition, in comparison with the half-duplex and full-duplex model, our proposed model shows better performance. The energy and data transfer are optimized at a distance of 20 m and the minimum harvested energy is observed at a distance of around 50 m.

V. CONCLUSION

In this paper, a new method of performing joint transmission of data and energy via wireless channel was proposed. A power splitter and relay were proposed to ensure proper management of power and command signals that were directed to the storage devices of different sensor nodes. When the relay received the data request-to-send command, its connection was switched from the sensor node to the sink node for information transmission. We used the carrier frequency of 2.4 GHz in the energy transfer and data processing using a 16-array antenna for the transmission of around 1 W power. Afterward, mathematical models are developed to explain the power processing in different stages of energy conversion and its reduction before being reserved in the storage device. Simulations were performed to verify the proposed model. It was found that the average value of the power of a single sensor node was found as 15 mW at a distance of 20m without any bit loss. However, with increasing distance, the bit loss was increased and the average received power was increased.

The proposed model was developed using a TDMA-based scheme and a directional beamforming technique to satisfy the energy requirements of the sensor nodes and to optimize the energy transfer. By dividing the energy time period into two cases, we successfully reduced the interference as well as we found better throughput with increasing distance compared with half-duplex, co-located and full-duplex, co-located, 80 dB SIC models.

ACKNOWLEDGMENT

This research was supported by the MSIT (Ministry of Science and ICT), Korea, under the ITRC (Information Technology Research Center) support program (IITP-2018-001396) supervised by the IITP (Institute for Information & communications Technology Promotion).

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