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Research Article

REACH: An Efficient MAC Protocol for RF Energy Harvesting in Wireless Sensor Network

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This paper proposes a MAC protocol for Radio Frequency (RF) energy harvesting in Wireless Sensor Networks (WSN). In the conventional RF energy harvesting methods, an Energy Transmitter (ET) operates in a passive manner. An ET transmits RF energy signals only when a sensor with depleted energy sends a Request-for-Energy (RFE) message. Unlike the conventional methods, an ET in the proposed scheme can actively send RF energy signals without RFE messages. An ET determines the active energy signal transmission according to the consequence of the passive energy harvesting procedures. To transmit RF energy signals without request from sensors, the ET participates in a contention-based channel access procedure. Once the ET successfully acquires the channel, it sends RF energy signals on the acquired channel during Short Charging Time (SCT). The proposed scheme determines the length of SCT to minimize the interruption of data communication. We compare the performance of the proposed protocol with RF-MAC protocol by simulation. The simulation results show that the proposed protocol can increase the energy harvesting rate by 150% with 8% loss of network throughput compared to RF-MAC. In addition, the proposed protocol can increase the lifetime of WSN because of the active energy signal transmission method.

1. Introduction

A Wireless Sensor Network (WSN) is a motive power for implementing Internet of Things (IoT) technologies and is used in many systems [1]. As a representative example, a system has been developed that periodically monitors and manages information about a target environment (e.g., temperature, humidity, and illumination) around the sensor [2–4]. There is a critical problem that the lifetime of the WSN is limited because of limited sensor batteries [5]. Also, it cannot be assumed that all sensors are easily physically accessible. As a result, researches have been conducted to increase the energy efficiency of sensor components in order to increase the limited lifetime of the WSN [6, 7]. Previous works showed that the power consumption of sensors can be reduced. However, they do not consider charging the battery, so the battery will be discharged inevitably. A sensor should be able to charge itself using a specific energy source. Radio Frequency (RF) energy harvesting has been proposed [8, 9] as a new energy source of sensors. It supplies stable power to peripheral sensors through Energy Transmitters (ETs) without being affected by the physical environment [10]. With these advantages, a lot of related works have been proposed [11] for determining the routing path [12], data aggregation method [13], improving the energy conversion efficiency [14], and duty-cycle control method [15]. But still, there has not been enough research on the new MAC protocol considering RF energy harvesting. Current researches of the MAC protocol are only related to energy harvesting time. In [16], a method is proposed to adjust the charging time of the sensor. The charging time is changed adaptively according to the data traffic pattern. In [17], a method is proposed to enable for a long time charging of sensors actively involved in data communication. The charging time is determined by an Important Index (IDX) of the sensor that requests energy. Both protocols use methods to allocate the time and channel for charging or requesting energy. They inevitably delay data communication. It is difficult to guarantee real-time communication in WSN when using the existing MAC protocol. To overcome this problem, we propose a method called RF Energy Autocharging and Harvesting (REACH). When there are no packets to be transmitted in the channel, an idle time continues. In REACH, ETs automatically transmit energy to charge the sensors during the idle time. This allows sensors to maintain long data communication times. The contributions of this paper are as follows:

(i) We propose REACH to charge automatically when idle time continues on the channel.

(ii) An improved MAC protocol considering RF energy harvesting is proposed to prevent real-time communications from being disrupted by charging.

(iii) We design REACH that shows 150% performance improvement in harvested energy with backward compatibility.

The rest of this paper is organized as follows. Section 2 introduces the existing MAC protocol considering RF energy harvesting. We explain the proposed REACH algorithm in Section 3. The simulation environment is described in Section 4. The results of performance analysis are presented in Section 5. Finally, conclusion is presented in Section 6.

2. Related Work

There are two representative MAC protocols considering RF energy harvesting: RF-AASP (RF-based energy harvesting technique and the Adaptive, Active Sleeping Period) and RF-MAC (Radio Frequency-Medium Access Control). The RF-AASP determines charging time depending on data traffic and RF-MAC determines it depending on how much the sensor has participated in data communication. However, they still have a problem that charging delays data communication. We describe the RF-AASP and RF-MAC in this section.

2.1. RF-AASP. In [15], an algorithm is proposed that adaptively changes the sleeping period of a sensor. The period changes depending on the traffic pattern and residual energy of sensors. A sensor with low energy checks traffic pattern and satisfaction of Quality of Service (QoS). Based on the result, the sensor adjusts variables like BO (Beacon Order) and SO (Superframe Order). The two adjusted variables determine sleeping period by the equation $t_{\text{sleep}} = 2^{\text{BO}} - 2^{\text{SO}}$. The sensor performs energy harvesting during the sleeping period to charge energy. When the traffic load is large, the RF-AASP may not guarantee a sufficient sleeping period for charging. In other words, the sensor may fail to charge sufficient energy and continues to request energy.

2.2. RF-MAC. In [16], an algorithm is proposed with a new procedure of energy harvesting. Energy harvesting occurs with the Request-for-Energy (RFE) packet. A sensor with low energy broadcasts the RFE packet. Peripheral ETs respond with Cleared-for-Energy (CFE) packets. When the sensor broadcasts the ACK, the ETs emit energy. In this case, the charging time of the sensor depends on the value of the Important Index (IDX). The IDX indicates how much the sensor has participated in data communication in the channel. This algorithm guarantees continuous data communication when there is no energy request. However, when the energy request occurs frequently, starvation can occur. A sensor to send data falls into starvation because of the higher priority of energy request.

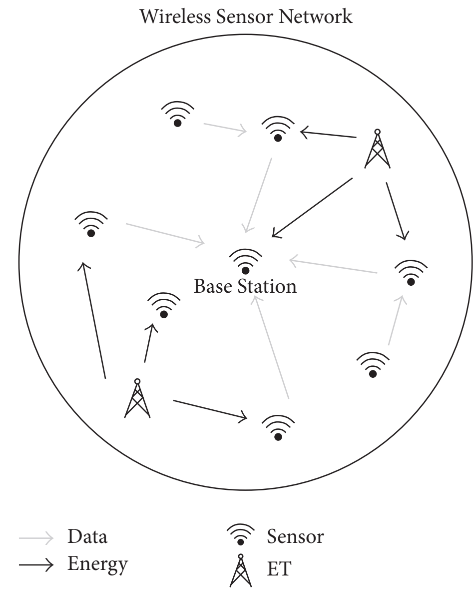

Figure 1: Target WSN.

3. The Proposed REACH Protocol

3.1. Target System. Notations and descriptions used in this paper are shown in the "Notations and Descriptions" section. Figure 1 shows a target network. A WSN consists of a large number of sensors and ETs. ETs are hardware that transmit energy to sensors. Sensors are the subjects of data communication and contend with each other through the CSMA/CA method. All the data from the sensors are transmitted to the Base Station (BS). ETs and sensors share the same frequency band and they have omnidirectional antennas. Therefore, energy and data signals cannot be transmitted at the same time. An energy request has a higher priority than data communication to prevent sensor outage and increase stability of the WSN.

3.2. REACH Algorithm. REACH consists of three steps. Algorithm 1 describes a pseudocode of REACH. First, a sensor gives $\text{CW}_{\text{random}}$ and $\text{SCT}_{\text{origin}}$ (Short Charging Time) to ETs using the existing energy harvesting process. ETs set parameters required for the REACH process based on the received values. The ETs determine the backoff to participate in channel contention. REACH process has a lower priority than data communication because ETs have longer backoff. Finally, the ETs determine the next action depending on whether they acquired the channel. They transmit RF energy signals to nearby sensors for $\text{SCT}_{\text{origin}}$ when they acquire the channel. They adjust the parameters after transmission so that REACH can be performed while reducing the interruption to data communication. Figure 2 shows a flow diagram of REACH. Dashed-line boxes represent the newly proposed process in REACH. Solid-line boxes represent the existing RF-MAC process.

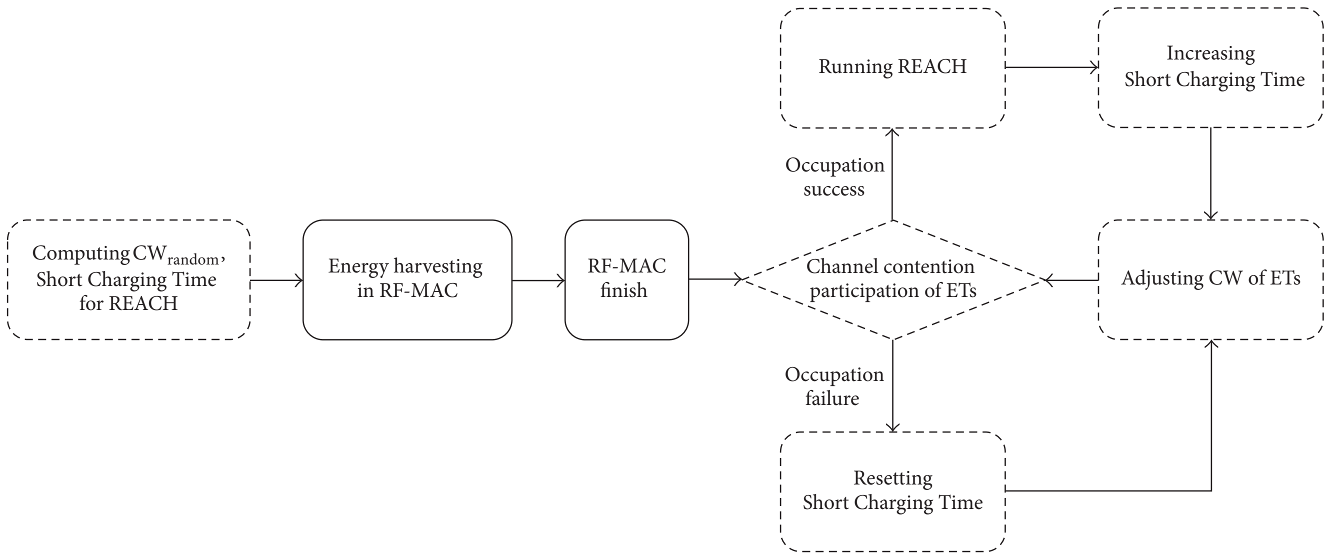

Figure 2: Flow diagram.

```
Step 1
Compute CW_random, SCT_origin
Transmit values to ETs
Save CW_random, SCT_origin with SCT_default, SCT_unit
While:
Step 2
    Determine backoff
Step 3
    Participate in channel contention
    If success to channel occupation then:
        Auto Charging as SCT_origin
        SCT_origin ⟵ SCT_origin + SCT_unit
        CW_random ⟵ CW_random + 1
    Else:
        SCT_origin ⟵ SCT_default
        CW_random ⟵ CW_random − 1
    End If
End While
```

Algorithm 1: REACH.

3.2.1. Step 1: Parameter Setting. This step uses a process in the existing charging when a sensor transmits optimization values to nearby ETs. The sensor calculates additional values to be used in the REACH process. Additional calculated values are CW_{random} and SCT_{origin}. These values are included in the ACK packet and transmitted to nearby ETs. CW_{random} is the number of contention windows used when ETs determine backoff to participate in channel contention. After the existing energy harvesting process, ETs must have the same backoff period as each other to set the same start timing of autocharging. CW_{random} cannot be the same without communication between ETs. For this reason, the sensor in this process determines the random value and transmits it to ETs. CW_{random} is randomly determined in the range of CW ($[CW_{min}, CW_{max}]$). CW_{min} and CW_{max} are the minimum and maximum number of contention windows, respectively. SCT_{origin} means the time that ETs automatically transmit energy to nearby sensors if ETs acquire the channel. Autocharging can interrupt data communications because of longer charging time if SCT_{origin} is too large. For this reason, SCT_{origin} should be determined to be of a reasonable length considering current channel conditions. SCT_{origin} expression is as follows:

$$SCT_{origin} = \frac{\sum t_{IDLE}}{\sum N_{data} + 1}. \quad (1)$$

($\sum N_{data} + 1$) represents the maximum number of times the channel was idle for a unit time. SCT_{origin} is calculated to the average of the idle times that existed between data communications. The initial value of SCT_{origin} becomes small since it is divided by the maximum number. SCT_{origin} does not significantly interrupt the data communication time. The sensor passes the random values to nearby ETs after the calculations are complete. The ETs store the values. Then, $SCT_{default}$ and SCT_{unit} are calculated and stored by the ETs. $SCT_{default}$ is the same as the initial SCT_{origin}. $SCT_{default}$ is used to initialize SCT_{origin} again when the channel cannot be acquired. SCT_{unit} is set to SCT_{origin}'s largest decimal unit. SCT_{unit} is used to increase SCT_{origin} after acquiring the channel. Once the transmission and storage process is complete, the ETs proceed with the existing RF-MAC charging process. The ETs proceed to the next step of the REACH process without deleting the received values after the charging process is finished.

3.2.2. Step 2: Backoff Decision. The ETs compute backoff to participate in channel contention after the charging process is finished. ETs must have the same backoff period to match the start timing of autocharging. This is because all ETs must transmit energy for charging at the same time to maximize the constructive interference. Besides, there is a disadvantage that the autocharging time is lengthened when ETs do not match the timing of transmitting energy. The following expression is proposed for synchronizing backoff of all ETs:

$$\text{Backoff} = \text{DIFS}_{AC} + \text{CW}_{random} \times \text{Slot}_{AC}. \tag{2}$$

In order to not have a serious impact on network throughput, the REACH process should have a lower priority than data communications. DIFS_{AC} and Slot_{AC} of backoff should be larger than the value of data communications. We set the two values to $\text{DIFS}_{AC} = \text{DIFS}_{data} + \text{DIFS}_{energy}$ and $\text{Slot}_{AC} = \text{Slot}_{data} + \text{Slot}_{energy}$. DIFS_{data} and DIFS_{energy} denote DIFS of data communications and energy requests, respectively. Slot_{data} and Slot_{energy} denote slot time of data communications and energy requests, respectively. All ETs have the same value of DIFS_{AC} and Slot_{AC} because these values are defined by the protocol. CW_{random} is broadcasted by the sensor that issued the RFE packet as mentioned in Section 3.2.1, so all ETs have the same CW_{random} value. As a result, all ETs have the same backoff period. ETs participate in channel contention like other sensors after backoff is calculated. SCT_{origin} and CW_{random} are then adjusted according to results of channel contention.

3.2.3. Step 3: Channel Contention. There are two cases of channel contention. The first case is a situation in which the channel is acquired by ETs. Autocharging is executed in this case. The other case is a situation in which the channel is not acquired by ETs. The stored values are reset and ETs rejoin the channel contention in this case.

If there is no data to send in the channel, ETs acquire the channel. The ETs will start autocharging for SCT_{origin} after waiting for backoff. ETs transmit energy at the frequencies used in the most recent existing charging process. Therefore, it can skip some processes like RFE-CFE exchange and frequency optimization. SCT_{origin} is increased by SCT_{unit} which was calculated beforehand after the autocharge is finished. ETs increase CW_{random} to make backoff for autocharging longer than data communication. ET's success in channel acquirement means that there was idle time for ETs to acquire the channel. It can be inferred that there is no data waiting for transmission on the current channel. There is also a high possibility that the channel will be idle in the future. Therefore, ETs increase SCT_{origin} to improve channel efficiency. SCT_{origin} becomes larger if the ETs frequently acquire the channel. If a particular sensor wants to send data while autocharging is executing, there will be a long delay. It is necessary to prevent the ET from frequently acquiring the channel. Therefore, ETs increase the number of contention windows to wait for a longer backoff time than before. CW_{random} is increased to not exceed CW_{max}. In summary, ETs increase the charging time to improve the efficiency when autocharging is executed. ETs also increase backoff at the same time to prevent the frequent autocharging occurrence.

If the channel is not acquired by ETs, the ETs adjust the values. SCT_{origin} is initialized to $\text{SCT}_{default}$ which was saved. CW_{random} is decreased. ETs again calculate backoff to try to acquire the channel. Failure to acquire the channel means that there is data to send in the channel and the REACH process is not available. In addition, it can be inferred

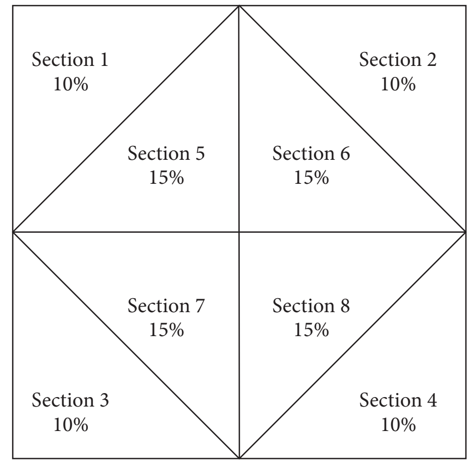

Figure 3: Sectioning of plane and distribution of nodes.

that there is a high probability that there will be data to be transmitted. It is needed as a way to minimize the effect on data communication even if the channel is acquired by ETs. ETs initialize the charging time to the smallest value to solve this problem. However, if the backoff has increased previously, it will take a long time to wait for a short period of autocharging. The efficiency is very low. CW_{random} is decreased to shorten the backoff of ETs. CW_{random} is decreased to not less than CW_{max}. In summary, ETs decrease the charging time to minimize effect on data communication. ETs also decrease the backoff to increase the efficiency of autocharging.

4. Simulation Environment

4.1. Node Setting. First, all nodes are randomly distributed evenly by dividing a $50 \times 50\,\text{m}^2$ grid plane into 8 zones. The reason for dividing the plane into 8 zones is to solve a problem of node gathering on one place in the plane. Figure 3 shows the specific zone on the plane and percentages of the number of nodes. A node is selected as a BS based on the location information of all sensors. The BS role will be taken by a node closest to the geographic center (25, 25). Data generated by sensor is transmitted to the BS node through the forwarding path. All sensors relay the data immediately without compressing or gathering the data. In this simulation, we assume that frame synchronization on all nodes is exactly the same.

Figure 4 shows how a sensor determines a sensor to forward data. Sensor A searches for sensors presented within 10 m from itself. Sensor A finds sensor B which is closest to the BS among the sensors existing within 10 m. And sensor A forwards the data to sensor B. The sensor selected as BS receives data but does not transmit data. We assume that there is one channel in the plane. Table 1 lists system parameters used by the simulator.

4.2. Numerical Modeling

4.2.1. Energy Consumption Model. We refer to sensor motes called Mica2 to set the energy consumption model of sensor

Table 1: System parameters.

Parameter	Symbol	Value
Slot time for energy (s)	$\text{Slot}_{\text{energy}}$	10μ
Slot time for data (s)	$\text{Slot}_{\text{data}}$	20μ
Minimum contention window	CW_{min}	32
Maximum contention window	CW_{max}	1024
SIFS for energy (s)	$\text{SIFS}_{\text{energy}}$	5μ
SIFS for data (s)	$\text{SIFS}_{\text{data}}$	10μ
DIFS for energy (s)	$\text{DIFS}_{\text{energy}}$	25μ
DIFS for data (s)	$\text{DIFS}_{\text{data}}$	50μ
Minimum voltage (v)	V_{min}	1.8
Maximum voltage (v)	V_{max}	3.0
Threshold for harvesting (v)	$V_{\text{threshold}}$	2.3
Channel speed (kbps)		250

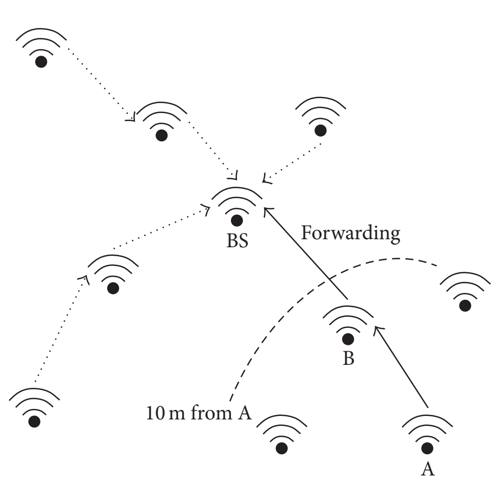

Figure 4: The forwarding node setup process.

Table 2: Currents at each state.

State	Symbol	Value (A)
Sleep	I_{sleep}	15μ
Waiting	I_{waiting}	8m
Transmit packet	I_{tx}	25m
Receive packet	I_{rx}	8m
Listening	I_{listen}	8m

used in simulation [18]. Table 2 shows currents at specific state of sensor. An I notation is the amount of consumed current in each state. In sleep mode, currents of 15 μA flow through a circuit. 8 mA currents flow in the circuit while a sensor listens to a channel. 25 mA currents flow while a sensor sends data and 8 mA currents flow while a sensor receives data. E_{consume} is the summation of the amount of consumed energy in each state (R represents the resistance of the circuit):

$$E_{\text{consume}} = E_{\text{sleep}} + E_{\text{tx}} + E_{\text{rx}} + E_{\text{listen}} = R \times \left\{ \left(I_{\text{sleep}} \times t_{\text{sleep}}\right) + \left(I_{\text{tx}} \times t_{\text{tx}}\right) + \left(I_{\text{rx}} \times t_{\text{rx}}\right) + \left(I_{\text{listen}} \times t_{\text{listen}}\right) \right\}. \quad (3)$$

4.2.2. Energy Harvesting Model. ETs transmit energy to nearby sensors at a power of 3 W. The propagation loss of energy sent from ETs is calculated by the Friis transmission equation [19]. Friis transmission equation shows a relationship between transmitting power (TP) and receiving power (RP). Suppose a transmitting ET is i and a receiving sensor is j. The Friis transmission equation between i and j is as follows:

$$\text{RP}_j = \text{TP}_i G_i G_j \left(\frac{\lambda}{4\pi d_{(i,j)}} \right)^2. \quad (4)$$

Since we assume the omnidirectional antenna, the two antenna gain values are always 1. A sensor can receive energy from multiple ETs located at various distances. In the RF-MAC charging process, ETs are separated into two groups according to the phase of wave. As a result, only constructive interference is caused by the energy waves at the sensor. An actual amount of harvested energy should add RP_j of the signal from each ET during a charging time t:

$$E_{\text{harvest}} = \sum_{i \in A_j} \int_0^t \text{TP}_i \left(\frac{\lambda}{4\pi d_{(i,j)}} \right)^2. \quad (5)$$

5. Performance Analysis

In this section, we compare the performances between RF-MAC and REACH. We built the simulation environment mentioned in Section 4 by using Java Language. Each experiment was performed 20 times and average values of the results were compared. In experiments of changing the number of sensors, the number of ETs is fixed at 100. Likewise, in experiments of changing the number of ETs, the number of sensors is fixed at 250. It is assumed that all data has a size of 50 bytes.

5.1. The Number of RFE Packet Generations. We compared the number of RFE generations by the number of sensors. Figure 5 shows the average number of RFE generations according to the number of sensors. Residual energy of the sensor drops below a threshold of energy harvesting; RFE generation is inevitable. When a RFE packet is generated, energy harvesting is performed. In this process, energy harvesting delays data communications because of higher priority. In the graph, REACH has substantially fewer RFE generations than the existing RF-MAC. Due to autocharging, the lifetime of sensors is increased and RFE generation is delayed. The number of RFE generations is reduced within the same time and delaying data communications will be reduced. However, when the number of sensors is large, the number of RFE generations becomes similar. This is because there are a lot of data communications in the channel. Autocharging cannot occur frequently because of lower priority than data communications. The amount of

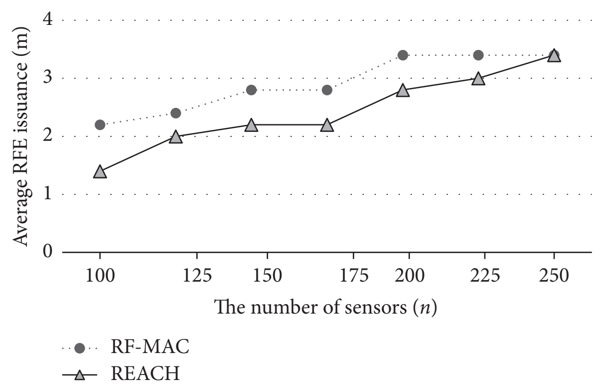

Figure 5: The number of generations of RFE packet.

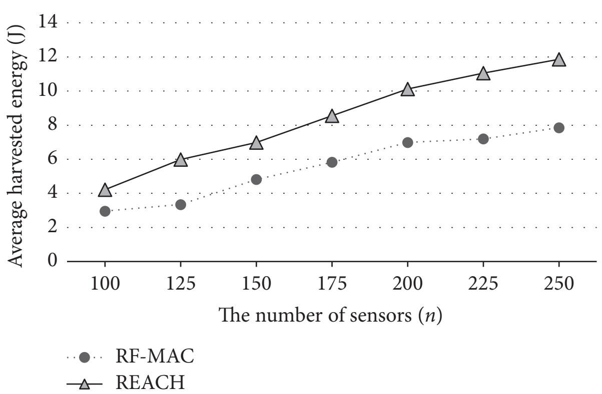

Figure 6: The amount of harvested energy by the number of sensors.

autocharging is reduced, and RFE is generated to charge sensors. As a result, the average number of RFE generations was reduced from 18% up to 36%.

5.2. The Amount of Harvested Energy. We compared the amount of harvested energy by the number of sensors in WSN. The harvested energy is the summation of the amount of RF energy received. Figure 6 shows the amount of harvested energy by the number of sensors in RF-MAC and REACH. Basically, both algorithms show that the amount of harvested energy increases as the number of sensors increases. As the number of sensors increases, sensors are located more closely on the experimental plane. In other words, there are many sensors around one ET. When the ET emits energy, a large number of sensors can be charged. REACH showed an overall 150% increase in harvested energy compared with the existing RF-MAC. Even though the number of RFE generations is reduced as shown in Section 5.1, the amount of harvested energy is rather higher.

We compared the amount of harvested energy by the number of ETs in WSN. Figure 7 shows the amount of harvested energy by the number of ETs in RF-MAC and REACH. As the number of ETs increases, both algorithms show increases in the amount of harvested energy. If the number of ETs increases, the probability that a sensor and an ET are close together also increases. Therefore, the amount of

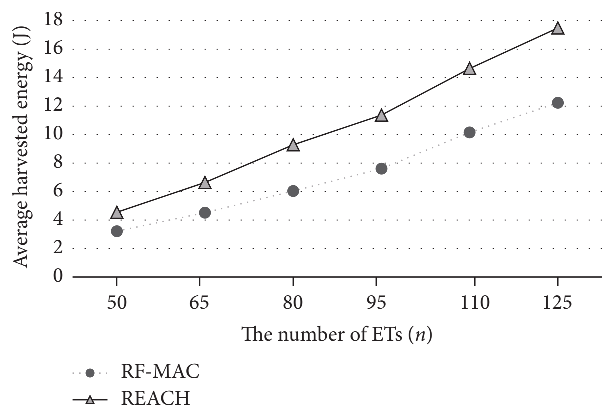

Figure 7: The amount of harvested energy by the number of ETs.

harvested energy is increased as the number of ETs increases. The difference between RF-MAC and REACH is not large when the number of ETs is small. This is due to the fact that a small number of ETs cannot charge a large amount of energy during autocharging. The efficiency of autocharging increases and the difference between REACH and RF-MAC increases when the number of ETs is large. Results show that REACH harvests 140% more energy than RF-MAC.

5.3. The Network Throughput. We compared the network throughput according to the number of sensors constituting WSN. Figure 8 shows the comparison of network throughput. As shown in Section 5.2, network throughput also tends to increase as the number of sensors increases. When the number of sensors is increased, sensors are located more closely. In the forwarding path setup process, there are many sensors within 10 m of one sensor. A straight line connecting the sensor and BS is the most optimal path for forwarding data from one sensor to the BS. When the number of sensors is great, the probability that a sensor closer to the optimal path is determined as the next hop sensor increases. An efficient forwarding path is set, and network throughput is increased. Regardless of the number of sensors, REACH shows a throughput loss of about 8%. This can be inferred by the inevitable impact of autocharging being set to minimize the impact of data communication.

We compared the network throughput by the number of ETs. Figure 9 shows the simulation results. Both algorithms tend to show a constant throughput regardless of the number of ETs. They emit energy simultaneously to increase the efficiency of charging. This behavior prevents the number of ETs from affecting network throughput. It can be inferred that as the number of ETs increases, the charging efficiency increases and no additional network throughput loss occurs. As with the previous simulation, the network throughput of REACH is lower by 10% than that of RF-MAC.

5.4. The Average Residual Energy of Sensors. We compared the average residual energy of sensors at every unit time. In this simulation, the unit time is 5 seconds. Figure 10 shows the average of residual energy of sensors every 5 seconds. The point where the residual energy in the graph soars

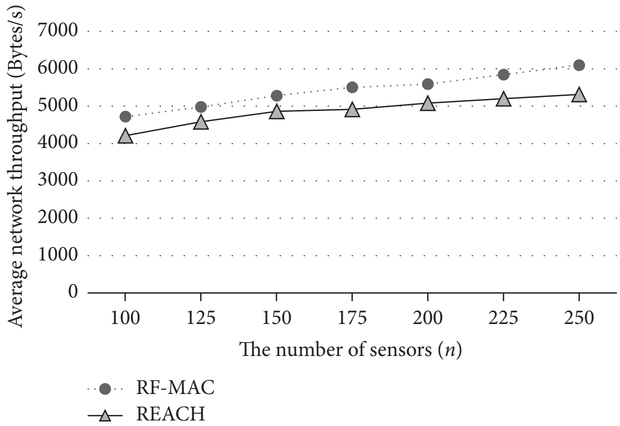

Figure 8: Network throughput by the number of sensors.

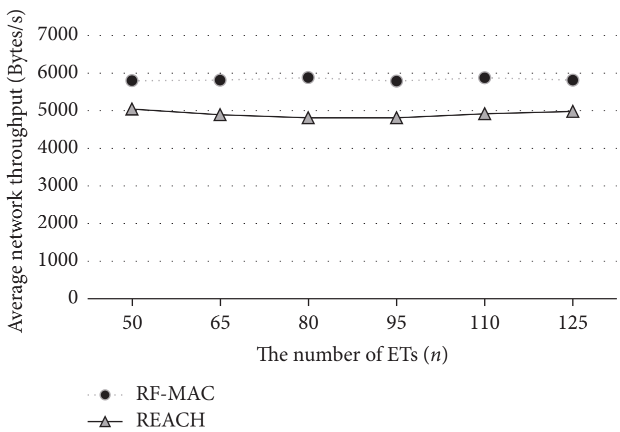

Figure 9: Network throughput by the number of ETs.

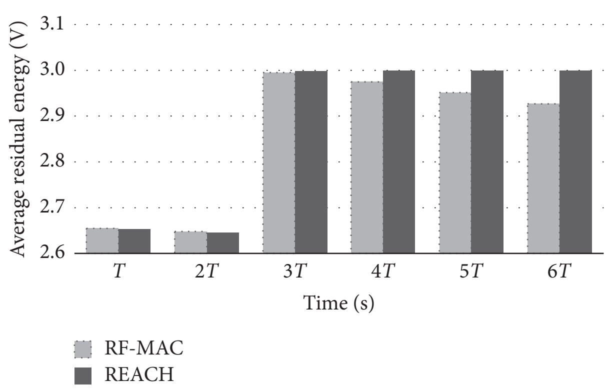

Figure 10: Average residual energy.

greatly is after the energy harvesting in the existing RF-MAC. Before energy harvesting, there are no significant differences between RF-MAC and REACH. There is a difference after the energy harvesting. The average of residual energy in the existing RF-MAC is reduced. However, the average of residual energy in REACH is still maintained as high energy because of autocharging. Autocharging affects data communication, but the overall lifetime increases. If there are many data communications, the average of residual energy becomes the same. Until then, REACH has maintained a high energy. As a result, REACH differs by 0.8% from the existing RF-MAC in the average of residual energy.

6. Conclusion

We have proposed a protocol that uses idle time of the channel to autocharge batteries of sensors. If the sensors do not have data to send, ETs emit energy. The sensors automatically charge by using the energy. Sensors can be held for longer periods of time without artificial charging requests when data communication is active. We compared the performance between the existing RF-MAC and REACH. As a result, REACH showed an increase in energy charging of 150% and decrease in network throughput of 8%. Also, we can see that the residual energy of the sensors is more than 0.8% at every point in time. Using REACH may result in a small loss of network throughput but it can increase the lifetime of the WSN in a stable manner. The proposed REACH still has some problems. Some network throughput is lost for autocharging. When there are a lot of data communications, eventually, the RF-MAC charging procedure is processed. The future work is the process of improving REACH that can be executed even in a situation when there are a lot of data communications.

Notations and Descriptions

$\mathrm{CW}_{\mathrm{random}}$: The number of contention windows of ET
$\mathrm{SCT}_{\mathrm{origin}}$: Current Short Charging Time
$\mathrm{SCT}_{\mathrm{default}}$: Default value of $\mathrm{SCT}_{\mathrm{origin}}$
$\mathrm{SCT}_{\mathrm{unit}}$: Incremental unit of $\mathrm{SCT}_{\mathrm{origin}}$
$\sum t_{\mathrm{IDLE}}$: Total amount of idle time in unit time
$\sum N_{\mathrm{data}}$: The number of data communication occurrences
$\mathrm{DIFS}_{\mathrm{AC}}$: The DIFS value for autocharging
$\mathrm{Slot}_{\mathrm{AC}}$: The slot time for autocharging
E_{consume}: The amount of consumed energy by sensor
E_{harvest}: The amount of harvested energy by sensor
E_{state}: The amount of consumed energy by sensor at each state
TP_i: Transmission power of object i
RP_i: Received power of object i
G_i: Antenna gain of object i
$d_{(i,j)}$: Distance between i and j
A_j: Set of ETs that received RFE sent from sensor j.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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