PADRE: Modulated Backscattering-based PAssive Data REtrieval in Wireless Sensor Networks

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***Abstract*— The most difficult challenge for the design of wireless sensor networks (WSN) is to maintain long network lifetimes since the sensor nodes are severely energy-constrained. Traditional WSN assumes employment of conventional RF transmitters which consume most of the stored power on the sensor node. In this regard, modulated backscattering (MB) emerges as a promising communication technique alternative, in which the sensor nodes reflect the incident signal of an RF source and modulate their data on the reflected signal. With the use of MB, the power consumption of the nodes reduce drastically since it replaces the most power consuming component of a typical sensor node, i.e., the RF transmitter. In addition, the nodes acquire relatively long-range communication ability through MB. Furthermore, the incident RF power can be converted into DC power in order to drive the sensing and processing circuitries. This, in turn, leads to the design of battery-free wireless passive sensor networks (WPSN), which stands as a radically distinct solution approach for the energy problems of WSN. The objective of this paper is to revisit the main design challenge of WSN from entirely different perspective. To this end, the fundamental principles of WPSN are first introduced. In addition, in order to realize the potential benefits of WPSN, a new clustering-based energy-efficient communication protocol, i.e., PADRE (PAssive Data REtrieval), is presented for WPSN operating via MB technique. Simulations show that PADRE protocol achieves high performance in terms communication reliability and network lifetime.**

***Index Terms*— Modulated Backscattering, Energy Efficiency, Wireless Sensor Networks, Wireless Passive Sensor Networks, Data Retrieval**

I. Introduction

The nodes of conventional wireless sensor networks (WSN) operate on small-size batteries which makes the power a severely scarce resource. Therefore, the main focus of the research community in WSN have thus far been on the development of energy-efficient communication protocols and computing algorithms [1]. However, when the limited energy stored in the batteries ultimately deplete, the operations of the sensor nodes stop since recharging the batteries in most application scenarios is impractical if not impossible.

An alternative sensor network architecture is the wireless passive sensor network (WPSN), a new WSN paradigm which eliminates the lifetime constraint of conventional WSN. In WPSN, the source of energy is an external RF source. The sensor nodes harvest the radio waves emitted by the RF source and operate as long as they are fed by the electromagnetic signals of RF source which makes the lifetime of the nodes theoretically bounded by the lifetime of the RF source. The nodes of WPSN, called *passive sensor nodes*, employ modulated backscattering (MB) [9], which is a promising communication technique to replace the power consuming active RF transmitter. With this approach, a passive sensor node modulates the incident signal from the RF source by switching its antenna impedance. The transmitter consists of only a switching circuitry. Therefore, it is possible to dramatically decrease the power consumption of the sensor nodes. However, the sensor nodes share the same medium and the same signal, i.e., the signal of RF source, to communicate their readings of the event. The fundamental operation principles of WPSN are presented in this paper.

Furthermore, a communication protocol needs to be devised to allow the sensor nodes to communicate in the presence of the RF signal from the source and reflected signals from the surrounding nodes. In order to address this need, this paper also presents PAssive Data REtrieval (PADRE) protocol. PADRE is a novel clustering-based data communication protocol that seeks to achieve extremely low-power information gathering at the sink. PADRE enables every node to convey its data by leveraging the MB technique. To the best of our knowledge, this is the first research effort on battery-free passive data retrieval through MB in a sensor network.

The remainder of the paper is organized as follows. In Section II, we give an overview of communication through modulated backscattering and explain the WPSN architecture in Section III. The operation of PADRE is presented in Section IV. The results of performance evaluation are presented in Section V. Finally, the paper is concluded in Section VI.

II. Modulated Backscattering

Conventional WSN employ RF radio technology for data communication. Therefore, a classical transmitter consists of many power-consuming active components such as mixers, voltage-controlled oscillators, and phase-locked loops. In contrast, the main wireless communication mean of WPSN is modulated backscattering (MB). The use of MB turns the transmitter of the sensor node into a simple switching circuitry. Incident signal from an RF source is reflected back and the

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data of the sensor node is modulated onto the reflected signal by switching the antenna impedance [9]. This makes it possible to replace the classical transmitter, and thus, reduce the power consumption of the sensor nodes in a drastic fashion. Moreover, MB offers relatively long-range communication since the communication range mainly depends on the power intensity of the incident signal and the sensitivity of the receiver.

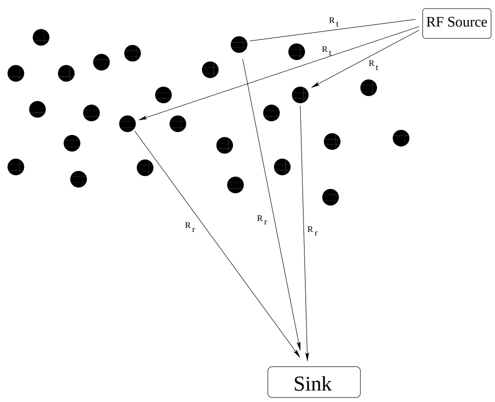

Fig. 1. Communication via Modulated Backscattering in WPSN.

To calculate the maximum attainable communication ranges, consider the network shown in Fig. 1. An RF source, at a distance of R_t meters, feeds the network. The sensor nodes modulate the incident signal and convey their data to the sink which is located at a distance of R_r meters. Note here that the RF source may also operate as the sink. In that case, $R_t = R_r$. The maximum range, at which the sink can extract the information from the reflected signal can be calculated with the well-known radar equation [2]

$$P_r = \frac{P_t G_t A_r}{(4\pi)^2 R_t^2 R_r^2}\sigma \qquad (1)$$

where P_r is the received power at the sink, P_t is the power transmitted from the RF source, $A_r = \frac{G_t \lambda^2}{4\pi}$ is the effective aperture of the sink antenna, G_t is the gain of the source antenna, λ is the wavelength of the RF signal, and σ is the radar cross section of the sensor node.

Here, assume that the source antenna emits 4W equivalent isotropically radiated power (EIRP). The receiver sensitivity is -100*dBm*. The sensor nodes are assumed to be equipped with a half-wave dipole antenna. Using (1), the maximum distance at which the sink can extract the data from the reflected signal is depicted in Fig. 2 for two distinct values of R_t. As observed in Fig. 2, at 1GHz, the sink can extract the information in the reflected signal from a distance of $3145m$ and $1572m$ when the RF source is at $50m$ and $100m$, respectively. When the RF source also assumes the duties of the sink ($R_t = R_r$), then it can be located as far as $396m$. This result shows that the communication with MB is an attractive alternative for conventional RF communication.

MB technique generates double sideband (DSB) modulated signals [9], [4], i.e., the data signals are located on both sides of the main signal in the frequency domain. The main signal resides at f_c, the frequency at which the RF sources broadcast unmodulated carriers. The difference between the frequencies

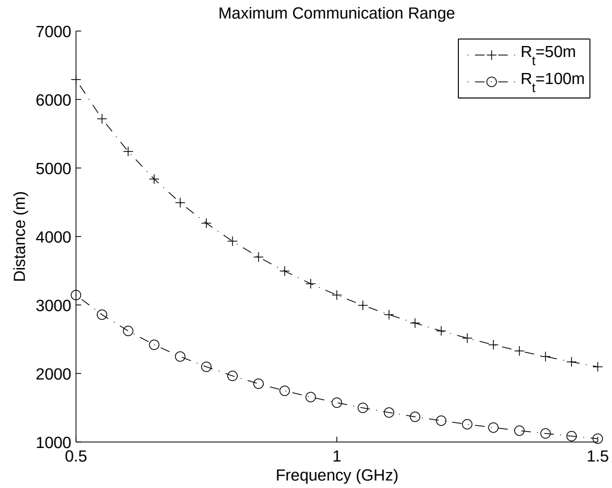

Fig. 2. Maximum Communication Range via MB.

of the main signal and the data signals corresponds to the frequency with which the sensor nodes switch their antennas. Hence, it also determines the data rate of the sensor node and therefore is called as *data switching frequency*, f_s. PADRE exploits this fact by first clustering the sensor network and assigning every cluster a different data switching frequency so that the data signals generated in different clusters reside at different frequencies around f_c. The detailed PADRE protocol description and operation principles are explained in Section IV. First, we introduce WPSN and highlight the differences between WPSN and conventional WSN.

III. Wireless Passive Sensor Networks

Unlike conventional WSN, the nodes of WPSN, called *passive sensor nodes*, are fed by an external power source, and is operable as long as power is delivered to the system. In WPSN, the source of energy, as alternative to the batteries of conventional WSN, is an RF power source. Accordingly, voltage is induced on the receivers of the sensor nodes, which is converted to DC. The DC power is kept in a charge capacitor to be used later[1].

The WPSN node hardware deviates from the conventional WSN hardware on the *power unit* and the *transceiver*. In a conventional WSN node, the *power unit* is a battery. In the WPSN node, however, the power unit consists of a *power generator*, which is an RF-to-DC converter, and a capacitor. The power harvested by the RF-to-DC converter is transferred to the rest of the units of the sensor node and extra power is stored, whenever available.

A receiver can convert the RF power to DC as long as $100mV$ of voltage is induced on the receiving antenna [8]. In this regard, the induced voltage on the WPSN antenna is

[1]Here, one conceivable solution is the use of ultra-capacitors, e.g., a $3V$, $10F$ ultra capacitor for an operation range of 1V and an average power consumption of $10mW$, a WPSN node with a fully charged ultra-capacitor may run about 30 minutes [3] with no RF power signal is present.

calculated by [2]

$$\frac{G_r \lambda^2}{4\pi} = \frac{|V_t|^2}{8W_i}[\frac{1}{R_r + R_L}] \quad (2)$$

where G_r is the gain of the receiving antenna of the WPSN node, λ is the wavelength of the incident signal, V_t is the voltage induced, R_r is the radiation resistance, R_L is the load resistance, and W_i is the incident power density which can be calculated by Friis transmission equation [2] as

$$P_r = P_t(\frac{\lambda}{4\pi R})^2 G_t G_r \quad (3)$$

where P_t is the power transmitted from the RF source, G_t is the gain of the transmitting antenna, and R is the distance between the RF source and WPSN node.

Assuming the WPSN node is equipped with an omnidirectional antenna with $G_r = 8.5dBi$ and $R_L = R_r = 50\Omega$, from (2) and (3), it is obtained that when the RF source emits $4W$ EIRP output power, then $100mV$ can be induced on the antenna from $26m$ at $1GHz$. On the other hand, when the emitted power is increased to $100W$ EIRP, then the range to induce $100mV$ is $130m$ at $1GHz$ which shows the feasibility of WPSN for specific applications such as military surveillance, homeland security where high power radio communications can be realized [7].

Next, we calculate the maximum distance at which a node can intercept $10mW$ power, an approximate power value to run the processor and the sensor hardware on a typical sensor network node [6] for successful operation of sensing and processing tasks in a WPSN node. We perform the analysis using (3) for two different RF source antenna assumptions, i.e., first an omnidirectional one, which can feed the surrounding nodes simultaneously, and afterwards a directional antenna is considered. The omnidirectional antenna has a gain of $12dBi$ and for the output power level, we use $P_t = 10W$. Accordingly, at $1GHz$, remote feeding is attainable up to only $8m$ with RF source equipped with omnidirectional antenna. On the other hand, for the directional RF source antenna, the range increase to $63.5m$. The improvement of range by use of a directive antenna is significant. However, the directional antenna transmits power only to a small portion of WPSN, where it is aligned to.[2]

Hence, the distances required to transmit and store power are $130m$ and $63.5m$, respectively, at $1GHz$. This analysis encouragingly implies that a sensor node may be fed by an external RF source, can store RF power, and operate on the RF power rather than batteries.

IV. PADRE: PASSIVE DATA RETRIEVAL

In this section, we introduce PADRE protocol in detail. The objective of PADRE is to achieve extremely low-energy battery-free passive data communication by using MB technique in WPSN. To the best of our knowledge, PADRE is the first protocol for effective and collaborative communication in WPSN.

[2]Employing several RF sources with rotating directional antennas might present an effective solution to this problem which is left out of scope of this paper

A. Overview

The operation begins with a *cluster setup phase*, during which the clusters are formed, followed by the *data retrieval phase* during which the data of the sensor nodes are communicated to the sink via MB. The RF sources which feed the network also serve as cluster-heads. The passive nodes determine to which cluster to join by choosing the RF source that is geographically closest, which can be determined according to the received signal strength. In WPSN, the network is divided into clusters around RF sources. The passive nodes harvest the electromagnetic waves emitted from the RF sources in order to power themselves. However, as explained in Section III, there is a maximum range to induce at least $100mV$. Therefore, each passive node needs to have an RF source in its vicinity.

B. Cluster Setup Phase

At the beginning, each RF source chooses a *data switching frequency*, f_s, randomly among possible alternatives which are determined a priori. It then broadcasts an advertisement packet which includes f_s, and thus, starts the clustering process. To avoid collision of the advertisement packets and arbitrate between the RF sources about the potential problem of choosing the same data switching frequency, the sources wait a random time τ for this advertisement. Other RF sources check the advertisements they receive from other sources before broadcasting their advertisements. If an advertisement is received which informs that the same data switching frequency is chosen, then another data switching frequency is chosen randomly among the remaining alternatives.

Each WPSN node decides the cluster to which it joins by comparing the received signal strength of the advertisements heard. The advertisement heard with the largest signal strength is the RF source which is assumed to be the geographically closest. A typical WPSN after cluster set-up is shown in Fig. 3.

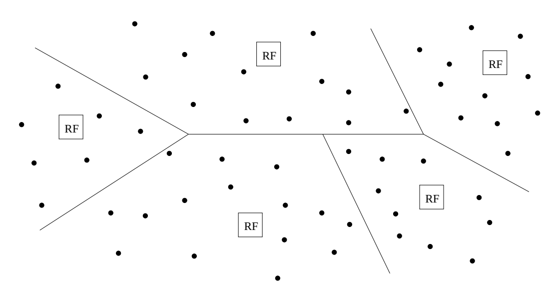

Fig. 3. WPSN with after cluster setup phase is over.

C. Data Retrieval Phase

Once the clusters are formed and the data switching frequencies are set, the RF sources start to broadcast an unmodulated carrier all at the same center frequency, f_c. When a passive sensor node has data to send, it modulates its source's signal by changing the antenna impedance [9]. Different from WSN, the high power of the incident signals of the RF sources enable the passive sensor nodes to send their data directly to the

Algorithm 1: Algorithm of the PADRE protocol operation. f_s is the data switching frequency determined distributively. f_c is the center frequency at which the RF sources broadcast unmodulated carriers.

```
RF Source:
  Select a data switching frequency f_s
  Wait and listen the channel for a random time τ
  if f_s not chosen
    Set the data switching frequency f_s
    Start to broadcast unmodulated carrier at f_c
  else goto 1
Passive node:
  Listen to advertisements (ADV)
  Choose the RF source with the strongest ADV signal.
  Send data employing CSMA/CA and MB with data
  switching freq. f_s.
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sink. As previously mentioned, the MB technique generates DSB signals where the difference in frequency between the carrier signal and the data signals is equal to the data switching frequency f_s. Therefore, the data signals generated in different clusters throughout the network reside at different locations in the frequency domain [3]. This is illustrated in Fig. 4, where f_s^k is the data switching frequency assigned to the cluster k.

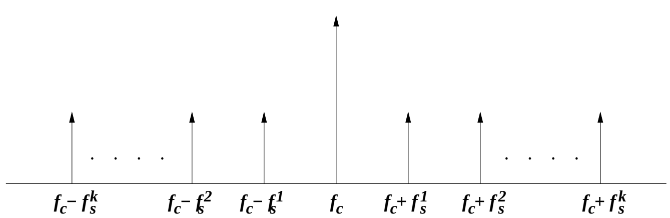

Fig. 4. RF source's signal and the DSB modulated data signals around it.

On the other hand, passive sensor nodes use the plain CSMA/CA medium access control mechanism to access the channel inside a cluster. The passive nodes listens to the channel through their receivers, and if the carrier is not present then they switch their antenna impedance to modulate the incident signal and reflect to communicate its reading directly to the sink. Note that the data rate of every cluster is equal to its data switching frequency, and thus, is different. The data rates of the clusters can be changed by the sink at any time, which also provides a unique feature to the WPSN architecture. For example, the highest data switching frequency can be assigned to a specific cluster, where the probability of event occurrence is highest. Similarly, any specific region which is of higher importance for monitoring can be given priority by assigning high switching frequency to the cluster in that region. Hence, the entire WPSN can be divided into separate areas according to the priority levels set by application-specific requirements. The overall PADRE protocol operation is outlined in Algorithm 1.

[3]Here, it is assumed that the sink is capable of receiving the signals of different frequencies at the same time [11].

V. Performance Evaluation

For the simulation experiments, we developed a simulation environment for WPSN in ns-2 [10]. Here, normally, the passive nodes have no energy. However, when the RF sources begin to feed the network, the passive nodes start to harvest the incident power and accumulate energy. For example, when a passive node is constantly intercepting $10mW$, it will have stored $0.1J$ after $10s$. For the experiments reported in this paper, it is assumed that the passive nodes start with $0.1J$ amount of energy. When the energy stored in a passive node depletes, then the node ceases to function until sufficient amount of energy is again accumulated as a result of energy harvesting. We expect that not all the passive nodes will be illuminated all the time by an RF source due to the directional antennas employed at the RF sources. Therefore, for the simulation experiments, the nodes wait for a random amount of time between $50s$ and $70s$ to gain $0.1J$ amount of energy. After that, they once again become active and start to function. The RF sources are assumed to have infinite amount of energy.

The RF sources constantly emit $4W$ EIRP at the center frequency of $f_c = 960MHz$. Any sensor node belonging to cluster i that receives the signal of its source could send its data by employing MB at the frequency $960MHz + f_s^i$. 100 passive nodes are randomly distributed in a $100mx100m$ topology. As the PADRE is a clustering-based data retrieval protocol, here, its performance is also compared with LEACH, since it is a well-known clustering-based communication mechanism for traditional WSN [5]. The sink is located at ($x = 1000$, $y = 1000$) for PADRE and at ($x = 50$, $y = 175$) for LEACH. The bandwidth of the channel is set to 1 Mb/s. The number of RF sources, and hence, clusters is 5. In LEACH, the nodes start with $0.5J$ amount of energy. The transmitter and receiver electronics consume 50 nJ/bit whereas the amplifier energy is 10 $pJ/bit/m^2$.

A. Communication Reliability

In the first experiment, we measure the number of data packets received at the sink over time and per amount of energy consumed in the network. According to Fig. 5, PADRE is able to deliver packets to the sink almost at a constant rate until a certain time after which the packet delivery rate starts to drop sharply. The reason can also be observed in Fig. 7, where we show the number of alive nodes over time. As the energy of the passive nodes deplete, they cease to function. Then, they wait until they have accumulated sufficient amount of energy to start sensing the environment and sending packets.

Also observed in the Fig. 5 is that the WPSN operating with PADRE outperforms the conventional WSN operating with LEACH [5]. This is due to several facts. First, in PADRE the clusters are static. Second, WPSN has high energy RF sources which use high power to induce sufficient voltage in the RF-DC converters of the passive nodes. In contrast, the operation of the WSN is divided into rounds and LEACH performs cluster formation at the beginning of every round to balance the energy consumption among all the nodes in the network.

On the other hand, LEACH sends more data packets per amount of energy consumed in the sensor nodes as observed in Fig. 6. However, this is true only for the periods when most of the passive nodes are out of energy and are waiting to store enough energy back in their capacitors. In the long run, as the sensor nodes die in the conventional WSN, the network stops functioning, which is not the case in WPSN.

alive nodes starts to increase after some time. The novelty of WPSN that it enables the passive nodes harvest energy from the electromagnetic signals emitted from the RF sources allows to increase system lifetime. The power load of network is successfully shifted to the RF sources. In contrast, in conventional WSN, when a sensor node dies it does not function anymore.

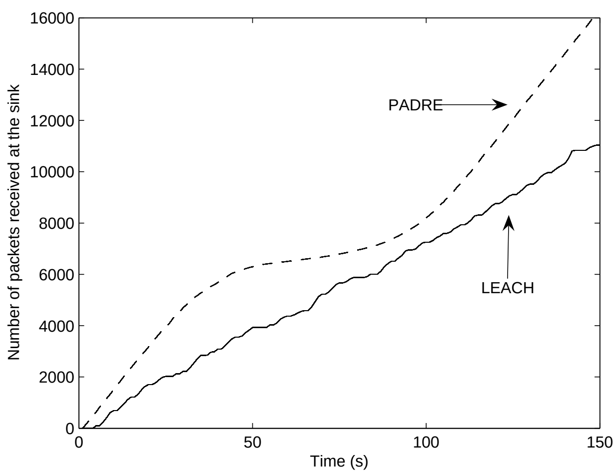

Fig. 5. Total number of data packets received at the sink over time.

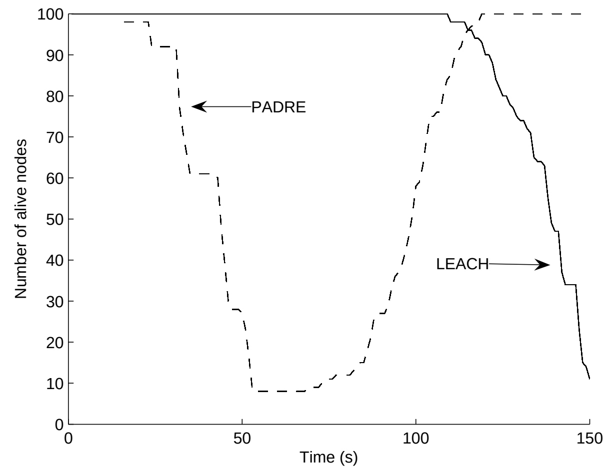

Fig. 7. Number of nodes alive over time.

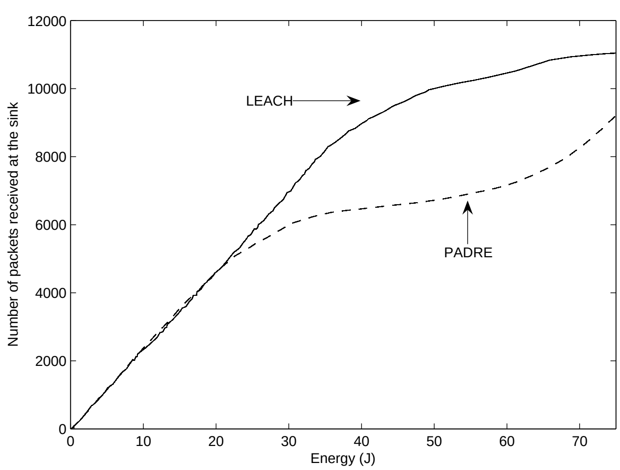

Fig. 6. Total number of data packets received at the sink per amount of energy consumed in the network.

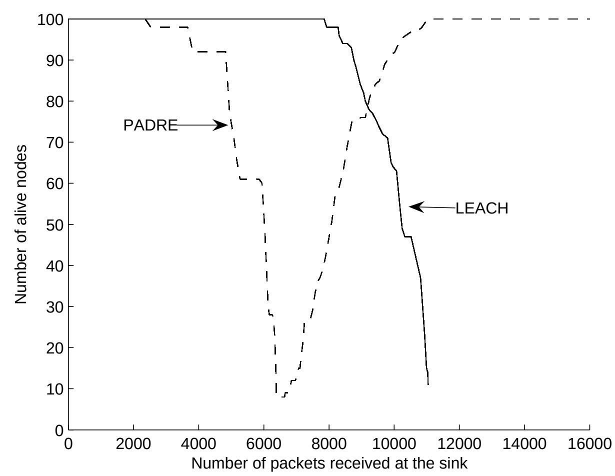

Fig. 8. Number of nodes alive per number of data packets received at the sink.

B. Network Lifetime

In the second experiment, we measure the number of alive nodes over time and per number of data packets received at the sink. The results are shown in Fig. 7 and 8. According to the experiment results, the sensor nodes start to die earlier in PADRE. This is due to the fact that the passive nodes initially have less energy. However, the passive nodes have the ability to harvest energy from the incident signals of the RF sources. Therefore, as seen in the figure, the number of

VI. CONCLUSIONS

In this paper, the fundamental problem of energy limitations in WSN is revisited. In order to take a radically different solution path for this problem, wireless passive sensor networks (WPSN) is presented which aims to significantly prolong network lifetime by employing modulated backscattering as the principal wireless communication technique. The basic theoretical framework and communication architecture of WPSN are introduced. To realize a practical

WPSN deployment, a clustering-based energy-efficient passive data retrieval (PADRE) protocol for MB-equipped WPSN is also presented. PADRE distributively divides the network into clusters and assigns each cluster a different data switching frequency with which the members of the clusters switch their antenna impedance to communicate their readings to the sink. Performance evaluation experiments show that PADRE in WPSN significantly improves the network lifetime without compromising communication reliability.

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