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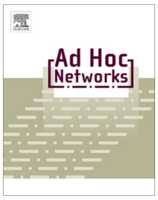

Passive wake-up radios: From devices to applications

He Ba [a,*], Ilker Demirkol [b,c], Wendi Heinzelman [a]

[a] Department of Electrical and Computer Engineering, University of Rochester, Rochester, NY, United States
[b] Department of Telematics Engineering, Universitat Politecnica de Catalunya, Barcelona, Spain
[c] Fundacio i2CAT, Barcelona, Spain

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ABSTRACT

Energy efficiency is one of the most important criteria in the design of a wireless sensor network. Sensor nodes are usually battery-powered and thus have very limited lifetime. In this paper, we introduce a novel passive wake-up radio device named WISP-Mote that uses a passive RFID tag as a wake-up receiver for a traditional sensor node. We characterize the WISP-Mote with field tests in different operating environments and present the wake-up probabilities based on the distance between the wake-up transmitter and receiver. We then perform simulations to compare the performance of a network with WISP-Motes and with duty-cycling of the sensor nodes, using the wake-up probabilities measured in our field tests. Additionally, potential applications that can benefit from WISP-Motes are discussed, and the advantages of using WISP-Motes are identified by simulation results based on these application scenarios. Results show that the wake-up radio sensor networks have great potential over duty-cycling approaches for energy efficiency, while providing similar latency and packet delivery performances.

1. Introduction

The emerging field of wireless sensor networks (WSNs) has garnered significant attention in the last decade. WSNs support numerous applications, such as environment and habitat monitoring, health monitoring, machine surveillance, and traffic control. However, the sensor nodes are usually powered by batteries and thus have very limited lifetime if no power management is performed. As the exchange of batteries is costly and in some cases not possible, energy efficiency is one of the most crucial factors in the design of WSNs.

Radio transmission and reception are the two major sources of energy drain. When a node is active and waiting to receive data, it wastes energy on idle listening. Since traffic loads are usually low in WSNs, such idle listening can waste enormous amounts of energy unless efficient communication mechanisms are employed.

To extend the lifetime of a sensor node, we can turn off its radio and set its microcontroller (MCU) into a sleep mode when it is idle and wake it up when there are possible transmissions. To wake up a sensor node, there are generally two approaches: a scheduled approach where a timer is set and the firing of the timer wakes up the node, namely duty cycling, and an on-demand approach where the node is woken up by a radio signal, namely radio wake-up.

In duty cycling, a node, or only part of the node (e.g., its radio component if using technologies such as wake-on-radio [1]), is periodically set into the sleep mode. The node can manage the trade-off between energy consumption and data latency, by setting the duty cycle value accordingly. With lower duty cycles, the node will consume less energy at the cost of higher latency for data delivery. Once a node wakes up during the active part of its duty cycle, it must listen to the channel for a period of time to determine whether other nodes or the sink are available for communication. This introduces complexities and adds overhead to the medium access control (MAC) protocol.

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* Corresponding author. Tel.: +1 5854891150.
E-mail addresses: ba@ece.rochester.edu (H. Ba), ilker.demirkol@entel.upc.edu (I. Demirkol), wheinzel@ece.rochester.edu (W. Heinzelman).

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Using radio wake-up techniques, such overhead can be reduced. A wake-up signal triggers a node to wake up from the sleep mode and start reception activities. Normally, the wake-up signal is sent or received by a secondary radio transceiver. In order to improve energy efficiency, the energy consumption of this extra wake-up radio transceiver should be extremely low. The energy benefit of using radio wake-up in comparison with duty-cycling is that nodes do not waste energy on idle listening of the main radio, since they are only awakened by neighboring nodes when there is a request for communication. In addition, using a wake-up signal reduces the overhead in control traffic since a node woken up through a wake-up radio knows that another node is ready to receive data.

Wake-up radio receivers can be categorized as active and passive based on whether the receiver uses a connected power supply. Active wake-up radio receivers require a continuous power supply while passive wake-up radio receivers harvest energy to power themselves from the wake-up radio signal transmitted by the sender. Active wake-up radio receivers have a relatively better sensitivity, in other words, their wake-up range is relatively longer. On the other hand, passive wake-up receivers operate within a relatively smaller range but do not require any attached power source.

One possibility to achieve a passive wake-up radio is to use a passive radio-frequency identification (RFID) tag as the wake-up signal receiver and an RFID reader as the wake-up radio transmitter, as off-the-shelf RFID tags and readers are readily available. Despite the low cost of this solution, there are two major challenges for implementing this approach in real-world applications: the limited wake-up range compared to the main radio communication range, and the energy cost for the wake-up signal transmitter. The former creates problems in terms of network coverage, while the latter makes it impossible for a battery-powered sensor node to wake up another node, i.e., multi-hop wake-up is unrealistic using this approach. However, these types of devices can be beneficial in scenarios where there is a mobile data sink (i.e., a data MULE [2]) or where the sensors are mobile (e.g., sensors on a person) and come in contact with a fixed sink at some point. For these scenarios, the sink can wake up the sensor nodes to query them for data whenever they are in the wake-up range.

In this paper, we describe and characterize a passive RFID-based wake-up radio sensor node that we developed, and we discuss and analyze the use of our passive wake-up radios in various scenarios. Our passive RFID wake-up device, which we call a WISP-Mote, is created by combining a WISP (Wireless Identification and Sensing Platform) [3], an RFID tag developed by Intel Research, and a Tmote Sky [4] sensor node. We characterized the WISP-Mote's performance by measuring its energy consumption for different operations and assessing its wake-up probabilities in different environments for various WISP-Mote to reader distances. Finally, we performed MATLAB simulations to show the benefits of using WISP-Motes by comparing the performance of a sensor network with WISP-Motes with a standard duty-cycling architecture. Our results show that the energy efficiency using the WISP-Motes is much greater than when using duty-cycling, without any loss in performance.

In addition to the introduction of the WISP-Mote concept and the characterization of the WISP-Mote wake-up range in our previous publications [5,6], our major contributions of this paper include:

- Providing comprehensive simulation analyses of the wake-up radio sensor network in comparison with a traditional duty-cycling sensor network to better understand the network performance in terms of packet delay, packet delivery, collisions, buffer size and energy consumption.
- CSMA has been added into the MAC protocol to make the simulations more realistic.
- Potential application scenarios are also investigated with the support of simulations.

The rest of this paper is organized as follows. In Section 2, we review the current state of the art in radio wake-up technology. Section 3 introduces our RFID wake-up sensor devices, including the hardware implementation and the energy consumption measurements. Field tests to determine the wake-up probability in relation to the distance from the RFID reader are presented in Section 4, followed by simulation results and performance analyses when using the WISP-Motes in different network scenarios in Section 5. As applications are the motivators for research in wireless sensor networks, Section 6 describes various potential applications of our passive wake-up radios and shows the benefits of these wake-up radios through simulations. Finally, Section 7 concludes the paper.

2. State of the art in radio wake-up

Remote wake-up is realized via a second receiver triggering the main data receiver when necessary. To gain a benefit in energy efficiency, the extra receiver must be lower power than the main data receiver (or, ideally, require no battery power to operate), because while the main receiver is in the sleep mode, only the wake-up receiver remains onto monitor the wake-up channel continuously or following a duty-cycling scheme.

2.1. Active wake-up receivers

Several different low-power active wake-up receivers have been proposed [7–13]. In [7], Otis et al. propose the use of a super-regenerative architecture with a 1.9 GHz bulk acoustic wave (BAW) resonator to reduce the power consumption of the wake-up radio. The power consumption of this radio is 400 μW for the receiver and 1.6 mW for the transmitter. This approach is further optimized to create a 65 μW wake-up receiver [8], using a 1.9 GHz BAW resonator matching network for RF signal filtering. This wake-up receiver can provide a sensitivity of −50 dBm at 40 kbps and −48 dBm at a maximum data rate of 100 kbps.

A different approach is developed by Le-Huy and Roy [9] and Von der Mark et al. [10], where zero-bias Schottky diodes are used due to their zero DC power consumption. The low-power 2.4 GHz wake-up receiver proposed in [9] is designed to work with a directional antenna and pulse width modulation in order to reduce energy dissipation. Simulation results show that the receiver can reach −50 dBm sensitivity with only 19 μW power consumption. A three stage wake-up scheme is introduced in [10]. In this approach, a very low power (on the order of nW) always-on stage is used to trigger an intermediate higher power (on the order of μW) stage for wake-up signal verification. Only if the wake-up signal is confirmed is the main transceiver activated.

Other approaches for active wake-up radios are described in [11,12]. Junaid et al. propose a wake-up receiver including a five stage charge pump used to increase the received signal voltage [11]. The only active parts of the wake-up circuit are the digital comparator and the voltage divider, which consume 350 nA and 526 nA, respectively. In [12], Van der Doorn et al. implement a wake-up receiver using only commercial components to reduce the extra hardware costs. Their design consumes 171 μW with −51 dBm sensitivity.

Although there are several hardware proposals for active wake-up radios, not many physical implementations or commercialized products are available today. Recently, Austria Microsystems announced their latest 3-channel low frequency wake-up receiver working at 15 – 150 kHz [13]. This product consumes 8.1 μW and can reach a sensitivity of about −37 dBm (as calculated from the provided specifications).

2.2. Passive wake-up receivers

Compared with active wake-up receivers, passive wake-up receivers do not require energy from a physically connected power supply; instead, they harvest energy from the transmitted wake-up signal. While this makes passive wake-up radios energy efficient, the wake-up range for passive wake-up radios is relatively shorter, i.e., the receivers' sensitivity is lower.

Currently, there are limited studies on passive radio wake-up receivers. Gu et al. propose a passive radio wake-up circuit that theoretically could operate at a range of 10 ft with 5 ms latency, according to SPICE simulation results [14]. If a comparator and an amplifier are added, which respectively consume negligible currents of 350 nA and 880 nA, the radio could theoretically reach up to 100 ft with 55 ms latency.

A performance study on the use of passive RFID wake-up radios is given by Jurdak et al. [15,16]. In their work, an RFID wake-up mechanism is proposed, namely RFIDImpulse, which assumes a commercial RFID reader and a passive RFID tag are attached to each sensor node, providing radio wake-up capability. The performance of the proposed mechanism is investigated through MATLAB simulations and compared with the BMAC protocol [17] and the IEEE 802.15.4 standard [18]. Their results show that RFIDImpulse outperforms both other methods in terms of energy efficiency and transmission rate for low and medium traffic scenarios. However, the analysis is based on an important assumption that all nodes have the capability to wake up their neighbors, which is not feasible currently, due to the considerable amount of energy required by the RFID reader, which sends out the wake-up signal, and its large size. In addition, their energy consumption analysis does not include the energy consumed by the nodes to wake up. In reality, the wake-up energy consumption includes the energy used for MCU boot-up and for radio initiation, which could be comparable to the energy consumed for radio transmission. Furthermore, the implementation described in [15,16] uses a coil instead of an RFID tag for the purpose of proof of concept.

In this paper, we introduce a passive RFID-based wake-up device named WISP-Mote and characterize its power consumptions during different operation modes, including waking up. To the best of our knowledge, the WISP-Mote is the first reported complete implementation of a passive radio wake-up device that provides both broadcast-based wake-up and ID-based wake-up. The provided characterization data are measured using our implemented WISP-Mote in various environments.

To have wide network coverage, WISP-Motes are used with mobile sinks in this paper due to their short wake-up ranges. The mobile sink wakes up the WISP-Motes when it gets within their wake-up range to collect their data. This is similar to the three-tier layered architecture described in [2]. In our scenarios, we investigate random walk along with two other mobility models and present their performance comparison.

3. RFID wake-up sensor device

In this section, we describe the implementation of our WISP-Mote and provide measurements of its energy consumption in different modes.

3.1. Design and implementation of the WISP-Mote

In our previous work [5], we introduced our hybrid sensor device with RFID wake-up receiver, namely the WISP-Mote, as shown in Fig. 1. We employ an Intel WISP (Wireless Identification and Sensing Platform) as an external wake-up signal receiver for a Tmote Sky mote. A WISP is an RFID tag with sensing and computing capabilities developed by Intel research. Using energy harvesting, it can be powered wirelessly by a UHF RFID reader. In our implementation, we use a UHF Gen2 Speedway RFID reader from Impinj [19].

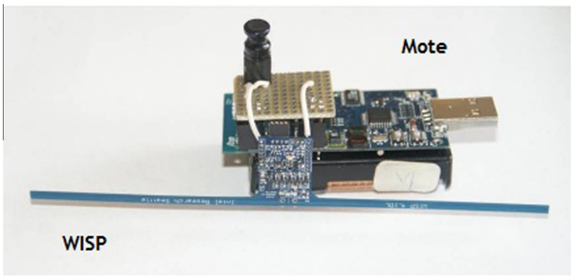

Fig. 1. A WISP-Mote.

Table 1
Power consumption measurements of a T-mote sky node.

Operation	Average current consumption (mA)	Duration (ms)
Wake-up	10.4	5
Transmit 12 byte packet	18.2	30
Receive and idle listening	20.2	
Sleep	0.2	

The RFID reader sends a continuous wave along with commands according to the standard C1G2 protocol [20] to the tag. The tag sends data back by modulating the reflection coefficient of the backscattered signal (via changing the antenna impedance) [21]. The tag also collects the energy from the received signal and stores it in a capacitor as its power supply. Therefore, using a WISP as a wake-up receiver does not consume extra power from the sensor node. The Tmote Sky mote [22] is a battery-powered wireless sensor node developed by UC Berkeley. By using the WISP to generate an interrupt signal to the Tmote Sky, a passive wake-up sensor node is created.

According to the destination of a wake-up signal, radio wake-up can be categorized as broadcast-based wake-up and ID-based wake-up. Using a broadcast-based wake-up radio, all sensors within range of the transmitted wake-up signal will be woken up, while an ID-based wake-up radio transmits a wake-up signal that contains the intended destination's address and thus only wakes up the node with a matching address. Using the WISP, we can implement both broadcast-based wake-up and ID-based wake-up.

For broadcast-based wake-up, whenever the WISP harvests enough energy from the reader's radio, it sends a pulse to wake up the mote from the sleep state. Thus, any WISP-Mote within the wake-up range of the reader will be awakened. Since in our RFID wake-up scheme there is no communication from the WISP to the reader, we programmed the WISP not to respond to any command sent by the reader. Therefore, we reduced the energy consumption caused by the MCU and other components on the circuit that typically perform the standard RFID communication protocol (e.g., C1G2 protocol). To reduce this energy consumption, we disable all functions of the C1G2 protocol on the WISP that are not required for the wake-up of the sensor node. Thus the only responsibility of the WISP for broadcast-based wake-up is to harvest energy from the reader and send an interrupt signal to the mote. By minimizing the energy required for the WISP, we maximize the wake-up range of the WISP-Mote.

In a dense network, this broadcast-based wake-up may bring a large number of collisions on the data channel, since all the nodes within the wake-up range will be awakened by the reader, and none of them is aware of the other nodes awakened at the same time. To reduce unnecessary wake-ups and to reduce collisions caused by these unnecessary wake-ups, we need the ability to wake up a certain node or a specified class of nodes. With this intention, we programmed the WISP to let it generate a trigger pulse only after receiving a packet that has its ID or Class number in the packet header. This functionality requires the demodulator to work and additional computation by the WISP's MCU, both of which consume extra energy from the WISP. Therefore, for any given distance, the wake-up probability of the ID-based wake-up is expected to be smaller than or equal to the wake-up probability for the broadcast-based wake-up. For a wake-up receiver with addressing capability, broadcast-based wake-up can be achieved by assigning a particular ID as a broadcast address.

To determine the performance of our WISP-Mote, we performed field tests of both broadcast-based and ID-based wake-up in various environments. Details of this characterization are discussed in Section 4. For both broadcast-based and ID-based wake-up, it is preferred that the nodes not be awakened by the sink when not necessary, i.e., when the nodes do not have any buffered data to send. To achieve this, we programmed the sensor nodes to disable the interrupt functionality of the wake-up signal input port when they have no data to send. Thus the node will wake up only when it has buffered data and it receives a wake-up signal. Otherwise, the node will remain in the low-power sleeping state. This reduces unnecessary energy waste.

3.2. Energy consumption measurements

Unlike active wake-up radios, which constantly consume energy, RFID wake-up radios do not consume any energy from the sensor node. This further enhances its energy efficiency. The Tmote Sky datasheet [22] provides the current consumptions in typical operating conditions, but lacks information about energy consumed when the node is waking up, which is essential for the energy consumption analysis of RFID-based wake-up sensor networks. In addition to current consumptions in transmitting and receiving, we measured the current and time consumed in booting and radio initiation, i.e., when the node is waking up from the sleep state. The results are shown in Table 1. Our measurements are consistent with those from the Tmote Sky datasheet. The results show that besides radio transmission and reception, a node's wake-up also consumes energy that cannot be ignored. These measurements are used in the energy analysis for our sensor network.

3.3. Sensor network system

Besides the WISP-Motes, in some applications, the sensor network may also include one or more base stations (BSs) and data MULEs (MULEs). MULEs are mobile data collectors that are equipped with both a mote and an RFID reader, and therefore have the capability to wake up the nearby WISP-Motes and to receive data from them. We assume that when the MULEs are close to a BS, they dump all of the collected data to the BS, or they can act as a gateway and send the data immediately e.g., using a cellular network. The MULE must have the ability to move and sufficient energy to power the RFID reader. In a real system, any moving agent, e.g., a vehicle, an animal or a human, that carries an RFID reader and a mote with adequate power supply can perform as a MULE.

This system is designed for a delay-tolerant network with energy constraints on the sensor nodes. The major advantage of this network is high energy efficiency for the sensor nodes. Energy waste is reduced by decreasing the number of unnecessary wake-ups and the time used for sensing the channel. The packet delay in the data MULE architecture is related to both the mobility behavior of the MULEs and the wake-up range of a MULE. Therefore, in order to evaluate the performance of our sensor network, the effective wake-up range of the WISP-Mote is required, which will be addressed in the next section.

In some other applications, data collectors can be set at specific locations and wake up the nodes when the nodes move close to the data collectors. These types of applications are discussed in Section 6.

4. Characterization of WISP-Mote

Field tests to determine the capabilities of our WISP-Mote are important to guide the design of appropriate protocols and the performance evaluation of the overall system. We perform field tests to characterize the wake-up probability of a WISP-Mote as a function of height and distance to the reader.

There are two main factors that have a very large effect on the wake-up probability in a real world implementation. The first is the distance from the reader to the WISP. The energy that a WISP is able to harvest is inversely proportional to the square of the distance due to path loss (assuming a free-space environment). When the harvested power is enough for the WISP to drive its MCU, the WISP will perform its function (either decoding the packet to check for the ID or automatically waking up the mote), otherwise it will remain asleep.

The second factor is the environment where the system is located. The environment plays a critical role because reflections can have large effects on the wake-up probabilities at different areas in the three dimensional space in front of the reader. The line-of-sight signal and reflections meet, and create constructive areas and destructive areas depending on their phase differences. In certain locations, there are destructive effects, causing dead zones where the node is unable to be awakened. There will also be constructive effects resulting in locations with much higher wake-up probabilities than the locations that are closer to the reader.

Because the ID-based wake-up scheme has higher energy consumption than the broadcast-based one, theoretically it should have a slightly reduced effective range in all environments. The main goal of this testing was to explore what is the effective range of both schemes, and to provide numerical support for later analyses of the trade-offs between wake-up radio based networks and duty-cycling networks.

This section will cover three different environments with both ID-based and broadcast-based wake-up to demonstrate the effects of distance and environment. We measure the wake-up probability as a function of distance and height to a reader in a hallway and an open-air environment, and the average wake-up probability as a function of distance in an office environment. The measurements are used in the network simulations described in Sections 5 and 6.

4.1. Experiment setup

We set up our experiments as follows. The reader is raised off of the ground to a height of 84 cm to reduce reflective effects due to the ground close to the reader. The height of 84 cm was chosen purely for convenience in the experimental set-up. Due to the necessity to vary both distance from the reader and height, the WISP-Mote was attached to a tripod, which allows both x-axis movement, towards and away from the reader, and y-axis movement, up and down with respect to the reader.

For the broadcast-based wake-up scheme, the data collector broadcasts a generic wake-up signal that causes every WISP-Mote receiving this signal to accumulate energy to wake up. After waking up, the WISP-Mote sends a packet to the data collector, which also includes a wake-up count. After sending the packet, the WISP-Mote promptly returns to sleep. In our single WISP-Mote field tests, no ACKs or back-offs are implemented, since the backward link quality is good (mote-to-data collector) compared to the forward link quality (data collector-to-tag) and since there is no contention in the network.

To calculate the wake-up probability, we set up the system as follows. Since we cannot control the commercial RFID reader to send a wake-up signal at particular times, instead we have the RFID reader send a continuous wave. To count the number of times that a WISP-Mote is able to be awakened by this continuous wave, we periodically enable the interrupt from the wake-up signal input port once every 0.5 s and disable it after the mote is awakened by the WISP. As a result, WISP-Motes can wake up as long as the wake-up receiver is harvesting enough power and the interrupt is enabled. The reader is then run for a fixed amount of time, in this case 100 s, and the final wake-up count sent by the WISP-Mote is recorded. We can then calculate the wake-up probability of the investigated scenario by dividing the observed number of wake-ups to the total possible wake-ups, i.e., 200 wake-ups.

The ID-based wake-up experiments were conducted in an identical manner, except that instead of simply broadcasting a generic wake-up signal, the data collector transmits an ID, against which the WISP compares its own ID before deciding whether to wake up the mote or not.

4.2. Wake-up probability

4.2.1. Open environment

The purpose of the open environment tests was to extract the WISP-Mote wake-up characteristics in an area with very few reflecting surfaces. This environment could be a large indoor area, or an outdoor area, but for testing purposes a large gymnasium was used.

Fig. 2 shows the test results for the broadcast-based wake-up in an open environment. The y-axis of the graph shows the vertical distance between the WISP-Mote and

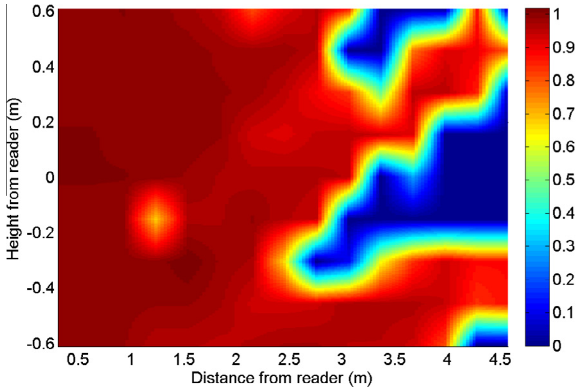

Fig. 2. Broadcast-based wake-up probabilities in an open environment.

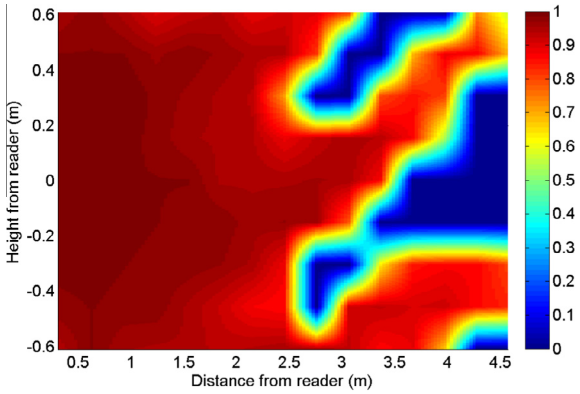

Fig. 3. ID-based wake-up probabilities in an open environment.

the data collector, and the *x*-axis shows the horizontal distance between the WISP-Mote and the data collector. The data collector is located at point (0,0) on the graph. The colors[1] at each point represent the wake-up probability at that particular point. As seen in Fig. 2, the WISP-Mote has almost 100% wake-up probability for all points within 2.5 m, and after that point, reflections from the ground start to have a significant effect on the wake-up probability. These reflections appear to match the two-ray ground model, and there are clearly areas where destructive interference creates dead zones, as well as areas where constructive interference enables 100% wake-up probability far from the data collector.

Fig. 3 shows the test results for the ID-based wake-up in the open environment. As expected, there has been a slight decrease of the wake-up range from the 3 m of the broadcast-based scheme down to 2.5 m for the ID-based one at a height of 0.2 m above the data collector. However, generally the ID-based scheme has a similar performance to the broadcast-based scheme in this environment. As in the broadcast results, the effect of the wake-up signal reflected from the ground is also evident in these results.

4.2.2. Closed environment

When such pronounced reflective effects are witnessed in an environment with only one reflective surface, it can be hypothesized that even more significant and far more unpredictable reflections will occur in a closed environment. The next set of tests took place in a long hallway.

As can be seen in Figs. 4 and 5, a closed environment vastly increases the amount of interference among the multiple copies of the received signal. For the broadcast-based wake-up, 100% wake-up only occurs at any height for only very small distances from the reader, and for ID-based wake-up, even at close distances, the impact of reflections is obvious.

4.2.3. Cluttered environment

In real-life applications, it is more likely that the sensor network will be deployed in a cluttered environment such as an office, a warehouse or a store. For the cluttered environment, it was infeasible to set up the in depth systematic tests as for the previous two environments, due to physical obstacles. Instead, the average wake-up probability was tested at different distances from the data collector. For each distance on the plots, ten measurements were taken in various spots within an office and then the average value is plotted.

Although not shown in the same detail as the previous graphs, Fig. 6 does illustrate that even more interference is occurring in the cluttered environment than in the previous two environments for both broadcast-based and ID-based wake-up. No wake-up was recorded at or outside of the 3 m mark, anywhere in the room. As the data show, the WISP-Mote has a relatively stable wake-up range in an open environment, a volatile but similar range wake-up in a closed environment, and a relatively shorter wake-up range in a cluttered environment.

4.3. Broadcast-based vs. ID-based wake-up

There are quite a few meaningful conclusions we can draw from this data about the differences between ID-based and broadcast-based wake-up, and also the effectiveness of the system as a whole. In every environment,

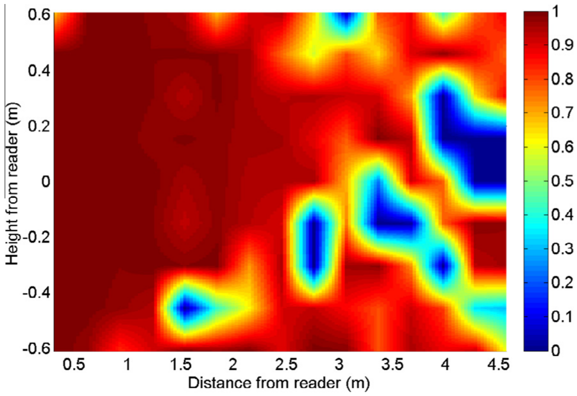

Fig. 4. Broadcast-based wake-up probabilities in a closed environment.

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[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.

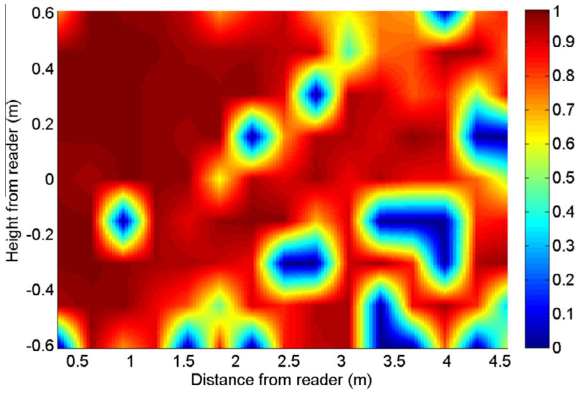

Fig. 5. ID-based wake-up probabilities in a closed environment.

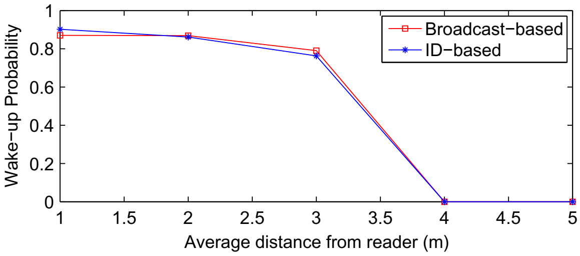

Fig. 6. Broadcast-based wake-up and ID-based wake-up probabilities in a cluttered environment.

comparing the average wake-up probabilities as a function of the distance from the data collector, we can see that the broadcast-based scheme results in slightly higher average wake-up probabilities. While the ID-based wake-up scheme sacrifices performance by a very small amount in terms of wake-up probability, it has the capability of waking up a particular class of nodes or an individual node.

If there are only specific nodes that need to be woken up, then ID-based wake-up can lead to significant energy savings, as it does not force all nodes to wake up and contend for the medium. In a scenario where all nodes serve the same purpose, then the usefulness of having ID-based wake-up may be reduced, but in the case where different nodes have different sensors and information, it may lead to very large savings in energy. In most scenarios, the very small sacrifice in wake-up range is less crucial than the increased functionality and possible energy savings. Detailed simulation-based performance analysis of the wake-up radio schemes will be provided in Sections 5 and 6.

To implement the ID-based wake-up, in some scenarios, the data collector has to know the node's ID so that it can wake up a specific sensor. One approach to enable the data collector to determine the nodes' IDs is to set a broadcast ID that can let the data collector wake up any node in the network. The data collector first uses the broadcast ID to wake up all the nodes in the nearby area and obtain their IDs. Then the data collector uses these node IDs to wake up each individual node one by one to acquire data from them if needed. Another approach that can be used in other scenarios, such as a health monitoring scenario, is to assign a group ID to classify various types of nodes (e.g., all heart monitor sensors are assigned an ID of 1, all blood oxygen sensors are assigned an ID of 2, etc.). The data collector only needs to know the group ID and is able to wake up the interested group of nodes on demand (e.g., any heart monitor in the area).

5. Simulations

As we introduced previously, the two challenges in the design of passive wake-up radio systems that limit their use in existing sensor network applications are the large energy cost of the wake-up transmitter and the short wake-up range. The power amplifier needed to send the wake-up signal requires a high power budget. However, most sensor network applications consist of low-power (usually battery-powered) sensor nodes and are expected to run for years. Notwithstanding the cost (which is also important in real systems), the huge power drain renders it hard to equip every node with a wake-up signal transmitter, e.g., in our system, the RFID reader. On the other hand, the limited wake-up range shortens the one-hop range. Therefore, currently, to achieve large network coverage, mobility is a necessity. Scenarios where the data collector moves to the sensors or the sensors move to the data collector are possible applications for our radio wake-up system. In the simulations in this section, we consider a data MULE scenario to compare the performance between our WISP-Mote RFID wake-up scheme and standard duty-cycling.

5.1. Simulation setup

We use MATLAB to simulate the performance of the WISP-Mote network and several duty-cycling networks (with duty cycles between 10% and 0.1%). In our simulations, we deploy static nodes according to a uniformly random distribution in a $200\,\text{m} \times 200\,\text{m}$ network, and we simulate 1 h of the network activities. We measure the latency, undelivered packet ratio, number of collisions, and energy as our performance metrics. For each option (WISP-Motes and duty-cycling), we run 20 simulations, where each simulation has a different random network deployment, and we plot the average value of each of the performance metrics.

We compare two sensor network systems, one with standard sensor nodes that employs duty-cycling and the other with the WISP-Motes that employs radio wake-up. Both systems have Data MULEs, i.e., mobile data sinks with a mote, an RFID reader (in the WISP-Mote network), and a very large power source. MULEs start with random locations and move according to a random direction mobility model. Each MULE uniformly randomly selects a speed from $[5\,\text{m/s}, 15\,\text{m/s}]$ and moves towards a direction chosen uniformly randomly from $[0, 2\pi]$. Whenever the MULE reaches the field boundary, it chooses another speed and direction randomly.

In the duty-cycling scenario with standard sensor nodes, each MULE broadcasts a beacon signal, which is actually a short packet, to indicate its presence to the nodes. On the other hand, in the radio wake-up scenario with WISP-Motes, each MULE sends out a wake-up signal continuously. The sensors will wake up with a probability related to the distance between the sensor and the MULE. The wake-up probability is calculated by the average value at each distance according to our field test results in Section 4. We have six wake-up probability models corresponding to broadcast-based wake-up and ID-based wake-up in an open environment, in a closed environment, and in a cluttered environment. We consider the broadcast-based wake-up probability model in an open environment in this section to provide general performance comparisons. Other wake-up probability models are used in other example applications in Section 6.

We describe the algorithms for both the WISP-Mote scenario and for the duty-cycling scenario in Algorithms 5.1 and 5.2. A non-persistent CSMA MAC protocol is used for both scenarios. It is important to note that both scenarios may benefit from more efficient protocols. However, designing a MAC layer protocol is not the focus of this paper. We choose a simple wake-up radio MAC protocol and a simple duty-cycling MAC protocol to facilitate the understanding of the benefits of using a wake-up radio in a sensor network.

In the WISP-Mote sensor network, once a sensor node is awakened by the MULE, it performs carrier sensing. If the channel is free, it transmits a packet. If not, it will back off for a random time.

For duty-cycling, a MULE has to announce its presence by sending out a beacon signal. When the MULE is not communicating with any sensor node, it sends a beacon signal once every 8 time slots and listens for responses during the remaining 7 time slots In our simulations, the transmission of a packet takes 6 slots and an ACK packet takes 1 slot. Once a sensor node is in the active part of its duty cycle, it will first listen to the channel for the MULE's beacon signal for 8 time slots in order to guarantee not missing the beacon signal if a MULE is nearby. If no beacon is received during this period of time, the node will go back to sleep. To reduce the chance of collisions, if the node receives a beacon signal, it will randomly select a time slot from the following 7 time slots to transmit. However, note that collisions may still occur due to the hidden terminal problem and due to the fact that nodes that are woken up by the same beacon may happen to select the same slot for transmission.

For both scenarios, the node will receive an acknowledgement (ACK) once the packet is received by the MULE. Based on the reception of an ACK, the sensor node can deduce two important facts: (1) the MULE is still close by; and (2) the channel was free of collisions. Therefore, in the next time slot, it is highly probable that the MULE is still within the communication range of the node. Therefore, a node that receives an ACK and has additional packets to send will continue to send packets, once again following the non-persistent CSMA MAC protocol regardless of whether it receives a wake-up signal. After the node starts sending the second continuous packet, it will stop sending and go back to sleep or its duty-cycling schedule when a collision occurs.

For energy efficiency considerations, when a node does not have any buffered data, for the WISP-Mote wake-up scheme we disable the wake-up interrupt, and for the duty-cycling schemes we stop the wake-up timer, as there is no need for the node to wake up. In addition, for both schemes we apply a binary exponential backoff to reduce the chances of collisions when an ACK is not received after sending data.

According to the algorithms, it is obvious that the wake-up radio sensor network does not consume energy on listening to the beacon signal. Therefore, when the MULE is not nearby, the wake-up radio node has zero energy consumption while the duty-cycling node still wakes up periodically to check for a beacon signal. However, we cannot simply assert that the wake-up radio network has better energy efficiency because energy efficiency is also affected by collisions and dropped packets, which are more complicated to analyze. We will discuss this (as well as other performance metrics) in the rest of this section and Section 6.

To simplify the simulations, we made the following assumptions.

- Propagation delay is ignored.
- Link is ideal (i.e., a packet is correctly received unless a collision happens).
- We assume that MULEs have the ability to communicate directly to the BS and ignore the MULE-BS latency. Therefore, packet delay is counted from the time a packet is generated until the time it is delivered to a MULE.
- We only consider the delay of delivered packets.
- We ignore the energy costs for sensing activities as they will not impact the performance evaluation.
- The mote's communication range is set to 40 m based on experiments described in [23] as well as our own field experiments.

In all simulations (except the limited buffer simulations), we evaluate the network performance in terms of: (1) the average latency per delivered packet, (2) the number of packets that remain in the buffer at the end of the simulation time (undelivered packet ratio, UPR), (3) the average collisions per delivered packet (where collisions are counted whenever two or more nodes try to send packets to the same MULE at the same time), and (4) the average energy consumption for delivering a packet. In the limited buffer simulations, we investigate the average buffer size and the packet delivery ratio (PDR) instead of (2) and (3).

5.2. Performance results

5.2.1. Effects of packet generation rate

In this set of simulations, we deploy 80 nodes in a 200 m × 200 m area, each node has an unlimited buffer size (the effect of limited buffer size is investigated in

Section 5.2.3), and we use 1 data MULE. The packet generation rate is varied between 0.2 pkt/min and 2 pkt/min. Fig. 7 shows the performance comparisons of six sensor network scenarios, five of them employing duty-cycling with different duty cycle values and a radio wake-up scenario with WISP-Motes. The results show that the 10% duty-cycling scheme has the best performance in terms of packet delay and UPR, while its energy efficiency is very poor compared to the other scenarios. At 0.2 pkt/min, 10% duty-cycling consumes about 6 times more energy than the other duty-cycling schemes for delivering 1 packet (380.8 mJ vs. 62.0 mJ) and about 88 times more energy than the WISP-Motes network (380.8 mJ vs. 4.3 mJ). This low energy efficiency is caused by a large amount of idle listening.

From Fig. 7, we can see that the latency, UPR and energy performance of both the WISP-Mote network and all duty-cycling networks are relatively stable for all packet generation rates investigated. The sensor nodes with lower duty cycles are not able to deliver packets to the MULE fast enough. Therefore, at the end of simulation, these nodes have more undelivered packets in their buffers, and hence a higher UPR. When the packet generation rate increases, the latency per delivered packet and the UPR only increase slightly. This is because in both algorithms, once a node successfully transmits a packet, the node is able to continuously transmit multiple packets until the MULE is out of the node's communication range or a collision occurs. As the results show, the WISP-Mote node has fewer collisions to successfully transmit a packet. This is because the short wake-up range of the WISP-Mote leads to fewer nodes awake at the same time compared to the duty-cycling network.

Algorithm 5.1.

```
Radio Wake-up Algorithm                              Energy Cost
for node $i = 1 \rightarrow N$ do
  if i has buffered data then
    if i is awakened by the MULE                     $E_{Wakeup}$
      or i has successfully Tx-ed a pkt then
      sense the channel                              $E_{CS}$
      if the channel is free then
        send one packet to the MULE;                 $E_{TxPkt}$
        if ACK Rx-ed then                            $E_{RxACK}$
          keep awake; $C = 3$;
        end if
      else if channel is busy or ACK is not Rx-ed then
        back off for a random number of
          time slots chosen from $[1,2^C]$;
        $C{+}{+}$; (*)
      end if
    else
      sleep;
    end if
  end if
end for
*$C = 3$ at the beginning, $C \in [3,8]$;
```

Algorithm 5.2.

```
Duty Cycling Algorithm                                  Energy Cost
for node $i = 1 \rightarrow N$ do
  if i has buffered data then
    if i is in the active period                        $E_{Wakeup}$
      or i has successfully Tx-ed a pkt then
      listen for beacon for up to 8 slots               $E_{Beacon}$
      if beacon signal Rx-ed then
        back off for $[1,7]$ slots
        sense the channel                               $E_{CS}$
        if the channel is free then
          send one packet to the MULE                   $E_{TxPkt}$
          if ACK Rx-ed then                             $E_{RxACK}$
            keep awake; $C = 3$;
          end if
        else if channel is busy or no ACK is Rx-ed then
          if i has Tx-ed a pkt in this active period then
            start the sleep period of the duty cycle;
          else
            back off for a random number of time slots
            chosen from $[1,2^C]$; $C{+}{+}$; (*)
          end if
        end if
      else
        start the sleep period of the duty cycle;
      end if
    end if
  end if
end for
* $C = 3$ at the beginning,$C \in [3,8]$;
```

The major advantage of the sensor networks employing passive radio wake-up is their energy efficiency. From the energy consumption results, we can see that 10% duty cycling has poor energy efficiency due to regular beacon signal listening, idle listening and collisions. The energy consumption per packet for the WISP-Mote network (4.3 mJ) is about 1/4 of the lowest energy consumption per packet for all the duty-cycling scenarios investigated (16.4 mJ). For two 2800 mAh alkaline batteries, the WISP-Mote can transmit more than 7 million packets, if not counting the sensing energy consumption. At 1 packet per minute data rate, the lifetime of a WISP-Mote may last more than 13.4 years, while the lifetime for the best duty-cycling approach is only 3.5 years.

5.2.2. Effects of node density

Fig. 8 shows the performance of the network as the node density increases from 0.002 to 0.02 node/m^2, with a packet generation rate of 1 pkt/min, unlimited buffer

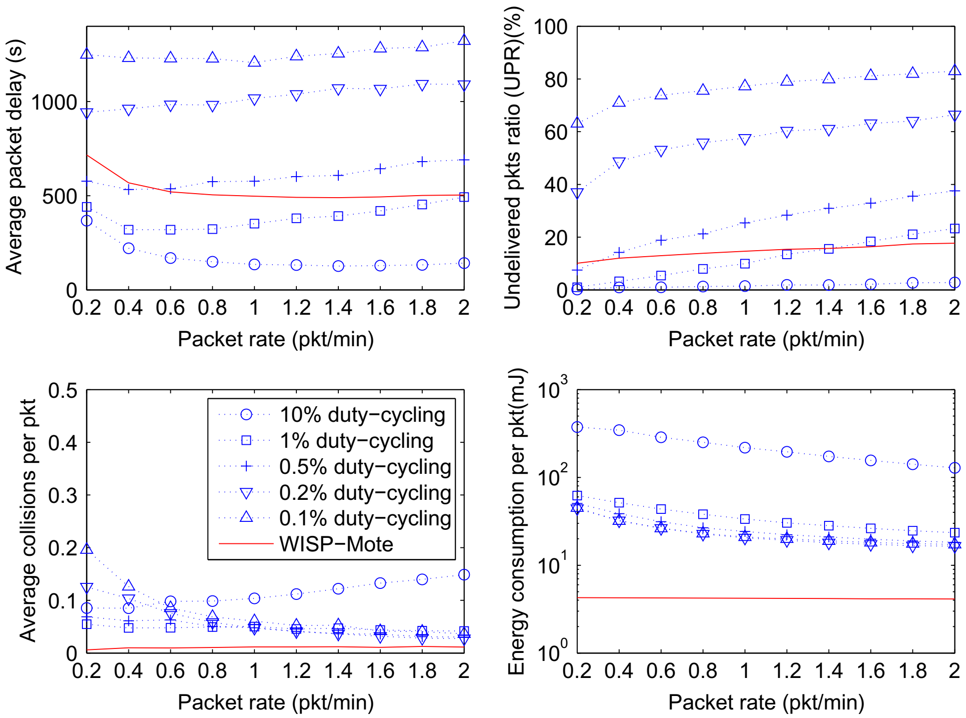

Fig. 7. WISP-Mote vs. duty-cycling with increasing packet rate (0.002 nodes/m^2, 1 data MULE, unlimited buffer).

size, and 1 data MULE. In other words, we increase the network from 80 nodes to 800 nodes, all of which are distributed in the 200 m × 200 m area. In our simulations, the nodes are not synchronized. For the duty-cycling sensor network, every node has a timer that is set randomly at the beginning of the simulation. Therefore, the lower the duty cycle is, the less chance nodes wake up at the same time, which will reduce collisions.

As we can see, the 10% duty-cycling scenario is greatly affected by node density in that the chance of collision for 10% duty-cycling is much higher than the other cases. Therefore, as the node density increases, the number of collisions of 10% duty-cycling increases significantly from 0.1 collisions per delivered packet to 1.6 collisions per delivered packet. Additionally, the packet delay increases from 134.8 s to 1110 s and the UPR increases from 1.7% to 62.6%. While the other duty-cycling networks have smaller probabilities of collisions, but we can see that their performances decrease much faster than the WISP-Mote network's performance.

At a high node density of 0.02 node/m^2, the WISP-Mote network outperforms the duty-cycling networks in delay, UPR, collisions and energy efficiency. It is expected that with even higher node density, the performance differences will be even more significant. Because of the limited wake-up range, the chance of the hidden terminal problem and multiple nodes being simultaneously awakened and selecting the same transmission slot is very low. Thus, the performance of the WISP-Mote sensor network decreases slower than the duty-cycling sensor networks when the node density increases.

5.2.3. Effects of buffer size

In the previous simulations, we assumed each sensor node had an unlimited buffer. In other words, the node will never drop a packet even if it cannot deliver all the packets before a new one arrives, and hence the node accumulates more and more packets. This, however, is not realistic and is not reasonable for certain applications, e.g., applications that only care about the recently updated sensed data. Thus, in this subsection we consider limited buffer sizes and investigate the effect of buffer size on the network performances.

In these simulations, we set the buffer size to be a small value, 10 packets, in order to show the impact of increasing packet rate given a fixed-size buffer. In real life, to have a higher packet delivery performance, the buffer size must be larger at the expense of longer packet latency. As the average packet delay only includes delivered packets, dropped packets are excluded from the packet latency calculations.

We can see from Fig. 9 that the packet delay decreases as the packet rate increases. The reason is that more and more old packets are dropped due to the limited buffer size and these dropped packets are not included in the calculation of the packet latency. The upper right subplot of Fig. 9 shows that the PDRs consistently decrease as the packet rate increases, which is reciprocal to the average buffer usage in the lower left subplot. The energy consumptions for the duty-cycling and WISP-Mote schemes are consistent with the previous results.

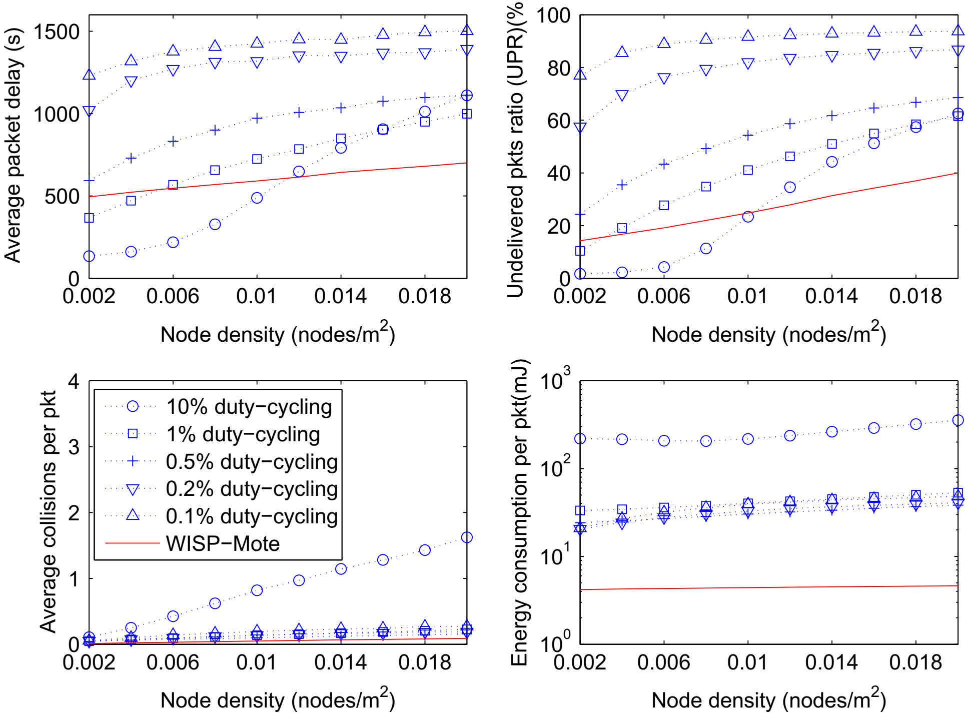

Fig. 8. WISP-Mote vs. duty-cycling with increasing node density (1 pkt/min, 1 data MULE, unlimited buffer).

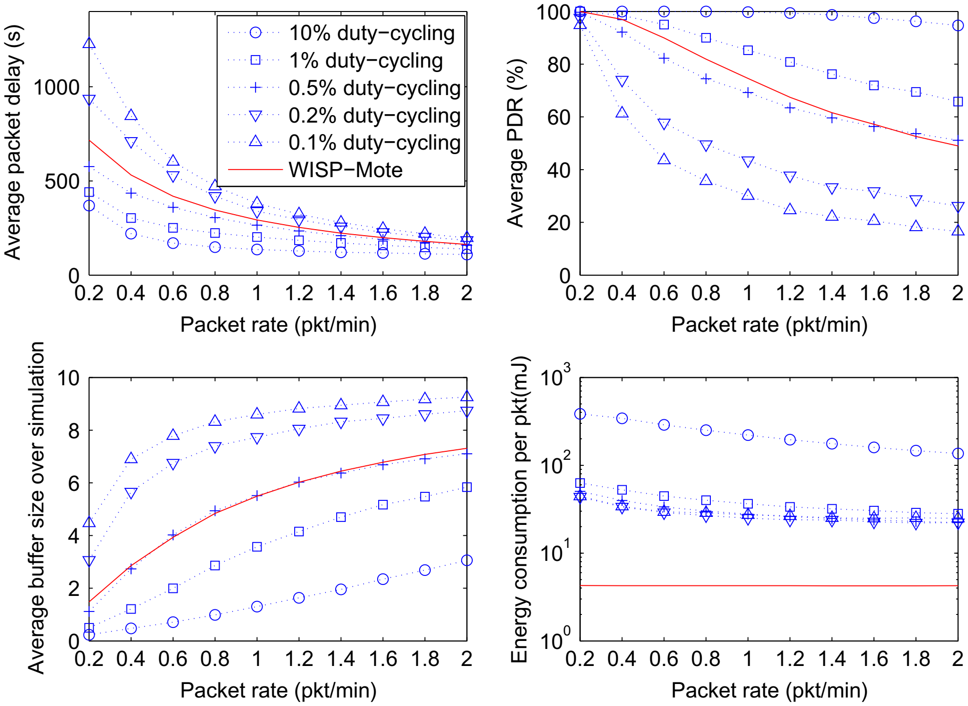

Fig. 9. WISP-Mote vs. duty-cycling with limited buffer size (0.002 nodes/m^2, 1 data MULE, buffer size = 10 pkts).

5.2.4. Effects of the number of data MULEs

The data MULE sensor network performance depends on both the properties of the sensor nodes and the characteristics of the data MULEs. The packet delay and UPR are related to how fast the MULE(s) can sweep over the entire network. The moving speed of a data MULE is clearly correlated to the network performance. The faster the MULEs move, the lower the latency and the undelivered packet ratio that can be achieved.

A more interesting investigation is the effect of the number of MULEs. Besides packet collisions, the beacon signal and ACKs sent by the MULEs can also collide. Since the WISP-Mote does not need to receive a beacon signal to be informed of the MULE's appearance, it will not be affected by beacon signal collisions. Furthermore, the wake-up range is much smaller than the communication range in the WISP-Mote network. This greatly reduces the probability of MULE-node link collisions for the multi-MULE scenarios.

As Fig. 10 shows, the latency and UPR both perform better when there are more MULEs in the network. When there are multiple MULEs on the field, there are chances that one node is talking to multiple MULEs. In this case, the ACKs will collide and the node will have to retransmit the packet. We also consider these as collisions. At the same time, when the number of MULEs increases, the nodes can transmit packets more efficiently. Therefore, the average collision per packet delivery remain stable when there are multiple MULEs in the field.

For the duty-cycling scenario, the energy consumption to deliver one packet drops because the nodes are wasting less energy on idle listening when there are more MULEs (since they do not wake up when they have no data to send). On the other hand, the energy efficiency for the WISP-Mote network remains quite stable. From the results, we can conclude that trading off with more infrastructure cost, we can achieve better performance by placing more data MULEs in the network.

5.2.5. Effects of the mobility model of the data MULEs

The MULE's mobility pattern is another factor that has impact on the sensor network performance. We can expect that the best prescheduled route is to let the MULE directly go to the nodes one by one, but that would require pre-knowledge of the network topology (which may not be available for certain types of applications), and would introduce extra complexity to the MULE.

In our simulations, we compare three different mobility models for the WISP-Mote scenario: Random Walk, Random Direction, and Snake Path. The Random Direction algorithm has been described in Section 5.1. For the Random Walk algorithm, each MULE selects a speed from [5 m/s, 15 m/s] and moves towards a direction chosen from $[0, 2\pi]$ for a period of time chosen from [0, 10 s]. All these selections are done in a uniformly random manner from the intervals given. In the Snake Path algorithm, each MULE sweeps over the entire field by following a snake-shaped route with a constant speed of 10 m/s.

As we can see from Fig. 11, the MULE with Snake Path algorithm has a higher efficiency of covering the entire network. The Random Walk algorithm is slightly worse than the Random Direction algorithm. When there are five MULEs, the network with 5 MULEs using the Snake Path algorithm can deliver 99.3% of the packets with an average latency of 112 s per packet, whereas the Random Direction mobility model has a latency of 156 s with 98.0% of the packets delivered. As for collisions, MULEs with prescheduled routes also outperform the other two approaches. Therefore, using data MULEs with prescheduled routes is the most efficient for collecting data from the sensors.

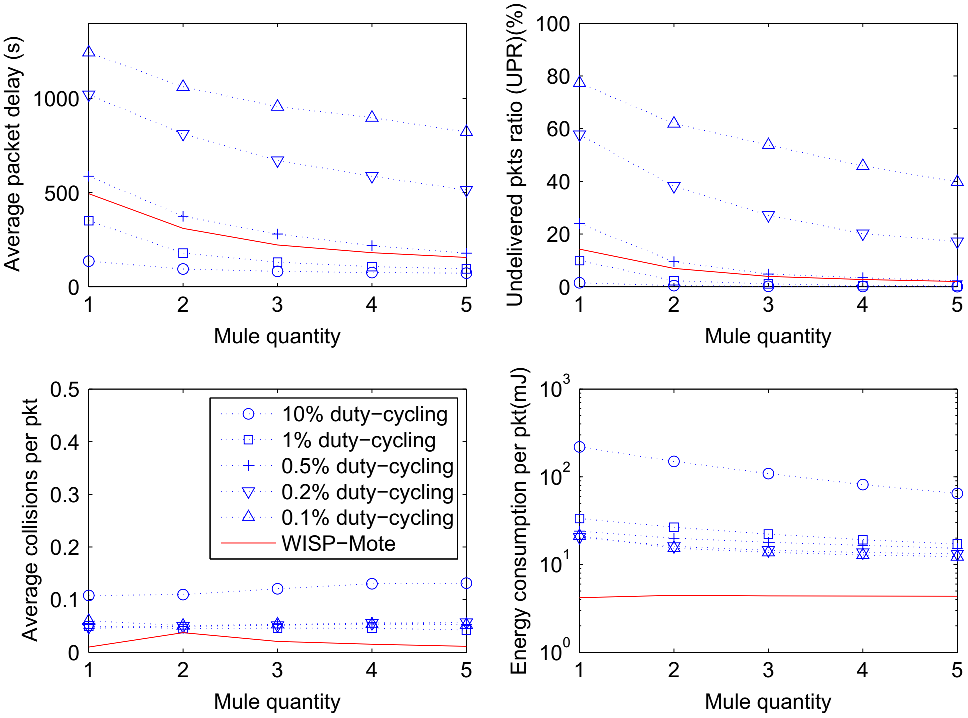

Fig. 10. WISP-Mote vs. duty-cycling with increasing MULE quantities (0.002 nodes/m^2, 1 pkt/min, unlimited buffer size).

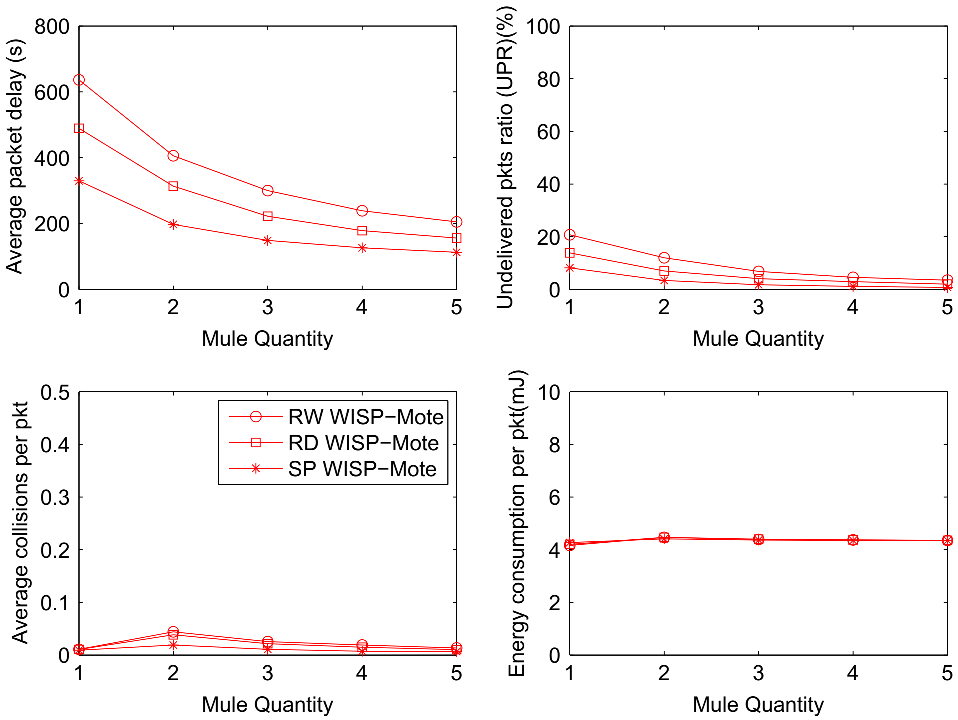

Fig. 11. Comparisons among different mobility models for the data MULE; RW = Random Walk, RD = Random Direction, SP = Snake Path (0.002 nodes/m^2, 1 pkt/min, unlimited buffer size).

6. Applications that can benefit from WISP-Motes

The applications that can benefit from passive wake-up radio sensor networks are determined by the characteristics of the network in terms of transmission range, asymmetric energy consumption values, and the equipment costs of the receiver and the transmitter. Considering the hardware costs and the energy constraints, it is expected that there will only be a few powerful nodes in a sensor network that have the capability to wake up the other nodes in realistic applications. Even if all the sensors are assumed to have enough energy, the wake-up range is relatively short due to path loss and the efficiency of power harvesting at the receiver. As a result, to cover a large area of sensor nodes, either the wake-up signal transmitter has to be mobile to wake up the sensor nodes and collect data, or the sensor nodes have to be mobile to move to the base station to deliver data. Based on these features and constraints, we present several potential real-world applications that can benefit from passive wake-up sensor networks.

6.1. Health monitoring applications

Body area networks bring inexpensive health monitoring to different environments. Wake-up radio technology has great potential for such applications. According to the characteristics of wake-up radios, patient monitoring in long-term care facilities (e.g., a sanatorium or an assisted living facility), is a potential application. In these places, patients are cared for over a relatively long period of time and require non-emergency but long-term health monitoring (e.g., the data from the patients only need to be collected by nurses several times per day). Instead of using traditional health monitors, which connect to the patient's body with wires limiting his/her daily activities, each patient can be equipped with various wireless sensor nodes for collecting different physiological information, e.g., heart rate, blood pressure, blood glucose, and insulin level. With all the equipment (the wake-up transmitter, the data receiver, the computer, and the power source) carried in a trolley, a nurse can easily gather all the sensor data from patients while periodically traveling throughout the patients' rooms.

We performed simulations for this scenario to compare the performance of duty-cycling, broadcast-based wake-up and ID-based wake-up. 1% duty-cycling is chosen for the duty-cycling scenario, as it has similar latency and packet delivery performance as the wake-up scheme in the previous data MULE scenario simulations. The wake-up probability models used for broadcast-based wake-up and ID-based wake-up are built based on our closed environment field test results.

We assume there are 36 rooms, each with an area of 20 m × 20 m. A "nurse" goes from room to room with a speed of 1 m/s to collect data from the 4 sensors on each patient. We also set the nurse with 20% probability of pausing while moving. The ID-based wake-up is beneficial in this scenario, since there are multiple nodes on each patient's body. If a broadcast-based wake-up is used, all of the nodes on a patient will be awakened with probability calculated based on our closed environment field test results, which would cause congestions. Therefore, waking up the nodes one by one based on their type (or patient

ID in other cases) will greatly reduce the chance of collisions and hence extend the nodes' lifetime.

The simulation results confirm our expectations. As we can see from Fig. 12, the delay for the three scenarios are generally about the same. However, both the WISP-Mote networks can deliver more packets than the 1% duty-cycling and consume about 5 times less energy. In terms of collisions, broadcast-based wake-up, as expected, has the highest number of collisions, which somewhat decreases its energy efficiency. ID-based wake-up, on the other hand, has zero collisions and consumes a little less energy (4.3 mJ/pkt) than broadcast-based wake-up (4.8 mJ/pkt). Overall, in the health-monitoring scenario, ID-based wake-up is the most energy efficient scheme with competitive performance in terms of delay and UPR.

6.2. Environmental applications

Wildlife monitoring is one of the potential applications for passive wake-up radio sensor networks. A branch of zoology research investigates the behavior of or interactions between species. It is important to gather information on individual animals such as their locations or physiological data, as well as environmental information such as temperature and humidity, to understand the effects of the environment and influences from other species.

The cost of collecting data by equipping animals with sensor nodes is much lower than the cost of other approaches, e.g., volunteers. However, it is usually difficult for scientists to retrieve the sensor nodes from wild animals for battery replacement or recharging individually. Hence, the energy-efficient operation of the sensor nodes is crucial, which is the main motivation for using the radio wake-up technique.

Scientists may put sensor nodes on the animals, e.g., using a sensor collar, as done by researchers in the ZebraNet project [24], and place data collectors (equipment including a wake-up signal transceiver, data transceiver, and large energy supply) at places where the animals are expected to congregate, such as ponds and rivers, or where the animals are expected to roam. When the animals get close to the data collector, the radio on them will be awakened and start transmitting the gathered sensor data to the data collector. Since the sensor nodes may last for years, the battery retrieval and replacement costs can be saved.

We simulate this scenario by assuming a 1000 m by 1000 m area with a pond at the center. Assuming animals will tend to come to the pond for water, we set a data collector at the pond sending out a broadcast-based wake-up signal continuously. Animals equipped with WISP-Mote sensor devices roam around this area and irregularly go to the pond for water. When the animals are roaming, they follow a random walk mobility model with average speed of 5 m/s. After a uniform random period of time with mean value of t_r, they move toward the pond and stay there for another uniform random amount of time with mean of t_s.

The ratio $R = t_s/t_r$ impacts the network performance as is shown by the results below. A larger ratio of R represents a longer stay at the pond, and as we can see from Fig. 13, this results in a lower packet latency. For duty-cycling, lower packet delay means less idle listening. In other words, the energy waste is reduced and hence the energy efficiency is increased.

On the other hand, for the WISP-Mote scenario, the average number of collisions before a successful packet delivery is much higher than for duty-cycling. Yet, the undelivered packets and the energy consumption of the WISP-Mote scenario is much lower than the 1%

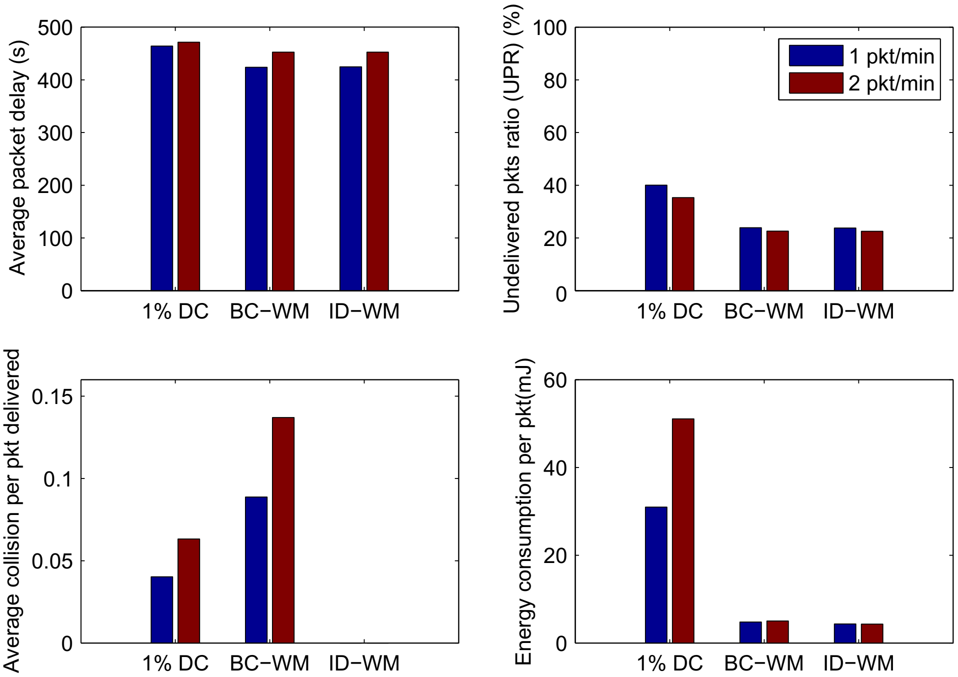

Fig. 12. Patient monitoring scenario (unlimited buffer), "BC-WM" stands for Broadcast-based WISP-Mote, "ID-WM" stands for ID-based WISP-Mote.

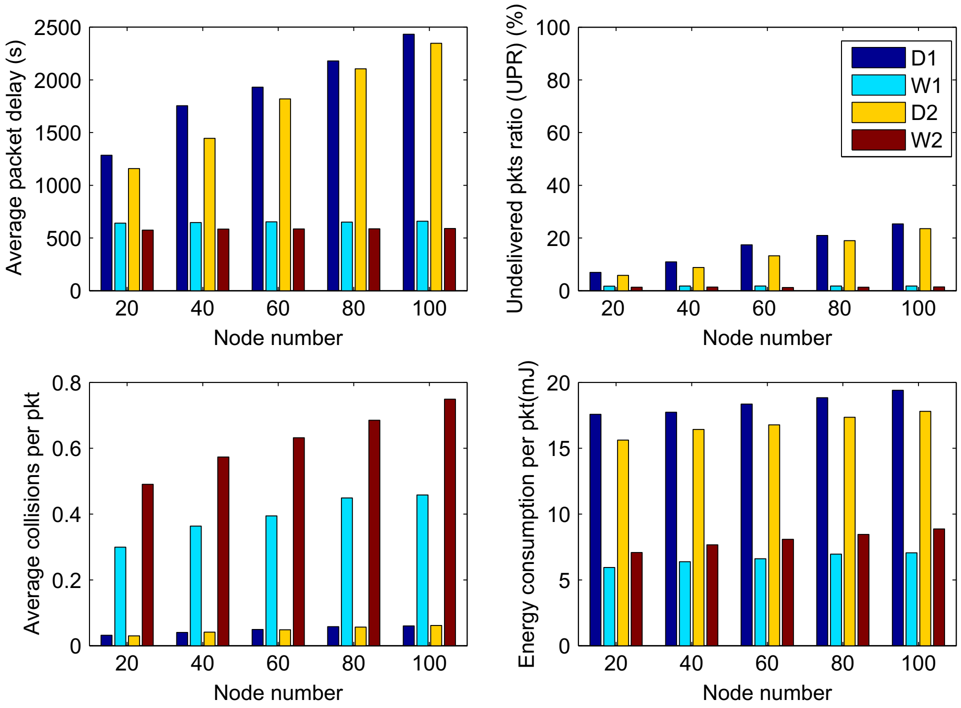

Fig. 13. Animal monitoring scenario; D1 = 1% Duty-cycling with $R = 1$, W1 = WISP-Mote with $R = 1$, D2 = 1% Duty-cycling with $R = 2$, W2 = WISP-Mote with $R = 2$ (0.2 pkt/min, buffer size unlimited).

duty-cycling scenario. This scheme will suffer from collisions if the number of nodes is large. As we can see, in this scenario, when R and the number of nodes increase, the average number of collisions per packet increases dramatically, which results in a decrease in the energy efficiency. One way to improve the network performance is to add a random delay before a WISP-Mote node performs carrier sensing. The maximum value of the delay should be adjusted according to the number of nodes in the network, which provides a good estimate of the probability of collision in practice. Since our goal for this paper is not to design an application specific protocol, we do not optimize the WISP-Mote algorithm here.

6.3. Other potential applications

Intelligent Transportation System (ITS) is a very promising application that aims to improve traffic safety while providing other benefits such as reducing fuel consumption and latency. Using transportation facilities to collect sensor data throughout the city, i.e., urban monitoring [25], can be part of the ITS. The sensor data may include traffic conditions and weather information that will be helpful for congestion avoidance and improving traffic safety. Battery powered sensor nodes can be easily attached to traffic lights, bus stations, toll booths, and traffic signs and may work for years due to the energy efficiency improvements from using wake-up radios. Buses, trains and garbage trucks are good candidates for performing data collection duties, as they can cover a fairly wide area [26,27] and they have no energy limitations so that transmitting a powerful wake-up signal is not a problem.

7. Conclusions

In this paper, we presented a novel device that utilizes current commercial sensor nodes and programmable RFID tags to implement a passive wake-up radio sensor network. Field tests in various environments are performed to characterize the wake-up probability as a function of distance between the wake-up transmitter and receiver. The results indicate that the wake-up radio performs the most stable as distance increases in an open environment compared to a closed environment and a cluttered environment. The results also prove that the wake-up range is very limited compared to the ZigBee-compliant sensor mote communication range. In addition, the radio wake-up transmitter requires high energy consumption that cannot be applied to all the sensor nodes considering the hardware cost and the energy budget. Both of these introduce a coverage problem.

To extend the sensor network coverage, mobility has to be introduced into passive wake-up radio based networks. We conduct detailed investigations on a data MULE scenario to study the impacts of packet generation rate, node density, node buffer size, MULE quantity, and MULE mobility model on network performance. The simulation results indicate that in the mobile scenarios we investigated, the passive wake-up radio sensor network achieves significantly better energy efficiency than duty-cycling. Furthermore, potential applications of passive wake-up radio sensor networks are discussed, and simulations are performed based on two specific application scenarios. The results reveal that passive wake-up radio sensor networks have comparable packet latency and packet delivery performance while greatly improving the energy efficiency.

Increasing the RFID reader-to-tag communication range will improve the performance of passive wake-up radio networks. The directional antenna and beam forming technique mentioned in [9] provide a possible solution to extend the wake-up range without increasing the wake-up transmitter power. As another approach, Omni-ID Corporation [28] has developed a patented technology called a “plasmatic structure” that captures incoming RF waves and creates a region of highly concentrated energy around the RFID, greatly extending the operational range.

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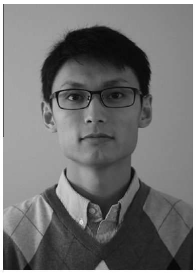

He Ba is a Ph.D. student at the University of Rochester in the Electrical and Computer Engineering Department. He received his B.S. degree from the Department of Electrical Engineering at Beijing Institute of Technology in 2008 and his M.S. degree from the Electrical and Computer Engineering department at the University of Rochester in 2011. His research interests lie in the areas of wireless communications, mobile computing and digital signal processing.

Ilker Demirkol is a postdoctoral research associate in Telematics Engineering at Universitat Politecnica de Catalunya, where he works on wireless networks, including wireless mesh, ad hoc and sensor networks, along with the wake-up radio systems. His research targets communication protocol development for aforementioned networks, along with performance evaluation and optimization of such systems. Demirkol received his B.Sc., M.Sc., and Ph.D. degrees in Computer Engineering from the Bogazici University, Istanbul, Turkey. Over the years, he has worked in a number of research laboratories and corporations, including University of Rochester and Baan Business Systems. He has held several positions both in academia and industry as Network Engineer, System and Database consultant, and Lecturer.

Wendi B. Heinzelman is a professor in the Department of Electrical and Computer Engineering at the University of Rochester, and she holds a secondary appointment in the Department of Computer Science. Dr. Heinzelman also currently serves as Dean of Graduate Studies for Arts, Sciences and Engineering at the University of Rochester. Dr. Heinzelman received a B.S. degree in Electrical Engineering from Cornell University in 1995 and M.S. and Ph.D. degrees in Electrical Engineering and Computer Science from MIT in 1997 and 2000, respectively. Her current research interests lie in the areas of wireless communications and networking, mobile computing, and multimedia communication.