Data Delivery Scheme for Wireless Sensor Network Powered by RF Energy Harvesting

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***Abstract*—Wireless Sensor Networks (WSNs) have traditionally been powered by portable energy sources, viz. batteries, which limit their operational lifetime. To ensure WSN sustainability, researchers have turned to alternative energy sources for power. Harvesting ambient energy to power WSNs is a promising approach but energy harvesting devices of the same footprint as wireless sensors are unable to provide sufficient energy for sustained operation; availability of energy is also highly unpredictable. Harvesting energy from radio waves can provide energy-on-demand using a radio transmitter to broadcast over the sensor network when the sensors need to be powered up to operate. However, only minute amounts of energy can be extracted from radio waves, presenting a monumental constraint in terms of the duty cycle and accomplishable tasks. We present our design of a data delivery scheme which aims to optimize the usage of the minute amounts of harvested energy through a sink synchronized protocol. The design has been implemented and experimentally validated utilizing commercially available RF energy harvesting devices.**

I. INTRODUCTION

Wireless sensor networks (WSNs) research has predominantly assumed that sensor nodes are powered by a portable and limited energy source, viz., batteries. Once a sensor's power supply is exhausted, it can no longer fulfill its role unless the source of energy is replenished. Therefore, it is generally accepted that the usefulness of a wireless sensor expires when its battery runs out. Battery-powered WSNs have some obvious disadvantages. Besides the need to replace the batteries (which can be infeasible at times), they also pose an environmental risk. This has led to the development of innovative new solutions that avoid using batteries, like harvesting ambient energy from the environment.

One emerging WSN application that can benefit significantly from the use of energy harvesting is precision agriculture [1] where sensor nodes are deployed outdoors to monitor soil conditions like temperature, moisture, and mineral content. In high value agricultural sectors, the information collected from the sensors can be used to manage the cultivation process to control pests and achieve high quality crops [2]. Energy supply remains a key limitation in agricultural WSNs where battery replacement can incur prohibitive costs, not to mention the potential of polluting the environment due to their heavy metal content. Conventional sources of ambient energy, like solar, wind, mechanical and vibration, are very dependent on the environment and this leads to a high level of unpredictability. On the other hand, harvesting energy from radio waves can provide energy-on-demand using a radio transmitter to broadcast RF signals over the sensor network when the sensors need to be powered up to operate. While this appears to be a promising solution, it has its limitations.

Current state-of-the-art RF energy harvesting (EH) technology is only able to harvest minute amounts of energy from radio waves, and with the exponential decrease in signal power over distance, the amount of energy that a node can obtain is very low if it is some distance away from the transmitter. When an RF signal propagates within a medium, it may be reflected, diffracted, and scattered. Each effect occurs to a different extent in various media, depending on factors such as wavelength and intensity of the wave, thickness and physical composition (permittivity and permeability) of the medium. Consequently, it is very difficult to estimate the amount of RF power that can be harvested at any location ahead of time.

With these challenges in mind, we design a data delivery protocol for a multi-hop WSN that is powered by RF EH. We adopt a sink-synchronized polling approach which aims to optimize the usage of the minute amounts of harvested energy available to sensor nodes. In the next sections, we discuss the related work on RF EH WSNs, followed by our protocol description and experimental validation process. We conclude with a discussion of prevailing challenges and open issues in RF energy harvesting powered WSNs, as well as areas for future research.

II. RELATED WORK

Research on network protocols for WSNs powered solely by EH [3] has only started to appear recently. Various Carrier Sense Multiple Access (CSMA)-based and polling-based medium access control (MAC) protocols have been evaluated in terms of throughput and fairness using simulations that used harvesting rate data obtained from empirical characterization of commercial EH devices [4]. The study also noted that nodes waiting to synchronize in slotted MAC protocols is counterproductive as energy is consumed while waiting and therefore needs to be replenished with longer harvesting periods, thus leading to lower throughputs.

While routing in WSNs with renewable energy sources has been studied [5], [6], [7], there are few specifically designed to support multi-hop data delivery in conditions where the energy harvested is insufficient to support the desired operations, which can lead to the sensors being forced into sleep mode or worse, losing timing synchronization and data, e.g.

the Energy Harvesting Opportunistic Routing (EHOR) protocol [8]. Furthermore, most if not all, assume that inactivity does not deplete any energy from the sensor which has been shown to be untrue; worse, leakage experienced by a charged supercapacitor increases with the amount of energy stored [9].

Energy-on-demand provided by RF EH has initiated some studies on its effect on routing [10] and MAC protocol design [11]. However, the minute energy that can be harvested and utilized in WSNs presents a monumental challenge to protocol design. In [10], the aim is to maximize throughput by routing through the nodes that are receiving more power from the energy source, namely, an RF transmitter. Using commercially available devices produced by Powercast [12], the authors measured the time taken to re-charge the 1mF capacitor on a P2000 series evaluation board using the Powercaster Transmitter. Based on this measured time, they validated their proposed scheme using simulation which assumes that nodes are re-charged and become active in perfect synchrony to transmit and receive packets in a multi-hop manner. A similar approach to modeling the RF EH process has been adopted in [11]. In this study, node synchronization is less of an issue as the target scenario is an adaptive MAC protocol for a single-hop WSN. In both studies, as well as others, many critical environmental factors involved in RF EH and synchronization of the sensor nodes have not been accounted for, which is typical of simulation-based studies.

Most reported work on WSNs using RF EH that have been experimentally validated are based on single-hop networks. A hardware design for utilizing RF EH in Zigbee-based WSNs has been proposed with algorithms for active and passive RF EH approaches [13]. Another study [14] demonstrated the effectiveness of harvesting energy television broadcast signals for use in WSNs and proposed a method to determine the duty cycle for the sensors which was validated using experimentation. As the EH efficiency is significantly influenced by the antenna, antenna design is focus of an RF EH system for outdoor soil monitoring in an agricultural WSN [2] where the aim is to minimize the size of the ground plane to meet the needs of the application. RF EH has also been proposed for a subsystem of a medical Wireless Body Sensor Network [15]. RF EH is used to provide energy to activate sensors which are idle thereby eliminating the need for sensors to expend energy to listen for activation signals. This scheme has also been experimentally validated with a prototype.

Our proposed design of a multi-hop WSN addresses the ultra low power constraints of WSNs that need to operate on RF EH and we demonstrate the viability of our scheme using a prototype implementation that utilizes commercially available RF EH technology.

III. Design

Active RF energy harvesting is a method whereby an RF energy transmitter (ET) transmits energy to the WSN nodes using RF waves. It is active in the sense that you need to turn on the ET before the nodes can harvest energy. Our aim is to reduce the power needs of the nodes to an absolute minimum at all costs. Therefore, a sink-synchronized polling approach has been adopted where the sink issues commands to the nodes instructing them to act and operate at specific times. Prior to issuing these commands, the sink will activate the ET to "send" power to the nodes. Taking into consideration the current state-of-the-art commercially available RF energy harvesting technology [12], a typical node in such a WSN needs to be able to operate with less than $10\mu W$.

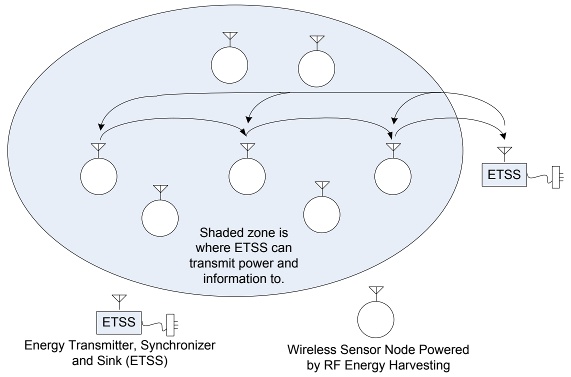


Fig. 1. WSN Architecture

A. Network Architecture

The proposed WSN architecture is shown in Figure 1. The sink also performs the role of a synchronizer (SYNCR) which broadcasts beacon signals for the nodes to synchronize their clocks and also the commands that instruct them to perform certain tasks, like, take sensor reading, transmit a packet, etc. The sink is connected to a sustained power supply and equipped with a strong enough transmitter to send signals directly to every node in the network. On the other hand, the nodes which operate at very low power can only transmit and communicate with their immediate neighbours. Therefore, nodes that are closer to the sink must relay data for other nodes in a multi-hop manner to ensure that sensor data from distant nodes can be successfully delivered to the sink.

B. Time Synchronization

A node spends most of the time harvesting energy from the RF signals transmitted by the ET, and when it has harvested enough energy, it becomes active and turns on its radio receiver to listen for commands from the SYNCR. The time duration between the instances a particular node listens for commands is different from other nodes and highly dependent on the power it can harvest from the RF signals. Due to this asynchronous condition among the nodes, a high level of redundancy is needed when transmitting the commands. This is done through the transmission of a SYNCR frame that comprises a Main command with an optional Sub command, carried over multiple packets, as shown in Figure 2.

Prior to sending a SYNCR frame, the ET will transmit RF signals to "charge up" the nodes. Each packet of the Main command contains the following information: MAC or link layer address of the source/sender (i.e. ETSS), sequence

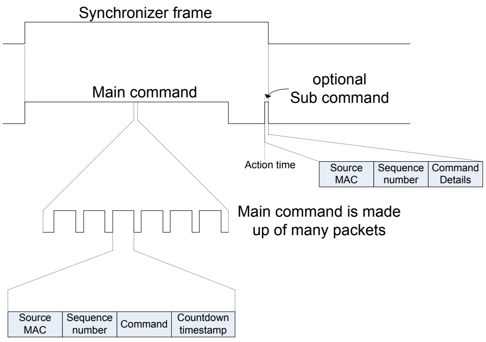


Fig. 2. Synchronizer Frame

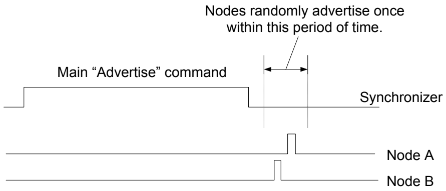


Fig. 3. Nodes Advertising Themselves

number, command to be executed and countdown timestamp. All the packets for the Main command of a SYNCR frame are identical except for the "countdown timestamp" which is the time duration till the instant when the command specified in the packet is to be executed, referred to as the *action time*. Each subsequent packet will contain a smaller value for the countdown timestamp as the *action time* approaches.

The Sub command packet is an optional packet sent at the very end of the SYNCR frame and it contains additional detailed information about the command. If there is no additional information to be communicated to the nodes for that command, the optional packet is not sent and nodes will just proceed to execute that command at *action time*.

C. Initialization and Banding

Banding is the process of grouping the nodes into bands (or tiers) according to their distance (in terms of the number of hops) from the sink. The SYNCR initiates the banding process by sending the "advertise" command that causes the nodes to advertise their presence. This allows both the SYNCR and the nodes to discover who their neighbours are. Specifically, as shown in Figure 3, when active nodes receive the "Advertise" command, they first synchronize their timing with respect to *action time*; starting from *action time*, each node will randomly pick an instant within a specified time interval (duration α) to broadcast a self-advertisement message containing its own identity, i.e. MAC address, and other relevant information, such as, the band that they are currently in (initialized to "0xff" representing the largest band number), their immediate neighbours and the total number of bands configured in the network (also initialized to "0xff"). Nodes follow the CSMA approach when broadcasting themselves, by sensing the channel and broadcasting only if the channel is free; else they wait for another "advertise" command from the SYNCR. The banding is auto-configured based on the connectivity between nodes which facilitates deployment; this is the unlike the "region" approach of EHOR [8] that is determined based on the distance between source and sink, and a desired number of regions which may not be optimal for prevailing conditions.

Nodes whose self-advertisements have been received by the SYNCR will be assigned to band #1. The SYNCR sends an "Assign Band 1" command that contains the addresses of nodes in band #1. As the SYNCR command can be heard by all active listening nodes, the other nodes whose addresses are not in this Band #1 list will not act on this command. Band #1 nodes then advertise themselves again, but this time, their advertisements will contain their identity (MAC address), their assigned band (i.e. "0x01") and total number of bands configured so far, i.e. "1". Neighbours of band #1 nodes (which have still not been assigned any band) will then configure themselves as band #2; this is based on the condition that they have heard from a neighbour whose band is lower than their own band and therefore they belong to the next band. The SYNCR will repeat the "advertise" command a few times to allow nodes in network to configure themselves. At the banding process is propagating outwards, the number of configured bands is propagating in the reverse direction towards the SYNCR. Once the number of configured bands stops increasing, the SYNCR will know that the banding process has finished.

D. Data Retrieval and Multi-hop Delivery

To retrieve data from the network, the SYNCR first sends a command to tell the nodes to take measurements from whatever sensors attached to nodes, e.g. temperature, humidity, etc. The SYNCR then sends "hop" commands to instruct nodes in the network to forward their data to the sink. The hop commands contain the maximum (farthest) band number that data should come from, which is the band where this cycle of data delivery starts; we refer to this band as the *initial band*. The "hop" commands also contain the list of acknowledgments (ACKs), which are the IDs (MAC addresses) of nodes that sent data in the previous cycle and the data have been received by the sink. These nodes will not send their data again but still participate in relaying data for other nodes. The SYNCR, when it sends a "hop" command, tells the nodes what band transmits first at action time, namely, the initial band. This allows the nodes to calculate the offset from action time for their receive (RX)/transmit (TX) slots, as shown in Figure 4.

When a node receives a "hop" command from the SYNCR, it starts to build a packet by concatenating data segments of sensor readings. These data segments may come from packets that it received from nodes in higher bands than itself which it must help relay to the sink, as well as, sensor data from its own sensors. A node can add its own sensors' data to the packet if it has not received any acknowledgments from the SYNCR for its own sensor data, since last being instructed to take sensor measurements.

Nodes in the same band randomly contest for their particular transmit time if they have a packet to send. Nodes choose a random time to transmit in their upcoming TX slot. During the

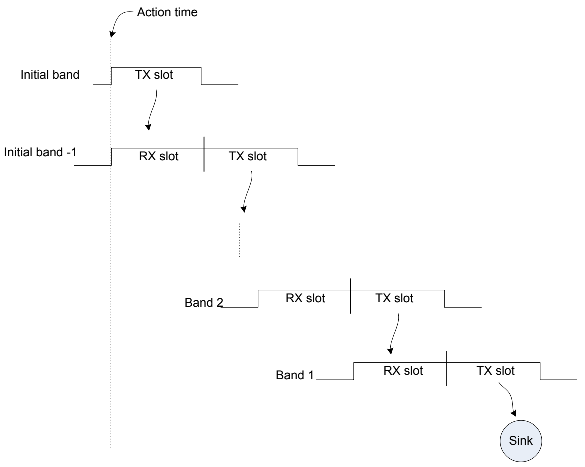


Fig. 4. Slot Scheduling for Data Delivery

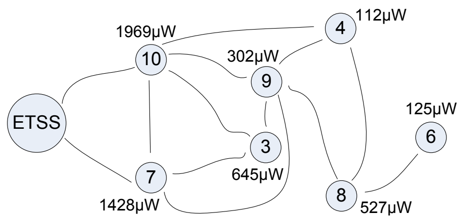


Fig. 5. Connectivity graph of nodes

TX slot, if the node hears another node in the same band as itself transmit before it transmits, the other node is considered to have won the slot and the packet is discarded. This is akin to CSMA except that the node aborts and discards the packet when it senses the channel busy. It is worth noting that turning off the radio between the end of RX slot and the selected transmission time is counterproductive because it takes as long as 4ms to re-initialize (turn on) the radio and consumes as much as $250\mu J$ which is higher than leaving the radio on. Such factors which may not be an issue in typical sensor platforms are often overlooked in protocol design but has a critical effect on ultra low power platforms such as the ones considered here.

IV. Performance Evaluation

The proposed protocol has been implemented on a custom-built sensor node platform [16]. An experimental validation has been adopted because analytical and simulation approaches cannot truly model the environmental conditions faced by energy harvesting systems.

A. Testbed Setup

Our testbed consisted of up to nine nodes in a room $6m \times 3.4m \times 2.4m$. We used one ET and one SYNCR cum sink that was connected to a host computer for data retrieval from the network. In addition, we used a packet sniffer to monitor the data segments as they traversed through the network. The radios themselves were set to the absolute minimum transmission power that the hardware allows, giving a distance of $1 \sim 2m$. The transmit power (and range) can be increased with almost no effect on the amount of energy the radios used as they operate at around 99% inefficiency when transmitting.

Before turning on the energy transmitter, we assumed that the reservoir capacitors are completely empty. We denote the minimum amount of power that they can operate at as P_{MIN} and let $P_{MIN} = 10\mu$W although our sensor node can operate with as little as 7μW [16]. Based on the technical specifications of the RF energy harvester subsystem, and the testbed configuration, the nodes would be receiving no less than 100μW of power as they are within $7m$ from the ET. Assuming a worst case scenario (i.e. $P_{MIN} = 10\mu$W), we determined the following:

- Time needed to charge the capacitors from empty to minimum operational state, $t_{initial} = 1.25$ hrs;
- Duration of Main command, $t_{TX} = 117$ secs;
- Interval between commands, $t_{Rest} = 577$ secs.

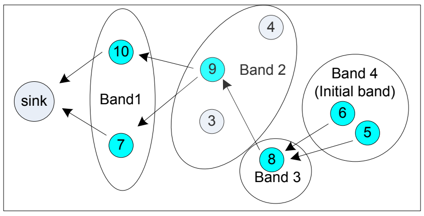
We used these values to initialize the network and to retrieve data from the network as a trial. The receive (RX) and transmit (TX) slots were set to 15ms, whilst 40ms was allowed for the nodes to advertise their presence.

B. Initial Trial Measurements

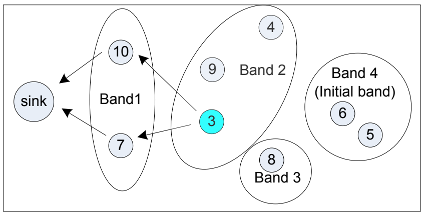
For our first test, we used seven nodes in the configuration as shown in Figure 5. After turning on the ET for at least one hour, we executed the network initialization process described in Section III-C. During initialization, the SYNCR executed command cycles that lasted about 12 minutes each. To ensure that all nodes were able to successfully execute each command, the SYNCR sent the “Advertise” command twice (for nodes to advertise themselves), then the “Assign Band 1” command twice (to set up Band#1), and then followed by more “Advertise” commands to instruct the other (non-Band #1) nodes to organize themselves into bands, until the number of bands reported back to the SYNCR remained unchanged for three consecutive “Advertise” commands.

After network initialization, we performed the data retrieval. First, the SYNCR sent a command (twice) to nodes instructing them to take sensor readings; both commands have the same sequence number so that nodes which received it both times would know that it was the same command. This is followed by the “hop” command with initial band set to “4”, which is the number of bands in the network. The command was repeated and, for each subsequent command, the SYNCR added the addresses of nodes whose data it had already received to the “turn-off” list. The SYNCR stopped sending “hop” commands once no data were received for two consecutive commands. The entire process took about four hours, including the one hour needed for charging the empty capacitors initially.

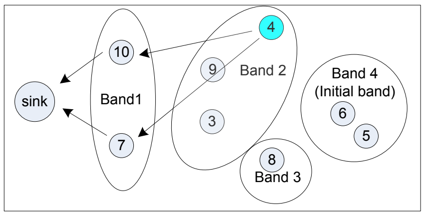
The data that were gathered from the nodes included network connectivity data and P_{MIN} values. The connectivity map of the testbed is shown in Figure 5; note that nodes 3 and 4 in band #2 were not directly connected. Nodes 3 and 8 despite being physically closer (as compared to nodes 3 and 9) were not directly connected. As expected from the estimates based on specifications of the RF energy harvester, the P_{MIN} value of the network was around 84μW which allowed us to



(a) 1^{st} "hop" command



(b) 2^{nd} "hop" command



(c) 3^{rd} "hop" command

Fig. 6. Data Retrieval Example

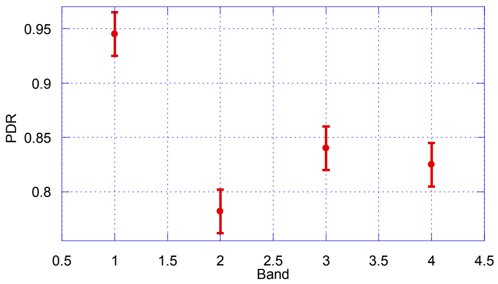


Fig. 7. PDR of data from different bands

reduce t_{TX} to 75 secs; the number next to each node shows the average amount of energy harvested by it. While the nodes' band changed over time due to fluctuations in signal strength, the banding shown in Figure 6 was the most common.

C. Experimental Results

The network experiments were conducted using $t_{TX} = 75$ secs as $P_{MIN} > 80\mu$W. This enabled the commands to be executed in shorter time which sped up the network initialization as well as data retrieval. Two performance metrics are of interest to us, namely, the packet delivery ratio (PDR) and the duplicates per transmission (DPT). PDR refers to the percentage of data segments generated by sensors that are successfully delivered to the sink. As the data segments are relayed through the network, more than one intermediate node may add copies of the same data segment to their packets and forward them. As energy is a premium in such a network, minimizing the number of duplicates is also critical while at the same time maximizing the PDR. The results are averaged over experiments in batches of 1000 trials.

An example of the multi-hop data delivery process over three "hop" commands is illustrated in Figure 6. The top diagram shows the transmission of data segments across the four bands. Nodes 5 and 6 in band #4 are able to send their small packets successfully to node 8 without colliding. However, for band #2 nodes, node 9 transmitted first and therefore won the transmission slot. Both nodes 3 and 4 sensed the channel and dropped their packets when they detected node 9 transmitting. In the second "hop" command, the SYNCR adds nodes 10, 7, 9, 8, 6 and 5 to the ACKs list as it has already received their data segments. Node 3 picks a transmission time within the TX slot and successfully sends its packet to nodes 10 and 7, which is then forwarded to the sink. Node 4 picks a transmission time that is too close to the end of the TX slot, and is unable to transmit its packet before the end of TX slot; therefore, it discards its packet. Finally, in the third "hop" command, which the SYNCR also adds node 3 to the ACKs list, node 4 is able to send its packet to the sink via band #1 nodes.

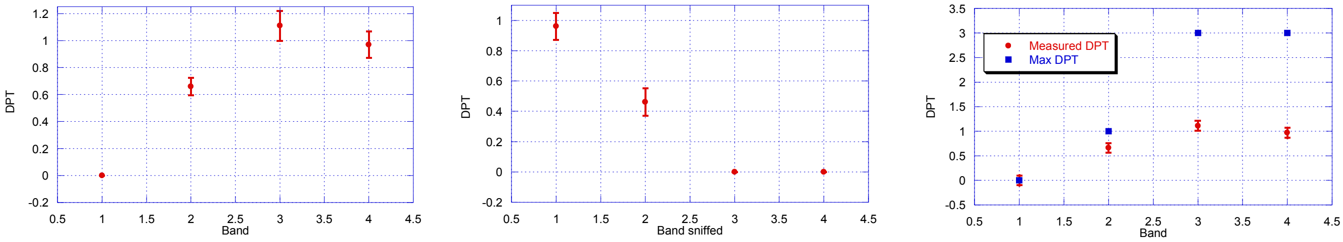
1) Packet Delivery Ratio: Figure 7 shows the PDR of data segments with respect to the band they originated from. The PDR of the nodes in band #1 is so high because of two reasons; firstly, the data segments sent by nodes in band #1 do not need to be forwarded and hence there is less probability of loss, and secondly, band #1 nodes are transmitting to the sink whose radio receiver is perpetually on making the RX slot effectively much longer than that for nodes in other bands.

The PDR of nodes in band #2 is relatively low compared to the other bands because there are more nodes in band #2 than any other band. The nodes in band #2 contend for the transmission slot (dropping packets when they sense the channel to be busy, i.e. other nodes transmitting) or causing collisions when they cannot hear each other and simultaneously transmit to a common receiver in band #1, resulting in lower PDR. While the carrier sensing mechanism is supposed to reduce contention for transmission slots, it does not eliminate contention altogether. The winning slot mechanism, for example, is unable to prevent nodes 3 and 4 transmitting at the same time as nodes 3 and 4 are unable to hear each other.

Nodes in band #4 have slightly lower PDR than those in band #3 because band #4 nodes require the band #3 nodes to relay their data segments; there is a chance that the data segments are not received by band #3 nodes and hence decreases the likelihood of the data arriving at the sink.

2) Duplicates Per Transmission: The lower PDR of data segments from band #4 nodes discussed in the previous section is also the reason for the DPT from band #4 nodes being less than those from band #3 nodes; less probability of data arriving implies less number of duplicates. Figure 8(a) shows that a small reduction in PDR can cause a much larger reduction in DPT. Looking at the nodes in band #3 and #4, we see that around a 2% reduction in PDR causes about 14% reduction in DPT in this case.

We also monitored the volume of duplicates at different bands caused by 700 data segments that originated from nodes



(a) DPT of data from different bands (b) DPT of band #4 data at different bands (c) Measured DPT vs Upper Limit

Fig. 8. Duplicates Per Transmission (DPT)

in band #4 and show the results in Figure 8(b). As there was one node in band #3 and it was the first intermediate band, there were no duplicates generated. However, as the data segments were forwarded to band #2, packets were received by multiple nodes which added the same data segment to their packets. This phenomenon repeated itself in band #1 causing the volume of duplicates to increase.

3) Upper Limit for DPT: Keeping the volume of duplicates low is important as unnecessary transmission consumes energy. Many factors can reduce the DPT. If PDR was 100% for all nodes, and nodes always transmitted when they had packet to transmit, then the theoretical upper limit for our testbed can be easily computed. Figure 8(c) compares the DPT as measured in our network to this theoretical upper limit for the DPT for data segments originating from the different bands. This demonstrates that our protocol significantly reduces the number of duplicates by as much as 70% for some nodes compared to the theoretical upper limit for DPT. On average the number of duplicates is reduced by somewhere between 50% and 60%. The undesirable consequence of this is the reduction in PDR by 14% to 18%.

V. Conclusion

The lifetime constraint of WSNs imposed by the use of batteries as power source can be eliminated with the use of renewable energy techniques, like ambient energy harvesting. However, this introduces new challenges in the likes of uncertainty in the energy supply which is very dependent of environmental factors. Energy-on-demand provided by RF energy harvesting has been actively studied as a viable solution to provide energy to WSN nodes in a more deterministic manner but the minute amounts of energy that can be harvested from RF signals present a daunting challenge to WSN protocol design. In this paper, we have proposed a sink-synchronized protocol designed specifically for such ultra low power scenarios, and validated the design with a proof-of-concept prototype and experimentation. There is still substantial work needed to improve the scalability of the design. Moving forward, besides the analytical model for this protocol, we are also developing techniques to auto-configure the system, starting with a worst-case P_{MIN} assumption, and after the SYNCR receives data from network, adapt t_{TX} and t_{Rest} according to the network's ability to harvest energy as specified by the most recent P_{MIN} values returned from the sensors.

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