SAMPLING SENSOR-FIELDS USING A MOBILE OBJECT: A BAND-BASED APPROACH FOR DIRECTIONAL BROADCAST OF SENSOR-DATA

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ABSTRACT
The idea of using mobile objects to gather samples from a sensor field has been recently proposed. A key challenge is how to gather the sensor data in a manner that is energy efficient with respect to the sensor nodes that serve as sources of the sensor data. In this paper, an algorithmic technique called Band-based Directional Broadcast is introduced to control the direction of broadcasts that originate from sensor nodes. The technique is studied by simulations that consider energy consumption and data deliverability.

KEY WORDS
Sensor data sampling, mobile object, directional broadcast, and sensor networks

1. Introduction

Recently, the concept of employing mobile objects (sometimes referred to as mobile sinks) to query a sensor network has been proposed [1, 5, 6]. Applications can exploit this mobility to dynamically sample a sensor field. One high-level application scenario can be illustrated by Figure 1. A mobile object is traveling along a path, and at some specific time (T_0) it decides to take a sample of the sensor field, i.e., collect sensor data from near-by sensor nodes. The larger circle denotes the sampling region. Each sensor in that region will consequently be activated and reply with its locally sensed data. As the mobile object continues its travel, it reaches another location at time T_1 from which it initiates another sampling task.

There are two interesting features associated with the task of sensor field data sampling. First, due to the mobility of the sampling object, there are many options for selecting a sampling region, as opposed to the static sampling region associated with a static sink. Second, it is possible to employ commonly existing mobile objects, for example taxis or buses, to help increase the coverage of the sensor field. So, it is possible to deliberately choose a mobile object and finely tailor its sampling regions to optimize a sampling task.

However, there are also challenges that arise from using these mobile sinks to gather sampled sensor data. One challenge is in controlling the process that sensors use to respond to a request for sensor data from a mobile sink, or in other words controlling how sensors route their sensed data to the mobile object. Routing tree-based protocols [2] [6] are not well suited for this situation because route discovery implies high energy cost, and a discovered route might not be easily reused when faced with a series of highly dynamic sampling tasks. Also, because sensor networks do not naturally allow for a global IP address for each sensor node, traditional IP-based routing methods used in classical communication and wireless ad-hoc networks can not be adopted in this case. In addition, power and cost constraints make it impractical to assume GPS capability for very low-cost sensors needed for large-scale sensor network applications, and effective accurate localization techniques are still in research stage. Thus, for sampling large-scale sensor networks, it is not desirable to depend on routing protocols that require sensors to be location-aware, such as location-based GAF (Geographic Adaptive Fidelity) [3] and cluster-based LEACH (Low-Energy Adaptive Clustering Hierarchy) [4].

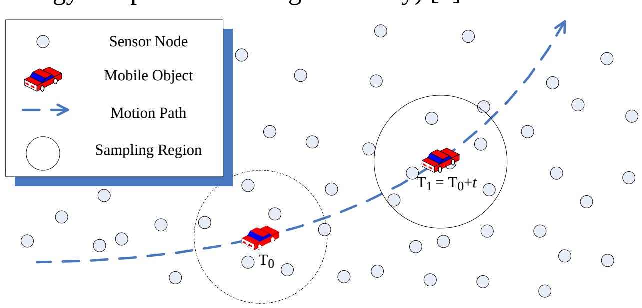


Figure 1. Sensor Field Sampling

Finally, an implied requirement for sensor field sampling is that there is a time constraint imposed by the mobility of the sink object. To facilitate the collection of sensor data from the sampling region, it is helpful if all the sensor data can be routed to the mobile object before the object has deviated significantly from where it initiated the sampling task. This suggests that sensors should respond quickly upon receiving a sampling request, and the sensor-data propagation method should be highly efficient.

The approach used in this paper is based on traditional broadcast. There are a few reasons to support this decision: broadcast is simple and puts no additional requirements on the sensor nodes; broadcast can be initiated immediately after receiving the sampling task since it requires no routing table/tree setup; and broadcast can naturally handle the mobile sink scenario since a sensor-data packet can reach the mobile object as long as the object is within transmission range of some broadcast, or re-broadcast, of that packet. However, one fundamental problem with using broadcast for gathering sensor data is that broadcast does not consider direction, and left unchecked would flood an excessively large geographic region. Note that this flooding could even extend beyond the intended sampling region, which means it suffers from very low energy efficiency.

In this paper, we present a new broadcast-based data gathering mechanism optimized for the purpose of sensor-field data sampling. We call the approach Band-based Directional Broadcast since it uses the concept of "bands," created by partitioning the sampling region by multiple concentric circles (see Figure 3 for a quick look). These bands are used to help control the direction of data flow for sensor data packets, without the need for sensor nodes to have any sophisticated directional antenna.

2. Related Work

2.1 Broadcast Mechanisms

Simple Flooding serves as the baseline of all broadcast mechanisms. In this protocol a node will rebroadcast whatever it receives exactly once. The rebroadcast (relaying) terminates when there are no more messages to broadcast. Generally, simple flooding has the best reliability and deliverability but the worst efficiency in terms of energy consumption [8]. A generalization of simple flooding is Probability-based Broadcast [8]. Upon receiving a packet it has not previously received, a node will rebroadcast the packet with a probability of p, but discard it with probability (1-p). Simple flooding sets p=1.

It is believed that there is an inverse relationship between the number of times a packet is received at a node and the probability of the node being able to reach additional areas on a rebroadcast [7]. So, in Counter-based Broadcast, a node will maintain a counter and a timer for each unique packet it receives. The timer is used to control how long the node holds a packet before considering rebroadcasting it. When the timer expires, the node checks how many duplicate copies of this specific packet have been received. If this number exceeds a previously assigned threshold, the packet is dropped; otherwise, a rebroadcast is initiated. In general, for a dense network, nodes will be less likely to rebroadcast packets, in comparison to sparse networks [7]. However, counter-based broadcast is inherently slow in terms of reaction time due to the need to wait for timer expiration before any rebroadcasts.

It is generally expected that with an increase in complexity, there is a benefit in performance. This is also true for broadcast mechanisms [8]. When sensor nodes are granted more power/knowledge – for example, the ability to acquire precise location information or 1-hop (even 2-hop) neighbor information – the broadcast methods become more and more efficient. However, sophisticated broadcast mechanisms (including area based, neighbor based, and distance based) do not fit well with the sensor sampling problem due to the requirements they would impose on the individual resource-constrained sensor nodes. Likewise, typical directional broadcast, which requires nodes to be equipped with a directional antenna [10], is not feasible for this sampling situation.

2.2 Use of Bands in Sensor Networks

There are a few previous works that use similar notions of bands, but in different contexts. In [9], bands are introduced to help measure and compare the energy consumption rate of sensors at different distances from the sink. An algorithm called EVEN is then proposed to avoid the notorious sink-hole problem. Sensors are statically deployed into specific bands with adjusted transition ranges that results in uniform energy depletion of all sensors. In contrast to this work, our research focuses on dynamic band-computation and on using band knowledge to reduce rebroadcast of sensor data.

In [6], an idea for using bands to help conduct routing is introduced. The sensor field is divided into many slices (formed by coronas, which are like our bands, and wedges, which cut across bands). Routing trees are then constructed with the help of these slices. However, as we have pointed out in Section 1, although tree-based routing can achieve good performance, the building of a routing tree requires high energy cost and additional setup time. Furthermore, a discovered routing tree for one specific sampling task cannot be reused by other sampling tasks. The work of [6] mainly focuses on a static sink, fixed query region, and continuous monitoring. In this case, such overhead might be reasonable, but for a sequence of "one-shot" highly dynamic sampling tasks, such overhead cannot be justified. The mobility of sink nodes further demands a rapid response by sensor nodes.

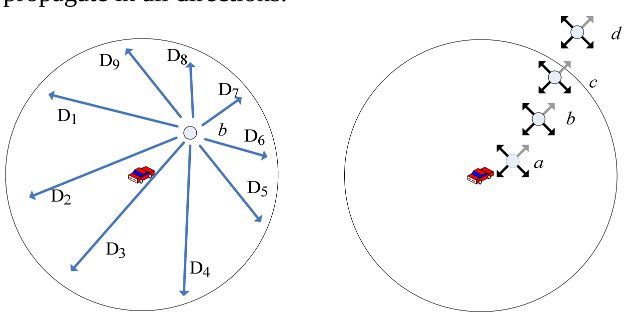
3. Band-based Sensor Data Sampling

3.1 Overview of Band-Based Directional Broadcast

As we discussed before, upon receiving a request for sensor data, sensors in the sampling region will immediately react by broadcasting their sensed data. However, one fundamental problem with using broadcast is that broadcast does not consider direction, and left unchecked would flood an excessively large geographic region. Considering Figure 2(a) as an example, sensor b will flood its reply in all directions, illustrated by the nine different arrows shown in the figure. Note that although it is not explicitly shown, this flooding could even extend beyond the intended sampling region. Intuitively it makes sense to control this flooding so that it is directed towards the mobile object. For example, ideally we would like to constrain the flooding to the directions of D_2 and D_3.

A closer look at the flooding situation is provided in Figure 2(b). Note that only some of the many sensor nodes and their broadcast are depicted. For the purpose of simplifying the presentation of the general idea, we currently assume that the mobile object is static. The impact of its mobility will be discussed in Section 3 C.

As desired, sensor *b*'s response will be rebroadcast by sensor *a* and received by the mobile object; but *b*'s packet will also be propagated to other sensor nodes, for example, *c*, or even node *d*, which is outside of the sampling region. The rebroadcasts of *b*'s data by nodes other than node *a* are not of direct benefit in terms of delivering the sensor data to the mobile object. Ideally it would be desirable if each broadcast could avoid sending packets in a direction that is "away from" the location of the mobile object (those directions depicted by the lighter grey-colored arrows). However, without the support of a directional antenna on each individual sensor node, a packet broadcast must still propagate in all directions.



(a) **(b)**

Figure 2. Broadcasting Sensor Data

Alternatively, we can seek to control the flooding at the receiver side. For example, upon receiving a packet from *b*, node *c* can choose to discard the packet, rather than initiating a rebroadcast. The challenge is for nodes to distinguish the arrival of packets from nodes that are located closer to the mobile object, without the assumption that nodes are location aware. In our solution we only rely on nodes knowing their bands, which provides a means to distinguish packets that move between bands.

Given a specific sampling task, we partition the entire sampling region into multiple concentric circles as shown by Figure 3, with the space between circles defining bands. We denote the inner-most band as Band 1 and the outer-most band as Band N (N=4 in Figure 3). Each sensor has an associated band number corresponding to the band that contains the location of that sensor. Note that all bands within the sampling region have the same width except Band N that defines the boundary for the sampling region.

Now, when a node broadcasts a packet, it should also attach its band number. Upon receiving a packet a node will make the rebroadcast decision based on the band number attached to the packet. If the node's band number is less than or equal to the packet's band number, the node will rebroadcast that packet; Otherwise the node discards the packet. As a simple example, nodes in Band 2 will rebroadcast packets sent by nodes in Band 2 or other "higher" bands, but they will discard packets sent from nodes in Band 1.

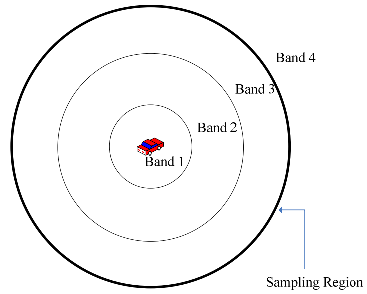


Figure 3. A 4-band configuration

3.2 Band Identification and Sensor Protocol

While various methods can be used to associate sensor nodes with bands, including the techniques used in [6] and [9], we suggest an alternative method that is quite natural for the sensor-sampling problem. Each time a mobile object decides to sample a region of the sensor field, it issues a Sampling-Initiation Signal (SIS), which is broadcast into the sensor network. We can take advantage of this sampling signal to help sensors obtain partial and relative knowledge on their locations, and thus determine a band number. It is well-known that an important characteristic of radio propagation is the increased attenuation of the radio signal as the distance between the transmitter and receiver increases [11]. Thus, when a mobile object issues a sampling signal, it can attach a function that maps signal strengths to band numbers. We assume that the mobile object understands its signal's attenuation pattern in its environment, and it defines the number of bands to be used. Further consideration of how it behaves is outside the scope of this paper.

When a sensor node receives the Sample-Initiation Signal, it calculates its own band number based on the signal strength of the received signal and the mapping function attached to that signal. For now we simply assume an ideal open-air environment, resulting in perfect circular bands as shown in Figure 3. In Section 4 we will relax this assumption and study the impact of band assignment errors caused by errors in location estimation.

To help formally describe this band assignment process, we first present the format of a sampling signal.
Sampling-Initiation Signal (SIS) =

(ST_ID, MO_ID, BMF)

where ST_ID is a unique identifier for the sampling task, MO_ID is the identifier of the mobile object, and BMF is the Band Mapping Function that maps signal strength to band number.

$$BMF(SIS\text{-}Strength) \rightarrow Band\_Number$$

This function is pre-calculated before the sampling signal is issued by the mobile object, and it is a one-time calculation/activity based on the desired total number of bands and the characteristics of the mobile object's transmitter. A simple generic implementation of this function is shown below:

$$\text{Band\_Number} = \begin{cases} 1 & when\ \lambda_1 \le SS-Strength < \lambda_0 = +\infty \\ 2 & when\ \lambda_2 \le SS-Strength < \lambda_1 \\ & \dots \\ N-1 & when\ \lambda_{N-1} \le SS-Strength < \lambda_{N-2} \\ N & when\ \lambda_N = 0 \le SS-Strength < \lambda_{N-1} \end{cases}$$

Note that in the above formula, λ_{N-1} establishes a threshold. Any sensor that receives the SIS with a signal-strength less than λ_{N-1} can simply view itself as being outside of the sampling region. Consequently this sensor would not reply to this SIS and not rebroadcast packets intended for this SIS, as will be presented later. Previously we indicated that a band is an area (between concentric circles). Using the above function as an example, we can have the following definition:

Band i = {(x,y) coordinates | a sensor node located at (x,y) will receive the sampling signal with a signal-strength greater than or equal to λ_i but less than λ_{i-1}}

Since a key idea of this paper is the way that bands are used to control flooding, we now describe the core behavior of sensor nodes by the protocol in Figure 4. To simplify the presentation and discussion, we only consider one sampling task; although handling multiple simultaneous tasks is quite straightforward due to the unique task ID in each SIS.

```
Upon receiving a Sampling-Initiation-Signal, SIS
    Calculate Band_Number based on received SIS strength and BMF;
    If (Band_Number ≠ N) {
        //N is the largest Band_Number in the BMF
        Generate a sensed data reply packet, p;
        Attach the ST_ID and Band_Number to p;
        Broadcast the generated packet p;
    }
    // only broadcast a reply packet if located within the sampling region

Upon receiving a sensor data packet P
    If (Band_Number attached to P ≥ Band_Number of this receiving sensor node)
        Rebroadcast the packet;
    Else
        Discard the packet;
```

Figure 4. Sensor Broadcast Protocol

3.3 Impact of Mobility of the Mobile Sink

Section 2 mentioned that one important difference between our approach and the scheme in [6] is that our Band-based Directional Broadcast scheme can handle a mobile object as the sink. This capability comes from the nature of broadcast. A sensor *sn* in Band *i* will flood its sensed data among the sensors in the following bands: Band *i*, Band *i*-1, ..., Band 1. So, as long as the mobile object moves within a “reasonable” speed range, it will receive *sn*’s reply. But, how fast is this “reasonable” speed? Assume that each band has the same width, *W*, and the mobile object moves at a speed *V*. To avoid any loss of a data packet (due to it not being able to reach the mobile object), a sensor data packet from Band *i* must be able to flood the entire set of bands {Band *i*, Band *i*-1, ...Band 1} before the mobile object moves out of the region associated with those bands. By assuming that this flooding process takes time *t*, we obtain:

$$W * i \ge V * t \qquad (1)$$

$$t = \frac{2 * W * i}{R_{SENSOR}} * T_{1\text{-}HOP} * \theta \qquad (2)$$

where R_{SENSOR} is the communication range of a sensor node, $T_{1\text{-}HOP}$ is the time used to rebroadcast a packet for one hop and θ is a parameter employed to compensate for non-linear packet propagation. By substituting (2) into (1):

$$V \le \frac{R_{SENSOR}}{2 * \theta * T_{1-HOP}} \qquad (3)$$

where we surprisingly find that the mobile object’s speed is not related to the Band number *i*. Given the properties of contemporary sensor nodes [12], we can determine that *V* can scale to hundreds of meters per second. Thus, the Band-based Directional Broadcast approach is appropriate for environments using conventional mobile objects.

4. SIMULATION RESULTS

4.1 Simulation Setup

To evaluate the effectiveness of our protocol, preliminary simulations were conducted using a custom simulator. The sensor field environment is set to be 1000 feet by 1000 feet with the sampling signal injected at the center (500, 500). We set the sampling region to be a 250-foot-radius circular region. Sensor nodes have a communication range of 50 feet. We instructed the mobile object to follow a Random Way Point mobility pattern with its speed ranging from 0 to 80 miles/hr. When the mobile object initiates the sampling task, we assigned a 5% packet loss rate on the transmitted Sample-Initiation-Signal. We used a simplified MAC-layer protocol for sensor-to-sensor communication; in other words, a 5% packet loss rate is employed for sensor-to-sensor communications. We varied the total number of sensors in our environment from 300 to 1100.

4.2 Studied Algorithms

We studied four different configurations of our band-based broadcast approach with the total number of bands set to be 2, 3, 6, and 11. The simulation results compare our band-based approach with the two existing broadcast methods discussed in Section 2: Simple Flooding and Counter-based Broadcast. The timer and counter are set to be 3 and 10, respectively for the later algorithm. None of the chosen methods require additional location or neighbor information, or any extra dedicated hardware. To prevent Simple Flooding and Counter-based Broadcast from flooding the entire sensor network (the whole 1000 by 1000 environment), the concept of a Return Hop Counter (RHC) [5] is used. Whenever a sensor node generates a reply in response to receiving a sampling signal, it will set an initial RHC value for the generated sensor-data packet and then broadcast the packet with that RHC value appended. Each time that packet is rebroadcast, the RHC value is decreased by 1. When the RHC reaches 0, the packet is immediately discarded. Thus, the propagation of the packet is limited by the initial RHC value attached to the packet. The calculation of the initial RHC value is based on the following formula, intended to capture the number of hops needed to route the packet from a source sensor node to the mobile object:

$$\text{RHC} = R_{MOBILE}/R_{SENSOR} * \theta \qquad (4)$$

Where R_{MOBILE} is the mobile object's injection range, R_{SENSOR} is the sensor's communication range, and θ is the same adjustment parameter used in Section III.C. For our experiments we set θ to be 2. Note that for $\theta > 2$, the number of packets sent and received would increase for both Simple Flooding and Counter-based Broadcast.

4.3 Studied Features

A key motivation behind the band-based approach is to reduce energy consumption due to rebroadcast of sensor data packets. To measure this, we considered two criteria: total packets sent and total packets received for serving each sampling task. But, by limiting the rebroadcast of packets, there is a potential to also negatively impact on the delivery of some data packets to the mobile object. Thus we also study deliverability for the different scenarios. All results in this section are averaged results over 100 runs.

4.4 Total Packets Sent

As the dominating factor of sensor energy consumption, packet sending plays a vital role. The simulation results for this feature are plotted in Figure 5. As can be seen, our band-based approach constantly outperforms the other two methods, and the savings are more pronounced when the network density is higher. The fact that without considering directions, every packet in Simple Flooding and Counter based broadcast will flood the entire flooding region is the reason for this observed result. Further, by increasing the total number of bands, the total number of packets sent decreased. This is due to the fact that with more bands, the broadcasts will be further restricted within smaller regions.

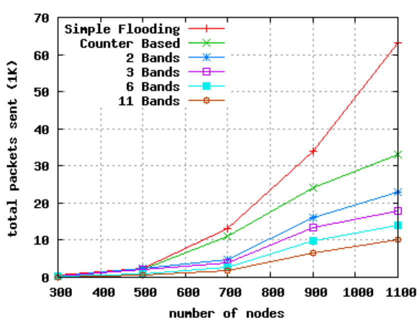


Figure 5. Total Packets Sent

4.5 Total Packets Received

Another factor related to energy consumption of sensor networks is packet receiving. Although receiving a packet is normally not considered as energy-consuming as sending a packet, broadcast techniques naturally cause a large number of packet receptions, so we should not overlook this impact. As Figure 6 shows, the trend for the studied protocols is similar to that for packet sending except that the *y*-scale now ranges up to 450K total receiving packets. This is quite natural since one packet sent can cause multiple packet receptions. However, using our approach, the reception of a packet does not necessarily result in a packet being sent.

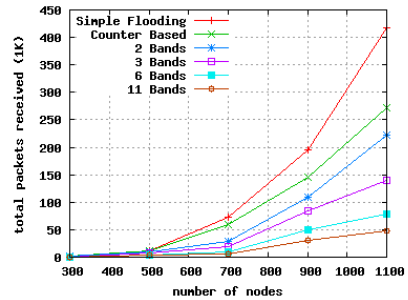


Figure 6. Total Packets Received

4.6 Deliverability

Since we have observed a significant reduction in the amount of packet sending and receiving with our band-based approach, it is important to also study how well our scheme performs when it comes to actual delivery of sampled sensor-data to the sampling mobile object. A measurement called deliverability is employed.

deliverability =

$$\frac{\#\, of\ \ sensor\ replies\ \ from\ sensors\ in\ the\ sampling\ \ region}{\#\ of\ \ sensors\ in\ the\ sampling\ \ region}$$

Figure 7 shows the simulation results for deliverability. It can be confirmed that since our scheme did eliminate some rebroadcasts, the delivery rate is slightly lower. This occurs when some connectivity (between a sensor node and the mobile object) is lost due to eliminating rebroadcasts that reach a higher-numbered band. Still, the deliverability rate is quite high, especially for higher density sensor fields; and since the goal is to do "sampling," some loss in deliverability to achieve significant savings in energy is well justified.

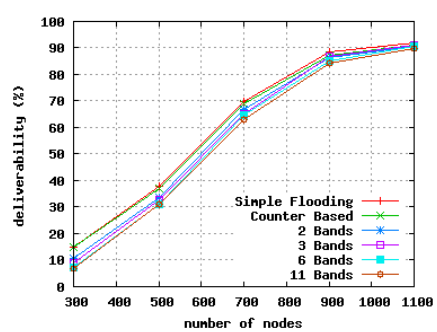


Figure 7. Deliverability

4.7 Impact of Band Assignment Errors

In the above simulations, we assumed that each sensor node correctly recognized its band, as if the sampling signal was transmitted in an ideal open-air environment.

However, since signal strength can be affected by physical properties of the surrounding environment, errors in band number assignments can happen.

Since we are using signal strength to determine bands, our bands represent a type of coarse-location information. Thus, to account for band assignment errors that will occur in practice, we adopted a well-recognized precision/error probability model [11] for range-based localization: a node has *x*% probability to estimate its location with an error larger than *y* feet and (100-*x*)% probability to estimate its location within an error of *y* feet. Based on [11], we set *y* to be 15 and varied *x*% among 0%, 20%, 40% and 60%. Thus, for each sensor, a probabilistically derived bias (deviation) was added to the sensor's actual location, and the sensor's band number was then determined. For this study, 1100 nodes were deployed. The simulation results are plotted in Figure 8. Note that a location estimation error does not necessarily imply a band assignment error. Consider a node locating at the center of a band with width *W*, as long as the location error is smaller than *W*/2, the node can still correctly recognize its band.

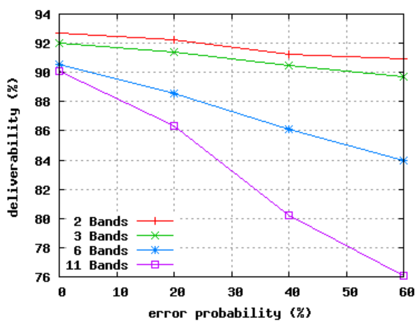


Figure 8. Deliverability with Band Assignment Errors

We found that as the error probability increased, the delivery rate decreased. However, this delivery decrease is not highly significant, even with an error probability as high as 60%. This observation is consistent with a design feature of our Band-based Direction Broadcast – the approach only needs coarse-grain, relative location information, rather than precise location information. As concluded in [11], a 20% error probability is a normal rate. Thus we have reason to believe that our scheme performs well even if many nodes do not perfectly self-identify their accurate location. Another observation is that when we employed more bands, the scheme became more sensitive to errors in band assignment. This is simply due to the fact that with more bands, the width W of each band gets smaller, and so the "error tolerance" capability (*W*/2) also gets smaller. Therefore, using more bands increases the probability that a location estimation error will result in a band assignment error. Not unexpectedly, there is a tradeoff to be considered when it comes to deciding on the number of bands to employ for a sampling task.

5. CONCLUSION

In this paper we proposed an energy-efficient protocol to aid in sensor-field sampling. The concept of bands is exploited to limit the propagation of sensor data broadcasting, providing a form of directional broadcast. Methods for defining and using bands are presented, and simulation results are provided to show the effectiveness of the approach.

Due to space limitations, we cannot explore all details associated with the approach. One important future work is to perform further simulations under non-perfect MAC layer protocols. Since our scheme prunes many rebroadcast packets, it reduces opportunities for packet collisions. It may be able to be further optimized with respect to this property. Also, further study can be done on analysis of energy concerns under error conditions.

Acknowledgements

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