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Analysis of Directional Broadcast in Wireless Ad Hoc Networks

K.Boopathi[1], [2] K.Priyadevi

Assistant Professor, Dept. of CSE, Muthayammal College of Engineering, Rasipuram, India[1]

Assistant Professor, Dept. of ECE, Mahendra College of Engineering, Salem, India[2]

ABSTRACT: Mobile objects can be used to gather samples from a sensor field. Civilian vehicles or even human beings equipped with proper wireless communication devices can be used as mobile sinks that retrieve sensor-data from sampling points within a large sensor field. 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 goal is to direct each broadcast of sensor data toward the mobile sink, thus reducing costly forwarding of sensor data packets.

The technique is studied by simulations that consider energy consumption and data deliverability.

I. INTRODUCTION

A mobile object (car) is traveling along a path, and at some time and location (for example, T0) 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 T1 from which it initiates another sampling task.

There are three 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. Finally, in comparison to sensor nodes, mobile objects have relatively large (and adjustable) transmission ranges. Thus, they can trigger sampling-region sensors by the single-hop transmission of a sampling signal. This feature is elaborated in Section 3.2. The sampling distance is only constrained by the mobile object’s transmission range, which should be more than sufficient for “local sampling” applications.

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 sensor data can be routed to the mobile object before the object has deviated significantly from the location at which it initiated the sampling task. This suggests

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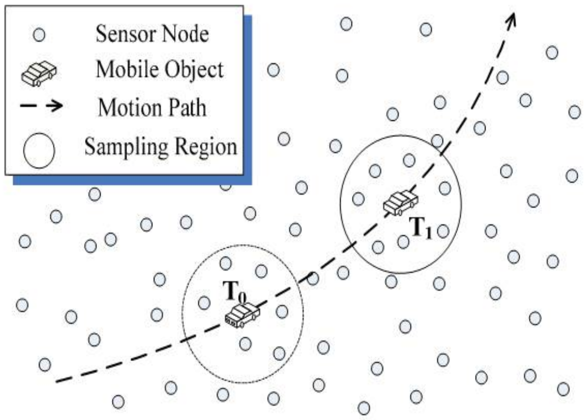

Fig 1 Sensor field sampling

that sensors should respond quickly upon receiving a sampling request, and the sensor- data propagation method should be highly efficient. In this paper, we make no assumptions about the nature of the sensor data, allowing for the possibility that sensors are heterogeneous with regard to data type (e.g., each sensor measures a different environmental property). Thus, deliverability of sensor data takes priority over performance of data aggregation operations.

The approach used in this paper is based on traditional software-based broadcast. Although it is understood that broadcast is to be generally avoided in sensor networks due to the problems associated with message flooding, there are significant advantages to using this basic mechanism, especially for the application at hand, sensor field sampling: broadcast is simple and does not require that sensor nodes be configured with special dedicated hardware; broadcast can be initiated immediately after receiving the sampling task since it requires no routing table or 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 rebroadcast, of that packet. The primary 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 the omni-directional broadcast suffers from very low energy efficiency.

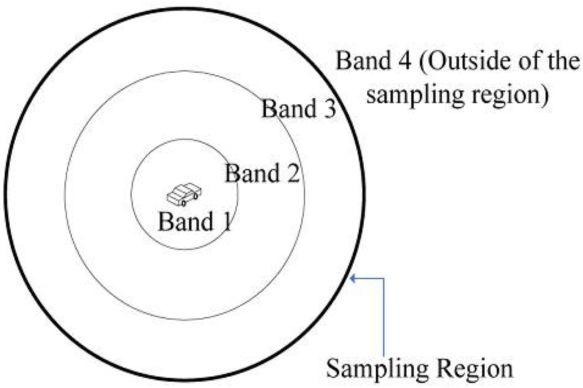

Fig 2. A 4-Band Configuration

we discuss a new broadcast-based sensor- data gathering mechanism. The mechanism is optimized for the purpose of sensor-field data sampling by a mobile object. It is called Band-based Directional Broadcast since it uses the concept of bands created by partitioning the sampling region using multiple concentric circles (see Fig. 2 for a quick look). These bands are used to help control the direction of data flow of sensor data packets, without the need for sensor nodes

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having any sophisticated directional antenna. The key idea is that our approach will reduce the propagation of packets that flow away from the sink mobile object—thus reducing broadcast events and sensor node energy consumption. This is accomplished by preventing packets that originate. from a sensor in any band from being propagated (rebroadcast) by sensors in a higher numbered band.

We know that media access control plays an important role in sensor node routing protocols. This is in part due to the fact that sensor nodes are low-power and have only a single signal-reception channel. One type of problem occurs when more than one sender simultaneously sends a packet to a common receiver. When no MAC scheduling protocols are used, packet collisions at the receiver side can occur, causing the receiver to obtain no useful signal. It has been shown that packet collisions significantly impair the performance of wireless sensor networks. There are two important conditions that increase the chances for packet collisions at a receiver node. The first condition is a large volume of broadcast activity within the vicinity of the receiving node; and the second condition is that these broadcast events occur within a short time-frame. Since our band-based scheme prunes many of the rebroadcast packets, it is expected to also reduce opportunities for packet collisions. Intuitively, less broadcasts/rebroadcasts will lead to fewer collisions.

Our band-based broadcast scheme can handle packet collisions by scheduling sensors in different bands to begin their initial broadcasts at different times. Using such a band scheduling technique introduces an explicit time drift between packets sent by nodes in two different bands, which consequently weakens the impact of the second condition for forming packet collisions.

II. BROADCAST MECHANISMS AND SCHEDULING

Since our sensor-data routing protocol is based primarily on broadcast, we now summarize several popular broadcast-based mechanisms and examine their applicability to the problem of sensor field data sampling by a mobile object.
Other non broadcast schemes that support transmitting sensor data to a sink node do not consider the case of a mobile sink and/or require the transmitting nodes to have some location awareness. Simple flooding serves as the baseline of all broadcast mechanisms. In this protocol, a node rebroadcasts exactly once each message it receives. 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.

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. So, in Counter-based Broadcast, a node maintains 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 of the packet. 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. However, Counter-based Broadcast is inherently slow in terms of reaction time due to the need to wait for timer expiration before any rebroadcasts

Another type of optimized broadcast can be collectively referred to as directional broadcast. These methods generally require “enhanced” sensor nodes equipped with dedicated directional antenna, GPS, or other localization devices. For many applications, such a requirement may not be feasible due to cost issues or deployment methods. In this paper, we propose a directional broadcast scheme that does not rely on sensor nodes having location information via any special hardware or complex localization algorithms. Our method is a light-weight software-based scheme that can also work collectively with other hardware-based approaches under various sensor node setups.

III. USE OF BANDS IN SENSOR NETWORKS

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

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, although tree-based routing can achieve good performance, the building of a routing tree requires high energy cost and additional setup time.

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Furthermore, a discovered routing tree for one specific sampling task cannot be reused by other sampling tasks. The work is mainly focuses on a static sink, fixed query region, and continuous monitoring. In that context, 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.

IV. COLLISION HANDLING

The problems associated with packet collisions in wireless systems have been broadly studied and motivated different collision handling methods, applicable to various situations. From the perspective of collision handling, what is unique about our work is that it addresses collision handling within the specific context of our band-based broadcast mechanism. In particular, we demonstrate that our approach reduces the probability of packet collisions by explicitly reducing packet broadcast/rebroadcast events and by providing a natural mechanism for scheduling the transmission of packets based on band identification. Within each collision domain (each band), we employ a fairly conventional means for packet collision reduction using random delays before broadcast. It is useful to note that a range of other, more sophisticated collision avoidance protocols, could also be adopted by our approach to handle intra band collisions. However, in general, these more advanced approaches will impose additional requirements on the sensor nodes, such as carrier sensing capability, multichannel or directional antenna.

V. BAND-BASED SENSOR DATA SAMPLING

Overview of Band-Based Directional Broadcast as discussed previously, upon receiving a request for sensor data, sensors in the sampling region will immediately react by broadcasting their sensed data. However, a fundamental problem here is that broadcast does not consider direction, and left unchecked would flood an excessively large geographic region. Considering Figure 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

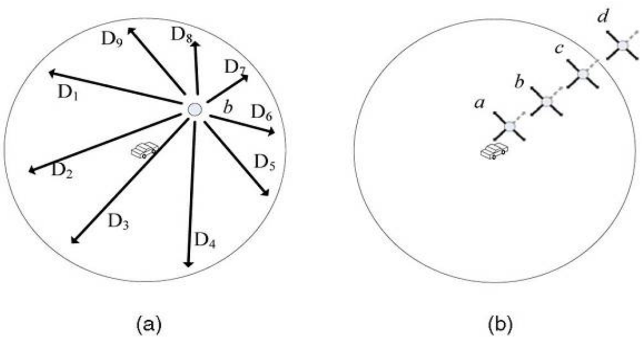

Fig 3. Broadcasting sensor data

could even extend beyond the intended sampling region. Intuitively, it makes sense to try and control this flooding so that it is directed toward the mobile object, to minimize energy consumption associated with transmitting and receiving messages. For example, ideally we would like to constrain the flooding to the directions of D2 and D3 .

A closer look at the flooding situation is provided in Fig. 3b. Note that only some of the sensor nodes and their broadcast/rebroadcast are depicted. To simplify the presentation of the general idea, we initially assume that the mobile object is static. (The impact of the object's mobility will be discussed) As desired, sensor b's response will be rebroadcast by sensor a and received by the mobile object; but b's packet will also propagate 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

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directions depicted by the dotted line segments). However, without the support of a directional antenna on individual sensor nodes, a
packet broadcast propagates in all directions. Despite this, 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 own bands. Thus, any node can identify received packets that originated from a different band, i.e., those packets that moved between bands.

VI. BAND IDENTIFICATION AND SENSOR PROTOCOL

While various methods can be used to associate sensor nodes with bands, including the techniques used in and, we suggest an alternative method that is highly efficient and 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 with an intended sampling range, RMOBILE. Using this sampling signal, sensors obtain partial and relative knowledge of their locations, and thus determine a band number.
It is well-known that a radio signal attenuates as the distance between the transmitter and receiver increases. Thus, when a mobile object issues a SIS, it can attach a function that maps signal strengths to band numbers. We assume that, 1) The mobile object has knowledge of its own signal's attenuation pattern in its environment, and 2) the object also defines the number of bands to be used. When a sensor node receives the SIS, it calculates its own band number based on the signal strength of the received signal and the mapping function attached to that signal.

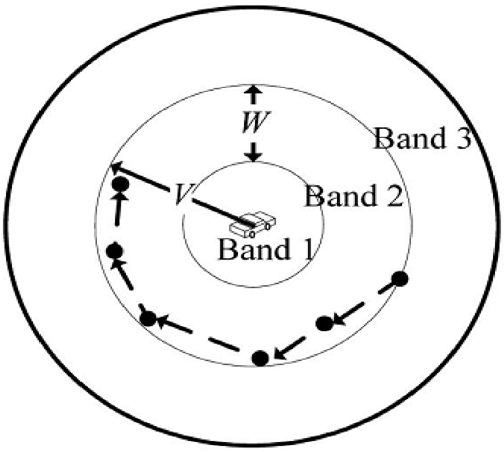

Fig 4. A Packet propagation path

For now, we simply assume an ideal open-air environment, resulting in perfect circular bands as shown in. In
we will relax this assumption and study the impact of band assignment errors caused by imprecision in location estimation.

VII.IMPACT OF BAND-BASED BROADCAST ON SINK-OBJECT MOBILITY

Our Band-based Directional Broadcast scheme can handle a mobile object as the sink. This capability comes from the nature of broadcast. As per the broadcast protocol, a sensor sn in Band i will flood its sensor data among the sensors in Band j, 1 j i. So, as long as the mobile object moves within a "reasonable" speed range, it will have the opportunity to receive sn's reply. This means that sensor nodes need not provide for cache management of packets that they forward, for the purpose of possible later delivery of those packets to the mobile object. This is significant since it further supports our goal of providing a low- complexity sensor node protocol. How fast is this "reasonable" speed? To avoid

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loss of any data packet (due to the packet not being able to reach the mobile object), a packet from Band i must be able to flood the entire set of bands fBand i; Band i À 1; . . . ; Band 1g before the mobile object moves out of the region associated with those bands, once the mobile object has injected a SIS. Assume that each band, excluding the outermost Band N, has the same width, W, and the mobile object moves at a speed V. As an example, consider Fig. 5, where the mobile object is moving away from some sensor node located at the outer edge of Band 2. For the mobile object to receive a data packet originating from this sensor node, the packet must propagate to some sensor node that is located in a position where it is able to directly communicate with the mobile object. Note that in using the band-based broadcast protocol, this packet will not be able to propagate into Band 3. Thus, in terms of a worst-case situation, the packet will have to follow a maximum length propagation path, as illustrated in Fig. 5; and the packet must arrive at the shown destination node before the mobile object has moved out of transmission range of that destination node.

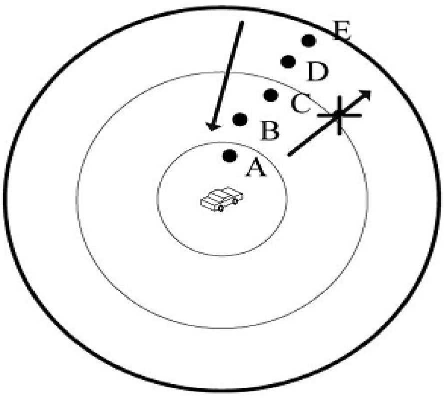

Fig 5. Inbound versus out bound packets

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VIII. PACKET COLLISION HANDLING

8.1 BAND SCHEDULING:

Media access control plays an important role in sensor-node routing protocols. High-end nodes, which are equipped with advanced hardware, can handle media access control easily by employing multichannel for sending and receiving. In this case, the requirements for media access control can be significantly relaxed. But, low-end nodes, which are designed to be low power and low cost, only have a single channel for receiving signals. For large-scale sensor net-works that deploy low-end nodes, the problem of media contention must be addressed.

A serious type of contention happens when more than one sender simultaneously sends a packet to a common receiver. The result can be packet collision at the receiver side, and the receiver obtains no useful signal then. It has been shown that packet collision significantly impairs the performance of the wireless sensor networks by expending more energy if retransmissions are used; or by reducing the number of successfully delivered packets if no retransmissions are allowed. As our approach does not use retransmissions, we are concerned with the latter effect. We capture the impact of the latter effect by defining a metric called deliverability.

Deliverability =

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

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Notice that deliverability is affected by the number of collisions as well as the number of rebroadcasts.

There are two important conditions that increase the chances for packet collisions at a receiver node. 1) The first condition is a large volume of broadcast activity within the vicinity of the receiving node; 2) the second condition is that these broadcast events occur within a short time-frame. Since the algorithm prunes naturally the broadcast/rebroadcast of "outbound" packets that cross band boundaries it is expected to also reduce opportunities for packet collisions. Intuitively, less broad- cast/rebroadcast will lead to fewer collisions since it weakens the impact of the first condition. Note that since the goal of the sampling task is to route

sensor data to the mobile object, messages from higher bands must still propagate through lower bands, where collisions can still occur. By scheduling the sensor nodes to begin their broadcasts at different time slots, we can extend our band scheme to also reduce the negative impact of such packet collisions by reducing the "time-correlation" of the broadcast packets. To achieve this objective, we introduce the concepts of stage and band-scheduling. By using band scheduling, we introduce an explicit time lag between the broadcasting of packets sent by nodes in two different bands, which consequently weakens the impact of the second condition for causing packet collisions. For sensor nodes in Band i, there exists a time window, called the band's stage and denoted Si, during which these nodes can broadcast their own sensor readings. Outside of this time window, these sensor nodes can only forward packets that originated in other (higher) bands. Employing a conventional means for packet collision reduction (during some specific stage), we assume that each sensor node delays for some random time before broadcasting its own sensor data. This will reduce collisions within a band. The maximum random-delay value is denoted as D and is used later in formulating the duration of a stage. For an N-band configuration, the response to a mobile sink's SIS is complete when all N - 1 bands have completed their stages, in a ordering defined by a given band schedule. The sum of the N - 1 stage-durations is a constant, independent of the band schedule that is used. We call this sum the Overall Reaction Time, denoted as ORT.
For an N-band configuration using band scheduling, the ORT is the elapsed time required to complete the sampling task.

$$ORT = \sum_{i=1}^{N-1}(t(i)) + (N-1)^{*}\Omega_D$$
$$= \sum_{i=1}^{N-1}\left(\frac{\pi^{*}W^{*}i}{R_{SENSOR}} {*}T_{1-HOP}{*}\theta\right) + (N-1)^{*}\Omega_D.$$

IX. TRADEOFFS

1. Minimize ORT,
2. Maximize deliverability, and
3. Maximize speed.

From the system designer's perspective, minimizing energy consumption (measured in terms of number of message broadcasts/rebroadcasts and receives) is of interest. Of the parameters under control, assuming a fixed RMOBILE and RSENSOR, N is the most important. (Recall that the SIS allows a mobile object to define the number of bands used to cover a sampling region.) We now identify some tradeoffs in optimizing our objective metrics.

X. CONCLUSION

We proposed a simple, energy-efficient protocol to aid sensor-field sampling by a mobile object. The protocol exploits the concept of bands to limit the propagation of sensor data broadcasting, providing a form of directional broadcast based on software control. Methods for defining and using bands were presented. Extensive simulations under two communication models were conducted to evaluate the performance and trade-offs of our band-based scheme. The first communication model assumed no collisions and a binary sensor-to-sensor communication model. The second communication model assumed collisions, and a decay communication model. The simulations indicated that the band-based scheme is quite efficient in directional broadcast, and moreover, performs much better than default Omni-directional broadcast. The scheme proposed in this paper is mostly a generalized model. It can be further optimized for different types of applications. For example, there are several directions for future work: 1) Handling data aggregation. Intuitively, some band schedules, for example, the outside-in schedule, have the natural capability to facilitate data

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aggregation for a sampling task. Their potential should be further exploited; 2) coordinating multiple sampling tasks. It is possible to have multiple sampling tasks, initiated by the same or different mobile objects, whose sampling regions overlap. It is desirable to have an efficient coordination mechanism such that overlapped regions need only reply once for the sampling tasks. The algorithm for multi root multi query optimization for a static network is a potential candidate to be adapted to the mobile environment; 3) avoiding packet loss. With our band-based approach there may not always be a next-hop node located in the same band, or lower band, and this will stop the propagation of sensor-data packets. In this case, some sensor data packets may become lost in terms of reaching the mobile object. As we discussed, this is a trade-off of utilizing the band-based broadcast. Future research can consider some techniques to selectively allow rebroadcast of packets that would otherwise be disallowed by the currently proposed band-based mechanism. The purpose would be to avoid packet loss, while preserving a form of controlled broadcast.

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