Interest Dissemination with Directional Antennas for Wireless Sensor Networks with Mobile Sinks

Yihong Wu, Lin Zhang, Yiqun Wu, Zhisheng Niu
State Key Lab on Microwave and Digital Communications
Department of Electronic Engineering
Tsinghua University Beijing, P.R. China, 100084
{wuyh02,wuyq02}@mails.tsinghua.edu.cn, {linzhang,niuzhs}@tsinghua.edu.cn

Abstract

Introducing mobile data sinks into wireless sensor networks (WSNs) improves the energy efficiency and the network lifetime, and is demanded for many application scenarios, such as battlefield vehicle security, mobile data acquisition, and cellular phone based sensor networks. However, highly mobile sink nodes cause frequent topology changes, resulting in high packet loss rate and poor energy efficiency of traditional reactive WSN routing algorithms. A directional-antenna-assisted reactive routing protocol for WSNs, IDDA (Interest Dissemination with Directional Antenna) is introduced to resolve this problem. Different from traditional interest diffusion routing protocols, IDDA exploits the antenna directivity to prearrange interest dissemination along the direction of motion. IDDA enhances important performance metrics in a target detection application scenario, namely, energy efficiency, packet delivery ratio, and target detection ratio. An analytical model is established to calculate the optimal width of the antenna beam pattern and optimal transmitting power. Extensive simulation results show that IDDA outperforms the traditional directed diffusion protocol in all three aforementioned metrics, which guarantees that IDDA can be applied to WSNs with highly mobile data sink nodes.

Categories and Subject Descriptors

C.2.2 [**Computer Communications Networks**]: Network Protocols; D.2.8 [**Software Engineering**]: Metrics—*complexity measures, performance measures*

General Terms

Algorithm, Design, Experimentation, Theory

Keywords

Mobile Sink, Wireless Sensor Network, Antenna Directivity, Reactive Routing, Cross-layer Optimization

1 INTRODUCTION

Wireless sensor networks offer a wide range of applications, including military sensing, traffic surveillance, infrastructure security and medical monitoring. Usually inexpensive and wirelessly connected, sensor nodes can be densely deployed in the vicinity of the phenomenon, gathering and delivering abundant real-time information about the events of interest to the observers. Furthermore, fitted with onboard processors, sensor nodes are also capable of cooperating with others by carrying out simple computations of data aggregation and transmitting only partially processed data rather than raw data.

It has already been shown [4, 7] that WSNs with static data sinks are vulnerable due to early battery depletion of the one-hop neighbors of the sink. This is natural because most of the data traffic is relayed to the sink by these nodes, thus greatly increasing their energy consumption, resulting in their untimely death and partition of the network topology. Consequently, nodes located remotely will be unable to report to the sink, which actually reduces the lifetime of the WSN greatly.

Introducing a mobile data sink into WSNs is a solution to balance the energy consumption throughout the network geographically. In this way, the cost for data relaying spreads over the entire network, rather than concentrating in the vicinity of the sink node. The energy efficiency as well as the lifetime of the network will considerably increase. Furthermore, mobile sinks are not only a solution to prolong network lifetime, but also a requirement from many applications. Basically, when a WSN user intends to gather data from several dispersed hot spots in the field, he can use a mobile data sink node to traverse the area, utilizing the *on-demand* routing strategy to collect data. Specifically, the mobile sink could be a tank patrolling across the battlefield, collecting nearby mine distribution information and being alert to ambush. Desirable as a mobile sink is, it poses new challenges for efficient sensor networking. First, frequent topology changes occur as the sink travels among sensors, causing a high control overhead to maintain the route, which may probably offset the energy saved from mobile sink strategy. Furthermore, high packet loss and transmission delay will result from changes of sink location. These problems are especially serious in applications where sinks move at relatively high speed. Examples of this scenario include reconnaissance vehicles equipped with computing and communication devices in a battlefield and emergency cars in disaster-rescue missions.

In this paper, we address the problems caused by the mobility of sink nodes, and propose *IDDA*, an *Interest Dissemination with Directional Antenna* scheme of reactive routing for WSNs with mobile sinks. In IDDA, with the prior knowledge of its velocity, the sink node uses a *directional antenna* to broadcast interest packets along its direction of motion, and this prearranges an interest dissemination in advance. When the mobile sink keeps moving along its orientation, IDDA collects data back from sensor nodes in the vicinity reactively. If the prearranged interest dissemination is carefully adjusted to a proper scale, the returning data will meet the mobile sink when it arrive at the data aggregation point, increasing the packet delivery ratio and reducing the power consumption.

The antenna pattern and transmitting power play very important roles in the protocol performance. We establish an analytical model to calculate optimal antenna pattern and transmitting power. To further improve IDDA's performance, we design a cross-layer (PHY+NET) technique in interest dissemination, which reduces energy consumption. Based on extensive simulation, we show that IDDA outperforms traditional reactive WSN routing protocol in energy efficiency, packet delivery ratio, and data acquisition quality.

The rest of the paper is organized as follows. Section 2 presents the system model and basic assumptions of our work. In Section 3, we analyze how the antenna pattern and transmitting power influence the protocol performance, and propose an algorithm to optimize the transmitting power and antenna gain of the mobile data sink. A power-aware scheme is also proposed in this section to avoid unnecessary interest disseminations. In Section 4 the protocol is presented. Simulation results are presented in Section 5 to evaluate the effectiveness of the algorithms and to analyze the impact of cross-layer design. The related work is summarized in Section 6. Finally, we discuss the implications of our algorithms in Section 7.

2 SYSTEM MODEL

Consider a sensor network, where N nodes are randomly deployed in a sensing field. A mobile sink node serves to collect information in its vicinity. A specific application scenario (Figure 1) is a battlefield, where a large amount of sensor nodes are scattered randomly, performing environment monitoring and intrusion detection. A vehicle travels through this field at a relatively high speed. In order to secure its safety, the vehicle needs to collect information, such as number of mines or positions of invading enemy within the periphery, say, a circular region with radius of 1000m and centered at its own position. Since the radio communication of the sensor nodes is much less than the radius, data have to be transmitted to the mobile sink in a multi-hop fashion.

We made the following assumptions about the sensor network architecture:

1. All the sensor nodes are fixed and are supported by non-renewable batteries. Each sensor node has a unique identifier and is aware of its own location (for example through a GPS receiver or other positioning techniques like [11, 12]). Omnitennas are used to transmit/receive packets. The received signal strength is measurable(soft demodulation output). All nodes are assumed to have a common communication radius R.

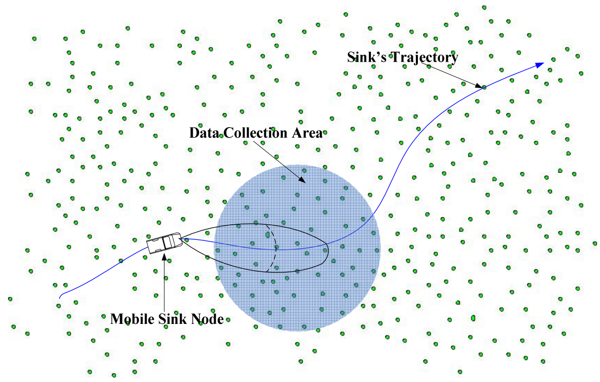


Figure 1. System model and application scenario: environmental data collection from a vehicle in a battlefield

2. The mobile sink node has prior knowledge about its movement, which means its current velocity and moving direction can be measured by itself. This is not a strict requirement in that the sink node is always incorporated with a vehicle and other apparatus like GPS. However, it is not necessary for mobile sinks to know locations of other sensor nodes.

3. Mobile sink nodes use a directional antenna to transmit packet, employing beamforming techniques to dynamically control its transmitting gain and maximum-radiation direction. However, its receiving antenna is omnidirectional and is assumed to have the same parameters as other nodes.

While the propagation model proposed here is simplistic, it is sufficient to illustrate how beam directionality and increased transmission power on the mobile sink motivate new algorithms for interest dissemination and data retrieval. We will comment on how changed assumptions regarding the propagation conditions affect algorithmic parameters in the conclusion.

3 IDDA: INTEREST DISSEMINATION WITH DIRECTIONAL ANTENNA

In this section we describe how antenna directivity is exploited to handle sink mobility efficiently. Moreover, methods to maximize successful packet delivery by optimizing power and beamwidth are presented through analytical evaluation. Finally, a power-aware design is introduced to further enhance successful routing in the network layer.

3.1 Basic Idea

Traditional reactive routing protocols can be used to address the varying topology brought by sink mobility, such as Directed Diffusion [3]. Interests (Data Queries) from the sink node are propagated through the network to establish a gradient field in a hop-by-hop fashion. Requested data will then flow down in the reverse path to the sink's one-hop neighbors and finally to the data sink. However, since the mobile sink node keeps moving after the original interest broadcasting, the gradient field established will be out-of-date when the requested data are routed back. This leads to severe packet loss especially when the data sink travels at a relatively high speed. Long latency of multi-hop data routing also aggravates this situation. Frequent topological changes trigger frequent route reconfiguration, resulting in high protocol overhead, which makes it uneconomic to resolve the problem at the network layer. Therefore, we should seek solutions combining information from lower layers to handle sink mobility problems.

The basic idea of IDDA is to establish paths in the network before sink's arrival. IDDA utilizes directional antenna to disseminate interest information, enabling cooperation between physical layer and network layer. If the movement of the sink node is predictable, a directional antenna and adaptive beamforming techniques could be used to aim the maximum radiation direction toward the sink's next position and broadcast interest along its trajectory. Significant energy savings could be achieved compared with broadcasting using an omnitenna, since most nodes covered by the omnitenna cannot communicate with the sink after the sink's location changes.

Let $\vec{v}$ denote the sink's velocity. Assume the sink requests data from the sensors at most K hops away. The Round Trip Time(RTT) for K-hop data collection is denoted by T_{RTT}. Thus before data is routed back the sink node will have traveled for a distance of

$$S = |\vec{v}| \cdot T_{\mathrm{RTT}}. \tag{1}$$

Therefore, at least a distance of S has to be covered by the sink's antenna beam. With the knowledge of T_{RTT} and $\vec{v}$, the sink node can dynamically control its beam pattern to ensure that it is still within the communication range of its one-hop neighbors when data is routed back.

Note that T_{RTT} is a parameter reflecting the current congestion level of the network. Assuming the transmitted packets share an equal length of L bytes, and the data rate of wireless links is R_{b} byte/s, in most cases, we have $T_{\mathrm{RTT}} \gg 2KL/R_{\mathrm{b}}$. This is primarily due to the traffic jam at the transport layer and the back-off scheme at the MAC layer. Furthermore, sleep and wake-up energy saving mechanism of sensor nodes also contributes to the delay. In fact, it is difficult to estimate T_{RTT} from previous data samples in realtime. Therefore, in our routing algorithm, T_{RTT} is a deterministic parameter set by the mobile sink. Ignoring the propagation delay, our protocol guarantees that data will be reported to the sink node after a delay of T_{RTT}. Furthermore, the sink will adjust T_{RTT} adaptively in a centralized way according to the network congestion situation. The T_{RTT} adjusting algorithm is presented in Section 4.4.

3.2 Optimized beamwidth and power configuration

In this part we present how to evaluate the optimal beamwidth and transmitting power analytically. Also we prove that as a generalized extension of the Directed Diffusion algorithm, our algorithm reduces gracefully to the classical case(omnitenna) in the special case of a static sink.

Assume the transmitting antenna of the sink node has a wavelength of λ, a gain of G_t and a power of P_t. Sensor nodes use an omnitenna to receive, whose gain is G_r and receiver power threshold is $P_{r,\min}$. For the free space fading model [10], the antenna beam covers a maximum distance of

$$R_{\max} = \sqrt{\frac{\lambda^2 P_t G_t G_r}{(4\pi)^2 P_{r,\min}}}, \tag{2}$$

where P_t and G_t are parameters that can be controlled to achieve optimal energy efficiency.

In most cases, the normalized power pattern $P_n(\theta)$ of an antenna varies with the angle [1], resulting in an irregular shape of beam pattern. For analytic tractability, we approximate the antenna with a uniform gain radiation pattern to obtain a sector-shaped beam as shown in Figure 2. By antenna theory [8] and assuming the same pattern in the vertical direction as the omnitenna, the beamwidth θ_p is given by

$$\theta_p = \int_{2\pi} P(\theta)d\theta = \frac{2\pi}{G_t}, \tag{3}$$

where $G_t \geqslant 1$. Within θ_p the antenna gain takes a constant value of G_t. When $G_t = 1$, $\theta_p = 2\pi$, representing an omnitenna.

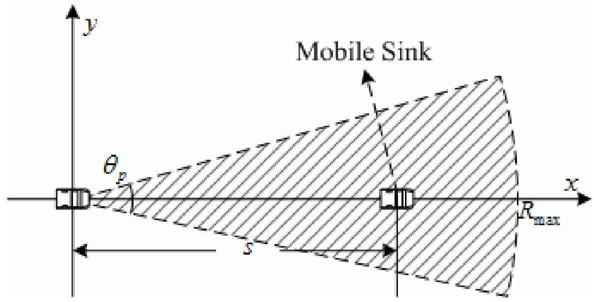


Figure 2. Sink position and beam pattern

In Figure 2, where the sink node is moving along the x-axis, we denote the area covered by the antenna beam by D_{beam}, whose radius is given by Eq.(2). The area of D_{beam} is

$$S_{beam} = \frac{1}{2}\theta_p R_{\max}^2 = \frac{\lambda^2 P_t G_r}{16\pi P_{r,\min}} \propto P_t. \tag{4}$$

Therefore, the area covered is proportional to the transmitting power, independent of the antenna gain (beamwidth). Assuming the sensor field takes a uniform node distribution $\rho(x,y) = \rho$, we observe that as long as the transmitting power is fixed, the nodes covered by the beam pattern form has a constant number on average. Define all these one-hop neighbors as interest disseminators, who are in charge of disseminating the interests of the data sink. However, the beamwidth also plays a role in determining the efficiency of

[1]The following discussion deals with beam pattern in two dimensions, where the variable φ in $P_n(\theta,\varphi)$ diminishes after the integral $\int_0^\pi \sin\varphi d\varphi = 2$

data collection, since obviously either too large or too small of a beamwidth will compromise routing performance. Next we consider how to optimize θ_p(equivalently G_t or R_{max}) to achieve the minimum communication cost.

By Eq.(1), the sink node has traveled a distance of s when data are routed back to the disseminators. In order to minimize packet loss due to limited communication range, we hope these disseminators to be concentrated in the vicinity of sink's new position. Therefore, we consider the following goal function as the optimization metric,

$$\theta_{p(\text{opt})} = \arg\min_{\theta_p} E\left[d^2_{\text{toSINK}}\right], \tag{5}$$

where $E\left[d^2_{\text{toSINK}}\right]$ is the average distance square from interest disseminator to the sink. The deviation-like nature of $E\left[d^2_{\text{toSINK}}\right]$ reflects the concentration level of interest disseminators relative to the sink location. It could also be interpreted as the average energy cost of communication under the free space fading channel. This method follows the energy consumption analysis in LEACH [5].

Evaluating the expectation we have

$$\begin{aligned} E&\left[d^2_{\text{toSINK}}\right] \\ &= \iint_{D_{beam}} \left[(x-s)^2 + y^2\right] \rho(x,y)dxdy \\ &= \iint_{D_{beam}} \left[(r\cos\theta - s)^2 + (r\sin\theta)^2\right] \rho(r,\theta) r dr d\theta \\ &= \rho \int_0^{R_{\max}} \int_{-\theta_p/2}^{+\theta_p/2} \left(r^2 + s^2 - 2sr\cos\theta\right) r d\theta dr \\ &= \rho \left(\frac{1}{4}R^4_{\max}\theta_p + \frac{1}{2}s^2 R^2_{\max}\theta_p - \frac{4}{3}sR^3_{\max}\sin\frac{\theta_p}{2}\right). \end{aligned} \tag{6}$$

Combining Eq.(2) and (3), we have

$$\theta_p = \frac{\eta P_t}{R^2_{\max}} \tag{7}$$

where $\eta = \frac{\lambda^2 G_r}{8\pi P_{r,\min}}$ is a constant. Plugging it into Eq.(6) yields

$$E\left[d^2_{\text{toSINK}}\right] = \rho\left[\frac{\eta P_t R^2_{\max}}{4} + \frac{s^2\eta P_t}{2} - \frac{4sR^3_{\max}}{3}\sin\left(\frac{\eta P_t}{2R^2_{\max}}\right)\right]. \tag{8}$$

By taking the derivative of $E\left[d^2_{\text{toSINK}}\right]$, the optimal $R_{\max}$ is given by the following transcendental equation

$$\frac{1}{2}\eta P_t R_{\max} = s\left[4R^2_{\max}\sin\left(\frac{\eta P_t}{2R^2_{\max}}\right) - \frac{4}{3}\eta P_t \cos\left(\frac{\eta P_t}{2R^2_{\max}}\right)\right]. \tag{9}$$

Note that because the communication range for receiving is R, there is no need for $R_{\max}$ to exceed $s+R$. Since there are two degrees of freedom in Eq.(8), namely P_t and $R_{\max}$, we set $R_{\max} = s+R$ to allow more area overlaps with the sink's receiving range. Therefore, solving the above equation numerically gives $P_{t(\text{opt})}$ and hence $\theta_{p(\text{opt})}$. Finally, from Eq.(3) we obtain the optimal parameter configuration for the transmission antenna:

$$G_{t(\text{opt})} = \frac{2\pi(s+R)^2}{\eta P_{t(\text{opt})}}. \tag{10}$$

As a generalization of Directed Diffusion, it is desirable for IDDA to reduce to the classical algorithm in the special case of a static sink. Now we examine the limiting behavior of the above solution for a given power P_t.

1. When sink is at rest, $v = 0$, by Eq.(1) $s = 0$. Then Eq.(8) is reduced into

$$E\left[d^2_{\text{toSINK}}\right] = \frac{\rho\eta P_t}{4} R^2_{\max}. \tag{11}$$

   Obviously the energy cost is minimized when $R_{\max}$ takes its minimum value. By Eq.(7), when $G_t = 1$, $R_{\max}$ achieves its minimum of $\sqrt{\eta P_t/2\pi}$. At the same time $\theta_p = 2\pi$, representing an omnitenna. Now our algorithm reduces to the classical version of Directed Diffusion.

2. When v is increasing, θ_p decreases monotonically as shown in Figure 3. The numerical treatment of Eq.(9) is presented in Appendix B. Some typical solutions are given in Table 1.

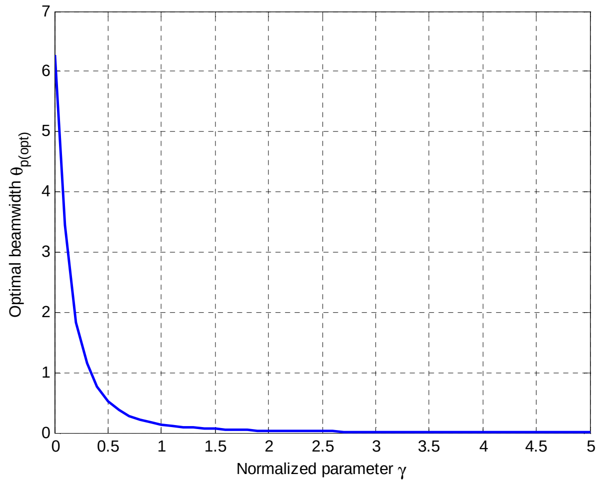


Figure 3. Numerical evaluation of optimal beamwidth $\theta_{p(\text{opt})}$ as a function of sink velocity v, where $\gamma = \frac{s}{\sqrt{\eta P_t}}$ is a dimensionless parameter proportional to sink velocity.

γ	0	1.000	2.000	3.000	4.000
$\theta_{p(\text{opt})}$	3.1416	0.0700	0.0176	0.0078	0.0044
γ	5.000	6.000	7.000	8.000	9.000
$\theta_{p(\text{opt})}$	0.0028	0.0020	0.0014	0.0011	0.0009

Table 1. Typical solutions of Eq.(19)

3. As v tends to infinity, θ_p tends to 0, which shows that the interest packet is broadcasted solely onto sink's direction of motion. This asymptotic property of Eq.(9) is proved in Appendix A.

In summary we observe the following properties in the optimal beamwidth of IDDA: θ_p decreases as $|\vec{v}|$ increases, and

$$\theta_p = \begin{cases} 2\pi, & |\vec{v}| = 0 \\ 0, & |\vec{v}| = \infty \end{cases}, \tag{12}$$

which is consistent with our intuition.

3.3 Controlling the Distribution of Interest Disseminators

In Figure 2, we observe that sensor nodes in the vicinity of the sink will be out of communication range after the sink moves away, thus their serving as interest disseminator would be a waste of energy. Unfortunately there is no antenna capable of producing a beam pattern that only covers a distant area. However, by using information from the physical layer, we can modify the forwarding strategy at network layer to prevent unnecessary interest dissemination.

A straightforward strategy is using received signal strength to decide whether to forward the interest packet or not. According to free space attenuation, stronger signal power implies shorter distance between receiver and sender. Sensor nodes check the signal strength of received interest packets: if the power level exceeds a certain preset threshold, interests will not be disseminated. However, from the previous discussion we find that the transmitting power of interest packets depends on the sink's velocity. Therefore instead of using signal power directly, we use an *equivalent received power*, i.e. the ratio of signal power to receiver threshold, to control interest dissemination.

Let

$$P_{r(\text{eq})} = \frac{P_r}{P_{r,\min}} \tag{13}$$

and set the threshold for $P_{r(\text{eq})}$ as α. The interest disseminating strategy is expressed as

a). do not disseminate, if $P_{r(\text{eq})} > 1/\alpha$;

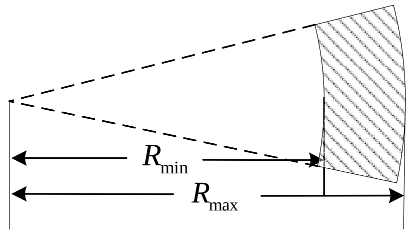
b). disseminate, if $P_{r(\text{eq})} \leqslant 1/\alpha$.

Comparing equivalent received power with this threshold provides nodes with a simple rule to decide if received interest packets should be propagated. In fact, the upper strategy limits interest disseminators in the range of $R_{\min} \leqslant R \leqslant R_{\max}$, as shown in Figure 4(a), where $R_{\min}$ is expressed as

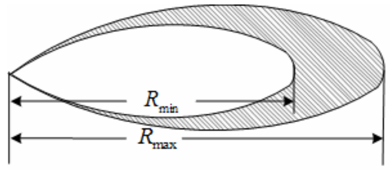
$$R_{\min} = \sqrt{\frac{\lambda^2 P_t G_t G_r}{(4\pi)^2 \frac{P_{r,\min}}{\alpha}}} = \sqrt{\alpha} R_{\max}. \tag{14}$$

Therefore, by means of this *energy-aware* dissemination, it is equivalent to produce a beam pattern that covers only the distant region from the transmitting antenna. The parameter α determines a trade-off between energy consumption and data collection quality. The less α is, the more interest disseminators there will be, which consume more energy and provide a better data collection service. If a power-aware algorithm is not applied, it equals to the case of $\alpha = 0$. We denote IDDA algorithm with $\alpha \neq 0$ as the *power-aware IDDA*.

Note that Figure 4(a) is obtained in the context of a simplified antenna model, where the antenna gain is assumed to be constant within the beamwidth. Actually in the real application antenna often has a nonuniform antenna gain and an irregular shape of beam pattern. It reaches the maximum at zero angle and gradually drops to zero as the angle grows. Thus the dissemination strategy will result in an interest dissemination area shown by Figure 4(b). From this figure we observe that some nodes near the data sink also locate in the shaded area and become interest disseminators. They will be out of communication range when the mobile sink moves and fails to deliver their data. This will offset the gain in packet delivery ratio to some extent; however, it is relatively small compared with energy saving achieved by power-aware IDDA.



(a) Uniform antenna gain



(b) Varying antenna gain

Figure 4. Interest dissemination area of power-aware IDDA (cont.)

Of course, with fading and shadowing effects the interest region is unlikely to have smooth boundaries in practice or even be one connected region. However, the interest dissemination zone will, statistically speaking, be better concentrated than without a threshold mechanism.

4 ROUTING AND DATA AGGREGATION

The operation of IDDA consists of three phases, namely, Initial Interest Broadcasting, Interest Dissemination, and Data Report. Three kinds of packets, namely, RESERVATION, INTEREST and DATA, are used in these three stages respectively. We take the special case of one-dimensional movement of a mobile sink as an example to describe the communication process. In Figure 5, the mobile sink broadcast a RESERVATION packet at point A_1, and expected data to be collected back at point B_1. When the sink moves to point A_2, it broadcasts again. The interest period is predetermined according to the desired refresh rate of data.

4.1 Initial Interest Broadcasting (Route Reservation)

The mobile sink node estimates the RTT for the data collection T_{RTT} via delay accumulation and lowpass filtering on the RTT sequence previously measured. This RTT estimation technique is illustrated in Section 4.4. Then the sink uses Eq.(10) to set the power and gain for the transmitting antenna and broadcasts the interest packet periodically. The packet type is RESERVATION, distinguishing it from packets forwarded by other nodes. The packet also contains T_{RTT},

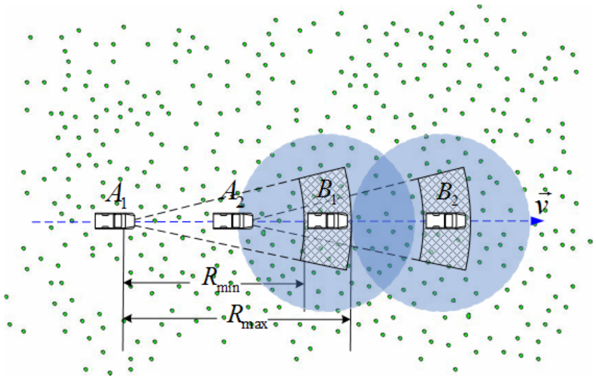


Figure 5. The general communication process of IDDA: data sinks send queries and receive data periodically

hop number k, total hop number K and the data type the sink desires [2]. For the RESERVATION packet from the sink the hop number is $k = 1$. When the interest is forwarded one hop, k increases by one. When k equals K dissemination will be terminated and data begin to flow back to the sink. Therefore K determines the range of data collection.

4.2 Interest Dissemination

Wakened by the received RESERVATION packet, sensor nodes decide whether to broadcast the packet by the dissemination strategy. The packet type is changed into INTEREST and hop number is incremented by 1. When K hops are reached, nodes will stop the dissemination process and turn into the data report phase. During the interest dissemination every node maintains an interest cache and gradient list. These two structures are described below:

1. **Interest Cache.** Distinct interests are stored in the interest cache. Two interests are distinct if their data types or sequence numbers are different. Duplicate interest packets are aggregated in the interest cache to avoid unnecessary dissemination in the network.

2. **Gradient List.** Each entry in the gradient list corresponds to an interest sequence number. It consists of a source node ID and a hop number. Each sensor stores the node ID from which the interest is received, and the hop number is also recorded from the received packet. This method establishes a path for directing data flow to the sink later. Note that nodes may receive other interests from the mobile sink when their data reports are not finished yet. Thus different paths should be maintained for different interests.

Because mobile sinks collect data and then leave the field, the probability for queries of the same data hitting the same nodes is relatively small. Therefore, a data cache is not equipped in IDDA algorithm. Similarly, path reinforcement is not used in IDDA due to the sink mobility. However, in the situation where sinks move circuitously, such as performing patrol or reconnaissance tasks, a data cache may be introduced to address duplicate data queries and further increase energy efficiency.

[2] Data is named using attribute-value pairs [3]

When an INTEREST packet is received, the node first compares it with entries in the interest cache. If no previous record is found, a new entry will be added to the interest cache and gradient list. If the same interest exists, the received packet will not be forwarded. If it has a hop number k smaller than that in the gradient list , the corresponding source ID and hop number will be updated. If multiple interests are received, the packet with the smallest hop number will be chosen. In the presence of the same hop number, the packet with the strongest signal strength is preferred.

4.3 Data Report

The interest propagation continues until K hops are covered, when sensor nodes stop dissemination upon receiving an INTEREST packet with $k = K$. If the data of a K-hop node matches the sink's interest, it will send a DATA packet to its parent node recorded in the gradient. On the other hand, after each node propagates the INTEREST packet, it waits for a certain duration to report its data to its predecessor. The round trip delay T_{RTT} is uniformly divided among K hops. Specifically, for nodes with a hop number of k, the waiting duration is

$$T_{\mathrm{wait}} = \frac{T_{\mathrm{RTT}}}{2} + (K-k-1)\frac{T_{\mathrm{RTT}}}{2(K-2)}. \qquad (15)$$

Therefore, every node is allocated a timeslot of $\frac{T_{\mathrm{RTT}}}{2(K-2)}$ to report to its parent node. The nearer a node is to the sink, the longer time it will wait. Eq.(15) is further explained in Section 4.4. During the counter time successfully received DATA packets from upstream nodes will be cached by the parent nodes. When the counter determined by Eq.(15) expires, data aggregation is performed to merge the cached data with local data to produce a representative DATA packet to send out. [3] In this way, data are aggregated and relayed via a multi-hop path until reaching the interest disseminators, who keep sending aggregated DATA packets until receiving sink's acknowledgement or reaching an certain retry limit, which ceases this round. Sensor nodes will go into sleep mode if not receiving INTEREST or RESERVATION for a fixed duration of time. Note that unlike Directed Diffusion, the above strategy does not require accurate time synchronization among nodes in the network, since no timestamp is used and all counter expirations are based on calculation of local timing.

We take a simple case with total hop number $K = 4$ as an example to illustrate the interest dissemination and data report processes, as well as the corresponding time line. As shown in Figure 6, interest dissemination results in a tree-structured topology, for example among sensor nodes. Note that the root refers to the interest disseminator and every tree corresponds to one disseminator.

The communication process is depicted in Figure 7. During interval T_1, interest packets are disseminated for three times from node 1 through all other nodes. With k reaching

[3] Note that it may happen that several children nodes begin to report data to their common parent node at the same time, resulting in channel contention. This problem is handled by the appropriate mechanism in MAC layer and we focus on the routing layer operation in our present discussion.

4, nodes 7, 8 and 9 start to report data to their parent nodes immediately. This process finishes at the end of T_2. Nodes 4, 5 and 6 do not report their data instantly; instead, they wait until their counters specified by Eq. (15) go off at $t = \frac{T}{2}$. Upon expiration, data aggregation is applied to cached packets from upstream nodes. For example, node 2 merges data from nodes 4 and 5 with its local data and sends the aggregated packet to node 1. The transmission is completed during T_3. Similarly, during T_4 data are sent to node 1, the interest disseminator. Finally when the counter of node 1 expires at $t = T$, it starts to transmit the aggregated data packet to the mobile sink. When it receives an ACK from the sink or hits a certain retry limit, transmission stops and this round of communication is completed.

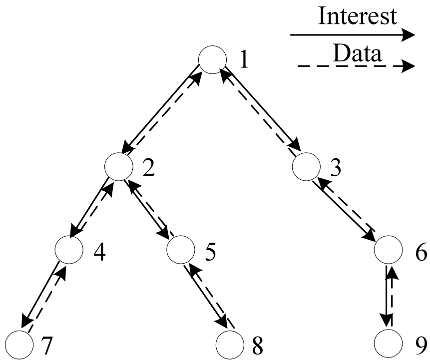


Figure 6. A simple case with total hop number $K = 4$.

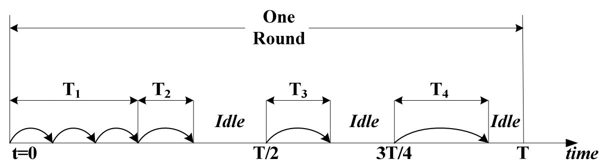


Figure 7. Time line showing IDDA operation with network topology shown in Figure 6.

4.4 RTT Estimation and Update

The initial value of T_{RTT} is chosen to be large enough so that upstream nodes can report data to their parents successfully. However, if T_{RTT} is too large the data collection quality will surely be compromised and the sink will consume additional transmitting power to cover a large area. We observe from Figure 7 that there are several idle periods in the time line. If we could record the accumulated length of these idle intervals and subtract it from the current RTT, a smaller RTT will be obtained that still allows a successful data report. On the other hand, if T_{RTT} is too small, it is possible that the allocated time slot is not enough to allow successful data report for each node. In this case, T_{RTT} should be enlarged to guarantee data delivery in next round. Therefore, we could add another field in the packet to record the accumulated idle period. For each non-leaf node, if DATA from children nodes are received during the counter time, it computes the time difference of receiving a data report from children nodes and the time when its counter starts, then adds it to the accumulated length. In the presence of several children nodes, the time of the last received packet is used. However, if corrupted packets are received or delivery failure is detected, it will subtract a doubled interval, that is, add $-\frac{T_{\text{RTT}}}{K-2}$ to the accumulated idle period to force an increased T_{RTT} in the next round. Finally the mobile sink subtracts the accumulated idle period from current T_{RTT} to obtain the T^*_{RTT}. Taking consideration of the previous estimated RTT, the Exponential Weighted Moving Average(EWMA) algorithm [15] is applied to produce a smoothed version of RTT. That is,

$$T_{\text{RTT}}(n+1) = \beta T_{\text{RTT}}(n-1) + (1-\beta) T^*_{\text{RTT}}(n), \qquad (16)$$

where n is the current sequence number of interest packets and β $(0 \leq \beta \leq 1)$ is the filter constant. Recent samples are given larger weight since they better reflect the current congestion level in the network. Assume that in the steady state of network communication each packet requires a fixed duration T_{const} to transmit. Then $T_{\text{RTT}}(n)$ will approach KT_{const} exponentially. The fast convergence of EWMA is desirable for IDDA in that the mobile sinks travel through regions where network congestion levels might be different. Then RTT will change adaptively and converge to the current congestion level quickly.

In summary, algorithms described in Section 4.1 – 4.4 for sensor nodes are shown in Figure 8.

5 PERFORMANCE EVALUATION

In this section, we evaluate the performance of IDDA and power-aware IDDA through simulations. We first describe our simulation metrics and implementation in Section 5.1. Then the effect of the parameter α in power-aware IDDA is evaluated in Section 5.2. From the simulation results we observe that there exists an optimum α corresponding to a maximum packet delivery ratio, and analyze its relationship with sink velocity. In Section 5.3, the impact of sensor density on packet delivery ratio and target detection ratio is evaluated. In Section 5.4 we compare IDDA and power-aware IDDA with Directed Diffusion and show that our algorithms have better performance in mobile sink scenarios.

5.1 Metrics and Methodology

For simplicity we assume the first order radio model [4] to compute the energy consumption in the communication process. In our simulation, the radio dissipates $E_{\text{elec}} = 50$ nJ/bit to run the transceiver circuitry and $\varepsilon_{\text{amp}} = 100$ pJ/bit/m^2 for the amplifier to achieve an acceptable SNR. Therefore, the energy costs for transmitting and receiving a l-bit packet over a distance of d are

$$\begin{aligned} E_T(k,d) &= lE_{elec} + ld^2\varepsilon_{amp}, \\ E_R(k,d) &= lE_{elec}. \end{aligned} \qquad (17)$$

Our packet-level simulation is performed in the following setting (Figure 8): a mobile sink is traversing a sensing field of 600m × 600m, where nodes are randomly deployed. The middle dashed line shows the sink's trajectory and direction. Sink starts from point A at $(0,300)$ and moves in $+\hat{x}$ direction. Each sensor node has a communication radius R of 20m and a sensing range S of 10m. When 3600 nodes are deployed, the node density is $\rho = 3600/(600\text{m} \times 600\text{m}) = 0.01/m^2$, which implies that one target is sensed by about $\rho\pi S^2 \doteq 3.14$ nodes simultaneously. This is reasonable for

```
1:  WaitForPacket(RESERVATION);
2:  if (counter expires)
3:      Switch to sleep mode;
4:  else
5:      Switch to active mode;
6:  // seq = n, hop number = k
7:  if (k == K) // leaf nodes
8:      Go to Line 31;
9:  else // non-leaf nodes
10:     Search interest cache for seq n and the same data
        type;
11:     if (not found)
12:         Broadcast INTEREST packet with hop number
            k+1;
13:         AddNewEntry(Interest Cache);
14:     elseif (k < previous hop number)
15:         or ((k == previous hop number)
16:         and(current signal strength > previous
17:             signal strength))
18:             UpdataEntry(Interest Cache);
19:             UpdataEntry(Gradient list);
20:     SetCounterTime(T_RTT/2 + (K - k - 1) T_RTT/(2(K-2)));
21:     Start Counter;
22:     while(counter not expired)
23:         if (receive DATA packet)
24:             Record ReceivingLastPacketTime;
25:     if(no DATA packets received)
26:         CurrentIdlePeriod = -T_RTT/(K-2);
27:     else
28:         CurrentIdlePeriod = CurrentTime-
            ReceivingLastPacketTime;
29:         Perform data aggregation;
30:     Accumulate idle period;
31: Data report to the parent node;
32: Go to Line 1;
```

Figure 8: Pseudo code of IDDA algorithm for sensor nodes

a robust target-detection application. Thus, we will deploy 3600 nodes in the sensing field unless noted otherwise. 100 targets are randomly scattered in the rectangular region confined by two outer dashed lines, which has a length of 600m and a width of 320m. The mobile sink requests data reported to it in $K = 10$ hops, or an equivalent range of $10R = 200$m. For simplicity, we assume perfect data aggregation such that multiple packets can be combined into one single representative packet. Also we use an initial round trip time of $T_{RTT} = 2$s for 10-hop interest diffusion and data report. The interest period is set to 2 seconds.

5.2 The Implication of Power-aware IDDA

As mentioned before, the parameter α controls the size of the interest dissemination area. Increasing α will shrink the number of interest disseminators, saving more energy but compromising detection quality. We propose three performance metrics to measure the efficiency of network operation, namely total energy consumption, Packet Delivery Ratio (PDR) and Target Detection Ratio (TDR). A packet is delivered to the mobile sink successfully if the corresponding interest disseminator locates within the sink's communication range. Also, a target is detected if packets containing its information are delivered to the data sink.

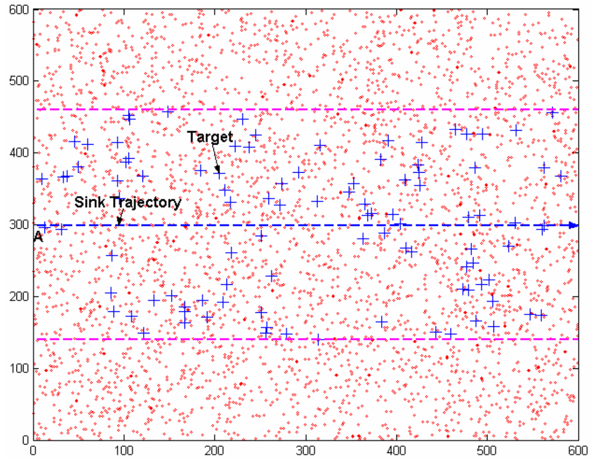


Figure 8. Simulation setup: a mobile sink traverses a square-shaped sensor field, performing target detection along its trajectory.

We investigate the effect of α on the network performance through simulation, by fixing v at 40m/s and varying α from 0 to 1. In Figure 9, the solid line shows the total energy consumption of power-aware IDDA normalized by the maximum energy cost at $\alpha = 0$. The dash line shows the target detection ratio, while the dash-dotted line shows the percentage of successful deliveries in all delivery attempts. Each point is averaged on 30 simulations. We observe that both energy consumption and detection ratio decrease as α increases, which is consistent with our analysis before. It is also worth noticing that there exists a maximum PDR corresponding to an optimal value of α. Around this α_{opt}, the detection ratio also reaches its peak (up to 90%). This is

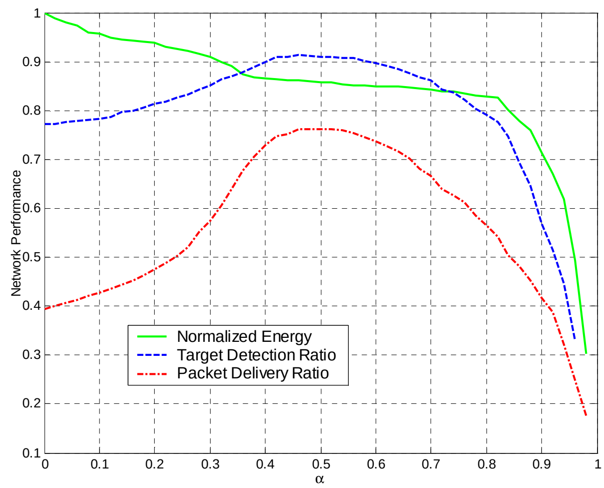


Figure 9. Network performance in power-aware IDDA as α varies from 0 to 1

mainly due to the limited communication radius. It is difficult to evaluate α_{opt} analytically; however, we could determine its range intuitively. From Figure 10 we observe that

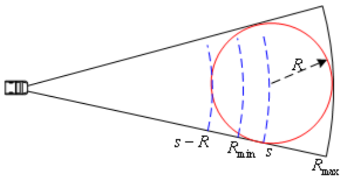


Figure 10. Optimal α to achieve maximum PDR

R_{min} should be at least $s-R$ in order to avoid unnecessary delivery failure. However, due to the fringe effect of the beam pattern, the maximum PDR occurs when R_{min} lies between $s-R$ and s, that is,

$$\left(\frac{s-R}{s+R}\right)^2 \leqslant \alpha_{opt} \leqslant \left(\frac{s}{s+R}\right)^2. \tag{18}$$

For our simulation, $s = 80m$, $R = 20m$, so we expect the optimal α to be $0.36 \leqslant \alpha_{opt} \leqslant 0.64$, which agrees well with the simulation in Figure 10. For the rest of the experiments, we set α_{opt} to $\left(\frac{s-R}{s+R}\right)^2$.

5.3 Impact of Node Density

In practical sensor networks, the node density varies significantly. The term *node density* can be comprehended in two ways here. On the one hand, the node density could be the average number of nodes per unit area of the sensing filed. In this way, with a fixed size of the sensing field, the node density depends on the total number of sensor nodes. On the other hand, the nodes are scattered randomly in the sensing field. The nodes may be dense in some places, and sparse in other places. Therefore, the node density varies inside the field. Although it would be interesting to consider the node density variation inside the sensing field, we do not attempt to address this issue here. We adopt the former definition, and evaluate the average performance of the algorithm. Generally speaking, the less nodes there are, the worse the network performance would be. This is because decreasing the node number will impair the connectivity of the network. For the multi-hop data routing in the network, it will be more difficult for the sink to collect the desired data. So the packet delivery ratio will decrease. The expected number of nodes which detect the same target will also decrease, thus decreasing the possibility of detection. So the target detection ratio will decrease in that condition.

The results above are apparent, but there may be other effects of the IDDA mechanism itself. To understand the impact of node density on the IDDA algorithm, we should diminish the effects brought by the communication radius and sensing range. The average number of nodes is with while node can communicate directly in the network are determined by $\rho\pi R^2$. Similarly, the number of nodes which detect a common target is determined by $\rho\pi S^2$. By keeping $\rho\pi R^2$ and $\rho\pi S^2$ constant, we can cancel the effects of parameters of the sensor nodes. The network performances of power-aware IDDA as α varies are shown in Figure 11 and 12.

In the simulation, the velocity of the sink node is fixed at 40m/s and α varies from 0 to 1. The number of sensor nodes varies from 1800 to 3600.

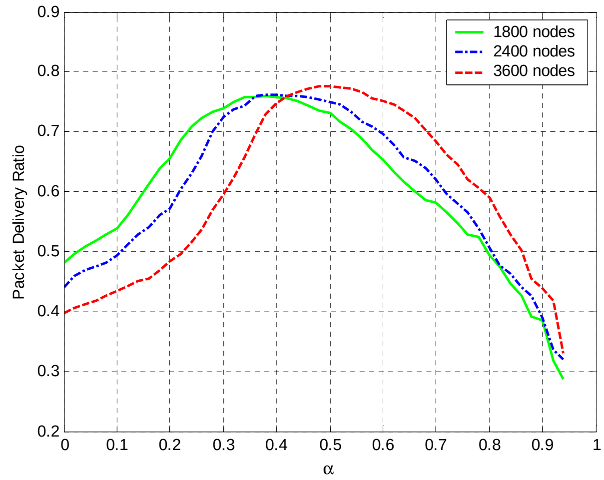


Figure 11. Successful packet delivery ratio with different node density

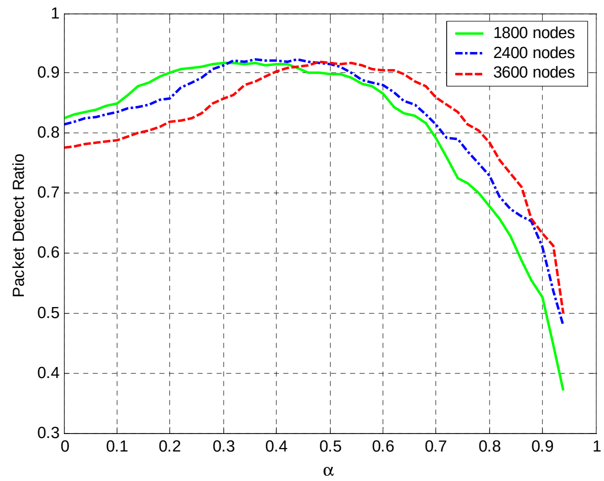


Figure 12. Successful target detection ratio with different node density

Figure 11 and 12 show that the IDDA algorithm still works well in lower node density; the peak values of the curves are almost the same. Alternatively speaking, the IDDA algorithm remains robust as the node density varies. We can also validate the conclusion of the optimal α in Section 5.2 by the two figures. When the node density decreases, larger communication range is needed. According to Eq.(18), when the communication range increases, the optimal α when the peak appears will decrease.

5.4 Performance Comparison

We compare IDDA, power-aware IDDA and the classical Directed Diffusion in terms of energy dissipation per data report, PDR and TDR. The mobile sink's velocity varies from 10m/s to 50 m/s. Note that the faster the mobile sink moves, the less time it takes to traverse the sensing field, hence the less data will be reported. In order to offset this effect, the energy consumption in the network is averaged on the number of data report attempts to the mobile sink, including failed deliveries. The simulation results are shown in Figures 13 – 15.

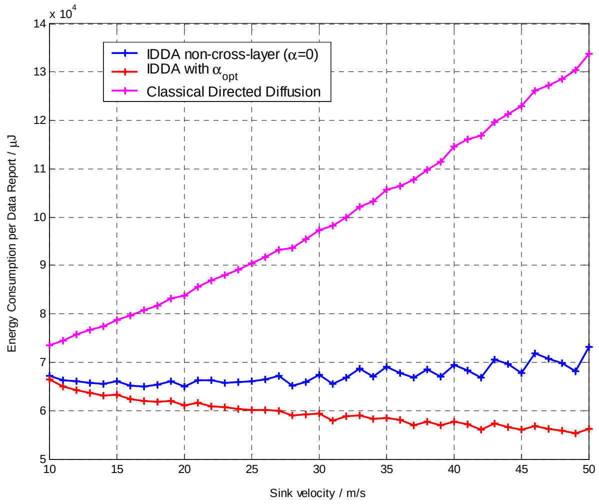


Figure 13. Comparison of energy dissipation per data report

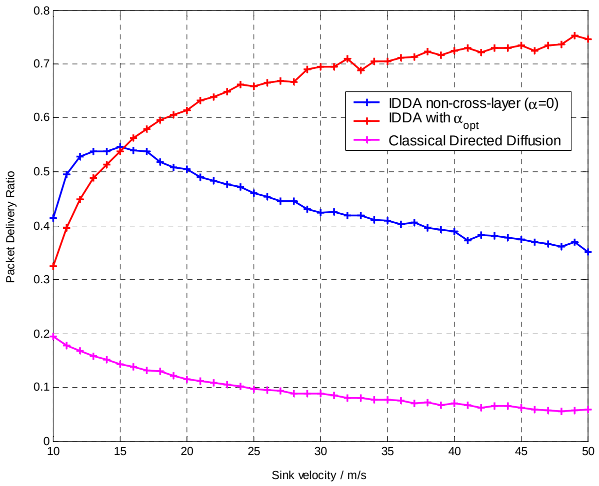


Figure 14. Comparison of successful packet delivery ratio

In Figure 13 we observe that there is considerable energy saving in our algorithms. Specifically, at $v = 50$ m/s the energy cost in Directed Diffusion is 1.8 times that of IDDA, and there is a further gain of factor 1.3 in power-aware IDDA over IDDA. The energy cost per data report in Directed Diffusion increases with v quickly, while in our algorithms it remains largely unchanged. This is because as v rises, the transmitting power of an omnitenna has to increase as v^2 in order to secure a data report. Instead, with a directional antenna, the data sink could concentrate its power on its direction of motion to achieve higher energy efficiency. Note that when v is small, the network consumes almost the same

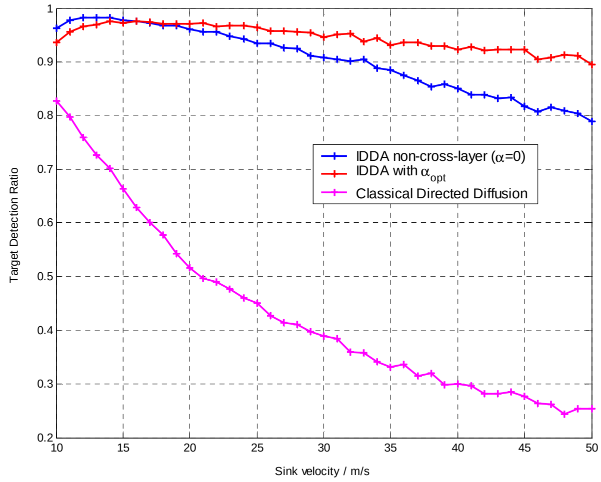


Figure 15. Comparison of target detection ratio

amount of energy for all three schemes. This agrees with our conclusion in Section 3.2 that the IDDA algorithm will reduce to Directed Diffusion as v approaches 0.

Figure 14 and Figure 15 also show that IDDA and power-aware IDDA outperform Directed Diffusion in packet delivery and target detection. While detection ratio in Directed Diffusion diminishes with v quickly, our algorithms are able to maintain a stable detection quality over varying velocity. It is interesting to note that the successful packet delivery in power-aware IDDA even grows with the velocity. This is because as v increases, the beamwidth became narrower. Hence less area falls out of sink's receiving range and more interest disseminators managed to deliver their aggregated packets to the mobile sink. Comparing Figure 13 and Figure 14 we could find that energy gain of power-aware IDDA to IDDA is not as much as that in PDR. For instance, at $v = 50$ m/s power-aware IDDA yields a 2.2-fold increase in PDR, but only gained a factor of 1.3 in energy dissipation. This could be explained as follows: power-aware IDDA saves more energy by eliminating unnecessary interest disseminators at the early stage of interest diffusion. However, although the number of disseminators is reduced in power-aware IDDA, after interest dissemination for many hops, it covers nearly the same size of area as in IDDA. This reduces the energy gain to some extent.

6 RELATED WORK

There is a growing interest in utilizing directional antennas in ad hoc or sensor networks. Research on improving the network performance by using directional antennas focuses mostly on MAC layer [17, 18, 19], and a few studies on improving the routing performance with directional antennas are reported in [20, 21]. Directional antennas have been shown to have the potential to provide dramatic increases in throughput and reduction in delay, and simultaneously requiring lower transmission power [17].

Although in general directional antennas can improve the network performance, its effect in sensor networks remains largely unclarified. This is because sensor nodes are often significantly less capable than the nodes in traditional networks. Also, the number of sensor nodes may be orders of magnitude higher than that of nodes in general wireless networks. Therefore equipping sensor nodes with directional antennas would impose great technical and physical difficulties on sensor node implementation. However, the number of data sinks in sensor networks are much smaller and they possess substantially more resources. Considering the above limitation of sensor networks, BeamStar, a low-cost data routing protocol, is proposed in [22]. It requires only sink nodes equipped with directional antennas, while omnitennas are used for sensor nodes. Its key idea is to shift the control and routing overhead from sensor nodes to data sinks. Sinks scan the sensor network with power-controlled directional antennas, and sensors infer their locations from sinks' control messages. Data forwarding decisions are based on location information at each node and the destination information set by sinks. Therefore, there is no need to maintain locations or routing tables in sensor nodes. This energy-efficient scheme reduces the control overhead on sensors, and prolongs the network lifetime. In this sense, IDDA bears a certain similarity to BeamStar, in that it also exploits the asymmetry in resources between common nodes and data sinks. In our algorithms a directional antenna with power and beamforming controllers are required in data sinks, which play a central role in sensor networks. Furthermore, the algorithmic complexity is concentrated on sinks while little overhead is imposed on sensor nodes.

On the other hand, more and more research has been devoted to address possible sink mobility in wireless sensor networks. TTDD, a protocol based upon virtual infrastructure, is described in [24]. A grid structure is initially built to divide the network into cells, where dissemination nodes are responsible for relaying the query and data to/from the proper sources. Queries from sinks are flooded *locally* within the cell until reaching a dissemination node. Requested data will flow down in the reverse path to the sink. In TTDD, the entire path would have to be altered when the sink switches to another dissemination node. In the case that mobile sink moves at a high speed, the path renewal may not keep pace with the sink's movement, resulting in severe performance degradation. In contrast, paths in IDDA are established before sink's arrival, which guarantees that IDDA works well with highly mobile sinks.

SEAD is another proposed method for routing to mobile sinks in wireless sensor networks[4]. Its basic idea is to construct a near-optimal dissemination tree for mobile sinks and designate several nodes on the tree as access points. Each mobile sink registers itself with the closest access node. When the sink moves out of range of the access node, the route is extended by including a new access node. However, SEAD could not handle the presence of multiple active sources, while directional interest dissemination and data aggregation techniques in IDDA are efficient in a multi-source scenario. EARM [13] is a routing mechanism similar to SEAD, in that it also tries to modify the existing path to accommodate the sink's location change. When the extended path behaves much worse than the optimal one, a new path will be established through rerouting. A major drawback of EARM is that data sinks are required to have knowledge of other nodes' locations. This would be a strict condition for self-configured sensor networks. But in IDDA only prior knowledge of its movement is required in data sink.

To exploit data redundancy and further conserve communication energy, data aggregation has been put forward as an essential paradigm for wireless routing in sensor networks [23, 3]. It reduces the amount of data transmitted from multiple nodes to a sink through in-network processing. One sensor node combines several data packets from different nodes and sends the representative packets to the sink. In Directed Diffusion, data aggregation is opportunistic. If multiple packets do not coincide at one node, packet cannot be aggregated. However in IDDA, every node is allocated a time slot to wait for data reported from children nodes. Therefore, data aggregation quality can be guaranteed.

7 CONCLUSIONS AND FUTURE WORK

In this paper, we described IDDA, a directional-antenna-assisted reactive routing protocol for wireless sensor networks with a mobile sink node. Interest packets are broadcasted periodically using a directional antenna in order to set up routes in the network before sink's arrival. The optimal beamwidth and transmitting power are evaluated analytically. It is worth noticing that as a generalization of Directed Diffusion algorithm, our approach reduces gracefully to the classical case(omnitenna) in the special case of a static sink. Furthermore, a power-aware dissemination algorithm is exploited and incorporated in IDDA to further reduce energy consumption. Finally, we compared IDDA and power-aware IDDA with Directed Diffusion in terms of energy dissipation per data report, packet delivery ratio and target detection ratio. Through extensive simulation we showed that our algorithms outperform traditional method and are efficient in handling sink mobility, for the simple physical assumptions of this paper. We expect that for many realistic propagation conditions powerful directional antennas can be used to improve the performance of directed diffusion when a mobile sink is present, as well as providing the obvious benefit of reducing latency for the initial interest diffusion.

Nonetheless, clearly many issues remain to be explored. Radio propagation assumptions strongly affect how much performance improvement can be expected from IDDA or similar algorithms. We have earlier noted that simple received energy thresholding mechanisms will not necessarily produce a predictable interest dissemination footprint for the directional antenna. The propagation loss law and assumptions regarding the receiver characteristics of the mobile sink also affect algorithmic parameters. For ground-to-ground communication, as between sensor nodes, fourth power loss is a better model than free space loss, while sink-to-node communication will follow a second power law for nearby nodes due to the higher antenna elevation, and fourth power loss for nodes that are far away. Consequently, the optimization of beamwidth depends on a variety of additional factors beyond those we have explored, and the exact benefits of an IDDA-like algorithm will vary accordingly.

One asset we have not exploited is the superior receiver of the mobile sink node, which in practice can have the same directionality for reception as transmission, and likely a lower noise figure than the lower-cost static nodes, in addition to its elevation advantage. At minimum this permits the mobile sink to gather information from the collection point at some distance greater than the nominal range of the static nodes, reducing latency. At most it might be able to directly communicate with all the nodes in the region of interest. However, the asymmetry in transmission power resources implies that for either fourth or second power distance losses the range in the forward direction will continue to exceed that in the reverse direction. Communicating with large numbers of nodes directly for the reverse link may also result in congestion, particularly as there will have been no data aggregation. A compromise might be to aggregate data to set of cluster heads, reducing latency at the expense of increased reverse-link communication compared to the version of the algorithm presented here. In addition, the superior resources of the mobile sink can also be combined with geographic information to further improve the network performance. Thus, there are many open research directions.

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A Proof of the asymptotic property of Eq.(9)

Proof: Let $t = 1/s$ and $P = 1/R_{\max}$, then Eq.(9) becomes

$$t = \frac{4}{CP}\sin\left(CP^2\right) - \frac{8}{3}P\cos\left(CP^2\right) \triangleq F(P).$$

Define

$$G(P) = \begin{cases} F(P) & P \neq 0 \\ 0 & P = 0 \end{cases}.$$

It is easy to show that $G(P)$ is continuously differentiable in P and its derivative is

$$\frac{\mathrm{d}G(P)}{\mathrm{d}P} = \begin{cases} \frac{16}{3}\cos\left(CP^2\right) - \frac{4\sin\left(CP^2\right)}{CP^2} + \\ \frac{16}{3}CP^2\sin\left(CP^2\right) & P \neq 0 \\ \frac{4}{3} & P = 0 \end{cases}.$$

By the inverse function theorem, there are neighborhoods $\mathcal{U}$ and $\mathcal{V}$ of 0 such that

$$G: \quad \begin{array}{c} \mathcal{U} \to \mathcal{V} \\ P \mapsto t \end{array}$$

is a bijective mapping with inverse

$$H: \quad \begin{array}{c} \mathcal{V} \to \mathcal{U} \\ t \mapsto P \end{array}$$

continuously differentiable in $\mathcal{V}$. Also,

$$H(0) = 0, H'(0) = \frac{1}{G'(0)} = \frac{3}{4}.$$

Therefore $H(t) > 0$ holds for small enough t. In terms of s and $R_{\max}$,

$$R_{\max} = \frac{1}{H\left(\frac{1}{s}\right)} \quad \text{for large} s.$$

and $R_{\max}$ is uniquely determined by s. Thus

$$\lim_{s\to\infty} R_{\max} = \frac{1}{\lim\limits_{t\to\infty} H(t)} = +\infty.$$

Expand $H(t)$ about 0 as $H(t) = \frac{3}{4}t + o(t)$, hence $R_{\max} = \frac{4}{3}s + o(1)$. Therefore, as s tends to infinity, $R_{\max(\text{opt})}$ asymptotically approaches $\frac{4}{3}s$, which concludes the proof.

B Normalization and numerical evaluation of Eq.(9)

First we normalized Eq.(9) to remove dimensions of variables. Define

$$\gamma = \frac{s}{\sqrt{\eta P_t}}$$

as a normalized parameter proportional to sink velocity. Therefore, by Eq.(3) we have

$$\frac{1}{\sqrt{\theta_p}} = 8\sqrt{2}\gamma\left[\frac{2\sin\theta_p}{\theta_p} - \frac{1}{3}\cos\theta_p\right], \tag{19}$$

where γ and θ_p are both dimensionless. Solving Eq.(19) numerically gives Figure 3, which shows that the transmitting beamwidth becomes more concentrated on the sink's direction of motion as sink velocity increases.