Proceedings of the 2004 IEEE
International Conference on Robotics & Automation
New Orleans, LA • April 2004

Supporting Many-to-One Communication in Mobile Multi-Robot Ad Hoc Sensing Networks

Saumitra M. Das, Y. Charlie Hu, C.S. George Lee, and Yung-Hsiang Lu
School of Electrical and Computer Engineering
Purdue University
West Lafayette, IN 47907-2035
{smdas, ychu, csglee, yunglu}@purdue.edu

Abstract—**In this paper, we study the problem of supporting communication in mobile sensor networks formed by teams of mobile robots equipped with sensors. We assume that in addition to communicating with each other by implicit or environmental means, the robots are equipped with wireless communication capability and effectively form a mobile ad hoc network (MANET). However, unlike typical MANETs where the primary communication pattern is *any-to-any*, such mobile multi-robot sensing networks need to support sensing applications which exhibit a *many-to-one* communication pattern. In this paper, we evaluate the ability of current ad hoc network routing protocols to support communication in such sensing networks using detailed simulations of 50 robots. We consider typical communication patterns that arise in sensing applications and their impact on success rates, routing overhead, and energy costs of the mobile sensor network.**

Index Terms* - *mobile robots, ad hoc sensor networks, wireless networks, communication patterns

I. INTRODUCTION

Wireless sensor networks are composed of a large group of nodes, with transducers for sensing environmental parameters and intelligence for disseminating this data. Sensor networks are primarily envisioned as static configurations of thousands of nodes.

Robots could be deployed in sensor networks to support a wide variety of applications. For example, a sensor network that is serviced and maintained by autonomous robots was described in [10]. A similar system could be envisioned in which apart from service and maintenance, the robots actually collect and relay data from the sensor network when desired. Specifically, reactive multiagent robotic systems [6], [5] could be used to mine the sensor network for information and form an ad hoc peer-to-peer network with other robots in the team to effectively disseminate sensed information and statistics to a *sink* which can be thought of as the operator of the multi-robot team. In this scenario, we conserve the energy of the sensor network by using them only for sensing and local short range communication with the team of mobile robots which disseminate collected sensed data to the *sink*.

Alternatively, the multi-robot team can itself have on board transducers for performing sensing, removing the need for an underlying sensor network. In this scenario, the robots form a mobile sensor network and coordinate with each other to perform the sensing tasks. Such a mobile sensor network has the advantage of adapting to the environment to provide sensing coverage in contrast to a static sensor network which rely on large numbers to ensure coverage. Low cost robots such as those presented in [15] could be augmented with transducers and used for such purposes.

In both these deployment models, we can classify communication in the system to be of two types: (1) *Coordination-oriented communication* between robots in the team and (2) *Data-oriented communication* between members of the robot team and the operator or *sink*. Coordination-oriented communication can be both implicit (e.g. through the environment, based on peer robot behavior) or explicit (e.g. using directed/unicast or broadcast intentional messaging).

Coordination-oriented communication is defined to be the transmission related to the coordination and control of robot teams and has been extensively studied in the literature. In particular, the use of communication for robot control was studied in [14]. It has been found that communication provides certain performance improvement for particular tasks [1]. The authors in [17] studied combined robot control/communication strategies for a team of wireless-networked robots performing a resource transportation task.

We define *data-oriented communication* to be the transmission of data information collected by the sensors (broadcast or unicast) that occur in the mobile sensor network. This communication occurs based on the application parameters and can be independent of the coordination-oriented communication that may occur for coordinating the team members.

In a mobile sensor network, we anticipate two sources of data-oriented communication. We expect that either the underlying sensor network or the robot's transducer itself senses application events (e.g. finding a certain substance) at random instants of time. These events are of timely interest and need to be reported to the operator right away. Additionally, we expect a periodic communication between the operator and each team member to determine various statistics and

---

[1] This work was supported in part by the National Science Foundation under Grant IIS-0329061.

the current status of the robot. This periodic communication should occur even when no events are being sensed. Both these patterns exhibit a *many-to-one* (from all robot team members to the sink) pattern. In contrast, in coordination-oriented communication, a large fraction of the packets will be between members of the robot team.

This many-to-one pattern has important consequences for communication performance in sensor networks. It was shown in [11] that c_N, the many-to-one capacity of a static wireless sensor network of size N is bounded by $\Theta(\frac{1}{N})$ $bits/sensor/slot$ where a slot is defined as the time in which each sensor can transmit and receive some W bits. Thus, data-oriented communication has a direct effect on the perceived capacity of the mobile sensor network from an operator's viewpoint since it affects the resolution of sensed information. Additionally, data-oriented communication can reduce the bandwidth available for coordination-oriented communication required for control and coordination of the mobile robots. Many-to-one traffic also results in non-uniform energy drainage and packet loss in the network due to increased network usage and interference around the sink.

In this paper, we study the performance of routing protocols in supporting data-oriented (many-to-one) communication. In static sensor networks, clustering and aggregation techniques can be used to overcome many challenges of many-to-one communication patterns. However, in mobile sensor networks, mobility makes the use of such techniques difficult. Thus, it is necessary to investigate general routing protocols for mobile ad hoc networks. In this context, we compare the performance of three well-known ad hoc routing protocols in supporting data-oriented communication in multi-robot mobile sensor networks.

The rest of the paper is as following. In Section II, we state our model for the mobile sensor network and its characteristics. In Section III, we describe protocols for data-oriented communications. In Section IV, we present the simulation results. Finally, Section V concludes the paper.

II. MOBILE SENSOR NETWORKS

We focus on an application scenario where many robots are used to form a mobile sensor network. Each robot has a simple sensory ability and limited computational power. This makes it practical to build a large number of such robots. It has be shown previously that teams of robots increase the performance of certain tasks. For example, it is shown in [16] that for a covering problem a team of robots can increase the task performance. The author described three methods for distributed covering of a graph G using miniaturized robots. They concluded that the number of robots k and the cut $\rho(G)$ are the primary factors that affect performance. The time bound is $O(\frac{n}{k} + \rho(G))$ where n is the number of vertices, $|V(G)|$. This shows that increasing the number of cooperative robots can significantly increase the covering speed. Thus, for the covering problem, it makes sense to construct a mobile sensor network using a multi-robot team. In effect, such a network is an *ad-hoc sensing network* in which traffic patterns can be any-to-any as well as many-to-one.

We focus on data-oriented communication and its performance impact on the system as as whole. We assume a finite 2-D map as the environment for the robot's movement and that each robot's mobility pattern is based on some path planning and dispatch mechanism. The specific algorithm used for planning and dispatching is orthogonal to the study in this paper. Therefore, we assume a random waypoint model [18] to approximate the robots' movement.

The application events (sensing and periodic tasks) are independent of the movement of the robots and can occur at random instants in time. Therefore, the locations of the robots at the instants when data-oriented communication occurs are also random.

The communication among the robots is based on wireless ad hoc communication (IEEE 802.11) in which robots forward each other's packets when the source and destination nodes of a packet are not within direct reach.

III. COMMUNICATION PROTOCOLS

In this section, we describe the three well-known routing protocols for mobile ad hoc networks which fall into two categories: on-demand and proactive. In on-demand protocols, routes are discovered only when data needs to be sent whereas in proactive protocols routes are continuously updated.

A. DSR

DSR [9] is a representative on-demand multi-hop routing protocol for ad hoc networks. It is based on the concept of source routing in contrast to hop-by-hop routing. It includes two mechanisms, *route discovery* and *route maintenance*.

Route discovery is the process by which a source node discovers a route to a destination for which it does not already have a route in its cache. The process broadcasts a ROUTE REQUEST packet that is flooded across the network in a controlled manner. In addition to the address of the original initiator of the request and the target of the request, each ROUTE REQUEST packet contains a route record, which records the sequence of hops taken by the ROUTE REQUEST packet as it propagates through the network. ROUTE REQUEST packets use sequence numbers to prevent duplication. The request is answered by a ROUTE REPLY packet either from the destination node or an intermediate node that has a cached route to the destination. To reduce the cost of the route discovery, each node maintains a cache of source routes that have been learned or overheard, which it uses aggressively to limit the frequency and propagation of ROUTE REQUESTS. The route maintenance procedure monitors the operation of the route and informs the sender of any routing errors. If a route breaks due to a link failure, the detecting host sends a ROUTE ERROR packet to the source which upon receiving it, removes all routes in its cache that use the hop in error. Both route discovery and maintenance benefit from optimizations

TABLE I

PARAMETERS USED IN THE DSDV SIMULATION.

Periodic Update Interval	15s
Missed updates before link declared broken	3
WST weighting factor	7/8
Route advertisement aggregation time	1s
Max. packets buffered per node per destination	5

TABLE II

PARAMETERS USED IN THE AODV SIMULATION.

Active route timeout	10s
Request retries	2
Time to hold packets awaiting routes	10s
Link failure detection	MAC layer only
Time before broken link removal	3s

such as overhearing routes and route errors made possible by the broadcast nature of the medium access environment. In this paper, we use the version of DSR that builds a topological view of the network and stores it in a graph data structure [8]. A single source shortest path algorithm can be used by a node to construct routes to nodes that have not been explicitly discovered or overheard.

B. Destination-Sequenced Distance-Vector (DSDV)

DSDV [12] is a proactive protocol based on distance vector routing. Each node maintains a routing table which lists the next hop and the hop count for all reachable destinations. Each routing table entry is tagged with a destination based sequence number to reduce propagation of stale routes. A node exchanges routing tables with its neighbors periodically or whenever a change in topology is detected. The routing table updates can be sent in two ways: (i) a full dump sends the full routing table to the neighbors and can span many packets, and (ii) an incremental update only sends those entries with a metric change since the last update. In this paper, we use the version of DSDV in which triggered updates are caused by the receipt of a new sequence number for a destination. We use the same set of parameters for DSDV as in [3], as listed in Table I.

C. Ad Hoc On-Demand Distant Vector (AODV)

AODV [13] shares on-demand behavior with DSR and the use of hop-by-hop routing and destination based sequence numbers with DSDV. Routes are obtained via a discovery process similar to DSR. A node satisfies the ROUTE REQUEST by sending a ROUTE REPLY back to the source or by increasing the hop count and re-broadcasting to its neighbors. As the ROUTE REQUEST propagates from the source to various nodes, a reverse path is set up from these nodes back to the source.

The destination sequence numbers in control packets ensure loop freedom and freshness of routing information. Timers are used to expire routes that have not been used recently. AODV ensures wider propagation of ROUTE ERRORS than DSR, achieved using a per destination predecessor list at each node. The AODV version in this study uses link layer feedback for detection of broken links [3]. The set of parameters used in the simulation are based on the AODV implementation for ns-2 [2] (version 2.1b8a) provided by the authors of AODV and are listed in Table II.

IV. EVALUATION

We evaluate the performance of the protocols under consideration using ns-2 [2]. We instrumented the ns-2 simulator to add energy logging and statistics for all three routing protocols.

A. Methodology

1) Mobility pattern: In our experiments, we adopt the widely used random waypoint mobility model for mobile ad hoc networks for the mobile robots, while keeping the sink stationary at a random location. This random waypoint mobility model is governed by an important parameter, *pause time p*. As the simulation starts, each robot chooses a random destination in the given area and starts moving towards the chosen destination with a speed chosen uniformly between 1 and 6 meters/second. Once the robot reaches the destination, it pauses for *p* seconds and chooses the next random destination. This effectively models the movement of a group of robots performing tasks in a sensing environment. The robot moves towards a particular area and spends some time at the location collecting sensed data. The robot then moves to the next position. We have considered *pause times* of 1200, 120 and 0 seconds for this evaluation. A pause time of 1200 seconds in a simulation of duration 1200 seconds signifies that the network is static. A pause time of 0 second signifies that the robots are in constant motion.

2) Traffic pattern: Each robot is involved in two kinds of many-to-one communication.

- Periodic Heartbeat: This models the behavior of the robot team operator or application user who may want periodic statistics on any team member's current state. For example, querying for the current battery level, sensed data, etc. This communication between a robot team member and the application user at the sink occurs periodically although not frequently. In our simulations, each robot team member sends a 64-byte status packet to the sink every 5 seconds.
- Sensing Impulse: Whenever a member of the robot team senses an event, it needs to report this to the application user at the sink over the multi-hop routing network. These events occur at random instants of time and the arrival of sensed events is modeled using a Poisson arrival process. In our simulation, each robot team member senses events with an average interarrival time of 2 seconds.

To measure the impact of communication patterns on the performance of routing protocols, we also evaluate the protocols using a general any-to-any communication model. Specifically, in the general communication model, each robot initiates data connections to randomly chosen other members or the sink. To isolate the impact of communication patterns on the routing performance, identical mobility scenarios and traffic volumes were used for both the general any-to-any and the many-to-one communication models.

3) The Energy Model: For a mobile robot, efficiently using its limited energy can extend operation duration and increase its reliability. In a mobile robot, energy is consumed in two ways: by electronic components (processors, memory, wireless communication, etc.) and by mechanic components (motors). We focus on the wireless communication energy costs in this study. Since our wireless communication is based on IEEE 802.11, we adopt the energy model and measurements for ad hoc networks proposed in [7], [4]. Specifically, for each communicated packet, we compute the reception energy as

$$E_{rx} = \frac{V * I_{rx} * Packet\ Size}{Bandwidth}$$

and the transmission energy as

$$E_{tx} = \frac{V * I_{tx} * Packet\ Size}{Bandwidth}$$

where I_{rx} and I_{tx} are the average current draw when receiving and transmitting data, respectively. We assume a 5V wireless network interface with a 2Mbps bandwidth. The values for I_{rx} and I_{tx} as specified in [7] were used.

4) Metrics: The following metrics are evaluated for the routing protocols: (1) Routing Overhead – The total number of packets including the control packets transmitted for the operation, with each hop-wise transmission of a control packet counted as one transmission; (2) Success Ratio – The ratio of the data received at the sink over the number of data packets transmitted by the robot team; (3) Average Delay – The average delay incurred in sending a data packet from a robot to the sink; and (4) Energy Consumed – The amount of energy consumed by the all the team members for data oriented communication. This includes energy spent only during sending and receiving both data and control packets.

B. Results

In this section, we first evaluate the impact of the many-to-one traffic patterns expected in mobile sensor networks on the performance characteristics of routing protocols. We then evaluate the performance of the routing protocols at varying levels of mobility while sustaining a many-to-one traffic pattern.

Figure 1 depicts the routing overhead and success ratio of the three protocols under the general any-to-any communication model versus the many-to-one model for mobile sensor networks with a pause time of 0 second. The results show that for on-demand protocols (AODV and DSR), the routing overhead increases when the many-to-one model is used instead of the any-to-any. This is because of the following reasons: (1) fundamentally the capacity of the network reduces in a many-to-one communication model, (2) increased multi-access interference and retransmissions due to concentration of traffic around the sink leads to congestion and repeated route discoveries which increase the overhead, and (3) load imbalance can cause packet drops since nodes close to the sink experience buffer overflows. Although DSDV maintains a similar routing overhead as expected for a proactive routing protocol, its success ratio drops when the many-to-one model is considered.

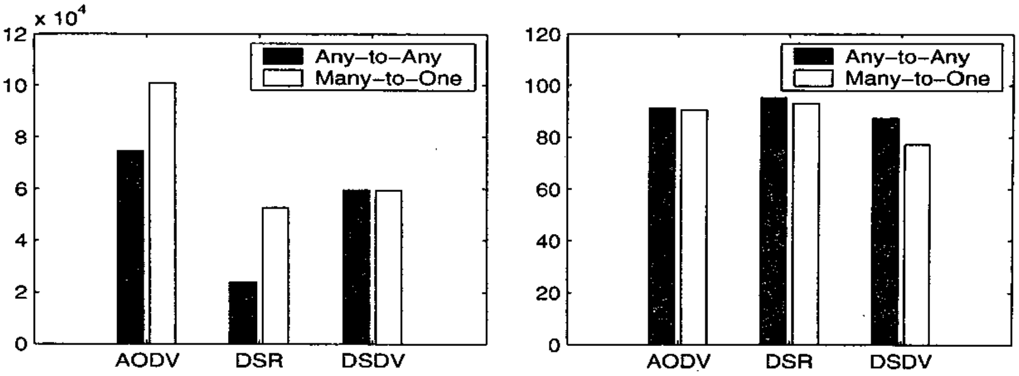
In summary, Figure 1 shows that data-oriented communication can have a significant impact on the routing performance of mobile sensor networks. In particular, the many-to-one communication traffic reduces the bandwidth available for coordination-oriented communication which can reduce the coordination and control response time and disrupt the coordination of the robots.

We further evaluate the effect of the many-to-one communication pattern on the performance of the routing protocols under varying mobility. Figure 2(a) depicts the communication overhead of the three protocols as the mobility in the network is successively decreased. DSR is shown to have the lowest communication overhead at all mobilities. Since AODV is an on-demand protocol in contrast to DSDV which is proactive, it has a low communication overhead in a static network. In a static network, while on-demand protocols have close to zero overhead, DSDV incurs a constant overhead of 60,000 packets as it uses periodic table exchanges for route maintenance. In fact, DSDV maintains a constant routing overhead for all values of mobility. This happens because the routing overhead in DSDV depends only on the periodic update interval (15s), the route aggregation time (1s), and the size of the network. The reason DSR outperforms AODV is that in a many-to-one traffic pattern, DSR can reuse routes that other nodes discover to the sink. In DSR, packets forwarded by nodes can be used to build routes to the sink. In addition, DSR stores multiple routes to the sink by virtue of its graph based caching structure and can construct routes that have not been explicitly discovered.

While AODV also benefits from intermediate nodes storing routes to the sink, it does not store multiple routes to the sink and cannot construct routes that are not explicitly discovered. This increases its overhead when routes break. AODV also incorporates statically defined route timeouts which cause route discoveries even when a route may still be valid.

The higher success rate and reduced communication overhead of DSR, however, come at the expense of higher energy consumption. This is shown in Figure 2(d) which plots the energy consumed for transmitting and receiving all traffic in the system. AODV does not use promiscuous overhearing and can thus disseminate information to the sink at lower energy.

When the network is static, both DSR and AODV have similar energy consumption. This is because neither discovers many routes. However, DSDV being a proactive protocol needs to exchange packets between robots team members and the sink at periodic intervals. Thus, the energy consumption due to routing is similar for all mobilities. However, due to



(a) Routing overhead (packets)

(b) Success ratio (%)

Fig. 1. Routing protocol performance with different communication models for a network of 50 robots.

the increased interference in the many-to-one model, packet retransmissions cause DSDV to have an increasing energy consumption as mobility increases. Also, since distance vector protocols do not converge easily when mobility is high, DSDV suffers in success ratios. In addition, the congestion caused by the many-to-one model increases the probability that routing table updates in DSDV are lost, leading to staleness in routing entries.

In static sensor networks, the many-to-one model causes non-uniform energy drainage in the network. We also measured this effect and found that due to node mobility, the mobile sensor networks we evaluated do not suffer from this problem.

V. CONCLUSION

In this paper, we studied the performance of three ad hoc routing protocols when applied to a mobile ad hoc sensing network for data-oriented communication. We showed that the many-to-one communication pattern unique to mobile sensor networks has performance implications on the reliability and energy consumption in mobile sensor networks. Specifically, the routing overhead for the AODV and DSR protocols increased by a significant amount when a many-to-one model was used instead of an any-to-any model. This occurred despite a constant traffic volume being maintained in the network for both models. Although DSDV maintained similar routing overhead for both models, its success ratio was adversely affected by the many-to-one model.

Our work shows that data-oriented communication can have a significant impact on bandwidth available for coordination-oriented communication. This can potentially reduce the coordination and control response time and adversely affects the coordination of the team of robots. Our work suggests that data-oriented communication should be modeled when simulation studies of robot teams are carried out.

REFERENCES

[1] T. Balch and R. C. Arkin. Communication in reactive multiagent robotic systems. *Autonomous Robots*, 1(1):27–52, 1994.

[2] L. Breslau, D. Estrin, K. Fall, S. Floyd, J. Heidemann, A. Helmy, P. Huang, S. McCanne, K. Varadhan, Y. Xu, and H. Yu. Advances in network simulation. *IEEE Computer*, 33(5):59–67, May 2000.

[3] J. Broch, D. A. Maltz, D. B. Johnson, Y.-C. Hu, and J. Jetcheva. A performance comparison of multi-hop wireless ad hoc network routing protocols. In *Proc. of ACM/IEEE MOBICOM*, October 1998.

[4] J. C. Cano and P. Manzoni. A performance comparison of energy consumption for Mobile Ad Hoc Network routing protocols. In *Proc. of MASCOTS*, August 2000.

[5] Y. U. Cao, A. S. Fukunaga, and A. B. Kahng. Cooperative mobile robotics: Antecedents and directions. *Autonomous Robots*, 4(1):7–23, March 1997.

[6] G. Dudek, M. Jenkin, E. Milios, and D. Wilkes. A taxonomy for multi-agent robotics. *Autonomous Robots*, 1996.

[7] L. M. Feeney and M. Nilsson. Investigating the energy consumption of a wireless network interface in an ad hoc networking environment. In *Proc. of IEEE INFOCOM*, April 2001.

[8] Y.-C. Hu and D. B. Johnson. Caching strategies in on-demand routing protocols for wireless ad hoc networks. In *Proc. of ACM/IEEE MOBICOM*, August 2000.

[9] D. B. Johnson and D. A. Maltz. *Dynamic Source Routing in Ad Hoc Wireless Networks*. Kluwer Academic, 1996.

[10] A. LaMarca, D. Koizumi, M. Lease, S. Sigurdsson, G. Barriello, W. Brunette, K. S. korski, and D. Fox. Making Sensor Networks Practical With Robots. Technical report, Intel Research, IRS-TR-02-004, 2002.

[11] D. Marco, E. Duarte-Melo, M. Liu, and D. L. Neuhoff. On the many-to-one transport capacity of a dense wireless sensor network and the compressibility of its data. In *Proc. of IPSN*, April 2003.

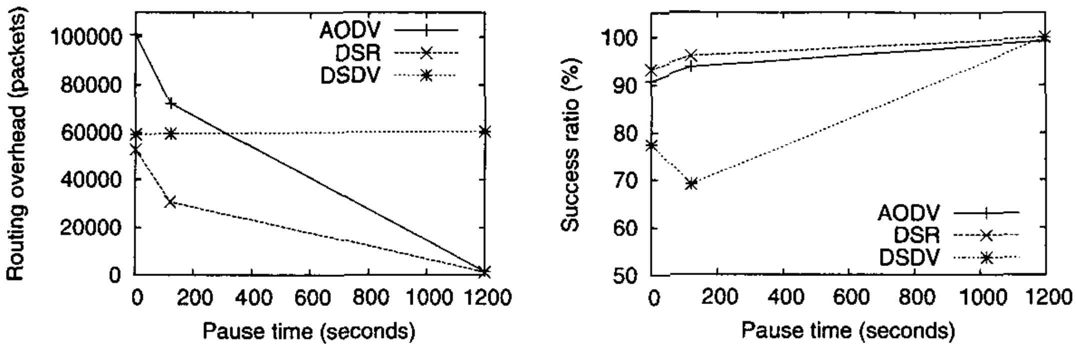
[12] C. E. Perkins and P. Bhagwat. Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers. In *Proc. of ACM SIGCOMM*, August 1994.

[13] C. E. Perkins and E. M. Royer. Ad hoc on-demand distance vector routing. In *Proc. of the IEEE WMCSA*, February 1999.

[14] P. E. Rybski, S. A. Stoeter, M. Gini, D. F. Hougen, and N. Papanikolopoulos. Effects of Limited Bandwidth Communications Channels on the Control of Multiple Robots. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 369–374, 2001.

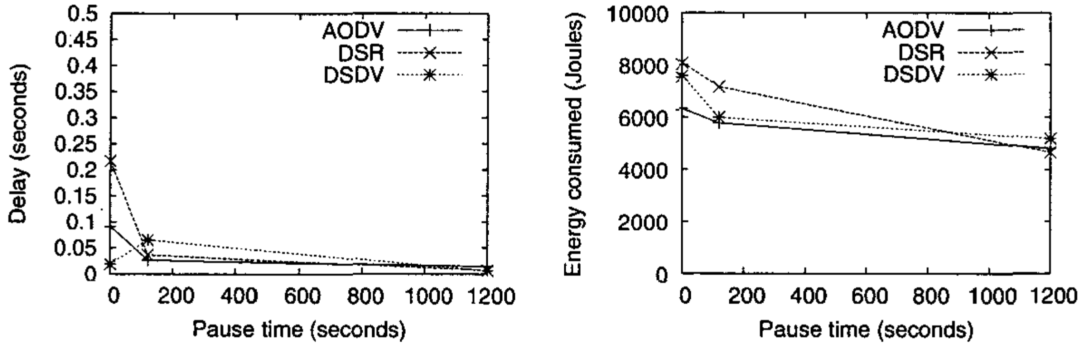
[15] G. T. Sibley, M. H. Rahimi, and G. S. Sukhatme. Robomote: A Tiny Mobile Robot Platform for Large-scale Ad-hoc Sensor Networks. In *International Conference on Robotics and Automation*, pages 1143–1148, 2002.

[16] I. Wagner, M. Lindenbaum, and A. Bruckstein. Distributed covering by ant-robots using evaporating traces. *IEEE Transactions on Robotics and Automation*, 15(5):918–933, Oct. 1999.



(a) Routing overhead

(b) Success ratio



(c) Avg. delay

(d) Energy consumption

Fig. 2. Routing protocol comparison with mobility. Average interarrival time of sensing impulses is set to 2 seconds.

[17] W. Ye, R. T. Vaughyan, G. S. Sukhatme, J. Heidemann, D. Estrin, and M. J. Matarić. Evaluating control strategies for wireless-networked robots using an integrated robot and network simulation. In *Proceedings of the IEEE International Conference on Robotics and Automation*, Seoul, Korea, May 2001. USC/Information Sciences Institute, IEEE.

[18] J. Yoon, M. Liu, and B. Noble. Sound mobility models. In *Proc. of ACM/IEEE MOBICOM*, September 2003.