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Research Article

Evaluation of Physical Carrier Sense Based Backbone Maintenance in Mobile Ad Hoc Networks

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Physical carrier sensing has to date mainly been exploited for improving medium access control in wireless networks. Recently, a parallel algorithm striving to extensively exploit physical carrier sensing for constructing and maintaining a connected dominating set (CDS), which is also known as spanner, backbone, or overlay network in wireless ad hoc networks with interference ranges larger than transmission ranges has been proposed. Existing evaluations of this algorithm are limited to theoretical asymptotic bounds and simulations of *static* networks. In this paper, we evaluate the physical carrier sensing-based CDS maintenance for *mobile* ad hoc networks through discrete event simulations. For a wide range of node speeds and node densities, we evaluate the CDS characteristics and message exchanges required for maintaining the CDS. We find that the algorithm maintains a stable leader set dominating all nodes in the network for a wide range of mobility levels but struggles to maintain connectivity at high mobility levels. We also quantify the portions of the control messages for CDS maintenance that are exchanged through physical carrier sensing. We find that the parallel algorithm manages to greatly reduce the reliance on intact message receptions.

1. Introduction

Efficiently maintaining topology control in the form of a connected dominating set (CDS), which is also widely referred to as spanner or backbone network, is a key challenge in mobile ad hoc networks (MANETs). A CDS is *dominating*, that is, each ordinary node is within the transmission range of at least one leader node, and *connected*, that is, all leader nodes are interconnected by paths through gateway nodes, such that each hop along the path is shorter than the transmission range. The CDS can facilitate a wide range of network layer functions, such as routing [1] and name resolution. Constructing and maintaining the CDS requires control message exchanges over the unreliable link and physical wireless layers. In recent algorithm-theoretic work [2] we have proposed an algorithm for constructing and maintaining a CDS in MANETs. The algorithm proposed in [2] considers a physical layer model with interference ranges longer than transmission ranges. This model with interference exceeding the transmission ranges is more realistic than the simpler, less detailed models, such as the unit-disk model, which considers only a disk-shaped transmission range and ignores interference, and the packet radio model, which considers disk-shaped transmission and interference ranges whereby both ranges are equal. Furthermore, while existing approaches exploit physical carrier sensing primarily for improving medium access control, our algorithm strives to extensively exploit physical carrier sensing for constructing and maintaining a CDS—a network layer task—while explicitly incorporating the medium access control in the network layer control message exchanges.

In this paper we present an original simulation study of the CDS maintenance algorithm proposed in [2] for MANETs. Our previous evaluations (i) provided only asymptotic performance bounds [2] which provide only rather loose characterizations of the actual performance for typical network scenarios, and (ii) considered only static ad hoc networks without any node mobility [3]. In this paper, we evaluate the actual performance of the CDS maintenance algorithm for typical *mobile* ad hoc network scenarios through simulations. We find that the first phase of the parallel algorithm proposed in [2], which is reviewed in Section 2.1, maintains a stable set leader nodes that dominate almost all ordinary network nodes even at high levels of mobility. The second phase of the algorithm maintains over a wide range of mobility levels a stable assignment of noninterfering leader transmission rounds such that transmissions by leaders never interfere with each other. The third phase of the algorithm interconnects neighboring leader nodes through paths traversing intermediate gateway nodes. We find that the gateway discovery and maintenance is highly effective at low speeds in keeping the CDS connected. However, at high levels of mobility, the algorithm has trouble to keep up the gateway connections, resulting in the CDS being connected only between 55% and 75% of the time.

Our simulations provide detailed insights into the control message exchanges in the individual phases of our algorithm. We find that over 95% of the control messages are exchanged through physical carrier sensing. In particular, most short messages are exchanged through physical carrier sensing, while most of the longer messages (carrying more information bits) require intact message reception. Nevertheless, we find that roughly one third of all information bits required for maintaining the CDS are exchanged through physical carrier sensing. In addition, typically around 75% of the bits that need to be exchanged through intact messages receptions are sent during the noninterfering transmission round maintained by phase II and are thus not subject to collisions.

This paper is structured as follows. In the following two subsections, we review related work and the network model, including the physical carrier sensing ranges. In Section 2, we give a brief overview of the CDS construction and maintenance algorithm proposed in [2]. In Section 3, we present our simulation evaluations of the CDS maintenance for MANETs. We explain our simulation setup and define our performance metrics. We then proceed to present both sample path simulation results as well as steady state simulation results characterizing the CDS and the control message exchanges. We summarize our conclusions in Section 4.

1.1. Related Work.

In this section we briefly review related work, which falls into three main areas, namely clustering in ad hoc networks, backbone (spanner) construction and maintenance in ad hoc networks, and exploitation of physical carrier sensing in wireless networks.

1.1.1. Clustering.

Numerous clustering mechanisms have been proposed in recent years for ad hoc networks, see, for instance, [4–9]. Key distinctions of our clustering, which is completed in phase I of our algorithm, are that we consider a network model with interference reaching farther than transmission ranges and exploit physical carrier sensing for rapid, low-complexity clustering of nodes without any prior topology knowledge.

Regarding the way mobility is addressed in existing clustering mechanisms, most existing clustering schemes divide the clustering process into two phases—cluster initialization and cluster maintenance. In contrast, Wang and Olariu [10] consider a unifying clustering approach that blends cluster initialization mechanism with cluster maintenance. Their tree-based algorithm requires each node to maintain a depth-2 breadth-first-search tree, rooted at itself, resulting in significant storage overhead. Our algorithm also integrates initial clustering and backbone construction with clustering and backbone maintenance. However, due to the *constant density* of our set of leader nodes (dominating set), the information about gateway nodes leading to neighboring leader nodes is limited to a constant amount of storage irrespective of the network density or total number of nodes in the network.

1.1.2. Backbone (CDS) Construction and Maintenance.

Constructing an optimal backbone network (CDS) is often formally characterized as finding minimum connected dominating sets and spanning sets. Distributed algorithms that approximate the minimum connected dominating set with polynomial or polylogarithmic running time include, for example, [11–17]. The first phase of our algorithm is an extension of the dominating set algorithm [18]. Comprehensive simulation comparisons of clustering and overlay network formation algorithms developed for unit-disk and packet radio models are reported in [19]. The comparison study [19] takes MAC packet collisions into consideration and classifies the algorithms according to their level of localization, that is, over how many hops does the information for forming the overlay travel, a classification also employed in [20]. Approaches with a high level of localization that require information from within only a 2-hop local neighborhood, such as approaches based on [14, 21], are compared with approaches that have lower levels of localization, such as algorithms based on [22, 23]. It is found that highly localized approaches tend to give the best performance. Our approach, which is developed for a more realistic network model with interference ranges larger than transmission ranges, is highly localized. In our backbone construction, information never travels further than twice the interference range (via two physical carrier sensing communication hops in phase II) or three times the transmission range (via three actual packet transmissions in phase III).

Kuhn et al. [24] as well as Parthasarathy and Gandhi [25, 26] developed distributed algorithms that compute constant factor approximations of a minimum dominating set in poly-logarithmic time. Both extend the unit disk model by taking interference into account, but nodes need to know an estimate of the size of the network. In contrast, our approach does not require any estimates of network size, nor network density.

For mobility management, existing approaches rely typically on an explicit *mobility control mechanism*, as for instance examined by Wu and Dai [27]. Dedicated local neighborhood information exchanges are used in [27] to control for node mobility. In contrast, our parallel algorithm phases continuously construct and maintain the CDS without an explicit mobility control mechanism.

1.1.3. Physical Carrier Sensing.

Physical carrier sensing has been studied from a variety of perspectives. In single-hop communication, physical carrier sense is used in many random-access schemes, such as 802.11's version of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA).

Many lines of work focus on the MAC layer—studying or optimizing the effect of CSMA on throughput and power consumption, see, for example, [28–37]. The problem of topology control in ad hoc networks (see, e.g., [38, 39]) has some similarity to our work in goals and approaches. For example, Muqattash and Krunz [40, 41] use virtual and physical carrier sense with power control to increase throughput and energy efficiency. Similarly, Tavli and Heinzelman [42] employ a cross-layer approach spanning the MAC and network layer to minimize energy for broadcast. However, to the best of our knowledge, our protocol is the first to directly exploit physical carrier sense for the network layer task of distributed CDS construction.

1.2. Network Model. We define a fixed *transmission range* r_t such that any two nodes closer together than r_t can reliably communicate, while nodes farther apart cannot. We define a fixed *interference range* r_i such that if a transmission fails due to interference, the interfering transmission must have originated at a node closer than r_i to the receiving node. Not all transmissions from nodes within r_i need to cause interference, but transmissions from nodes outside of it never will. In a typical network, r_i is 2-3 times larger than r_t; our simulations use a ratio of $r_i/r_t = 2$.

We suppose that each node can perform physical carrier sensing, achieved in 802.11 through Received Signal Strength Indicator (RSSI) measurements, to detect when the medium is busy. We define the *certain-sensing range* r_{st} and the *nonsensing range* r_{si} for the carrier sense operation: signals traveling less than r_{st} are sensed with probability close to one, whereas signals traveling farther than r_{si} are sensed with close to zero probability, and in between with arbitrary probability. These ranges can be tuned by adjusting the SNR threshold at the receiver, which is accomplished through the Clear Channel Assessment rules in 802.11. However, the ratio of the sensing ranges $r_{\mathrm{si}}/r_{\mathrm{st}}$ is fixed due to the physical radio propagation characteristics to ≈2-3 typically, and in our simulations we set $r_{\mathrm{si}}/r_{\mathrm{st}} = 2$.

We note that this model is a close match for the actual performance of current wireless interfaces. Forward error correction mechanisms allow for relatively sharp cutoffs between the area where messages are almost always received (*transmission range*; a range r such that the communication cost is less than the transmission range r_t, i.e., $r < r_t$), where they may still interfere (*interference range*; $r_t < r < r_i$), and where they never interfere ($r > r_i$). We refer to nodes as “connected” if a series of hops between pairs of nodes within transmission range exists between them. We briefly note that the algorithm in [2] accommodates nondisk shaped transmission, interference, and sensing areas. However, in this study focused on the effects of mobility, we consider only disk-shaped transmission, interference, and sensing areas.

2. CDS Construction and Maintenance Algorithm

2.1. Overview of CDS Construction. The algorithm presented in [2] constructs a CDS in three phases.

(i) Phase I elects “leader” nodes in a distributed probabilistic fashion such that (a) every node in the network is either a leader or within the transmission range r_t of at least one leader, and (b) leaders are spaced at least $r_t/2$ apart.

(ii) Phase II creates a distributed assignment of leader time slots such that each leader can communicate with neighboring nonleader nodes without interfering with other leaders' transmissions; more specifically, each leader becomes an “owner” of a particular round within the frame such that two leaders owing the same round are spaced at least $r_i + r_t$ apart.

(iii) Phase III connects leaders that are up to $3r_t$ apart by up to two gateway nodes; in particular, lists of local gateway nodes are created in both leader and nonleader nodes.

The timing structure of the algorithm is organized according to locally synchronized *rounds*, such that each round contains 11 slots to accommodate phases I–III (see Figure 1). A sequence of $k = 60$ rounds forms a *frame*; setting the parameter $k = 60$ accommodates all possible network densities and sizes, as shown in [3]. The beginning of each frame is not required to be synchronized between nodes, only the round/slot timing.

The CDS construction relies on both carrier sensing (accomplished through sensing with a specific setting for either r_{st} or r_{si}, which may vary from slot to slot) and actual packet receptions for information exchange between nodes. We measure the amount of information bits exchanged through each mechanism with the following rules for each communication slot. The durations of the individual slots depend on the information contained in them, which is either presence/absence of sensed physical carrier (neglected in byte count), node address (counted as 6 bytes), or time stamp (counted as 2 bytes); in addition, we count 6 bytes of overhead for each slot. For all slots, except the third slot of phase I, which is examined in Section 2.2, the lengths of the control messages sent in the individual slots are established in [3] and are summarized in Table 1. Based on $k = 60$ rounds/frame, a 1 Mbit/s transmission rate and a 20 μs spacing between slots, a frame (including the third slot of phase I) is 219.6 ms long.

2.2. CDS Maintenance. The algorithm evaluated in [3] considers static networks, which can be accommodated with only the first two slots in phase I. The third slot in phase I is needed to recover from arbitrary placements of leader nodes [2], as may arise with node mobility. More specifically, phase I—the leader election phase executed for a static network—ensures that leaders are at least spaced $r_t/2$ apart. If our protocol were to start with a configuration with two leader nodes closer than $r_t/2$ together (which could arise through node mobility), the algorithm with two slots in phase I may not succeed in establishing a dominating set. To overcome this problem, we add a third slot in phase I, called the “self stabilization” slot. In this slot, every active node sends a simple signal with a constant probability p in every round;

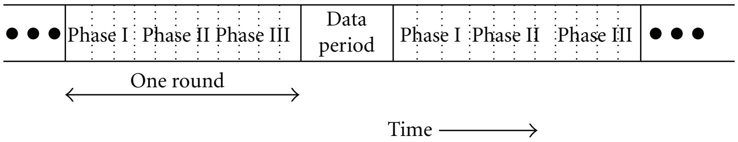


Figure 1: Illustration of algorithm timing structure: A round contains three slots for phase I, four slots for phase II, and four slots for phase III. k rounds make up one frame.

Table 1: Summary of slot lengths and information exchanged.

Phase	Slot	Message vulnerable to collision	Exchanged information (bits/msg)	Message length (bytes)
I	1	No	1	6
	2	No*	1 or 48*	12
	3‡	No	1	6
II	1	No*	1 or 64*	14
	2	No	1	6
	3	No	1	6
	4	No	1	6
III	1	Yes	96 or 1†	18
	2	No	50 or 98	18
	3	Yes	112	20
	4	No	$208 \cdot 12$	$6 + 26 \cdot 12$

*Phase I slot 2 and Phase II slot 1 can be used to collect information in advance for Phase III, provided the messages do not collide. When this mechanism is used in simulation, the larger number of information bits is recorded.

‡Phase I slot 3 is the self-stabilization slot.

†In Phase III slot 1, active leader nodes may only sense a busy or free carrier when the number of ordinary nodes transmitting is not equal to one. This carrier sensing determines the leaders reply type in the next slot.

any reasonable value of p is proven to give fast convergence back to a valid configuration in [2]. Another active node becomes inactive if it senses a message in this slot and is closer than $r_t/2$ to the transmitting node, as determined by setting the certain sensing range $r_{st} = r_t/2$.

All three phases of the algorithm run in parallel. Each round contains slots for all three phases, as illustrated in Figure 1. Once a given phase has stabilized, the next phase can self-stabilize without any global signal that this transition has occurred. Running in parallel is important for the algorithm to adapt to mobility: when the network topology changes, the three phases running continuously in parallel re-establish leader nodes, owner nodes, and gateway nodes.

3. Evaluation of CDS Maintenance for Mobility

To evaluate the performance of our CDS maintenance algorithm for mobile ad hoc networks, we conducted simulation experiments for $N = 200$, 400, and 600 node networks. We present (i) sample-path simulation results providing detailed insights into the responses of the different algorithm phases to node movements, and (ii) aggregate (steady-state) simulation results providing insights into the overall performance of our algorithm. Due to space constraints, we present detailed results for the case $N = 400$ and summarize the results for the $N = 200$ and 600 cases, which are presented in detail in [43].

We conducted our simulation studies using a custom built simulator based on OMNeT++. We consider a 200 × 200 m square network area and set the transmission range to $r_t = 30$ m and the interference range to $r_i = 60$ m (and $r_{si} = 2r_{st}$). In order to conduct a worst-case analysis of interference, we let all transmissions within $(0, r_i)$ interfere.

3.1. Simulation Setup

3.1.1. Random WayPoint Mobility Model. We use the Random WayPoint mobility model (RWP) [44, 45], which initially selects a random destination and a random speed for each node. Once a node reaches its destination it pauses for 100 frames which, according to our frame length, is approximately 21.96 seconds. This pause time achieves a mix of stationary and moving nodes throughout the simulation duration, which appears to be a realistic mobility scenario for the considered networks with relatively large numbers of nodes. A new random destination and speed are again chosen for the node at the end of the pause time, which is synchronized to the beginning of a frame.

For our simulation, we use maximum speeds, $V_{\max}$ [m/s], of 0.01, 0.1, 1, 5, 10, 20, and 30. The speeds are chosen from a uniformly random distribution in $[V_{\min}, V_{\max}]$. We select the minimum speed $V_{\min}$ based on [46], which showed a “speed decay” problem when directly using the RWP model. Yoon et al. [46] define α as the ratio of the node’s maximum speed $V_{\max}$ to its minimum speed $V_{\min}$, that is, $\alpha = V_{\max}/V_{\min}$. Yoon et al. [46] find that a smaller $V_{\min}$ value, that is, a larger α, considerably delays the process of the average speed of the nodes’ settling around its long run time average. However, a large value for $V_{\min}$ would mean less randomness in the range $[V_{\min}, V_{\max}]$. Taking into consideration these trade-offs and other simulation parameters, we have set $\alpha = 4$ for our simulations. With $\alpha = 4$, the long run time average nodal speed is about 87% of the initial average speed $(V_{\max} + V_{\min})/2$ [46].

3.1.2. Simulation Time Structure. At startup, we simulate the CDS construction algorithm on a static ad hoc network whereby the nodes are uniformly randomly placed on the network area and have no prior knowledge of their neighbors or topology. We define the CDS to be stable when the status of each node (leader/owner status and gateway list length) remains unchanged for ten consecutive frames. Once the

CDS is stable we start simulating node mobility using the Random WayPoint model. Consistent with [46], we allow the mobile system to warm up for 200 frames before we start collecting data for the aggregate simulation experiments.

In our simulations, we consider only the rounds, each made up of 11 slots, and set the data period in Figure 1 to zero. The results for a nonzero data period can be inferred from the presented results for a zero data period by scaling the speed as follows. Let s [m/s] denote the speed in the zero data phase model and let v [m/s] denote the speed in the model with an L byte data phase, which has duration $L\,[\text{byte}] \cdot 8\,[\text{bit/byte}]/10^6\,[\text{bit/s}]$, that is, is long enough to transmit a packet of L bytes with the considered transmission rate of 1 Mbps. Note that the corresponding frame lengths are 219.6 ms in the model with zero data phase and, noting that there are $k = 60$ data phases in a frame, $219.6\,\text{ms} + L\,[\text{byte}] \cdot 8\,[\text{bit/byte}] \cdot 60/10^6\,[\text{bit/s}] = (219.6 + 0.48L)$ ms with an L byte data phase. Then, a movement by $s \cdot 219.6$ ms in the zero data phase model is equivalent to a movement by $v \cdot (219.6 + 0.48L)$ ms in the L byte data phase model, that is, $v = s/(1 + 0.48L/219.6)$.

3.1.3. Performance Metrics. Aside from counting the numbers of leader, owner, and gateway nodes, and measuring the overhead of the CDS algorithm, we assess the connectedness and dominance properties of the CDS (backbone network). In particular, at the end of each frame, we determine (i) whether the mobile network is connected, (ii) whether the current CDS is connected, and (iii) whether the current leader nodes are a dominating set of the present topology.

We use Dijkstra's shortest path algorithm to evaluate the network and backbone connectivity status. To determine if the network is connected, we check if there exists a path between any given node to all the nodes in the network through a series of links between nodes within the transmission range r_t. The measure "Network Connected" gives the long run fraction of time (in frames) when the mobile ad hoc network is connected. Similarly, the measure "CDS Connected" gives the long run fraction of time (in frames) when the backbone network is connected. We define the CDS to be connected if each and every pair of leader nodes is connected through a series of links that pass through the leader nodes' respective gateway(s).

For each frame, we define the measure "CDS dominating" as the proportion of ordinary nodes covered by leader nodes plus leader nodes to the total number of nodes in the network. In order for an ordinary node to be covered, the node must be located within the transmission range r_t of at least one leader. A CDS is defined to be fully (100%) dominating when every ordinary node of the network is at most one r_t hop away from a leader node.

3.2. Sample Path Simulation Results. After the CDS has stabilized for the static network and the 200 frames warm-up of the mobility simulations are over, each simulation is run for 2000 more frames. All these three parts of the simulations are depicted in the sample path simulation plots. Each data point in the plots represents the average of 18 independent runs.

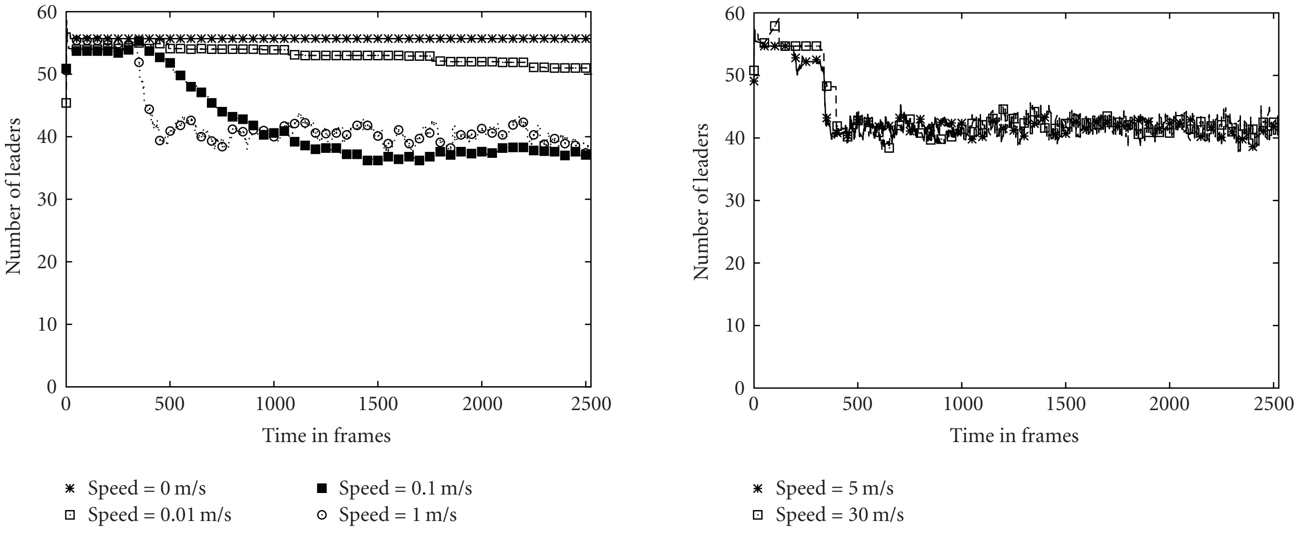
3.2.1. Numbers of Leader, Owner, and Gateway Nodes. We plot in Figures 2, 3, and 4 the number of leader nodes determined by phase I, the number of leader nodes owning noninterfering transmission rounds determined by phase II, and the number of gateway nodes determined by phase III of our algorithm, respectively, as a function of time in frames. Each line depicts data for a different maximum node speed, ranging from 0 m/s to 30 m/s. (We omit the curves for 10 m/s and 20 m/s from these plots as they overlap with the curves for 5 m/s and 30 m/s; the aggregate results for 10 m/s and 20 m/s are provided in Table 2.)

We observe from Figures 2 and 3 that the numbers of leader and owner nodes very quickly reach a stable plateau for the initially static network. When mobility is introduced around 285 frame times into the simulation, the numbers of leaders and owners drop relatively slowly for low node speed and quite fast for higher node speeds to the level around 40 leaders and owners, which remains stable for the remainder of the simulations. Throughout, the number of owners tracks quite closely the number of leaders, indicating that phase II is highly agile in finding noninterfering transmission rounds for the leaders. The results for the 200 and 600 node networks are very similar; the only difference is that in the 200 node network there are around 50 leaders/owners in the static network and roughly 38 leaders/owners in the mobile network. For the 600 node network, there are approximately 58 and 43 leaders/owners in the static and mobile network, respectively.

The lower number of leaders/owners in the mobile network, compared to the static network appears to be due to the RWP model, which tends to concentrate the nodes toward the center of the network area with increasing simulation time. When phase I runs its self-stabilization slot and finds two leaders closer than $r_t/2$ together, one of them loses its leader status. Overall, we conclude from the mobility simulations that our algorithm maintains stable numbers of leader nodes and nodes owning noninterfering transmissions rounds even with relatively high levels of node mobility.

From Figure 4 we observe that for very low speeds (0.01 m/s and 0.1 m/s) the number of gateway nodes increases very slowly during the mobility simulation as the gateway connections are refined by the constantly running parallel algorithm phases. The number of gateway connections from a given leader node to neighboring leader nodes is bounded due to the constant density enforced by phase I on the leader set (i.e., two leaders must be at least r_t apart). Overall, we observe that the gateway discovery process is highly effective in establishing and maintaining gateway node connections than for low to moderate speeds up to 1 m/s.

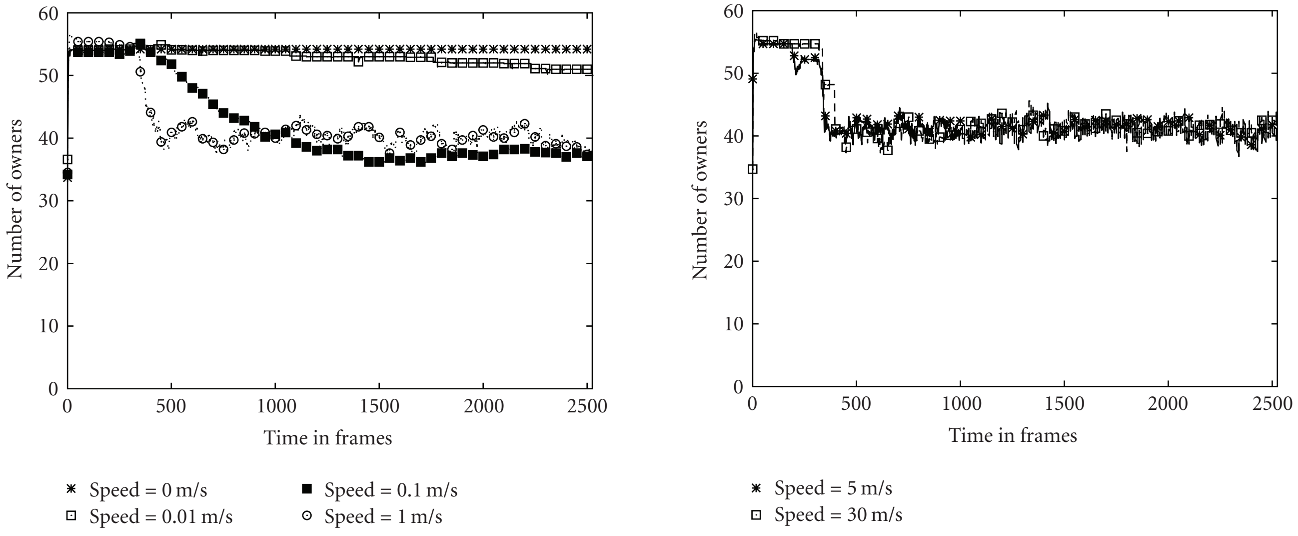
We observe from Figure 4 that for high speeds (5 m/s to 30 m/s), the number of gateway nodes initially drops during the mobility simulation and then settles around a stable level from around 1000 frame times onwards in the simulation runs. For these smaller number of gateway nodes, the CDS connectivity drops to between roughly 55% and 75% (as further examined in Section 3.4 and Table 2). The drop in gateway nodes and CDS connectivity to fairly low levels for high node mobility indicates that phase III is



(a)

(b)

Figure 2: Detailed sample path simulation results: effect of mobility on evolution of number of leader nodes as a function of time in frames for $N = 400$.



(a)

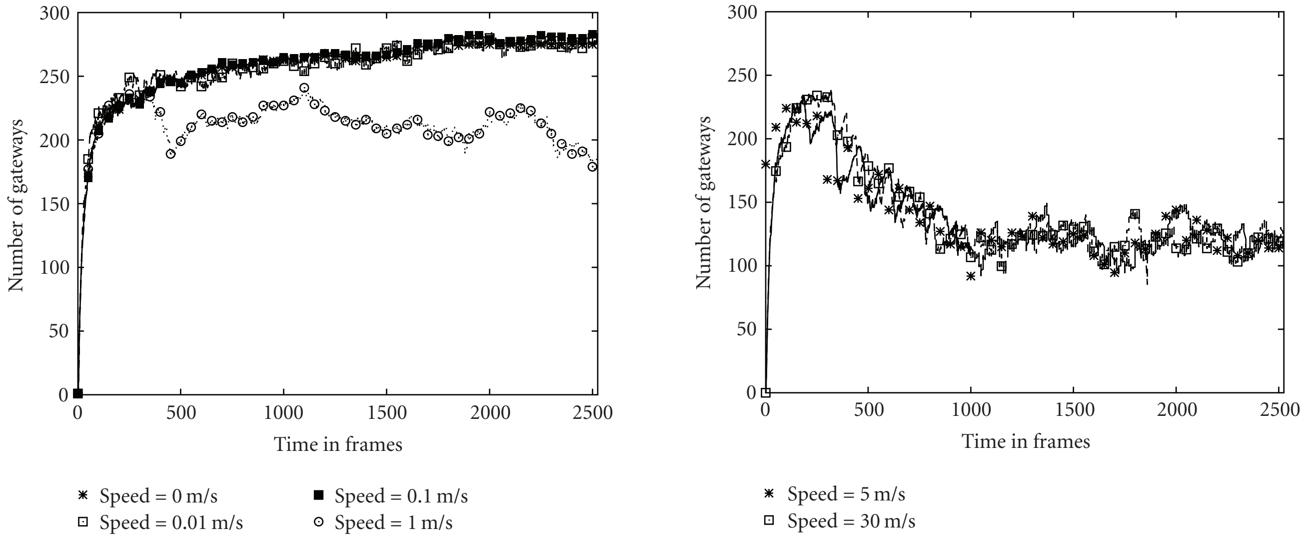
(b)

Figure 3: Detailed sample path simulation results: effect of mobility on evolution of number of owner nodes as a function of time in frames for $N = 400$.

not fast enough for keeping up with finding new gateway nodes as nodes move in and out of each other's transmission range relatively quickly. As reviewed in Section 2.1, Phase III requires a four-way exchange (with two of the exchanges requiring intact message receptions) between leader nodes and neighboring ordinary nodes for identifying gateway nodes. The simulation results appear to indicate that this four-way exchange is too slow to keep up with fast moving nodes.

Overall, we may conclude that the CDS maintenance is agile enough to maintain functional sets of leader nodes and ownerships of noninterfering transmission rounds up to high levels of mobility. On the other hand, the connectivity through the gateway nodes is high (close to 90% or higher) for small and moderate levels of mobility (up to about 1 m/s, see Figures 4 and 6); for higher levels of mobility, the gateway connectivity drops. Developing more agile gateway discovery and maintenance mechanisms that support high gateway connectivities at high levels of mobility is an important direction for future research.

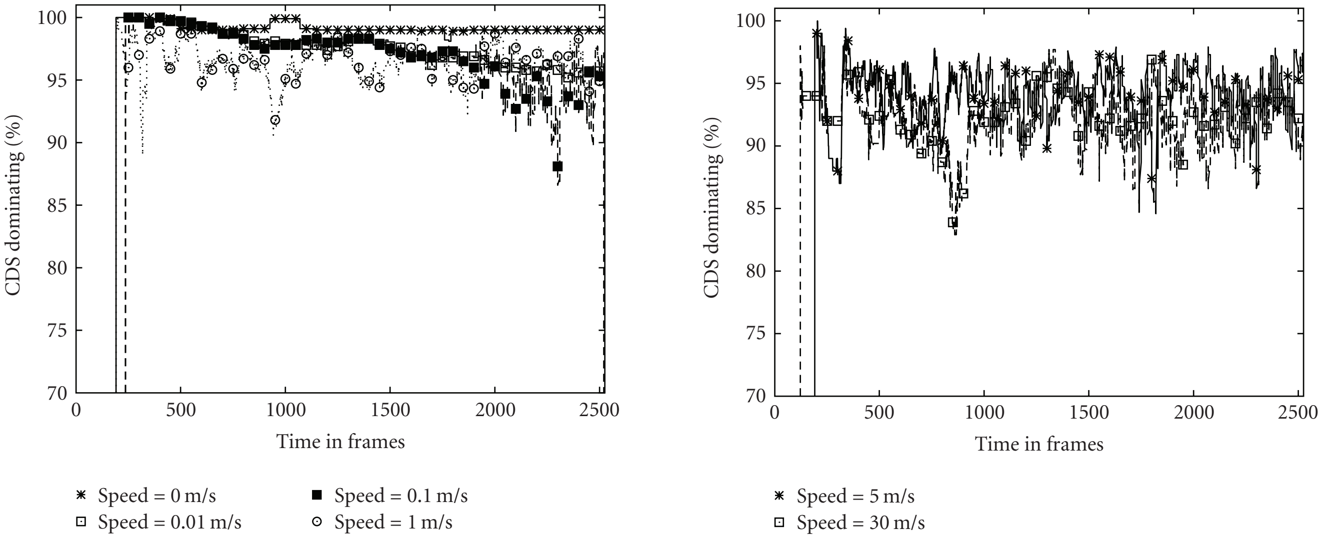
3.2.2. Connectivity and Dominance Properties. We present in Figure 5 the per-frame "CDS Dominating" percentage for different node speeds for the $N = 400$ node network. We observe from the plots that the leaderset covers typically more than 90% of the mobile nodes for all considered speeds;



(a)

(b)

Figure 4: Detailed sample path simulation results: effect of mobility on evolution of number of gateway nodes as a function of time in frames for $N = 400$.



(a)

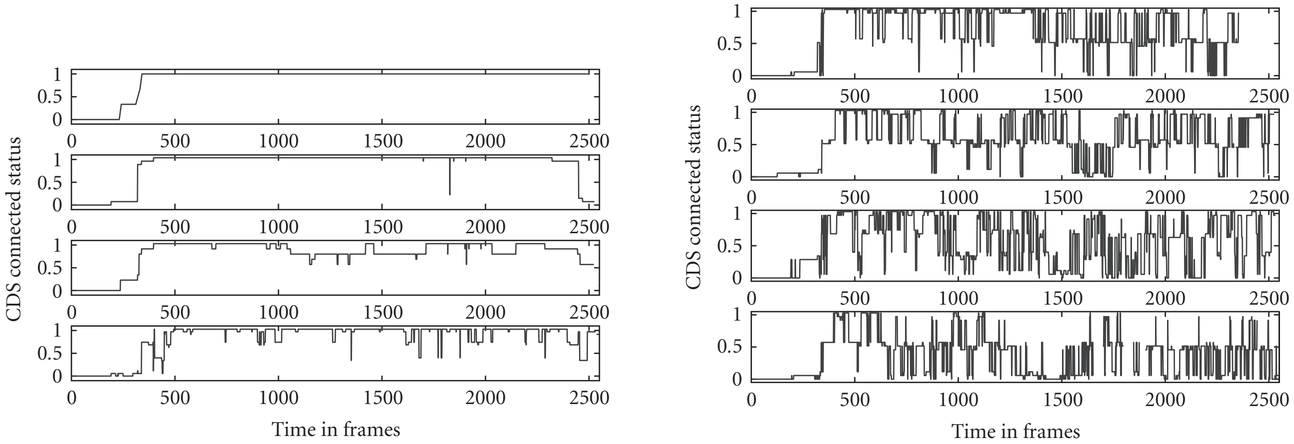
(b)

Figure 5: Detailed sample path simulation results for dominating set status of the CDS for $N = 400$.

similar observations were made for the $N = 200$ and $N = 600$ networks. The corresponding long-run average CDS dominating percentages with 95% confidence intervals for the mobility phase of the simulation are reported in Table 2.

In Figure 6 we plot the mean values of the "CDS Connected" measure across the 18 independent simulation replications as a function of time in frames. The plotted mean is one when CDS Connected is one in all 18 replications at the considered time. We observe from Figure 6(a) that the CDS is connected almost always at low speeds (up to 0.1 m/s), as also confirmed by the corresponding long-run average across the mobility phase (see Table 2). For the higher speeds considered in Figure 6(b), and in Table 2, we observe that the mean CDS connected measure drops to levels between 55% and 75%. We observe from Figure 6(b) that for those higher levels of mobility, the CDS connectivity fluctuates randomly with periods of brief CDS connectivity in close to all 18 replications taking turns with periods with CDS connectivity in fewer replications. The periods without CDS connectivity in any replications are relatively rare and brief even at the highest mobility levels.

In summary, we find that the dominance and connectivity results reflect the performance of the leader and gateway discovery and maintenance mechanisms evaluated in the preceding section. The leader set is quite stable even at high mobility levels and correspondingly we find high levels of



(a) Speeds from top to bottom are: 0 m/s, 0.01 m/s, 0.1 m/s, and 1 m/s

(b) Speeds from top to bottom are: 5 m/s, 10 m/s, 20 m/s, and 30 m/s

Figure 6: Detailed sample path simulation results for connectivity status of the CDS for $N = 400$.

CDS dominance even at high speeds. Similarly, the gateway node numbers are stable for low to moderate speeds and correspondingly the CDS connected values are high at low to moderate mobility levels. For high levels of mobility, the gateway node numbers drop, and so do the CDS connected values.

Wu and Dai in [27] state that without a mobility control mechanism in place, a connected dominating set may lose its global domination and connectivity status due to node movement. However, we demonstrate through our simulations, that by using physical carrier sensing to form locally noninterfering rounds and running the phases of the algorithm in parallel, we are able to achieve global domination and connectivity for our backbone network without making use of any explicit mobility control mechanism.

3.3. Overhead: Transmitted Bytes for CDS Maintenance. In Figure 7 we plot the number of bytes transmitted by a node per frame for each phase for different node speeds. Note that the three algorithm phases run continuously in parallel and we count the packets sent by a node in each phase in every frame throughout each simulation run. We note that the total number of transmitted bytes by a node per frame, which is obtained by adding the numbers of transmitted bytes for the three phases, is approximately 200 bytes per frame, irrespective of the level of mobility. From our more detailed evaluations, we found that this total number of 200 transmitted bytes per frame is roughly the same for the 200 node and 600 node scenarios. The main difference for the different node numbers is that at high speeds the relatively contribution of phase III is higher for the 200 node network and lower for the 600 node network than for the 400 node network.

Overall, the results for the algorithm overhead indicate that the overhead stays essentially constant even for high network densities and high mobility levels. Correspondingly, the energy required for the overlay network maintenance (which is typically proportional to the number of transmitted bytes) is roughly constant.

3.4. Aggregate Simulation Results. We summarize our aggregate simulation results in Table 2 by computing the overall CDS characteristics in terms of the average number of leader nodes, leader nodes owning noninterfering leader transmission rounds (owners), and gateway nodes as well as the overhead for CDS maintenance in terms of the number of messages and bits transmitted, received, collided, and sensed per node for various node velocities for the $N = 400$ node network. For this analysis we define a collision to be an event in which a node that could have received a message is only able to sense a busy carrier. These collisions, however, do not imply retransmissions. To arrive at our aggregate results, we use the 2000 frames of mobility simulations and discard data from the static network simulations of the CDS and the 200 frames of warm-up period. Each statistic is obtained, by collecting samples of every frame for every of the 18 independent replications, totaling the collected samples, averaging across the number of collected samples from the 18 replications, and dividing by the number of nodes in the network.

Table 2 first gives the means and 95% confidence intervals for the numbers of leader, owner, and gateway nodes during the mobility phase for the range of maximum node speeds. The table also reports the long run fraction of frames that the network is connected as well as the fraction of frames that the CDS is connected and the percentage of dominance. As the sample path plots in the preceding sections indicated, we confirm from Table 2 that the numbers of leaders and owner nodes drop only slightly from the levels for static and close to static networks (speeds of 0 m/s and 0.01 m/s) to the levels for mobile networks (speeds of 0.1 m/s and higher). Correspondingly, the levels of dominance drop only relatively little from the 100% achieved for static networks. On the other hand, the number of gateway nodes and correspondingly the CDS connectivity drop quite appreciably from the level for static and close to static networks (speeds 0–0.1 m/s) to the level for moderately mobile networks (speed of 1 m/s) and again considerably to the level for highly mobile networks (speeds 5–30 m/s).

Table 2: CDS characteristics and number of exchanged messages and bits per node per frame for **N** = 400.

Speed (m/s)	0	0.01	0.1	1	5	10	20	30
# of leaders	51 ± 0	51 ± 2	39 ± 2	40 ± 3	42 ± 3	42 ± 3	42 ± 4	42 ± 4
# of owners	51 ± 0	51 ± 2	39 ± 2	40 ± 3	42 ± 3	42 ± 3	42 ± 4	42 ± 4
# of gateways	255 ± 4	252 ± 5	268 ± 5	213 ± 3	126 ± 2	115 ± 3	112 ± 5	125 ± 2
Network conn. (%)	100 ± 0.4	100 ± 1.5	99 ± 2.1	99 ± 1.0	99 ± 0.6	97 ± 1.2	97 ± 0.8	97 ± 0.9
CDS conn. (%)	100 ± 0.4	6 ± 1.8	94 ± 2.7	88 ± 2.2	74 ± 3.4	60 ± 2.4	56 ± 2.2	54 ± 2.1
CDS dom. (%)	100 ± 1.1	96 ± 1.5	96 ± 4.3	96 ± 6.4	94 ± 7.6	94 ± 5.3	94 ± 6.7	92 ± 10
Phase I								
# of msgs tx	4.1 ± .03	4.6 ± .02	3.3 ± .01	3.3 ± .01	3.2 ± .03	.1 ± .04	3.2 ± .04	3.2 ± .05
# of msgs sx	57	59	59	59	59	59	59	59
= # of bits sx	±.07	±.09	±.02	±.01	±.01	±.05	±.01	±.01
# of msgs rx	0.05	0.05	0.08	0.3	0.9	1.2	1.3	1.4
# of bits rx	2.4 ± .02	2.4 ± .12	.8 ± .09	14 ± .12	43 ± .17	58 ± .22	65 ± .34	67 ± .37
Phase II								
# of msgs tx	27 ± .37	27 ± .17	25 ± .19	24 ± .08	22 ± .22	21 ± .14	20 ± .18	20 ± .36
# of msgs sx	107	113	113	113	112	112	112	112
= # of bits sx	±1.5	±1	±1	±1	±1	±1	±1	±1
# of msgs rx	2.8±.03	2.6 ± .03	2.5 ± .02	2.1 ± .01	1.9 ± .01	1.9 ± .01	1.9 ± .03	1.9 ± .04
# of bits rx	182 ±2.4	167 ±2	156 ±2	137 ±1.3	128 ±.45	127 ±1	127 ±.5	125 ±.5
Phase III slot 1								
# of msgs tx	0.9 ±.005	1.4 ±.01	1.5 ±0.01	2.5 ±.02	3.0 ±.06	3.1 ±.04	3.1 ±.04	3.2 ±.02
# of msgs sx	.16	.18	.17	.17	.18	.18	.18	.18
= # of bits sx	±.001	±.003	±.002	±.001	±.002	±.004	±.003	.004
# of msgs rx	.14	.14	.2	.25	.24	.24	.24	.24
bits rx	14 ± .2	16 ± .2	20 ± .4	24 ± .6	23 ± .4	23 ± .1	23 ± .4	23 ± .4
# of collisions	.08	0.08	.08	.08	.08	.08	.08	.08
Phase III slot 2								
# of msgs tx	.12 ±.001	.12 ±.032	.09 ±.002	.10 ±.068	.10 ±.091	.12 ±.017	.10 ±.073	.11 ±.043
# of msgs rx	.67 ±.003	.70 ±.005	.43 ±.001	.29 ±.001	.30 ±.006	.31 ±.009	.32 ±.002	.31 ±.043
bits rx	36 ±.015	34 ±.01	22 ±.002	16 ±.001	15 ±.002	15 ±.003	15 ±.003	15 ±.002
Phase III slot 3								
# of msgs tx	.02	0.02	.004	.003	.003	.003	.003	.003
# of msgs rx	.53	.11	.09	.09	.09	.09	.09	.05
bits rx	59 ± 1.1	12 ± 1.1	10 ± 1.3	10 ± .15	10 ± .09	10 ± .04	10 ± .2	5.9 ± .2
# of collisions	0.05	0.05	0.07	0.06	0.07	0.07	0.07	0.08
Phase III slot 4								
# of msgs tx	.02 ±.062	.03 ±.039	.02 ±.028	.01 ±.052	.01 ±.022	.01 ±.043	.01 ±.015	.01 ±.033
# of msgs rx	.08	.008	.007	.004	.004	.005	.004	.005
bits rx	171 ±3.0	164 ±3.1	142 ±5.6	70 ±1.8	82 ±1.9	92 ±1.6	76 ±1.7	89 ±6.2
Phase III totals								
# of msgs tx	1.0 ± .01	1.5 ± .01	1.6 ± .02	2.6 ± .06	3.1 ± .05	3.2 ± .04	3.2 ± .04	3.3 ± .06
# of msgs rx	.4 ± .02	0.95 ± .02	0.72 ± .02	0.63 ± .008	0.63 ± .09	0.64 ± .01	0.65 ± .03	0.66 ± .07
bits rx	281 ± 5	226 ± 3	194 ± 7	121 ± 5	130 ± 2	140 ± 2	124 ± 2	134 ± 7

Table 2: Continued.

Speed (m/s)	0	0.01	0.1	1	5	10	20	30
Totals								
# of msgs tx	33 ± .01	34 ± .02	30 ± .01	29 ± .01	27 ± .01	27 ± .01	27 ± .01	26 ± .01
# of msgs sx	164	172	172	172	171	171	171	171
= # of bits sx	±1.6	±1.2	±1.3	±1.0	±1.1	±1.4	±1.5	±1.6
# of msgs rx	4.3±0.02	3.6 ± 0.04	3.3 ± 0.03	3.0 ± 0.06	3.4 ± 0.07	3.7 ± 0.02	3.8 ± .02	3.9 ± .01
bits rx	465 ± 7.2	395 ± 6.3	354 ± 5.6	273 ± 7.5	301 ± 8.1	325 ± .5	316 ± .3	327 ± .6

Next, in Table 2, we compare the information reception that is due to physical carrier sensing versus intact message receptions by expressing both quantities in bits. We find that the vast majority (over 97.5%) of the messages exchanged by nodes are received through carrier sensing rather than through intact message receptions. We also observe that between 26% and 38% of all information bits received by a node per frame are received through physical carrier sensing. Form our more extensive evaluations we found that these percentages are slightly higher (between approximately 33% and 44%) for the 600 node network, and somewhat lower (between roughly 12% and 30%) for the 200 node network.

Overall, these percentages of messages and bits received through physical carrier sensing observed from Table 2 are significantly higher than the corresponding percentages observed for constructing a CDS in a static network in [3]. This is mainly because the evaluation in [3] only considered the periods when the individual phases were active for constructing the CDS. That is, phase I exchanges were only considered until the set of leaders was stable. Phase II exchanges were only considered from the time the leader set was stable to the time the ownership status was stable. Similarly, phase III exchanges were only considered from the time the ownership status was stable to the time the gateways were stable. In contrast, for the present evaluation in Table 2 we consider all exchanges by all phases all throughout the simulations. As a result, phases I and II, which rely exclusively on physical carrier sensing and are constantly active for maintaining the leaders and owners in the mobile network, contribute relatively more to the overall message exchanges.

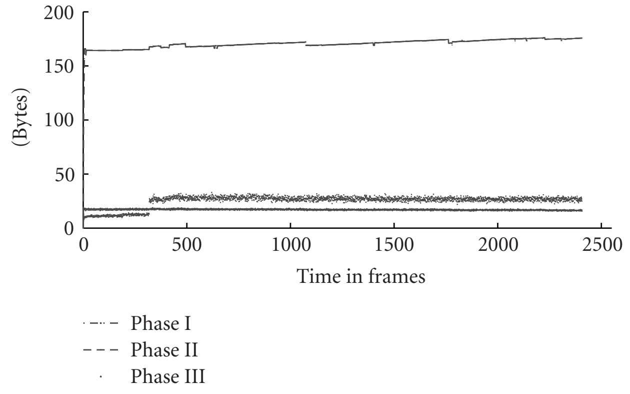
Examining closer the message exchanges for the individual phases in Table 2, we observe that the number of transmitted messages in phases I and II drops with increasing speeds, essentially mirroring the trends of the numbers of leader and owner nodes. The numbers of sensed bits, which are needed for the functions of phases I and II, stay relatively constant. Overall, these results on transmitted messages and sensed bits, in conjunction with the results for leader and owner nodes indicate that these two algorithm phases are well-suited for a wide range of mobility levels. We briefly note also that the total number of received bits in phases I and II, which are information collected in advance for phase III, stays roughly constant across the range of speeds (although the relative contributions from phase I and II vary).

Turning to phase III, we note that information exchange through physical carrier sensing takes only place in slot 1 (see also Table 1). The contribution of these sensed bits to the overall control information exchange in phase III is negligible. All other slots rely on the reception of intact control messages, whereby slot 4 has by far the longest control messages (exchanging the list of gateway nodes). Indeed, we observe that slot 4 contributes by far the most toward the information bits exchanged in phase III. Further, we observe that for increasing node speed there is a decrease in the number of sent as well as received messages in slots 3 and 4. This indicates that nodes moving at higher speeds are not able to participate in the gateway information update process as much as nodes that are moving with lower speeds, resulting in the decline in the number of gateway nodes for increasing node speeds.

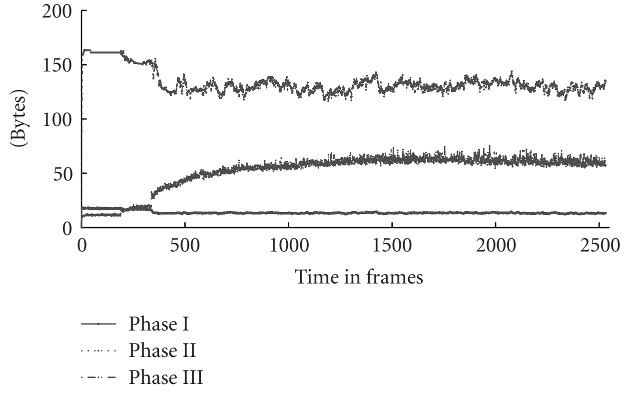
Finally, we note that the number of collisions, which are only possible in slots 1 and 3 (see Table 1), are quite low for all mobility levels. Consequently, the number of bits received in phase III that have not experienced a prior collision is essentially equal to the total number of bits received in phase III. Furthermore, all bits received in slots 2 and 4 were not vulnerable to collisions due to the noninterfering transmission rounds (established in phase II) and the reservations established in slots 1 and 3. We observe from Table 2 that typically close to three quarters of the information bits exchanged in phase III are not vulnerable to collisions.

4. Conclusion

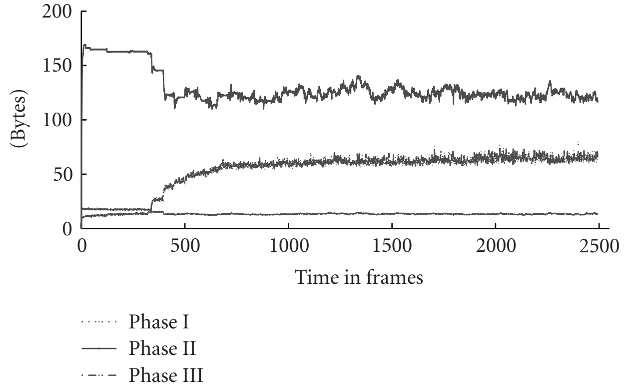
We have evaluated the parallel algorithm for construction and maintenance of a connected domination set (CDS) in wireless ad hoc networks proposed in [2, 3] for different levels of node mobility. Throughout, the examined algorithm considers interference ranges larger than transmission ranges and incorporates medium access control in the control message exchanges. We found that the first phase of the algorithm, which requires only control message exchanges through physical carrier sensing, maintains a leader set covering over 90% of all ordinary nodes up to high levels of mobility. Similarly, exclusively with control messages exchanged through physical carrier sensing, the second phase of the parallel algorithm maintains a stable assignment of noninterfering transmission rounds to leader nodes. We found that for low levels of mobility (speeds up to 0.1 m/s), phase III of the algorithm maintains leader connections through gateways ensuring that the CDS is connected over 90% of the time. For higher levels of node mobility, the connectivity steadily drops (down to about 55% of the time for a speed of 30 m/s), indicating that the algorithm is



(a) Speed = 0 m/s



(b) Speed = 5 m/s



(c) Speed = 30 m/s

Figure 7: Detailed sample path simulation results: number of transmitted bytes by a node in Phase I (bottom curve), Phase II (top curve), and Phase III (middle curve) for backbone creation and maintenance per frame for $N = 400$.

not agile enough to maintain gateway connections at those higher levels of mobility.

Regarding the goal to maximize the information extracted from the ongoing transmissions through physical carrier sensing, we found that the parallel algorithm manages to exchange over 97.5% of the control messages and roughly 30% of the control information bits for CDS maintenance through physical carrier sensing.

Improving the agility of the gateway connection discovery and maintenance is an important direction for future research. As demonstrated by the results for leaders and owners of noninterfering transmission rounds, the first two phases of the parallel algorithm maintain this "infrastructure" of leaders and noninterfering rounds up to high levels of mobility. Future research should explore how this infrastructure could be better exploited for keeping the CDS connected at higher node speeds.

Another important direction for future work is to examine how other network layer functions in MANETs, such as routing and name resolution, can be integrated with the physical carrier sensing based CDS algorithm. The goal of such integration should be to exploit as extensively as possible physical carrier sensing for these other network layer functions so as to reduce the reliance on control message exchanges through intact message receptions.

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Signal Processing-Assisted Protocols and Algorithms for Cooperating Objects and Wireless Sensor Networks

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With the advent of the so-called Internet of Things (IoTs), we will witness an unprecedented growth in the number of networked terminals and devices. In attaining this IoT vision, a class of energy- and, in general, resource-constrained systems like Wireless Sensor Networks (WSNs), networks of cooperating objects and embedded devices such as RFIDs, or networks for Device-to-Device (D2D) and Machine-to-Machine (M2M) communications are to play a fundamental role. The paradigm shift from general-purpose data networks to application-oriented networks (e.g., for parameter or random field estimation, event detection, localization, and tracking) clearly calls for further optimization at the physical, link, and network layers of the protocol stack. Interestingly, the above-mentioned estimation/detection/localization/tracking problems have been addressed for years by the signal processing community, this resulting into a number of well-known algorithms. Besides, some inspiration could be also borrowed from other communication schemes, such as MIMO and beamforming techniques or cooperative communications that were traditionally developed for wireless data networks, or even from other fields such as mathematical biology (e.g., networks of coupled oscillators). However, the challenge now is to enhance such algorithms and schemes and make them suitable for decentralized and resource-constrained operation in networks with a potentially high number of nodes. Complementarily, the vast literature produced by the information theory community, on the one hand, reveals the theoretical performance limits of decentralized processing (e.g., distributed source coding) and, on the other, offers insight on the scalability properties of such large networks and their behavior in the asymptotic regime. Realizing the information-theoretic performance with practical decentralized networking, radio resource management schemes, routing protocols, and other network management paradigms is a key challenge.

The objective of this Special Issue (whose preparation is carried out under the auspices of the EC Network of Excellence in Wireless Communications NEWCOM++) is to gather recent advances in the areas of cooperating objects, embedded devices, and wireless sensor networks. The focus is on how the design of future physical, link, and network layers could benefit from a signal processing-oriented approach. Specific topics for this Special Issue include but are not limited to:

- Decentralized parameter estimation
- Estimation of random fields
- Distributed MIMO and beamforming
- Decentralized and cooperative time and frequency synchronization
- Cooperative event detection
- Data gathering and data fusion
- Data-centric multihop techniques and routing
- Scalability and asymptotic laws for in-network distributed estimation/detection
- Energy-saving algorithms and protocols
- Feedback-limited scheduling and MAC protocols
- Decentralized joint source-channel coding
- Cooperative localization and tracking
- Topology control in resource-constrained networks
- Low-complexity opportunistic networking protocols

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Special Issue on Radar and Sonar Sensor Networks

Call for Papers

Although radar and sonar rely on two fundamentally different types of wave transmission, Radio Detection and Ranging (RADAR) and Sound Navigation and Ranging (SONAR), both are remote sensing systems with important military, scientific, and commercial applications. RADAR sends out electromagnetic waves, while active SONAR transmits acoustic (i.e., sound) waves. In both systems, these waves return echoes from certain features or targets that allow the determination of important properties and attributes of the target (i.e., shape, size, speed, distance, etc.). Because electromagnetic waves are strongly attenuated (diminished) in water, RADAR signals are mostly used for ground or atmospheric observations. Because SONAR signals easily penetrate water, they are ideal for navigation and measurement under water. The networking of radars or sonars is two emerging research areas, known as radar sensor networks and underwater sensor networks. The goal of the Special Issue is to publish the most recent results in the development of radar sensor networks and underwater sensor networks. Researchers and practitioners working in this area are expected to take this opportunity to discuss and express their views on the current trends, challenges, and state-of-the-art solutions addressing various issues in radar and sonar sensor networks. Review papers on radar sensor networks and/or underwater sensor networks are also welcome. Topics to be covered in this Special Issue include, but are not limited to:

- Waveform design and diversity
- UWB radar sensor networks
- Interferences analysis
- Coexistence with other sensor networks
- Network capacity
- MIMO radar
- MIMO radar
- Medium Access Control (MAC)
- Routing
- Underwater channel modeling
- Underwater communications
- Network coverage
- Energy efficiency
- Security and privacy
- Navigation and positioning (localization)
- Sensor fusion
- In-network information processing
- Target detection and tracking
- Other applications

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