On the Broadcast Storm Problem in Ad hoc Wireless Networks

(Invited Paper)

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***Abstract*— Routing protocols developed for ad hoc wireless networks use broadcast transmission to either discover a route or disseminate information. More specifically, reactive routing protocols has to flood the network with a *route request* (RREQ) message in order to find an optimal route to the destination. Several applications developed for vehicular ad hoc wireless networks (VANET), which is a subset of MANET, rely on broadcast to propagate useful traffic information to other vehicles located within a certain geographical area. However, the conventional broadcast mechanism may lead to the so-called *broadcast storm* problem.**

In this paper, we explore how serious the broadcast storm problem is in both MANET and VANET by examining how broadcast packets propagate in a 2-dimensional open area and on a straight road or highway scenarios. In addition, we propose three novel distributed broadcast suppression techniques; i.e., *weighted p-persistence*, *slotted 1-persistence*, and *slotted p-persistence* schemes. Our simulation results show that the proposed schemes can achieve up to 90% reduction in packet loss rate while keeping the end-to-end delay at acceptable levels for most VANET applications. They can also be used together with the route discovery process to guide the routing protocols to select routes with fewer hop counts.

I Introduction

Broadcast transmission is used for at least two very different purposes in MANET. Firstly, many MANET routing protocols broadcasts RREQ messages in order to search for a route to a particular host. In this case, the goal is to propagate the RREQ message to the destination as quickly and efficiently as possible, i.e., RREQ message *from the optimal path* should be the first one to arrive at the destination. Alternatively, some applications, especially ones that were developed for vehicular ad hoc wireless networks (VANET), may rely on broadcast transmission to disseminate data packet to nodes in a certain geographical area. However, it is well-known that blindly broadcasting the packets may lead to frequent contention, and collisions in transmission among neighboring nodes. This problem is sometimes referred to as the *broadcast storm* problem.

In this paper, we explore how serious the broadcast storm problem is in two very different scenarios; (i) in MANET where problem rises during the route discovery process, and (ii) in VANET where most applications typically favor broadcast transmissions. While multiple solutions exist to alleviate the broadcast storm problem in a usual MANET environment [1–6], none of these solutions address the problem in the VANET context, nor do they study the impact of broadcast storm on routing decisions.

While most studies, to the best of our knowledge, focus on improving the performance in terms of latency, overhead, and network reachability, in this paper, we also consider packet loss ratio, route discovery time, and the number of hops chosen by the routing protocols as our performance metrics. More specifically, we propose three light-weight broadcast techniques; *weighted p-persistence*, *slotted 1-persistence*, and *slotted p-persistence*, which give priority to shortest path route and offer up to 90% reduction in packet loss rate while keeping the latency at acceptable levels for most applications and also providing maximum network reachability. The proposed schemes are distributed and rely on GPS and/or received signal strength information, but do not require any other prior knowledge about network topology.

The remainder of this paper is organized as follows. Related research are discussed in Section II. The impact of broadcast storm in MANET and VANET is quantified and discussed in detail in Section III. The algorithms proposed for mitigating the broadcast storm are described in detail in Section IV. The performance of the three broadcast techniques are presented in Sections V and VI. Finally, the main findings and contributions of this paper are summarized in Section VII.

II Related Work

In the following, we briefly describe related research activities in VANET and other broadcast techniques proposed for general MANETs.

Unlike other forms of MANETs, applications developed for VANET have a very specific and clear goal of providing intelligent and safe transport systems. Emergency warning for public safety is one of many applications that is highly time-critical and requires a more intelligent broadcast mechanism than just blind flooding. In [7], the authors study how broadcast performance scales in VANET and propose a priority based broadcast scheme which gives higher priority to nodes that need to transmit time-critical messages. The proposed algorithm categorizes nodes in the network into multiple classes with different priorities and schedules the packet transmission accordingly. Although this technique is not designed to solve the broadcast storm problem per se, it can indirectly mitigate the severity of the storm by allowing nodes with higher priority to access the channel as quickly as possible.

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In the MANET context, on the other hand, several approaches have been proposed to cope with the broadcast storm. A distributed *gossip-based* routing, introduced by Haas et al. [1], is designed to tackle the overhead problem by suggesting that each node re-forwards the packet with some probability $p \leq 1$. Inspired by [1], we also propose probabilistic schemes that utilize the Global Positioning System (GPS) information in order to improve the packet penetration rate, i.e., the rate at which the message percolates through the network in terms of distance per unit time.

In [2], various threshold-based techniques were proposed by Tseng et al., e.g., the *counter-based*, *distance-based*, and *location-based* schemes. Depending on the scheme considered, a node receiving the broadcast packet compares the predetermined threshold value with its local information, e.g., the number of duplicate packets received, the relative distance between itself and the sender, or the additional area that can be covered if it rebroadcasts the message. The criteria to adaptively adjust the thresholds according to the number of neighbors were also presented by Ni et al. in [3]. The results show that, with the aid of a positioning device such as the GPS, the location-based scheme seems to offer the best performance in terms of the packet penetration rate and the link load. Although our schemes employ a similar concept with the schemes in [2,3], we use a light-weight distributed algorithm to calculate the forwarding probability and/or the waiting time before rebroadcast instead of using threshold values. In addition, we also investigate the usability of our schemes in both MANET and more importantly VANET where most applications rely on broadcast protocol and have different routing requirements.

Instead of making a decision at the receiver, Laouiti et al. have proposed a sender-based multi-point relay (MPR) technique [4] where the sender controls the number of retransmissions by selecting a subset of its neighbors to relay the message. Although MPR can significantly reduce the broadcast redundancy, the amount of overhead introduced by this scheme may be high as it requires that each node has perfect knowledge about its 1-hop and 2-hop neighbors in real-time in order to properly choose the set of relay nodes. In our work, the proposed schemes do not require a node to keep track of its neighbors.

In addition to the transmission logic set by either the sender or the receiver, there are some studies which tackle the broadcast storm problem by using the available hardware. In [5], directional antennas are used by Hu et al. to mitigate the broadcast redundancy and alleviate the contention at the MAC layer. In [6], Lipman et al. have proposed the use of a reliable minimum spanning tree (RMST) algorithm in conjunction with a wireless interface that has multi transmit power levels. Although the use of a spanning tree algorithm ensures 100% reachability, the practicality of the algorithm may be limited to the hardware used since most wireless cards only provide limited access to adjusting the physical parameters and there are typically only 4-7 transmit powers available which might not be sufficient for this algorithm.

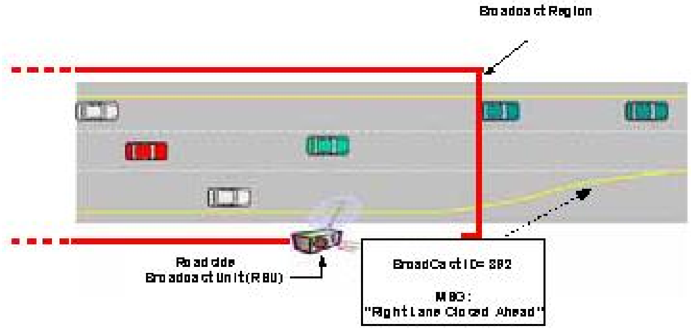


Fig. 1. Traffic Alert System.

III Impact of Broadcast Storm in MANETs and VANETs

It is well-known that excessive broadcast redundancy as a result of broadcast storm leads to severe contention at the link layer, packet collisions, inefficient use of bandwidth and processing power, and most importantly the service disruption due to high contention. Typically, mobile hosts in MANET discover the routes during an explicit route discovery process by flooding the network with the route request (RREQ) broadcast packet. Upon receiving the RREQ packet for the first time, a mobile node either rebroadcasts the packet or replies to the source if it has a route to the destination or if it is the destination of the RREQ packet.

Some routing protocols, however, have various features designed to avoid flooding the network and creating broadcast storm [8,9]. Techniques which are specified in the protocol standard include the use of *Expanding Ring Search* to help control the broadcast region to within a few hops away from the source. A node can also cache each routing entry for a longer time and can also reply on behalf of the destination (Gratuitous Route Reply) to speed up the discovery process. A node running Dynamic Source Routing (DSR) can be in a promiscuous mode so that it can construct a routing table by eavesdropping the other nodes' conversation.

Other techniques previously described in Section II can also further suppress the broadcast redundancy, but may reduce the network connectivity and prolong the route discovery process. Since the goal of the route discovery is to acquire the route in the least amount of time without injecting excessive traffic into the network, the main drawback of broadcast storm in MANETs is the contention delay which may prolong the route acquisition time, disrupt the other on-going communications, and lead to inefficient route selection, all of which are very undesired consequences.

In VANETs, however, broadcast is typically used for disseminating the traffic-related information, e.g., detour route, accident alert, construction warning, etc., to within a certain area, as shown in Figure 1. While these may not be as time-critical as requesting a route, the traffic message should persist in a network for *a longer period of time*, e.g., a few hours up to a few days. Therefore, the roadside unit (RSU) that broadcasts traffic information should periodically rebroadcast the message to keep it alive for as long as needed. As a result, broadcast storm may arise if the traffic density on the road and the frequency at which the RSU broadcasts the message are high. The direct impact of broadcast storm in this case is the waste of processing time and bandwidth and the increase in the medium access delay. Although these imply that the message will take a few seconds longer to reach the vehicles that are many hops away from the broadcast unit, as we will show in this paper, this increase in delay is negligible from the end user's perspective. However, a more serious impact of the broadcast storm is the safety-related service disruption. For example, other urgent safety messages might get lost or get delayed during the broadcast storm. In the following, we present a simulation study to illustrate and quantify the impact of broadcast storm in VANETs.

A Case Study I: Highway Scenario or 1-Dimensional Network

In order to understand how the broadcast packet gets propagated on a highway network, we modified AODV in OPNET v.11 [10] to include the broadcast mechanism and studied how the network behaves under different traffic densities, i.e., from 10 cars/km to 100 cars/km on a 10 kilometer road section with 4 lanes. Each vehicle in the network communicates with one another using a 5.9 GHz 802.11a communication device with 10 MHz channel. The transmission power is set to 20 mW and the receiver sensitivity threshold is -95 dBm so that the transmission range is approximately 1 km, according to the Friis propagation model used in OPNET. In the scenario considered, the RSU broadcasts a 25 Kb packet on a 10 km road section. The message is broadcasted once, and various statistics, such as contention delay, packet loss ratio, propagation delay, etc., are collected during the broadcast storm. A similar highway scenario is considered for MANET where source node initiates a route discovery to find a route to the destination that is located 10 km down the road using the AODV protocol. Statistics collected for this P2P communication are number of hops and the route discovery time.

The link layer contention delay statistics, measured from all the vehicles receiving the broadcast packet during the broadcast storm, at four different traffic densities are shown in Table I. Results presented are averaged over 1000 simulation runs. Observe that the contention delay increases with increasing traffic density which also results in the increase in the number of vehicles in the same collision domain (or within the carrier sensing range which is typically twice the transmission range).

In MANET, this wide range of contention delay may cause inefficient route selection if the routing protocol uses the shortest path algorithm. For example, the RREQ packet from the shortest-path route may get lost or delayed because of the high contention in a dense network. As is shown in the traffic jam scenario with 100 cars/km in Table I, it takes 17 hops to propagate the broadcast message to the farthest node, while it takes only 12 hops under light traffic conditions. For peer-to-peer applications such as file transfer or voice communication, taking a longer route with more hop count is very inefficient as it is well-known that multi-hop throughput drops drastically as a route gets longer.

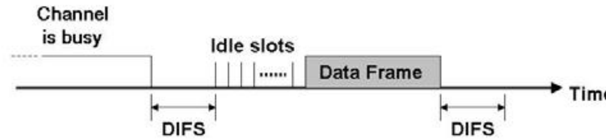


Fig. 2. IEEE 802.11 medium access method.

The high link layer contention could also lead to a long route discovery delay which comprises of RREQ broadcast packet delay from the source to the destination and the RREP unicast packet delay from the destination back to the source along the chosen route. Observe that while it takes only 17 ms to obtain the route in the light traffic condition, it takes almost twice as long in the traffic jam condition. However, the route discovery delays in all of the scenarios considered should be acceptable to most peer-to-peer applications as they are much less than a second.

The rest of Table I shows the time it takes to propagate the broadcast message to a node that is 10 kilometers away and the packet loss statistics under four different traffic conditions. Interestingly, despite the carrier sensing and back-off mechanism used in 802.11a, there is a high chance of packet collision in the dense network, i.e., packet loss ratio is 60% in the traffic jam condition. This is because nodes that receive the broadcast packet within the same period of time and will contend for a chance to retransmit the packet are likely to be in the same collision domain and may pick the same back-off time slot.

In 802.11 network, after sensing an idle channel for DIFS (distributed inter-frame space) period of time, a node has to do the random back-off before it can transmit a data packet by randomly picking the time slot from 0 to the minimum contention window size which is 15 in 802.11a, as shown in Figure 2. During the back-off mode, a node decreases the back-off timer by one for each idle slot, pauses if the channel is sensed busy, and resumes if the channel is idle again for the DIFS time duration. Finally, when the timer reaches zero, the packet can be transmitted. Therefore, the chance of packets colliding with one another will be high in a dense network given that there are only 15 back-off time slots. This is because nodes who pick the same time slot will transmit the packet at the same time and cause packet collision.

The major impact of broadcast storm in VANET, however, is neither the extra number of hops taken nor the long delay because the total end-to-end delay in the traffic jam scenario is only about 7 ms longer than that in the light traffic conditions. This implies that even at high traffic density condition (100 cars/km) it takes only less than 25 ms for vehicles that are 10 km away from the RSU to receive the first broadcast message. To the drivers, this delay is negligible if the broadcast packets do not contain an urgent message. However, as is also shown in Table I, the high packet loss ratio during the broadcast storm may cause other urgent safety messages to get lost. Therefore, in order to avoid losing important messages, it is crucial to design a routing protocol that can suppress the broadcast redundancy in VANET.

TABLE I
BROADCAST PROPAGATION STATISTICS ON A 10 KM ROAD

Traffic Condition	Traffic Density [cars/km]	MAC Delay [ms]			Number of Hops	Route Discovery Delay [ms]	Packet Loss Ratio [%]	Total Delay [ms]
		Average	Maximum	95^{th} Percentile				
Light	10	0.05	0.72	0.40	14.74	17.05	15.90	14.14
Moderate	25	0.32	2.22	1.43	17.06	21.59	34.70	16.58
Heavy	50	1.45	7.77	4.20	18.93	28.80	49.07	17.44
Jam	100	3.71	13.48	9.30	19.76	33.76	60.32	21.09

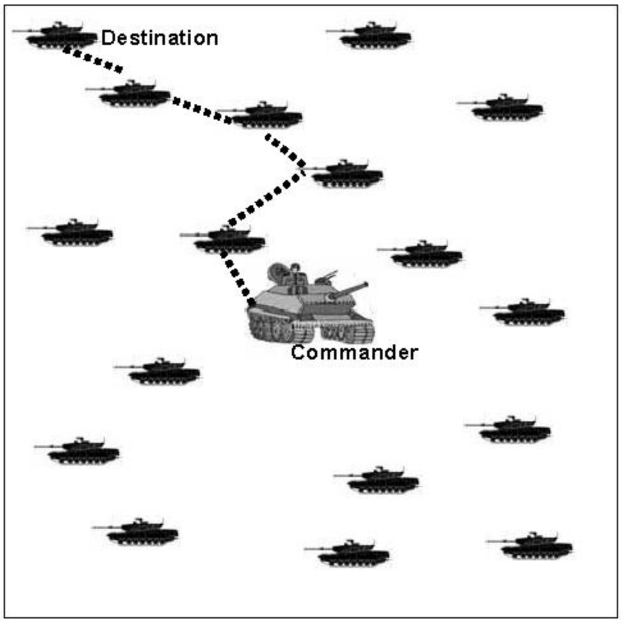


Fig. 3. Battle Field Scenario.

B Case Study II: Battle Field Scenario or 2-Dimensional Network

A typical network topology commonly assumed in a MANET study is the two dimensional battle field network where nodes are randomly placed in a 2 dimensional open space. For this case study, we consider an open area of 4×4 km^2 network with 500 mobile nodes moving randomly within the considered area. Assume that a commander acts as a source node and is located in the middle of the field. In this case, nodes who are at the four corners of the battle field will be the farthest ones from the source, as shown in Figure 3. For this scenario, we also consider two possible scenarios where (i) the source only wishes to broadcast data packets to all the nodes in the network and (ii) the source wishes to establish peer-to-peer communication with one of the nodes at the corner of the battle field.

Similar to the previous highway case study, each node in the network communicates with one another using a 5.9 GHz 802.11a communication device over a 10 MHz channel. However, the transmission power is reduced to half of the previous case, i.e., the transmission power is set to 10 mW instead of 20 mW, so that the transmission range is approximately 500 m and there are at least 10 hops from the source to the destination at the corner.

TABLE II
BROADCAST PROPAGATION STATISTICS IN A BATTLE FIELD

Number of Nodes	Route Discovery Delay [ms]	Number of Hops	Total Delay [ms]	Packet Loss Ratio [%]
500	22.06	16	14.61	85.90

Table II shows the broadcast propagation statistics in the battle field environment, where the results shown are averaged over 50 simulation runs. Observe that the loss rate is relatively high compared to the VANET scenario. This is possibly due to the large number of interferers, i.e., the average number of neighbors or node degree is 27 for the parameters considered, which also leads to hidden node terminal problem as the collision avoidance is typically disabled for broadcast transmission. As a result, the average number of hops taken to reach the destination node at the corner is 16 hops; as we will show in a later section this number can be as low as 10 hops. When loss rate exceeds 85%, we have also observed that AODV failed to discover a route 50% of the time. Therefore, it is almost impossible to do any data or voice communication in such a scenario.

Based on the results of these two case studies, we propose three distributed broadcast techniques to cope with the aforementioned broadcast storm problem.

IV BROADCAST SUPPRESSION TECHNIQUES

The basic broadcast techniques follow either a *1-persistence* or a *p-persistence* rule. Despite the excessive overhead, most routing protocols designed for multi-hop ad hoc wireless networks follow the brute-force 1-persistence flooding rule which requires that all nodes rebroadcast the packet with probability 1 because of the low complexity and high packet penetration rate. Gossip-based approach, on the other hand, follows the p-persistence rule which requires that each node re-forwards with a pre-determined probability p. This approach is sometimes referred to as probabilistic flooding [1]. In both schemes, repeated reception of the same message or any expired messages should be ignored by broadcasting nodes in order to avoid inevitable service disruptions due to network saturation.

In the following, we propose three new broadcast schemes which allow each node to calculate its own re-forwarding probability based only on its local information.

A Distance-Based Schemes

1) Weighted p-Persistence Broadcasting:

Rule: *Upon receiving a packet from node* $\boldsymbol{i}$*, node* $\boldsymbol{j}$ *checks the packet ID and rebroadcasts with probability* p_{ij} *if it receives the packet for the first time; otherwise, it discards the packet.*

Denoting the relative distance between node i and j by D_{ij} and the average transmission range by R, the forwarding probability, p_{ij}, can be calculated on a per-packet basis using the following simple expression,

$$p_{ij} = \frac{D_{ij}}{R}. \tag{1}$$

Note that if node j receives duplicate packets from multiple sources within the waiting period of WAIT_TIME (for example 2 ms) before retransmission, it selects the smallest p_{ij} value as its re-forwarding probability, i.e., each node should use the relative distance to the nearest broadcaster in order to ensure that nodes who are farther away transmit with higher probability. If node j decides *not* to rebroadcast, it should buffer the message for an additional WAIT_TIME + δ ms, where δ is the one-hop propagation delay which is typically less than WAIT_TIME. In order to prevent the message "die out" and guarantee 100% reachability, node j should rebroadcast the message with probability 1 after WAIT_TIME + δ ms if it does not hear the retransmission from the neighbors.

Unlike the p-persistence or the gossip based scheme, the weighted p-persistence assigns higher probability to nodes that are located farther away from the broadcaster given that the GPS information is available and accessible from the packet header. This is illustrated in Figure 4(a).

2) Slotted 1-Persistence Broadcasting:

Rule: *Upon receiving a packet, a node checks the packet ID and rebroadcasts with probability* **1** *at the assigned time slot* $T_{S_{ij}}$ *(after packet reception) if it receives the packet for the first time and has not received any duplicates before its assigned time slot; otherwise, it discards the packet.*

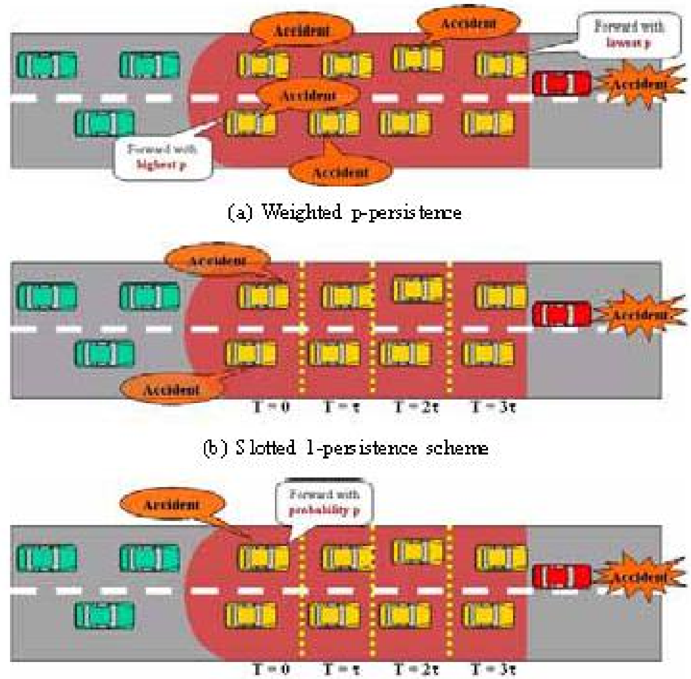
Given the relative distance between node i and j, D_{ij}, the average transmission range, R, and the pre-determined number of slots N_s, $T_{S_{ij}}$ can be calculated as

$$T_{S_{ij}} = S_{ij} \times \tau \tag{2}$$

where τ is the estimated 1-hop delay, which includes the medium access delay and the propagation delay, and S_{ij} is the assigned slot number which can be expressed as

$$S_{ij} = \begin{cases} \left\lceil N_s \left(1 - \frac{D_{ij}}{R}\right)\right\rceil & ; D_{ij} \leq R \\ 0 & ; D_{ij} > R \end{cases} \tag{3}$$

The time slot approach follows the same logic as the weighted p-persistence scheme, but instead of calculating the re-forwarding probability, each node uses the GPS information to calculate the waiting time to retransmit. For example, in Figure 4(b), the broadcast coverage is spatially divided into 4 regions and a shorter waiting time will be assigned to the nodes located in the farthest region, i.e., farthest nodes broadcast immediately after reception, nodes in the next to last region broadcast τ seconds after reception, etc. Hence, in the case where a node receives duplicate packets from more than one sender, it takes on the smallest D_{ij} value. Similar to the p-persistence scheme, this approach requires the transmission range information in order to agree on a certain value of slot size.



(a) Weighted p-persistence

(b) Slotted 1-persistence scheme

(c) Slotted p-persistence scheme.

Fig. 4. Broadcast Suppression Techniques.

3) Slotted p-Persistence Broadcasting:

Rule: *Upon receiving a packet, a node checks the packet ID and rebroadcasts with the pre-determined probability* $\boldsymbol{p}$ *at the assigned time slot* $T_{S_{ij}}$*, as expressed by Eqn. (2), if it receives the packet for the first time and has not received any duplicates before its assigned time slot; otherwise, it discards the packet.*

Each node in this scheme should also buffer the message for a certain period of time (e.g., $[N_s - 1] \times$ WAIT_TIME + δ ms) and retransmits with probability 1 if nobody in the neighborhood rebroadcasts in order to prevent the message "die out". Figure 4(c) illustrates the concept of the slotted p-persistence with 4 slots. Similar to the p-persistence case, the performance of this scheme also depends on the value chosen for the re-forwarding probability **p**. We address this problem in detail later, in Section V.

B Received Signal Strength Based Schemes

Because nodes may not be able to receive the GPS signals in some areas, e.g., in tunnels, shadowed areas, urban areas with many high-rise buildings or in an indoor environment, etc, the proposed broadcast techniques can also be modified to use the packet received signal strength (RSS) information instead of the the GPS information. In the absence of GPS signal, each node can obtain the RSS of the broadcast packet received from the DSRC device driver and determine whether or not to rebroadcast the packet based on the RSS measured and the prior knowledge about the transmit power and receiver sensitivity. In the following, we outline the modifications needed to change the proposed broadcast schemes described in Section IV-A to use RSS information.

In the weighted p-persistence case, each node can compare the RSS of the received packet to the range of RSS which is given by

$$\mathrm{RSS}_{\mathrm{range}} = \mathrm{RSS}_{\mathrm{max}} - \mathrm{RSS}_{\mathrm{min}} \tag{4}$$

where the $\mathrm{RSS}_{\mathrm{max}}$ and $\mathrm{RSS}_{\mathrm{min}}$ correspond to the maximum and minimum possible values of RSS measured in the considered environment; these values can either be obtained experimentally or calculated by applying an appropriate propagation model, e.g., the Friis model or the two-ray model [11].

Given that $\mathrm{RSS}_{\mathrm{range}}$ is the same for all vehicles, Eq. 1 can be reformulated as

$$p_{ij} = \frac{\mathrm{RSS}_{ij} - \mathrm{RSS}_{\mathrm{min}}}{\mathrm{RSS}_{\mathrm{range}}} \tag{5}$$

where RSS_{ij} is the RSS of the broadcast packet received at node j.

Similarly, the slotted schemes could be modified to use the RSS information instead of the relative distance to determine the waiting time. Given the number of slots, Eq. 3 can be modified as follows:

$$S_{ij} = N_s - \left\lceil \frac{(\mathrm{RSS}_{ij} - \mathrm{RSS}_{\mathrm{min}}) \times N_s}{\mathrm{RSS}_{\mathrm{range}}} \right\rceil \tag{6}$$

V Performance Analysis

In this section, we compare the performance of the proposed broadcast schemes with the conventional 1-persistence flooding and p-persistence flooding or gossiping schemes. Each node has a broadcast range of 500 meters. The slot size is assumed to be 100 meters, so that the broadcast coverage can be divided into 5 time slots. The re-forwarding probability is assumed to be 0.5 in the p-persistence and the slotted p-persistence cases. Note that while [1] suggests that the forwarding probability should be greater than 0.65 in a two-dimensional network topology with average degree 8, in this work we considered a network of degree 10 or higher so it suffices to rebroadcast with probability of 0.4 or higher especially in a one-dimensional network topology [12].

A One-Dimensional Highway Network

1) Network Model: In order to understand the fundamental impact that each of the broadcast schemes has on the network performance, we developed a network simulator to create random vehicle traffic on a straight road where each vehicle can perform the basic broadcast operations proposed in Section IV without the complication of the MAC and MANET routing protocol. For each simulation run, a new topology is created and one broadcast message is propagated for 100 hops, i.e., Time-To-Live (TTL) of the packet is set to 100. Vehicle's speed is assumed to be uniformly distributed between 25-30 m/s and all vehicles are moving in the same direction. We assume that all the nodes within the broadcast range of the transmitter can correctly receive the packet. Upon receiving the broadcast message, each node keeps track of the number of packets it receives and immediately retransmits the packet. Other statistics such as packet loss ratio and propagation delay will be presented later in Section VI as we will also include the effect of 802.11a MAC and the routing protocol.

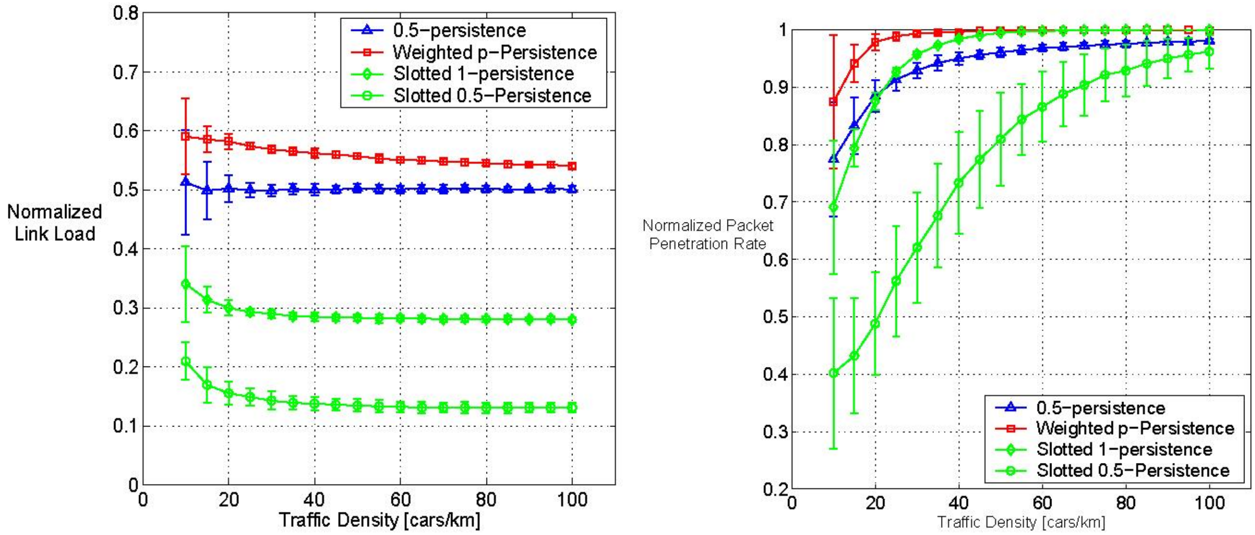
2) Link Load: The link load measures the amount of broadcast traffic received at each node over a unit time. Obviously, the higher the load, the lower the useful throughput. Figure 5(a) shows the link load, normalized with respect to the link load measured from the 1-persistence case, at different network densities for all the techniques mentioned in Section IV. Intuitively, the link load depends on the number of retransmitting nodes, e.g., if every node decides to retransmit, as in the 1-persistence case, then a high link load is expected. The p-persistence is introduced in order to reduce the number of nodes required to re-forward the broadcast packets. Typically, given the re-forwarding probability **p**, the number of packets received at each node, on average, will be reduced by a factor of **1-p**.

Besides lowering the re-forwarding probability, one can further reduce the load by partitioning the network into multiple broadcast regions as in the slotted cases. By doing so, nodes in the farthest broadcast region retransmit with high probability while the closer ones are refrained from retransmitting. As a result, the link load is reduced dramatically when the slotted scheme is employed.

3) Packet Penetration Rate: According to the results presented in Section V-A.2, it can be observed that the smaller the re-forwarding probability, the better the performance in terms of the link load. However, the re-forwarding probability also affects the rate at which the packet propagates across the network, i.e., the packet penetration rate. In a typical route discovery case where the source seeks to establish a route to a known destination, this metric also affects the route acquisition time, i.e., the faster the packet penetration rate the faster the route acquisition time. For certain applications such as on-the-road emergency warning system, for example, this rate determines how fast the warning message travels across the network.

Figure 5(b) shows the packet penetration rate normalized with respect to the rate achieved by the conventional 1-persistence scheme. It can be observed that both the slotted 1-persistence and the weighted p-persistence can achieve an excellent performance since the farthest node in the broadcaster's coverage retransmits with probability one or close to one. The slotted 1-persistence, on the other hand, performs poorly in a sparse network because of the waiting delay prior to retransmitting the packet. However, the normalized rate converges to one if on average there are at least 50 vehicles per kilometer.

As for the p-persistence case, the achievable performance depends on the pre-assigned probability parameter **p**. Intuitively, the smaller the probability, the lower the link load. However, small probability may also result in poor packet penetration rate in a sparse network. Therefore, setting the forwarding probability to a certain fixed value without the knowledge of the network topology might not yield an optimal performance. According to the simulation results, not shown in this paper due to space limitation, it can be observed that there is almost no benefit from using the re-forwarding probability in



(a) Normalized Link Load

(b) Normalized Packet Penetration Rate

Fig. 5. Normalized Link load and packet penetration rate performance measured from a single-lane network with random traffic distribution. All results are shown with 95% confidence intervals.

a very light traffic condition as in the 10 nodes/km case, which corresponds to when each node has approximately 9 neighbors in the network considered. However, at higher traffic density the re-forwarding probability should be set to at least 0.5 in the p-persistence case and 0.8 in the slotted p-persistence case in order to achieve at least 80% of the maximum performance.

B 2-Dimensional Square Network

For simplicity, we first consider a simple grid topology where each node has exactly four nearest neighbors at a distance D with the spatial density $\rho = \sqrt{1/D^2}$. In the following, we show simulation results for a grid network where the four nearest neighbors are 100 meters away and the transmission range considered is 500 meters.

Figure 6 shows the link load comparison of four different broadcast techniques normalized with respect to the link load measured from the 1-persistence broadcast case. Similar to the results in the 1-D case, the slotted 1-persistence scheme seems to offer the best performance since it can reduce the overhead traffic substantially, i.e., the routing overhead is reduced by a factor of **1-p** in the p-persistence case and close to 70% in the slotted 1-persistence case. Although decreasing the reforwarding probability **p** implies lower link load, it has an adverse effect on the penetration rate, as shown in Figure 7. Observe that despite the superb performance in terms of mitigating link load, both slotted and non-slotted p-persistence schemes lead to poor performance when **p** is low. Hence, in order to achieve an optimal performance, a protocol may require additional network topology information such as the spatial density to determine a proper reforwarding probability. For example, in a particular network considered with ρ = 0.01, **p** should be 0.3-0.4 in order to suppress at least 60% of the broadcast redundancy while maintaining an acceptable level of packet peneration rate.

On the other hand, the penetration rate achieved by the slotted 1-persistence and the weighted p-persistence schemes

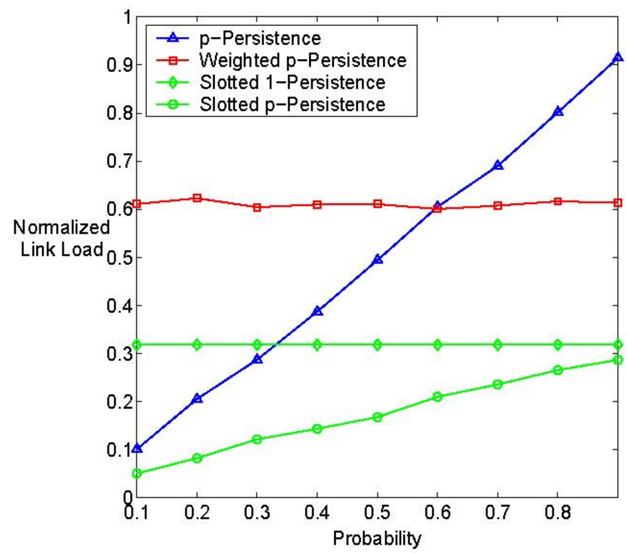


Fig. 6. 2-dimensional network: Link load normalized with respect to the link load in the 1-persistence case.

match that of the 1-persistence scheme. One should note that this is due to the regularity of the grid topology, i.e., the probability of having a node who will transmit with probability 1 as soon as it receives the broadcast packet is a deterministic value, which depends on the transmission range, node density, and the number of slots considered. For a particular network considered, for example, there is always at least one node who does not have to wait before retransmission in the slotted 1-persistence case and there are always nodes with reforwarding probability set to 100% in the weighted-persistence case. If one were to consider a random topology, the performance would deteriorate slightly at low probabilities, e.g., to lower than 50%.

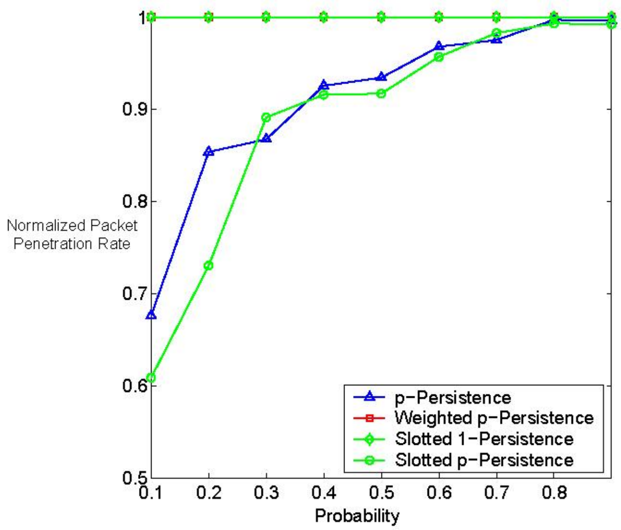


Fig. 7. 2-dimensional network: Packet penetration rate normalized with respect to the rate measured in the 1-persistence case.

VI Packet Loss Ratio and Delay Analysis and Discussion

In the previous section, we have shown that significant improvement in terms of link load and packet penetration rate can be achieved by using the proposed broadcast suppression schemes. However, in order to quantify how much each scheme can alleviate the impact of the broadcast storm, it is important to translate these metrics into more meaningful ones, i.e., packet loss ratio and the total end-to-end delay. In general, high link load causes high contention at the link layer and, hence, high packet loss rate. Similarly, low packet penetration rate also implies long delay. Therefore, in order to create a realistic broadcast storm scenario for collecting these statistics, we resort to OPNET simulator.

In order to mimic the link layer contention, we configure the wireless node in OPNET to use IEEE 802.11a protocol with 10 MHz bandwidth so that the range is approximately 1 km. AODV routing protocol is modified to handle special broadcast packet by adding a node's location in the routing packet header. Upon receiving the broadcast packet, each node accesses its current location and uses one of the broadcast rules described in Section IV to determine whether or not the packet should be rebroadcast. For example, if the weighted p-persistence is chosen, each node will simply calculate the re-forwarding probability based on Eqn. (1).

Because it is possible to receive multiple broadcast packets with the same ID, each node has to wait for a period of WAIT_TIME to allow for some or all duplicate broadcast packets sent by other relay nodes to arrive, where WAIT_TIME is longer than the sum of processing delay, MAC delay, and propagation delay. This WAIT_TIME is also a common parameter across the three schemes proposed since each node has to use its relative distance to the nearest node who has previously rebroadcast the packet to determine its forwarding probability or time slot before transmission. Assume that the processing delay at each node is much smaller than the MAC delay. The WAIT_TIME has to be greater than most of the MAC delay experienced by all of the nodes in the network so that each node has a chance to receive most of the duplicate broadcast packets. According to the MAC delay statistics shown in Table I, the 95^{th} percentile of the MAC delay for the 1-persistence scenario considered in Section III is under 5 ms in most scenarios. These statistics suggest that it is sufficient to choose the WAIT_TIME to be at most 5 ms if the traffic density is below 100 cars/km. Note that in a scenario with more than 100 cars/km, the broadcast suppression mechanisms can virtually reduce the level of the contention and cause the 95^{th} percentile of the MAC delay to be significantly less than the values presented in Table I.

Similarly, the estimated 1-hop delay τ has to account for both the WAIT_TIME and the propagation delay. Given that nodes have to be within 1 km from one another in order to correctly receive the packet, the propagation delay will be negligible compared to the WAIT_TIME. Hence, it is reasonable to assume that τ is approximately equal to WAIT_TIME.

A One Dimensional Highway Network

In the following, we consider 1000 simulation runs of a 10 kilometer road section with random traffic, similar to the scenario considered in Section III. The WAIT_TIME is assumed to be 5 ms and the slot size is approximately 200 m so that there are approximately 5 slots. The forwarding probability is set to 0.5 in the slotted p-persistence scenarios.

1) Packet Loss Ratio: Figure 8 shows the broadcast packet loss ratio at four different traffic densities. Without using any of the suppression schemes, the packet loss ratio is 60% in the worst case. Note that this packet loss ratio in the scenario considered pertains to the loss of the duplicate broadcast packets only, therefore even if half of the broadcast duplicate packets get lost, each node can still receive the broadcast message since not all of them get lost during the broadcast storm. Hence, the reachability of the broadcast message should be satisfactory in all scenarios, i.e., most vehicles should receive the broadcast message with high probility if the network is well-connected. However, as discussed earlier in Section III, this high packet loss rate could pose serious problems to other applications, i.e., any urgent messages transmitted during the broadcast storm may get lost or delayed due to link layer contention and software/hardware resource limitations. By making use of the GPS or RSS information, it is possible to reduce this high loss ratio in the worst case by up to 90%, i.e., from 60% down to about 5% if one uses the slotted p-persistence approach. Notice that these results are highly correlated with the link load results presented in Figure 5(a) in that among the three schemes proposed, the slotted p-persistence yields the best performance while the worst scheme remains to be the weighted p-persistence.

2) Latency: The total end-to-end delay of the proposed schemes, on the other hand, is significantly longer than that in the 1-persistence case especially in a sparse network. As shown in Figure 10, the total delay increases from 15 ms to 90 ms under light traffic conditions with 10 cars/km when the slotted p-persistence is used. The increase in the total delay is partly due to the number of hops chosen by the

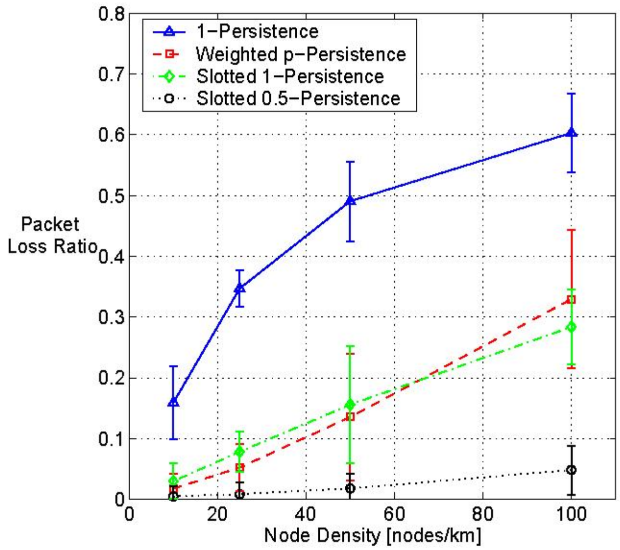


Fig. 8. Packet Loss Ratio on highway at various traffic densities. All results are shown with 95% confidence intervals.

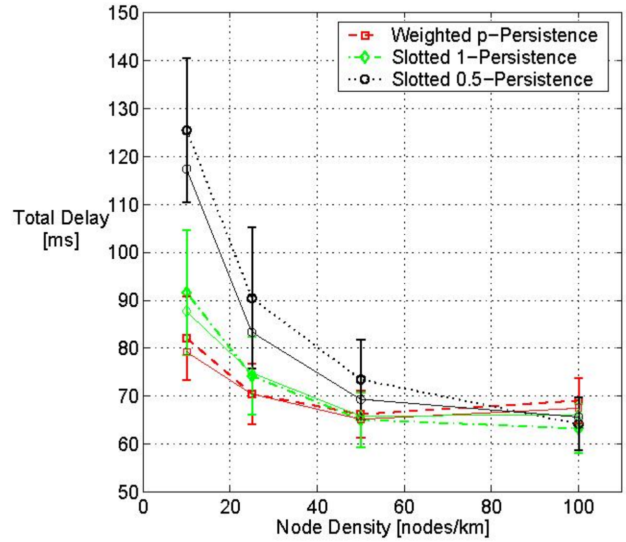


Fig. 10. Time required to disseminate the broadcast message to nodes that are 10 km away. All results are shown with 95% confidence intervals.

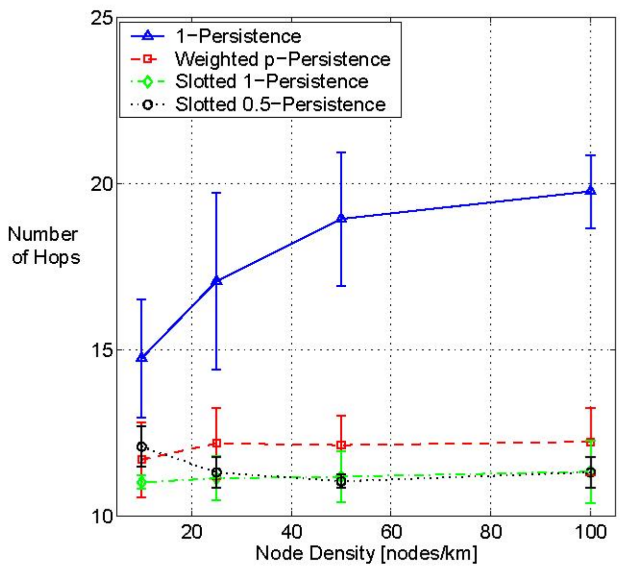


Fig. 9. Number of hop chosen during the route discovery process at various traffic densities on a one-dimensional network. All results are shown with 95% confidence intervals.

routing protocol and mainly due to the scheduling and waiting time of 5 ms required before contending with other nodes for retransmission at each hop. Since the proposed schemes give priority to shortest path route, the number of hops chosen during the route discovery process is almost at the minimum possible value which is roughly 10 hops for the considered scenario, as shown in Figure 9. Observe that traffic density does not have much impact on the number of hops chosen by the routing protocol when one of the broadcast suppression techniques is employed.

Given that the time slot is 5 ms, the total delay is mainly due to the scheduling and the waiting time imposed by the broadcast schemes, i.e., the transmission delay and the propagation delay are much smaller than 5ms. For example, the transmission delay of a packet of size 250 KB is approximately 40 μs and the per hop propagation delay is at most 2 μs. In the following we briefly outline how to approximate the total delay given that we know how many hops it takes to reach the destination.

- *Weighted P-Persistence*: In the weighted p-persistence scheme, each node has to wait for at least τ_w or WAIT_TIME seconds before contending for transmission. If nobody transmits after WAIT_TIME period, then everybody should transmit after 2×WAIT_TIME. Let the number of nodes within a transmission range be $N_R = \rho R$, where ρ is the traffic density in [nodes/km] and R is the transmission range. According to Figure 5(a), at least 40% of the nodes refrain from transmitting. The probability that at least one of the nodes in the transmission range transmits can be expressed as

$$p_1 = 1 - (0.4)^{N_R} . \quad (7)$$

Hence, the probability that nobody transmits is given by $p_0 = 1 - p_1$. Finally, the average end-to-end delay T_{wp} can therefore be approximated as

$$E\left[T_{wp}\right] \approx n_h \times \left[p_1\left(\tau_w + \tau_{proc}\right) + p_0\left(2\tau_w + \tau_{proc}\right)\right] \quad (8)$$

where n_h is the number of hops and τ_{proc} is the processing delay at each hop. A typical value of τ_{proc} ranges from 0 to a few milliseconds depending on how busy a node is. In the simulation, this value is set to be uniformly distributed between 0 and 2 ms.

- *Slotted 1-Persistence*: For this scheme, the end-to-end delay also depends on the number of slots and the network density. Assume that the network is well connected so that there is at least one node within a transmission range of the broadcaster. Let the number of nodes per

TABLE III

COMPARISON OF BROADCAST PROPAGATION STATISTICS IN A BATTLE FIELD

Broadcast Strategies	Route Discovery Delay [ms]	Number of Hops	Total Delay [ms]	Packet Loss Ratio [%]
1-Persistence	22.06	16.00	14.61	85.90
Weighted p-Persistence	30.40	12.22	27.42	80.50
Slotted 1-Persistence	116.61	9.66	113.61	79.30
Slotted p-Persistence	189.62	10.62	186.43	78.33

slot be denoted by $N_{slot} = \rho L$, where L is the length of the slot in km. Assuming that the spacing between two consecutive nodes has an exponential distribution, the probability that there is at least one node in a slot can be expressed as

$$p_1 = 1 - e^{-N_{slot}}. \tag{9}$$

Hence, the probability that there is nobody in a slot is given by $p_0 = 1 - p_1$. Given the number of slots N_s and the τ_w, one can calculate the expected delay per hop, T_h, as follows

$$E[T_h] = \tau_w \times p_1 + 2\tau_w \times p_1(p_0) + \ldots + N_s\tau_w \times p_1(p_0)^{N_s-1}. \tag{10}$$

It can be shown that the expected delay per hop in (10) can be expressed in closed-form as

$$E[T_h] = \tau_w \frac{1 - (N_s+1)\,p_0^{N_s} + N_s p_0^{N_s+1}}{p_1}. \tag{11}$$

Finally, the expected end-to-end delay for the slotted 1-persistence scheme can be given by

$$E[T_{s1p}] = n_h \times (E[T_h] + \tau_{proc}). \tag{12}$$

- *Slotted p-Persistence*: The end-to-end delay for this scheme can also be calculated by using the same approach as that in the slotted 1-persistence case. The only difference is that the number of candidate nodes to rebroadcast the message will be reduced by a factor of (1-p). Hence, instead of (9), the probability that there is at least one node transmitting in any given slot is

$$p_1 = 1 - e^{-pN_{slot}}. \tag{13}$$

The expected total delay given that there is at least one node in the transmission range that transmits can also be calculated using (12) with p_1 and p_0 calculated from (13). However, if nobody transmits during $N_s \times \tau_w$, then the algorithm converges to the slotted 1-persistence case and the expected delay per hop becomes $N_s \times \tau_w$ plus the expected delay in (12). Similar to (7), the probability that nobody in any of the slots transmits is p^{N_R}, where p is the pre-determined forwarding probability.

Figure 10 shows that the analytical results (shown in solid lines) match the simulation results well in most scenarios.

Observe that when using the slotted scheme, the total waiting time at each hop can be longer than 5 ms in a sparse network because there may not be any nodes in the slot with minimum waiting time. As expected, the slotted p-persistence scheme introduces the longest propagation delay due to the uncertainty imposed by the pre-specified forwarding probability. These results also match with the packet penetration rate prediction presented in Figure 5(b).

Despite a much longer total delay, however, the message can still propagate 10 km in less than 150 ms under all schemes. Therefore, as long as the delay is within an acceptable range specified by the applications, the forwarding probability can be decreased or the number of slots can be increased to further improve the packet loss ratio. For peer-to-peer applications, although the proposed schemes introduce a much longer route discovery delay, the quality of the chosen route is expected to be much better since the number of hops chosen by the routing protocol reduces significantly.

B Two Dimensional Battle Field Network

For a two-dimensional battle field network case, we also consider a network similar to that used for the case study in Section III-B. The number of slot size is set to 100 m so that there are approximately 5 slots. The forwarding probability is assumed to be 0.5 in the slotted p-persistence case.

Table III shows the average statistics obtained from 50 simulation runs. Observe that the loss rate does not improve much in a 2-D network scenario, this is probably due to the hidden node terminal problem. However, despite the high loss rate, the proposed schemes were able to force the routing protocol to select a route with fewer hops. Hence, although the proposed schemes may not be suitable for broadcast applications where the content of the packet is typically large, they can definitely be applied to the route discovery process in the existing routing protocols so that RREQ from the shortest path route reaches the destination node with high probability.

VII CONCLUSIONS

Since broadcast transmission is used extensively during the route discovery process and by some applications (especially by the ones that are developed for VANET), the routing protocols should be designed to address the broadcast storm problem to avoid unnecessary loss of urgent data packets during the period of broadcast storm. In this paper, we have proposed three novel techniques which depend only on the local positions of the receiver and the transmitter nodes. The algorithms are completely distributed and computationally efficient in that they require only minor computations. In the absence of the GPS information, it is shown that the proposed algorithms can also be modified to use the RSS of the packet received to determine whether or not the packet should be retransmitted.

The proposed schemes are tested against both one-dimensional highway and a generic 2-dimensional square topologies. The results show that the proposed slotted p-persistence schemes can reduce the broadcast redundancy and packet loss ratio by up to 90% in a highway network while they can still offer an acceptable end-to-end delay for most applications; e.g. using roadside unit to inform drivers about the detour, construction, etc. In a 2-dimensional topology, on the other hand, the proposed schemes do not offer much improvement in terms of packet loss rate, but they can be used to guide the routing protocol to select a route with fewer hops.

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