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ORIGINAL ARTICLE

Analysis and evaluation of distance-to-mean broadcast method for VANET

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Abstract Multi-hop broadcast is a critical component in embedded communication systems. Some vehicular ad-hoc network (VANET) applications in particular use broadcast communications extensively. Statistical broadcast methods offer an efficient means of propagating broadcast messages in this context due to their low overhead and high efficiency.

Currently, five fundamental statistical broadcast methods are known: stochastic, counter, distance, location, and the latest method, distance-to-mean (DTM). Utilizing positional information, the DTM method calculates the spatial mean of the neighbors from which a node has received the message, then finds the distance from the node to that of spatial mean. This distance is used as the variable to discriminate between rebroadcasting and non-rebroadcasting nodes. Simulation results are presented exploring the reachability characteristics of DTM, indicating a behavioral phase transition with respect to decision threshold.

Detailed comparative evaluations of a straightforward protocol built using DTM show it is more efficient than a similar protocol built using the distance method. DTM is also compared to *p*-persistence and is shown to exhibit a higher level of reachability across a broad range of scenarios.

1. Introduction

Wireless broadcast plays an important role in the operation of embedded wireless systems. Research in this area has demonstrated that blindly retransmitting broadcast packets (flooding) can lead to an explosive growth of traffic called the *broadcast storm* problem (Ni et al., 1999), that reduces battery life and attenuates communication performance as a result of collisions and congestion.

Further, emerging classes of embedded systems use broadcast as a primary data delivery mechanism. Vehicular Ad-hoc NETworks (VANETs) are a class of wireless networks in which mobile vehicles communicate with each other in an ad-hoc fashion. VANET applications such as traffic data dissemination use broadcast extensively as the means of

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communication, so solving the broadcast storm problem in an efficient way is critical.

VANETs are one type of mobile ad-hoc network, characterized by high levels of mobility compared to other systems in this class. For any vehicle, its set of neighbors is likely to be continuously changing. On a bi-directional road with vehicles traveling at 20 m/s, two vehicles traveling in opposite directions will only be neighbors for about 10 seconds, assuming a 200 m transmission radius. Mobility patterns like these present special challenges to routing protocols, which often rely on some degree of stability in network topology.

Among multi-hop broadcast routing protocols, many use information pertaining to network neighborhood to make routing decisions. For example, the popular Multi-Point Relaying (MPR) (Qayyum et al., 2002) protocol proactively designates nodes to retransmit broadcast messages by selecting them from a node's 2-hop neighborhood in such a way as to minimize the number of transmissions in that neighborhood while still covering all neighbors. For this and similar methods to work effectively, the currently available local topology needs to be reasonably accurate, a challenge in the context of VANET.

An alternative class of multi-hop broadcast protocols called statistical protocols do not use network neighborhood information to make routing decisions. Instead, these methods use locally measurable quantities which nodes measure and compare to a threshold value in order to decide for themselves to retransmit broadcast messages or not. For example, in the counter method (Ni et al., 1999) nodes use a backoff mechanism to determine how many of its neighbors retransmit a particular broadcast message. If the number is less than a given threshold when the backoff expires, the node proceeds to retransmit the message itself, otherwise it remains silent. Methods such as these are more resilient to the dynamic nature of VANETs, since they rely relatively little on topology.

There are five fundamental methods that fit into the category we call statistical methods: stochastic broadcast, counter method, distance method, location method, and distance-to-mean (DTM) method. The former four have been used to build many protocols including some using a hybridization of these statistical methods with topological methods.

In this work we analyze in detail the newest fundamental method, DTM, initially proposed in Slavik et al. (2011). Like the other four fundamental methods, DTM is a base method on which statistical protocols may be built. As we will argue, DTM is based on the same heuristic as the location method but is simpler to calculate in practice, making it an attractive alternative to the location method in situations where it has been applied.

The remainder of the paper is organized as follows. In Section 2 we discuss related work. Section 3 provides background on statistical broadcasting techniques and gives the context into which DTM is presented. Section 4 describes the DTM method. Section 5.2 presents simulation results of a DTM-based protocol and compares it to existing protocols. Section 6 gives the concluding remarks.

2. Related work

In this paper we present a new fundamental statistical broadcast method specifically targeted for VANET application. The existing fundamental statistical methods: stochastic, counter, distance, and location, are described in Ni et al. (1999). Based on the stochastic broadcast method, several works have addressed threshold adaptivity to density (Cartigny et al., 2002; Li et al., 2005; Bako et al., 2008). Similarly density-adaptive versions of the counter method have been proposed in al Humoud et al. (2008) and Mohammed et al. (2009). Density-adaptive versions of both counter and location methods are given in Tseng et al. (2003). We have proposed the DADCQ protocol, a statistical protocol based on the distance method that is adaptive to node density, distribution pattern, and channel quality in Slavik and Mahgoub (2013).

In the context of multi-hop broadcast for VANET, several techniques have been proposed. Tonguz et al, using a combination of the counter and stochastic methods and distance-biased assessment delay, proposed the *p*-persistence method (Tonguz et al., 2006; Wisitpongphan et al., 2007). A more comprehensive study of these methods in highway scenarios is rolled into a scheme called DV-CAST (Tonguz et al., 2010) and for urban environments into a variant called UV-CAST (Viriyasitavat et al., 2010). *p*-persistence is used as a comparison protocol in this work.

Bako et al adopt a stochastic broadcast method originally proposed in Kyasanur et al. (2006) for VANET (Bako et al., 2008). Notable from this work is the Advanced Adaptive Gossiping (AAG), a hybrid protocol that uses 2-hop topological data to set forwarding probabilities used as in a traditional stochastic broadcast algorithm. Another similar protocol that uses stochastic broadcast in conjunction with 2-hop topological data is the Neighbor Coverage based Probabilistic Rebroadcast (NCPR) protocol (Zhang et al., 2012).

Osafune et al propose MHVB (Osafune et al., 2006) and E-MHVB (Mariyasagayam et al., 2007), which use the distance method with constant threshold value to suppress rebroadcasts. Korkmaz et al propose Urban Multi-hop Broadcast (UMB) (Korkmaz et al., 2007), which is fundamentally unidirectional but does contain provisions for branching at intersections to cover wider areas.

The concept of DTM was briefly introduced in Slavik et al. (2011) and used to design a protocol in Slavik and Mahgoub (2011). This previous work neglected a thorough analysis, evaluation, and comparison of DTM which this paper addresses. This paper contains new discussion of the background protocols, novel analysis and figures related to DTM, and more realistic simulation evaluations and comparisons to similar protocols.

3. Statistical broadcasting methods

As described in the Introduction, statistical broadcasting techniques are those that conform to the following pattern: nodes self-elect whether or not to retransmit a received broadcast and the decision to rebroadcast is made by comparing a locally measured value to a decision threshold. Protocols built on statistical methods contain several components outlined in this section. First we describe in turn the original four fundamental methods that form the background context under which DTM is created: stochastic, counter, distance, and location. These methods are originally described in Ni et al. (1999). Next we describe the statistical threshold value. Finally, we describe the assessment delay algorithm, a process used in most of the fundamental methods to measure the target quantity.

3.1. Stochastic method

The stochastic method, also known as probabilistic broadcast or gossiping, is a simple method in which each node independently and uniformly randomly decides whether or not to retransmit a received broadcast message. The procedure is simple; when a node receives a new broadcast message, it generates a uniform random number S in the interval $[0,1]$ and compares it to a threshold S_t. If $S < S_t$, the message is rebroadcast. Otherwise, the node remains silent.

The chief advantage of this method is its simplicity. The number of nodes rebroadcasting a message is reduced but no external information is needed to accomplish this. Naturally, this leads to its performance being highly dependent on network conditions and the selected value of S_t. If S_t is too small, too few nodes will retransmit to propagate the message. Whether or not S_t is too small depends on external quantities such as node density and channel quality. Practical protocols built using the stochastic method must dynamically set S_t in response to changes in external conditions, undermining the simplicity of the underlying method.

3.2. Counter method

The counter method is based on the heuristic that if many of a node's neighbors are retransmitting a broadcast message, it will likely not improve the overall broadcast propagation by retransmitting the message again itself. To determine how many of its neighbors retransmit, nodes in the counter method use an assessment delay. In assessment delay procedure, nodes backoff some amount of time after receiving a new message, during which time it listens to see if the message will be received again. In the counter method, nodes simply count the number of times the message is received during the backoff in order to count the number of neighbors that so far have retransmitted the message C. When C is small, it is beneficial for the node to rebroadcast in order to keep the broadcast propagation going. More formally, nodes will compare the measured value of C to a given threshold C_t and if $C < C_t$, retransmit the message.

The counter method typically reduces the number of nodes retransmitting more effectively than stochastic broadcast. In exchange for introducing a delay to measure the number of retransmitters, the counter method is able to take external network conditions into account for its rebroadcast decision. This makes the method more resilient to environmental changes but practical protocols built using this method still may dynamically change C_t to improve performance.

3.3. Distance method

Geometrically, if a node has received a broadcast message from another node that is located close to it there will be little additional area covered if it chooses to rebroadcast. The distance method exploits this observation by selecting retransmitting nodes to be those that have not received the broadcast message from another node nearby. To quantify this, a node using the distance method also employs an assessment delay to observe which of its neighbors retransmits the message. Then, using received signal strength or node location information (e.g., shared GPS readings) it finds which of these neighbors is nearest and calculates the distance to that node, called D. If D is larger than the given threshold value D_t, the node will retransmit the message.

The distance method introduces a new requirement that nodes either be able to accurately estimate transmit distances based on received signal strength or that they have positioning sensors. In exchange, the distance method often gains a performance advantage over the counter method and stochastic broadcast.

3.4. Location method

The heuristic underlying the distance method is that each broadcast retransmission in the system should attempt to cover the most additional physical area as possible. The location method addresses this heuristic more directly by using node location to calculate the area covered by previous transmissions and the amount of area that would be covered by potential new transmissions. When a new broadcast message is received, a node using this method first performs an assessment delay to observe the location of other neighbor nodes that also retransmit the message. It then calculates the intersection of transmit areas of those neighbors with its own transmit area. Finally it is able to calculate how much new area would be covered if it were to retransmit, L. If L is greater than a given threshold L_t, the node retransmits.

The location method often is the most efficient of the four fundamental methods in selecting nodes to rebroadcast, but it also has the most strict requirement on node capabilities. Nodes are required to measure their location relative to each other. In the VANET context, however, this requirement is most often met since new vehicles are typically equipped with GPS or similar sensors. Thus high-performing methods such as distance and location are attractive for VANET broadcast applications.

The other disadvantage of the location method is its relative computational complexity. The location method assumes an idealized omni-directional transmission pattern so the transmit area is a circle. Thus to calculate how much area will be gained by retransmitting, nodes must perform the non-trivial calculation of the union of intersections between possibly several pairs of circles. When proposing the method, Ni et al suggest using a grid-filling technique to estimate this area (Ni et al., 1999).

3.5. Threshold function

A key component of statistical broadcast protocols is the decision threshold (S_t,C_t,D_t, and L_t). Because network conditions often affect the optimal value of the threshold, in practical protocols it is typically re-calculated dynamically at each node for broadcast message reception using the most current topological information available to the node. The calculation using current network information such as node density occurs via the threshold function. If the threshold function is too aggressive, messages will not propagate through the network. If it is too conservative, too many nodes will elect to rebroadcast and the protocol will not be efficient (Slavik and Mahgoub, 2013).

3.6. Assessment delay

Each fundamental method except stochastic broadcast uses a delay procedure to measure the target quantity used in the threshold comparison. In the counter method, for example, nodes use a time delay to observe how many neighbors retransmit a message. This procedure is referred to here as an assessment delay. The assessment delay procedure follows this pattern:

(1) When a node receives a message for the first time, calculate a delay time T and set a backoff timer for that time.
(2) If the message is received before the timer expires, process the message, calculate a new delay time, and restart the timer.
(3) When the timer expires with no new messages received, use the fundamental method to make a rebroadcast decision.

There are many ways to determine the delay time T and how it is determined can have a significant impact on protocol performance. The two most common methods are uniform backoff and distance-biased backoff. In uniform backoff, T is chosen uniformly in the range $[0, T_{max}]$. With distance-biased backoff, T is set inversely proportional to the distance d from which the message was received: $T = (1 - d/r)T_{max}$ where r is the maximum expected transmission range.

Many broadcast protocols use a uniform assessment delay, which is also referred to as a Random Assessment Delay (RAD) (Williams and Camp, 2002). The distance-biased assessment delay is used notably in p-persistence (Wisitpongphan et al., 2007), the broadcast method employed by DV-CAST (Tonguz et al., 2010) and UV-CAST (Viriyasitavat et al., 2010), as well as the DTM-based protocol presented in this work.

4. Distance-to-mean method

In this section we describe and analyze the latest statistical method called distance-to-mean (DTM). DTM is related to the distance and location methods by using a similar heuristic, that nodes should favor rebroadcasting when doing so will cover a large amount of physical area that has not been covered by the node's neighbors. The distance method approximates this by using the distance to the nearest neighbor from whom the broadcast message has been received as a proxy for coverage, and the location method uses positional information to estimate the coverage area directly (Slavik et al., 2011).

DTM method estimates coverage by considering the distance from the node to the spatial mean (defined below) of the neighbors from whom the message has been received already. Nodes measure the variable M as the distance to spatial mean of transmitting neighbors. When M is small, it means the neighboring transmitters are distributed evenly around the node, indicating it should favor not rebroadcasting. Fig. 1 illustrates the DTM heuristic for cases when M is small and when M is large. These figures illustrate the correlation between M and additional area covered by rebroadcast.

Positional information is used in the distance-to-mean method to calculate the spatial mean of neighboring nodes. Spatial mean is defined for a set of points (x_i, y_i) as

$$(\bar{x}, \bar{y}) = \left(\frac{1}{n} \sum_{i=1}^{n} x_i, \frac{1}{n} \sum_{i=1}^{n} y_i \right) \tag{1}$$

The DTM variable M is defined as described above for a node positioned at (x,y) and normalized to a value between zero and one by dividing by the maximum expected transmission radius r.

$$M = \frac{1}{r} \sqrt{(x - \bar{x})^2 + (y - \bar{y})^2} \tag{2}$$

The algorithm for the DTM procedure, including assessment delay, is given in Algorithm 1.

Algorithm 1 DTM Procedure

```
Definitions:
$M_t$: DTM threshold value
$r$: Maximum expected transmit radius
if Broadcast message received for the first time

    {Assessment Delay Algorithm}
do
    Record location of sender
    Set assessment delay backoff timer
while Message received again

{DTM Method}
Calculate $M$ according to Eqs. (1) and (2)
if $M > M_t$ then
    Rebroadcast the message
    end if
end if
```

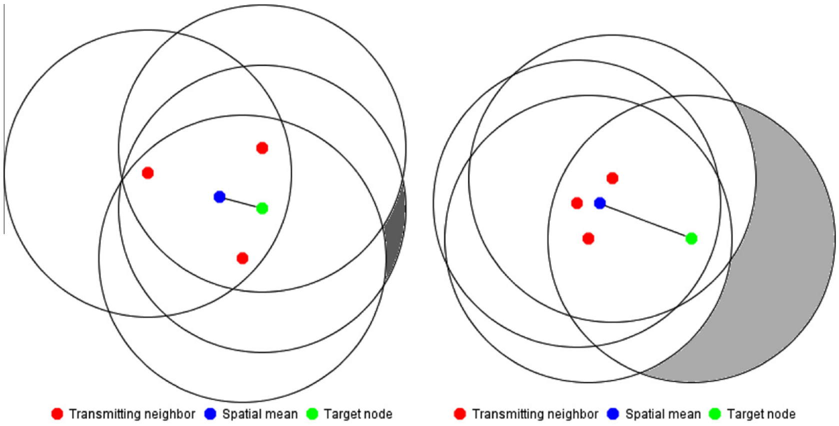
5. Evaluation

5.1. Reachability characteristics

In this section we use WiBDAT, a fast high level multi-hop broadcast simulation tool (Slavik et al., 2011), to examine properties of reachability with DTM in conditions of no mobility and simple disc model of transmission. WiBDAT uses stochastic models to represent fading and collisions so that only the network layer broadcast protocol is simulated directly. This makes the simulator fast and scalable, which is useful here since many simulation runs are required to measure a distribution of reachability. Later in this work we use JiST/SWANS, a detailed wireless network simulator better suited for protocol evaluations. WiBDAT is used for results presented in this section only.

A WiBDAT simulation run places nodes in a field as specified then selects a node near the center to be the source to originate a broadcast. When the broadcast propagation is complete, the simulation ends. To produce the graphs in this section, we set M_t to various fixed values and run WiBDAT simulations with uniform node distribution and no fading.

Reachability here is defined as the fraction of nodes in the network that receive the broadcast message. Fig. 2, originally presented in Slavik and Mahgoub (2011), shows how reachability in DTM varies with the threshold value M_t in these conditions. The results show a behavioral phase transition. In the supercritical phase, reachability is nearly one in all simulation runs. A sharp behavioral change occurs around a critical value



(a) Small M (b) Large M

Figure 1 Illustration of DTM heuristic. Shaded region shows additional area covered by target node retransmitting. DTM method favors rebroadcasting when M is large.

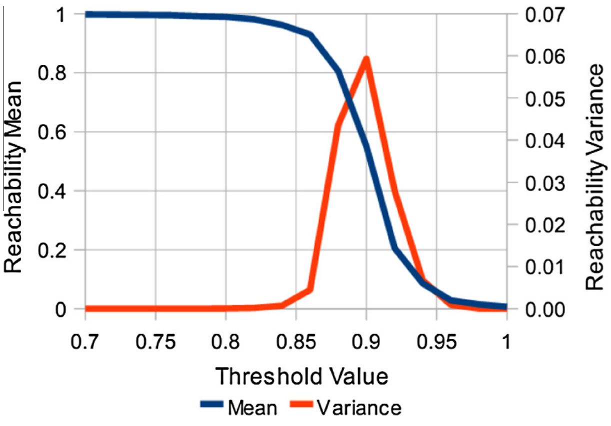


Figure 2 Reachability vs threshold value in the DTM method [Slavik and Mahgoub, 2011].

of M_t, in which reachability quickly transitions from 1 to 0 and the variance of the reachability spikes, indicating the reachability is highly variable from run to run. Above the critical value of M_t, message propagation is severely limited. This graph is produced with node density set to 20 neighbors on average and 100 simulations per threshold value.

Here a lower threshold value implies more nodes rebroadcasting and thus higher wireless bandwidth consumption. Thus a goal for designers using DTM is to operate safely in the supercritical phase while being near enough the transition to provide low wireless bandwidth consumption.

In the supercritical phase, the reachability approaches 100% in all simulation runs. Figs. 3 and 4 show more details of the critical and sub-critical phases (Slavik and Mahgoub, 2011). These graphs are obtained using WiBDAT to aggregate 10,000 simulation runs on a network with node density set to 15 and the distance-to-mean threshold set to *0.9* and *0.95*. The graphs show estimated probability distributions, so the vertical axis is unitless probability density of the random variable reachability on the horizontal axis.

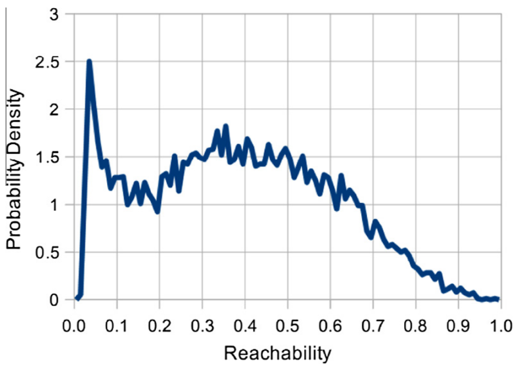


Figure 3 Reachability probability density function, M_t = 0.9 (critical phase) [Slavik and Mahgoub, 2011].

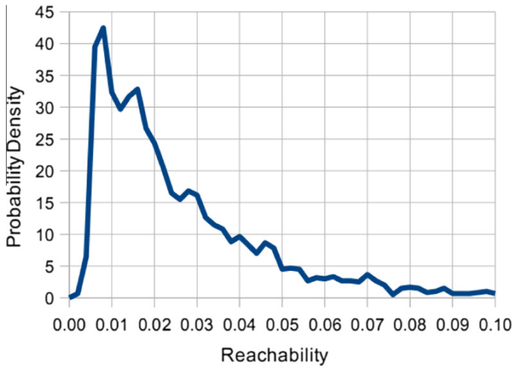


Figure 4 Reachability probability density function, M_t = 0.95 (subcritical phase) [Slavik and Mahgoub, 2011].

5.2. Protocol comparison

In this section we present an evaluation of the performance of DTM with existing protocols. We use the distribution of JiST/SWANS (Barr, 2004) produced by the Ulm University along

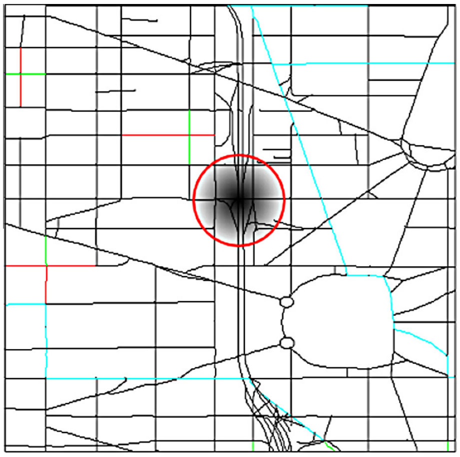


Figure 5 Urban mobility scenario map with overlaid maximum transmission range.

with VanetMobiSim (Fiore et al., 2007), a realistic vehicular mobility generator. We evaluate the protocols under two different mobility scenarios. The first is an urban scenario based on a 2 km square region of Washington, D.C. shown in Fig. 5, built using TIGER data published by the U.S. Census Bureau. The second is a highway scenario that restricts node movements to an 1800m square. Node movement uses Intelligent Driver Model with Lane Changing with a given maximum speed. Mobility traces of these scenarios created with VanetMobiSim are then used by JiST/SWANS to generate node movement.

The network simulation begins with a 60 second warm up period followed by 1000 seconds of broadcast activity. During the active period, a new 128-byte broadcast message is originated about every 1 second by a randomly chosen node. Signal propagation is modeled with two-ray ground propagation with Rician fading. Radio parameters are set to mimic IEEE 802.11p (5.89 GHz, 3 Mbps) (IEEE, 2013) with about 400 m transmission range. JiST/SWANS models both packet collisions and channel fading. Nodes use single-channel 802.11 MAC layer signaling and IPv4 layer 3 addressing.

For this work, we apply DTM in a very straightforward way. We use a fixed threshold value of $M_t = 0.4$ (note that unlike the results in Section 5.1, here we have fading, mobility, and a wider range of node distributions so we must use a more conservative value of M_t to maintain high reachability). The assessment delay method used is distance-biased (as described in Section 3.6) with $T_{max} = 50$ ms.

In comparison, we use a similarly straightforward application of distance method (Dist) and the p-persistence protocol. The distance method protocol uses $D_t = 0.4$ and distance-biased assessment delay with $T_{max} = 50$ ms. p-persistence protocol parameters are set to $p = 0.5$, $N_s = 5$, and $\tau = 5$ ms.

Each protocol is submitted to two sets of tests. In the first, the number of nodes is varied from 250 to 500 in increments of 50, holding the Rician fading parameter K at 10. The second varies K from 0 to 20 in increments of 5 with the number of nodes fixed at 250. Lower values of K indicate more intense fading and thus higher probability of packet loss. These tests are executed on both the urban and highway maps with maximum vehicle speed set to 25 m/s.

Results are presented in Figs. 6–9 with each figure showing two graphs. The first, reachability, shows the average fraction of nodes that receive a broadcast message. The second plot shows the number of bytes sent per node that received the message and is a measure of the efficiency of the protocol.

First compare Dist and DTM. These two protocols are identical except Dist uses the distance method and DTM uses the distance-to-mean method; both use distance-biased assessment delay and a fixed retransmit threshold. In all four sets of results, the two protocols exhibit nearly identical reachability, and both are tuned such that the fixed threshold achieves high reachability in each test. In terms of bytes sent to accomplish that level of reachability, DTM uniformly consumes less wireless bandwidth than Dist. This separation shows the improvement of the DTM fundamental method proposed here over the distance method. In these results, the DTM method is about 20% more efficient than the distance method.

Next compare DTM to the p-persistence protocol. p-persistence is a known high-performing broadcast protocol for VANET so sets a good benchmark for broadcast protocols in VANET. p-persistence is a very efficient protocol and its performance quality shows in these results as well. However DTM keeps pace with p-persistence in terms of bytes sent per covered node, with each one having the advantage in different circumstances. The weakness of p-persistence is in reachability, particular in the highway scenario. In this respect DTM is clearly superior, delivering high reachability in all scenarios where p-persistence does not. Thus overall, DTM is the only protocol in these tests to provide high levels of reachability along with minimal levels of bandwidth consumption.

The weakest scenarios for both DTM and Dist are when fading is intense (K is small). Both these protocols use fixed threshold values (M_t and D_t). A clear improvement would be for the threshold value to adapt to fading so that performance

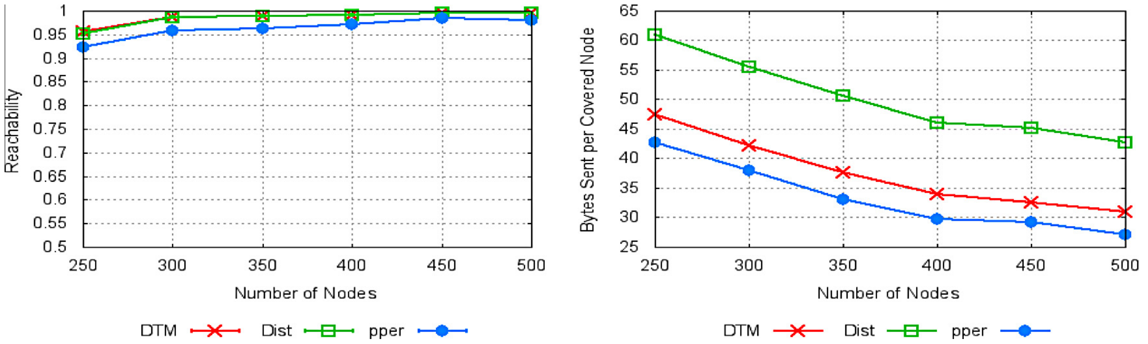


Figure 6 Performance vs number of nodes in the urban scenario.

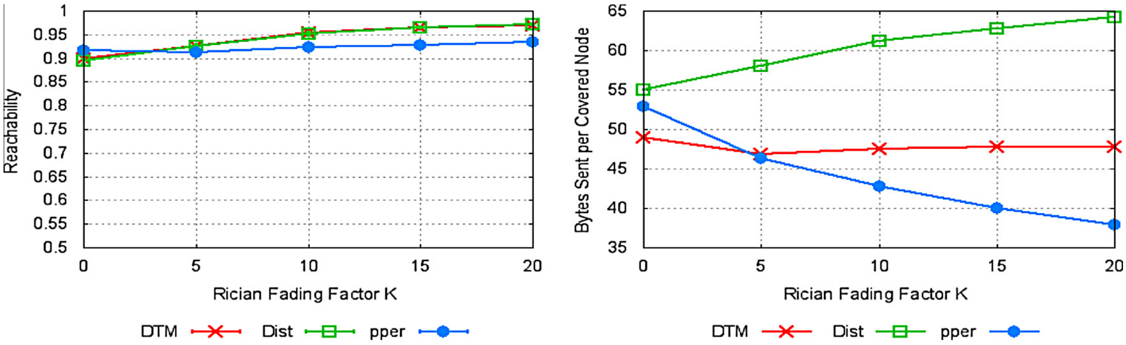


Figure 7 Performance vs fading intensity in the urban scenario.

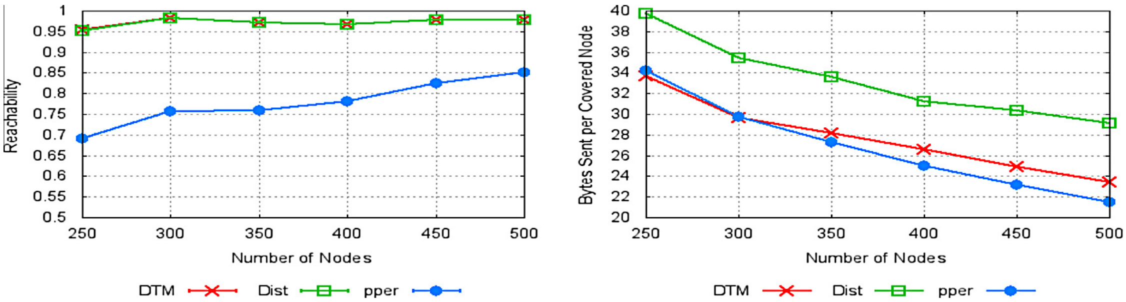


Figure 8 Performance vs number of nodes in the highway scenario.

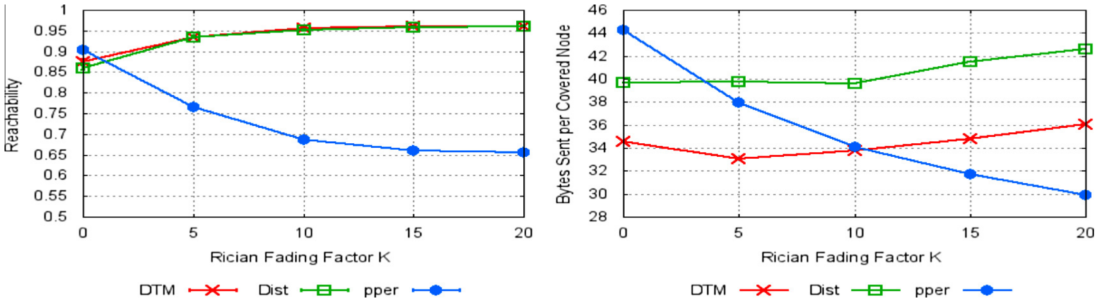


Figure 9 Performance vs fading intensity in the highway scenario.

is compensated in these scenarios (Slavik and Mahgoub, 2013). In this work it is desirable to present a protocol based on the DTM method in a straightforward way, but future work could likely increase performance by adding threshold value adaptivity.

6. Conclusion

We have presented new analysis, evaluations, and comparisons of the fundamental statistical method for multi-hop broadcast in VANET called distance-to-mean. This method first uses an assessment delay to observe neighbors that retransmit a given broadcast message. Utilizing positional information, it calculates the spatial mean of these neighbors then finds the distance from the receiving node to that spatial mean. When this distance is large, the node will cover a larger amount of additional area by rebroadcasting than when that distance is small. Thus the DTM method sets a threshold value such that any node that measures this distance to be greater than the threshold will retransmit the message.

Simulation results are presented showing the reachability characteristics of the DTM method. DTM exhibits a behavioral phase transition with respect to the decision threshold. When the threshold is set too high, the system quickly degenerates such that broadcast messages do not propagate through the system. Results are presented showing the distribution of reachability in both the critical and subcritical phases of this behavior.

Finally, evaluation results are then presented comparing the performance of the DTM method with the distance method and with the *p*-persistence protocol. The protocols are compared in a broad range of scenarios spanning various node densities and fading intensity on both urban and highway mobility patterns. Unlike *p*-persistence, DTM gives high levels of reachability across all simulation scenarios. Compared to the distance method, DTM offers about 20% less bandwidth consumption on average.

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