Effects of Location Uncertainty on Position-Based Broadcast Protocols in Inter-Vehicle Communication Systems

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***Abstract*— Inter-Vehicle Communication (IVC) systems are envisioned as the primary means to enable intelligent transportation systems and to increase vehicle traffic safety. Majority of applications envisioned for IVC systems rely on broadcast dissemination of information in the application area. Several broadcast protocols proposed for IVC systems utilize position information to optimize the system performance. However, errors in positioning systems may adversely affect the performance of such protocols. In this paper, we study the effects of position uncertainty on different IVC broadcast protocols. Our position uncertainty model accounts for correlated as well as uncorrelated errors of GPS receivers in urban settings. Our simulation results show that negative effects of position errors are minimized when they are used to calculate relative distances for nodes.**

I. INTRODUCTION

Inter-Vehicle Communication (IVC) systems are envisioned as the primary means to enable intelligent transportation systems and to increase vehicle traffic safety. Federal Communications Commission (FCC) allocated Dedicated Short-Range Communication spectrum for IVC at 5.9GHz to increase traveler safety, reduce fuel consumption and pollution, and continue to advance the nations economy [1]. The US Department of Transportation (USDOT) sponsored standard process under ASTM voted to base DSRC on IEEE 802.11a [2]. However, the suitability of IEEE 802.11a for vehicular networks is still an important research question. The results of the simulations using IEEE 802.11a protocol show that it is worth doing further research on communication designs that might utilize the channel more efficiently even for single hop broadcast [3].

The topology and the node movement of vehicular networks are constrained by roads. The resulting communication network is a special type of Mobile Ad-Hoc Network (MANET) where the mobility rate is high but movement direction and speeds are predictable. In MANETs, blind flooding is the first approach to achieve broadcasting since it does not require local or global topology information. However, it has been shown in [4] that serious redundancy, contention, and collision problems occur as a result of flooding. Although [4] proposes techniques to improve blind flooding, they are not effective for all ranges of node densities and packet loads. This is an important issue for IVC applications since both node density and packet load fluctuate significantly in vehicular networks.

Using vehicle positions in MAC layer protocols is a potential technique that can improve broadcasting performance in vehicular networks. In [5],[6], methods to eliminate redundant packets while broadcasting is proposed using the topology information. However, in an IVC network, the large number of vehicles and high mobility make such proactive approaches impractical [7]. In [7], the IEEE 802.11 protocol is adapted for broadcasting in IVC systems by employing a distance based waiting approach before retransmissions. Although this approach distributes the highly correlated rebroadcast times, problems such as hidden nodes, collisions at high packet traffic rates, reliability, and broadcast storms still persist. To address the shortcomings of flooding based protocols, Urban Multi-hop Broadcast protocol (UMB) [8] is proposed. UMB is a broadcast protocol specifically designed for vehicular networks with infrastructure support. In UMB, sender nodes attempt to select the furthest node in the broadcast direction to assign the functions of forwarding and acknowledging the packet without any apriori topology information i.e., senders select the furthest node without knowing the ID or position of their neighbors. The UMB protocol broadcasts packets at intersections with the help of repeaters, where buildings obstruct the line-of-sight between road segments incident to an intersection.

Vehicle position acquisition is primarily performed via satellite-based positioning systems. Such systems are preferred over alternatives due to their global coverage and relative low cost of receivers with respect to vehicles. Currently, two existing positioning systems, GPS and GLONASS, are operational. Such systems exhibit important shortcomings in positioning accuracy, especially in urban canyons where signals from satellites are obstructed by tall buildings. With the addition of other error sources, such as atmospheric and multipath effects, satellite-based positioning systems can produce errors in the order of tens of meters. Since the majority of applications in IVC systems are safety-related, the use of position-based broadcast protocols for such applications are questioned. Despite valid concerns of vendors and research community, to the best of our knowledge, there is no study that confirms or denies the suitability of position-based broadcast protocols in IVC systems.

In this paper, we investigate the effects of GPS errors in position-based MAC layer broadcast protocols. We evaluate the positioning error effects only from MAC layer's point of view, and defer the study of effects of such errors on application accuracy to our future work. To model the high correlation between position errors experienced by the vehicles, we propose a method to generate correlated GPS errors for simulations. We show through simulations that position based MAC layer protocols that use relative positions do not experience a serious problem due to GPS errors. Furthermore, we confirm that our position based UMB protocol outperforms flooding based protocols under GPS errors as well as in error-free environments.

II. DISTANCE BASED MULTIHOP BTOADCAST PROTOCOLS FOR IVCS

In this section, we provide the outlines of two distance based multihop broadcast protocols: UMB [8] and 802.11-distance [7].

A. UMB

UMB is an efficient IEEE 802.11 based Urban Multihop Broadcast protocol for inter-vehicular networks with infrastructure support whose details can be found in [8]. Unlike flooding based broadcast protocols, UMB assigns the function of forwarding and acknowledging the packet to only the furthest node without any apriori topology information. At the intersections where the communication among incident road segments are blocked by buildings, UMB employs repeaters installed at intersections to forward the packet to all road segments. We assume that each vehicle is equipped with a GPS receiver and an electronic road map. Since the vehicle mobility is high and vehicles leave and enter the network frequently, the topology of this network changes fast. Therefore, the UMB protocol is designed to operate without exchanging location information among neighboring nodes.

1) Directional Broadcast:

a) RTB/CTB Handshake: To mitigate the hidden node problem while minimizing the overhead, sender vehicles engage in RTS/CTS like handshake with only one of the recipients among the sender's neighbors. To pick this vehicle, the protocol divides the road portion inside the transmission range into segments. If there is more than one node in the furthest non-empty segment, this segment is divided iteratively into subsegments with smaller widths. If these segment based iterations are not sufficient to pick only one node, the nodes in the last sub-segment enter to a random phase.

First Request to Broadcast (RTB) attempt: When the nodes in the direction of the dissemination receive the first RTB packet, they compute their distance to the source node. Based on this distance, they send an energy burst (channel jamming signal) called *black-burst* which is used to select the furthest node. The length of the black-burst signals are directly proportional to the vehicles' distance to the source. The duration of the black-burst signal in the first iteration is computed as, $L_1 = \lfloor d \cdot \frac{N_{max}}{R} \rfloor \cdot SlotTime$, where L_1 is the black-burst duration in the first iteration, d is the distance between the source and the vehicle, R is the transmission range, N_{max} is the number of segments created, and $SlotTime$ is the length of one slot. As a result of this computation, the furthest node sends the longest black-burst.

Collision among CTB packets: When there is more than one vehicle in the furthest non-empty segment, they all find the channel empty after sending their black-bursts and send CTB packets. However, since all vehicles start sending the CTB packets at the same time, their CTB packets will collide. When the source node detects a transmission but cannot decode the CTB packet, it detects the collision and repeats the RTB packet. This time, only the nodes which have sent CTB packets join the collision resolution. To pick only one node, the furthest non-empty segment is divided into N_{max} sub-segments. This process continues iteratively until a successful CTB packet is received by the source or D_{max} iterations are completed

b) Transmission of DATA and ACK: After receiving a successful CTB, the source node sends its broadcast packet. In this broadcast packet, the source node includes the ID of the node which has successfully sent the CTB. This node is now responsible for forwarding the broadcast packet and sending an ACK to the source.

2) Intersection Broadcast: When a node is selected to forward a packet and it is outside the transmission range of a repeater, it continues with the directional broadcast protocol as described in Section II-A.1. On the other hand, if the node is inside the transmission range of a repeater, the node sends the packet directly to the repeater using the point-to-point IEEE 802.11 protocol. As a result of GPS errors, a vehicle may still continue directional broadcast even when it is inside the transmission range of a repeater. This condition will not harm the protocol operation since when a repeater hears RTB packet, it sends the longest black-burst and wins the contention to send the CTB packet.

B. Distance Based Flooding

In addition to UMB, we evaluate GPS errors on two more MAC layer protocols. In this paper, we will refer to these protocols as *802.11-distance* and *802.11-random*. They are flooding based modifications of IEEE 802.11 standard which route packets without the network topology information or any neighborhood knowledge. They try to avoid collisions among rebroadcast packets by forcing vehicles to wait before forwarding the packet. According to these protocols, every node must rebroadcast every distinct packet they receive once.

The first protocol, 802.11-distance, employs the idea proposed in [7], where the waiting time of the vehicles is inversely proportional to their distance from the source. The waiting time WT is computed as follows:

$$WT = (-\lfloor \frac{\hat{d}}{Range} * maxSlot \rfloor + maxSlot) * SlotTime, \quad (1)$$

where $maxSlot$ is the maximum possible number of slots a node waits before forwarding the packet. This waiting time aims the furthest node to broadcasts the packet first. As in IEEE 802.11 standard, nodes decrease their waiting time counters when they find the channel empty and freeze them when the channel is busy. System proposed in [7] computes the waiting time continuously, however in 802.11-distance implementation, waiting times are discrete since all waiting times are computed as multiples of $SlotTime$ in IEEE 802.11 standard.

The second protocol, 802.11-random is not a distance based protocol but it is very similar to 802.11-distance. In this protocol, when a node receives a broadcast packet, it will wait for a random duration (WT) before forwarding the packet.

$$WT = nSlots * SlotTime, \quad (2)$$

where $nSlot$ is random number between [0,$maxSlot$].

TABLE I

GPS ERROR REPORTED FOR NOVEMBER 1, 2005 (50^{th} PERCENTILE, ROOT MEAN SQUARE AND 95^{th} PERCENTILE STATISTICS) [9]

	Position Error
50%	2.51 m
RMS	3.11 m
95%	5.33 m

III. GPS ERRORS

Although the errors are expected to be smaller after Galileo Positioning System becomes operational, current global positioning systems are not error free. Table I presents GPS errors reported by the GPS Operations Center, which reports daily GPS error statistics. The important sources of the GPS error are:

- Ephemeris data: Errors in the transmitted location of the satellite.
- Satellite clock: Errors in the transmitter clock.
- Ionosphere: Errors caused by ionosphere effects.
- Troposphere: Errors caused by troposphere effects.
- Multipath: Errors caused by reflected signals entering the receiver antenna.
- Receiver: Errors in the receiver's measurements caused by thermal noise and software accuracy.
- Shadowing: Errors caused by tall buildings, trees, etc.

A. Correlation (ρ_{ij}) and Covariance Matrix (C_e)

In VANET environment, GPS errors experienced by the vehicles are correlated because the error components such as satellite clock, ephemeris data,shadowing, and atmospheric effects are the same in a few hundred miles. To incorporate the correlation in modeling GPS errors, we generate a random error vector (E_i) for each vehicle i satisfying a predetermined covariance matrix C_e. The correlation between two vectors is expressed using a standardized form of covariance between E_i and E_j which is called the correlation coefficient (ρ_{ij}). While constructing C_e, we will assume that $\rho_{ij} = \rho$ for all vehicle pairs:

$$\rho_{ij} = \begin{cases} \rho & i \neq j \\ 1 & i = j \end{cases} \quad (3)$$

Once correlation coefficient is determined, the covariance matrix C_e for a given standard deviation σ can be constructed as:

$$C_e = \begin{pmatrix} \sigma^2 & \rho\sigma^2 & \dots \\ \rho\sigma^2 & \sigma^2 & \dots \\ \vdots & \vdots & \ddots \end{pmatrix} \tag{4}$$

B. Generating Error Vectors (E_i)

E_i vectors satisfying C_e given in Eq. 4 can be generated as follows:

1) For K vehicles, generate K independent vectors from normal distribution N(0,1) and insert them to rows of matrix $X = [X_1 X_2 \dots X_K]^T$. Since these vectors are generated independently, the correlation coefficient between them is 0. Moreover, if the vectors are long enough, their variances become approximately equal to 1. As a result, the covariance matrix C_x between the rows of X becomes:

$$C_x = \begin{pmatrix} 1 & 0 & 0 & \dots \\ 0 & 1 & 0 & \dots \\ 0 & 0 & 1 & \dots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} = I \tag{5}$$

2) In multivariate normal random variables, the linear transformation of original random variables produce a new set of variables whose covariance matrix ($C^{'}$) becomes

$$C^{'} = L C_x L^T \tag{6}$$

where L is the linear transformation matrix in operation $E = LX$.
We use this property of multivariate normal random variables to generate a set of error vectors. Since the covariance matrix (C_x) in step 1 is I, the result of linear transformation gives.

$$C^{'} = LIL^T = LL^T \tag{7}$$

3) Using Eq. 7, we can find the appropriate transformation matrix L which transforms C_x to C_e ($C_e = LL^T$). Note that C_e is our target covariance matrix and it can be decomposed into a lower (L) and upper triangular (L^T) matrices using Cholesky's factorization if it is positive semidefinite.
4) Once the linear transformation matrix L is obtained in step 3, multiply matrix X with L to obtain correlated GPS error vectors (E_i).

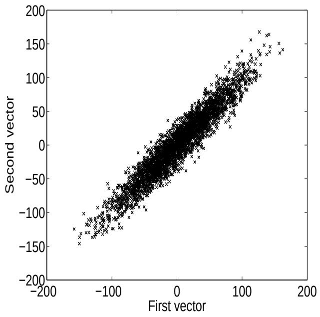

Fig. 1. Correlated $\rho = 0.95$

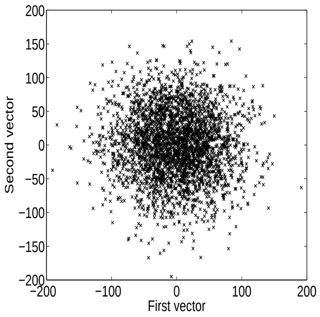

Fig. 2. Uncorrelated

$$\begin{pmatrix} E_1 \\ E_2 \\ E_3 \\ \vdots \end{pmatrix} = \begin{pmatrix} L_{11}X_1 + L_{12}X_2 + L_{13}X_3 & \dots \\ L_{21}X_1 + L_{22}X_2 + L_{23}X_3 & \dots \\ L_{31}X_1 + L_{32}X_2 + L_{33}X_3 & \dots \\ \vdots & \ddots \end{pmatrix} \tag{8}$$

C. Example

In this section, we generate two random error vectors whose correlation coefficient ρ_{ij} is 0.95 and the standard deviation is 50 m. Our target covariance matrix is

$$C_e = \begin{pmatrix} 50^2 & 0.95 \cdot 50^2 \\ 0.95 \cdot 50^2 & 50^2 \end{pmatrix} = \begin{pmatrix} 2500 & 2375 \\ 2375 & 2500 \end{pmatrix} \tag{9}$$

As a result of steps described in Section III-B, we obtained vectors whose correlation (Σ) and covariance (C) matrices are as follows:

$$\Sigma = \begin{pmatrix} 1 & 0.9528 \\ 0.9528 & 1 \end{pmatrix}, C = \begin{pmatrix} 2491.7 & 2371.7 \\ 2371.7 & 2506.9 \end{pmatrix} \tag{10}$$

Figure 1 shows the obtained vectors with $\rho = 0.95$. The effect of correlation can be observed by comparing this figure with Figure 2 which shows uncorrelated vectors with the same variance.

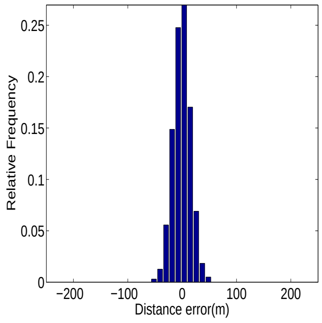

Fig. 3. Distance error - Correlated Position Errors $\rho = 0.95$

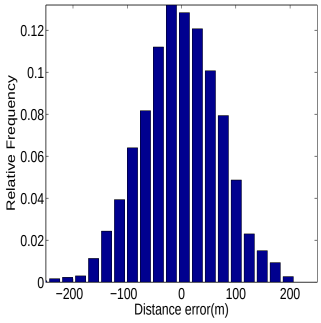

Fig. 4. Distance error - Uncorrelated Position Errors

D. *Correlated vs. Uncorrelated Errors*

The uncorrelated errors have a larger impact than the correlated errors in protocols where the relative positions are used instead of absolute positions. UMB and 802.11-distance protocols use relative vehicle positions in protocol operation. In these protocols, waiting or black-bursting is done based on the distance between two vehicles that is computed by subtracting the destination vehicle's position from the source vehicle's position. When the errors are correlated, this substraction cancels some portion of GPS errors. Mathematically, it is subtracting one random variable from the other ($D = X - Y$). The variance of the new random variable D depends on the correlation between X and Y. If the correlation coefficient ρ is zero, the variance of D (σ_D^2) becomes

$$\sigma_D^2 = \sigma_X^2 + \sigma_Y^2 \tag{11}$$

where σ_X^2 and σ_Y^2 are the variances of X and Y, respectively. On the other hand if there is correlation between X and Y, the variance of D is smaller by $\rho \cdot \sigma_X \cdot \sigma_Y$. As a result, the variance of D becomes

$$\sigma_D^2 = \sigma_X^2 + \sigma_Y^2 - 2 \cdot \rho \cdot \sigma_X \cdot \sigma_Y \tag{12}$$

Figure 3 and 4 show the relative frequency distribution of distance errors due to uncorrelated and correlated position errors for $\sigma = 50m$. It can be observed that the correlated errors cause much less spread than uncorrelated errors. As a result, when the position errors are uncorrelated, the standard deviation of distance errors ($\sigma_{correlated} = 70.71$) becomes even larger than the standard deviation of position errors. On the other hand, when the position errors are correlated, the standard deviation of the distance error ($\sigma_{correlated} = 15.81$) becomes much smaller than the standard deviation of position errors.

IV. PERFORMANCE EVALUATION

A. *Simulator*

In order to evaluate the performance of the system, we have developed the Wireless Simulator (WS), which is based on an event driven simulation library CSIM [10]. WS models the MAC layer and the physical layer of the wireless network. The vehicle movement and the road structure is simulated by a separate simulator written in MATLAB.

B. *Simulation Parameters*

The simulated road structure (Figure 5) includes one intersection with 1000 m road segments. Each road segment contains two lanes, one for each direction of traffic flow. The vehicles are randomly placed on road segments with exponentially distributed interspaces. For the sake of simplicity, lane changes, turns and overtaking is not modeled for vehicle movement. Each vehicle is assigned a speed from a Gaussian distribution with mean 40 km/h and standard deviation 5 km/h at the beginning of simulation and this speed remains constant during the simulation. We have done simulations for high (50 veh/lane/km) and low (10 veh/lane/km) vehicle densities.

Uncorrelated and correlated GPS error vectors for each vehicle are generated using the method described in Section III with 50 m standard deviation. To generate uncorrelated vectors, the correlation coefficient is set to 0 and to generate correlated vectors, the correlation coefficient is set to 0.95. We assumed that the errors experienced by the vehicles are same for 100 ms. Note that it is not expected to get more than 10 position samples per second from the GPS equipment.

The common parameters of the simulator are summarized in Table II. Other parameters of the MAC layer and the physical layer are taken from the ASTM E2213-02 standard document [11]. The UMB protocol is simulated with the following parameters: N_{max} =10, D_{max} =5.

C. *Performance Metrics*

Three metrics have been defined to observe the effect of GPS errors on the protocol performance:

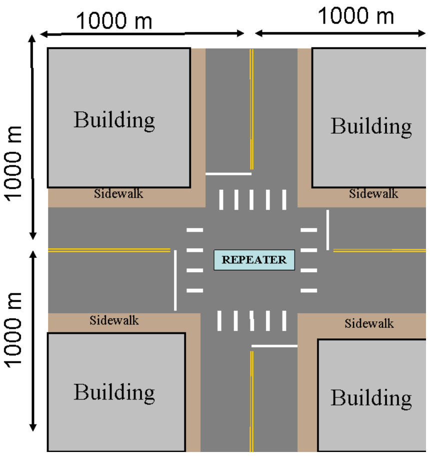

Fig. 5. Road Structure: one intersection, 2000 m x 2000 m

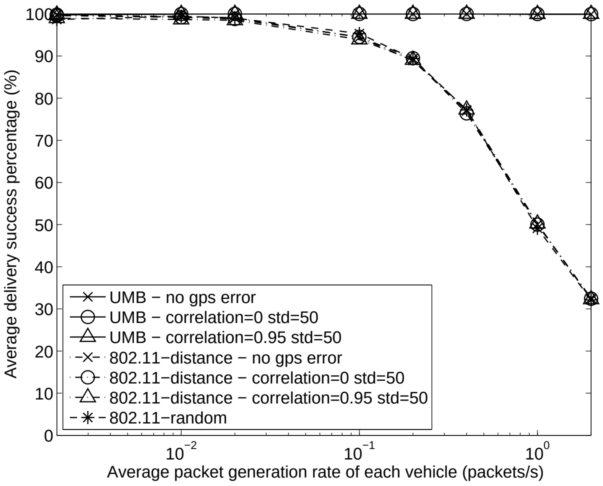

Fig. 6. Successful Packet Delivery Percentage (low vehicle density)

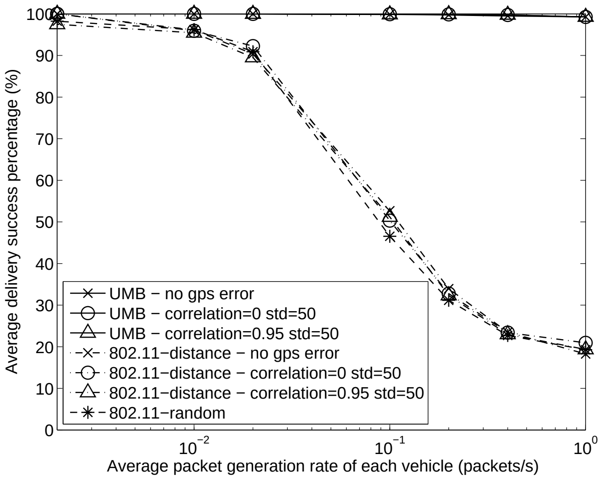

Fig. 7. Successful Packet Delivery Percentage (high vehicle density)

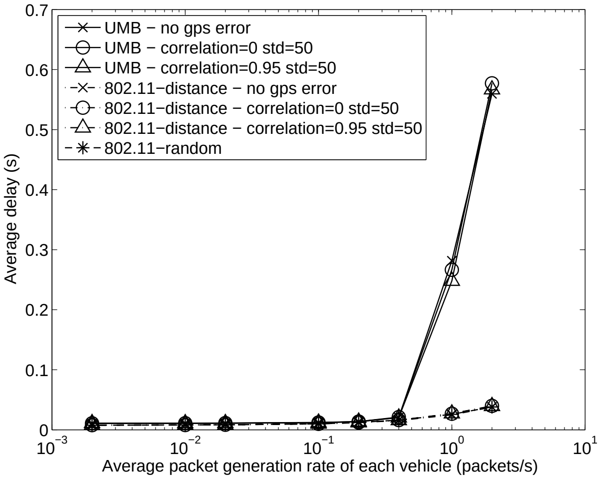

Fig. 8. Delay (low vehicle density)

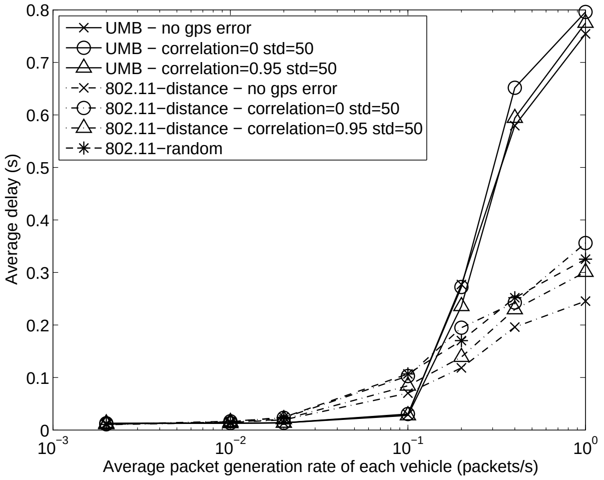

Fig. 9. Delay (high vehicle density)

TABLE II

PARAMETERS OF THE SIMULATOR

description	value
transmission range	350 m
data rate	3 Mbps
frame body	500 bytes
base protocol	802.11p
$maxSlot$	32
simulation time ($simtime$)	40 s
simulation repetitions	30

1) *Success Percentage*: Success Percentage of a packet is the ratio of the cars that receive the broadcast packet to the total number of cars. When the average success percentage is lower than 100%, it means that the broadcast packets were not received by all vehicles.
2) *Delay*: $Delay$ refers to the time elapsed between the instant the packet enters the source queue and the reception time of the packet by another node.
3) *Load Generated per Broadcast Packet* is the total number of bits transmitted to disseminate a packet to the whole network. In order to compute the average load, we divide the total number of bits sent by the total number of broadcast packets generated during simulation. This metric gives the total traffic generated by one broadcast packet in the network. Note that small values correspond to efficient usage of the channel. When a packet is lost, it can reach only some part of the network and it generates a smaller load compared to a packet that

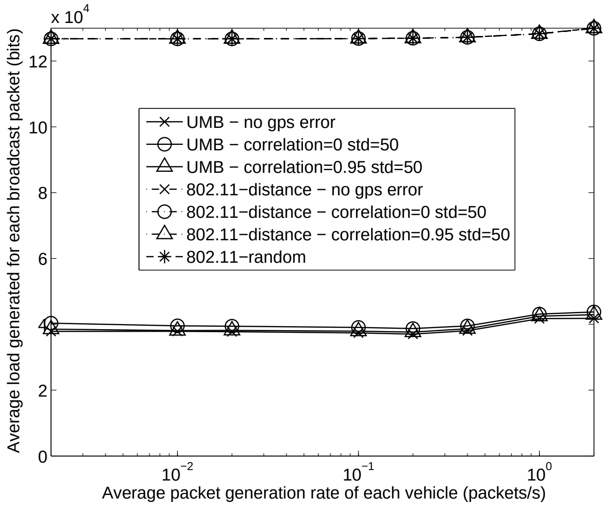

Fig. 10. Load Generated per Broadcast Packet (low vehicle density)

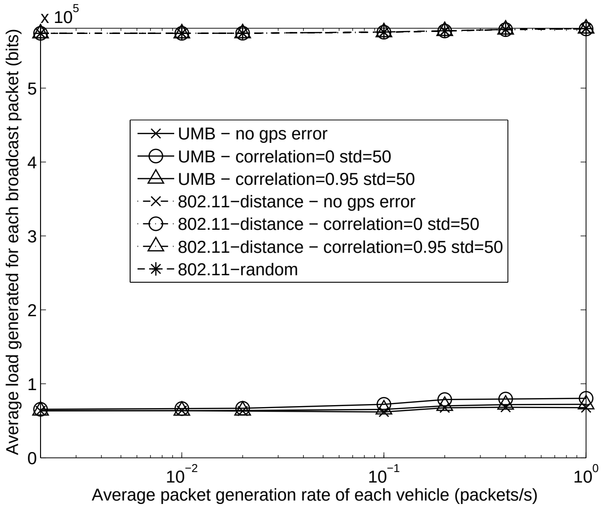

Fig. 11. Load Generated per Broadcast Packet (high vehicle density)

reaches all nodes. For fair comparison, we divide the load generated by the $SuccessPercentage$ and define a normalized metric for *the average load generated per broadcast packet*. We have observed that this normalized metric is approximately constant for all packet generation rates.

D. Results

1) Successful Packet Delivery Percentage: Figure 6 and Figure 7 depict the average success percentage when the vehicle density is 10 veh/lane/km and 50 veh/lane/km, respectively. Figures show that GPS errors do not have a significant effect on packet delivery percentage. In UMB, the protocol may fail to select the furthest vehicle due to GPS errors; however, this new vehicle still behaves like the furthest vehicle and forwards the packet after acknowledging the source. As a result, since the packet is not forwarded by the furthest vehicle, it travels less distance in every hop but it continues its dissemination.

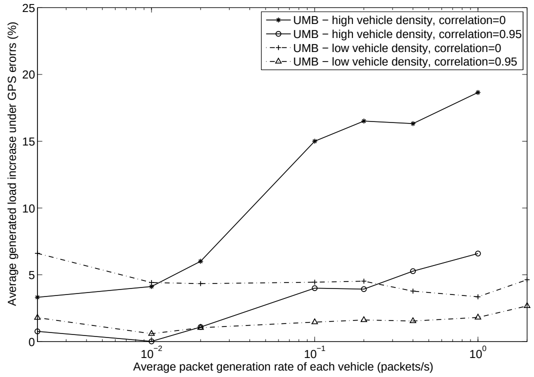

Fig. 12. Load percentage increase in UMB under GPS errors

Similarly, 802.11-distance is not significantly effected by GPS errors because it is a flooding based protocol and the GPS errors only effects the timing of rebroadcasts. In error free protocol operation of 802.11-distance, distance based waiting is used to avoid collisions among rebroadcast packets of the same source. However, when other broadcast packets exist in the system, the broadcast packets may still collide; therefore, distance based waiting will behave similar to the random waiting even in error free operation. Introducing GPS errors makes the distance based waiting more close to random waiting.

Both of these figures show that our UMB protocol achieves approximately 100% successful packet delivery. When the packet generation rate is increased, we observe only a slight decrease ($\approx 1\%$) in the success rate of UMB. 802.11-distance and 802.11-random protocols perform poorly because of packet collisions due to hidden nodes and the lack of the acknowledgment mechanism. The successful packet delivery performance of the 802.11-distance and 802.11-random is worse when the vehicle density is high. This performance decrease is because of the increase in the unnecessary rebroadcasts due to the higher number of vehicles. When the number of vehicles is increased, overall packet generation rate of the system also increases.

2) Delay: Figures 8 and 9 show the average delay of three protocols under different GPS errors. It can be observed that the delay of all three protocols increase as the load is increased. At high loads, the UMB protocol's delay is higher than the 802.11-distance and 802.11-random protocols' delay. However, recall that the successful packet delivery percentage of flooding based protocols are extremely low at high loads as discussed in Section IV-D.1. Since 802.11-distance and 802.11-random cannot disseminate the packets to all parts of the network, their queueing delays are low.

In the UMB and 802.11-distance protocols, GPS errors increase the delay especially at high vehicle densities. In UMB, delay increases because a closer vehicle may forward the packet instead of the furthest vehicle. As a result packets travels less distance than they would travel in error free operation in each hop. In 802.11-distance, the furthest vehicle may rebroadcast the packet after some delay since a closer vehicle may send it before. Figure 9 show that, uncorrelated errors cause higher delay especially at high loads as predicted in Section III-D.

3) Load Generated per Broadcast Packet: Figures 10 and 11 show the normalized average load generated per broadcast packet. This metric includes all rebroadcast and control packets to disseminate the information to the whole network. In both figures, it is observed that the UMB protocol generates less load than 802.11-distance and 802.11-random protocols because the UMB protocol assigns the function of forwarding the broadcast packet to only one vehicle while flooding based protocols assign this function to every vehicle. As the packet load increases, the packets of the 802.11-random and 802.11-distance protocols start to collide and their success percentage decreases. Since the packets do not reach some parts of the network, the load generated per packet becomes lower. However when we normalize the average load by dividing it by the success percentage, we observe that this normalized values are almost constant at all rates.

In flooding based protocols, no control packets are used and the number of rebroadcast packets depends on the number of nodes in the network. As a result, the GPS errors do not affect the load generated in 802.11-distance protocol. On the other hand, errors increase the load generated in the UMB protocol and the impact is larger when the errors are uncorrelated as shown in Figure 12. Figure 12 shows the load percentage increase of UMB under GPS errors. This figure is a different representation of the same data presented in Figures 10 and 11 to provide a zoom-in view of the load increase. Note that the absolute load increase of UMB protocol in Figures 10 and 11 is very small when compared with the load generated by the flooding based protocols. Due to GPS errors, instead of the furthest vehicle, a vehicle closer to the source vehicle can be chosen in the UMB protocol. Consequently, more number of forwarding should be performed to deliver the packet to the whole network.

V. CONCLUSIONS

In this paper, we investigate the effects of GPS errors on position based MAC layer protocols for IVC systems. Our position uncertainty model accounts for correlated as well as uncorrelated errors of GPS receivers. It is shown through simulations that MAC layer protocols that use relative positions do not experience important changes in successfully delivery of messages under GPS errors. As in error-free scenarios, our position based UMB protocol outperforms other flooding based protocols. The GPS errors increase the load generated to disseminate the information in UMB protocol. However, this increase is around 5% when the errors are correlated.

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