Analysis of Reliabilities under Different Path Loss Models in Urban/Sub-urban Vehicular Networks

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***Abstract*—This paper studies the impact of propagation path losses in urban/sub-urban vehicular networks. The impact has been analyzed considering both the network-layer and application-layer reliabilities. We have built a realistic vehicular simulation environment and performed an extensive simulation experiment in a semi-urban traffic environment. The results show that there are significant performance differences between LOS (Line-of-Sight)/OLOS (Obstructed-LOS)/NLOS (Non-LOS) path loss model and any other studied loss model. With a moderate communication distance between a transmitter and a receiver (300 m), while with the other existing loss models the network-level reliability is around 60%, with the LOS/OLOS/NLOS model that falls below 30%. Moreover, the application-level reliability of LOS/OLOS/NLOS model is not more than 55% for the delay sensitive safety application.**

I. Introduction

The rapid growth of metropolitan areas has exacerbated traffic congestion and accidents. In the US, the DOT's NHTSA [1] documents roughly 35,000 fatalities and nearly 4 million injuries on roadways on an annual basis and estimates the annual economic loss to exceed $836 billion [2]. In addition, drivers spend billions of unproductive hours waiting in traffic and consume 3.1 billion gallons of fuel every year [3]. Connected and automated vehicle (CAV) technologies are poised to alleviate these economic losses and save lives. DOT estimates that about 82% of accidents involving unimpaired drivers can be addressed by the successful deployment of connected vehicle (CV) technology [4]. Given the ubiquitous connectivity in nearly every aspect of modern society, there are now worldwide efforts from public and private stakeholders to come together and provide vehicles and road-side infrastructure with communication capabilities. In this paper, we focus on the performance analysis and improvement for connected vehicles under realistic propagation loss environments.

DSRC (Dedicated Short Range Communication), also known as Wireless Access in Vehicular Environment (WAVE), supports both V2V and V2I communications. WAVE includes IEEE 1609.1∼0.4 standards and SAE J2735 message set dictionary and the emerging J2945.1 communication minimum performance requirement [5]. The periodically broadcast safety messages (also called heartbeat message), such as Cooperative Awareness Message (CAM) [6] or Basic Safety Message (BSM) [4], bears the vehicle's instantaneous maneuvering information, such as, location, speed, heading, acceleration, deceleration etc. A vehicle with the on-board Global Navigation Satellite System (GNSS)-based devices (e.g., GPS device), transmits and receives the safety messages. Upon receiving safety messages from neighbor vehicles, using CVSS (Cooperative Vehicle Safety System) application [7], a vehicle can generate neighborhood map and warn and display the safe maneuver instructions to the driver audibly/visually.

Due to the high expense of test bed deployment and pre/post experimental validation, a realistic simulation platform is still of high interest [8]–[10]. Although a significant number of vehicular researches assumes perfect physical layer and ignore the propagation losses [11], radio signal could be attenuated by the obstacles (e.g., buildings, trees, big vehicles etc.) between the two connected vehicles [8], [12]. In this paper, we study the V2V communication performance under different path loss models.

Although packet delivery ratio (PDR) is a commonly used performance metric in vehicular research [6], PDR is not adequate to reflect the true system performance measurement in CVSS (Cooperative Vehicular Safety System) applications. The CVSS application has the memoryless property [13]; where the current received packet is enough to provide the updated maneuver information of other vehicles. To measure real-world driver-level experience, application-level performance metrics are often used, such as T-window reliability [8], [13] and application-level latency metric [9]. *For a given Tx-Rx pair and communication range, T-window reliability can be defined as the probability that at least one packet has been successfully received within a predefined time-frame/window (application dependent).* For example, receiving one packet per second from a 'stationary vehicle' may be sufficient for nearby/approaching vehicles to take alternative actions for avoiding a collision. In contrast, for a successful 'lane changing' application, more packets per second may need to be received. The objective of this work is to analyze how bad the application-level reliability is under a realistic traffic environment and how to improve it.

There is no self-supporting simulator which can perform the network traffic and CVSS application simulation together. However, there are efforts to combine different simulators together for realizing the V2X (Vehicle-to-Everything) applications [14]. In this work, we have built an integrated simulator environment for measuring and improving the performance of CVSS application. Our integrated simulator consists of ns-3

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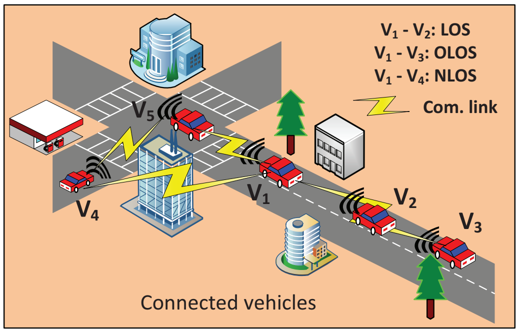


Fig. 1. System architecture of connected vehicular networks.

(Network Simulator-3) [15], PTV VISSIM [16] and MATLAB COM (Component Object Model) for facilitating real-time communication between ns-3 and VISSIM for performing safety application simulation.

In summary, we have the following contributions in this paper,

1) We have studied the network-level reliability (PDR) and application-level reliability (T-window reliability) for V2V communication in urban/sub-urban environments under different path loss models.
2) We have built an integrated simulation environment, and have performed an extensive simulation study with a realistic traffic situation in a traffic environment in the neighborhood of CU-ICAR (Clemson University-International Center for Automotive Research).

The reminder of this paper is organized as follows. System architecture, path loss and fading models, research challenges, and reliability metrics are described in Section II. Section III describes the simulation setup and performance evaluation. Finally, Section IV concludes this paper.

II. System Model

A. System Architecture

Fig. 1 shows the typical architecture of connected vehicular networks. According to DSRC standard, safety messages (BSM) are periodically (commonly at 10 Hz) broadcast through the control channel (CCH) [6]. The nature of the communication link between two vehicles depends on the locations of the vehicles and the presence of obstacles between the vehicles. Based on the position and nature of obstacles, the communication link between two vehicles can be LOS (Line-of-sight), OLOS (Obstructed-LOS) or NLOS (Non-LOS). Hence, the received signal strength depends on the type of communication links, the distance between a Tx-Rx pair, and the type of underlying communication loss model. A typical system architecture is shown in Fig. 1, where, the communication link between each pair of vehicles might be different. For instance, V_1-V_2 is LOS, on the other hand V_1-V_3 (obstructed by V_2) is OLOS and V_1-V_4 (obstructed by building) is NLOS. We want to study the network-level and application-level reliabilities of CVSS applications under such scenarios.

B. Path loss and fading

In the urban/suburban vehicular network, significant radio signal attenuation might occur due to the distance, multipath signal fading, and shadowing [8], as distance between Tx-Rx varies with time and signal may propagate through the obstacle(s). The vehicular communication models that do not consider realistic road topologies and obstacles, may lead to inconsistent results.

Ray-tracing can accurately capture the effect of obstacles, however, the approach suffers from high computational cost [12]. As an alternative, stochastic models such as Rician, Rayleigh, Nakagami-m models can be used to characterize the wireless channel. However, as stochastic models do not consider the obstacle geometry, they diverge from the realistic communication behavior [8], [12]. Hence, Sommer et al. [12] proposed an empirically verified method to capture the effect of obstacle shadowing in vehicular networks. In our path loss analysis, the following generalized equation is used in computing receive power $P_{Rx}(d)$ at the receiver,

$$P_{Rx}(d) = P_{Tx} + G - \sum PL(d)$$

where, d is the distance between transmitter Tx and receiver Rx; P_{Tx} is the transmit power; G is the antenna gain. $PL(d)$ is the path loss component due to large-scale fading, deterministic obstacle shadowing, and/or of stochastic fast/slow fading.

The path loss models are generally classified into the following three different categories:

1) Abstract propagation loss models: We study the abstract loss model as a benchmark loss model. An abstract propagation loss model is not a realistic loss model, as it does not consider the distance between the transmitter and receiver or the geometry of the propagation environment. We consider the Random propagation loss model as a representative abstract propagation loss model. We use the Normal distribution to implement the Random propagation loss model. The probability density function of the Normal distribution is,

$$f(x|\mu,\sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{1}$$

where, μ is the mean and σ^2 is the variance. μ and σ are set to 40 dB and 25 dB [17], respectively for generating the random loss between a Tx-Rx pair.

2) Stochastic fading models: Stochastic fading models calculate the small scale fading for the set of rays transmitted in a Tx-Rx pair via different paths. We use Nakagami-m fading model. The Nakagami-m fading model, which is a special case of Gamma distribution, determines signal power reception probabilistically dependent on model parameters m and Ω. The pdf is,

$$f(r|m,\Omega) = \frac{2m^m}{\Gamma(m)\Omega^m} r^{2m-1} e^{\{\frac{-mr^2}{\Omega}\}}, r \geq 0$$

where m is the Nakagami parameter (i.e., shape parameter with the constraint $m > 1/2$), $\Gamma(m)$ is the gamma function and Ω is the average power of multipath scatter field, which controls the distribution spread, $\Omega = E[r^2]$. When $m = 1$, Nakagami reduces to Rayleigh distribution [18].

3) Deterministic path loss models: A number of empirical path loss models have been proposed for studying propagation loss in different scenarios [17]. We have studied the following deterministic path loss models.

a) Friis propagation loss model: The Friis propagation loss model calculates quadratic path loss that occurs in the free space. The path loss in Friis model for Tx-Rx distance d is,

$$PL(d) = 10 \times \log_{10}\left(\left(\frac{4 \times \pi \times d \times f}{c}\right)^2\right)$$

where, f is the frequency, which is set at 5.9 GHz and c is the speed of light in vacuum (3×10^8 m/s). We plug Nakagami-m fast fading model on the Friis propagation loss model for realizing realistic loss in the vehicular environment.

b) LOS/OLOS/NLOS empirical path loss model: The commonly used piecewise-linear dual-slope loss model is used for calculating LOS/OLOS path loss. Accordingly, with path loss exponent n_1 power decays until breakpoint distance (d_b), and from then power decays with path loss exponent n_2 and standard deviation σ_2. Hence, the path loss for distance d between a Tx and a Rx, due to LOS/OLOS model is [9],

$$PL(d) = \begin{cases} PL(d_0) + 10n_1 \log_{10}\frac{d}{d_0} + X_{\sigma_1}, & \text{if } d \leq d_b \\ PL(d_0) + 10n_1 \log_{10}\frac{d_b}{d_0} + 10n_2 \log_{10}\frac{d}{d_b} + X_{\sigma_2}, & \text{if } d > d_b \end{cases} \quad (2)$$

TABLE I
PARAMETERS FOR LOS/OLOS PATH LOSS MODEL

Model	n_1	n_2	σ_1	σ_2	$PL(d_0)$
LOS	1.17	4.3	7.5	5.09	65.36
OLOS	0.57	3.89	5.24	6.43	74.7

where, $PL(d_0)$ is the measured path loss at a reference distance d_0 in dB; d is the distance between Tx and Rx, which is extracted from the received BSM packet. The fading component, X_σ is a zero-mean Gaussian distributed random variable with standard deviation σ. n_1 and n_2 are the path loss exponents estimated by linear regression. We use n_1, n_2, X_{σ_1}, X_{σ_2} values fitted from field test data [19]. The reference distance (d_0) and breakpoint distance (d_b) are set to 10 m and 200 m, respectively. Table I summarizes the fitted values for LOS/OLOS model.

Overall path loss using LOS/OLOS at receiver of distance d is calculated as follows,

$$\begin{aligned} PL_{LOS/OLOS}(d) = {} & Prob(LOS|d) \times PL_{LOS}(d) \\ & + Prob(OLOS|d) \times PL_{OLOS}(d) \end{aligned} \quad (3)$$

where, $Prob(LOS|d)$ and $Prob(OLOS|d)$ are the probabilities of LOS and OLOS components, respectively. $Prob(LOS|d)$ and $Prob(OLOS|d)$ are calculated using the following exponential equations,

$$Prob(LOS|d) = 1.12e^{-0.0067d} \quad (4)$$

$$Prob(OLOS|d) = 1 - Prob(LOS|d) \quad (5)$$

When d is short, there is less chance that there is an obstacle in Tx-Rx communication link, hence the probability of being LOS increases. In contrast, increasing d increases the chance of obstacle(s) in Tx-Rx communication link caused by other vehicles or road curvature. This increases the chance of being OLOS.

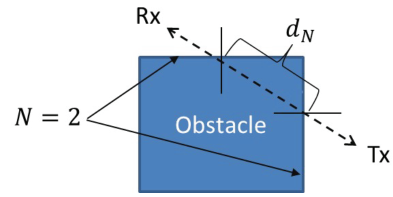


Fig. 2. Path loss due to obstacle.

For realizing the NLOS communication loss, Sommer et al. [12] proposed an approximated method validated by the empirical results. For implementing this method, we use 2-D object maps and draw a ray between a Tx and Rx. Then we calculate how many walls are penetrated by the ray and how much distance is traveled through the walls. By using the CGAL (Computational Geometry Algorithms Library) feature [20], we have implemented that by adding code in ns-3. Hence, path loss due to NLOS is computed by,

$$PL_{NLOS}(d) = \alpha \times N + \beta \times d_N \quad (6)$$

where, N counts the number of penetrated wall through the obstacles, and d_N measures the penetrated distance through the obstacles by the drawn ray from Tx to Rx. Coefficient α and β are the attenuation per wall (dB), and the attenuation per meter travel distance (dB/m). α and β values are set based on the respectively, type of construction wall (e.g., brick, mortar etc.), and type of buildings (e.g., houses, garages etc.). For instance, Fig. 2 shows an instance of NLOS path loss scenario due to an obstacle. Hence, the overall path loss captured by the LOS/OLOS/NLOS model is,

$$PL_{LOS/OLOS/NLOS}(d) = PL_{LOS/OLOS}(d) + PL_{NLOS}(d) \quad (7)$$

C. Research challenges

Some research works show that the presence of building obstacle(s) in Tx-Rx communication link could degrade the network-level performance (e.g., PDR) significantly [8], [12]. However, note that the application-level reliability is the driver's perceived measurement metric. Intuitively, the application-reliability even could be satisfactory with lower PDR, unless there is serious consecutive packet losses, Hence, we are interested in studying the performance for reliability metrics in CVSS applications under a realistic path loss model.

D. Reliability metrics

1) Network-level reliability metrics: We adopt the following metrics for measuring the network-level reliability.

a) Packet Delivery Ratio (PDR): It is the widely accepted metric for measuring the network-level reliability. PDR is defined as the ratio of the number of actually received packets to number of expected received packets for a given communication range.

b) Per received packet latency (PRPL): PRPL is the average duration of receiving a packet from its generation. PRPL only considers the received packets in latency calculation.

c) Expected per-packet Latency (EPPL): For comparing system performance among the models in terms of latency, considering only successfully received packets is not a fair performance metric [9], hence we consider the latency both for received packets and dropped packets. In terms of a received packet, the latency is the duration from generating a packet to its reception at the receiver. In terms of a dropped packet, latency is equivalent to the packet generation interval. With the 10 Hz broadcast frequency, the lifetime of a packet is 100 msec. Hence, the average expected per-packet latency (EPPL) is,

$$EPPL = \frac{N_{rcv} \times PRPL + N_{drop} \times 100}{N_{rcv} + N_{drop}}$$

where, N_{rcv} is the number of received packets and N_{drop} is the number of dropped packets.

2) Application-level reliability: Network-level reliability metric alone do not truly measure the driver's perceived experience. The sporadic one or two packets losses may not be experienced by the driver, as the recent received packet may be enough to get the updated state of the vehicle. For measuring the application-level reliability we study the following reliability metrics.

a) T-window reliability: For a given Tx-Rx pair and communication range, T-window reliability is defined as the probability that at least one packet has been successfully received within a predefined time-frame/window (application dependent). The end user application may not experience any undesired effect, if a receiver vehicle successfully receives at least one packet within the tolerance time-window (T-window). A time instance is called reliable if at least one packet is received within the T-window time, otherwise, that instance is called unreliable. Hence, an average T-window reliability of an application is calculated as the ratio of number of reliable instances to the total number of instances as follows,

$$\text{T-window-reliability} = \frac{n_{rl}}{n_{rl} + n_{url}}$$

where, n_{rl} is the number of reliable instances and n_{url} is the number of unreliable instances.

The typical CVSS applications based on the tolerable time window (T-window) and the Tx-Rx distance requirement are categorized into several groups [13]. The major CVSS applications fall in the following four categories: SVA (Stop/Slow Vehicle Ahead) advisor, EEBL (Emergency Electronic Brake Light) advisor, FCW (Forward Collision Warning), and LCA (Lane Change Advisor). In this work, we will maintain T-window limit in $[0.1 - 1.0\ sec]$, and vary the Tx-Rx distance in the range $100 \sim 1000\ m$. A lower T-window value means the application is more delay sensitive, such as FCW (typical T-window value is 0.3 sec), on the other hand, a higher T-window value means the application is less delay sensitive, such as SVA (the typical T-window value in such case is 1 sec).

b) Per received instance latency (PRIL): PRIL is defined as the average duration of receiving the first successful packet for specific Tx-Rx pair within T-window time. Note that PRIL only considers the reliable instances.

c) Expected per-instance Latency (EPIL) : EPIL measures the average expected duration from generating a packet to the time the first successful received packet at the receiver for a given Tx-Rx pair within a given T-window. In the EPIL calculation, both reliable and unreliable instances are considered. Hence, the average EPIL is calculated as follows,

$$EPIL = \frac{n_{rl} \times PRIL + n_{url} \times \text{T-window}}{n_{rl} + n_{url}}$$

III. Performance Evaluation

A. Simulation model

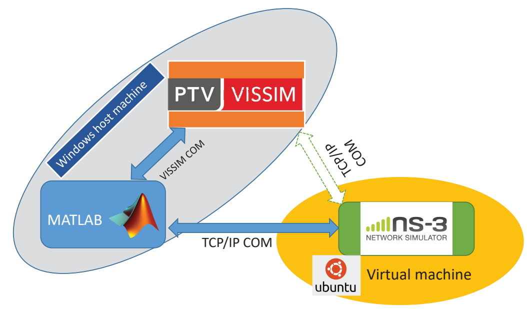


Fig. 3. Simulation setup.

Fig. 4. A portion of vehicular traffic simulation with PTV VISSIM at the neighborhood of CU-ICAR.

TABLE II
NS-3 SIMULATION PARAMETERS

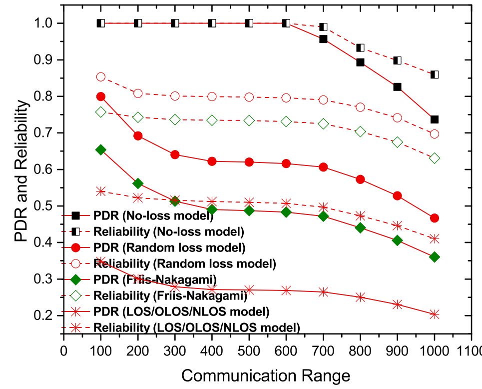
Parameter	Value
Number of vehicles	60
Safety message size	500 bytes
Transmission rate	10 Hz
Carrier frequency	5.9 GHz
Channel bandwidth	10 MHz
Channel access	802.11p OCB
Data rate	6 Mbps
Transmit power (P_{Tx})	23 dB
Mobility model	Waypoint mobility model
Antenna gain (G)	3 dB
VISSIM update rate	0.1 sec
Simulation time	50 sec

The simulation model is based on the system architecture described in Section II-A. Fig. 3 shows the integrated simulator, which consists of PTV VISSIM for traffic simulation [16], ns-3 for discrete-event network simulation [15], MATLAB scripting for setting up traffic parameters in VISSIM through

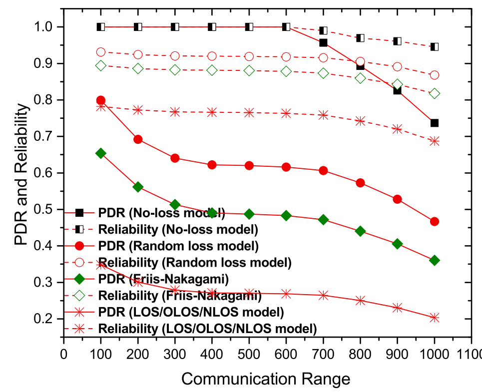
VISSIM COM (Component Object Model) and setting real-time communication with ns-3 and VISSIM via TCP/IP socket API.

The VISSIM COM interface through MATLAB scripting is used to initiate the desired test track network in VISSIM and send and receive traffic parameters/data in VISSIM-MATLAB interface. In every simulation step (100 msec interval), MATLAB sends VISSIM vehicles' position information to ns-3. ns-3 uses waypoint-mobility-model to create and track the vehicle's position and speed. The over 1.5 km long simulation test track network is set consisting the traffic neighborhood of CU-ICAR (Clemson University-International Center for Automotive Research) for simulating realistic traffic behavior. A portion of simulation network is shown in Fig. 4. The simulation area contains buildings, which will be treated as two dimensional polygons obstacles for modeling the obstacle shadowing for LOS/OLOS/NLOS loss model. Using the OpenStreetMap [21] the desired test network (.osm file) is extracted which is then passed through the SUMO *polyconvert* utility [10] for extracting the buildings' footprint. The yielded .xml file will be used as input obstacle file in ns-3. For NLOS modeling with the buildings (Eq. 6), default α and β value are set to 9 dB and 0.4 dB/m, respectively.

Table II shows the explicit parameters used for VISSIM and ns-3 simulations. The justification of the used parameters' values can be found in [3], [4], [8], [9], [13]. The shape parameter m of Nakagami-m is set to 1.5 while Tx-Rx distance is within 80 m, otherwise it is set to 0.75. The default parameters of other loss models are discussed in Section II-B.



(a) With T-window=300 msec.



(b) With T-window=1 sec.

Fig. 5. Impact of path loss model on PDR and reliability.

B. Performance analysis

In this section, we discuss the impact of different types of loss models on the network-level and application-level performance metrics for connected vehicles in urban/sub-urban area. We adopt three different loss models as representatives of different categories loss models discussed in Section II-B. We continued the simulation until 95% confidence interval was achieved.

1) Impact of path loss model on PDR and Reliability: Fig. 5 shows the comparative network-level (PDR) and application-level performance (T-window reliability) of different loss models against no-loss model. For all the models, with the increasing communication distance, both PDR and reliability decline. In the PDR curves, we observe four different trends. With no-loss model, PDR is the maximum. PDR starts dropping only after 600 m communication distance. However, this is not the case, when path loss model is considered. The Random loss model has around 38% more packet drops than no-loss model. PDRs of Friis-Nakgami reside in the middle of Random and LOS/OLOS/NLOS models. The LOS/OLOS/NLOS model has the highest PDR drops. With 400 m communication range, the LOS/OLOS/NLOS model has the 72%, 56%, and 47% lower PDRs than respectively, the no-loss model, the Random loss model, and the Friis-Nakagami model. These results reflect that without considering a realistic a path loss model, the claimed performance is too optimistic. The similar performance trend is also observed for the T-window reliability measurement.

However, with the increasing Tx-Rx distance, though PDRs significantly reduce under the different loss models, the reliability does not decline that much. With the higher T-window values, reliability values are higher. When T-window equals 0.3 sec (Fig. 5a), reliability of the Random loss model is just over 70%. However, other loss models have lower reliability than the Random loss model. The Friis-Nakagami has around 60%, on the other hand, the LOS/OLOS/NLOS model has the lowest reliability (around 50%). For LOS/OLOS/NLOS model, when T-window equals to 1 sec (Fig. 5b), the reliability range is 70-80%, whereas, for T-window=0.3 sec, the range is 40-55% under varying Tx-Rx communication ranges. In summary, with the realistic loss model (such as LOS/OLOS/NLOS), reliability is just over 50% for the communication ranges 100-600 m for the delay sensitive safety application, which is definitely not a satisfactory performance.

2) Impact of path loss model on latency: Fig. 6 shows the required latency both for per received packet and per reliable instance. Clearly, while considering the received packets, the latency is negligible (around 2 msec). However, for received instances, the latency is higher. Under different T-window values, the no-loss model has the lowest latency and the LOS/OLOS/NLOS model has the highest latency. However, the maximum latency with the LOS/OLOS/NLOS model is below 30 msec (when T-window equals 1 sec), which is well below the latency requirement for CVSS applications (100 msec).

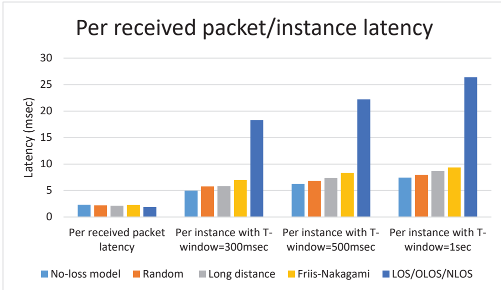


Fig. 6. Per received packet/instance latency.

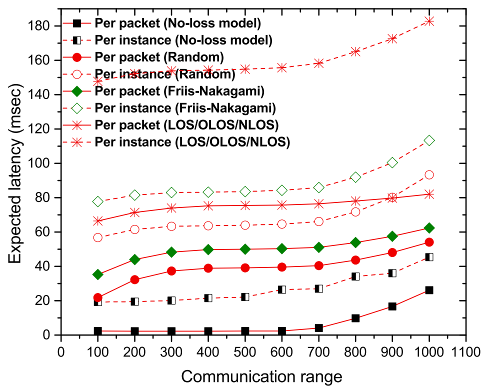


Fig. 7. Expected Latency for T-window=300 msec.

Fig. 7 shows the comparative average expected latency for per received packet and per received instance. With the increasing communication distance between Tx-Rx, latency increases. For each loss model, expected per-instance latency (EPIL) is higher than expected per-packet latency (EPPL). This is expected, as each dropped packet contributes 100 msec latency (packet generation interval) in EPPL; in contrast, each unreliable instance contributes T-window equivalence latency in EPIL. Note that T-window $\geq$ 100 msec. For the comparative performance among the models, similar to the PDR and reliability results (Sect. III-B1), the no-loss model has the best latency performance and the LOS/OLOS/NLOS model has the worst latency performance. The Random loss model ranks second and is followed by the Friis-Nakagami loss model. However, the maximum expected latency with the LOS/OLOS/NLOS model is 183 msec which is well below the tolerable T-window value (300 msec).

IV. Conclusion and Future Work

In this paper, we have studied the network- and application-level reliabilities in the connected vehicular networks. For performing a realistic traffic and network simulation, we have developed an integrated simulator. We have found that there is a significant performance difference between a realistic path loss model such as LOS/OLOS/NLOS and any other existing path loss model. We also found that with a moderate communication distance (300 m) between a Tx-Rx pair, the average network-level and application-level reliabilities with LOS/OLOS/NLOS model are as low as 30% and 55%, respectively, which is not satisfactory at all.

In our future work, we want to use the calculated network- and application-level reliabilities for dynamically adjusting broadcasting rate, transmission power and feedbackless relaying mechanism for improving PDR and reliability in the following broadcast period.

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