A Mobility-Aware and Quality-Driven Retransmission Limit Adaptation Scheme for Video Streaming over VANETs

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***Abstract*—An adaptive medium access control (MAC) retransmission limit selection scheme is proposed to improve the performance of IEEE 802.11p standard MAC protocol for video streaming applications over vehicular ad-hoc networks (VANETs). A multi-objective optimization framework, which jointly minimizes the probability of playback freezes and start-up delay of the streamed video at the destination vehicle by tuning the MAC retransmission limit with respect to channel statistics as well as packet transmission rate, is applied at road side unit (RSU). Periodic channel state estimation is performed at the RSU using the information derived from the received signal strength (RSS) and Doppler shift effect. Estimates of access probability between the RSU and the destination vehicle is incorporated in the design of the adaptive MAC scheme. The adaptation parameters are embedded in the user datagram protocol (UDP) packet header. Two-hop transmission is applied in zones in which the destination vehicle is not within the transmission range of any RSU. For multi-hop scenario, we discuss two-hop joint MAC retransmission adaptation and path selection. Compared with the non-adaptive IEEE 802.11p standard MAC, numerical results show that the proposed adaptive MAC protocol exhibits significantly fewer playback freezes while introduces only a slight increase in start-up delay.**

***Index Terms*—VANETs, video streaming, multi-objective optimization, MAC retransmission limit adaptation.**

I. INTRODUCTION

VEHICULAR ad-hoc networks (VANETs) belong to a general class of mobile ad-hoc communication networks with vehicles acting as fast moving mobile nodes. More specifically, a VANET consists of 1) on-board-units (OBUs) installed on the vehicles 2) roadside units (RSUs) deployed along sides of the urban roads/highways which facilitate both vehicle-to-vehicle (V2V) communications between vehicles and vehicle-to-infrastructure (V2I) communications between vehicles and RSUs. Intelligent transportation systems (ITS) for vehicular ad-hoc networks (VANETs) have stimulated the development of several interesting applications such as vehicle collision warning, security distance warning, driver assistance, cooperative driving, cooperative cruise control, etc [1]. The vehicle engine provides sufficient power for intensive data processing and communications. The on-board buffer storage, positioning system, and intelligent antenna further facilitate efficient video forwarding and collaborative downloading among vehicles or from/to RSUs. Video communication within a VANET has the potential to be of considerable benefit in an urban emergency, as it allows vehicles approaching the scene to better understand the nature of the emergency. However, emergency events may not occur frequently, especially when the network size is small. Streaming of high quality video to fast-moving vehicles is a promising application which faces fundamental challenges attributed to the high mobility and dynamic nature of the network. In order to have a smooth playout, it is necessary to have enough packets in the playback buffer at the destination [2]. Robust video streaming applications must be able to tolerate link failures or deep link fading, which normally occur due to node mobility or the unwillingness of the user to share node resources in a multi-hop network [3]. Hence, different protection schemes to be deployed in different layers of the protocol stack should be explored; for example, in [4], a modified version of packet reservation multiple access (PRMA) which can adapt to the traffic and data dynamics, is proposed.

Dedicated short range communications (DSRC) which is based on IEEE 802.11 standard has been introduced with the goal of having high data rate at low cost to the vehicles. For transmission using DSRC, there are two different mechanisms that can be deployed at the link layer to cope with the time-varying wireless channel conditions: 1) switching among different PHY modes, each with a different modulation scheme and data rate. 2) performing link layer (or MAC sublayer) retry. In this paper, we focus on the retry mechanism. According to the DSRC, when a transmitted packet is not acknowledged properly, retries can be performed and repeated until a certain limit is reached. Packets are dropped when they reach their retry limits. Retry is an efficient means to improve the reliability of the link. In the current wireless access in vehicular environments (WAVE) standard, this retry limit is normally configured statically, and there is no recommendation or guidance on how the retry limit can be adapted based on the channel conditions or the workload. However, the retry limit may affect not only the link packet erasure rate but also the playback buffer filling rate and hence the streaming quality of the video. The design of this scheme is based on a key observation, such that, for a given traffic characteristic and channel condition there exists an optimal retry limit setting for

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the wireless link under which the total losses due to both link erasure and buffer overflow will be minimized. It is observed that when traffic characteristics or channel conditions change, the optimal setting also changes, but always stays at a value that can balance the link erasure rate and the overflow rate.

Previous works, such as [5], focus on networking quality metrics like throughput and transmission delay. In this paper, a multi-objective MAC retransmission limit adaptation scheme, which jointly minimizes the video streaming quality metrics (start-up delay and frequency of playback freezes) over urban VANET scenarios, is proposed. We map these quality metrics onto MAC retransmission limit to formulate and solve the proposed multi-objective optimization. We study the variation of these two metrics as a function of MAC retransmission limit and found two separate regions for packet arrival rates, λ_{ij}, to be considered in our formulated optimization problem. Let μ_{ij} be the packet playback rate at the destination vehicle buffer. For $\lambda_{ij} \leq \mu_{ij}$, frequency of playback freezes increases with second degree function and the start-up delay decreases with exponential rate. For $\lambda_{ij} > \mu_{ij}$, although it is expected that the number of playback freezes be zero, there is a finite probability for playback freezes to occur. This can be derived by applying diffusion approximation in the $\lambda_{ij} \geq \mu_{ij}$ region. In this region, the probability of occurrence of a playback freeze is incorporated in the objective function, rather than the mean number of freezes. We analyze the optimization problem in both regions and estimate the optimal MAC retransmission limit to maximize the video quality according to the metrics under consideration. We specifically address the mobility impact on channel estimation and Doppler shift, access connectivity probability and interference caused by neighboring vehicles in the design of the proposed adaptive quality-driven MAC retransmission limit adaptation scheme. In the multi-hop scenario, we discuss the computation of access probability used in the MAC adaptation scheme and propose cross-layer path selection scheme followed by a discussion on mobile IP management to maintain continuous video streaming. The proposed scheme can achieve significantly fewer playback freezes while introducing only a small increase in start-up delay.

It is highly desirable to always have successful direct transmission without retransmission in any system; however, such situation is not always available mainly because probing the system for prior knowledge of how to achieve successful direct transmissions can be a futile exercise. For this reason, in most systems including VANETs, retransmission will be necessary in order to allow the same transmission to be delivered without constant interruption, which is the reason why the destination vehicle has playback mechanism and is the motivation why in this work we consider frequency of playback freezes and start-up delay as criteria to optimize retransmission limit. The contributions of this paper are as follows: 1) A MAC retransmission limit adaptation scheme proposal based on multi-objective optimization of playback streaming quality; 2) incorporation of the impact of mobility on vehicle access to the RSU and Doppler shift in the design of the adaptation scheme; and 3) extension of the proposed MAC retransmission scheme to multi-hop scenarios by proposing a cross-layer joint path selection and MAC retransmission adaptation. Protection strategies, like priority queueing and selective dropping, can be combined with adaptive retransmission adaptation to considerably improve the robustness and efficiency of video transmission.

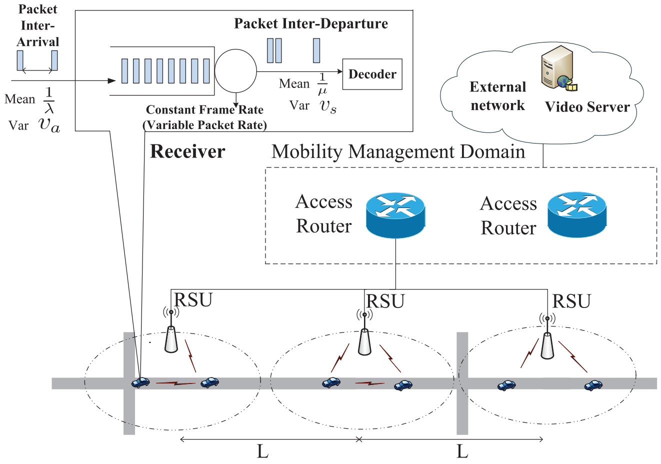

Fig. 1. Network topology.

The remainder of the paper is organized as follows. The network topology and system model are discussed in section II. Section III describes the proposed cross-layer multi-objective MAC protocol design. Section IV presents simulation results and validation of analytical results. Concluding remarks are summarized in section V.

II. NETWORK TOPOLOGY AND SYSTEM MODEL

We consider a vehicular network based on DSRC in which vehicles are equipped with on board units (OBUs) and broadcast the location, direction, speed, acceleration and traffic events to their neighbors [6]. We consider an infrastructure-based one-dimensional VANET as shown in Figure 1 wherein the RSUs are distributed uniformly along the road with intermediate distance of L and vehicles are randomly distributed according to a Poisson distribution. The RSUs are spaced by 700m, with an effective radio coverage of 350m each. The radio coverage of each vehicle is approximately 200m.

The video is streamed from an access router (AR) to the proper RSU, and from there to the destination vehicle. While the destination vehicle is in the transmission range of the RSU, they connect directly in a one-hop fashion. When the destination vehicle gets closer to the next RSU compared with its distance to the previous RSU, the AR switches the video streaming to the next RSU. In what follows, we first discuss the quality metrics to be optimized, issues like physical channel model, mobility modeling, access provision to the RSU, effect of Doppler shift on channel estimation, formulation of the optimization problem and our solutions on how to consider all the raised issues in the design of an effective MAC protocol in VANET scenarios.

A. Physical Channel

The RSUs receive video streams from media server via a backbone network, which is assumed to have high bandwidth and lossless channel. Many scatterers are present in the urban area. In addition to the scattering, there is a strongly dominant signal seen at the receiver, usually caused by line of sight which can be modeled by a log-normal shadowing model.

A standard for vehicle-to-infrastructure (V2I) communication in the 5.9 GHz unlicensed national information infrastructure (UNII) has been developed [7]. The wireless link is assumed to be a memoryless channel. The packet error rate, p_{ij}, between nodes i and j for a packet of B bits can be approximated by the sigmoid function.

$$p_{ij} = \frac{1}{1 + e^{\xi(Y_{SNR} - \delta)}} \tag{1}$$

where Y_{SNR} is the average signal-to-noise (SNR) of the received signal; ξ and δ are constants corresponding to the modulation and coding scheme for a given packet of length B. The goal is to support high mobility platforms using the IEEE 802.11 protocol. We assume that each RSU adopts some type of link adaptation scheme in order to maximize its outgoing link throughput. It can select adaptive modulation and coding schemes based on the detected SNR of the link.

B. Medium Access Control and Downlink Scheduling

WAVE adopts enhanced distributed channel access (EDCA) which is a contention-based channel access scheme with quality of service (QoS) provision, i.e., different packets are categorized based on their priority and different scheduling is applied for each category. Safety message delivery is categorized as an event-driven application with highest priority in which the safety messages will propagate from the source outwards as far as possible. Video packets are associated with lower priority compared to safety messages. The typical channel operations can be summarized as follows [8]. Both RSU and OBU support at least one control channel (CCH) and multiple service channels (SCHs). First, upon power on, an OBU monitors the CCH until a WAVE service advertisement (WSA) sent by an RSU is received. A WSA carries the information of available SCHs and their access parameters, such as channel numbers. Based on the WSA information, the OBU then synchronizes with the RSU, and the OBU can exchange data with the RSU in SCHs. With a single channel, an OBU can work on either CCH or SCH at a time. If two or more channels are facilitated in a WAVE device, the operations in CCH interval and SCH interval can be conducted simultaneously. In this paper, we consider single-channel WAVE devices only as this is common for OBUs. This paper focuses on streaming of videos with same level of priority.

C. Impact of Mobility

1) ***Related Works on Connectivity of Mobile Nodes:*** Connectivity of ad-hoc networks with finite number of nodes uniformly distributed over a one-dimensional network is analyzed in [9]. Connectivity probability of one-dimensional ad-hoc networks in which location of nodes have non-identical distribution is investigated empirically in [10] which leads to an optimization of the number of nodes required to maintain the connectivity. Connectivity of mobile nodes in a VANET over a single highway with multiple lanes, which allows the vehicles to pass each other, is studied in [11]. In [12], connectivity requirements in terms of required penetration rate (number of nodes equipped with communication devices) and transmission power for dissemination of time-critical information in a one-way or two-way VANET are derived while taking important physical-layer parameters, such as fading, propagation path loss, transmit power, and transmission data rate, into consideration. Another approach proposed in [13] which applies the exponential inter-arrival time distribution between vehicles in order to obtain the inter-vehicle distance distribution and, accordingly, to derive explicit expression for the expected connectivity distance. In [14], two idealized mobility models for vehicular mobility were described, namely, Freeway model and Manhattan model. The freeway model is limited to movement of vehicles in one direction. The Manhattan model considers movement of vehicles in two opposite directions and the possibility of turning at intersections. In sparse situations, the mobility of the vehicles may be considered independent from each other; however, for dense situations, this assumption is not correct.

2) ***Mobility Model :*** A mobility model has been developed in [15] to represent the steady state distributions of both node population and node location based on the assumption that vehicles arrival rate to the highway follows a Poisson distribution. Furthermore, statistics of connectivity have been investigated using the proposed mobility model. The proposed traffic model in [16] is a combination of a deterministic fluid dynamic model and a stochastic model. The former model is used to characterize the general flow and evolution of traffic stream while the latter model is applied in order to address the random movement of an individual vehicle. In [17], a queueing network is considered which comprises queues of customers in cascade, each with several classes of customers.

Aside from the mobility model we select to use in this work, the goal is to estimate an important stochastic attribute of VANET, which is the probability of connectivity of vehicle to the RSU along the road. This probability will be used in the design of the proposed adaptive retransmission scheme. We rely on the results in several works (e.g., [18]) which prove that inter-vehicle distance along the highways follows exponential distribution. Based on this assumption, the connectivity probability bounds presented in [19] can be applied in the design of the MAC adaptation scheme.

3) ***Access Connectivity Probability:*** The access probability (AP) is the probability that an arbitrary vehicle is connected to an RSU, which is a function of key VANET parameters such as inter-RSU distance, vehicle density, and transmission ranges of RSUs. The RSUs are deployed uniformly along the road with Euclidean distance L between two adjacent RSUs and vehicles enter the street according to a Poisson distribution, i.e., the distance between vehicles follows an exponential distribution. Let the coordination reference be at the first RSU (RSU1) and the second RSU (RSU2) be located at distance L from RSU1. The distance of the vehicle from the reference is denoted by x. Let $g_R^{\zeta}(x)$ denote the probability that a vehicle and RSU separated by distance x are directly connected under channel model ζ which in our work, is the log-normal shadowing. The probability that the vehicle is connected either to RSU1 or RSU2 is

$$P_a(x) = 1 - (1 - g_R^{\zeta}(x))(1 - g_R^{\zeta}(L - x)) \tag{2}$$

In [19], the access probability in two-hop connection scenarios is computed under a unit disc model and log-normal shadowing fading model. We apply a similar approach to compute the access probability of vehicles in direct connection scenario under a log-normal shadowing fading model, which is commonly used to model the real world signal propagation where transmit power loss increase logarithmically with Euclidean distance between sender and receiver due to shadowing effect caused by the VANET's environment. The received signal power in dB is given by $p_{rx} = p_0 - 10\alpha\log_{10}\frac{l}{d_0} + N_\sigma$. p_0 is the received signal power at the reference distance d_0, α is the path loss exponent, N_σ is the Gaussian random variable with zero mean and variance σ^2, and l is the Euclidean distance between RSU and the destination vehicle. The RSU and the destination vehicle can establish a direct connection if the received signal power at the destination, p_{tx}, is greater than or equal to a certain threshold p_{th}. According to [19], by assuming symmetric wireless connection between RSU and vehicles and assigning $p_{th} = p_0 - 10\alpha\log_{10}\frac{R}{d_0}$, where R is the transmission range of RSUs, the result for g_R^{ζ} under the log-normal shadowing model can be greatly simplified as follows.

$$g_R^{\zeta} = Pr(p_{rx} \geq p_{th}) = Q(\frac{10\alpha}{\sigma}\log_{10}\frac{x}{R}) \tag{3}$$

where $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{\frac{-x^2}{2}}dx$ is the tail probability of the standard normal distribution. When $\sigma = 0$, the log-normal model will be simplified to a unit disc model with $g_R^{\zeta} = Pr(x \leq R)$. Substitution of (3) into (2) will result in direct access probability as

$$P_a(x) = 1-(1-Q(\frac{10\alpha}{\sigma}\log_{10}\frac{x}{R}))(1-Q(\frac{10\alpha}{\sigma}\log_{10}\frac{L-x}{R})) \tag{4}$$

4) ***Impact of Doppler Shift on Channel Estimation:*** Due to the fast movement of vehicles and potential obstacles appearing along the road between RSU and the destination vehicle that cause shadowing effect, the level of SNR in the wireless channel, and hence packet error rate, is subject to change. Hence, it is imperative to address this issue in the design of an adaptive MAC scheme. The MAC needs to adapt itself to the wireless channel condition. We consider the effect of Doppler shift on the channel coherence time (i.e., the duration of time in which the channel remains stationary). The estimator deployed at the RSU receives feedback on received signal strength (RSS), $Y(t)$, from the destination vehicle. Let $\overline{Y}_{RSS}(t-1)$ be the average RSS up to packet $t-1$; the estimated SNR of the $(t+1)$th packet, $\hat{Y}_{SNR}(t+1)$, by using an exponential moving average, is as follows [20].

$$\hat{Y}_{SNR}(t+1) = (1-\gamma)[\alpha\overline{Y}_{SNR}(t-1)+(1-\alpha)Y(t)]+\gamma\hat{Y}_{SNR}(t) \tag{5}$$

where $\hat{Y}_{SNR}(t)$ is the average SNR at the receiver, which is fed back to the RSU via the CCH. $0 \leq \alpha \leq 1$ and γ are the estimation parameters which capture the properties of the moving average. The receiver informs the RSU in two events: 1) when the difference between the average SNRs is more than a predefined threshold, Δ_{SNR}, or 2) when $\overline{Y}_{SNR}(t)$ stays in the channel longer than the channel coherence time, T_c, which is a function of the maximum Doppler frequency shift, f_m, i.e., $T_c = \frac{0.423}{f_m}$. The frequency decreases when the vehicle moves away from the RSU and increases when it moves toward the RSU according to the Doppler frequency shift, $f = (1-\frac{V_s-V_r}{c})f_0$, where f_0 is the center frequency of the signal, while V_s, V_r and c are vectorial velocities of sender, receiver and waveform in free space, respectively. Obviously, in VANETs the velocity of RSU is equal to zero. Substitution of the updated SNR given by (5) into (1) results in the updated link loss probability between RSU and destination vehicle, which will be used in designing the quality-driven adaptive MAC retransmission protocol. Once the vehicle has a distance more than its transmission range to the RSU, the signal level can not be updated and hence the previous (latest) value is used for packet error probability estimation.

III. FORMULATION OF MULTI-OBJECTIVE OPTIMIZATION PROBLEM

A. Performance Metrics

We assume that each vehicle has an infinite buffer, which is a reasonable assumption given the high storage capability that can be deployed in vehicles. The video playback process can be divided into two phases: 1) charging phase and 2) playback phase. The charging phase starts once the buffer becomes empty. Thus, the playback is kept frozen until the buffer is filled with b packets (i.e., b is a threshold of the playback). To derive an analytical formulation for streaming start-up delay (charging phase) in video streaming at the destination vehicle, the playout buffer can be modeled as a $G/G/1/\infty$ queue that follows the diffusion approximation method presented in [2]. By applying the diffusion approximation, the transient solution of the queue length can be exploited by obtaining its p.d.f. at any time instant t. The average start-up delay and its variance are given by

$$E(D_s) = \frac{b}{\lambda} \tag{6}$$

$$Var(D) = bv_a \tag{7}$$

where b is the playback threshold, v_a is the variance of inter-arrival rate of packets at the destination buffer and λ is the arrival rate of the packets at the destination vehicle. The playback terminates when the buffer becomes empty again. According to [2], the average number of streaming freezes after t seconds and its variance can be approximated using diffusion approximation as follows:

$$E(F) \approx -\frac{\lambda(\lambda-\mu)}{\mu \cdot b}t \tag{8}$$

$$Var(F) \approx \frac{\mu^3\lambda^3(v_a+v_s)+3v_a\lambda^4(\lambda-\mu)}{b^2\mu^2} \tag{9}$$

where μ is the service rate of the buffer and v_s is variance of service interval at the destination buffer.

B. MAC Retry Limit Adaptation

In existing wireless local area networks (WLANs) environments, various protection strategies are available at various layers of the protocol stack for different tradeoffs among throughput, reliability and delay. These include 1) switching among different modulation and channel coding schemes, 2) retransmission and forward error correction (FEC) at the MAC layer, 3) FEC, Automatic retransmission request (ARQ), or hybrid ARQ along with error resilient video coding schemes and error concealment strategies at the application layer, and

$$\begin{aligned} E(D_s) &= \frac{b}{\lambda'_{ij}} = \frac{b}{P_a(x)\lambda_{ij}(1 - P^T_{ij}(M_{ij}, p_{ij}(x)))} \\ &= \frac{b}{P_a(x)\lambda_{ij}(1 - p_{ij}(x)^{M_{ij}+1} - \frac{P_a(x)\lambda_{ij}\cdot n(M_{ij}, p_{ij}(x)) - C_{ij}}{P_a(x)\lambda_{ij}\cdot n(M_{ij}, p_{ij}(x))})} \\ &= \frac{b}{P_a(x)\lambda_{ij}(1 - p_{ij}(x)^{M_{ij}+1} - \frac{P_a(x)\lambda_{ij} - P_a(x)\lambda_{ij}p_{ij}(x)^{M_{ij}+1} - C_{ij} + C_{ij}p_{ij}(x)}{P_a(x)\lambda_{ij} - P_a(x)\lambda_{ij}p_{ij}(x)^{M_{ij}+1}})} \\ &= \frac{b(1 - p_{ij}(x)^{M_{ij}+1})}{P_a(x)\lambda_{ij}(1 - p_{ij}(x)^{M_{ij}+1})^2 - P_a(x)\lambda_{ij}(1 - p_{ij}(x)^{M_{ij}+1}) + C_{ij}(1 - p_{ij}(x))} \end{aligned} \tag{10}$$

Hence, the effective arrival rate of packets at the destination buffer, λ', is

$$\lambda'_{ij} = \frac{b}{E(D_s)} = \frac{P_a(x)\lambda_{ij}(1 - p_{ij}(x)^{M_{ij}+1})^2 - P_a(x)\lambda_{ij}(1 - p_{ij}(x)^{M_{ij}+1}) + C_{ij}(1 - p_{ij}(x))}{(1 - p_{ij}(x)^{M_{ij}+1})} \tag{11}$$

$$\begin{aligned} E(F) =& \frac{\lambda'_{ij}(\mu_{ij} - \lambda'_{ij})}{\mu_{ij}b} \\ =& \frac{1}{\mu_{ij}b}\frac{P_a(x)\lambda_{ij}a^2 - P_a(x)\lambda_{ij}a + C_{ij}(1 - p_{ij}(x))}{a} \times (\mu_{ij} - \frac{P_a(x)\lambda_{ij}a^2 - P_a(x)\lambda_{ij}a + C_{ij}(1 - p_{ij}(x))}{a}) \\ =& \frac{1}{\mu_{ij}ba^2}[P_a(x)\lambda_{ij}a^2 - P_a(x)\lambda_{ij}a + C_{ij}(1 - p_{ij}(x))] \times [\mu_{ij}a - P_a(x)\lambda_{ij}a^2 - P_a(x)\lambda_{ij}a + C_{ij}(1 - p_{ij}(x))] \\ =& \frac{1}{\mu_{ij}ba^2}[-P^2_a(x)\lambda^2_{ij}a^4 + P_a(x)\lambda_{ij}\mu_{ij}a^3 + (P^2_a(x)\lambda^2_{ij} - \mu_{ij}P_a(x)\lambda_{ij})a^2 + (-2P_a(x)\lambda_{ij} + \mu_{ij}) + \\ & C_{ij}(1 - p_{ij}(x))a + C^2_{ij}(1 - p_{ij}(x))^2] \end{aligned} \tag{12}$$

4) packetization optimization at the various layers [21]. In the following, we analyze how MAC retry limit may affect buffer overflow (loss due to congestion) and link loss due to packet drop. Analysis of such problem in general will be very generic.

Intuitively, when the wireless link experiences high packet error rate due to noise or collision of packets from parties which use the common wireless medium, more packet retransmissions are required in order to correctly deliver the packet. On the other hand, this will increase the probability of buffer overflow. Hence, there is a tradeoff between these two types of packet loss. To find the optimal retry limit, the transmitter is required to estimate the channel which it intends to use for packet transmission via transmission of pilot signals [1]. Due to high mobility of vehicles, continuous channel estimation seems a formidable task. Hence, without loss of generality, a static log-normal shadowing channel model is considered, which is a practical model for urban environment. Of course, a series of channel estimation can be done in practice to find the channel characteristics closest to the environment which the network is designed for. In addition, packet drop due to overflow is performed before packets are put on the link. Let M_{ij} and $p_{ij}(x)$ be the link retry limit and packet error probability for link $(i \rightarrow j)$ between intermediate nodes (vehicles), i and j, respectively. The mean number of transmissions when the vehicle is at distance x from the RSU, $n(M_{ij}, p_{ij}(x))$, for a single packet until it is successfully received by node j or it reaches the retry limit is calculated as follows.

$$n(M_{ij}, p_{ij}(x)) = \frac{1 - p_{ij}(x)^{M_{ij}+1}}{1 - p_{ij}(x)} \tag{13}$$

where $p_{ij}(x)$ is the most recently updated link loss probability of the channel between the RSU and the vehicle at distance x from it. The blocking probability of the link, $P^B_{ij}(M_{ij}, p_{ij}(x))$, for the fluid model with arrival rate λ_{ij} (packets/s) and channel service rate (channel maximum capacity) C_{ij} (packets/s) is

$$P^B_{ij}(M_{ij}, p_{ij}(x)) = \frac{P_a(x)\lambda_{ij}\cdot n(M_{ij}, p_{ij}(x)) - C_{ij}}{P_a(x)\lambda_{ij}\cdot n(M_{ij}, p_{ij}(x))} \tag{14}$$

The link packet drop probability after M_{ij} unsuccessful retries can be calculated as

$$P^D_{ij}(M_{ij}, p_{ij}(x)) = p_{ij}(x)^{M_{ij}+1} \tag{15}$$

The overall packet loss probability, assuming $P^B_{ij}(M_{ij}, p_{ij}(x))$ and $P^D_{ij}(M_{ij}, p_{ij}(x))$ are small, is approximated as

$$P^T_{ij}(M_{ij}, p_{ij}(x)) \cong P^B_{ij}(M_{ij}, p_{ij}(x)) + P^D_{ij}(M_{ij}, p_{ij}(x)) \tag{16}$$

C. Derivation of Quality Metrics

The effective arrival rate of packet at the destination buffer is given by the following.

$$\lambda'_{ij} = P_a(x)\lambda_{ij}(1 - P^T_{ij}(M_{ij}, p_{ij}(x))) \tag{17}$$

where λ_{ij} is the packet input rate by the transmitter (RSU) before the signal enters the channel and λ'_{ij} is the effective packet arrival rate at the destination buffer. Substitution of the effective arrival rate in start-up delay (6) will result in 10. Let

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[1] Estimation is performed at the receiver and fed back to the transmitter, which also sustains transmission delay.

$a = (1 - p_{ij}(x)^{M_{ij}+1})$. The frequency of playback freezes in 1 second interval ($t = 1sec.$) can be derived by substitution of λ'_{ij} from (17) in (8) which well result in 12.

D. Optimization Framework

Multi-objective optimization (or programming) is the process of simultaneously optimizing two or more conflicting objectives subject to certain constraints. The optimization problem that we consider involves the maximization of two objective functions are not necessarily of equal importance. The solution to this problem can be described in terms of decision vector $(x_1, x_2, ..., x_n)$ in decision space X. A function $f : X \rightarrow Y$ evaluates the quality of the specific solution by assigning it an object vector $(y_1, y_2, ...y_n)$ in object space Y.

The tradeoff between frequency of freezes and start-up delay can be calculated from (6) and (8), yielding

$$E(F) = \frac{b\mu_{ij}E(D_s) - b^2}{b\mu_{ij}E^2(D_s)} \tag{18}$$

where μ_{ij} is the packet playback rate at the destination buffer inside the vehicle. Let $\hat{D}$ and $\hat{F}$ be the maximum tolerable start-up delay and frequency of video playback freezes, respectively. Our objective is to manage the MAC retransmission limit M_{ij} to maximize the video perceived quality within the tolerable range of start-up delay, $\hat{D}$, and frequency of playback freezes, $\hat{F}$, i.e.,

- P1:$(\lambda'_{ij} > \mu_{ij})$

$$\begin{aligned} \min_{\lambda'_{ij}} \quad & P + w_1 E(D) \\ s.t. \quad & P\{D > \hat{D}\} \leq \xi \end{aligned} \tag{19}$$

- P2:$(0 < \lambda'_{ij} \leq \mu_{ij})$

$$\begin{aligned} \min_{\lambda'_{ij}} \quad & E(D) + w_2 E(F) \\ s.t. \quad & P\{D > \hat{D}\} \leq \xi \\ & P\{F > \hat{F}\} \leq \eta \end{aligned} \tag{20}$$

where $w_1, w_2 > 0$ are weighing factors that can be adjusted based on the user's requirements and $0 < \xi, \eta \ll 1$ are predefined scalars. P1 and P2 are nonlinear optimization problems which are computationally very intensive to perform in real-time streaming systems. To reduce the search space, in order to decrease the computations, we can apply the one-sided Chebyshev inequality on (6),(7),(8) and (9), subject to the constraints of (20). Since $\xi \ll 1$, we can assume $\frac{1-\xi}{\xi} \approx \frac{1}{\xi}$, which will simplify the solution as follows.

$$(\hat{D} - \frac{b}{\lambda'_{ij}}) \geq \sqrt{\frac{bv_a}{\xi}(1-\xi)} \Rightarrow \lambda'_{ij} \geq \frac{b}{\hat{D} - \sqrt{\frac{bv_a}{\xi}}} \tag{21}$$

By applying the Chebyshev inequality on the maximum tolerable playback freezes constraint in (20), we have

$$\lambda'_{ij} \leq \sqrt[5]{(\frac{b\hat{F}\mu_{ij}^2}{3v_a})^2} \tag{22}$$

Substitution of the constraints in P1 and P2, together with (21) and (22), will result in smaller yet more conservative search space which can significantly reduce the computational complexity at a cost of user's utility.

E. Analysis of Multi-hop V2I connection

The results of the preceding subsection are applicable in situations where there are direct (one-hop) connections between the vehicle and the RSUs. In this subsection, we extend our scheme to consider zones with no RSU coverage where two-hop connection can be a solution and improve the overall quality of streaming. To follow the footsteps of one-hop approach and extend it to the two-hop scenario, we first analyze the access probability for two-hop communication. Also, when there are intermediate nodes (vehicles) to relay the packets, the problem of routing and path selection becomes important. Ideally, a scheme which combines routing and MAC must be based on cross-layer (network layer and MAC layer) design, i.e., we must take full advantage of combined parameters of both layers in order to achieve near-optimal results.

1) Access probability for two-hop connection: The probability that a vehicle located at position x, $0 \leq x \leq L$, is connected to either RSU1 or RSU2 in at most two-hop connection, according to **Theorem 1** in [19], is given by:

$$\begin{aligned} p_a(x) &= 1 - (1 - p_1(x))(1 - p_2(x)) && (23) \\ p_1(x) &= 1 - (1 - g_b^C(x))(1 - g_b^C(L - x)) && (24) \\ p_2(x) &= 1 - e^{-\int_0^L g_v^C(\|x-y\|)\rho p_1(y)dy} && (25) \end{aligned}$$

In the above, $p_1(x)$ is the probability of vehicle being directly connected to either RSU1 or RSU2; $p_2(x)$ is the probability of vehicle being connected to at least one vehicle which is connected to either RSU1 or RSU2; g_b^C and g_v^C are probabilities of connectivity of V2I and V2V channels, respectively, which are functions of the distance between transmitting and receiving nodes and channel model C. Under the log-normal shadowing model, the access probability for two-hop connection of vehicle to RSU can be obtained for different values of α and σ by computing (23) using numerical integration technique. The access probability computed by (23) is inserted in (12) to derive the expected frequency of freezes for two-hop scenario. Based on the estimated connectivity probability, retransmission limit is determined by the RSU following the cross-layer optimization in conjunction with path selection described in subsection III-E2. Equal retransmission limit will be used for transmission over the first hop (transmission from RSU to intermediate vehicle) and for relaying over the second hop (transmission from intermediate vehicle to destination vehicle).

2) Cross-layer MAC-NET packet delivery: The routing protocol is location-based, which means that each mobile node incorporates its geographical location while broadcasting "Hello" messages for neighbor discovery. The algorithm is based on greedy geographic routing tailored for video streaming application. In other words the algorithm selects a path which optimizes the streaming metrics as follows. First, the RSU applies greedy geographic routing and selects a cluster of N_D nodes which are closest to the destination such that the distance of these nodes to the destination must be smaller than a predefined threshold, σ. If there are no nodes in the neighborhood of the relaying node which satisfy this condition and the destination node is not in the transmission range of the RSU, the closest node to the destination will be selected.

Let $R_i \in R$ be the MAC retransmission value for all the packet of the ith video segment where R is the set of all admissible values. Let $\zeta_i \in Z$ denote the transmission path of packet π_i where Z is the set of all paths possible from the RSU to the destination vehicle by applying the modified greedy routing. The frequency of streaming freezes for the current video slice, $E[F_i]$, and the transmission delay D_i depends on R_i and ζ_i. The problem can be formulated as the selection of optimal transmission path and MAC parameter for all segments of the video clip so as to minimize the frequency of streaming freezes under a delay constraint in a multi-hop V2I channel. Let M be the total number of video segments of the clip and $D_T \approx \frac{1}{\mu}$ be the delay threshold for a video segment, where μ is the video frame playback rate. The minimization problem is formulated as follows:

$$\begin{aligned} \min_{R_i \in R \ \zeta_i \in Z} \quad & \textstyle\sum_i^M E[F_i] \\ s.t. \quad & \max\{D_i, \dots, D_M\} \leq D_T \end{aligned} \tag{26}$$

3) IP Mobility: To maintain continuous streaming, a change of RSU for controlling the transmission of video to the destination vehicle is necessary. We apply our proposed IP mobility management scheme (described in detail in [22]) to multi-hop VANETs with handover prediction. The scheme works in conjunction with a geo-routing algorithm and relies on the IPv6 support for VANET using geo-networking features. The geo-routing layer forwards IP packets in the multi-hop path, in a way that creates a virtual point-to-point link between the destination vehicle and the access router (AR), without IP header forwarding at intermediate vehicles or the RSU.

IV. PERFORMANCE EVALUATION AND MODEL VALIDATION

A. Adaptation of Retransmission Limit under Static Channel

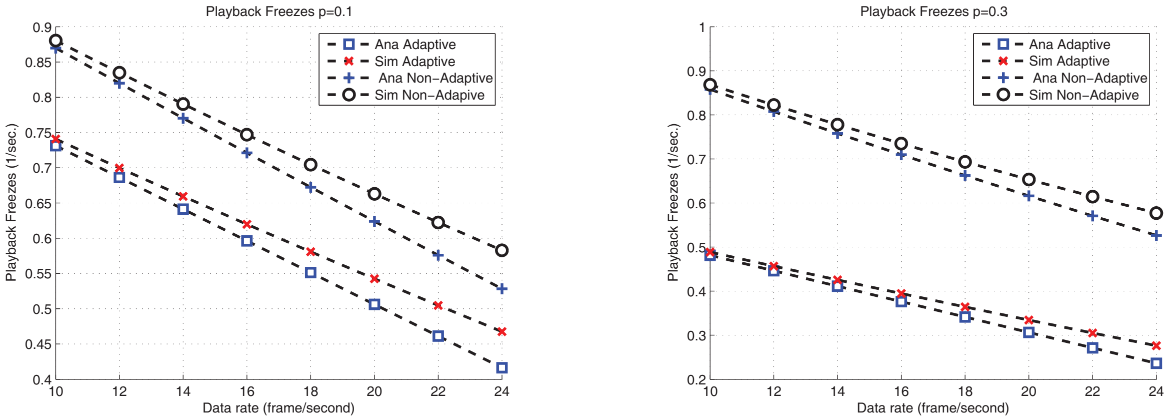
The simulations are conducted in Matlab. The analytical results are computed using the derived formulas in previous sections for average start-up delay and frequency of playback freezes. For the simulations, we have written IEEE 802.11p MAC as a Matlab code and simulated the packet transmission in a drive-thru scenario where a vehicle starts from an RSU (RSU1) and moves with constant speed toward the next RSU (RSU2) considering all the protocol details (collisions, backoffs, competition between nodes for accessing the channels, etc.). The transmission delay resulted from the Monte-Carlo simulations is then used to find the effective arrival rate of the packets at the destination and hence to derive the metrics (start-up delay and frequency of playback freezes). The simulations are repeated 10000 times with 95% confidence interval for each video frame rate ranging from 10 to 25 frames per second.

When the MAC protocol runs the adaptation algorithm in the background to calculate the optimum limit for retransmissions, it can achieve higher quality in terms of video playback freezes as shown in Figures 2(a)-2(b). However, the adaptation protocol introduces extra computations to the standard WAVE protocol that results in slight increase of start-up delay as shown in Figures 2(c)-2(d). In addition, the impact of channel packet loss on the performance of the algorithm and its comparative performance with the standard WAVE protocol are shown in Figures 2(a)-2(d). Here, it is assumed that the channel state remains static and hence there would be no channel update during the streaming period. As we change the channel loss probability, the difference between the adaptive algorithm and the standard algorithm for both playback freezes and start-up delay, is more obvious. As packet transmission rate increases, we observe a decrement in the frequency of video playback freezes. However, the start-up delay shows increasing attribute for the standard WAVE protocol while having constant value for the adaptive protocol. The limit of retransmission is fixed in the standard protocol, while the adaptive protocol tends to select higher retransmission limit as the data rate increases which results in higher start-up delay within delay constraint (if the packet transmission delay exceeds the delay threshold, D_T, it will be dropped) for higher data rates. Having generally lower frequency of freezes in the adaptive protocol compared to the standard MAC protocol is a direct consequence of protocol optimization, which is basically designed to select the retransmission limit with consideration of updated channel conditions in order to minimize playback freezes. The drop in the number of freezes with increment of the transmission rate is due to more successful transmissions and hence more video packet available to be streamed at the playback buffer for each time instant compared to the standard protocol. An increase in the number of vehicles which are also connected to RSUs and compete for channel will increase the number of packet collisions and hence the transmission delays which results in decrement of effective packet arrival rate at the destination vehicle. Consequently, we have higher start-up delay and playback freezes. Consideration of channel models which consider multi-path fading such as Rician model will make the computation of $P_a(x)$, in subsection II-C3, difficult which is only possible using complex numerical integration methods.

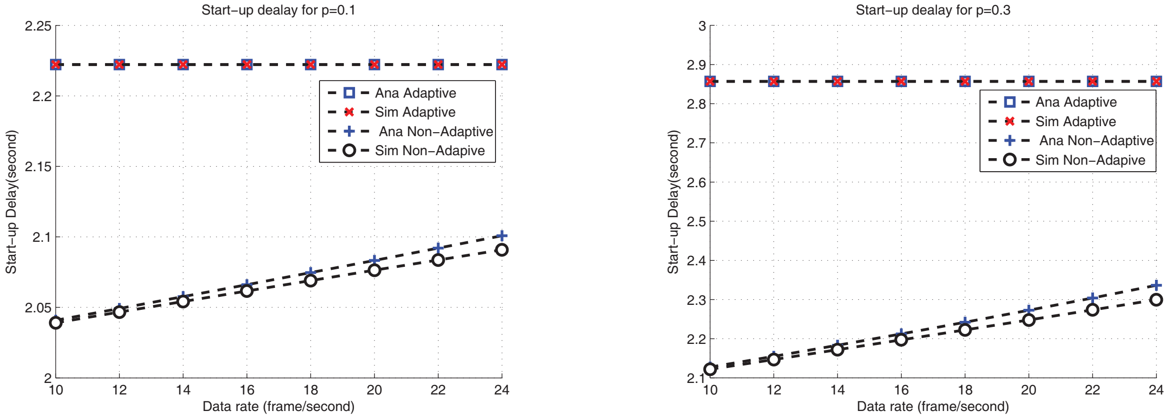
B. Adaptation of MAC Retransmission Limit with Channel Dynamics

We simulate a drive-thru video streaming scenario as shown in Figure 1, in which RSUs are deployed along the road and the vehicles compete for communications using IEEE 802.11p. We validate the developed analytical model in two scenarios: 1) when the inter-RSU distance, L, is completely in the coverage range of the RSUs, i.e., $0 < L \leq 2R$ and 2) when L exceeds the communication range of base stations and hence there are areas in which the vehicle does not have access to an RSU. In each scenario, we change the transmission rate and evaluate the achievable gain by the proposed scheme compared to the standard IEEE 802.11p protocol in terms of the video quality metric (frequency of playback freezes) and its tradeoff with other temporal metric, i.e., start-up delay. The impacts of (i) frequency of channel estimation updates, (ii) inter-RSU distance on access probability, and (iii) quality metrics on system performance are obtained.

1) $0 < L \leq 2R$*:* The simulation parameters are selected as follows. The inter-RSU distance is $L = 1500m$, the speed of vehicles is fixed at $V_s = 50km/h = 13.88m/s$, maximum



(a) Frequency of Playback Freezes (b) Frequency of Playback Freezes



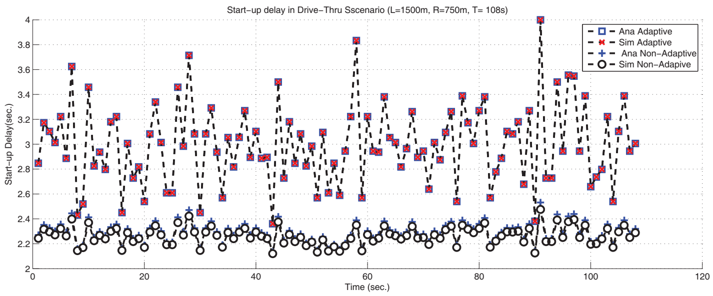
(c) Start-up delay (d) Start-up delay

Fig. 2. Performance evaluation of the proposed retransmission limit adaptation scheme vs. frame transmission rate.

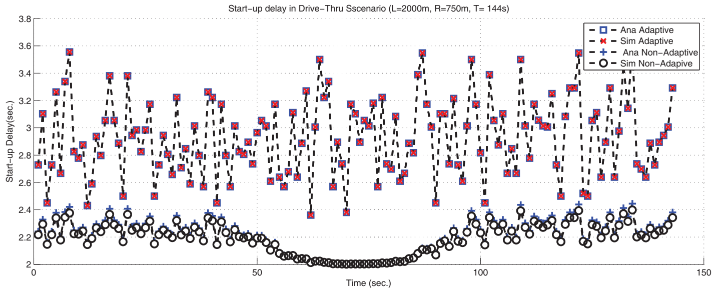
Doppler shift according to the speed of the vehicle and the base frequency of the WAVE protocol (5.9 GHz) is calculated to be $f_m = 273.15Hz$ and hence the coherence time is $T_c = 1.5$s. The log-normal shadowing parameters are as follows. The path loss exponent $\alpha = 2$, and variance of the normally distributed noise is $\sigma = 1$ with mean equal to zero. Accurate and timely update of channel state and selection of MAC parameter by consideration of current data rate, received signal strength, and quality of access to RSU in selecting an optimized retransmission limit is the contribution of the proposed adaptation scheme on and above those of the standard MAC protocol. This information can be embedded in the new control messages to be transmitted in CCH intervals and hence it is compatible with the current IEEE 802.11p protocol.

In this scenario, the RSU maintains access to the destination vehicle while the vehicle gains the opportunity to access the channel. The vehicle is always within the transmission range of the RSU (R=750m); however, as the vehicle moves away from the responsible RSU, with log-normal shadowing, there is a drop in RSS and hence it is expected that the vehicle experiences higher packet loss. Also, if the distance between the RSU and the vehicle is larger than the vehicle's transmission range, it can not inform the RSU of its RSS and hence the adaptation would be performed only with respect to the transmission rate of the video packet at the transmitter (RSU) side. As the vehicle moves toward the next RSU, the RSS will increase and so does the quality of the video streaming. The proposed adaptive protocol has considerable gain of more than 0.3 to 0.6 freezes/second compared to the standard protocol, i.e., drop of 30 to 60 percent in the number of streaming freezes (Figure 3(c)). Such gain in frequency of freezes is achieved while the start-up delay is maintained below 4 seconds (Figure 3(a)).

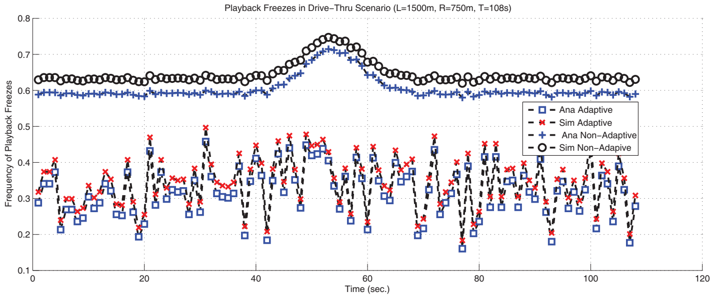
2) $2R \leq L$*:* The inter-RSU distance is selected to be $L = 2000m$, which means that there are zones along the road in which the vehicle is not within the communication range of the RSU. Hence, the remaining packets in the receiver's playback buffer decreases with higher pace. Therefore, the likelihood of playback freezes increases during the intervals of low access to RSUs. The proposed adaptive protocol has generally better performance in terms of playback freezes compared to the standard IEEE 802.11p protocol; however, the extra steps for optimization causes the start-up delay to be slightly larger than the standard protocol (at most 2 sec.) which is negligible compared to much lower performance gain achieved in terms of playback freezes that has higher impact on the end user's level of satisfaction. A zone with no coverage is expanded symmetrically about 500m around the middle of the inter-RSU distance. The access probability drops significantly in this zone and its impact on streaming quality is considerable as can be seen in Figures 3(d) and 3(b). The values for frequency



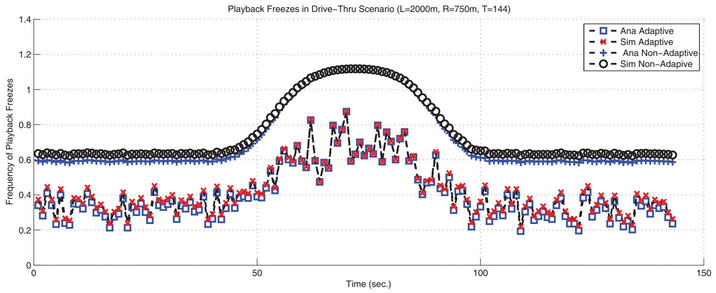
(a) Start-up delay



(b) Start-up delay



(c) Frequency of Playback Freezes



(d) Frequency of Playback Freezes

Fig. 3. Performance evaluation of the proposed retransmission limit adaptation in drive-thru scenarios.

of playback freezes have increased compared to the previous scenario ($0 < L \leq 2R$). Our proposed method outperforms the standard algorithm in such scenarios with more sparse RSU deployment when the connectivity imposes challenge on maintaining high video streaming quality. We have assessed the impact of Inter-RSU distance on the performance of the proposed algorithm and its performance compared to that of the standard protocol.

C. *Impact of Inter-RSU Distance*

In each step, we change the inter-RSU distance, L, to show the impact of mobility and network access connectivity on the received video quality. The exact analytical results are verified by the simulation results. Figure 4 shows the approximate analytical values which are reasonably close to the simulation results. Same situation can be observed for the result in Figure 5. As L increases, it is more difficult for all vehicles to be connected to the RSUs due to the larger possible distances between the vehicles and the RSUs. This causes a drop in the

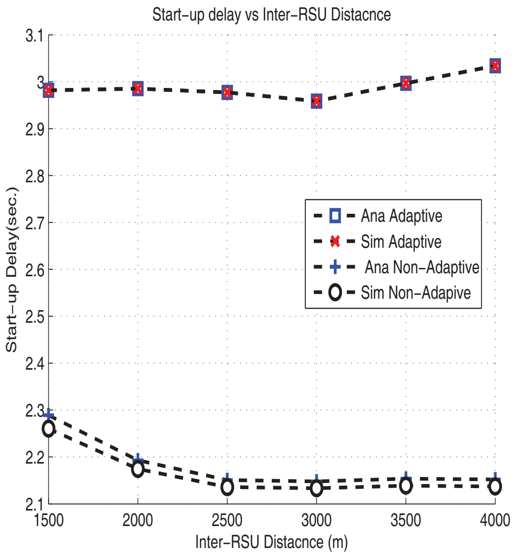


Fig. 4. Start-up delay vs inter-RSU distance.

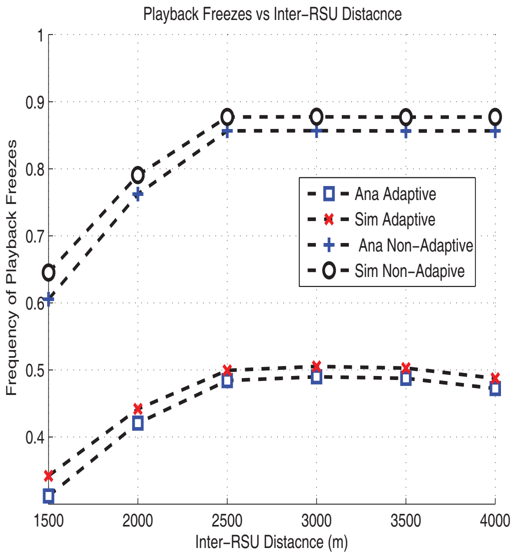


Fig. 5. Frequency of playback freezes vs inter-RSU distance.

access probability, and it tends to zero as L goes to infinity. Comparison with the standard MAC shows that our algorithm has fewer playback freezes while introducing a slight increase in start-up delay.

V. CONCLUDING REMARKS

In this paper, an adaptive MAC retransmission limit adaptation scheme has been proposed in which the adaptation is based on an optimization of playback streaming quality. A multi-objective optimization framework is applied at the RSU, which jointly minimizes the probability of playback freezes and start-up delay of the streaming at the destination vehicle by tuning the MAC retransmission limit with respect to channel statistics (packet error rate and packet transmission rate). The proposed scheme can achieve significantly fewer playback freezes while introducing a small increase in start-up delay. Future work includes adaptation of other MAC parameters such as contention window (CW) size and consideration of more complex and comprehensive distribution models for deployment of RSUs.

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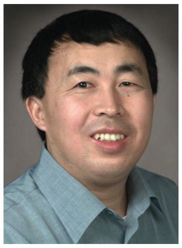

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