Rapid Dissemination of Public Safety Message Flows in Vehicular Networks

Izhak Rubin[1], Yu-Yu Lin[1], Andrea Baiocchi[2], Francesca Cuomo[2], and Pierpaolo Salvo[2]
[1] Electrical Engineering Department, UCLA, Los Angeles, CA, USA
[2] DIET at University of Roma “La Sapienza”, Rome, Italy
Email: rubin@ee.ucla.edu; yuyu@seas.ucla.edu; {andrea.baiocchi, francesca.cuomo, pierpaolo.salvo}@uniroma1.it

Abstract —We consider a Road Side Unit (RSU) that aims to broadcast critical public safety message flows to vehicles that travel along a linear highway. The RSU is able to transmit such message flows directly to only a limited group of vehicles travelling in its close vicinity. To assure delivery of these messages to all other vehicles traveling along the highway, we make use of a Vehicular Ad Hoc Network (VANET) system to provide vehicle-to-vehicle multi-hop transport of these messages. We propose a VANET networking scheme that is identified as a Vehicular Backbone Network (VBN), under which vehicles that are located close to properly selected nominal positions are elected to serve as Relay Nodes (RNs). We study the optimal cross-layer design of such a network system, by presenting an analytical model to jointly select the operational data rate, scheduling mechanism and the inter-RN targeted distance levels. We show that a high level of coverage of highway vehicles, coupled with very low incurred queueing delays, can be achieved by employing a flow admission control mechanism at the source. We consider a high intensity vehicular traffic flow regime under which vehicles that are elected to serve as RNs are generally located close to designated nominal positions, as well as lower rate stochastic traffic flow conditions. Furthermore, we demonstrate the capability of the system, when properly configured, to employ a vehicular Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA) access scheme to well emulate the operations of the system when managed by the use of spatial-reuse Time Division Multiple Access (TDMA) scheduling scheme. Our mathematical analyses and designs are well confirmed through the execution of system simulation analyses.

Index Terms—Vehicular ad hoc networks, vehicular backbone networks, IEEE 802.11p, flow admission control.

I. INTRODUCTION

The Intelligent Transportation System (ITS) along with systems that manage the flow of automatic guided vehicles are being developed for the provision of services that enhance in-road safety. Vehicles make decisions, including whether to take detour or slow down, based on receipt of critical safety messages. To secure the successful delivery of critical messages to vehicles that may be located along the highway away from the source, an implementation of a robust vehicle-to-vehicle multi-hop networking scheme is required. The resulting Vehicular Ad Hoc Network (VANET) system must be designed to support the transport of critical message flows in a manner that assures a high packet delivery ratio (PDR), guaranteeing rapid message delivery to vehicles that travel along a targeted segment of the highway.

Networking mechanisms that are based on the use of flooding oriented message forwarding approaches tend to suffer from the occurrence of broadcasting storm problems [1], caused by duplicated receptions and relaying of packets. Heuristic networking schemes that employ mechanisms such as distance based forwarding [2], [3], can incur performance degradations caused by packet losses [1]. More sophisticated mechanisms, such as those that employ cluster-based forwarding techniques described in [4], [5], often lead to performance improvement but can require the use of highly complex procedures for forming clusters and for electing cluster heads. More importantly, these existing forwarding protocols do not provide a systematic design guideline such that the optimal configuration of the system performances, including throughput rates, end-to-end delays, and packet delivery ratios, can be analytically determined.

In contrast, we offer to synthesize a VANET networking mechanism that is based on the dynamic location-aware formation of a Vehicular Backbone Network (VBN). The latter is a hierarchically structured network system, designed as a special case of the Mobile Backbone Network (MBN) system that we have previously studied [6]. In contrast with the algorithms used to manage an MBN, the VBN system is configured in accordance with the characteristics of vehicular movement along a linear highway system.

Vehicles that reside at locations that are close to predetermined nominal positions, as determined through the use of Global Positioning System (GPS) data, are elected to act as Relay Nodes (RNs), serving to forward messages to their neighboring RNs. Nominal positions are calculated by using formulas that lead to an optimized operation, achieving high throughput performance and low packet discard ratios [7]-[10].

In our recent studies of the VBN system [7]-[10], we have generally assumed the system to employ a MAC layer scheduling protocol that operates as a spatial-reuse Time Division Multiple Access (TDMA) scheme. It employs a reuse-M operation (with the reuse level M

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Corresponding author email: rubin@ee.ucla.edu.
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properly set) to effectively mitigate the impact of interference signals induced by simultaneous transmissions executed by relay nodes situated across the highway. Such an operation requires the involved vehicles to acquire and maintain slot synchronization. In turn, an asynchronous distributed operation can be implemented by using a Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA) based Medium Access Control (MAC) mechanism. However, the latter MAC scheme can lead to the occurrence of frequent packet collisions and discards. To assure high delivery ratios while attaining high throughput rates, we impose a traffic pacing mechanism at the source by regulating the minimum levels of the time durations used by the Road Side Units (RSU) to transmit flow packets. In this manner, by properly configuring the pacing operation, we demonstrate here the capability of the underlying networking mechanism to significantly reduce the probability of packet collisions. In addition, we show this operation to virtually eliminate packet queueing delays that may be incurred at elected forwarding relay nodes by exploiting the tandem queueing structure [11] represented by the synthesized backbone network that covers the linear highway system. By applying this properly configured flow pacing mechanism, we also demonstrate the ability of the CSMA/CA based IEEE 802.11p [12] MAC scheduling system to achieve performance behavior that well emulates the performance attained under the use of an optimally configured spatial-reuse TDMA scheme. The precision of the analytical models derived in this paper, serving to analyze and design the system, is well confirmed via simulation evaluations.

The paper is organized as follows. Related works are summarized in Section II. In Section III, we introduce the proposed VBN scheme, as well as present the related models. In Section IV, we present mathematical models that are used to configure the system and the flow control mechanism, and to calculate the system's performance behavior, under the assumption that elected RNs are situated very close to the designated nominal positions. These analyses are extended in Section V to account for stochastic deviations of elected RNs from such nominal positions, as incurred under random vehicular flows. In Section VI, we conduct a delay analysis of the VBN system. In Section VII, we present and discuss the performance behavior of the properly configured network system, based on the conduct of analytical and simulation evaluations. The results also well confirm the precision of our analytical models. Conclusions are drawn in Section VIII.

II. RELATED WORK

Considerable recent research work has been carried out in studying the broadcasting of message flows in VANET systems. A multitude of message forwarding mechanisms have been proposed and studied for multi-hop transport of messages in such systems. TDMA and CSMA/CA MAC scheduling schemes have been considered. Most such studies have aimed to distribute vehicular safety messages, such as those originating by a vehicle and targeted to reach other vehicles that travel in its vicinity.

Preliminary forwarding mechanisms proposed in VANET system are inspired by those developed for Mobile Ad Hoc Network (MANET) systems, often focusing on mitigating the broadcast storm problem [1] induced by the occurrence of simultaneous transmissions by restricting the number of forwarding nodes. Mechanisms that employ delay based (or Distance Based Forwarding) approaches [2], [3], [13], [14] aim to select from a group of vehicles that receive a message the vehicle that is located further away from the transmitting source of the message. Each group member will initiate a timer that will expire after a delay time that is set to be inversely proportional to the distance of the vehicle from the location of the message's source vehicle. The node whose timer expires first elects itself to act as the forwarder of the underlying message. Vehicles that hear another vehicle to forward the message, defer to the latter. Under a probabilistic based approach, vehicles elect themselves in a probabilistic manner to act as relays, with the latter probability based on their distance from the transmitter [15] or on the number of their neighbors [16], [17]. Such protocols tend to incur high packet loss rates and long distribution delays as the network size and loading levels increase.

Cluster based mechanisms [4], [5], [18], [19] have been proposed and studied as well. Vehicles that are elected to serve as cluster heads are used to coordinate message transmissions within each cluster area. Cluster-based mechanisms have generally been proven to offer enhanced and more stable performance behavior. They result in systems that can offer higher throughput rates and packet delivery ratios, at the cost of the increased overhead required in conducting the process used to elect vehicles that serve as cluster heads. While our VBN scheme is a cluster oriented scheme, it involves a sophisticated cross-layer operation (in terms of the setting of the underlying code rate, MAC scheduling parameters and a specific targeted distance between elected RNs). Also, though proven to generally outperform distance-based and probabilistic-based mechanisms, published studies of cluster-based methods have not offered mathematically tractable methods for the optimal setting of network system parameters in a manner that assures the RSU with desired performance guarantees that are essential for the distribution of public safety message flows.

Commonly studied VANET systems have been designed to employ the IEEE 802.11p CSMA/CA based MAC scheme [20], [21]. Such a mechanism supports a distributed operation while suffering from hidden terminal problems and high packet collision rates. On the other hand, a MAC scheme that is based on a TDMA protocol [22], [23] offers a more reliable message distribution setup, particularly when considering the broadcasting of public safety messages, but requires synchronization and coordination in controlling the transmission schedule which can demand excess system resources. We consequently describe in this paper a mechanism that makes use of a properly configured traffic pacing scheme, while employing a CSMA/CA MAC protocol, achieving a highly robust, high throughput and low delay performance behavior, and in this way serving to well emulate the performance behavior attained by the use of an optimally configured spatial reuse TDMA scheme.

III. SYSTEM MODEL

A. Vehicular Backbone Network

We consider the dissemination of message flows along a linear highway. An RSU continuously broadcasts messages to vehicles located in its vicinity. To extend coverage, a VANET system is used to provide for vehicle-to-vehicle packet transmissions among vehicles traveling along the road. We restrict the number of vehicles that are elected to act as RNs by introducing the concept of a dynamically configured Backbone network (Bnet). As illustrated in Fig. 1, each vehicle associates itself with an RN. An RN and its associated user stations form an Access net (Anet). Flow packets are received by all vehicles but are forwarded only by the RN vehicles that are members of the current Bnet. We configure the VBN system in a way such strives to have RNs separated from each other by a distance *D*, as shown in Fig. 1.

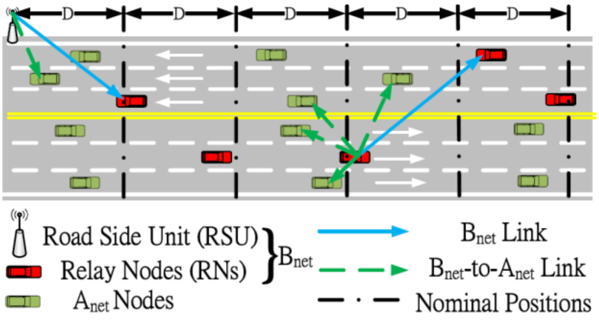

Fig. 1. The vehicular backbone network (VBN) architecture.

As we show in the following sections, the value of *D* is chosen, jointly with the setting of the transmission rate and the flow control pacing scheme, to maximize the throughput rate of the system and to achieve a high packet delivery ratio. We have separately studied such system in which RNs are separated by varying distance values; however, we have shown such a layout to not yield much improvement in the attained throughput rate.

A distributed algorithm for the self-election and dynamic re-election of RNs has also been developed and implemented [8]. Upon receipt of a control beacon from the RSU announcing the selected RNs, each vehicle is able to identify the RN with which it will associate. This can be done on a geo-location basis, whereby a vehicle associates itself with the closest RN. We note that a vehicle that is elected as a relay node serves in this role for a period of time that is dictated by the maximum deviation (from the underlying nominal position) that will be permitted (to assure limited degradation in the throughput rate that will be realized if the deviation level is beyond a certain value; we have shown the attained throughput rate to be robust to such deviations provided they are within a prescribed limit). We have shown that such a time period is of the order of a second or more even when vehicles travel at high speeds [7], [8]. This is contrasted with the time it takes an RN to transmit a single packet which is of the order of millisecond. Thus, a vehicle can engage in the forwarding of thousands of packets during the time that it is assigned the role of a relay node. To assure a reduced rate of RN re-elections, and thus also reduce the involved control overhead, we have described in [8] a distributed RN election protocol; this protocol also attached higher election priority to vehicles that travel at lower rates (residing in slower lanes). A version of this distributed election protocol, identified there as a Lane Based Election (LBE) protocol, makes use of the ability of vehicles to identify the lane in which they travel to implement an effective and highly timely and low overhead election algorithm.

B. System Models and Assumptions

Messages are issued by the RSU for broadcasting or multicasting along a linear highway of length *L*. To simplify our analysis, at no loss of generality, we consider here the forwarding of message across a road segment that is stretched on one side of the RSU. Each vehicle employs an omni-directional antenna, and uses a radio transceiver that operates in a half-duplex mode. The MAC layer scheduling protocol considered here is a spatial reuse TDMA scheme, or a CSMA/CA based protocol such as the one that follows the IEEE 802.11p VANET system protocol.

A set of nominal positions separated by distance *D* are pre-calculated for use as the positions of vehicles that will act as RNs. Vehicles that are closest to these nominal positions are elected to act as RNs, through the use of location data and control beacons issued by the RSU or neighboring RNs [7]. In this paper, we assume that the vehicular traffic density is sufficiently high so that it is possible to elect RN vehicles that are located at (or close to) the nominal positions. We have also studied the system when elected RNs are subjected to stochastic deviations from the nominal positions.

We use a simplified path loss model to calculate the signal power detected at a receiver which is located at distance *d* away from the transmitter. When considering rural or suburban areas in which vehicular transmissions across the highway are not subjected to multipath effects, such a path loss model has been found to serve as a good predictor of signal attenuation, as described by the following channel gain $G(d)$ function:

$$G(d) = G_t G_r \left(\frac{c}{4\pi f_c d_0}\right)\left(\frac{d_0}{d}\right)^{\alpha} \qquad (1)$$

where G_t and G_r are the respective transmit and receive antenna gains. $c = 3 \times 10^8$ (m/s) is the speed of light, f_c = 5.9 (GHz) is the carrier frequency, d_0 is the reference distance, and α is the path loss exponent. Typical values for α range from 2 to 4, as suggested by measurements conducted by [24]. The received power is thus expressed as

$$P_r(d) = P_t G(d) \tag{2}$$

where P_t is the transmit power level.

IV. OPTIMAL CONFIGURATION OF THE VBN SYSTEM WHEN RELAY NODES RESIDE AT IDEAL LOCATIONS

Assume the employed Modulation/Coding Set (MCS) used at the sending module to induce a code rate of R_c (bps/Hz), the assigned bandwidth to be W (Hz), so that a transmission data rate is set to $R = R_c W$ (bps). Under a prescribed targeted Bit Error Rate (BER), the corresponding required Signal-to-Interference-Plus-Noise Ratio (SINR) threshold is denoted as $\gamma_{th}(R)$.

Consider the transmission of a packet at rate R across a single inter-RN link from an $RN(k)$ to the downstream $RN(k+1)$. The neighboring RNs are at distance D from each other. To allow effective time-simultaneous transmissions of packets along the highway, we configure the system so that during the time that an RN is transmitting its packet across its inter-RN link, there will be no other transmitting RNs that are located within a range that is set equal to D_I (identified as the interference range) centered around the targeted RN receiver.

Consider a reuse-M spatial-TDMA setting. Consider a time slot at which $RN(k)$ transmits a packet to its downstream neighbor $RN(k+1)$. At the same time, other RNs may also execute packet transmissions. The two RNs that are scheduled to transmit packets at that same time and induce the bulk of interference at the receiver of $RN(k+1)$, consist of the RN that is located a range of $(M-1)D$ away from the receiver on one side and the other RN that is located at $(M+1)D$ away from the receiver on the other side. We thus define the interference range $D_I(R)$ as the corresponding distance that satisfies the following equation:

$$\gamma_{th}(R) = \frac{P_r(D)}{P_r\left(D_I(R)\right) + P_r\left(D_I(R) + 2D\right) + P_N} \tag{3}$$

where P_N is the noise power detected at the receivers of vehicles traveling along the highway.

Under a reuse-M TDMA operation, given the values of R and D, under the requirement that all packet transmissions are successful, and that admitted packets incur no queueing delays, we conclude that the highest throughput level will be achieved by setting the reuse level to the lowest M value that assures such an operation. Hence, the optimal M level to be employed is given as:

$$M^* = \left\lfloor \frac{D_I(R)}{D} \right\rfloor + 1. \tag{4}$$

We note that a level of 100% Packet Delivery Ratio (PDR) is achieved under such a TDMA scheme. The attained throughput level is equal to $\frac{R}{M^*}$ (bps). The latter also represents the flow admission control threshold level, assuring all packets that are admitted into the VBN to incur no in-transit queueing delays at intermediate RN queues, experiencing just frame latency and transmission time delays, as they traverse the tandem queueing system representing the elected RN-Bnet of the VBN. To achieve such an excellent performance behavior under the use of a CSMA/CA MAC, we follow the following lower bound in setting the carrier-sensing threshold CS_{th}:

$$CS_{th} \geq 2 \sum_{k=1}^{\left\lfloor \frac{L}{M^* D} \right\rfloor} P_r(kM^* D), \tag{5}$$

where L is the total length of the linear network. In this way, aiming the CSMA/CA system to emulate a TDMA reuse-M operation, we allow a node that is at sufficiently long range from a transmitting node to carry out its transmission in a time simultaneous manner. We have not specified here an upper bound level for the CS_{th} value noting that the possibility for simultaneous activity of nodes that reside in close proximity is largely eliminated by the use of the packet pacing mechanism at the source, by the linear topological layout, and by the tandem queueing structure of the relay backbone. We have found the default setting for this threshold to be generally applicable.

Based on the above setting, including the selection of $M^*\left(\gamma_{th}(R), D\right)$ and CS_{th}, the end-to-end throughput rate of the flow controlled network, aiming to attain 100% PDR, under CSMS/CA MAC, is expressed as:

$$TH^{ideal} = \frac{B}{\left(T_{OH} + \frac{B}{R} + \sigma \times CW_{\max} + DIFS\right) M^*} \tag{6}$$

where B is the payload size, T_{OH} represents the time it takes to transmit the frame overhead, σ is the CSMA/CA mini-slot length, $DIFS$ is the length of the Distributed Coordination Function Inter-frame Space and $CW_{\max}$ is the contention window size. The denominator expression accounts for the transmission time, the CSMA/CA overhead, the backoff time (which is conservatively set equal to the maximum contention window size) and the DCF Inter-frame Space (DIFS).

Note that this throughput rate identifies the maximum level of offered load that the system can accommodate in assuring performance at 100% PDR level. A different operating point, at which a higher throughput rate may be achieved, may be configured at the cost of providing a PDR level that is lower than 100%. However, in Section VII, we show through numerical examples that such a design to not lead to significant throughput rate improvement since the corresponding decrease in PDR is dependent in a highly non-linear manner on the resulting increase in the carried load, inducing a very rapid degradation of the PDR level as the attained throughput rate increases beyond the above calculated value.

V. SYSTEM CONFIGURATION AND TRAFFIC PACING WITH STOCHASTIC DEVIATIONS OF RN LOCATIONS

In the previous section, we consider a system for which vehicles that are elected to serve as RNs are situated at locations that correspond to specified nominal positions. In reality, due to random variations in vehicular movements, as is also the case when the vehicular density rate is lower, vehicles that are elected to serve as RNs will deviate in a stochastic manner from those nominal positions. We study in this section the impact of such stochastic deviations on the performance of the system and on the values of the parameters with which the system should be configured to operate in an optimal fashion.

For this purpose, we model the flow of vehicles along the highway as a stochastic Poisson Point Process (PPP) with density λ (vehicles/km). The applicability of this model has been confirmed by measurements that show inter-vehicle distances to be accurately modeled by an exponential distribution [25]. Given the predetermined distance *D* between nominal positions, the spatial deviations of elected RNs (the vehicles which are assumed at an election time to be situated closest to the nominal positions) from the nominal positions, denoted as Δ, are thus modeled to be governed by a truncated exponential distribution (as shown in [7]):

$$f_{\Delta}(\delta) = \begin{cases} \dfrac{\lambda e^{-2\lambda|\delta|}}{1-e^{-\lambda D}} & -\dfrac{D}{2} \le \delta \le \dfrac{D}{2} \\ 0 & o.w. \end{cases} \tag{7}$$

Following the analysis approach presented in Section IV, we proceed here to evaluate the interference region D_I, given a transmission rate *R* level (and hence the associated SINR threshold γ_{th}) and given a prescribed value of *D*. However, due to the stochastic deviations incurred in relay positions, it is not possible now to determine an interference distance level D_I that assures the system with a perfect PDR level; i.e., PDR = 100%. Instead, we note that for each selected value for D_I, there would be a probability p that a packet will not be able to be fully distributed across the highway. This event will happen when at least one of the inter-RN links (also identified often as the bottleneck link) is sufficiently long to induce an SINR at the link's receiver that is lower than that required to sustain reception at the prescribed data rate.

Considering the RN backbone network to be topologically characterized as a tandem queueing chain, we set the dominant deviation to be represented by the random variable $\Delta^{(K)} = \max\{\Delta_1, ..., \Delta_K\}$, where Δ_n are independent and identically distributed random variables, whose distribution is equal to that of Δ. We assume that the vehicular density is sufficiently high such that there exists an RN associated with each nominal station. In this case, we set $K = \left\lfloor \frac{L}{D} \right\rfloor$ to represent the number of elected relay stations located along a highway of length *L*.

Consider an inter-RN link for which the transmitter and receiver are separated by a range of $D + \Delta^{(K)}$. Assume the interference at the corresponding receiver is dominated by a signal that propagates along the distance D_I. Then, the probability that a message transmission along this link, executed at data rate *R*, will fail is given by:

$$p(D_I; D, R) = P\left\{ \frac{P_r\left(D+\Delta^{(K)}\right)}{P_r(D_I) + P_N} < \gamma_{th}(R) \right\} \tag{8}$$

For a given value of D_I, and assuming the use of a reuse-*M* MAC scheme, to assure the highest possible throughput rate, we need to select the lowest acceptable *M* value. Consequently, to assure the dominating interferer is an RN that is located a distance of D_I away, we set *M* to be given by:

$$M\left(D_I(R), D\right) = \left\lceil \frac{D_I(R)}{D} \right\rceil + 1 \tag{9}$$

Note that instead of choosing $M = \left\lfloor \frac{D_I(R)}{D} \right\rfloor + 1$ as in the ideal case discussed in the previous section, using (4), we now set *M* to a value that is computed by using the ceiling function to account for the impact of stochastic deviations. This value of *M* is then used to guide the pacing operation at the source RSU, setting the minimum time intervals between the transmissions of consecutive packets at the RSU to be equal to *M* slots.

Based on (8) and (9), under given values for *R* and *D*, using an input flow control pacing operation that is based on the calculated value for *M*, and assuming a reuse-*M* TDMA MAC scheme to be employed by the relay nodes, we calculate the value for the maximum attainable throughput rate to be given as:

$$\cdot TH^{stochastic} = \max_{D_I}\left[1 - p\left(D_I; D, R\right)\right] \times \frac{B}{\frac{B}{R} M\left(D_I\left(R\right), D\right)} \quad (10)$$

When a CSMA/CA MAC mechanism is used, we wish to show that a low delay networking operation can be executed, effectively emulating the operation and performance induced when the above configured reuse-*M* TDMA procedure is used. For this purpose, we account for the overhead embedded in the CSMA/CA operation to write the following expression for the highest attainable throughput rate under a CSMA/CA scheme, given the values of *R*, *D*, and enacting a pacing operation:

$$TH^{stochastic} = \max_{D_I}\left[1 - p\left(D_I; D, R\right)\right] \times \frac{B}{\left(T_{OH} + \frac{B}{R} + \sigma \times CW_{\max} + DIFS\right) M\left(D_I\left(R\right), D\right)}. \quad (11)$$

We use the resulting value of D_I that yields the highest CSMA/CA throughput rate and (9), to calculate the corresponding value of *M* to be employed by the CSMA/CA based RN backbone network. This value of *M* is also the one that will be used by the RSU in pacing the transmission of its packets. In this manner, we are able to assure critical packets that are distributed across the highway to experience negligible queueing delays while being transported across the backbone network. This is confirmed through the performance illustrations presented in the following section. We observe there, for the underlying illustrative scenarios, that when the operating point of the design is set in this manner, the resulting packet delivery ratio (PDR) level is generally higher than 99%.

VI. DELAY ANALYSIS

The probability distribution function of the end-to-end time delay incurred by packets that are broadcasted across the relay backbone of the VBN system is calculated in the following manner, using the results presented in [11]. We assume the system to be configured in the manner presented above, including the incorporation of the optimal pacing based flow admission control mechanism that we have described. Under such a setting, the backbone network is modeled as a tandem queueing system which is driven by the RSU source. As observed, under the application of the pacing scheme, packet queueing delays (or waiting times) incurred at relay nodes located within the network (not including the RSU node) are effectively null. Hence, the end-to-end queueing delay incurred by a packet is equal to that incurred at the RSU source.

Assuming the (application layer based) message loading rate of the source node to be lower than the throughput capacity rate calculated by us for the configured system, the queueing of packets at the source is determined by the steady-state distribution of the queueing delay (or waiting time) distribution incurred at a source node that is modeled as a *G/G/1* node. For example, when messages arrive at the RSU in accordance with a Poisson process, the RSU node is modeled as an *M/G/1* queueing system, whereby the effective service time of a message, $T = E\left[S_{RSU}\right]$, is set equal to the time interval of the pacing process.

By then using the Pollaczek-Khintchine Equation (PKE), we obtain a mathematical expression for the end-to-end mean message waiting time $E\left[W\right]$, expressing the mean time that a message waits in the RSU system prior to the start time of its transmission. As noted above, this value also expresses that aggregate end-to-end mean waiting of a packet as it flows across the backbone queues.

The end-to-end mean message delay $E\left[D\right]$ of a packet, expressing the total time incurred to deliver the message across the highway, is then calculated as:

$$E\left[D\right] = E\left[W\right] + E\left[S_{RSU}\right] + KE\left[S\right] \quad (12)$$

where K represents the number of RNs established along the highway, and $E\left[S\right]$ represents the effective transmission time of a packet frame by an RN. When a CSMA/CA MAC frame is used, we note that the effective transmission time duration accounts for the time it takes the MAC entity to complete the transmission of its MAC frame, which can be approximated as follows:

$$E\left[S\right] = \frac{B}{R} + T_{OH} + \sigma \times E\left[CW\right] + DIFS \quad (13)$$

where is the average length of the backoff timer.

For example, when the RSU queueing system is modeled as an *M/D/1* queueing system (assuming messages to arrive in accordance with a Poisson process and packets to be of fixed length), we have

$$E\left[W\right] = \frac{T}{2\left(1-\rho\right)} \quad (14)$$

where $\rho = \eta E\left[S_{RSU}\right] = \eta T < 1$ is the traffic intensity parameter, noting that η is the packet arrival rate and T is the effective service time of a packet by the RSU transmission module. The end-to-end mean packet delay (at steady state) is then given as

$$E\left[D\right] = E\left[W\right] + T + KE\left[S\right] \quad (15)$$

VII. PERFORMANCE EVALUATIONS: NUMERICAL V.S. SIMULATION RESULTS

In the following, we illustrate the system's performance behavior and the selection of the best design parameters, as well as compare our analytical results with simulation based evaluations. We have developed a C++ based simulation program for the purpose of studying the behavior of the vehicular networking systems and mechanisms presented in this paper. We present results that exhibit the attained end-to-end throughput rate performance of a VBN system in which a single source RSU is active, multicasting an ongoing flow of packets across the highway, aiming to reach (at a high PDR) all highway vehicles distributed across a stretch of the highway that is *L* (km) away from the RSU.

Throughout the simulation, the CSMA/CA based 802.11p MAC layer protocol is used. The length of this highway is equal to *L*=6 (km). The other simulation parameters are set as follows: (dB), $f_c = 5.9$ (GHz), $d_0 = 1$ (m), and $P_N = -104$ (dBm). The payload size of a packet is *B*=2000 (Bytes). The contention window size is set equal to 16 (CSMA/CA slots). The vehicular traffic density follows the statistics of a Poisson point process with parameter $\lambda = 100$ (vehicles/km).

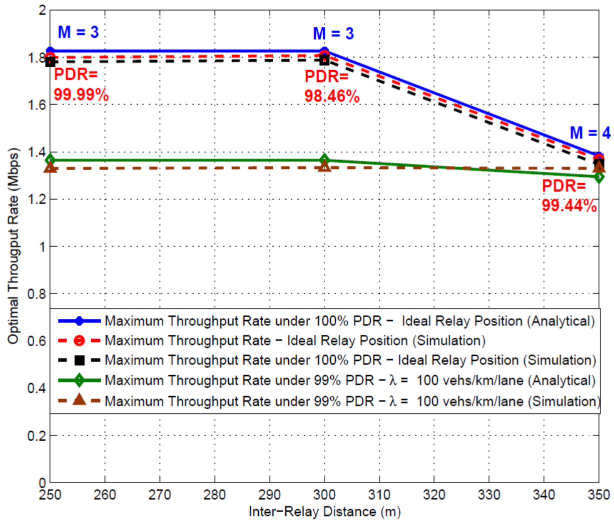

Fig. 2. End-to-end throughput rate for *R* = 6 (Mbps)

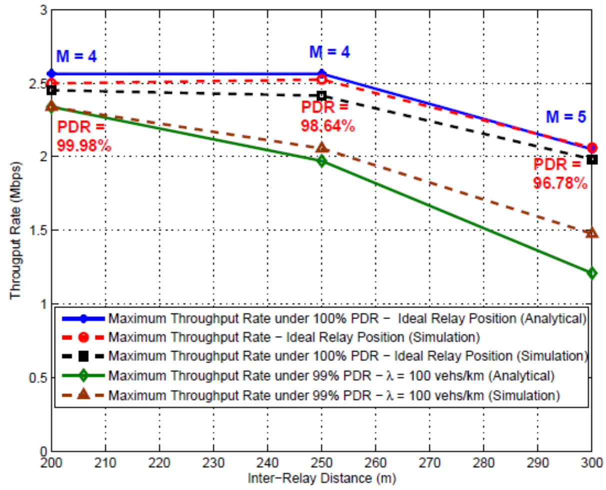

Fig. 3. End-to-end throughput rate for *R* = 12 (Mbps).

A. RNs Elected at Nominal Positions

We first consider a highway that is subjected to a high vehicular traffic flow rate so that RNs are assumed to be located at designated nominal locations. In Figs. 2, 3, 4, and 5, we display the throughput rates vs. *D* performance behaviors for operations that use different code and data rate *R* values when operating at the corresponding optimal (with respect to the underlying *D* and *R* values) reuse levels *M*. We show the throughput rates attained by the emulating CSMA/CA schemes as calculated by using our analytical formula (blue curves), and the results obtained by simulations. For the latter, we show in black curves the performance attained under targeted PDR = 100%; and in red curves, we exhibit the performances of systems that are configured to attain the highest throughput rates (among such MAC schemes and configurations) while yielding imperfect PDR values (which are noted in the graphs).

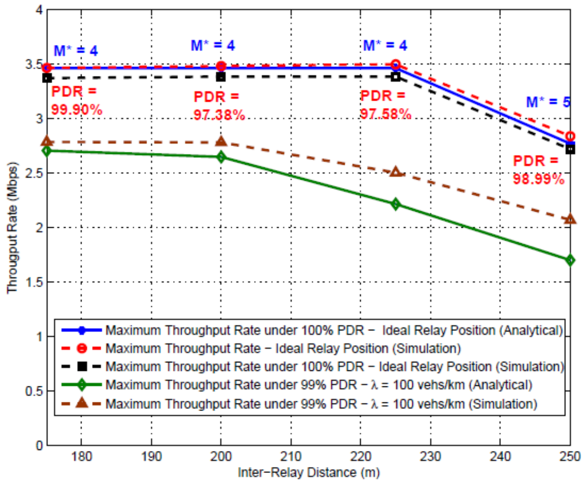

Fig. 4. End-to-end throughput rate for *R* = 18 (Mbps)

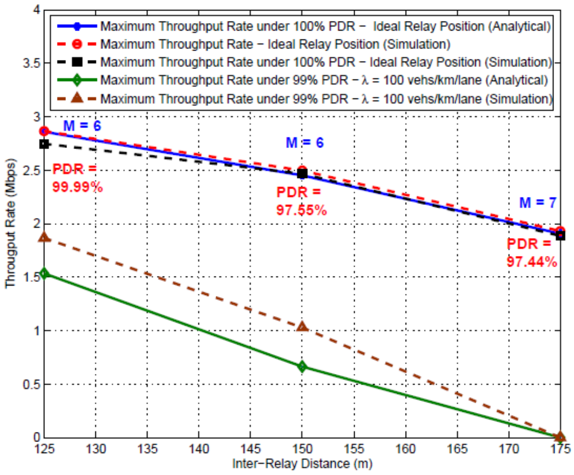

Fig. 5. End-to-end throughput rate for *R* = 24 (Mbps)

The following observations are drawn. The results confirm the precision of our analytical calculations (represented by the blue lines), noting the latter to well match the performance behavior results obtained through simulations (red and black dashed lines), for all considered inter-relay distance and transmission rate values.

We note that the inter-relay distance (*D*) is selected such that only one receiving RN resides in the forwarding range of a transmitting RN. Since the data traffic pacing operation yields 100% PDR, we do not need to provide for potential benefits that may be attained by allowing additional relay nodes to receive the transmission of the same packet, since we have designed the system to incur a very low probability of packet collision. We also note that the latter design does not lead to an increase in the systems throughput rate while potentially inducing higher interference levels and longer multi-hop packet routes.

We observe that as the inter-relay *D* distance increases, the throughput rate generally decreases, since the interference range D_I then increases and a higher value for *M* must be set. We can also see that when we operate at a higher transmission rate, the value of *M* needs to be set higher (for example, we set $M = 4$ for $R = 6$ (Mbps) and $M = 6$, 7, or 9 for $R = 24$ (Mbps)). This is induced by having to require a higher SINR threshold level as R increases, and consequently inducing a higher value for $D_I\left(R\right)$.

Such tradeoff leads us to the joint optimal selection of $\left(R, D\right)$ to achieve the highest throughput rate under the guarantee of 100% PDR level. The joint optimization solution leads to setting the optimal $\left(R, D\right)$ pairs to be: *R*=18 (Mbps) with *D* chosen between 180−225 (m), achieving an end-to-end throughput rate of 3.4 (Mbps).

We have also examined the maximum attainable throughput rate levels when PDR levels that are lower than 100% are acceptable. We have found the corresponding operating points to achieve throughput rates that are only negligibly higher, while yielding PDR values that span the range 96%−99%, in examining all transmission rate and *D* settings. This is explained by noting the highly non-linear performance behavior of the PDR value as a function of the admitted load rate.

We note that in our simulations, we have set the selected values for *D* to be greater than half of the forwarding range; the latter is defined as the maximum transmission distance realizable under the absence of any interference sources, under a given transmission rate. In this manner, we guarantee that there is only a single RN that resides within the forwarding range of the RN transmitter, eliminating the possibility that more than one vehicle will be receiving the same packet and then transmitting it simultaneously by selecting the same value of the backoff counter, causing with probability $\frac{1}{CW_{\max}}$ a packet collision event. Such an occurrence is undesirable when aiming to configure the system to yield a high packet delivery ratio for the effective distribution or critical messages.

B. Impact of Stochastic Deviations

In Fig. 2, Fig. 3, Fig. 4, Fig. 5, we display the throughput rate performance attained under stochastic deviations incurred in the positions of elected RNs. The carrier sense threshold levels are chosen to satisfy (5). We note that the attained value for the throughput rate becomes more sensitive to stochastic deviations as the data rate level is increased. For instance, when *R*=6 (Mbps), we experience a 20% loss in the throughput rate level due to stochastic deviations; while under *R*=24 (Mbps), the throughput degradation level reached 30% under a properly select *D* level. In turn, much higher degradation levels can be incurred at high data rates if the value for *D* is not properly configured. The best parameters to use for configuring the system are noted to be given by the use of a 18 (Mbps) data rate and a specification of an inter-RN distance of *D*=175 (m), for both the non-stochastic and stochastic traffic cases. Under this setting, when a stochastic vehicular traffic flow model is used, we observe the optimized networking configuration to sustain a throughput rate of 2.8 (Mbps) with PDR greater than 99%. In comparison, we note that under the non-stochastic setting the attained throughput capacity rate is equal to 3.5 Mbps with a PDR level of 100%.

Thus, impacted by the stochastic deviations in the positions of elected relay nodes, it is not feasible to guarantee a PDR level of 100%. This is induced by the possibility of an existence of an inter-RN link whose range is longer than the realizable forwarding range (at the underlying data rate). Yet, the joint operation and configuration of the system in a manner derived in this paper, while engaging also in a flow admission control pacing oriented operation, guarantees a PDR level that can be generally as high as 99%. In fact, such a high packet delivery ratio level can be sustained when operating at any one of the examined data rates, when properly configuring the pacing based flow control operation.

Our performance evaluation results well confirm the precision of our mathematical in predicting at high precision the realized end-to-end throughput rates, under all examined values of *R* and *D*, given a high, yet reasonable, value of the vehicular density λ. The analytical values provide lower bounds on the estimated values of the throughput rates by incorporating the maximum possible value of the CSMA/CA contention window size. The calculated performance estimates are noted to be more accurate at low transmission rates, in which case the packet transmission time becomes a dominating component in the calculation of the throughput rate. A higher accuracy of the derived formula can be achieved by replacing in (11) the maximum contention window size by the average contention window size, particularly when operating at higher transmission rates, in which case the impact of the value set for the backoff counter on the throughput rate level becomes more significant.

VIII. CONCLUSIONS

We study the reliable delivery of public safety message flows across a vehicle-to-vehicle wireless VANET. The VANET network is synthesized through the use of a Vehicular Backbone Network (VBN) approach, under which vehicles that reside closest to targeted nominal positions are elected to serve as RNs.

The analysis presented in this paper focuses on a highway system that is subjected to relatively high vehicular traffic flow rates, so that it is generally feasible to elect vehicles that reside in close proximity of targeted nominal positions to act as relay nodes. Yet, we also demonstrate design approaches to a system that is subjected to lower vehicular traffic rates, inducing stochastic variations in the positions at which elected relay nodes are located.

We show that when employed in conjunction with the use of a reuse-M TDMA operation, with properly employed values for M, and using optimal settings for the inter-RN distance and the code rate levels, the VBN system exhibits a high throughput rate and no (or minimal) in-transit packet loses and queueing delays.

Furthermore, we show that when properly configured, the corresponding VBN system which employs a CSMA/CA MAC is able to effectively emulate the performance behavior achieved under the spatial TDMA MAC scheme, realizing the performance of a centralized operation under a distributed mechanism.

The results presented in this paper are also of prime importance for the design and activation of a backbone network that consists of relay stations that are placed in a static (or quasi-static) manner along the highway (such as at highway intersection points, on traffic lights, and at strategic locations). Consider then the use of a dedicated frequency band of such a backbone network for the multicasting of packets issued by a RSU station across the highway. Using the results of this paper, we can proceed to configure the backbone network by identifying the message pacing and flow admission control process to be employed by the RSU, by specifying those relay stations that should be activated to form the backbone network, and by configuring their corresponding optimal communications network system parameters. In this way, we enable the resulting backbone network to forward message flows across the highway in a high throughput and low end-to-end message delay manner.

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Izhak Rubin received the B.Sc. and M.Sc. from the Technion - Israel Institute of Technology, Haifa, Israel, and the Ph.D. degree from Princeton University, Princeton, NJ, all in Electrical Engineering. Since 1970, he has been on the faculty of the UCLA School of Engineering and Applied Science where he is currently a Distinguished Professor in the Electrical Engineering Department. Dr. Rubin has had extensive research, publications, consulting, and industrial experience in the design and analysis of commercial and military computer communications and telecommunications systems and networks. Such design and analysis projects include network systems employed by the FAA for air traffic control, terrestrial and satellite based mobile wireless networks, high speed multimedia telecommunications networks, advanced cellular cross-layer operations, mobile backbone ad hoc wireless networks, mechanisms to assure network resiliency and automatic failover operations. At UCLA, he is leading a research group in the areas of telecommunications and computer communications networks. He serves as co-director of the UCLA Public Safety Network Systems Laboratory. During 1979-1980, he served as Acting Chief Scientist of the Xerox Telecommunications Network. He served as co-chairman of the 1981 IEEE International Symposium on Information Theory; as program chairman of the 1984 NSF-UCLA workshop on Personal Communications; as program chairman for the 1987 IEEE INFOCOM conference; and as program co-chair of the IEEE 1993 workshop on Local and Metropolitan Area networks, as program co-chair of the 2002 first UCLA/ONR Symposium on Autonomous Intelligent Networked Systems (AINS), and has organized many other conferences and workshops. He has served as an editor of the IEEE Transactions on Communications, Wireless Networks journal, Optical Networks magazine, IEEE JSAC issue on MAC techniques, Communications Systems journal, Photonic Networks Communications journal, and has contributed chapters to texts and encyclopedia on telecommunications systems and networks. Dr. Rubin is a Life Fellow of IEEE.

Yu-Yu Lin received the B.S. degree in Electrical Engineering and Computer Science Honors Program from National Chiao-Tung University, Hsinchu, Taiwan, in 2008, and the M.S. degree in communication engineering from National Taiwan University, Taipei, Taiwan, in 2010. He is currently working toward his Ph.D. degree in the Electrical Engineering Department at the University of California, Los Angeles. During 2012, he worked as a research assistant in the Intel-NTU Science and Technology Center for Connected Context Computing, where he participated in the development of game theoretical analysis for cognitive radio and cooperative complex networks. He is the recipient of the 2013-2014 Graduate Dean's Scholar Award of UCLA. His current research interests include the cross design of networking protocols of vehicular ad hoc networks and power line communications networks.

Andrea Baiocchi received his "Laurea" degree in Electronics Engineering in 1987 and his "Dottorato di Ricerca" (PhD degree) in Information and Communications Engineering in 1992, both from the University of Roma "La Sapienza". Since January 2005 he is a Full Professor in the Department of Information Engineering, Electronics and Telecommunications of the University of Roma "Sapienza". The main scientific contributions of Andrea Baiocchi are on traffic modeling and traffic control in ATM and TCP/IP networks, queueing theory, and radio resource management. His current research interests are focused on congestion control for TCP/IP networks, wireless access interface protocols, specifically for VANET applications, and on traffic analysis and monitoring. Andrea's research activities have been carried out also in the framework of many national (CNR, MIUR) and international (European Union, ESA) projects, also taking coordination and responsibility roles. Andrea has published about one hundred and twenty papers on international journals and conference proceedings, he has participated to the Technical Program Committees of almost sixty international conferences; he also served in the editorial board of the telecommunications technical journal published by Telecom Italia for ten years.

Francesca Cuomo received her "Laurea" degree in Electrical and Electronic Engineering in 1993, magna cum laude, from the University of Rome Sapienza. She earned the Ph.D. degree in Information and Communications Engineering in 1998 (Univ, Rome Sapienza). From 2005 she is Associate Professor at the University of Rome Sapienza and teaches courses in Telecommunication Networks. Prof. Cuomo has advised numerous master students in computer engineering, and has been the advisor of 8 PhD students in Networking. Her current research interests focus on: Vehicular networks and Sensor networks, Cognitive Radio Networks, Reconfigurable radio systems, Energy saving in the Internet and in the wireless system. She has participated in several National and European projects on wireless network systems such as the RAMON, VICOM, INSYEME, IST WHYLESS, IST EPERSPACE, IST CRUISE. Francesca Cuomo has authored over 90 peer-reviewed papers published in prominent international journals and conferences. She is an IEEE Senior Member. She has been in the editorial board of the Elsevier Computer Networks journal and now is member of the editorial board of the journal Ad-Hoc Networks (Elsevier). She has been the TPC co-chair of several editions of the ACM PE-WASUN workshop.

Pierpaolo Salvo received his master degree cum laude in Telecommunications Engineering from the University of Rome "Sapienza" in January 2010. He is currently a Ph.D. student at the Faculty of Engineering of the University of Rome "Sapienza". From April 2010 to March 2011, he worked in the CNIT laboratory of the University of Rome "Sapienza", as the winner of the annual scholarship for graduates of the CNIT (National Interuniversity Consortium for Telecommunications) related to the project TERI (Telecommunication Research in Italy). From December 2010 to June 2011, he participated to the project "In.Sy.Eme", whose main aim was the establishment of an integrated system to support communications and information processing during the intervention in emergency scenarios. From November 2010 to now, he takes part in the “ICT Action IC0902 – Cognitive Radio and Networking for Cooperative Coexistence of Heterogeneous Wireless Networks”, supported by the EU RTD, which aims to integrate the cognitive capabilities in all the layers of a communication system, with the aim to establish a European platform for cognitive radio networks. In February 2011, he achieved the certification: Certification for AMTEC External Security Professional (Elsag Datamat). In May 2011, he received the degree award in 2011 from the “Fondazione Roma Sapienza” in the information engineering area.