GPS aided inter-vehicular wireless networking

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***Abstract*—To support in an efficient way infotainment and public safety multicast applications in Vehicular Ad-Hoc Networks (VANET), a fundamental aspect is the optimization of the broadcast capacity. The objective is to disseminate packet flows to a wide set of vehicles by extending the coverage area of the broadcast packet flows distributed from a Road Side Unit through the use of vehicle-to-vehicle multi-hop communications. To this aim, we synthesize and study Vehicular Backbone Network (VBN) systems. Several vehicles that are situated along the highway are dynamically self elected based on their locations along the highway, to act as relay nodes that disseminate and forward flow packets. We analytically provide rationale for the criteria to be used in electing relay nodes. This is based on the computation of targeted optimal geographical positions for them under which the system's broadcast capacity is maximized, while striving also to reduce the number of elected relay nodes.**

I. INTRODUCTION

Vehicular networking has significant potential to enable applications associated with traffic safety, info-mobility, urban sensing and info-tainment [1][2]. The interest in this area is proved also by the definition and use of specific standards, namely the IEEE 802.11p and 1609, to support Wireless Access in Vehicular Environment (WAVE) and to deliver safety and non-safety applications to vehicles on the road [3].

A key component for providing services by using VANETs involves the use of data broadcasting that allows users in vehicles to receive information relevant to an event that is detected on the road as well as to receive data from a road oriented infrastructure, through the Road Side Unit (RSU) [4] [5]. Several solutions have been proposed for data broadcasting with the goal of addressing the broadcast storm problem, extending the coverage area, and controlling the dissemination delay. A key development, among many works, that have been carried out to deal with the broadcast storm problem in VANETs is the Distance Defer Transmission (DDT) scheme presented in [6]. The DDT approach is based on a simple but quite effective way for reducing redundant rebroadcasts and consequently ensuing medium contentions and collisions. It assigns the tasks of relaying messages in each neighborhood solely to the receiver that is located farthest away from the sender. Under the Road Oriented Dissemination (ROD) protocol [7], data is disseminated separately in each direction, aiming to optimize data dissemination at an intersection. To fulfill their goals, these schemes make use of vehicular GPS positions, which are inserted in the header of broadcast messages.

A different approach has been described in [8]. The authors propose the Urban Multi-Hop Broadcast (UMB) protocol that selects the vehicle that is located farthest away from the transmitter to relay a message, and uses repeaters at intersections to retransmit messages to overcome the problem of large buildings obstructing a message path. The objectives of UMB are to avoid MAC collisions caused by hidden nodes, to improve the efficiency of channel use, to upgrade the reliability of message transmissions, and to disseminate messages in all directions at an intersection.

In comparison with the bulk of previously published papers, our focus here involves broadcasting for a different kind of applications, namely info-tainment and public safety based multicasts. In this paper, we present a networking approach for this purpose. Our key performance objective is to maximize the aggregate broadcast flow rate that can be accommodated (while avoiding network system overloading), which represents the system's broadcast throughput capacity rate *broadcast capacity* [9] that can be sustained in the considered dissemination area. To this aim, we leverage two main concepts: multi-hop communications and a double-tier communication structure based on a backbone. See the use of the concept of two layer hierarchical systems for general mobile ad hoc wireless networks in [10] and the references therein, where such Mobile Backbone Network, MBN, systems are synthesized and studied (noting that the approach there is not based on targeted distance or grid location specifications for placing backbone nodes, as performed here).

Multi-hop networking methods have been extensively used in VANETs to extend the coverage area and to disseminate information (e.g., in [8], [11]) and in general to route unicast data. Two tiered hierarchical structures have been introduced in the framework of well known clustering schemes. The work of [12] forms and exploits a backbone of vehicles, called Backbone members (BM), for an efficient broadcasting of alert messages in VANETs. They propose a Dynamic Backbone Assisted MAC (DBA-MAC) protocol for relaying broadcast messages in a reliable and fast way.

In contrast with previously published papers, we embed in the networking approaches presented herein mechanisms that address issues relating to the broadcasting process (i.e., the broadcast storm problem and the desired wide scope coverage area) while achieving a high throughput capacity level of the

VANET wireless network, by synthesizing a network system that aims to limit the impact of interference signals induced by concurrent transmissions and consequently employ optimal adaptive rate cross-layer networking operations.

The rest of the paper is organized as follows. Section II sketches the basic idea of the Vehicular Backbone Network (VBN) and introduces the VBN approach. Section III provides mathematical analysis of the VBN system and derives a model that can be used to determine the best values to be selected for the targeted distances between vehicles elected to act as relay nodes (RNs) in forming the backbone of the VBN. Finally, Section IV concludes the paper and sketches key objectives for future work.

II. BASIC PRINCIPLES FOR BUILDING A VBN

The basic idea of the Vehicular Backbone Network (VBN) scheme is to have, at any given instant of time, certain vehicles elect themselves as relay nodes (RNs). RNs act as base stations do in a cellular network, except that they are mobile, dynamically elected, and may serve as backbone forwarding nodes for a limited period of time, and/or for a limited number of packets. In this way, vehicles are divided into two hierarchically distinct sets. The backbone network (B_{Net}) consists, at each instant of time, of elected RNs and the communications links that interconnect them. For each RN, the remaining vehicles and access channels associated with this RN form the so called A_{Net} (vehicular access network). Thus, a single A_{Net} consists of the vehicle that acts as a local RN and the non-RN close-by vehicles (also identified as its clients) that associate with it. Client vehicles communicate with their RN across the A_{Net}. They receive broadcast data by detecting packet transmissions issued by their associated RN across their A_{Net}'s broadcast wireless channel. When having to send a packet to the RSU (or to other vehicles along the highway), a non-RN client vehicle sends its packets to its associated RN across its A_{Net}'s multi-access wireless channel. The latter RN then initiates the transport of the packet to its destination (e.g., to the RSU) across the vehicular B_{Net}. Though the networking structure described herein is intended to be employed for such joint unicast/multicast flows over a two dimensional highway system, we note that in this paper, however, we focus on the synthesis and analysis of a network that serves the downstream distribution of broadcast flows from the RSU to highway vehicles traveling along a single linear highway road. Once a vehicle that acts as a RN transmits a message, the latter is received by its neighboring RNs as well as by its A_{Net}'s client nodes. A picture representing an example of the communications paradigm considered in this paper is shown in Figure 1.

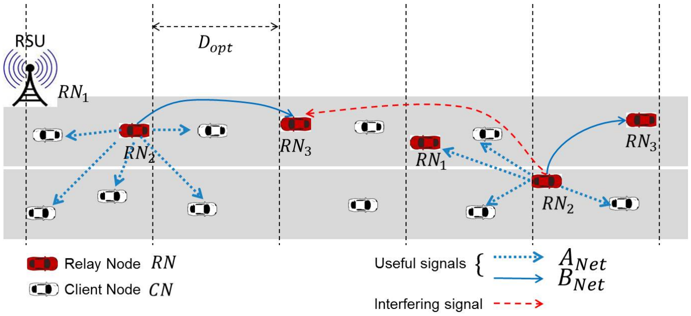

Fig. 1. Illustrative designations of desired relay positions along a linear road of two lanes. Red vehicles are the elected RNs; CNs designate vehicles that are in the transmission range of a RN, capable of receiving the useful signal relayed by their RN.

The general concept behind the setting of the preferred locations at which it is advantageous to elect vehicles to serve as RNs is explained as follows. If during any period of time, and over a given geographical space, we can regulate the positions at which RNs are located, we can then proceed to manage and predict the interference power and SINR values induced at such designated RN receivers. This allows us to engage in effective adaptive-rate cross-layer operations. Making use of these targeted SINR levels, we are able to best select a preferred modulation/coding set (MCS) to be used across each backbone link. Through such a combined dynamic adaptation of the backbone network topological layout and of the employed data link data rates, we aim to attain a high throughput rate level. Furthermore, it is generally essential to reduce the end-to-end delay incurred by a broadcast packet that is distributed across the highway system. For this purpose, we also aim to effectively reduce the number of RNs that a packet must traverse along the highway.

The protocol stack architecture involving the entities discussed for the VBN protocol, is made up of a physical layer equipped with multiple modulation/coding schemes, a MAC layer supporting either CSMA/CA, like in IEEE 802.11p, or a TDMA based scheme. As in the ETSI ITS architecture, we design additional layers, including Access Control, Network and Transport, Facilities and Application layers. The intelligence conveyed by the algorithm used to elect RNs, and to induce such nodes to forward packet flows across the B_{Net}, is embedded in a Forwarding (sub)Layer (FL), which can be implemented in the application (which can be service specific) and/or network layers of the protocol stack noted above. In this paper, we make use of only a broadcast MAC layer service; the intelligence for selective forwarding, to avoid the broadcast storm induced issue of flooding, lies entirely in the FL. The VBN protocol makes use of information collected at the Facilities Layer, which includes statistical parameters relating to signal propagation across the communications channel and vehicular movement and traffic process parameters, as monitored and collected by the vehicle. This can be used to adapt the target value of the designated inter-RN range, $D(\alpha, \lambda)$. Forwarding can be enhanced via a retransmission mechanism based on overhearing implicit ACK of broadcast packets, which do not envisage explicit ACK messages at the MAC layer, and an Automatic Rate Fallback mechanism that is used to adjust the link MCS and transmission bit rates.

We assume that a signaling procedure is defined to elect relay nodes by a distributed message exchange on the Control CHannel (CCH). As a matter of example, an in-depth discussion and evaluation of such a procedure is given in [12][13]. A relay node sends a SEEK_CANDIDATE message with its coordinates and a direction flag; every node along the tagged direction sets a timer whose value is a decreasing function of the distance from the receiving and the clsest nominal relay location and schedules the transmission of an ELECT control message as soon as the timer expires. A node receiving an ELECT message cancels its own scheduled message transmission. The first sent ELECT control message determines the winner of the election run in each link neighborhood. The node that has triggered the entire procedure acknowledges the ELECT message with ELECT_ACK. This three way handshake procedure is defined in the DBA-MAC by L. Bononi and colleagues [12].

Once a node is elected as a relay it uses a Service CHannel (SCH) to send data. The SCH use schedule is defined in the election process. Each relay node defines a multi-frame of order three, based on the DSRC frame[1]. As depicted in Figure 2, an elected relay node follows a reuse-three schedule on the selected SCH. First it receives data from its upstream node (depicted as a “blue” period of time in the figure). At the following frame, in the second half when it can access the SCH, the node forwards the received data to the next relay (transmit phase: “red” period of time in the figure). In the following frame (and last frame of the time division access cycle), the node listens to the SCH channel to check how much of the data it has just forwarded is sent forward by the intended downstream relay node (overhear phase: “black” period of time in the figure). This provides also an indirect ACK of the reception of data by the downstream forwarder, in case no explicit ACK has been sent in the previous phase[2].

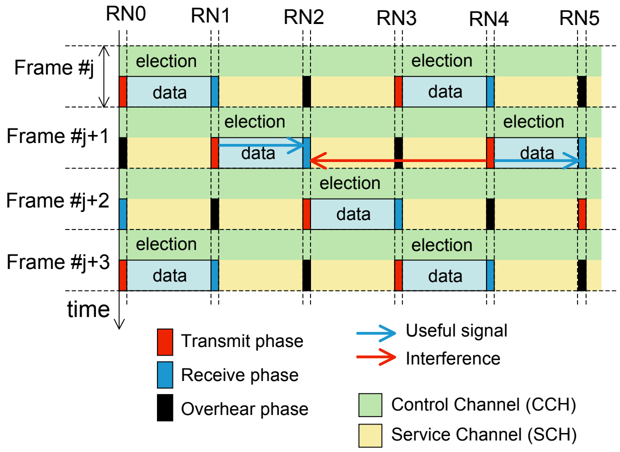

Fig. 2. Example of data schedule of order three by using a Service CHannel (SCH); relay node election takes place in the Control CHannel (CCH).

In the following Sections, we address the analysis of this paradigm first in an idealized setting where Relay Nodes (RNs) are placed precisely at designated nominal positions. Then we present the results of our analysis concerning the impairments induced by the election of vehicles to act as RNs when such vehicles are located at random distances from those designated nominal RN locations due to the stochastic nature of the vehicular traffic process.

III. BROADCAST CAPACITY ANALYSIS AND MODELS

We carry out performance analysis of the VBN system by deriving its broadcast capacity rate in two phases. In the first phase, we consider an idealized setting where vehicles that elect themselves to act as relays (RNs) are able to position themselves in preferred geographical locations in a stationary manner (Section III-A); for example, while parking, or when moving at a relative slow speed. Our second phase analysis accounts for the impairments brought about by vehicular movements, inducing, at times, vehicles that are elected as RNs to locate at highway positions that display random deviations from their ideally targeted locations (Section III-C). We show that, for each underlying vehicular density level, there exist optimum values for the data rate and for the targeted inter-RN distance that should be configured.

In both cases, we consider a linear road, assuming the RSU to be located at $x = 0$. Using our backbone based and spatial time division oriented MAC schemes, we aim to evaluate the capacity rate attainable across backbone links and along the highway in supporting the end-to-end delivery of broadcast flows that are initiated at the RSU. The link capacity C_L represents the throughput capacity rate attained across a (single hop) mobile backbone link, when averaged over all such dynamically established links. The broadcast capacity C_B represents the throughput capacity rate of information delivered from the RSU to vehicles that are distributed across the highway; such vehicles are assumed to be located at a distance of up to ℓ away from the RSU, on both sides. It thus represents the throughput capacity rate achieved in delivering packet flows originating at the RSU over a road span of length 2ℓ. To evaluate the achievable capacity level, we use Shannon’s formula for the link’s AWGN channel (assuming interference is akin to white noise). This amounts to assuming the availability of a continuous set of modulation and coding sets (MCS), operating at best code rates. Practical adaptive schemes attain code rate results that are often close to those given by this relationship. Thus, the attainable channel capacity rate (assuming a low bit error rate target level) is calculated as $W \log_2(1 + \text{SINR})$, where W is the allocated bandwidth level ($W = 10\ MHz$ in case of a DSRC channel according to WAVE or ETSI standards) and SINR is the Signal to Interference+Noise Ratio monitored at the link’s receiver, namely $\text{SINR} = P_{tx}G(d)/(P_N + P_I)$, where $G(d)$ is the path gain at distance d, P_N and P_I are, respectively, the noise and interference received power levels. We have $P_N = N_0 W$, where N_0 is the white noise spectral density, commonly set for

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[1] In DSRC a frame of duration 100 ms is defined. It is split into two subframes, of equal duration. In the first half, the OBU has to listen (and possibly transmit) on the CCH. In the second half of the frame it can switch to a SCH.

[2] Note that if the broadcast mode of MAC layer is used, all locally connected nodes can receive the data, not only the downstream forwarder.

such systems to be equal to $-174\ dBm/Hz$. In the numerical examples of this Section we assume $P_{tx} = 500\ mW$.

The employed propagation model accounts for a deterministic path gain[3] that depends on the distance between the transmitter and the receiver. A classic model for $G(d)$ is $G(d) = \kappa(d_0/d)^\alpha$ for $d > d_0$, with $\kappa = G_{tx}G_{rx}[c/(4\pi f_c d_0)]^2$. This is referred to as single exponent Path Loss Model (PLM). In the following we assume no antenna gains, $G_{tx} = G_{rx} = 1$, and $c = 3 \cdot 10^8 m/s$, $f_c = 5900\ MHz$ and $d_0 = 1\ m$. With these values $\kappa = -47.86\ dB$. Besides the single exponent PLM, we use also a two exponent path loss model (2exp PLM), synthesized from highway measurements in [1]. With that model, the path loss exponent changes value at a cross over distance of $d_c = 120\ m$, being $\alpha = \alpha_1 \approx 2.07$ for $d < d_c$ and $\alpha = \alpha_2 \approx 3.94$ for $d > d_c$.

A. Broadcast capacity with nominally placed RNs

Assume that RNs are located at positions $x_{0,k}, k \in \mathbb{Z}$. Let $C_{L,k}$ denote the capacity of the link between RNs k and $k+1$. Then $C_B = \eta \min_{k \in \mathcal{R}(\ell)} C_{L,k}$, where $\mathcal{R}(\ell)$ is the set of RNs that are situated within a distance ℓ of the RSU and η is the spatial reuse factor (expressing the average number of simultaneous transmissions executed across the backbone network). We note that the throughput rate is limited by the (bottleneck) link that implements the lowest rate. Hence, assuming system and communications conditions to be spatially homogeneous, it will be most efficient to configure the system such that consecutive RNs are spaced D apart from each other, starting from the RSU, so that the corresponding RN desired locations on each side of the RSU are: $x_{0,k} = kD$.

Consider an RN that transmits its packets (across the B_{Net}) to its neighboring next RN, which is located a distance D away. The received power is $G(D)P_{tx}$. Assume pipelined transmission of broadcast flow packets to take place (so that multiple simultaneous transmissions of packets take place along the highway, at a given instant of time), using a MAC layer scheduling scheme that achieves reuse factor given as $\eta = 1/M$. As a matter of example, a reuse-M scheme can be achieved by using a time division schedule, with $1/M$-th of each time frame devoted to packet transmissions by a single relay in each chain of M consecutively placed relays. Then, the interference power monitored at each such RN receiver is given by $P_I = P_{tx}\sum_{k=0}^{\infty}[G(y_{r,k}) + G(y_{l,k})]$, where $y_{r,k} = (M-1)D + kMD$ and $y_{l,k} = (M+1)D + kMD$, for $k \geq 0$. The resulting SINR level detected at the receiver is equal to SINR $= \frac{G(D)P_{tx}}{P_N + P_I}$. In the following, we develop mathematical expressions by assuming a single exponent path loss model, i.e., $G(d) = \kappa d_0^\alpha d^{-\alpha}$ for $d > d_0$. Then, we have

$$SINR = \frac{\frac{\kappa d_0^\alpha P_{tx}}{D^\alpha}}{P_N + \frac{\kappa d_0^\alpha P_{tx}}{D^\alpha}\xi_M(\alpha)} \quad (1)$$

with $\xi_M(\alpha) \equiv \sum_{k=1}^{\infty}\left[\frac{1}{(kM-1)^\alpha} + \frac{1}{(kM+1)^\alpha}\right]$. As an example, we have $\xi_3(2.5) = 0.255$, $\xi_3(3) = 0.158$ and $\xi_3(3.5) = 0.103$. For compact notation, we define the SNR at D as $\gamma(\alpha, D) \equiv \kappa d_0^\alpha P_{tx}/(D^\alpha P_N)$. The link capacity rate is then given by:

$$C_L = W \log_2\left(1 + \frac{\gamma(\alpha, D)}{1 + \gamma(\alpha, D)\xi_M(\alpha)}\right) \quad (2)$$

For a given value of M, for the RSU initiated broadcast application under consideration, noting that the RSU is given the opportunity to transmit packets for a single slot during each M-slot time frame, the broadcast capacity of the highway network is

$$\begin{aligned} C_B = \frac{C_L}{M} &= \frac{W}{M}\log_2\left(1 + \frac{\gamma(\alpha, D)}{1 + \gamma(\alpha, D)\xi_M(\alpha)}\right) \\ &= \frac{W}{M}\log_2\left(1 + \frac{\gamma_0}{\hat{D}^\alpha + \gamma_0\xi_M(\alpha)}\right) \quad (3) \end{aligned}$$

with $\gamma_0 \equiv \kappa P_{tx}/P_N$ and $\hat{D} \equiv D/d_0$.

Given values of W, γ_0, M and α, this is a monotonously decreasing function of $\hat{D}$. When $\hat{D} \ll (\gamma_0\xi_M(\alpha))^{1/\alpha}$, the system operates in *interference dominated region*. In that case the SINR reduces to SINR $\approx 1/\xi_M(\alpha)$ and it becomes essentially independent of the transmission power and of the path gain. In the opposite case, when $\hat{D} \gg (\gamma_0\xi_M(\alpha))^{1/\alpha}$, the system operates in a *noise dominated region*, where SINR $\approx \gamma_0/\hat{D}^\alpha$ and the throughput capacity rate decreases sharply with increasing distance values.

Figure 3 shows a plot of the broadcast capacity C_B (upper, solid line curves) and of the transport capacity C_T (lower, dashed line curves) as a function of D for different reuse schemes (values of M), for the case that RNs can be placed at the nominally specified locations, under $\alpha = 3$ and $P_{tx} = 500\ mW$. The calculated C_T value is given by $C_T = (D/\ell)C_B$. Since the setting of longer D values leads to the establishment of a lower number of relay nodes, it induces lower end-to-end message delay levels. The transport throughput product metric thus accounts for the aim of achieving higher throughput and lower delay levels. While C_B accounts only for link attenuation and interference and it is hence decreasing[4] with D, the transport capacity C_T encloses in a single metric the trade-off between shorter links, obtained by reducing D, that could allow higher bit rates, and smaller steps forward of the messages at each hop realized with smaller values of D.

We note that reuse 4 and 5 schemes yield somewhat better throughput rate performance for D values that are lower than about 150 m, while a reuse-3 scheme delivers higher throughput at longer D levels. Reuse 3 turns out to offer best performance when using the transport capacity metric. We note that the optimal values to be set for the inter-RN distance are not very sensitive to the realized spatial reuse level.

Similar performance behavior and system design comments apply when the two exponent path loss model is used (see

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[3] To simplify the analysis, we are neglecting random gain components like shadowing that account for unequal field coverage in the area of propagation of the signal from the transmitting antenna.

[4] For very low values of D, it can even be increasing in case of the 2exp PLM, due to the variability of the path loss exponent with distance.

Figure 4). The behavior of the C_B curves is impacted by the two slope values defined for the path gain curve. When the strongest interferers are closer, a lower value of the path loss exponent prevails ($\alpha_1 \approx 2.07$, so that there is an advantage to increasing the D level so as to move interferers away. When the strongest interferer, which is located as distance $(M-1)D$, has a distance greater than the path loss crossover distance (which is equal to about 120 m for this model), the monotonous decreasing behavior of C_B with D becomes dominant.

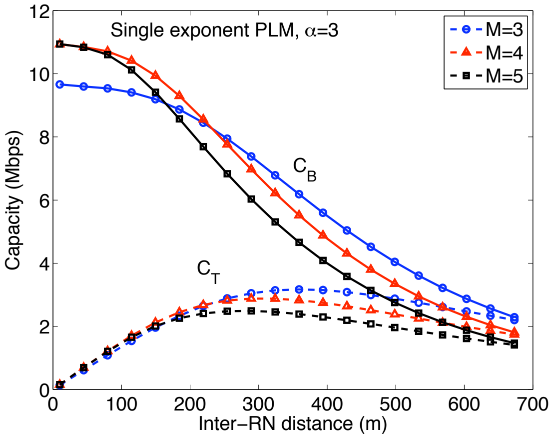

Fig. 3. Broadcast throughput C_B and transport capacity C_T as a function of inter-relay distance D for single exponent path loss model and different values of the reuse M.

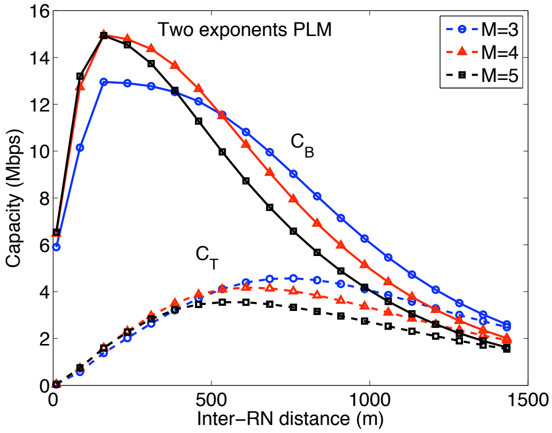

Fig. 4. Broadcast throughput C_B and transport capacity C_T as a function of inter-relay distance D for two exponents path loss model and different values of the reuse M.

In Figure 5, we show the broadcast capacity rate vs D for various values of the path loss exponent, under $M = 3$, and under a single exponent loss model. We note that for D levels that are shorter than about 100 m, higher path loss exponents lead to higher throughput rates, since the system's links operate then in the interference dominated region, so that under a reuse 3 scheme, the SINR level at each RN receiver is equal to about 2^α. For longer D levels, the inter-RN link enters a noise limited operational mode, so that the throughput rate attenuates rapidly with distance for the higher α levels.

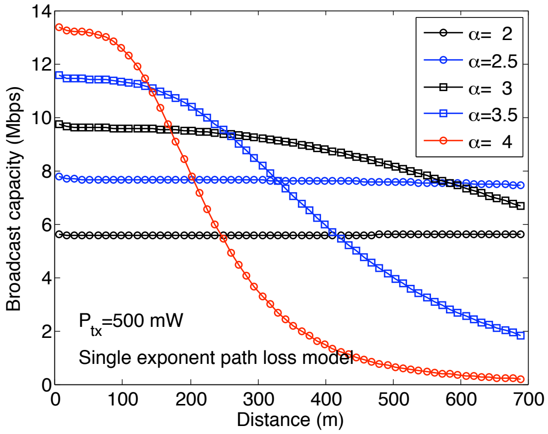

Fig. 5. Broadcast throughput C_B as a function of inter-relay distance D for single exponents deterministic path loss model and different values of the path loss exponent α.

B. Calculation of ideal targeted inter-RN distance $D(\alpha)$

The parameter $D(\alpha)$ is defined as the ideal (no location jitter incorporated) distance at which the dominant component of the interference power along the linear highway is equal to the noise power: $P_I = P_N$.

For a channel model that employs a single path loss exponent parameter, we thus obtain $D(\alpha)$ to be given as follows:

$$D(\alpha) = [\gamma_0 \xi_M(\alpha)]^{1/\alpha} \approx \frac{1}{M-1}\left(\frac{\kappa P_{tx}}{P_N}\right)^{1/\alpha} \quad (4)$$

where we have used the approximation $\xi_M(\alpha) \approx 1/(M-1)^\alpha$, for $M \geq 3$. This amounts to neglecting all interferers but the strongest one. By introducing the above noted numerical values, we obtain the following:

$$10\log_{10} D(\alpha) = \frac{1}{\alpha}(P_{tx}^{(dBm)} + 44.73) - 10\log_{10}(M-1) \quad (5)$$

The following observations are noted.

1) For $D < D(\alpha)$, the system operates in an interference dominated mode, and then the broadcast throughput rate holds at a steady level vs. D and vs. P_{tx}. In this mode, the system SINR value improves exponentially with alpha, in proportion to about 2^α for the reuse-3 scheduling scheme, and in proportion to about 3^α and 4^α for reuse 4 and 5 schemes, respectively. The rate changes in proportion to $\log(1+\text{SINR})/M$, where M is the reuse level, so the for higher SINR levels, it varies, in this range, in proportion to approximately (when only the closest interferer is accounted for) $\alpha(M-1)/M$.
2) $D(\alpha)$ decreases with alpha, as for larger values of alpha, the received interference signal power level is reduced so that the impact of the noise power becomes dominant. This is well noted in the graphs.

3) For $D > D(\alpha)$, the system operates in a noise dominated regime, so that the SINR level monitored at a receiving RN is mostly proportional to $1/D^{\alpha}$, so that the rate decreases faster with D for higher alpha values. This is observed in the graphs, except that for lower alpha values we note that the system has not yet entered the noise dominated zone for distances lower than 800 (or so) meters. When operating in the noise dominated mode, the rate varies in proportion to $\log(1+\gamma(\alpha, D))/M$. Hence, in this mode, better performance is obtained under lower alpha values (leading to less rapid attenuation of the desired signal). It is therefore desirable then to reduce the inter-RN distance D levels, leading to higher SINR and rate levels. It is also noted that lower reuse (M) values will then yield higher throughput rates, since the interference reduction attained through the use of a higher reuse level is not as effective when the system operates in a noise dominated mode.

C. Broadcast capacity under stochastic deviations in relay node locations

When stochastic vehicular traffic flows are applied, it will generally not be possible to select (and hold) vehicles that have been elected to act as RNs at the ideal locations noted above. Rather, the locations realized for the placement of RNs would deviate from the targeted nominal positions. In the following, we assume a single exponent path gain model and $M = 3$. Results are obtained via our analytical model and are confirmed by performing Matlab based simulations.

The protocol used to synthesize the backbone network that consists of elected RNs is defined as follows. A grid of nominal positions of RNs is defined and announced by the RSU. This grid consists of positions located at $\{kD, k \in \mathbb{Z}\}$ ($k = 0$ corresponds to the RSU). We consider a segment of road of length 2ℓ, with the RSU located at its center, namely the segment $[-\ell, \ell]$. The road segment is divided into intervals of length D, $(-D/2 + kD, D/2 + kD]$, with $k = -n, \dots, n$, and $n = \lceil (\ell - D/2)/D \rceil$. In each interval, the vehicle closest to the center of the interval (nominal position) gets elected, provided there are vehicles at all in the interval. That is to say, the VBN is formed by selecting the closest vehicle to each grid position, provided there exists a vehicle that is within a distance $D/2$ from that nominal grid position. We assume vehicle positions to follow a Poisson process with intensity λ. Hence, the average number of elected relays is $m = 1 + 2n(1 - e^{-a})$, with $a = \lambda D$. The 1 term accounts for the RSU.

In Figs. 6 and 7, we compare the broadcast capacity of the VBN with randomly scattered vehicles distributed across the highway, vs. $a = \lambda D$, under single exponent and under two-exponent path loss models, respectively. The values of α and λ are prescribed, so that the abscissa is proportional to D. The solid curves display the broadcast throughput capacity rate performance behavior when RNs are located at exact nominal (grid) locations, while the asterisk curves display the performance when vehicles are randomly situated and relays have been elected in accordance with the above mentioned VBN protocol under a given nominal inter-RN distance D.

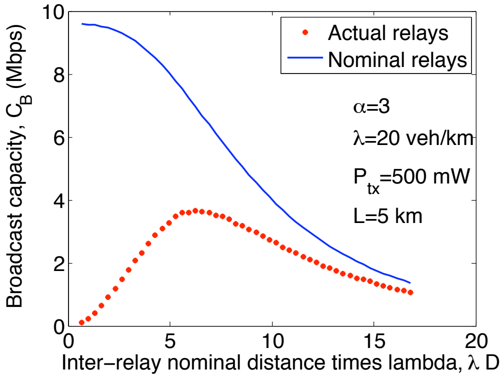

Fig. 6. Average broadcast capacity C_B as a function of $a = \lambda D$ for $\lambda = 20\ veh/km$ and $\ell = 5\ km$, under a single exponent path loss model. Comparison between random vehicle positions (asterisks) and ideal RNs positioning (solid line).

The following observations are made. The ideal broadcast capacity rate (i.e., the one derived when RNs can be placed at targeted grid locations) decreases monotonically as D increases, except a possible initial effect for small values of D in case of the two exponent path loss model. In turn, when random locations of vehicles are accounted for, there appears a trade-off and an ensuing optimization. For small values of $a = \lambda D$, statistical variations of vehicular positions dominate, so that elected RNs are situated at locations that may deviate widely from targeted nominal positions. Hence, the realized link rate levels also deviate widely. Since, the broadcast capacity value is dominated by the link which must be operated at the lowest rate, the overall throughput capacity rate is reduced. As the λD value increases, we find that the attained throughput capacity rate starts to sharply diminish as the communications distance increases, as the system then enters into a noise dominated operational region. Since the relative stochastic variation in the positions taken by vehicles (relative to grid locations) are now reduced, the two performance curves (at high D values) attain similar capacity rate levels. In between, the selection of D such that intermediate values of λD are attained, offers the best compromise for the robust design of the mobile backbone system.

D. Broadcast capacity performance evaluation model

In this Section, we focus on the derivation of a model to predict the broadcast capacity in case of randomly scattered vehicles. Consider a tagged link, whose RN transmitter stands for the nominal location k, and denote with D_1 the distance between this transmitter and its intended RN receiver (located downstream the highway at grid location $k + 1$). Let D_{j+1} denote the distance between the receiver and the its $j - th$ strongest interferer ($j \geq 1$). Then:

$$\text{SINR} = \frac{\frac{G(D_1)P_{tx}}{P_N}}{1 + \sum_{j \geq 2} \frac{G(D_j)P_{tx}}{P_N}} \tag{6}$$

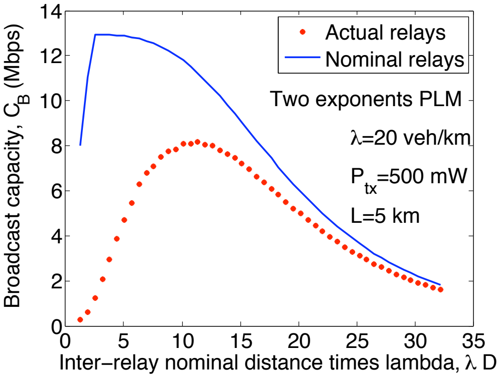

Fig. 7. Average broadcast capacity C_B as a function of $a = \lambda D$ for $\lambda = 20\ veh/km$ and $\ell = 5\ km$, under a two exponent path loss model. Comparison between random vehicle positions (asterisks) and ideal RNs positioning (solid line).

We assume a reuse-3 spatial-TDMA schedule and a power law path loss model with exponent α. By focusing on the strongest interference component, the expression for the SINR is simplified to become:

$$\text{SINR} \approx \frac{G(D_1)P_{tx}/P_N}{1+\psi(\alpha)G(D_2)P_{tx}/P_N} \tag{7}$$

where we let $\psi(\alpha) \equiv 2^\alpha \xi_3(\alpha)$ to provide an approximate account for the contribution of secondary interference signals. We denote with a hat distances normalized with respect to the nominal value of the inter-RN distance D. We then obtain,

$$\text{SINR} \approx \frac{\gamma(\alpha, D)/\hat{d}_1^\alpha}{1+\psi(\alpha)\gamma(\alpha, D)/\hat{d}_2^\alpha} \tag{8}$$

where $\gamma(\alpha, D) \equiv \kappa d_0^\alpha P_{tx}/(P_N D^\alpha)$ denoted the SNR of the single hop nominal link.

The random variable $\hat{d}_j$ can be written as the sum of three independent random variables $\hat{d}_j = K_j + Z_2 - Z_1$; Z_i is the deviation of a relay node from its nominal position, $Z_1, Z_2 \in (-1/2, 1/2)$ and K_j is the number of empty D intervals between two consecutive RNs ($j = 1$) or between a receiver and its strongest interferer ($j = 2$). Hence, for $a = \lambda D$, we have

$$\mathcal{P}(K_1 = k) = e^{-a(k-1)}(1-e^{-a}), \qquad k \geq 1$$

and

$$\mathcal{P}(K_2 = h) = (1-e^{-a})^2(h-1)e^{-a(h-2)}, \qquad h \geq 2$$

Since vehicles are assumed to be scattered along the line according to a Poisson process with parameter λ, a simple approximation of the distribution of the random variable Z_i is obtained by setting it to have the same distribution as the random variable $Z = S\min\{Y_1, Y_2\}$, where Y_i are statistically independent negative exponential random variables, each with mean $1/\lambda$, and S is a binary random variables taking values 1 and -1 with equal probabilities. Then, the p.d.f. of $\delta_1 \equiv \hat{d}_1 - \text{E}[\hat{d}_1]$ can be approximated as

$$f_{\delta_1}(x) = \frac{a\,(1+2a|x|)\,e^{-2a|x|}}{2-(1+a)e^{-2a}}, \quad x > -1 \tag{9}$$

The average of $\hat{d}_1$ is $\text{E}[\hat{d}_1] = 1/(1-e^{-a}) \equiv \mu$.

Further, we use the approximation $\hat{d}_2 = \max\{1, 2\mu - \delta_1/2\}$, which is a mean value approximation with a correction factor used to account for the deviation of the receiver from its average position[5]; the max operator is used to force the distance between the strongest interferer and receiver to be equal to at least one interval of length D, based on the way that relay nodes are elected and scheduled to transmit their messages. Then, we have

$$\text{SINR} \approx \frac{\gamma(\alpha, D)/(\mu+\delta_1)^\alpha}{1+\psi(\alpha)\gamma(\alpha, D)/(\max\{1, 2\mu-\delta_1/2\})^\alpha}$$

The broadcast capacity is the minimum of the capacities of the links set up between RNs that are located along the road span $[-\ell, \ell]$. Let $\mathcal{R}$ be the set of indexes of the links on the left and right of the RSU and let $\delta^* = \max_{k \in \mathcal{R}} \delta_{1,k}$, where $\delta_{1,k}$ denotes the random variable δ_1 associated to link k. Since the SINR of a link is monotonically decreasing with δ_1, we obtain,

$$C_B(\delta^*) = \frac{W}{3} \min_{k \in \mathcal{R}} \log_2(1+\text{SINR}_k) =$$

$$= \frac{W}{3} \log_2 \left(1 + \frac{\gamma(\alpha, D)/(\mu+\delta^*)^\alpha}{1+\frac{\psi(\alpha)\gamma(\alpha, D)}{(\max\{1, 2\mu-\delta^*/2\})^\alpha}} \right)$$

The expected value of $C_B(\delta^*)$ is calculated by averaging using the pdf of δ^*, yielding

$$C_B = \text{E}[C_B(\delta^*)] = \int_{-1}^{\infty} C_B(x) f_{\delta^*}(x)\, dx \tag{10}$$

Since $C_B(\delta^*)$ is a monotonous function of δ^*, we can even express the probability distribution of $C_B(\delta^*)$ as $\mathcal{P}(C_B(\delta^*) > c) = \int_{-1}^{\Delta(c)} f_{\delta^*}(x)\, dx$, where $\Delta(c) \equiv C_B^{-1}(c)$, for $c > 0$.

There remains to calculate the p.d.f. of δ^* given the expression we have found for the p.d.f.s of the random variables $\delta_{1,k}, k \in \mathcal{R}$. As an approximation, we assume the random variables $\delta_{1,k}, k \in \mathcal{R}$ to be statistically independent and have the same probability distribution.

The number of RNs in the road span $[-\ell, \ell]$ is a random variable, denote with N. The probability distribution of N is

$$\mathcal{P}(N = r+1) = \binom{2n}{r} p^r (1-p)^{2n-r}, \quad r = 0, \ldots, 2n \tag{11}$$

with $n = \lceil (\ell - D/2)/D \rceil$ and $p = 1 - e^{-a}$. It is $N \geq 1$ because of the RSU. The pdf of δ^* conditional on $N = r+1$

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[5] Since the distance between transmitter and receiver deviates from the mean by δ_1, it is assumed here that half of such deviation is allocated to each side, hence $\delta_1/2$ is the deviation of the receiver from its average position, leading to the approximation of the average strongest interferer distance being reduced from its nominal value of 2μ by as much as this deviation.

is $(r+1)f_{\delta_1}(x)F_{\delta_1}(x)^r$. Removing the conditioning, we get[6]

$$\begin{aligned} f_{\delta^*}(x) &= \sum_{r=0}^{2n} \mathcal{P}(N=r+1)(r+1)f_{\delta_1}(x)F_{\delta_1}(x)^r = \\ &= f_{\delta_1}(x)[mF_{\delta_1}(x)+e^{-a}][e^{-a}+(1-e^{-a})F_{\delta_1}(x)]^{2n-1} \end{aligned} \qquad (12)$$

where $m = 1 + 2n(1-e^{-a})$ is the average number of RNs.

A simpler approximation, still checked to be numerically quite accurate is to let $f_{\delta^*}(x) = mf_{\delta_1}(x)F_{\delta_1}(x)^{m-1}$, $x > -1$, where $F_{\delta_1}(x)$ is the cumulative distribution function of the density in Eq. (9).

The (approximate) evaluation of the average broadcast capacity as presented above can be easily carried over to the case of a more general path loss model, where the deterministic path gain is expressed by a monotonous function of the distance d between transmitter and receiver, $G(d)$. In that case, we can write

$$\mathrm{E}[C_B] = \frac{W}{3}\int_{-1}^{\infty} c(x)f_{\delta^*}(x)\,dx \qquad (13)$$

with

$$c(x) \equiv \log_2\left(1+\frac{P_{tx}G(D\mu+Dx)}{P_N+\psi(\alpha)P_{tx}G(D\max\{1,2\mu-x/2\})}\right)$$

We observe that $\mathrm{E}[C_B]$ depends on only four normalized parameters: α, $\nu = 2\lambda\ell$, a and $\gamma_\lambda = g_0P_{tx}\lambda^\alpha/P_N$. The second one, ν, represents the average number of vehicles served by the broadcast channel along the road segment $[-\ell,\ell]$. The last one, γ_λ, represents the SNR value measured at a distance equal to an average vehicle spacing.

Figures 8 and 9 show the broadcast throughput capacity rate as a function of $a = \lambda D$, for various values of the vehicular traffic flow density λ, for $\ell = 5\ km$ and, respectively, for the single exponent loss model with $\alpha = 3$ and for the two exponent loss model. By comparing simulation (asterisk points) with analysis results (solid lines), we observe that the behavior of the broadcast throughput capacity rate function is quite well captured by the mathematical model. The quality of the approximation is remarkably good in spite of the simplifying assumptions that we have made, including: i) only the strongest interferer has been considered; ii) distances between the transmitter and its receiver and between the receiver and the strongest interferer have been replaced by mean values plus a deviation; iii) the SINR values monitored by intended receivers across different links, in the range $[-\ell,\ell]$, have been assumed to be statistically independent of one another.

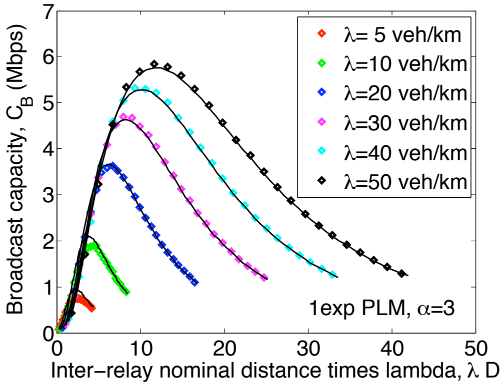

Fig. 8. Average broadcast throughput as a function of the product of inter-relay distance D and vehicle density λ for $\ell = 5\ km$. Comparison between simulation (*) and model (solid line).

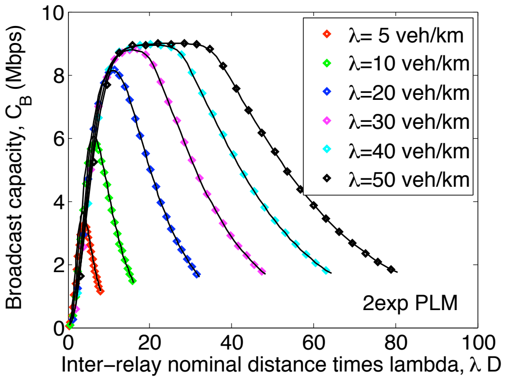

Fig. 9. Average broadcast throughput as a function of the product of inter-relay distance D and vehicle density λ for $\ell = 5\ km$. Comparison between simulation (*) and model (solid line).

IV. CONCLUDING REMARKS

We introduce and study a multi-hop networking VANET protocol that is identified as a Vehicular Backbone Network (VBN) mechanism. The objective is to disseminate broadcast packet flows to the bulk of vehicles that travel over an extended area. The basic idea of the VBN scheme is to have, at any given instant of time, certain vehicles elect themselves as relay nodes (RNs), setting their code rates to levels that achieve the highest feasible rate (subjected to the underlying SINR conditions). To achieve a high level of throughput capacity rate, we develop a mathematical model that determines the setting of optimal inter-RN distance D levels, by accounting for signal interferences caused by concurrent RN transmissions and taking into consideration the stochastic character of vehicular traffic flows.

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[6] We use the identity

$$\sum_{r=0}^{2n}\binom{2n}{r}z^{r+1}p^r(1-p)^{2n-r} = z(1-p+pz)^{2n}$$

from which we obtain by deriving both sides

$$\sum_{r=0}^{2n}\binom{2n}{r}(r+1)z^rp^r(1-p)^{2n-r} = [1-p+p(2n+1)z](1-p+pz)^{2n-1}$$

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