Vehicular backbone network approach to vehicular military ad hoc networks

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Abstract—We consider a tactical command center that issues broadcast data message flows for dissemination to all vehicles traveling as team members of a convoy, or along a multi-lane linear road segment. We propose a networking protocol which uses location aware data to identify and select certain vehicles that reside at preferred locations to act as relay nodes, forming a dynamic multi-hop backbone network. The presented mechanism, identified as a Vehicular Backbone Network (VBN), optimally sets the rate of the adaptive coding scheme for the backbone links, while jointly configuring the targeted inter-relay distances and the proper reuse level for a reuse-\(M\) spatial-TDMA medium access control (MAC) scheme. We present a fast and efficient mechanism for the dynamic and spatially distributed implementation of the backbone-node election process. For this purpose, we make use of the spatial structure governing the mobility of vehicles across a multi-lane linear highway. To assure the robustness of the election scheme, we assume the backbone synthesis process to be performed at a Forwarding Layer, above the MAC layer, and thus be transparent to the character and operation of the employed (whether contention-less or contention oriented) MAC layer protocol. We present a mathematical model for the determination of the VBN system’s parameters that serve to produce the highest throughput capacity rate.

I. INTRODUCTION

We consider a road segment (of length \(L\) meters) that may consist of multiple lanes (\(K\)) across which vehicles travel. A communications channel is employed for the purpose of broadcasting message flows from a source node to all nodes traveling along the segment. The source node can be a tactical command center that issues such data for dissemination to all vehicles traveling along the road. Equivalently, the source node may be a command vehicle that travels with a convoy and issues message flows that must be efficiently disseminated to convoy vehicles that are within a specified range from the command vehicle. Though we limit the models described in this paper to linear layouts, networking mechanisms that are extensions of those described herein apply to ring and other mesh layouts and to each linear segment of a meshed formation or a vehicular swarm.

The system is assumed to have no fixed backbone network infrastructure. Hence, communications from the source node to the other vehicles along the road, or to those vehicles that are members of a team convoy, proceeds by using a multihop ad hoc networking (MANET) techniques. Vehicular ad-hoc network (VANET) studies and experiments generally focus on applications associated with traffic safety, info-mobility, urban sensing, and infotainment [1] [2] [3]. Wide interest in this area has resulted in the development of VANET architectures and standards, including Wireless Access in Vehicular Environment (WAVE) recommendations [4]. The latter makes use of Standards such as IEEE 802.11p and IEEE 1609. Also, ETSI has standardized a VANET protocol based on a profile of IEEE 802.11p, called ITS-G5, which uses the carrier sense multiple access (CSMA) MAC [5]. The control channel is used to distribute critical safety oriented messages, often as hello/beacon type status packets [6].

Vehicular ad hoc networks are frequently utilized in military systems, where TDMA (and/or FDMA/CDMA) based MAC mechanisms are occasionally preferred. Such systems need however to sustain a high throughput rate in the dissemination of critical command and control message flows, under limited message delays, assuring mobiles with a high rate of packet reception. To this aim, we describe in this paper a networking approach that is based on the dynamic synthesis of a simple backbone, coupled with the use of a cross-layer adaptive link code rate setting, and the employment of a flow admission control mechanisms. Hierarchical systems for use in networking across general MANETs have been presented in [7] and the references therein, where such Mobile Backbone Network (MBN) systems are synthesized and studied. In this paper, we adapt and significantly modify this concept for the underlying cross-layer forwarding operations, as well as the introduction of a spatially distributed backbone node election mechanism, which operates above the MAC layer, by making use of the unique spatial geometry of the ordered movement of vehicles traveling in convoy (swarm) formation or across a linear highway. We identify such a backbone based network system as a Vehicular Backbone Network (VBN).

There have been several proposals dealing with the division of the network in two tiers, including the use of clustering mechanisms For typical VANET applications, cluster-heads, or relay node (RNs) are elected based on a multitude of criteria. In [8], [9] and other papers, selection is made of the farthest node from the transmitter to relay a message. Vehicles make use of vehicular GPS positions, which are inserted in the header of broadcast messages. Backbone members are elected in [10] for an efficient broadcasting of alert messages in VANETs. The backbone network is constructed iteratively on a link-by-link basis, aiming to reduce dissemination delays. Several other related papers include [11], [12]. Yet, most such papers deal with the dissemination of safety message, where the key issue is to collect and deliver, in a very quick way, isolated warning messages. In [13], the authors develop
a cluster-based multichannel communications scheme for an infrastructure-free VANET.

In contrast, our scheme synthesizes a backbone network based on the overall topological layout of this structure, aiming to attain a high end-to-end throughput rate, while maintaining low end-to-end packet delays and high coverage. To achieve such high rate, we consider the spatial pipelining of packet flows across the linear highway. Such an operation induces signal interferences between packet transmissions that are simultaneously executed across multiple highway backbone links. To our knowledge, the maximization of such an end-to-end metric through the cross-layer synthesis of the backbone network, without the modification of the underlying MAC scheme, has not been carried out in any other published work targeted for such VANET systems.

The rest of the paper is organized as follows. In Section II, we introduce the VBN approach and describe its principle of operation. A distributed algorithm for the dynamic construction of the VBN is described in Section IV. It is based on the system model described in III. Mathematical derivation of the broadcast throughput capacity for a VBN, under a cross-layer adaptive rate spatial TDMA mechanism, is presented in Section V. Concluding remarks are noted in VI.

II. BASIC PRINCIPLES FOR SYNTHESIZING A VBN

The basic idea of the Vehicular Backbone Network (VBN) is to have certain vehicles elect themselves as Relay Nodes (RNs) and form a backbone network. RNs, also identified as Backbone Nodes (BNs), act as base stations do in a cellular network (from topological layout viewpoint, since they do not actually act as base stations do, noting that BNs are not attached to a fixed infrastructure), except that they are mobile, dynamically elected, and serve as forwarding nodes for a limited period of time. In this way, vehicles are divided into two hierarchically distinct sets. The backbone network \(B_{Net}\) consists, over a period of time, of elected RNs and the communications (backbone) links that interconnect them. A single \(A_{Net}\) (access net) consists of the link media employed in a military network environment, \(A_{Net}\) is formed above the link layer, that is identified as the Forwarding Layer (FL). Thus, to avoid making changes to the MAC layer protocol, we assume hereby that the MAC scheme may employ a TDMA or a CSMA/CA type MAC layer protocol. Furthermore, due to the often fluctuating and unreliable nature of the link media employed in a military network environment, we include added robustness (duplication) elements into the distributed election protocol, realizing that at times, some vehicles may not be able to acquire the system state during certain periods of time. Due to space limitations, we only outline the key principles governing the RN election process.

To not impact the mechanisms implemented for physical and MAC/link layer operations, we assume the election of BNs, and the forwarding operations, to be implemented in a separate layer, above the link layer, that is identified as the Forwarding Layer (FL). Thus, to avoid making changes to the MAC layer protocol, we assume hereby that the MAC scheme may employ a TDMA or a CSMA/CA type MAC layer protocol. Furthermore, due to the often fluctuating and unreliable nature of the link media employed in a military network environment, we include added robustness (duplication) elements into the distributed election protocol, realizing that at times, some vehicles may not be able to acquire the system state during certain periods of time. Due to space limitations, we only outline the key principles governing the RN election process.

III. SYSTEM MODEL

The recommended location for the \(n\)-th BN is the highway span covering the segment \(L_n - D_n/2, L_n + D_n/2\), and is also denoted as \(L_n\). The grid of segments is defined with reference to the location of the source vehicle. We assume that \(D_n = D\), for each \(n\). It is desirable for the vehicles to implement an efficient distributed election algorithm that allows them to elect in each segment a vehicle to act as the segment’s BN, whereby it is advantageous that the elected vehicle in segment-\(n\) will be sufficiently close to the desired vehicle.
ideal location $L_i$. The BN election algorithm presented herein makes use of election control packets that are transmitted in accordance with the election algorithm. It is highly desirable, as we proceed to assume in this paper, to institute an election protocol that involves distributed local election processes that are performed (spatially and temporally) in parallel along the highway segments at renewal rates that match the dynamics of each segment. The radio modules are assumed to operate in half-duplex mode, as is generally the case for many related system implementations. We recognize that it is often desirable to use an election facilitator, including the use of the current BN as such. However, we structure the protocol in a manner that would allow the system planner to avoid the use of a current BN as a facilitator.

We assume that the $n$-th segment $L_n$ is divided into sub-segments, each of which is of length $s = 2\ell$, which identifies the minimum effective spacing between vehicles along each lane. One such sub-division pattern, assumed henceforth, is represented as follows. The first sub-segment, identified as sub-segment 1, spans this road’s segment across the interval $ss(1) = (L_n - \ell, L_n + \ell)$. The second sub-segment, identified as sub-segment 2, spans the locations across the road consisting of the interval $ss(2) = (L_n + \ell, L_n + 2\ell)$. Sub-segment 3 is set as $ss(3) = (L_n - \ell, L_n - 2\ell)$; etc. We have chosen each sub-segment to cover a contiguous span of the highway. Since across each lane there can only be a single vehicle residing in a span of length $s$, the maximum number of vehicles that can reside, at a given time, in any such sub-segment, is upper bounded by a total of $K$ vehicles (i.e., the number of lanes). The set of vehicles that reside at a given time in $ss(i)$ is identified as group-$i$ vehicles, and is denoted as $G(i)$. A vehicle member of group-$i$ that resides in lane $k$ is identified as $G(i, k)$; the latter is also used to denote the set of such vehicles. To illustrate the numbering of lanes, we can attach lower numbers to the slower lanes, while within each speed category attach a lower number to the lane in which vehicles travel towards the control vehicle (or RSU). In this manner, lower lanes 1 and 2 are used to identify the slowest lanes.

IV. THE BACKBONE NODE ELECTION ALGORITHM

In the following, we describe a protocol and algorithm that is used in a distributed manner by vehicles that determine, based on their current position along the road, to be members of segment-$n$ ($L_n$).

A. Initiation of the Election Process

If currently there already exists an elected BN for this $L_n$ segment, this BN may be allowed to act as a facilitator. If there exists a managing controller station, it may be employed in this role. When no such BN or facilitator currently exists, an opportunistic election of such a vehicle can be invoked: when a vehicle observes (over a minimum period of time) its segment to not be managed by a BN (or controller), it will elect itself as a facilitator, and then act to initiate the BN election algorithm and to serve as a temporary facilitator. When it is not feasible to synthesize a connected backbone that follows the requirements imposed by the VBN system controller, the system resorts to the use of an alternate method. For example, reduction of the code rate and the use of packet by packet forwarding along the infeasible link, as long as this condition persists. The controller would continuously engage in the re-calculation of VBN system parameters, aiming to re-establish, when it becomes feasible, the VBN structure.

B. The Backbone Node Election Scheme

A vehicle that contends to be elected as a BN, will be governed by the following protocol to send, when proper to do so, a bid or ACK/confirmation packet. Each such packet will include, among other elements, data that identifies key attributes of the vehicle. Such attributes are used for identifying the desirability of using this vehicle to act as a BN, depending upon the system’s performance objective. It is assumed herein that it is desirable to elect vehicles that are closest to the specified ideal location for a BN, within a margin of range difference of the order of $s$. If the lane at which a vehicle resides is taken into consideration, we assume that within each segment, it is initially desirable to give preference to vehicles that reside at a lower numbered lane, if this can be established promptly; otherwise, it is considered equally effective, among vehicles residing in a sub-segment, to elect a vehicle that travels at any lane. We assume the MAC layer to employ a broadcast mode for the transmission of election bid/confirmation packets, so that no MAC layer ACK packets are produced and no MAC layer retransmissions are executed. If a MAC layer that uses such ACK and retransmission operations is employed, the election process would be significantly simplified in that a successful transmission of an election bit packet would be readily detected by the segment vehicles, avoiding the need for those subsequent bid and ACK transmissions noted below. The following procedures and rules are employed for the BN election process.

The election process proceeds by giving preference to a vehicle that belongs to $G(i)$ to elect itself as BN before such an election opportunity is granted to a vehicle that belongs to $G(j)$, when $i < j$. Vehicles that belong to the same group, say group $G(i)$, contend for election over a specified sequence of successive windows, whereby the $n$-th such period is denoted as $W(i, n)$; it consists of $W(i, n)$ slots, $1 \leq W(i, n) \leq K + 1$. We note the dependence of the latter on $K$, for reasons to be explained in the following.

Since the election algorithm is executed at the Forwarding Layer, each such slot is of a duration $T(slot)$ that is sufficiently long to allow for processing of an election packet at the forwarding layer and for operations at lower layer protocol entities. Thus, this duration must allow for the time that it takes for the MAC layer entity to transmit a packet, permitting sufficient time for other vehicles to receive and process such a frame, provided it was promptly transmitted. For example, assuming such a packet to contain several hundred bits, and a transmission rate across the control channel of 6 Mbps, such a time slot would normally be of duration that does not exceed 1-
1.5 msec. For a vehicle that travels at a speed of 30 meters/sec (or 108 Km/Hr), a traversal of a 50 meters segment would take about 1.66 sec, which is more than three orders of magnitude longer than the slot duration. Accordingly, since the election algorithm will typically be completed after a relatively small number of slots, it can be efficiently executed to adapt to the mobility of vehicles traveling along the highway. This is even more so when we consider the synthesis of a backbone within a moving convoy, for which re-elections are prompted by stochastic variations that relate to the relative positions of vehicles within the convoy.

When the participation of \( G(i) \) vehicles in the election algorithm is initiated, such members, if any, schedule to transmit their election bid packets by selecting a slot, say slot \( j \), from a window of length \( W(i,1) \) slots. The set of vehicles in \( G(i) \) that travel in lane \( k \) and select slot \( j \) is denoted as \( G(i,j,k) \). The set of vehicles in group \( i \) that select slot \( j \), independently of the lane that they are using, is denoted as \( G(i,j) \). We nominally set \( W(i,1) = K + 1 \), numbering the slots consecutively as slots \( 0, 1, 2, \ldots, K \). The algorithm starts with vehicle members of Group 1. If a facilitator exists, slot 0 of the window is used by the facilitator to initiate the window, specify its length, and identify the facilitator and its attributes. We identify two protocol versions. The Lane Based Election (LBE) algorithm makes use of the lanes in which a vehicle resides. The Group Based Election (GBE) algorithm does not use such attributes. Due to space limitation, we highlight the principles of the former one, noting the latter scheme to proceed in a similar fashion, under the noted variations.

C. Lane Based Backbone Node Election

Under a lane based election (LBE) algorithm, a vehicle (in the first sub-segment) that resides in lane \( k \) selects to transmit its election bid packet in slot \( k (1 \leq k \leq K) \) of window \( W(i,1) \), provided it did not previously detect a bid packet that has been successfully received by its MAC entity. Otherwise, its own bidding process is terminated. In this manner, it is expected that the vehicle that resides in the lowest numbered occupied lane will be able to transmit a successful election bid packet and be recognized as the winning bidder by the other vehicles. It will not however be able to as yet detect its own success, since its transceiver is assumed to operate in a half-duplex mode. To resolve this issue, we make use of the transmission of ACK packets that confirm the successful reception of a bid packet. If no facilitator is used (and for robustness purposes also otherwise, if activated), following the reception of a successful bid, a contending vehicle in the segment, if any, which has just dropped its bid, will prepare to send such an ACK packet in its selected slot within the current window, provided that it has not yet detected (within this window) any ACK. In the latter case, the sending of the ACK is cancelled since now the election of a new BN has been confirmed. In case of multiple ACK message transmissions within the window, the first successful one is selected. If no such successful ACK is executed in this window, the elected vehicle will become a temporary facilitator, and use slot 0 of the following window to announce and confirm its election. Different (MAC layer) reception/transmission success or failure outcomes may be experienced in operations by different group vehicles, so that multiple successful ACK packet transmissions may be received at a vehicle. A resolution provision is used. For example, the last (in window) ACK packet to be successfully executed may be declared as identifying the winner. In turn, the sender’s MAC ID (address), or attributes, can be used as basis for selection among such candidates.

If a facilitator is employed, the latter will send such an ACK in slot 0 of the next established period, identified as window \( W(i,2) \). Further, if multiple successful bids are received, the facilitator can select the one with the best attributes to act as the new BN provided its attributes are better than those of the current BN. In doing so, the facilitator is capable of overriding previous announcements.

For example, if a vehicle residing in lane \( k = 1 \) is the winning one, the contention is terminated after a single slot. If there is a vehicle in slot \( k = 2 \), it will then proceed to send a confirming ACK. If there is a facilitator, it will confirm this election by sending an ACK packet in slot 0 of the following frame. The election process is then effectively terminated after this single slot.

D. Group Based Backbone Node Election

Under a group based election (GBE) algorithm, the identity of the lane in which a vehicle resides is not known or not taken into consideration. A vehicle that belongs to \( G(i) \) selects at random slot \( j \) from within the \( K \) contention slots included in window \( W(i,1) \), constituting the set \( j = 1, 2, \ldots, K \). This vehicle will then proceed to send its bid packet at the start of slot \( j \), provided it did not detect any other vehicle to have successfully transmitted a bid packet in an earlier slot. Otherwise, its bidding process is terminated, and it will schedule to send an ACK packet in accordance with the rules stated above for the LBE algorithm.

Upon the termination of window \( W(i,1) \), window \( W(i,2) \) is initiated. A candidate vehicle, which has transmitted a bid packet in window \( W(i,1) \) and its transmission was not detected to be followed by a successful transmission by another vehicle during this window will transmit an election confirmation packet in window \( W(i,2) \) by selecting a slot in the manner mentioned above. If there was no successful bid transmitted in \( W(i,1) \), the operation in \( W(i,2) \) repeats the one of \( W(i,1) \). If there was a successful transmission performed in \( W(i,1) \), preceded possibly by collisions (or by idle slots), the vehicles assigned to earlier slots will drop their bids and the later vehicle (whose transmission was successful, though not yet ACKed) will transmit a confirmation (i.e., repeat bid) packet in \( W(i,2) \). If a bidding vehicle hears no other confirmation packet to follow its own transmission in this period, it assumes itself to be the only surviving bidder; its election is then also recorded by the other vehicles. In turn, if a bidding vehicle hears confirmation packet(s) to be successfully transmitted following the transmission of its own bid in this
period, it drops its bid; the last successful transmission in the period, if any, can then be used to identify the surviving winner. If needed, this operation is allowed to continue for a prescribed limited number of windows, terminating when this threshold is reached, or earlier when there is a window which contains at least a single successful transmission. In the latter case, the current BN, if any, announces the newly elected BN. In turn, if there is no current facilitator, the vehicles that consider themselves as surviving bidders proceed to transmit in the subsequent window their own BN bid confirmation packets. Using the same rule under which survivors drop their bids if they hear subsequent successful transmissions, the process will generally terminate after a short number of frames, typically observing the issue of a single confirmation packet.

If the election process undertaken by vehicles that belong to group-i does not result in an election and announcement / confirmation of a BN within N frames (typically, within $N = 2 - 5$ frames), $G(i + 1)$ packets will start their bidding process, using the same rules. The process is terminated upon the confirmed election of a BN, or after iteration through all groups, and/or expiration of a timeout threshold. It is repeated after a specified period of time.

E. Backbone Node Re-election

A BN sends periodically announcements to identify itself to its segment members. An elected BN will trigger a re-election process when it detects itself to deviate from the ideal location by a specified margin of $D/m$ [meters], for a prescribed parameter $m$, and/or based on a time threshold. The BN then identifies its parameters and mobility plan. Only nodes in the underlying $L_m$ interval that expect to have better parameters, participate in the re-election process.

F. Performance Illustration

As an illustration, consider first a lane based election protocol. The VBN controller is configuring the system, based on observed system parameters to have a sufficiently high $\lambda D$ product, where $\lambda$ denotes the vehicular spatial traffic rate (aggregated over all lanes) while $D$ represents the targeted value for the inter-RN distance. The product is generally set to have a value higher than 10. The reason for it is confirmed by the analysis presented in the next section, noting that at such higher product values, several vehicles are highly likely to reside in each segment, so that an elected BN is more likely to be located closer to the underlying targeted position. For example, for $\lambda = 60$ vehicles/Km, $D = 200$ meters, we have $\lambda D = 12$. Assume the minimum spacing between vehicles across a lane to be equal to $s = 50$ meters. An average of 3 vehicles then reside in a sub-segment. Assuming the number of vehicles residing in a sub-segment to follow a Poisson distribution with a maximum number that is truncated at $K = 6$ (lanes), we obtain the probability that there are no vehicles residing in a single sub-segment to be approximately equal to 0.05. The probability that there will not be vehicles over the 4 sub-segments is equal to about $6 \times 10^{-4}$. Hence, with probability 95%, there will be a vehicle residing within 50 meters of the targeted location, and its election will take place within the first frame of 7 slots, and acknowledged by slot 0 of the next frame, terminating therefore after less than 8 slots, which is a duration of about 12 msec. Under this scenario, the election process will involve the transmission of a single bid packet and a single confirmation / ACK packet (possibly reinforced by another ACK issued by a facilitator). Hence, assuming a packet of length 128 bits, a re-election cycle duration of 1 sec, the data rate of the election process over all segments (performed simultaneously in time over the segments in a spatial reuse manner) is of the order of only 0.256 Kbps.

As another example, consider a group based election process, under the following scenario. Consider the parameters: $D = 100$ m, $s = 50$ m, $K = 4$ (lanes). The inter-RN segment is divided into two sub-segments, corresponding to two groups. Each frame consists of $K+1 = 5$ slots. Under a high vehicular traffic rate: $G(1)=G(2)=4$ vehicles. Assume that no carrier sensing based delays are induced at the MAC layer. No retransmissions are carried out since the control packets are sent under a broadcast mode. With probability $(1 - 1/4)^3 = 0.422$, there will be a single successful transmission in slot 1. Also we find that the probability that there will be a successful transmission of a bid packet that precedes the occurrence of any other transmission is higher than 0.547. The probability of a collision in the first used slot is computed as equal to 0.262. Thus, with approximate probability 0.55, a successful transmission will occur. It will be confirmed (ACKed) by another vehicles successful transmission in the same frame with probability of at least $(1 - 1/2)^2 = 0.25$; and otherwise, by a confirming transmission of the winning vehicle (or facilitator) in the subsequent frame of $K+1$ slots. Under this scenario, a BN will be elected within a delay of $K = 2$ slots and a transmission of about 2-3 control packets, every re-election cycle time. With probability (no higher than) 0.45, there will be no successful transmission occurring during the first frame. The same process is repeated in the second frame. The probability of a successful bid packet process completed in the first or second frame is higher than about $0.55 + 0.45 \times 0.55 = 0.7975$; and it will be completed in the first 3 frames with probability that is higher than about $0.55 + 0.45 \times 0.55 + 0.55 \times 0.45 + 0.55 \times 0.45 \times 0.55 = 0.9088$. The average number of frames elapsed until a successful election is completed is equal to about $1/0.55 = 1.818$ frames. With the addition of a confirmation frame, it will thus take an average of 2.8 frames, or 14 slots, or about 21 msec. At 1 sec re-election cycle time, the corresponding average control packet rate would then be equal to about 0.358 Kbps.

V. BROADCAST THROUGHPUT CAPACITY ANALYSIS

We address the analysis of the VBN broadcast throughput in two phases. First, we consider an idealized setting where vehicles that elect themselves to act as Relay Nodes (RNs) are able to position themselves in preferred geographical locations in a stationary manner (Sec. V-A). Our second phase analysis accounts for the impairments due to vehicular movements,
inducing RNs to be at positions that display random deviations from their ideally targeted locations (Sec. V-B).

We consider a linear road. Using our backbone based and spatial time division oriented multiple access scheme, 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 (or at a command vehicle). The link capacity $C_{L}$ represents the throughput capacity rate attained across a (single hop) backbone link, when averaged over all such dynamically established links. The broadcast capacity $C_{B}$ represents the throughput capacity rate of information delivering from the RSU to vehicles distributed across the highway and located at a distance of up to $\ell$ away from the RSU, on both sides. Then $C_{B} = (1/M) \min_{k \in R(t)} C_{L,k}$, where $R(t)$ is the set of RNs that are situated within a distance $\ell$ of the RSU and, according to the TDMA schedule, one out of each $M$ consecutive RNs can transmit at any given time.

We use Shannon’s formula for the AWGN channel (assuming interference is akin to white noise) with a gap factor of $\Gamma = 10 \ dB$. This model entails a continuous spectrum of code rates. Hence, the attainable link capacity rate (assuming $10^{-5}$ symbol error rate target level) is calculated as $C_{L} = W \log_{2}(1 + \text{SINR}/\Gamma)$, where $W$ is the allocated bandwidth level ($W = 10 \ MHz$ in case of a DSRC channel according to WAVE or ETSI standards) and $	ext{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 such systems to be equal to $-174 \ dBm/Hz$. For comparison, we consider also discrete modulation and coding sets (MCS) as available in IEEE 802.11p, the variant of WiFi designed for VANET. A given code rate of the discrete set is achievable if the link SINR overcomes a threshold, as given in the standard of IEEE 802.11p. The employed propagation model is derived from highway measurements fitted by using a two exponent based deterministic path loss model [1], namely $G(d) = \kappa (d_{0}/d)^{\alpha_1}$ for $d_{0} < d < d_{c}$ and $G(d) = \kappa (d_{0}/d_{c})^{\alpha_1} (d_{c}/d)^{\alpha_2}$ for $d > d_{c}$. Numerical values of parameters as estimated by measurements are: $d_{c} = 120 \ m$, $\alpha_1 = 2.0763$, $\alpha_2 = 3.9369$, $\kappa = -47.86 \ dB$.

A. Broadcast capacity with nominally placed RNs

We assume that RNs are evenly spaced out along the linear road, at positions $kD$, $k \in \mathbb{Z}_{c}$. Consider a RN that transmits its packets to its neighboring next RN, which is located a distance $D$ away. Thanks to the reuse $M$ TDMA schedule, the resulting SINR level detected at the receiver is equal to:

$$SINR = \frac{G(D) P_{tx}}{P_{N} + P_{tx} \sum_{k=1}^{\infty} [G(kMD-D) + G(kMD+D)]}$$

The broadcast throughput capacity is $C_{B} = \frac{C_{B}^{\text{net}}}{M}$. Figure 2 shows a plot of the broadcast throughput capacity $C_{B}$ based on Shannon capacity formula (solid line curves) and under discrete code rates (dashed line curves) as a function of $D$, for $M = 3, 4, 5$, $\ell = 5 \ km$ and $P_{tx} = 500 \ mW$. The shape of the curves can be explained as follows. For very low $D$ values, the nearest interferers are quite strong, since the path loss exponent for short distances is $\approx 2$. As $D$ increases, the interferers gets further away and the resulting interference drops quickly as the path loss exponent becomes $\approx 4$. When $D$ keeps growing though, the noise becomes eventually the dominating impairment and the achievable link capacity falls off. Discretization of the code rate implies a flattening of the curve and some loss of efficiency.

It turns out that $M = 5$ gives consistently the best results for $P_{tx}$ ranging between $100 \ mW$ and $1 \ W$, with discrete code rates; $M = 3$ can reach slightly better results if the transport capacity $C_{T}$ is considered, namely $C_{TB} \equiv D \cdot C_{B}$. This is due to the quite longer distances $D$ allowed by reuse factor 3, even though a lower $C_{TB}$ level is attained with respect to that possible with $M = 5$. With continuous code rates, $M = 5$ yields consistently the best optimal values of $C_{TB}$.

B. Broadcast capacity under stochastic deviations of RNs

When stochastic vehicular traffic flows are applied, the locations realized for the placement of RNs would deviate from the targeted nominal positions. We assume vehicles to be scattered according to a Poisson process with parameter $\lambda$ (vehicles per unit length). According to the election protocol defined above, a grid of nominal positions $kD$ of RNs is defined and announced by the RSU. The road is divided into intervals of length $D$, $(-D/2 + kD, D/2 + kD)$, with $k = -n, \ldots, n$, and $n = \lceil(D/2)/D\rceil$. 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.

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 $D_{2}$ be the distance between the tagged RN receiver and the closest interfering RN. By focusing on the strongest interference...
component, the expression for the SINR is simplified to:

$$\text{SINR} \approx \frac{G(D_1)P_{tx}}{P_N + \psi_M G(D_2)P_{tx}}$$  \quad (1)$$

where $\psi_M \equiv (M-1)^{\alpha_2} + (kM + 1)^{-\alpha_2}$ provides an approximate account for the contribution of secondary interference signals.

The random variable $D_1$ can be written as the sum of three independent random variables $D_1 = D(K_j + Z_2 - Z_1)$; $Z_i$ is the deviation of a RN from its nominal position, $Z_1, Z_2 \in (-1/2, 1/2)$ and $K_j$ is the number of empty intervals between two consecutive RNs ($j = 1$) or between a receiver and its strongest interferer ($j = 2$). Based on the Poisson spatial distribution assumption, the p.d.f. of $\delta_1 \equiv (D_1 - E[D_1])$ can be approximated as $(a = \lambda D)$

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

The average of $D_1$ is $E[D_1] = D/(1 - e^{-a}) = D\mu$. Further, we use the approximation $D_2 = D \max\{M - 2, (M - 1)\mu - \delta_1/2\}$, which is a mean value approximation with a correction factor used to account for the deviation of the receiver from its average position. The max operator is used to force the distance between the strongest interferer and receiver to be equal to at least $M - 2$ intervals of length $D$, based on the way that RNs are elected and scheduled to transmit their messages. Then, $\text{SINR} \equiv S(\delta_1)$ is given by

$$S(\delta_1) = \frac{P_{tx} G(D\mu + D\delta_1)}{P_N + \psi_M P_{tx} G(D \max\{M - 2, (M - 1)\mu - \delta_1/2\})}$$

Since the SINR of a link is monotonously decreasing with $\delta_1$, we obtain $C_B = (W/M) \log_2(1 + S(\max_{k \in \mathcal{R}(\delta_1)} \delta_1))$ and therefore $E[C_B] = \int_{-\infty}^{\infty} C_B(x) f_{\delta_1}(x) dx$, where we have defined the random variable $\delta^* = \max_{k \in \mathcal{R}(\delta_1)} \delta_1, k$. As an approximation, we assume the random variables $\delta_1, k \in \mathcal{R}$ to be statistically independent. Then, given the average number $m$ of RNs in the considered road span, we approximate the pdf of $\delta^*$ as $f_{\delta^*}(x) = m f_{\delta_1}(x) F_{\delta_1}(x)^{-m-1}, \quad x > -1$, where $F_{\delta_1}(x)$ is the cumulative distribution function of the density in eq. (2). The average number of elected RNs, including the RSU, is $m = 1 + 2\ell/(D\mu)$.

In case of discrete or fixed code rates, $C_L$ and $C_B$ are found with the same p.d.f. of the SINR, by comparing the SINR value with thresholds $S_i$ (required SINR level). The probability of code rate $R_t = \int_{x_i}^{x_{i+1}} f_{\delta^*}(x) dx$, where $x_i$ is the maximum value of $x$ such that $S_i \geq S_i$.

Figures 3 compares simulation (mark points) with analysis results (solid lines) of $E[C_B]$ as a function of $a = \lambda D$, for various values of $\lambda$ and $\ell = 5 km$. The quality of the approximation is remarkably good in spite of the simplifying assumptions that we have made.

When random locations of vehicles are accounted for, there appears a trade-off and an ensuing optimization. For small values of $\lambda D$, elected RNs are situated at locations that 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 $\lambda D$ value increases, the attained throughput capacity rate sharply diminishes as the communications distance delves the system deep into the noise dominated region. In between, the selection of $D$ such that intermediate values of $AD$ are attained, offers the best compromise for the robust design of the mobile backbone system.

C. Optimization of the VBN

For given vehicular density, reuse factor $M$ and power level, the optimal value of $D$ can be found by maximizing $E[C_B]$. Figure 4 shows the optimized $E[C_B]$ value as a function of $\lambda$ for $\ell = 5 km$ and $P_{tx} = 500 mW$. Comparison among continuous (dash-dot), discrete (solid) and fixed code rate (dashed) highlights that a significant improvement can be gained by means of adaptive coding in case $M = 5$ or even $M = 4$. Little improvement is found for $M = 3$, due to excessive interference. Opposite to adaptive coding, with fixed coding, increasing $M$ makes $E[C_B]$ decrease.

For continuous code rates, $E[C_B]$ is always positive, since
there is no lower limit to the link capacity rates. In case of discrete code rates, there is a minimum feasible rate for the link (3 Mbps in our setting), hence there is a non null probability that at least one link fails to achieve an SINR large enough to sustain this minimum rate. Same reasoning holds for the fixed code rate case, where the target link rate is fixed to 6 Mbps in our numerical examples. Figure 5 plots the probability of failure of maintaining end-to-end flow continuity as a function of $\lambda$ for $\ell = 5$ km and $P_{tx} = 500$ mW. Even for small vehicle density levels, discrete rate coding guarantees failure probabilities below 1% and fastly decreasing with $\lambda$, for $M = 5$. In any case, discrete code rates lead to superior performance with respect to fixing a target link rate.

Figure 6 plots the optimal value of the inter-RN distance $D$ as a function of $\lambda$ for $\ell = 5$ km and $P_{tx} = 500$ mW. Comparison among continuous (dash-dot), discrete (solid) and fixed code rates (dashed).

VI. FINAL REMARKS

Through simulation evaluations, we have tested the election algorithm and the performance of the VBN scheme also under a CSMA/CA IEEE 802.11p type MAC protocol. For this purpose, we have configured the VBN system parameters at the values obtained above by using the presented VBN-TDMA based analyses. The carrier sensing sensitivity threshold was adjusted to yield a high spatial reuse level, following the values identified in our mathematical model. We have determined the system to then continue to exhibit excellent delay-throughput performance behavior. A high throughput capacity level has been confirmed. Through the application of the flow admission control process noted above, we have confirmed the system to yield a high packet delivery ratio and to exhibit very low end-to-end packet queueing delay levels, as dictated by the operation of the corresponding tandem queueing network noted in [15]. We have recently been also carrying out performance comparisons of the hierarchical VBN scheme presented in this paper with protocols that conduct a non hierarchical operation, such as those that use distance based forwarding (DBF) approaches (as commonly used in the bulk of VANET studies), under the CSMA/CA MAC protocol. Under such mechanisms, vehicles that are located further away from the vehicle whose packet they have received tend to elect themselves to forward received packets. Forwarding vehicles are then determined on a packet-by-packet basis (and often several vehicles, in close proximity to each other, act to forward the same packet). In turn, under the VBN technique, a cross-layer adaptive-rate operation is used to optimally synthesize the backbone, and then an elected BN serves as the only vehicle in its segment that is forwarding packets, performing this task for a relatively long period of time (typically, involving the forwarding of a large number of packets). Our analyses have well confirmed the significant performance improvement attained by the VBN approach, assuring broadcast flows with high throughput, low delay, and very low packet discard ratio leading to a high probability of coverage of vehicles traveling along the highway.

REFERENCES


