Lane Based Backbone Synthesis Protocols for Vehicular Ad Hoc Networks

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***Abstract*— Vehicular ad hoc networks (VANETs) are configured to provide for communications with highway vehicles. We have recently introduced a network architecture to support such communications through the dynamic synthesis of a backbone network, identified as a Vehicular Backbone Network (VBN). Nominal positions across each road are optimally selected and announced as best locations to use for packet forwarding purposes. During each election period, within each designated subsegment situated in the vicinity of these nominal locations, a vehicle whose location is relatively close to the nominal position is elected to temporarily act as a relay node (RN). Through cross-layer settings, the relay nodes interconnect, forming a VANET backbone network. Vehicles inter-communicate through access to or from the backbone relay network. In this paper, we present distributed protocols that are employed by highway vehicles, in parallel in each segment, to elect relay nodes. Vehicles can have the capability to sense the lane in which they travel, and to gather statistics concerning the distance spacing between vehicles. We present a highly effective Lane Based Election (LBE) algorithm for the election of relay nodes. The protocol is implemented at a forwarding layer that is located above the MAC layer and is thus independent of the latter. We present mathematical analyses, confirmed by simulations, that assess the probability that a successful relay node election process will take place within a very brief period of time. For systems that do not make use of vehicular knowledge of their lane residency, we present a Group Based Election (GBE) algorithm and characterize its delay-throughput performance. We show both classes of algorithms to operate in a highly effective manner, serving to construct and update the layout of a backbone in a timely manner with high probability of success.**

I. Introduction

Consider a Road Side Unit (RSU) that broadcasts message flows intended for reception by vehicles traveling along a linear segment of a highway [6] [11]. Since the RSU is able to reach only vehicles that travel within a limited range from its location, multi-hop networking methods are employed, assuming that no fixed backbone infrastructure is available to assist the forwarding of these messages [2] [7] [8]. Recently published standard recommendations for VANETs involve the use of a IEEE 802.11p CSMA/CA type MAC scheme. Such VANET systems must use proper message forwarding and networking mechanisms to avoid the occurrence of excessive packet collisions, which can lead to throughput degradations induced by the occurrence of broadcast storm events [1]. Several classes of forwarding protocols have been proposed and studied in aiming to resolve such problems. General approaches involve the election of certain vehicles to act as relay nodes (RNs) based on the use of distance-based forwarding (DBF) schemes. The latter involve the election of vehicles on a packet-by-packet basis (preferring those that are located farther away from a forwarding node) to act as forwarding nodes [2] [4]. Another class of networking mechanisms involve the synthesis of cluster-based forwarding layouts [3] [5]. Packets are then propagated along the highway by using a dynamically adapted multihop backbone network. Such a location aware cross-layer adaptive backbone based architecture has been presented by I. Rubin et al. in [10], and identified as a Vehicular Backbone Network (VBN). Studies involving the analysis and synthesis of the VBN system have also been recently described in [12], [13], [9], and [14]. The VBN based operation makes use of geo-location (or, alternatively, relative locations of vehicles that are members of a team, formation, platoon, or a swarm, with respect to a reference station or vehicle) information involving the relative positions of road vehicles to elect effective relay nodes. We have presented mathematical models that are used to dynamically determine the optimal layout of RN nominal locations, based on observed highway propagation conditions and vehicular traffic parameters.

In this paper, we present distributed election algorithms that can be effectively implemented by each vehicle at a Forwarding Layer (FL) that resides above the MAC layer. These protocols are used to execute a bidding based election process by highway vehicles. Vehicles bid to elect themselves to serve as temporary RNs. Elected RNs form a dynamically synthesized backbone network. To implement an effective election protocol that effectively completes the election process in a timely manner, we assume here that each vehicle makes use of its ability to monitor the lane in which it travels. In addition, we take advantage of the current observed spacings between neighboring vehicles. The contributions of this paper are two fold. Firstly, noting that the Lane Based Election (LBE) and Group Based Election (GBE) algorithms have been outlined in [9], we hereby provide an expanded specification of the protocols, describing the underlying election protocol by presenting its finite state machine model. Secondly, we derive mathematical expressions and carry out analytical and simulation based evaluations aiming to exhibit the performance features of the underlying election algorithms. We note the applicability of the proposed election algorithms to a wide range of other VANET message flow scenarios,

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including the formation of a dynamic backbone to aid in the uplink and downlink routing of multicast and unicast flows among highway vehicles. Our proposed election protocols are also of key importance in serving to synthesize backbones for formation (or swarm) oriented mobile groups of vehicles (including the convoy systems discussed in [9]).

In Section II, a basic description of the VBN VANET system is given. In Section III, we describe the proposed backbone node election algorithms and protocols. In Sections IV and V, we model and analyze the performance behavior of the proposed election algorithms. Using the mathematical analyses developed in this paper, and by also carrying out Monte Carlo simulations, we validate the precision of our mathematical analyses and display the performance features of the proposed algorithms. We show the proposed schemes to produce a successful election of a relay node, in each segment, with high probability, and in a short period of time. Conclusions are drawn in Section VI.

II. THE VEHICULAR BACKBONE NETWORK

Under the Vehicular Backbone Network (VBN) architecture, certain vehicles traveling along the highway under consideration are elected to act as relay nodes (RNs). Each RN establishes a communications link with its neighboring relay nodes, forming the VANET backbone network (Bnet). At election time, it is desirable to elect those vehicles that reside closest to identified nominal locations (while also preferring those that travel at the slowest lanes) to act as RNs. Re-elections are triggered periodically, or as required. In this manner, each RN acts as a base station node that temporarily manages the access of messages to/from vehicles that travel in its local vicinity, as well as being responsible for forwarding messages that it receives across the backbone network to its neighboring RNs. As noted above, to avoid making changes to link layer and MAC Layer protocols that have already been implemented, we assume that the backbone node election algorithm is nested in a Forwarding Layer (FL)which lies above the link layer protocol. The operation would thus be independent of the specific link's multiple access scheduling scheme being employed. In particular, TDMA or CSMA/CA type MAC layer protocols would typically be employed.

III. THE BACKBONE NODE ELECTION SCHEME: SYSTEM CONFIGURATION

Assume the RSU to be located at the 0 position and divide the highway into segments of length D. The nominal position for the n-th RN is then at $L_n = nD$; it covers the n-th segment $(L_n - D/2, L_n + D/2)$. This structure can be extended to both sides of the RSU. We assume each segment to be divided into equal length sub-segments, each of length of $s = 2l$. The first sub-segment, denoted as $ss(1)$ covers the span $(L_n - l, L_n + l)$. The following sub-segments span the interval regions $ss(2) = (L_n + l, L_n + 3l)$, $ss(3) = (L_n - 3l, L_n - l)$, and so on. To simplify the election algorithm and improve its efficiency, the length of each sub-segment is predetermined (being recomputed and announced periodically, or as needed) in a manner that aims to assure (with high probability, under currently observed vehicular flow statistics) that a single vehicle per lane resides in each highway span of length s. Therefore the maximum number of vehicles that can reside in a sub-segment is bounded (with high probability) by the number of lanes (K). In recent analyses, we have shown that higher throughput rates are attained when elected RNs reside close to the computed nominal positions (while then also optimally configuring the underlying transmit/code rate and pacing flow control operations) [10], [9]. Hence, we strive to elect, in each segment, a vehicle that is located close to the identified nominal position. Consequently, a vehicle located in $ss(i)$ is given precedence for electing itself as the segment's RN over other vehicles that are located in the same segment but reside in more remote sub-segments $ss(j), j > i$. The election algorithm starts by running a bidding based process that involves the vehicles that reside in $ss(1)$. If no successful election takes place, it then iteratively proceeds to trigger elections that include vehicles that reside in subsequent sub-segments. Clearly, when the vehicular traffic rate in the underlying segment is at a medium to high level, the system layout is readily set to assure the existence of at most one vehicle per lane in a sub-segment, and the existence of a positive number of vehicles over all lanes within a sub-segment. For low vehicular traffic rates, it may at times not be feasible to synthesize a connected dominating backbone network. Under such conditions, the protocol would default to a properly configured group based election (GBE) scheme described in a latter section, or under even lower vehicular rates to a basic DBF based operation, whereby a low link data rate would be selected to realize a higher probability of v-to-v connectivity. Otherwise, the optimal settings used for the VBN system include the use of an adaptive rate cross-layer operation, under which the link data rate is optimally configured [10], [9]. The election of RNs that manage different segments is performed in an independent manner; these processes are thus executed in parallel. The following two sections describe the proposed election algorithms. Under the assumption that each vehicle is aware of its own lane, we propose the Lane Based Election (LBE) algorithm. We propose the use of the Group Based Election (GBE) algorithm when lane residence information is not employed. For both algorithms, to evaluate the robustness of protocol behavior, we focus our studies here on the case where no facilitator is authorized, or present. Otherwise, when re-election is triggered, the use of a current RN as a facilitator would serve to simplify the process, as outlined in [9].

IV. LANE BASED BACKBONE NODE ELECTION (LBE) ALGORITHM

A. Protocol description

The Lane Based Election (LBE) algorithm starts (when triggered at initiation or when a re-election prompt is recognized) with the election of a RN among vehicles located in the first sub-segment. We assume segment vehicles to operate in a time synchronous manner, transmitting their election packets within selected time slots that are organized to form time frames, identified as windows. This can be accomplished, for example, by inducing the currently elected RN, or facilitator, to transmit a brief beacon to which local users will time synchronize the starts of their time slots. Each window is divided into $K+1$ time slots, where K is the number of lanes. The duration of a time slot is set to be equal to the transmission time of an underlying (maximum length) packet. During the first window, a vehicle traveling in lane $i(1 \leq i \leq K)$ uses slot i to transmit an outstanding election control packet, if any, and if instructed to do so by the election protocol. It will then send (i.e., request its MAC layer to transmit) a bid packet (for serving as a RN) given that it did not previously receive a bid (or ACK) packet from another vehicle. In the case that it has previously received a bid packet sent by another vehicle, which has not yet been ACKed by another vehicle, the vehicle's LBE protocol would prepare an ACK packet to this bid that it would plan to send at its designated time slot i, serving to acknowledge the bidder (noting that we assume vehicles to use half-duplex radio modules, so that the sending vehicle, and possibly others, may otherwise not know whether the transmission of its bid packet has been successful), given that it has not by that time received any ACK packet sent by other vehicles. If such an ACK packet is received, this vehicle cancels its plan to send its ACK message; it then excuses itself from further participation in the bidding process. Due to the possible occurrence of MAC layer reception and/or transmission failures, multiple bid or ACK packets may be received. In this case, if no ACK packets have yet been received, the latest bid packet received by a vehicle is regarded as the outstanding bidder for which the vehicle will prepare to send an ACK at its designated slot (unless, as noted above, an ACK is received at an earlier slot). Also, the latest ACK packet received in a window is used to identify for a vehicle the winner of the RN election process; in this case, its election protocol finite state machine will transition to the idle state. If a vehicle successfully transmits a bid packet that is not detected to be followed by other bid packets or by any ACK packet, it will consider itself as the elected RN. It will then use time slot 0 of the second window to send a confirmation packet, announcing itself as the RN node. (As noted in [9], if a facilitator is used, the latter can use slot 0 to announce and ACK the election of segment RN, broadcasting such confirmation to all segment vehicles.) Following this protocol, a vehicle in a lowered numbered lane (typically a lower speed lane) is more likely to be elected. This is advantageous since slower vehicles stay longer within closer range to the nominal position, leading to reduced election process control overhead. In Figure 1, we present a finite state machine diagram that describes the states and state transition flows involving the LBE process undertaken by each participating vehicle that resides in an underlying sub-segment. A step by step algorithm for a vehicle in lane i is presented in the following column.

Algorithm Lane Based Election

Begin window 1,
The vehicle is initially waiting to send a Bid at time slot i
for each time slot $ts \in [1, K]$ **do**
    if $ts < i$ **then**
        if the vehicle hears a Bid **then**
            vehicle cancels its Bid, if any is outstanding,
            and waits to send an ACK at slot i if none is
            yet received
        end if
        if the vehicle hears an ACK **then**
            vehicle will cancel any outstanding Bid or
            ACK, if any, and enter IDLE state
        end if
    end if
    if $ts = i$ **then**
        vehicle sends either a Bid or ACK, if any is
        outstanding
        if the vehicle sends a Bid **then**
            it considers itself as an RN Candidate and sets
            its RN status state to TRUE
        end if
    end if
    if $ts > i$ **then**
        if the vehicle is an RN Candidate
          (having sent a Bid in $ts = i$) **then**
            if the vehicle hears a BID or an ACK for
            another station **then**
                sets its RN status state to FALSE
            end if
            if the vehicle hears an ACK for itself **then**
                sets its RN status state to TRUE
            end if
        end if
    end if
end for
End window 1
Begin Window 2,
At time slot $ts = 0$
if the vehicle has its RN status state at TRUE **then**
    the vehicle sends a confirmation packet announcing
    itself as the RN
end if
End Window 2

B. Performance Analysis under the LBE Protocol

To evaluate the performance of the LBE algorithm, we assume that the minimum spacings between cars are monitored; sub-segments lengths are consequently set so that there is (with high probability) at most one vehicle per lane in every sub-segment. Yet, it is noted that the algorithm will generally continue to successfully accomplish its election task even when a certain lane may contain at times multiple vehicles.

To account for the occurrence of transmit or receive failure events, we assume the following parameters in our analyses. A vehicle whose MAC layer entity is tasked by the election algorithm to transmit a packet may fail in completing successfully this task. Key conditions that induce such a failure

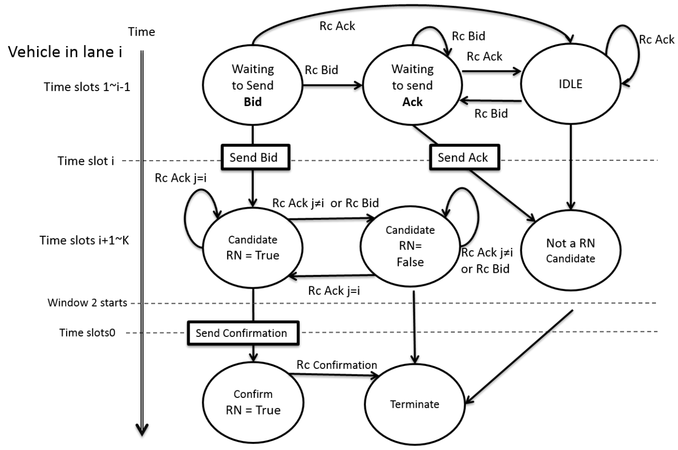

Fig. 1. LBE algorithm Finite State Machine

include the following two classes of events: a. Transmit failure event type-1, under which the MAC layer entity proceeds to transmit the packet as requested but the transmitted packet is lost due to channel noise corruptions, or due to collisions with other packet transmissions, or due to other causes, so that none of the other vehicles that are in range to potentially receive the packet have actually been able to successfully receive it. The transmitting vehicle may not however be aware that the packet has been lost. We denote the probability of such a type-1 transmit failure event occurrence as P_{te1}. b. Transmit failure event type-2, under which the MAC layer entity fails to transmit the packet due to the occurrence of a failure event at the NIC/radio transmit module. When this happens, we assume that the MAC layer entity will inform the election protocol entity residing at the forwarding layer on its failure to transmit, and will not attempt to retransmit the underlying packet during the election period under consideration; for the underlying analysis we then assume this packet to be lost. We denote the probability of such a type-2 transmit failure event occurrence as P_{te2}. We use P_{te} to denote the probability of transmit failure when the failure event could be of either type.

Similarly, we assume that it is possible for reception failure events to take place. We assume that a vehicle's receiver would fail to correctly detect and receive a (successfully) transmitted (bid or ACK) packet with (receive error) probability P_{re}.

We assume these (transmit and/or receive) error events to occur in a statistically independent manner over time (i.e., over distinct time slots) and over space (i.e., from vehicle to vehicle), as well as be mutually independent (in relation to transmit and receive error events).

The following metrics are used to evaluate the performance of the election algorithm: 1. The successful RN election probability under the LBE algorithm ($P_n(sLBE)$), given that n vehicles reside in the sub-segment; it is defined as the probability that the algorithm terminates with the election of a single RN within a time period that is not longer than W windows. We set a nominal value of $W = 2$. 2. The probability that the elected RN is the one located in the lowest numbered occupied lane, given that a single RN is elected and that n vehicles reside in the sub-segment, ($P_n(lLBE)$). 3. The time it takes to complete the election algorithm, given that a successful relay node is elected, is upper bounded by the duration of two window times.

Clearly, by its definition, when $P_{te} = P_{re} = 0$, the LBE algorithm is guaranteed to terminate with the slowest vehicle elected as the RN given that there is at least one vehicle in the sub-segment. The ensuing time delay is then equal to 2 frames. Under the occurrence of a transmit or receive packet failure, it is possible that the algorithm will terminate with none or multiple vehicles elected as RNs. Furthermore, under such failure events, the slowest vehicle may not be the one that is elected as the RN.

For the analysis, consider a tagged sub-segment. For it, let K represent the number of highway lanes and set n to denote the number of vehicles (across all spanned lanes) that reside in the underlying sub-segment at a given time period (during which the election algorithm being analyzed is executed). When $n = 1$, regardless of the values assumed by P_{te} and P_{re}, we have $P_n(sLBE) = P_n(lLBE) = 1$, since then the sole vehicle residing in the sub-segment will proceed to self-elect itself as the RN, sending a confirmation message in slot 0 of the subsequent frame. It is assumed that this confirmation will be successful; otherwise, we note that the elected RN will periodically announce itself as the segment's RN; it will issue a re-election notice at a time that it is determined that it has incurred an excess deviation from the ideal RN position.

In the following, we derive mathematical bounds on the probability of having one of the sub-segment vehicles electing itself successfully as the RN, within a specified number of frames (we henceforth set the default number of such frames to be equal to 2). We carry out this analysis by first assuming transmit failure events to dominate, hence setting $P_{re} = 0$. We then perform analysis under the assumption that receive failure events dominate. Subsequently, we consider the combined occurrence of transmit and receive failure events. We derive a lower bound on the probability of successfully electing a RN in a tagged sub-segment within a specified period of time. We also carry our simulation based evaluations, confirming the precision of the derived analytical bounds.

For $n \geq 2$, under the presence of transmit failures (and no receive failures, $P_{re} = 0$) , we have: $P_n(sLBE|P_{re} = 0) = 1 - (P_{te})^n$, whereby either a type-1 or type-2 transmit failure error event may take place. This result is obtained by noting that the occurrence of at least a single successful bid packet transmission would result in the successful election of a vehicle as a RN.

Assume next that the presence of packet receive failure events dominates ($P_{te} = 0$). In the following, we present a lower bound on the probability of successfully electing a vehicle as a RN within W frames (assuming a nominal value of $W = 2$). Given that a bid was sent by a vehicle, we set C to represent the event that the bid is ACKed (within the same frame in which the bid packet was sent) by a vehicle that is located in the next occupied lane (if any), and that all other vehicles receive the bid message and/or the ACK message. Then, $P(C)$ is calculated to be given as:

$$P_n(C) = (1-P_{re})[(1-P_{re})+P_{re}(1-P_{re})]^{n-2}, n \geq 2. \quad (1)$$

where the first term $(1 - P_{re})$ in the bracket expresses the probability of a successful receipt of a Bid and the second term accounts for the probability of failure of receiving a bid but still successfully receiving an ACK. The probability of successfully electing one RN among n vehicles while assuming no transmit errors ,$P_n(sLBE|P_{te} = 0)$, is lower bounded by the following expression for $n \geq 2$:

$$\begin{aligned} & P_n(sLBE|P_{te} = 0) \\ = & \sum_{i=1}^{n} P(\text{only } i^{th} \text{ vehicle elected}) \\ \geq & \sum_{i=1}^{n-1} P(i^{th} \text{ vehicle bids}) P_i(C) \\ + & P(n^{th} \text{ vehicle bids}) P(\text{the bid is heard by all others}) \\ \geq & \sum_{i=1}^{n-1} (P_{re})^{i-1} P_i(C) + (P_{re})^{n-1}(1-P_{re})^{n-1}. \end{aligned}$$

For notational simplicity, we denote $P_n(sLBE|P_{te} = 0)$ as $P_n(s0)$. When assuming both receive and type-1 transmit positive error probabilities, we obtain the following expression as a lower bound for $P_n(sLBE)$, for $n \geq 2$:

$$\begin{aligned} & P_n(sLBE) \\ \geq & \binom{n}{n-1} (P_{te1})^{n-1}(1-P_{te1})(1-P_{re})^{n-1} \\ + & \sum_{i=2}^{n} \binom{n}{n-i} (P_{te1})^{n-i}(1-p_{te1})^i(1-(p_{re})^2)^{n-i} P_i(s0). \end{aligned}$$

To explain the above noted expression, we observe that we have approached this mathematical analysis by proceeding in two steps. First, we consider the event under which a single vehicle has successfully transmitted a bid message while all the other vehicles have failed to transmit any bid or ACK message. We note that it is then necessary for all other $(n-1)$ vehicles to hear that bid message in order to end with a single elected RN. The expression presented above was derived under the assumption that transmit error events, when they occur, are of type-1. In this case, we note that if no vehicle has been able to successfully transmit any message, all vehicles would elect themselves as candidate relay nodes (since they are not aware of the failure of their transmissions) and this would result in an election failure. Secondly, we consider the case that more than two vehicles (say, i vehicles, $i \geq 2$) have not incurred transmit errors. The other$(n - i)$ vehicles that have failed to transmit a bid message would need to hear a bid or ACK message to induce a successful RN election outcome. The probability that at least one such message is received by such a vehicle is equal to $(1-(P_{re})^2)$. The resulting expression is multiplied by the probability that a single RN is successfully elected from a group of i contending vehicles, assuming no transmit errors (and a positive receive error rate), yielding the stated lower bound formula. When type-2 transmit errors are involved, a vehicle that fails to transmit a message is aware of its failure and can thus inform the forwarding layer entity that executes the election algorithm. Consequently, the lower bound formula presented above for the probability of successful election of a RN is modified by setting the factors $(1 - P_{re})^{n-1}$ and $1 - (P_{re})^2$ there to a value of 1 (i.e., not including these factors). In Table I, we exhibit values for the lower bound calculated for $P_n(sLBE)$, for several selected values of n, P_{te1} and P_{re}.

TABLE I
LOWER BOUND ON THE PROBABILITY OF SUCCESSFULLY ELECTING A RELAY NODE.

(P_{te1}, P_{re})	$n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
(0,0)	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
(0.1,0)	0.9900	0.9990	0.9999	1.0000	1.0000	1.0000
(0,0.1)	0.9900	0.9882	0.9798	0.9703	0.9606	0.9510
(0.1,0.1)	0.9641	0.9867	0.9804	0.9779	0.9698	0.9510

In the following, we evaluate the probability, denoted as $P_n(lLBE)$, that the elected relay node is located at the lowest numbered occupied lane. To obtain a lower bound for this probability, we define events A, B and S as follows. A represents the event that a vehicle residing at the lowest numbered occupied lane is elected as the RN. B designates the event that the transmission of a bid by a vehicle located in the lowest numbered occupied lane is successful. S identifies the event that the algorithm terminates within two windows ($W = 2$) with the election of a single RN node. The lower bound is given by the following expression (assuming no receive error events to occur):

$$\begin{aligned} P_n(lLBE) &= P(A|S) = P(B|S) = \frac{P(B \cap S)}{P(S)} \\ &= \frac{P(B)}{P(S)} \geq P(B) = (1-P_{te}). \end{aligned} \quad (2)$$

When receive error events may occur, we define D to designate the event that the vehicle at the lowest numbered occupied lane is elected as the RN. We then obtain a lower bound on $P_n(lLBE)$ to be given given by,

$$P_n(lLBE) = P(D|S) \geq P(D \cap S) \geq P(C), n \geq 2. \quad (3)$$

C. Performance behavior results

We have executed Monte Carlo simulations for a multitude of system scenarios, assuming the following system parameters: The number of lanes (K), number of vehicles (n), P_{te}, P_{re}. For each set of selected parameters, we have run the system's simulation program, using the LBE algorithm, by generating a total of 10^5 repetitions. The results are exhibited in Figure 2. We show the performance results for the probability of success, $P_n(sLBE)$, for varying values of P_{te1} and P_{re}, as obtained under the simulations, as well as under the use of our derived mathematical expressions. The

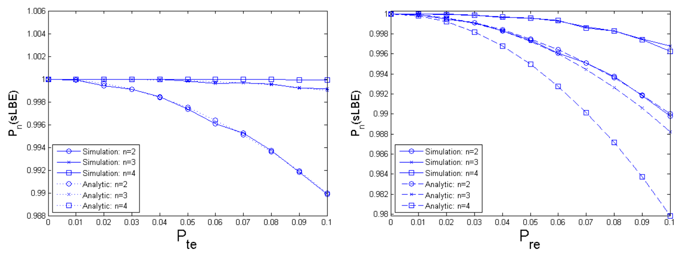

Fig. 2. Left figure shows the successful RN election probability ($P_n(sLBE)$) vs. Transmit error (P_{te1}), Number of Lanes (K)= 7, and Vehicles (n). Right figure displays the successful RN election probability ($P_n(sLBE)$) vs. receive error (P_{re}), number of Lanes (K)= 7, and Vehicles (n).

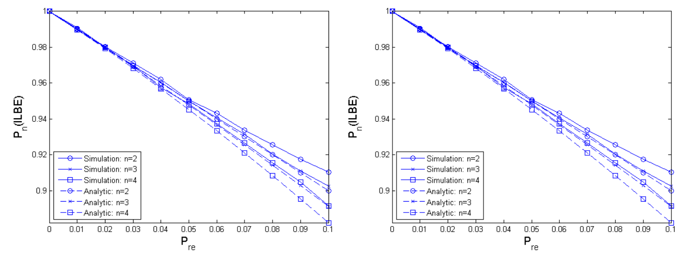

Fig. 3. Left figure shows the lowest numbered lane RN election probability ($P_n(lLBE)$) vs. transmit error (P_{te1}), number of lanes (K) = 7, and vehicles (n). Right figure displays the lowest numbered lane RN election probability ($P_n(lLBE)$) vs. receive error (P_{re}), number of lanes (K) = 7, and vehicles (n).

TABLE II
EFFECT OF TRANSMIT AND RECEIVE ERRORS ON THE SUCCESSFUL RN ELECTION PROBABILITY.

(P_{te1}, P_{re})	$n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
(0,0)	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
(0.1,0)	0.9900	0.9991	0.9999	1.0000	1.0000	1.0000
(0,0.1)	0.9900	0.9968	0.9963	0.9964	0.9965	0.9963
(0.1,0.1)	0.9641	0.9867	0.9922	0.9926	0.9916	0.9920

TABLE III
EFFECT OF TRANSMIT AND RECEIVE ERRORS ON THE LOWEST NUMBERED LANE RN ELECTION PROBABILITY VS. THE NUMBER OF NUMBER OF VEHICLES (n), FOR A NUMBER OF LANES (K) = 7

(P_{te1}, P_{re})	$n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
(0,0)	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
(0.1,0)	0.9095	0.9017	0.8999	0.9005	0.9008	0.8994
(0,0.1)	0.9103	0.9024	0.8913	0.8863	0.8800	0.8725
(0.1,0.1)	0.8388	0.8188	0.8078	0.7994	0.7919	0.7892

simulated system performance results are noted to be consistent with those predicted by using our analytical expressions. We observe that while the success probability $P_n(sLBE)$ decreases as the values of P_{te} and P_{re} increase, it never-the-less stays quite high. In Table II, we present characteristic values for $P_n(sLBE)$ obtained under our simulations, for several selected values of n and for various assumed values for the parameters P_{te1} and P_{re} . We note that, in comparing with type-2 transmit failures, occurrences of type-1 transmit error events lead to more severe performance degradations. Hence, we focus the presentation of performance results on the inclusion of only type-1 transmit error events, noting a value of $P_{te1} = 0.1$ to be characteristic of such potential degradations. Based on the displayed performance evaluations, we conclude that the LBE algorithm is effectively executed, terminating successfully with high probability, with the election of a single RN, in a time period that spans two windows. We also note that under practical implementation conditions, the duration of each frame is of the order of several milliseconds, or less, while a vehicle will typically take a period of the order of a second or more to transition a significant portion of a road segment (before initiating a new election process), even when moving at a high speed. Furthermore, noting that the transmission of a data packet is of the order of a millisecond, or less, a vehicle is able to transmit a large number of packets while serving continuously as a relay node, yielding an effective VBN operation. If vehicles move as a team (or platoon) and RN elections are set in reference to the location of a designated team leader, an even longer time period between re-election intervals can be invoked.

In Figure 3, we exhibit the performance results obtained by simulations and by using our analytical expressions for the $P_n(lLBE)$ metric, under various assumed transmit and receive error rates. The simulation results confirm the precision of our analytical bounds. The figures also show that though $P_n(lLBE)$ decreases as the values of P_{te} and P_{re} increase, it still allows the system to operate in a highly efficient and effective manner. In Table III, we display simulation results obtained for $P_n(lLBE)$ for several parameter values. As expected, the probability $P_n(lLBE)$ is somewhat reduced under the occurrence of transmit or receive packet losses. Yet, the system is able to generally maintain a high performance level. Simulation results also show that when the LBE algorithm terminates with a single RN, there exists a high probability that the elected vehicle resides in the lowest numbered occupied lane.

D. Solutions to exception conditions

It is possible for the LBE election process to terminate without resulting in the election of a relay node. This can be caused by the occurrence of various MAC layer transmit and/or receive failures, or simply because no vehicle resides in the sub-segment. When this happens, the election algorithm proceeds to the next sub-segment, and the same election process is then repeated. After execution over all sub-segments, or when a prescribed timeout period elapses, without having a relay node elected, it is possible to re-start the election process. As noted above, if it turns out that the vehicular density is low, the election algorithm automatically falls back to a GBE or DBF mechanism. In the case that the LBE algorithm terminates with multiple RNs, the problem will typically resolve itself after several frames. Elected RNs broadcast periodically control beacons, as well as announce their role in frame headers that are included in their data transmissions.

V. Group Based Backbone Node Election (GBE) Algorithm

A. Protocol description

Under the group based election (GBE) algorithm, it is assumed that a vehicle is unaware (or does not make use) of the lane that it occupies. Vehicles located in the same sub-segment synchronize their common window start and end times. Each window is divided into K time slots. For each window, each vehicle that is part of the bidding process in the underlying sub-segment would select a time slot whose position (and corresponding identifier) is chosen randomly from the discrete set $[1, K]$. Upon the start of the election process, the GBE entity at a participating vehicle plans to instruct its MAC entity to transmit a bid or ACK packet at its selected time slot, if appropriate as dictated by the GBE protocol. The decision as to whether to send such a bid or ACK packet follows a protocol logic which is similar to that described above for the LBE algorithm, with the exception being that packet sending times are selected at random within each window. A vehicle that has successfully transmitted a bid packet and later hears an ACK for its own bid considers itself as a RN candidate. If its bid is not ACKed, and it does not hear any ACK sent for another bid, it will proceed to send a confirmation packet in the next window (at a randomly selected slot), announcing itself as the segment's elected RN. In turn, if at any time, a vehicle receives a confirmation packet that identifies another vehicle as the elected RN, it terminates its bid. If no RN candidate is identified during the current window, the election process is repeated during the next window. The election process terminates when the number of employed windows reaches a certain threshold (e.g., setting it equal to a maximum duration T). A vehicle that hears an ACK message that confirms the bid made by another vehicle will assume that a RN candidate has been identified and will not continue to participate in the bidding process that may subsequently take place. If the process does not result in a successful election within a sub-segment, the process would proceed to the next sub-segment. Other elements are similar to those described for the LBE algorithm. In Figure 4, we present a finite state machine based description of the GRE protocol.

B. Performance Analysis and Behavior under the GBE Protocol

In assessing the performance of the GBE algorithm, the following metrics are used: 1. The successful RN election probability under the GBE algorithm (P_{sGBE}), defined as the probability that the algorithm terminates in the successful election of a single RN (within the window time period T); 2. The average number of windows (W_{avg}) elapsed to termination, given that the algorithm terminates successfully with the election of a single RN.

In carrying out our analysis, we assume that there is at most a single vehicle per lane per sub-segment. We further assume that the MAC layer protocol (e.g., a CSMA/CA scheme) utilizes a contention window that consists of a fixed length of 16 mini slots (whereby the sensing of a transmission signal that occurs during a mini-slot period will cause busy channel state determination at the half-duplex radio receivers that are not transmitting over this mini-slot period). A MAC entity that is instructed to transmit a packet, schedules this transmission to take place at a time that is determined by the random selection of a minislot within this contention window. The vehicle(s) that selects the lowest numbered mini slot within a contention window will use this time slot to transmit its packet. Others will be able to sense that the channel is then busy and consequently drop their transmission attempts. We note that a broadcast MAC service is assumed, so that no packet re-transmissions are undertaken. When two or more vehicles select the same lowest numbered mini slot, a collision event is declared, and we assume that then no successful packet reception is realized. We set the number of lanes to be equal to K; the number of vehicles in a sub-segment is equal to n, which is assumed to be greater than 1. The case $n = 1$ leads to a single successful bid transmission; the bidder will send a confirmation packet in the subsequent window.

In the following, we derive a lower bound for the probability of a successful election, P_{sGBE} given that there are no transmit or receive errors. We set A to represent the event that at least two packets are successfully transmitted and received in a single window. Event B identifies the joint event that, in a given window, vehicles select distinct mini-slots and that this selection does not include the case under which all vehicles choose the same slot. Let A_i and B_i denote the respective events when they take place in the i^{th} window. A lower bound for the probability of occurrence of event A, P(A), is given by the following expression:

$$\begin{aligned} P(A) &= P(A_i) \geq P(B_i) = P(B) \\ &= \frac{Perm_n^{16K} - C_1^K Perm_n^{16}}{(16K)^n}, i = 1, 2, ..., T \quad (4) \\ &\quad \text{(where Perm is permutation)} \end{aligned}$$

A lower bound for P_{sGBE} is then expressed as follows:

$$\begin{aligned} P_{sGBE} &= P(A_1 \cup A_2 \cup ... \cup A_{T-1}) \\ &= 1 - (1 - \frac{Perm_n^{16K} - C_1^K Perm_n^{16}}{(16K)^n})^{T-1} \quad (5) \end{aligned}$$

We proceed next to derive a bound on the average time (in terms of the corresponding number of windows) elapsed to successful termination, W_{avg}. Let X denote a random variable that represents the number of windows it takes for the RN to be elected, given that the algorithm terminates with a single RN. The probability mass function (pmf) of X is given by the following expression:

$$p_X(x) = \frac{P(A)(1 - P(A))^{x-2}}{1 - (1 - P(A))^{T-1}}, x = 2, 3, 4, ...T. \quad (6)$$

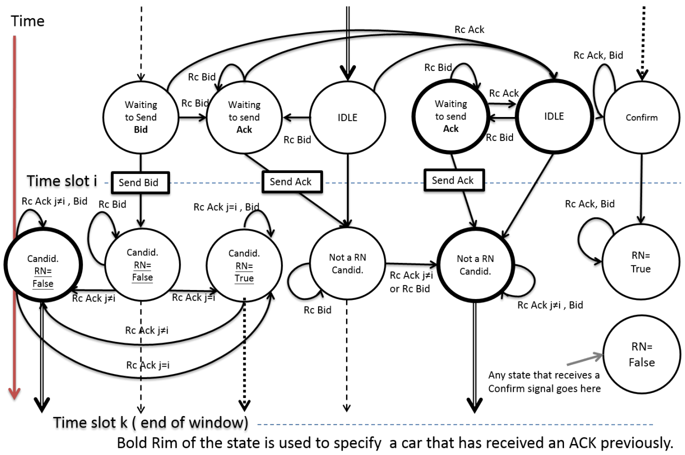

Fig. 4. Finite State Machine for the GBE Algorithm.

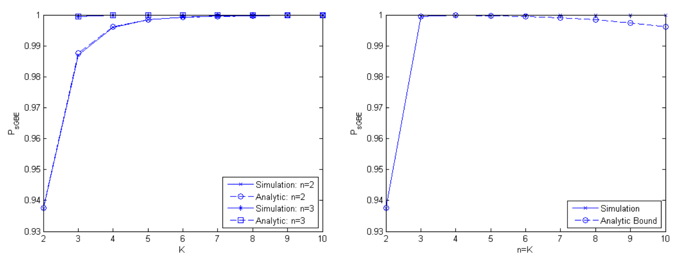

Fig. 5. Left figure shows the successful RN election probability (P_{sGBE}) vs. number of lanes (K), where n is number of vehicles. Right figure is the case where number of lanes (K) = number of vehicles (n).

A lower bound on the expectation of X is then given as:

$$
\begin{aligned}
E[X] &= \sum_{x=2}^{T} x P_x(x) = \sum_{x=2}^{T} x \frac{P(A)(1-P(A))^{x-2}}{1-(1-P(A))^{T-1}} \\
&\geq \frac{P(B)(1-P(B))^{x-2}}{1-(1-P(B))^{T-1}}. \qquad (7)
\end{aligned}
$$

The last inequality is proven by observing that the expectation of X as a function of $P(A)$ is a decreasing function of $P(A)$ for $0 \leq P(A) \leq 1$.

In Figure 5 and Figure 6, we respectively display the behavior of the probability of successful RN election and of the average time to termination metrics. Our analytical bounds are well confirmed vs. simulation results. We show the GBE algorithm to have a high probability of successfully terminating with the election of a single RN, in a time period of 5 windows. A short average execution time is realized (recalling that a minimum of two windows is required).

VI. Conclusions

In this paper, we describe lane based and group based election algorithms, as employed for vehicular backbone networks (VBN) [9]. We present finite state machine specifications for these protocols. We then provide analyses that are used to characterize the performance behavior of these algorithms. Included are measures that characterize the probability of

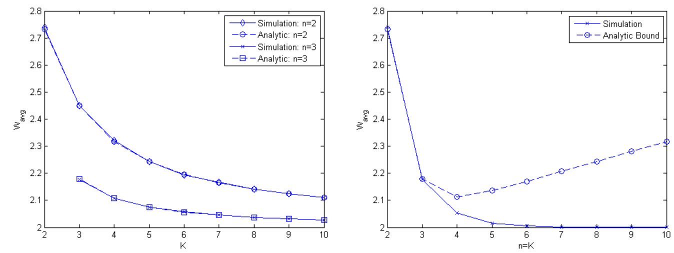

Fig. 6. Left figure shows the average number of windows (W_{avg}) vs. the number of lanes (K), where n is number of vehicles. Right figure is the case where number of Lanes (K) = Vehicles (n).

successful termination within a specified time period with the election of a single relay node. Vehicles make effective use of status data, including lane association and inter-vehicular spacings, to produce a highly efficient election process and VANET network operation.

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