Abstract — Vehicular Ad Hoc Networks (VANETs) will play a vital role in reducing the number of road accidents and fatalities as well as vehicular traffic optimization. Though an instance of Mobile Ad Hoc Networks (MANETs), the highly mobile and dynamic environment of VANET introduces new research challenges. To quickly adapt to the highly mobile and constantly changing topology and still meet the desired application requirements, it is vital for the VANET media access control (MAC) protocol guarantees wireless channel access with minimal delay and minimal exchange of control messages. This paper proposes an innovative Relative-Position-Based MAC Nucleus (RPB-MACn). By combining the dedicated communication channel pair and the dedicated directional antenna associated to the relative position of vehicles, a conceptually contention-free RPB-MACn mechanism for VANET is realized (when coupling with dynamic power control mechanism). Consequently, RPB-MACn can meet all the key requirements of the MAC protocol in a VANET system.

Keywords—VANET, MAC, RPB-MAC, Relative Position.

I. INTRODUCTION

There is a growing belief that the success of the Vehicular Ad Hoc Network (VANET) based inter-vehicle communications will open the door for a plethora of additional applications [1]. The system will allow vehicles to share various real-time road and traffic data for the purpose of safety and efficient driving [2]. The services of VANET based inter-vehicle communication may range from automated highway systems to distributed passenger teleconference [1].

However, achieving dependable and efficient VANETs imposes many challenges due to its high mobility and constantly changing topology. Although VANET communication between vehicles falls in the realm of Mobile Ad Hoc Networks (MANETs), the inherent high mobility introduces many new challenges, which makes the existing protocols for ad hoc networks not suitable for inter vehicle communication. To quickly adapt to the highly mobile and constantly changing topology with desired throughput and tolerable delay, it is essential for the VANET media access control (MAC) protocol to guarantee wireless local channel access with minimal delay and minimal exchange of control messages. In an environment with high mobility as VANET, if the delay caused in acquiring the channel is high, it can render the transmitted data completely outdated due to change in topology.

To date, many MAC mechanisms [1-6] have been proposed for MANETs and VANETs. However, there are no existing distributed MAC protocols efficiently providing point-to-point data communications graciously with low collision and low latency to meet the performance requirements (Table 1) imposed by VANET applications. Some suggested that the Dedicated Short Range Communications DSRC specification should be an extension of IEEE 802.11 [7]. However, both the studies on the performance of applying 802.11 in the realistic VANET scenarios show that, even the delay introduced by the 802.11-like MAC can be within 100ms, the corresponding throughput can only reach 60% in maximum [10] [11]. Therefore, the dominating conventional 802.11-like MAC protocol family for VANET, which uses the virtual carrier sense augmented CSMA/CA mechanism, can hardly meet the performance requirements imposed by the highly dynamic VANET applications [12].

Table 1: Requirements of VANET MAC vs. Properties of RPB-MACn

<table>
<thead>
<tr>
<th>Key requirements for VANET MACs</th>
<th>Salient Properties of RPB-MACn</th>
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<tbody>
<tr>
<td>Fully distributed &amp; scalable</td>
<td>Highly local, scalable &amp; distributed</td>
</tr>
<tr>
<td>Real-time (low &amp; bounded delay) channel access</td>
<td>Enabled by collision-free multiple reception to support high channel availability</td>
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<tr>
<td>Efficient bandwidth utilization</td>
<td>Maximum throughput &amp; low operation overhead</td>
</tr>
<tr>
<td>Efficient broadcast service to support anonymous addressee</td>
<td>Efficient unicast/multicast/broadcast services</td>
</tr>
<tr>
<td>Robust performance to high mobility</td>
<td>Enable by the implementation of the run-time static relative position</td>
</tr>
<tr>
<td>No hidden/exposed terminal &amp; deaf problem</td>
<td>Enabled by multiple reception and duplex capability</td>
</tr>
<tr>
<td>Position information available</td>
<td>Static relative positions embedded at run-time</td>
</tr>
<tr>
<td>No synchronization required</td>
<td>Requires no clock synchronization</td>
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Driven by the essential features (Table 1) required by life-critical VANET applications, we propose a relative-position based MAC nucleus (RPB-MACn) for VANETs. By fully exploiting the unique run-time static relative position property among neighboring vehicles, our RPB-
MACn conceptually promises collision-free dynamic channel accesses, enabled by the combination of statically configured directional antennas and the statically assigned dedicated transceiver channel pairs.

Table 1 summarizes some key salient features of RPB-MACn: i) Unlike the prior proposals on the position-based [15,16] and the directional antenna supported MAC design [1, 17, 18, 19] that are heavily burdened by the oppressive position estimation and tracking problem, the static relative positions of neighboring vehicles are inherently embedded at run-time in RPB-MACn; ii) The flexible Directional (one or multiple directional transmissions) and Omni transmissions (simultaneous 8 directional transmissions) modes enables the unicast, multicast, and broadcast services in RPB-MACn, which provides the comprehensive platform for the upper layer multi-hop communication protocol design; And if the radio transmission power of all vehicles can be dynamically controlled within the range of its immediate neighbors, iii) MACn is not susceptible to the hidden/exposed terminal problems like the omni antenna ad hoc systems and the new hidden terminal problems and deafness problem discussed in the prior work [1, 17, 18, 19]; and iv) when coupling with dynamic power control, RPB-MACn also enables collision-free channel access, which can guarantee real-time channel access yet requires no synchronization among participating nodes.

The rest of the paper is organized as follows. In section II, our observation of the unique run-time static relative position relation among neighboring vehicles is discussed. The relative position-based MAC design concept for VANETs based on this observation is presented in section III. Section IV presents our RPB-MACn mechanism design in detail. The augmenting solutions for the baseline RPB-MACn to support various real-world VANET scenarios are proposed in section V. We conclude the paper in section VI with the discussion of future work.

II. RUN-TIME STATIC RELATIVE POSITION RELATION AMONG NEIGHBORING VEHICLES

With the unique roadway geometry constraint, at any particular time, a vehicle may be surrounded by a maximum of 8 immediate neighboring vehicles (c.f. vehicle C in fig.1). This scenario is named as the standard surrounding setting and any other scenario is named as a non-standard surrounding setting. For a host vehicle in standard surrounding setting, although its neighboring vehicles change from time to time, at any moment, only one vehicle can be in one of the 8 particular relative positions (i.e., front, back, left, right, left-front, right-front, left-back, and right-back) w.r.t itself. This leads to the run-time static relative position relation among neighboring vehicles.

From the host vehicle’s perspective, if each relative position w.r.t. itself is used to represent the run-time locally unique identity of one neighboring vehicle running into that particular relative position, although different vehicles will run into a particular run-time static relative position of the host vehicle from time to time, at any particular time, the host vehicle always “sees” the static relative position formatted neighbor vehicle identities, such as “vehicle on my right”, “vehicle in my front”, etc. Therefore, the host vehicle can always treat any vehicles running into one particular relative position as one single same vehicle represented by that particular relative position as the run-time unique local identity. Consequently, a host vehicle may use the 8 known static relative positions w.r.t. itself as the locally unique temporary identity to schedule the access control among neighboring vehicles at run-time.

III. RELATIVE POSITION-BASED MAC: USING DIRECTIONAL ANTENNAS OVER SINGLE WIRELESS CHANNEL

In this section, we introduce the concept of developing a relative position based VANET MAC solution using directional antenna, wherein the static relative positions of neighboring vehicles are inherently embedded at run-time. Therefore, no burdensome position estimation and tracking are required for the directional antenna enabled MAC as the prior work on directional antenna based MACs for MANETs [1, 17, 18, 19]. Fig. 2 depicts such a directional antenna enabled MAC design based on the run-time static relative position property in VANETs. Here, all vehicles are equipped with 8 statically configured directional antennas, each dedicated to one relative position vicinity, operating over the single wireless channel to communicate with its 1-hop neighbors. With the constraint of the road geometry, this static directional antenna configuration enables neighbor vehicles have directional antenna pointed to each other. As shown in fig. 2, when vehicle A hears any message from the directional antenna covering its right side, A knows this neighboring vehicle (B in this case) must be on its right-side of 1-hop vicinity. Hence, the relative position information of the neighbors is implicitly achieved.
Since all the vehicles are equipped with 8 directional antennas of the same configurations, A can communicate with C (which uses its back directional antenna) over its front antenna. At the same time, A can communicate with E (which uses its front antenna) over its back antenna, and so forth. In principle, with the run-time static relative position property and the spatial reuse capability of directional antennas, a vehicle can simultaneously communicate with all its immediate neighbors each over a dedicated directional antenna at run-time.

Further, if the radio transmission of all vehicles is controlled within the range of its immediate neighbors, the VANET point-to-point communication can be restrained within the 1-hop vicinity. Therefore, the relative position based MAC solution enabled by the directional antennas can be well scaled in the multi-hop VANETs, without hidden terminal or exposed terminal problem as other omni or directional antenna based MAC solutions for MANETs suffered. As such, a conceptually collision-free access control in the highly dynamic VANETs is automatically achieved. However, this relative position based MAC solution using directional antennas over one single wireless channel can function validly if and only if: i) the directional antennas have perfect directivity gain (with negligible side- and back- lobe gain); ii) and the VANET system is operated in a perfect free space environment.

In reality, with the realistic directional antenna pattern and the real world multipath VANET wireless channel, the side and back lobe effects of the directional antenna make it more difficult for each directional antenna to receive messages perfectly from the vehicles in the expected relative positions. Indeed, the radio propagation in VANET wireless environment is even worse than a common land radio mobile environment [8]. In our preliminary study, the 2-ray ground pass loss model [20] and the shadowing effect [21] are considered for the large-scale propagation to model the realistic VANETs wireless channel. We examine the reception power distribution of a directional vehicular transmitter-receiver pair over the distance up to 1000 meters (specified by DSRC).

Fig. 3(a) is the 3-D reception power distribution over the 5cm horn directional antenna (18 degree of main lobe) given the directional transmission power of 20dBm (100mW). It is obvious that the amount of signal received from directions other than the intended directional main lobe is rather large. Fig. 3 (b) demonstrates a scenario to examine the side-lobe interference effect over a single realistic wireless channel for the front directional antenna of vehicle A. For each simulation run, we choose $y$ as a constant number from 0 to 1000m, then we vary $d$ from 0 to 1000m with the step of 1m. We examine how much percentage of positions out of all the testing ranges that the interference from the side lobes is larger than the signal from the main lobe. Fig. 3(c) shows the distribution of interference area, for instance, it shows over 25% examining positions have 60% interference area.

IV. RPB-MACn: A RELATIVE POSITION BASED COLLISION-FREE MAC NUCLEUS FOR VANETs

To solve the interference problem among multiple receptions of directional antennas over single wireless channel in the above design, we propose an innovative mechanism wherein the run-time static relative positions of the neighboring vehicles are tied to the combination of the directional antennas and the dedicated communication channels. As shown in fig. 4, besides using multiple directional antennas covering 8 directions, we also assign different wireless channel pairs to different antenna transceivers, each dedicated to a specific sector of the 1-hop vicinity covered by the directional antenna. As such, each directional antenna transmits and receives messages over its own dedicated wireless channels, which can be implemented using well known channel allocation techniques such as Code Division Multiple Access (CDMA) or Orthogonal Frequency Division Multiplexing (OFDM).

Fully exploiting the run-time static relative position property, here we propose an innovative static channel assignment scheme suitable to the highly dynamic VANETs. Let $T_n$ indicating the transmission over wireless channel $n$, while $R_n$ indicates the reception over channel $n$. In our static channel assignment scheme, the transceiver channel code pairs are assigned to the directional antennas following the same uniform sequences for all the vehicles. As shown in fig. 4, transmission channel $T_1$–$T_8$ are assigned to the 8 transmitters clockwise starting from the front antenna for all the vehicles. If vehicles drive in the same direction, a host vehicle A always communicates with the back antenna of a vehicle (B) in its front. Since the front antenna transmits over channel 1 ($T_1$), the back antenna of
vehicle C must use channel 1 to receive (R1), while the back antenna of vehicle C transmits over channel 5 (T5), the front antenna of the host vehicle A must receive over channel 5 (R5). With the run-time static relative position property, when the static uniform channel assignment sequence is applied to all the vehicles with the transmission channels T1→T2→T7→T8 to all 8 antennas clockwise starting from the front antenna, the corresponding reception channel assignment is automatically and uniquely determined (i.e., R5→R6→R8→R1→R3→R4) to all the antennas clockwise starting from the front antenna. As a result, in fig. 4, all the vehicles are assigned with the following transceiver channel pairs: T1/R5 (front); T2/R6 (right-front); T3/R7 (right); T4/R8 (right-back); T5/R1 (back); T6/R2 (left-back); T7/R3 (left-front); T8/R4 (front).

Therefore, by utilizing the run-time static relative position property, our static channel assignment scheme (which is defined at VANETs design phase, not at run-time) can suit all the dynamic VANETs scenarios at run-time. With this combination of the dedicated directional antenna and the dedicated transceiver channel pair tied to each unique relative position, conceptually, the collision-free (interference-free) simultaneous multiple receptions among neighboring vehicles can be achieved. If the radio transmission of all vehicles can be dynamically controlled within the range of its immediate neighbors for each of the 8 relative positions, conceptually, our design can realizes a contention-free RPB-MACn mechanism. As a result, it can provide information on the relative position and the orientation among vehicles on initial contact.

V. RPB-MACn IN REALISTIC VANET ENVIRONMENTS

For simplicity, we present the core innovative idea of our RPB-MACn mechanism in the standard surrounding position setting in previous sections, and assume that all the vehicles are with the same size and maintain same orientation and direction. In this section, we further verify and discuss the applicability of the RPB-MACn mechanism in the realistic VANET environments, where different vehicles can be in any non-standard surrounding position and hold different orientation directions with each other.

A. Coverage Overlaps Effect vs. Various VANET Settings

In figures 2 & 4, the neighboring vehicles are simply in what we referred as the standard surrounding position of vehicle A. In reality, as a highly dynamic network, although constrained by the roadway geometry, nodes in VANETs can be in various non-standard surrounding positions with each other. How should the omni-radio space be divided into multiple zones covered by multiple directional antennas such that vehicles can communicate efficiently with each other in any non-standard settings? To answer this question, we investigate the Coverage Overlap Effects of the multiple directional antennas.

The cases wherein vehicles are not in standard surrounding positions along the side of the host vehicle are considered here. If the zone coverage of each directional antenna is designed to be big enough with some overlaps between neighboring antennas, when vehicles are in the standard positions as shown in figure 5 (a), vehicle A will communicate with vehicle B via all the 3 communication channel pairs (T4/R8, T3/R7, T2/R6), while it will communicate with vehicle C or D only via 1 communication channel pair each. This way, vehicle A can still distinguish what is the relative position of the vehicle it is communicating with in even higher precision.

With the Coverage Overlap Effects, Figure 5(b) shows that when B and C are in the non-standard surrounding positions of vehicle A, A will communicate with each of them via 2 different communication pairs (vehicle B: T4/R8 and T3/R7; vehicle C: T3/R7 and T2/R6). At any moment, the relative positions of vehicle A and its neighbors will form either the standard surrounding positions or certain non-standard surrounding positions. Therefore, the coverage overlap effect provides a valid means for a vehicle to identify the relative positions of its neighboring vehicles with even higher precision.

However, the idea of applying the coverage overlap effect to provide the higher relative positioning precision will introduce collision into the ideal content-free RPB-MACn mechanism. For example, vehicles B and C in Figure 5(b) are both in the positions covered by one of the directional antenna zone. Consequently, collisions can occur at the channel pair (T3/R7) which is used by more than one neighboring vehicles. One potential solution could
be applying a simple and efficient dynamic scheduling mechanism to avoid the collisions among vehicles covered by the same antenna/channel zone.

B. Vehicles with Different Sizes

There can be a situation where a larger vehicle like a trailer might have smaller vehicles as its neighbors. Considering the case when a trailer has three vehicles moving adjacent to it, this is depicted in figure 6.

![Figure 6: Neighboring Vehicles with Different Sizes](image)

In this situation, a larger vehicle like a trailer can be equipped with a set of pairs of directional antennas (each ties with one transceiver pair) applying the same dedicated channel on the longer side. Hence, when a larger vehicle has multiple smaller vehicles moving adjacent to it, it can communicate with all of them each using one of the multiple directional antennas. Although the same dedicated transceiver channel pairs are used for multiple vehicles along the longer side of the trailer, the different antennas on which the signal is received, can tell the finer relative positions of the smaller vehicles to the trailer.

C. Vehicles with Different Orientations

There can be a situation when two oncoming vehicles need to communicate with each other (figure 7). If we use the baseline RPB-MACn scheme as depicted in figure 4, vehicles A and B can not communicate with each other even they are in each other’s transmission range since they both use the same transceiver channel pair T6/R2. One approach to solve this problem is adding one additional receiver channel as shown in figure 4. As a result, A can transmit message to B over communication channel 6 (A: T6; B: R6) and A can receive from B over channel 2 (A: R2; B: T2); while B can transmit message to C over channel 2 (B: T2; C: R2).

![Figure 7: Vehicles with Different Orientations on Straight Road](image)

This principle can be generalized by having each directional antenna equipped with multiple, say 8, receivers each using different radio channels so vehicles can communicate at all orientations.

![Figure 8: Different Orientation on Curving Road](image)

With the baseline RPB-MACn mechanism shown in figure 4, when vehicles move along a curving road as shown in figure 8, two neighboring vehicles can not communicate with each other through their front and back channel pair since they are off sight of each other’s direction. However, if each directional antenna is equipped with 8 receivers over 8 different channels (R1~R8), no matter what transmitting channel the sending vehicle is using, there is always one of the 8 receiving channels matching it and can therefore receive the message over that matched channel (e.g., the zones depicted with the dashed lines in figure 8).

![Figure 9: Vehicles moving in opposite directions at intersection](image)

Equipping the vehicles with additional receivers on all the eight directions of the vehicles also helps vehicles to communicate at intersections. This is depicted in figure 9. When two vehicles at an intersection are taking left turn in opposite directions, the multiple receivers at the diagonal sides can help them communicate with each other and avoid potential hazardous situations when they come too close to each other. Further, the single transmitter & multiple receivers scheme can help vehicles to communicate in areas such as parking lots. For instance when two vehicles are backing up towards each other, the additional communication channel pairs at the back and front ends of the vehicle can communicate with each other.

VI. CONCLUSION AND FUTURE WORK

We proposed an innovative design for the VANET MAC protocol which combines the dedicated directional antenna with the dedicated communication channel pairs...
tied with the relative positions among neighboring vehicles. Our proposed RPB-MACn mechanism satisfies the key requirements for VANET applications with high efficiency.

To validate our RPB-MACn design schemes in terms of the performance, and the efficiency of each design components over the realistic dynamic multipath VANET environments and real-world vehicular mobility models, we will verify our schemes via comprehensive simulations and experimentations. We will use simulation tools such as ns-2, Matlab, and OPNET to setup the PHY layer parameters aligning with the DSRC specifications [7] over the realistic VANETs platform supporting the realistic vehicular traffic mobility models [22]. Ultimately, we will build a testbed to verify our design via experiment and possibly field test. Extensive experiments will be conducted to examine the performance of this innovative protocol in the real world VANET environments, to determine the design parameters such as antenna size, message transmission power and various parameters related to directional antenna deployments onto the vehicles.

REFERENCES
