Distributed and Adaptive Reservation MAC Protocol for Beaconing in Vehicular Networks

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Abstract—In vehicular ad hoc networks (VANETs), beacon broadcasting plays a critical role in improving road safety and avoiding hazardous situations. How to ensure reliability and scalability of beacon broadcasting is a difficult and open problem, due to high mobility, dynamic network topology, hidden terminal, and varying density in both the time and location domains. In this paper, wireless resources are divided into basic resource units in the time and frequency domains, and a distributed and adaptive reservation based MAC protocol (DARP) is proposed to solve the above problem. For decentralized control in VANETs, each vehicle's channel access is coordinated with its neighbors to solve the hidden terminal problem. To ensure the reliability of beacon broadcasting, different kinds of preambles are applied in DARP to support distributed reservation, detect beacon collisions, and resolve collisions. Once a vehicle reserves a resource unit successfully, it will not release it until collision occurs due to topology change. The protocol performance in terms of access collision probability and access delay are analyzed. Based on the analysis, protocol parameters, including transmission power and time slots duration, can be adjusted to reduce collision probability and enhance reliability and scalability. Using NS-3 with vehicle traces generated by simulation of urban mobility (SUMO), simulation results show that the proposed DARP protocol can achieve the design goals of reliability and scalability, and it substantially outperforms the existing standard solutions.

Index Terms—VANET, Beaconing, Broadcasting protocol, Preamble, MAC, TDMA, Congestion control.

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1 INTRODUCTION

VEHICULAR communication networks have emerged as a promising solution to improve road safety and efficiency. As an important component of Intelligent Transportation Systems (ITS) [1]–[4], it is anticipated to support many applications such as intelligent navigation, emergency message dissemination, in-car entertainment, and autonomous driving assistance. Driving will become easier, more comfortable, and safer than ever before, accompanied by higher fuel efficiency and less traffic jams. To achieve the above benefits, efficient and reliable information exchange among neighbor vehicles is critical [5]–[9].

Different technologies and architectures have been proposed and developed for vehicular communication networks, including vehicle-to-vehicle (V2V) communications, vehicle-to-infrastructure (V2I) communications, or a hybrid of them [7], [10], [11]. For V2V, vehicles within each other's communication range communicate directly. Thanks to the low control overhead and delay, V2V is suitable for vehicles exchanging data, including position, speed, and event-related information timely and periodically. V2I allows vehicles communicate with roadside infrastructure to coordinate and exchange data. When possible, a hybrid V2V/V2I network can allow a vehicle to communicate with the roadside infrastructures either directly (single-hop) or indirectly through a multi-hop V2V relay path [12]. To support V2V/V2I communications, U.S. Federal Communication Commission (FCC) has approved Dynamic Short Range Communication (DSRC) with seven non-overlapping channels, six service channels (SCH) and one control channel (CCH), each with 10 MHz bandwidth [13], [14].

In vehicular communication networks, beacon broadcasting is a fundamental and critical issue. Besides the possible accidents avoidance by knowing the status of the surrounding vehicles, when a collision or accident occurs, beacons can carry important safety messages to avoid chain reaction and catastrophe. Therefore, reliable beacon broadcasting in vehicular networks is crucial. In this paper, we focus on beacon broadcasting in vehicular ad hoc networks (VANETs) using V2V communications. Therefore, vehicles' status information and safety-related messages can be disseminated timely and independently to the neighbor vehicles, no matter whether or not infrastructure is available and accessible.

The media access control (MAC) protocol in DSRC is specified in the IEEE 802.11p standard. Similar to the IEEE 802.11 Distributed Coordination Function (DCF), it uses the carrier sense multiple access/collision avoidance (CSMA/CA) mechanism to access the shared medium [15]. However, since the number of packet collisions increases with the density of vehicles increases, reliable beacon reception cannot be ensured over a certain distance in a congested vehicular network by employing the IEEE 802.11p MAC protocol. Although we have seen various distributed congestion control (DCC) solutions, no existing solutions can fully address the reliable and scalable beaconing problem yet, given the challenges of high mobility, dynamic network topology, hidden terminal, varying density in both time and location do-

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mains, and the inherent difficulties in supporting reliable broadcast services in ad hoc networks [16].

In this paper, we address the broadcasting problem by carefully leveraging the distributed reservation mechanism, the coded preambles, and the adaptation of power and resource unit parameters for effectively sharing the resources in the time/frequency/space and code domains. The main contributions of this paper are summarized as follows.

- First, we propose a novel Distributed and Adaptive Reservation-based beacon broadcasting MAC Protocol (DARP), in which vehicles coordinate the channel access in the time and frequency domain. We employ a preamble mechanism in the frame structure to detect and resolve beacon collisions.
- Second, we analyze the protocol performance in terms of access collision probability and access delay. Based on the analysis, how to fine tune the protocol parameters to ensure reliability and scalability is proposed.
- Finally, using NS-3 [17] with vehicle traces generated by simulation of urban mobility (SUMO) [18], extensive simulations have been conducted to validate the analysis and evaluate the performance of DARP.

The rest of the paper is organized as follows. In Section 2, the related works are introduced. The system model and protocol design are explained in Section 3 and 4, respectively. Performance analysis and how to optimize the protocol parameters are presented in Section 5. Section 6 presents the performance evaluation and simulation results, followed by the concluding remarks in Section 7.

2 RELATED WORKS

IEEE 802.11p has been proposed for wireless access in vehicular communication networks [15]. This standard does not have an efficient and acceptable performance in beacon broadcasting scenario for high density networks. Employing CSMA/CA protocol can lower the collisions, but the performance degrades dramatically when the density is very high [19], [20]. For the broadcasting scenario, acknowledgment (ACK) and request-to-send/clear-to-send are removed due to the ACK explosion and frequent collisions, respectively. Consequently, the collisions are no longer detectable, the contention window size has to remain unchanged, and the hidden terminal problem remains unsolved [21], [22]. Furthermore, due to the small size of each beacon message and advanced techniques such as high-order modulations and multi-input-multi-output combining with a large bandwidth, e.g. 10 MHz in IEEE 802.11p, the transmission time interval (TTI) is shorter than typical WiFi applications. When the TTI becomes closer to the propagation delay, the channel utilization performance of CSMA/CA degrades to the Aloha protocol [23]. Therefore, although time division multiple access (TDMA) protocol needs time synchronization to access different time slots, it is still one of the main choices in collision-free MAC protocols.

The existing TDMA-based protocols can be classified into two categories, centralized resource allocation and distributed medium access.

2.1 Centralized Protocols

Centralized control methods can effectively reduce collisions. Normally, additional control nodes or infrastructure are needed which may not be practical in remote areas. In [24], Sahoo *et al.* proposed the Congestion Controlled Coordinator based MAC (CCC MAC) where no extra control nodes are needed, and a vehicle will be selected as a coordinator for each road segment. In order to perform centralized scheduling, the global information and scheduling messages need to be collected and delivered, respectively, which increases the control overhead.

The time slot-sharing MAC (SS-MAC) approach proposed in [25] supports distributed periodical message broadcasting with different beaconing rates. In this method, time slots are shared among different users after collecting occupancy states of time slots. In the state-of-the-art time slot-sharing work for vehicular communication networks, two algorithms were proposed for slot sharing and vehicle-slot sharing. SS-MAC relies on the broadcast frame information from neighbor nodes to select time slot to use, and to detect collisions. In dense networks where multiple new users within each other's communication range access the channel simultaneously, and the broadcast frames may be unreliable due to channel impairments, how to avoid and detect collisions remain an open issue. As shown in Section 5, such collisions between new arrivals may occur in dense network scenarios. This motivated our work, and in the proposed protocol, DARP, preambles are responsible for the avoidance and resolution of hidden terminals and collisions, and sending the preambles by different users in the communication range can reduce the negative impact of channel impairments.

2.2 Distributed Protocols

In [26], a new distributed and adaptive congestion control algorithm, LInear Message Rate Integrated Control (LIMERIC), is proposed. This algorithm takes advantage of full-precision control inputs available on the wireless channel aiming to converge to a fair and efficient channel utilization. The purpose of this algorithm is to achieve fairness such that all the nodes converge to the same rate. In this algorithm, there is a trade-off between the convergence speed and the distance to the optimal value. However, the only case in which convergence can be guaranteed is when all vehicles are in range.

Javier Ros *et al.* in [27] have studied the problem of broadcasting without any infrastructure support. The aim is to enhance the reliability by minimizing the total number of retransmissions under different traffic scenarios. They focused on non-safety and delay-tolerant applications and proposed the Acknowledged Broadcast from Static to highly Mobile (ABSM) protocol which is a distributed adaptive one. Using ABSM, a vehicle in the network receiving a broadcast beacon will not retransmit it instantly. It will wait to detect whether retransmissions from other vehicles in the network cover the whole area or not. In this protocol, the vehicles which received the beacon will feedback the reception through sending an ACK. It results in a high volume of overhead in high mobility scenarios. In highly dense environments, increased beacon collisions may raise the redundant retransmissions and degrade the protocol performance [28].

In [29] and [30] a multichannel TDMA protocol has been developed based on ADHOC MAC [31]. The protocol provides a single- or multi-hop broadcasting on the CCH. Disjoint sets of time slots are assigned to the RSUs and vehicles moving in the opposite directions. This scheme can alleviate the hidden terminal problem, while the overhead of frame transmission may lower the network throughput. Space-division-TDMA (SD-TDMA) utilizes different channels adaptively in a dynamic topology to broadcast the vehicles beacons. Since the protocol provides the vehicles geographic locations, most users can access the SCH and acquire time slots based on the provided information. A distributed protocol has been proposed in [32] which assigns a SCH to each segment of the road. Even though some feedback overhead is introduced in this protocol, time slots utilization and contention increases and alleviates, respectively. [33] has proposed a TDMA-based distributed congestion control scheme in which the beacon rate changes adaptively. The beacon rates in the protocol are chosen according to the vehicle's danger coefficient to avoid rear-end collisions. In this work, each vehicle adopts a greedy algorithm to solve the distributed beacon rate adapting problem and broadcast the results to the neighbors. This work in congestion control is orthogonal to the proposed DARP, and the idea of congestion control can be applied to the system adopting our MAC protocol to enhance the overall performance.

Another TDMA-based approach is introduced in [34] as mobility-aware TDMA MAC (MoMAC). In this protocol, each frame is divided into different sections corresponding to different lanes, directions, and intersections. Two common mobility scenarios have been considered in this work which may potentially lead to an excessive level of collisions. The one-hop nodes' information is stored in the header of each packet which may increase the signalling overhead. Also, the protocol may face resource underutilization when the traffic densities in both directions are highly different. SCMAC is another MAC protocol introduced in [35] focusing on cooperative medium access control. This protocol exploits the CCH in different time slots, and the future state of the channel is broadcast through the cooperative beaconing process. The beaconing period is adaptive and determined based on the current node density. Although the protocol performance is reasonable in terms of collision probability and reliability, the hidden terminal is not considered in this work, which may cause unexpected packet losses.

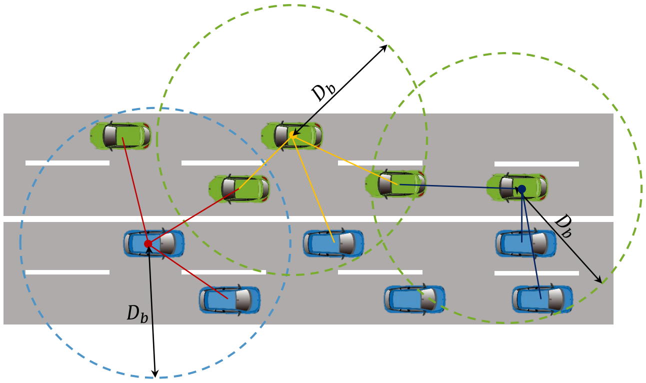

Fig. 1: Vehicles in a VANET with beaconing range of D_b.

Another category of existing works focuses on distributed multi-hop broadcasting. The authors in [36] proposed the DRIVE protocol in order to broadcast data in an area of interest. The problem of broadcast storm is mitigated, and the delay and control overhead can also be reduced. Bharati *et al.* proposed the Cooperative Relay Broadcasting (CRB) method in [37]. The transmission efficiency is improved in this protocol by utilizing unused slots and finding the best helper nodes.

In practice, a vehicle can analyze the received beacons, and piggyback the abstract of critical information in its own beacon broadcasting to disseminate it to a larger area. Most of the information included in the beacon message is just useful for the nearby vehicles and should not occupy too much wireless resources. Therefore, in this paper, we only focus on the single-hop beacon broadcasting. In DARP, we stick to distributed control methods, in order to reduce the overhead and make the protocol usable in remote areas. Different from the majority of the distributed control methods, we apply the request-to-reserve scheme, allow dynamic transmission power adjustment, and introduce a new preamble mechanism by which the problem of hidden terminal is solved and the collision probability is significantly reduced.

3 SYSTEM MODEL

Consider a VANET in which the vehicles have been distributed randomly in a multi-lane road as shown in Fig. 1. Short status messages, i.e. beacons, are transmitted by each user[1] periodically to notify the neighbors its presence. T and W denote the beaconing period for each vehicle and the total channel bandwidth, respectively. As

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[1] The words "user" and "vehicle" are used interchangeably throughout this paper.

TABLE 1: Important Notations

Symbol	Definition
$P_{t,i}$	Transmission power of vehicle i
N_a	Number of available resources
N_v	Number of vehicles
N_p	Number of available *preambleR*
N_{ch}	Number of available sub-channels
N	Average number of effective neighbors
T	Beaconing period
L_b	Time duration of each beacon
L_p	Time duration of each preamble
D_b	Beaconing range
D_r	Average reuse distance
d	Inter-vehicles distance
P_f	Access failure probability
P_C	Access collision probability
S_p	Second kind p-associated Stirling number
λ	vehicle density
Γ	SINR threshold

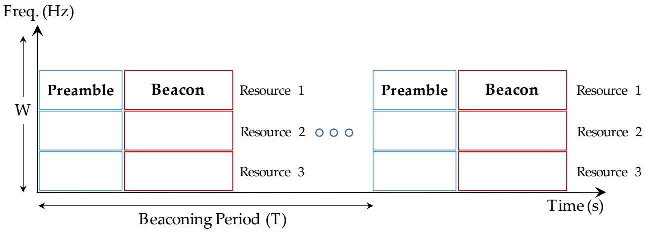

Fig. 2: Available resources in one beaconing period and bandwidth of W, in DARP.

shown in Fig. 2, in each period, channel time is divided into some slots, and channel bandwidth is divided into sub-channels. Time synchronization is achieved assuming that each vehicle can use the global positioning system (GPS) for global synchronization. However, in the case that the GPS signal is lost, the GPS local oscillator should be sufficiently stable to keep the users synchronized. Within a beaconing period, a time slot in one sub-channel is defined as a resource unit.

Each resource unit consists of two parts, one for the preambles (short control messages) and the other for the beacons (which carry the data). The preambles are used to detect reservation and beacon collisions. It is assumed that once a resource unit is reserved successfully by a vehicle for beaconing, it will not be released until the vehicle leaves the system or collision happens due to topology change. Also, it is assumed that each user has a packet or beacon ready for transmission at the beginning of the reserved time slot.

For the wireless channel model, we consider the path-loss determined by the transmission distance between the vehicles. The path-loss model in device-to-device communications can be applied here [38]. The relationship between the reception and the transmission power as a function of the distance between the transmitter and receiver, d, is given by $P_r = P_t K_0 d^{-\alpha}$, where K_0 is a constant depending on the channel and antenna characteristics, and α is the path-loss exponent. The Signal-to-Interference-plus-Noise Ratio (SINR) between two vehicles, v_i and v_j, is given by

$$\mathrm{SINR}_{ij} = \frac{P_{t,i} K_0 d^{-\alpha}}{I_j^x + N_0}, \tag{1}$$

where $P_{t,i}$ is the transmission power of v_i and N_0 represents the noise power. Assuming v_i is using the resource x, I_j^x is the interference power received by v_j on the same resource. In this paper, v_j, a neighbor of v_i, can successfully receive a beacon from v_i if the received SINR is greater than the threshold Γ, i.e. $\mathrm{SINR}_{ij} \geq \Gamma$, and we name v_j as an effective neighbor of v_i. Γ should be set based on the Modulation and Coding Scheme (MCS) that is used for the beacon broadcasting, and may be fixed in a zone. Table 1 summarizes a few important notations in the paper for convenient reference.

4 PROTOCOL DESIGN

DARP design objectives and its accessing procedure are explained in the following subsections, respectively.

4.1 Design Objectives

To ensure reliable and scalable beacon broadcasting, the design objectives of DARP are summarized as follows. (I) The probability of beacon collision should be maintained low, and collisions should be detectable and be stopped timely. (II) When new vehicles try to access (or re-access) the network, the vehicles which have already occupied resources should not be affected. (III) The wireless spectrum resource is precious, so it should be efficiently utilized in order to support as many users as possible, especially in high density scenarios. (IV) As the focus of this paper is on the beacon broadcasting scheme, a stable and periodic transmission should be guaranteed if a vehicle has successfully occupied a resource. (V) Overshooting the beaconing range is undesirable, so beacons should be received by a target number of neighbors regardless of the topology. (VI) The protocol should work in any places, including the remote areas without any infrastructure, and it should be scalable for high density networks.

As mentioned in Section 2, CSMA/CA-based protocols alone cannot satisfy the above design objectives for beacon broadcasting. Since the beaconing procedure has a predictable transmission pattern (the users have beacons to broadcast at the beginning of each frame) and fixed data size[2], reservation solutions are more suitable. Hence, we propose a distributed reservation scheme to ensure reliability and scalability. Once a resource is reserved successfully, the vehicle can use it periodically. Therefore, if the topology is given and fixed over a certain period of time, the number of users successfully reserving the resource for beaconing can be monotonically increased.

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[2] The assumption of *fixed data size* means a fixed MAC layer protocol data unit (MPDU), which is the unit of maximum data size exchanged between MAC entities.

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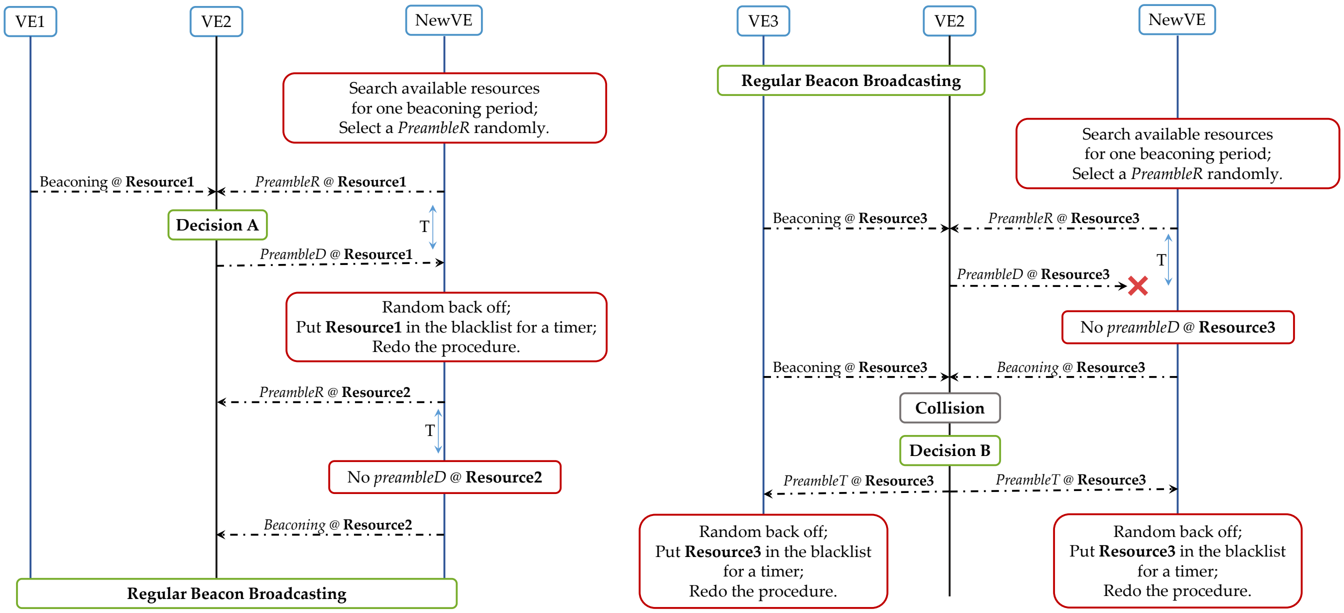

(a) Case I (b) Case II

Fig. 3: Diagram of DARP in accessing and beaconing process.

The preamble mechanism has been used in cellular systems as an effective way even in superdense scenarios [39]. Preambles are responsible for collision detection, and by employing orthogonal preambles, the code dimension diversity is obtained, which can help to detect and avoid access collisions without affecting the existing beaconing users. Although preambles introduce more signaling overhead, the overhead is negligible compared to the achieving gain and collision-free communication. The preamble combined with distributed reservation can address the first four design objectives mentioned above.

In order to ensure the applicability of DARP in remote areas, the distributed reservation solution is adopted. Although a centralized control may further enhance the performance based on the global information, significant control overhead will be introduced by collecting requests and sending scheduling decisions, which may sacrifice the performance gain. To guarantee a certain number of neighbors can effectively receive the beacons, a distributed dynamic power control method is introduced as well. These two methods can ensure that the last two objectives can be satisfied.

4.2 Accessing and Beaconing Procedure

Preambles are sequences which are responsible for collision detection and facilitation of accessing the channel. These sequences are generated from cyclic shifts of root Zadoff–Chu sequences. The amplitude of the sequences is constant which provides low peak-to-average-ratio from the implementation point of view. Moreover, the cross-correlation between any two preambles of the same Zadoff–Chu root sequemce is zero based on which there is no interference from reception of different preambles [40].

In DARP, four types of preambles are defined, regular (*preambleR*), data transmission (*preambleDT*), decline (*preambleD*), and terminate (*preambleT*), which are used for channel access, data transmission, access request rejection, and transmission stop, respectively. Since the preambles are coded in a way that are orthogonal to each other, a receiver can detect all the preambles transmitted simultaneously in the same resource unit. *PreambleR* is used to make reservation, and *preambleD* is deployed to solve the hidden terminal problem. Detecting and resolving beacon collisions caused by topology changes can be done by *preambleDT* and *preambleT*, respectively. In this paper, we assume that there are 64 available preambles.

Among these 64 preambles, 50, 12, 1, and 1 preambles are allocated to *preambleR*, *preambleDT*, *preambleD*, and *preambleT*, respectively [39].

Considering Fig. 3 as an example, we explain how DARP works. In Case I, a new vehicle (*NewVE*) tries to enter the network with two existing vehicles, *VE1* and *VE2*. *VE1* and *NewVE* cannot sense each other, while *VE2* can sense both of them. First, in order to make a reservation, *NewVE* needs to listen to the channel for one beaconing period to identify which resource units have not been occupied. Then, it selects one of the resource units randomly and sends a reservation message which is a *preambleR* on the chosen resource unit.

Decision A is made if a vehicle receives either a *preambleR* for the resource unit currently occupied by its neighbors, or multiple *preambleR*s for the same resource unit are received simultaneously. Since the preambles are orthogonal to each other, vehicles are capable of detecting multiple preambles at the same time. In the case that some vehicles choose the same *preambleR* in order to occupy a resource, the selection process will be successful. However, in the next period, beacon collision will be detected by colliding or other existing vehicles.

Upon receiving a *preambleR*, the existing vehicles check whether a *Decision A* should be made. In Case I, Fig. 3(a), when *VE2* receives *NewVE*'s *preambleR* for Resource1 while Resource1 has been occupied by *VE1*, it makes a *Decision A* and sends a *preambleD* in the next period to *NewVE* at the preamble part of Resource1. If *NewVE* cannot use the chosen resource due to the reception of *preambleD*, it will put the resource in a blacklist for a random period of time and select another resource unit right after reception of *preambleD* to make a reservation. On the other hand, if *NewVE* picks an unoccupied resource, sends a *preambleR*, and does not receive any *preambleD*s in the next period at the chosen resource, the reservation is successful and it can occupy the resource unit. Right after elapsing the preamble part of the chosen resource, the vehicle can start the beaconing process.

However, if two vehicles select the same resource and the same *preambleR* for reservation, both of them will find their reservations successful. To address this issue, for each beacon transmission, each vehicle always randomly selects a *preambleDT* and sends it in the preamble part, by which the beacon collisions can be quickly detected and resolved.

A *Decision B* is made when a vehicle receives non-decodable beacons in succession, or receives different *preambleDT* at the same resource. Consequently, a *preambleT* will be sent out at the chosen resource. Upon receiving a *preambleT*, the vehicle should put the resource in the blacklist for a timer and access the network again. In Case II, Fig. 3(b), the case with an error in receiving *preambleD* on *Resource3* has been shown. Failure in reception of *preambleD* which may be due to transmission error or interference, causes channel access for NewVE. In this case, two users, VE3 and NewVE, send beacon on a signle resource. If they use two different *preambleDT*, VE2 will detect a collision and make Decision B. By making this decision, it will send a *preambleT* on *Resource3* and both of the users will release the resource. In the rare case that NewVE choose the same *preambleDT* as VE3 is using, VE2 receives non-decodable beacons in succession and similarly, it detects a collision and sends a *preambleT* to terminate the beaconing.

5 PERFORMANCE ANALYSIS AND PARAMETER OPTIMIZATION

In this section, we first investigate *Access Collision Probability* and *Access Delay* as the performance metrics to evaluate the protocol performance. Then, we study how to optimize protocol parameters to enhance the performance.

5.1 Access Collision Probability

Access collision probability is defined as the probability that at least two vehicles access the same resource. In this subsection, we derive the probability mass function (PMF) of the access collision. Since the dynamic change of available resources and chain collisions are not considered here, the analysis is an approximation.

We assume a fixed topology which has N_v vehicles and N_a available resources. Obviously, the number of resources should be greater than or equal to the number of vehicles, i.e. $N_a \geq N_v$. Otherwise, some vehicles may never access the channel and access collision is unavoidable. In order to find the number of collisions, the resources occupied by at least two vehicles should be counted. To give a better insight, we can model the problem as a problem of distributing N_v distinguishable balls among N_a distinguishable baskets. For the case of zero collision, it is simple and straightforward. The total number of ways assigning N_a baskets to N_v balls in a way that each basket has at most one ball equals to $\frac{N_a!}{(N_a-N_v)!}$.

Before we move to the next part, the number of ways which m balls can be distributed in k baskets in such a way that all these k baskets have at least p balls should be found. This problem is called p-associated Stirling number of the second kind, $S_p(m,k)$. The triangular recurrence relation for these numbers is [41]

$$S_p(m+1,k) = k\,S_p(m,k) + \binom{m}{p-1} S_p(m-p+1,k-1). \tag{2}$$

For the case of $p=2$, it is simplified as

$$S_2(m+1,k) = k\,S_2(m,k) + m\,S_2(m-1,k-1). \tag{3}$$

The problem can be divided into different cases. Here, C_{mi} represents the total number of combinations where m is the number of baskets with more than one ball, while i indicates the number of baskets with exactly one ball. For the case that $i=0$, we select N_v balls and m baskets in $\binom{N_v}{N_v}$ and $\binom{N_a}{m}$ ways, respectively. The baskets have $m!$ permutation among each other. Also, there are $S_2(N_v,m)$ ways that these N_v balls can be distributed among m baskets with the condition that each basket has at least two balls. Therefore, the total number of combinations will be

$$C_{m0} = \binom{N_v}{N_v}\binom{N_a}{m} m! S_2(N_v,m). \tag{4}$$

In the next step, we can generalize this distribution for an arbitrary i. (N_v-i) balls are chosen to be distributed in m baskets in $\binom{N_v}{N_v-i} S_2(N_v-i,m)$ ways. Also, there are $\binom{N_a}{i+m}(i+m)!$ ways to choose $(i+m)$ baskets among N_a baskets. Therefore, the total number of combinations in this case is

$$C_{mi} = \binom{N_v}{N_v-i}\binom{N_a}{i+m}(i+m)! S_2(N_v-i,m). \tag{5}$$

It is obvious that the variable i starts from zero and its maximum value is $(N_v - 2m)$. The extreme case happens if $2m$ balls are chosen for m baskets, and the remaining $(N_v - 2m)$ balls are assigned to i different baskets. The total number of choices in which m baskets have more than one ball is the summation of C_{mi} over i. The total number of possible choices in distributing N_v balls among N_a baskets and collision states are $N_a^{N_v}$ and $\lfloor \frac{N_v}{2} \rfloor$, respectively. If A_m is defined as the event in which m resources are in collision, $P(A_m|N_v, N_a)$ will be the corresponding probability. This probability is

$$P(A_m|N_v, N_a) = \sum_{i=0}^{N_v - 2m} \binom{N_v}{N_v - i} \binom{N_a}{i+m} \frac{(i+m)! S_2(N_v - i, m)}{N_a^{N_v}}. \tag{6}$$

It is worth mentioning that if the N_v's PMF is known, a more precise access collision probability will be achieved.

5.2 Access Delay

The access delay is defined as the time duration needed by a new vehicle to access a resource successfully for beacon broadcasting. It is assumed that the number of vehicles contending for the resources is stable. Once a vehicle tries to access a resource, if it is not allowed to use it, it will receive a *preambleD* from the neighbors and if there are not any, the vehicle itself will detect the occupied resource. Afterward, it attempts again to choose another resource. Reception of a *preambleD* is due to two different cases, (a) access collision, (b) collision with a hidden terminal.

In order to find the probability of failure in accessing a resource, we define D_b as the beaconing range in which the vehicles can receive the broadcast beacon. This range can be determined based on the SINR threshold. We consider two regions around a tagged vehicle, namely S_1 and S_2 corresponding to $0 \leq r \leq D_b$ and $D_b \leq r \leq 2D_b$, respectively. S_1 contains N_v vehicles contending for the available resources, and the vehicles in S_2 are treated as hidden terminals. We define S_1 and S_2 regions only for the preamble transmission, since they are responsible for collision detection and hidden terminal avoidance. Preamble and beacon may have different transmission ranges, but we intentionally make the preamble range the same as the beacon one by setting an appropriate preamble SINR target. In this way, preamble and beacon can have the same range in the analysis. This assumption leads to conservative analytical results.

The access failure probability is as follows.

$$P_f = \sum_{m=0}^{\lfloor \frac{N_v}{2} \rfloor} \left[1 - \frac{N_a - m}{N_a} \frac{N_a - 2D_b\lambda}{N_a} \right] P(A_m|N_v, N_a), \tag{7}$$

where λ is the vehicle density, and the terms $\frac{N_a - m}{N_a}$ and $\frac{N_a - 2D_b\lambda}{N_a}$ are corresponding to successful channel access in S_1 and S_2 regions, respectively. The probability of having a successful channel access after X failed trials follows a Geometric distribution which for $k = 1, 2, 3, \ldots$ is

$$Pr\left\{X = k\right\} = {P_f}^{k-1} \left(1 - P_f\right). \tag{8}$$

Therefore, the expected value of k is $\frac{1}{1-P_f}$. Once a vehicle is going to access a resource, first, it will search available resources for one period. When a resource is selected and *preambleR* is transmitted, the vehicle will be notified whether it can use the resource after a period of time, T. If not, it will attempt to access another resource. The duration between reception of the notification and the next try (including the very first resource selection after scanning the available resources) is a random variable, z, following a Uniform distribution, $z \sim U(0, T)$, and obviously, its mean is $T/2$. Now, based on this analysis, the access delay can be calculated as follows.

$$\mathbb{E}\left[Access\, Delay\right] = T + \left(T + \frac{T}{2}\right) \frac{1}{1 - P_f}. \tag{9}$$

Here, we assumed that the users in S_2 are occupying different resources from the users in S_1 which is an extreme case. Based on the assumptions, the obtained access delay will be an upper-bound of the delay in the real scenario.

In order to make DARP scalable, two parameters can be optimized. The first one is the total number of available resources per period, N_a. It is obvious that a larger number of resource units can reduce the access collision probability. This parameter can be increased by either reducing the time duration of each resource, L_b, or increasing T. However, the maximum period of beacon broadcasting should be determined by the quality of service requirements. Therefore, we only focus on the former case. We cannot blindly choose the shortest resource length because assuming a fixed packet size, a shorter length results in a higher beacon transmission rate, and a higher receiving SINR is required. In the following analysis, we optimize the length of each resource based on the number of effective neighbors, MCS selections, and the target SINR.

The second optimization parameter is the transmission power. In DARP, rather than using a fixed power, each vehicle is allowed to adjust its transmission power in a distributed way. A larger power may not necessarily increase the received SINR and the number of effective neighbors. The reason is that it also increases the interference which consequently decreases the SINR, and results in less number of effective neighbors. Different from existing works on the power control issue in VANET [42]–[44], we set beacon transmission power not only based on the density of the vehicles, but also on the selected MCS, the target SINR, and the number of effective neighbors.

These two parameters can be optimized according to different objective functions, such as minimizing the average access delay, maximizing the average number of effective neighbors, etc. In this paper, we assume that

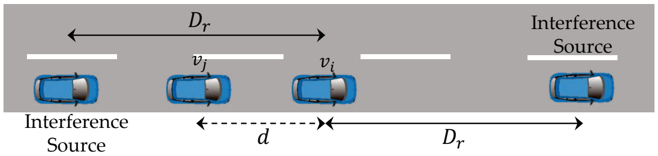

Fig. 4: The reuse distance from two interference sources.

a target average number of effective neighbors, N, can be guaranteed, then collision probability, P_C, will be minimized by adjusting vehicle's transmission power P_t and L_b. P_t will not exceed the vehicle's maximum transmission power, $P_{\max}$, and we also assume a minimum transmission power, $P_{\min}$, to ensure the minimum range of the beacon broadcasting. Therefore, $P_t \in [P_{\min}, P_{\max}]$.

The average reuse distance for a resource is given by

$$D_r = \frac{T\,N_{ch}}{(L_p + L_b)\,\lambda}, \tag{10}$$

where N_{ch} and L_p are the number of available sub-channels and duration of a preamble, respectively. The reuse distance is shown in Fig. 4. We consider the closest interfering vehicles on each side (in front and behind) as the dominant interference sources. Therefore, the SINR as a function of distance is

$$\text{SINR} = \frac{P_t\,K_0\,d^{-\alpha}}{N_0 + P_t\,K_0\,(D_r - d)^{-\alpha} + P_t\,K_0\,(D_r + d)^{-\alpha}}. \tag{11}$$

In order to bound the SINR to Γ at $d = D_b$, equation $f(D_b) = \Gamma$ should be solved.

Given a fixed block error rate, the relationship between Γ and MCS can be found in [39]. For a fixed size of the beacon, if L_b is reduced, the transmission rate needs to be increased, and thus a higher SINR threshold should be applied. Therefore, Γ is a function of L_b, i.e. $\Gamma = g(L_b)$. Based on [39], $g(.)$ is a monotonically decreasing function.

Based on the total vehicle density, the average number of effective neighbors in the beaconing range is estimated by $N = 2\lambda D_b$. By substituting equation (10) and simplifying the equation $\Gamma = f(D_b)$, the following equation will be obtained.

$$\frac{1}{\Gamma} = \frac{N_0}{P_t K_0}(\frac{2\lambda}{N})^{-\alpha} + (\frac{2\lambda D_r}{N} - 1)^{-\alpha} + (\frac{2\lambda D_r}{N} + 1)^{-\alpha}. \tag{12}$$

Between two adjustable parameters in the above equation, L_b should be coarsely set according to different areas such as downtown, uptown, highway, and etc. L_b can be known for the vehicles based on the predefined information associating with the GPS location. Therefore, when a vehicle enters a district with different setting of L_b, it will release the previous occupied resource and re-access the network using the new setting of L_b.

Each vehicle can adjust its transmission power based on the vehicle density in a smaller region around it. However, we roughly assume a homogeneous distribution for all vehicles in a large region, so the average density is used to facilitate the selection of L_b. If N_v is given, the objective function of the optimization problem is the access collision probability, P_C. By minimizing the access collision probability, the access delay will be minimized as well. The PMF of access collisions was obtained in Section 5.1.

Minimizing the access collision probability is equivalent to maximizing the number of available resources. In other words, the more resources are available, the lower the access collision probability is. Thus, we can consider the total number of available resources as the objective function with the same constraints. The total number of available resources equals to

$$\begin{aligned} N_a &\approx (D_r\lambda - N)^+ \\ &= \left(\frac{TN_{ch}}{L_p + L_b} - N\right)^+, \end{aligned} \tag{13}$$

where $t^+ = \max(0, t)$. Considering the existing MCS table and fixed-size beacon message, L_b should be chosen within several choices.

To maximize N_a in (13), a search on the possible L_b choices should be run in the ascending order. Based on the achieved L_b and (12), P_t will be calculated and the search will end once the power constraint is satisfied. Since N_a decreases monotonically with L_b, the search procedure can give the optimal result. If all the possible options of L_b cannot satisfy the power constraint, the L_b corresponding to the largest non-negative P_t, $P_t < P_{\min}$, should be selected. It guarantees the average number of effective neighbors, while does not overshoot it too much. On the other hand, if all the possible values of P_t are negative when $P_t < P_{\min}$, the one corresponding to the smallest non-negative P_t is the solution.

Different average densities result in different optimal L_b. The performance of the above procedure can be examined by $\lambda_{\max}$ and $\lambda_{\min}$ for the peak and off-peak hours, respectively. Once the optimal L_b is obtained, by estimating the real-time vehicle density, $\hat{\lambda}$, and substituting it in (12), the corresponding power is calculated.

Remark 1. The total number of available resources in the protocol is a function of each resource duration, L_b, and the total number of channels. For the case that the protocol is confronted an ultra-dense environment where the power control scheme is not deployed and L_b is fixed, there may be some users which cannot acquire any resource and lead to starvation. To solve this issue, power control or other congestion control mechanisms should be devised, which could be important further research topics.

6 SIMULATION RESULTS

This section presents the performance assessment of DARP simulated by NS-3 driven by SUMO traces. SUMO is a microscopic traffic flow simulator which can generate real vehicle routes and simulate how traffic changes in a large road network. To generate a traffic trace, SUMO needs a road map which can be defined

TABLE 2: Transmission Power for Different Vehicle Densities

Beacon duration	$N = 10$		$N = 15$	
	λ (Vehicle/km)	Power (dBm)	λ (Vehicle/km)	Power (dBm)
$L_b = 1\,\text{ms}$	[0.054, 0.4]	[−7, 25]	[0.081, 0.4]	[−0.45, 25]
$L_b = 2\,\text{ms}$	[0.036, 0.054]	[18.7, 25]	[0.055, 0.081]	[18.76, 25]
$L_b = 3\,\text{ms}$	[0.0295, 0.036]	[21.94, 25]	[0.044, 0.055]	[21.65, 25]
$L_b = 6\,\text{ms}$	[0.02, 0.0295]	[19.6, 25]	[0.031, 0.044]	[19.7, 25]
	< 0.02	25	< 0.031	25

TABLE 3: MCS and Beacon Duration

Order	MCS	SINR range (Γ)	Beacon duration
0	Transmission failed	$(0, 0.6]$	—
1	QPSK, Rate 1/3	$(0.6, 2.135]$	$L_b = 6\,\text{ms}$
2	QPSK, Rate 2/3	$(2.135, 4.565]$	$L_b = 3\,\text{ms}$
3	16-QAM, Rate 1/2	$(4.565, 19.498]$	$L_b = 2\,\text{ms}$
4	64-QAM, Rate 2/3	$(19.498, \infty)$	$L_b = 1\,\text{ms}$

TABLE 4: Simulation Parameters

Parameter		Value
Simulation time		19 s
Average vehicle speed		70 km/h
Beaconing period		84 ms
Beacon size		375 Byte
Number of channels	DARP	5
	IEEE 802.11p	1
Channel bandwidth		10 MHz
Noise spectral density		−174 dBm/Hz
Maximum transmission power		25 dBm
Maximum beaconing range		250 m
Modulation	DARP	QPSK, 16-QAM, 64-QAM
	IEEE 802.11p	QPSK
Number of preambles		64
Preamble duration		1 ms
Path-loss coefficients (α, K_0)		(3.68, $10^{-4.38}$)

directly or be imported. NS-3 uses the SUMO's output trace file to define the vehicles' position and change their driving route dynamically [45]. Using this platform, extensive simulations have been conducted to evaluate DARP in two different scenarios: (I) a linear network, and (II) a map-based network. For each of these scenarios, four different MAC approaches have been used and compared, including DARP, DARP without power control (W/O PC), IEEE 802.11p, and IEEE 802.11p with power control (W/ PC). In the simulation, DARP is implemented as follows. Each vehicle keeps a list recording the status of all resource blocks. The operation of each vehicle is based on the knowledge from the list. Multi-channel devices are installed such that the vehicles can listen to all channels and broadcast their beacons on the selected resources. IEEE 802.11p is implemented based on the existing NS-3 modules with data rate of 3 Mbps and beaconing range of 250 m. The physical layer platform used for DARP is the same as IEEE 802.11p in which the total number of subcarriers and symbol interval are 52 and $8\,\mu$s, respectively. The bandwidth of the IEEE 802.11p system and DARP are 10 MHz and 50 MHz, respectively. The packets are successfully received by a vehicle if the received SINR is more than the determined threshold, and failed when there are more than one transmitters using the same resource block within the receiver's beaconing range i.e., the received SINR is not high enough.

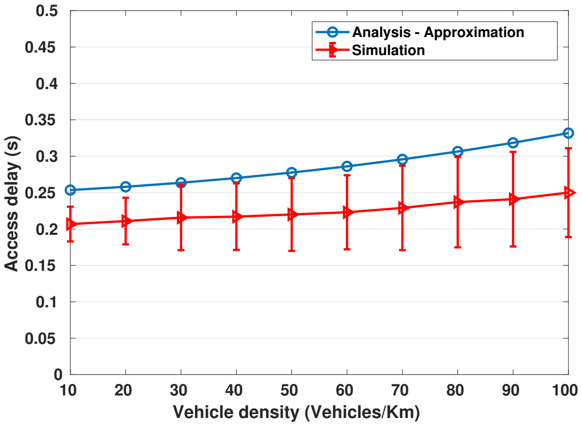

Fig. 5: Comparison of access delay for different number of vehicles.

The transmission power for different vehicle densities can be calculated using (10) and (11) based on the target SINRs 0.6, 2.135, 4.565, and 19.498 which corresponds to the beacon duration of 6 ms, 3 ms, 2 ms, and 1 ms, respectively. The results for $N = 10$, 15 can be found in Table 2. In DARP simulation, we applied four different MCS options which the target SINR range given 10% block error rate and the corresponding beacon duration are summarized in Table 3 [39], [46]. The simulation parameters are summarized in Table 4. The channel model used in the simulation is the path-loss model described in Section 3. Ordinarily, the beaconing period is 100 ms [47]. However, in the simulations, the beaconing period is set to 84 ms which is the least common multiple of resource duration for different MCSs.

We used the beacon loss ratio (BLR) as a performance metric for the protocols comparison. This metric is defined as

$$\text{BLR} = 1 - \frac{\#\,\text{of received beacons}}{\#\,\text{of expected to be received beacons}}. \tag{14}$$

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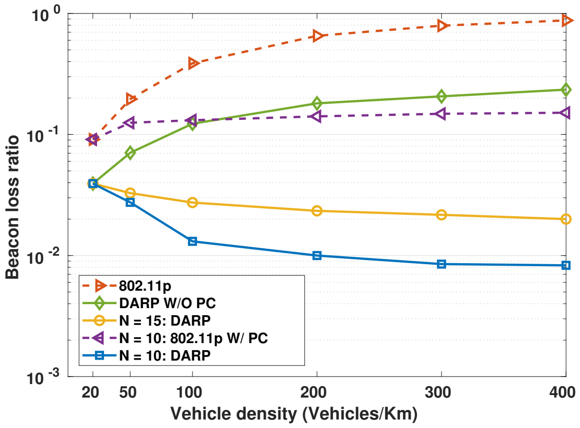
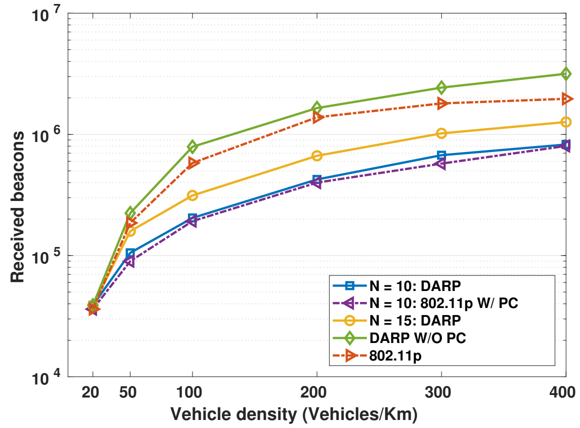


(a) Beacon loss ratio



(b) Received beacons

Fig. 6: Linear network.

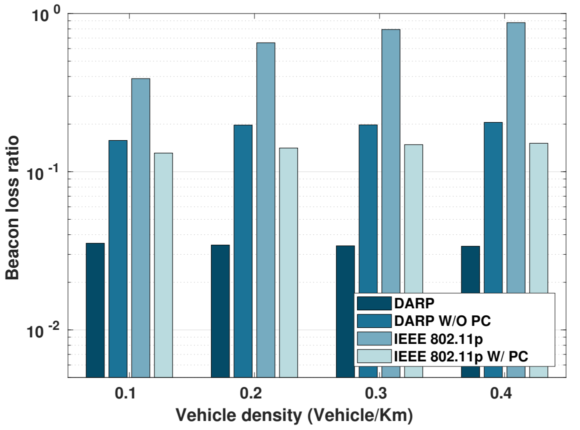


Fig. 7: Comparison of beacon loss ratio for different protocols for $N = 10$, with the same bandwidth, $W = 10$ MHz.

For the linear networks simulation, we consider a road with effective length of 2 km, meaning that the road length is more than 2 km to avoid the users on the edge with less neighbours. The results from DARP and DARP W/O PC are compared to the results from IEEE 802.11p and IEEE 802.11p W/ PC.

Fig. 5 compares the access delay simulation results with the analytical ones for different vehicle densities. The beaconing range of the vehicles is set to 250 m and the power control mechanism is not deployed to have a fair comparison with the theoretical results. The beacon duration is set to 1 ms and there are totally 210 available resources. The simulations have been run ten times, and the average values along with the standard deviations have been graphed. As it was mentioned in Section 5.1, the derived access collision probability and access delay are approximations. Thus, the analytical results give an upper bound of the access delay. There is a small gap between the bound and the access delay in the simulation, and the gap tends to be higher when the density is very high and the chain collisions occur more frequently. Nevertheless, from Fig. 5, even when the density of the vehicles increases by a fold of ten, the access delay merely increases to around 0.25 seconds. Thus, the proposed DARP is scalable, and can guarantee an almost stable access delay up to a certain number of users.

Fig. 6(a) and Fig. 6(b) present the BLR and the number of received beacons for different vehicle densities, respectively. The simulations have been run for two different numbers of effective neighbors. It can be seen from the results that DARP protocol has a one- to two-order lower BLR in comparison to that using the IEEE 802.11p protocol. For IEEE 802.11p W/ or W/O PC, and DARP W/O PC, the loss ratio increases when the vehicle density increases, due to heavier collisions. The BLR using DARP remains around 0.01 when the vehicle density is above 100 vehicles/km. When the density is low, due to a larger distance between vehicles and higher transmission errors, the loss rate is higher. Hence, we note that the loss ratio for DARP is slightly higher when the density is much lower than 100 vehicles/km. As it is expected, the performance of IEEE 802.11p in terms of BLR is degrading by increasing the density, while DARP achieves 96% and 75% gains in W/ PC and W/O PC scenarios, respectively. Due to occupying all of the available resources, the BLR will reach the saturated state by increasing the vehicle density.

By increasing the vehicle density, it is expected to have more received beacons in all of the schemes which is verified by the results in Fig. 6(b). The figures in Fig. 6 can be considered jointly. From Fig. 6(b), more beacons can be received in DARP compared to the IEEE 802.11p (for both W/ and W/O PC). From Fig. 6(a), it is observed that due to less collision probability and less hidden terminals, the proposed protocol when bundling five 10 MHz channels can achieve lower BLR compared to IEEE 802.11p that uses only one default channel. According to these figures, DARP is more reliable and scalable. In DARP W/O PC, the beacons are transmitted with a fixed beacon duration and the maximum power. Accordingly, the beaconing range of the users are maximum which includes more users compared to the case with power control capability. Therefore, more number of beacons are received in DARP W/O PC, Fig. 6(b). On the other hand, higher transmission power results in more mutual

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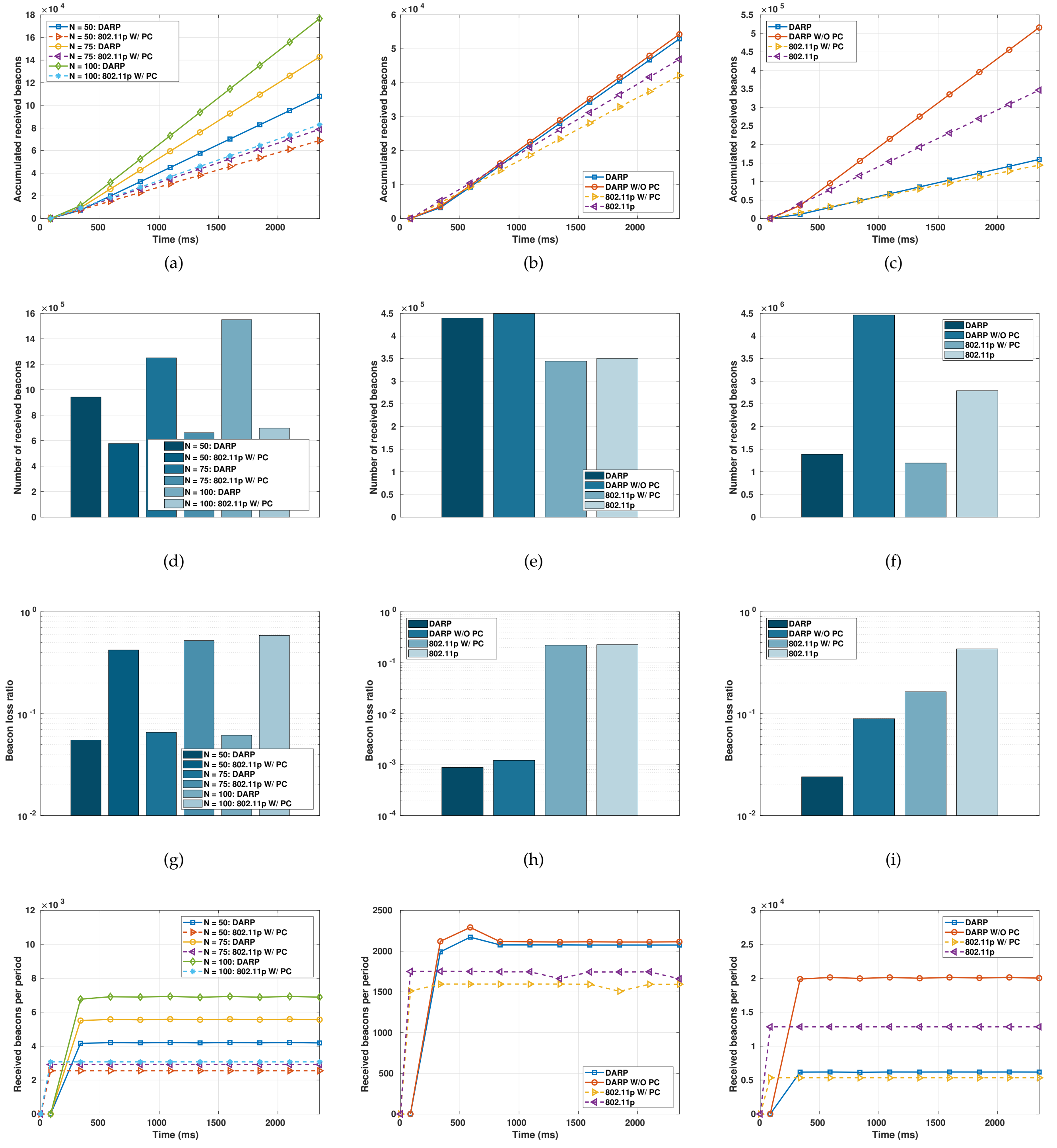

(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

(j) (k) (l)

Fig. 8: Accumulated received beacons, number of received beacons, beacons loss ratio, and received beacons per period for ultra-dense, City1, and City2 scenarios.

interference and losses. As the result, the loss ratio increases for DARP W/O PC in Fig. 6(a). Fig. 7 depicts the BLR of different protocols for $N = 10$ with the same bandwidth ($W = 10$ MHz). Contrary to the results in Fig. 6, in Fig. 7, DARP and IEEE 802.11p protocols are using two 5 MHz and one 10 MHz channels, respectively. The results verify the DARP's outperformance in terms of BLR compared to the IEEE 802.11p when both of the protocols occupy the same bandwidth.

Fig. 8 shows the accumulated received beacons, number of received beacons, beacons loss ratio, and received beacons per period of DARP and IEEE 802.11p for map-based networks and different scenarios of ultra-dense linear network where the vehicle density and number of effective neighbours are $\lambda = 0.4$, $N = 50, 75, 100$, respectively. For the map-based scenarios, we compare DARP with IEEE 802.11p for two different cities, based on real maps. City1 is a low density city block whose size is 3000×3000 m^2 with 99 moving vehicles, while City2 is a high density 4300×2200 m^2 city block in which 500 vehicles are moving. The mobility model is created with the help of SUMO, and the simulation is run by NS-3. In the simulations, just the mobility models were used and the radio channel models, i.e., shadowing and fading effects were not taken into account.

Figs. 8(a, d, g, j) show the results corresponding to an ultra-dense linear topology. Fig. 8(a) depicts the accumulated received beacons for DARP and IEEE 802.11p W/ PC for different number of effective neighbors. It shows that by the time passage and accommodating more vehicles, DARP can exchange 50% to 100% more beacons. The total number of received beacons illustrated in Fig. 8(d) showing it changes slightly by increasing the number of effective neighbors in IEEE 802.11p W/ PC, while these numbers are doubled in DARP. In terms of BLR depicted in Fig. 8(g), DARP maintains a reduction of 80%. Based on Figs. 8(a, d, g), it can be concluded that DARP is scalable and reliable in ultra-dense scenarios. Fig. 8(j) depicts the number of received beacons of the protocols in one beaconing period. The results in this figure confirms the results shown in Fig. 8(a) and Fig. 8(d). The received beacons per period in all of the scenarios and protocols will reach the saturated state with small fluctuations after a certain amount of time. In other words, by the time passage, the accessing process will reach the stable state.

Figs. 8(b, e, h, k) illustrate the results corresponding to City1 which is a low density city block. As it is observable in these figures, in this scenario, DARP and DARP W/O PC have approximately the same performance due to sparsity. As shown in Fig. 8(b), the accumulated received beacons in DARP and DARP W/O PC are roughly 25% and 15% higher compared to IEEE 802.11p W/ PC and IEEE 802.11p, respectively. DARP and DARP W/O PC achieve 28% gains in total number of received beacons which is shown in Fig. 8(e). In addition to higher number of received beacons, the proposed protocol maintains lower BLR which is half of the results from IEEE 802.11p as shown in Fig. 8(h). The number of received beacons per period is shown in Fig. 8(k). As expected from Fig. 8(b), the rate of receiving beacons in each period by considering time passage is 30% higher in DARP in comparison to IEEE 802.11p W/ PC. According to the results, in low-density scenarios, power control mechanism does not help improving the performance of the protocols. Moreover, DARP is quite reliable even in sparse regimes.

The results corresponding to City2 which is a busy city with dense roads and a high vehicle density are shown in Figs. 8(c, f, i, l). Based on Figs. 8(c, f), since the beaconing range is fixed and maximum in the scheme W/O PC, both of the protocols perform better in terms of number of received beacons and accumulated ones. When the power control mechanism is applied to the protocols, the beaconing range is reduced due to the high density of the city causing the lower number of received beacons. This trend is observable in Fig. 8(l) as well. DARP W/O PC and IEEE 802.11p have higher beacon reception rate in comparison to DARP and IEEE 802.11p W/ PC. From beacons loss ratio point of view, DARP W/ and W/O PC have smaller loss ratio showing in busy and high density scenarios, the performance of the proposed protocol is acceptable.

Fig. 8 shows that in all scenarios, a reservation-based protocol will outperform a contention-based one in terms of the BLR. It can be concluded that the BLR of DARP in both cases, W/ or W/O PC, are significantly lower than IEEE 802.11p W/ or W/O PC. It can also be concluded that DARP has a higher number of received beacons. Consequently, the proposed protocol is scalable and reliable in dense scenarios.

7 CONCLUSION AND FUTURE WORKS

In this paper, the beacon broadcasting problem was studied. The CSMA/CA-based MAC protocols performance degrades when the density becomes high, and DARP, the novel distributed and adaptive reservation-based broadcasting MAC layer protocol was proposed to address broadcasting and delivery of beacons. In order to detect and mitigate the beacon collision probability, four different kinds of preambles were used in the proposed protocol under the assumption of periodic beaconing and a fixed MDPU. In DARP, as a decentralized and reservation-based protocol, the channel access chance of a vehicle is controlled by its neighbors and the occupied resources will not be released until collision occurs due to topology change or the vehicle leaves the system. Transmission power and the resource duration were optimized in the protocol to minimize the access collision probability. The $50\,$MHz DARP with variable data rate was simulated by NS-3 and SUMO traces for two different scenarios, linear network and map-based network, and compared to the $10\,$MHz IEEE 802.11p fixed data rate protocol. The results showed a substantial improvement in DARP in comparison to the existing standard performance. Although the access delay of the proposed protocol is at least two beaconing periods, it can secure stable and reliable communication in different scenarios. The simulation results demonstrate that the proposed DARP with power control is highly scalable and efficient in realistic vehicular network scenarios.

A simple version of SINR corresponding to the two dominant sources of interference and constant length resources were investigated in this paper. A more general case of the SINR and also, the resources with variable length may be took into account as the extension of this protocol. Furthermore, priority level can be assigned to the broadcasting packets in order to make difference between safety and non-safety messages broadcasting.

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