A Reliable Token-Based MAC Protocol for V2V Communication in Urban VANET

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Abstract—**Safety applications developed for vehicular environments require every vehicle to periodically broadcast its status information (beacon) to all other vehicles, thereby avoiding the risk of car accidents in the road. Due to the high requirements on timing and reliability posed by traffic safety applications, the current IEEE 802.11p standard, which uses a random access Medium Access Control (MAC) protocol, faces difficulties to support timely and reliable data dissemination in vehicular environments where no acknowledgement or RTS/CTS (Request-to-Send/Clear-to-Send) mechanisms are adopted. In this paper, we propose the Dynamic Token-Based MAC (DTB-MAC) protocol. It implements a token passing approach on top of a random access MAC protocol to prevent channel contention as much as possible, thereby improving the reliability of safety message transmissions. Our proposed protocol selects one of the neighbouring nodes as the next transmitter; this selection accounts for the need to avoid beacon lifetime expiration. Therefore, it automatically offers retransmission opportunities to allow vehicles to successfully transmit their beacons before the next beacon is generated whenever time and bandwidth are available. Based on simulation experiments, we show that the DTB-MAC protocol can achieve better performance than IEEE 802.11p in terms of channel utilization and beacon delivery ratio for urban scenarios.**

1. INTRODUCTION

Vehicular Ad Hoc Networks (VANETs) differ from traditional mobile ad-hoc networks in terms of their high node mobility, highly dynamic topology, and unpredictable radio conditions. In combination with the high requirements on timing and reliability posed by traffic safety applications, VANET communication faces difficult challenges that need to be addressed on a protocol design level. Recently, IEEE 802.11p, a protocol suit based on the IEEE 802.11 Wireless Local Area Network (WLAN) standards adapted to specific case of vehicular networking, was incorporated into the IEEE 802.11 standard [1]. IEEE 802.11p defines the physical and Medium Access Control (MAC) layer protocols of the Wireless Access to Vehicular Environments (WAVE) protocol suit and operates in the 5.9 GHz band. IEEE 802.11p MAC layer is directly based on the random access MAC method used in IEEE 802.11 WLAN, Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). It has been widely reported in literature [2], [3] that IEEE 802.11p cannot prevent neighboring vehicles from simultaneously transmitting at high densities, causing packet collisions and unpredictable delays. Moreover, there are no acknowledgements or RTS/CTS (Request-to-Send/Clear-to-Send) frames to increase reliability by counteracting channel contention and interferences. Although many VANET MAC schemes have been proposed, many fail to encompass the highly varying topologies and node densities of a vehicular network, and to adapt successfully to the vastly different conditions and requirements of urban, rural and highway scenarios. In this paper, we propose a low-overhead token-based MAC protocol for VANETs that combines random access with a token passing technique. The proposed protocol, called Dynamic Token-Based MAC (DTB-MAC) has been implemented on top of a random access MAC protocol, providing a token passing technique whenever enough vehicles reside within each other's vicinity to allow a cluster to be formed. Hence, DTB-MAC acts as a random access MAC scheme at low node density, while it successfully deploys the token passing method at high node densities, i.e. when random access protocols like IEEE 802.11p start to struggle. For increased reliability and bandwidth efficiency, DTB-MAC bases its choice of token holder on the deadline of pending beacon packets, thereby using the available resources where they are needed the most for timely and reliable safety data exchange. DTB-MAC was evaluated for highway scenarios in [4]. In this paper, we target the challenges of urban traffic and show that the proposed MAC scheme copes very well with the high node density and obstacle prone environment of an urban scenario.

2. Background and Related Works

The European Telecommunications Standards Institute (ETSI) has standardized a profile of IEEE 802.11p adapted to the 30 MHz frequency spectrum at the 5.9 GHz band allocated in Europe that today comprises one control channel and two service channels. Typical Cooperative-Intelligent Transport System (C-ITS) safety applications rely on the exchange of two basic message types, periodic status updates and event-triggered hazard warnings. ETSI therefore defines two types of messages: periodic Cooperative Awareness Messages (CAM) [5], and event-triggered Decentralized

Environmental Notification Messages (DENM) [6]. In this paper, we focus on the periodic beacons (CAMs) that form the basis of a majority of ITS safety applications. We assume the periodic generation of beacons and see the generation of a new beacon as the deadline of its predecessor. This assumption falls in line with North American standardization, where beacons are periodic, while ETSI recently decided upon a set of kinematic CAM triggering rules that trigger beacons when needed rather than keeping it strictly periodic. Although these kinematic triggering rules could be incorporated into DTB-MAC's algorithm, for now they remain as future work.

A MAC protocol for a typical VANET application has to be flexible enough to cope with high mobility and frequent topology changes. Therefore, the IEEE 802.11p MAC is based on a completely decentralized approach: the CSMA/CA random access MAC method used in IEEE 802.11 WLAN. In CSMA/CA a node attempts to transmit only if the channel is sensed free during a certain time period (Arbitration Inter Frame Spacing, AIFS). If the channel is busy, or if it becomes busy during the AIFS, the node picks a random backoff time, which is counted down only during time periods when the channel is sensed free. When the backoff value reaches zero, the node transmits directly without any further delay. Despite its listen-before-talk approach, packets might still collide, rendering their content useless to the intended receiver. For the strict timing and reliability requirements of a safety-critical data exchange, this is not a feasible solution.

To address the short-comings of IEEE 802.11p-based approaches, TDMA-based techniques [3], [7], [8] have recently received much attention in the VANET literature because they are able to provide guaranteed delay. TDMA-based schemes rely on assigning different time slots to vehicles that are closer to each other in order to minimize the contention chances among vehicles, reusing the same slot times for the farthest vehicles.

The effectiveness of TDMA-based MAC protocols have already been compared by several authors [3], [9], [10]. The overall results show that TDMA-based solutions provide several benefits [11], including: high reliability, deterministic access time, efficient channel utilization, and equal access to the channel for all vehicles. However, these methods typically require slot synchronization, and they are not very dynamic when it comes to changing the beacon period or scheduling retransmissions. Even if they are able to provide adaptability, a high level of coordination and overhead are still required [7]. Similarly, retransmissions usually introduce additional overhead for control data and scheduling, and also a centralized control unit to determine if retransmissions are needed, and when.

The token ring approach can be implemented on top of IEEE 802.11 to offer QoS provisioning in terms of reserved bandwidth and bounded delay when operating under high densities. The wireless token ring protocol (WTRP) [12] was the first scheme using this idea in vehicular environments. However, it is still incapable of adapting to the fast topology changes typical of these environments. Some modifications were proposed in order to solve this issue: in [13], a wireless dynamic token protocol (WDTP) is presented which defines different subsets of vehicles and, in each subset, there is a master node responsible for token management. In [14], a token-based scheduling scheme is presented where vehicles do not have to maintain an ordered list of their neighbour nodes, and where each vehicle stochastically passes the token to others. Nevertheless, the authors assumed that the network must be fully-connected, which is not the case in VANETs. In [15], a multi-channel token ring MAC protocol (MCTRP) is presented for inter-vehicle communications. Previously proposed token-based methods for vehicular networks are centralized, requiring synchronization or any additional overhead for control traffic, therefore, becoming an unsuitable approach for inter-vehicle communications. In this paper, we propose a decentralized token-based MAC protocol that adapts easily to changes in the beacon frequency and the number of platoon members.

3. Token-Based MAC Protocol

In this section we provide a detailed description of the proposed Dynamic Token-Based MAC (DTB-MAC) protocol. A "token" refers to the privilege given to an individual vehicle (the terms "vehicle" and "node" will be used interchangeable throughout this paper) to access the channel without competition. A token is passed from node to another node within a pre-defined group. We define the concept of a "virtual ring", i.e. a group formed by vehicles that are temporarily within each other's vicinity. How these virtual rings are formed, as well as how vehicles join and leave a virtual ring, is described in this section. Furthermore, we introduce the scheme that allows each token holder to choose the proper candidate within its virtual ring to become the next token recipient, and that provides a token recovery mechanism in case a token is lost. This is done in a completely decentralized fashion with no need for a central token manager, which lends itself well to the properties of the highly mobile and flexible network topology of a VANET.

Vehicles broadcast periodic beacons (CAMs) to surrounding nodes to make their presence known. Once in the "awareness horizon" of neighboring vehicles, its presence can be considered and integrated into their safety applications. The more periodic beacons are lost, e.g. due to congestion and difficulties to access the channel, the longer our vehicle remains invisible to its neighbors, which will lead to uninformed and subsequently dangerous decisions by any security application. Token passing provides a way to assign a unique channel access to an individual node, i.e. the node that currently holds the token. Notice that DTB-MAC does not require any extra packet transmission for token passing. We use a pickybacking approach where nodes are notified about the next token holder simply by listening to the beacon. The beacon even holds information about the remaining time until the sender's next expected beacon generation, T_{rem}. Based on T_{rem} values from recently received beacons, each node maintains an up-to-date picture of upcoming beacon generations in its vicinity. This neighbor list is used by the node currently holding the token to find the best candidate to pass the token to. In order to avoid the distribution of outdated information, a beacon is dropped as soon as a new beacon is generated. This means that each beacon has a deadline. By choosing the vehicle with the lowest T_{rem} as the next token holder, we assure that the node that is closest to its deadline, and in most need to communicate, is granted access to the channel. Hereby, the number of deadline misses and packet drops is considerably reduced.

3.1. Ring Establishment and Maintenance

We consider a highly mobile vehicular environment where nodes can be members of one or multiple virtual rings. Figure 1 provides an illustrative example of the virtual ring, while Figure 2 shows the transition between different states a node goes through when becoming an active member of a virtual ring:

- **Token Holder Node (THN)**: a node which is allowed to transmit.
- **Backup Token Holder Node (BTHN)**: a node which is allowed to transmit if the THN node fails to transmit.
- **Ring Member Node (RMN)**: a node which is in a ring but cannot transmit since it does not hold the token.
- **Dissociative Node (DN)**: a node which does not belong to any ring and is not part of a ring joining procedure either.
- **Semi-Dissociative Node (SDN)**: a node which does not belong to any ring, but is attempting to join a ring following a beacon reception.

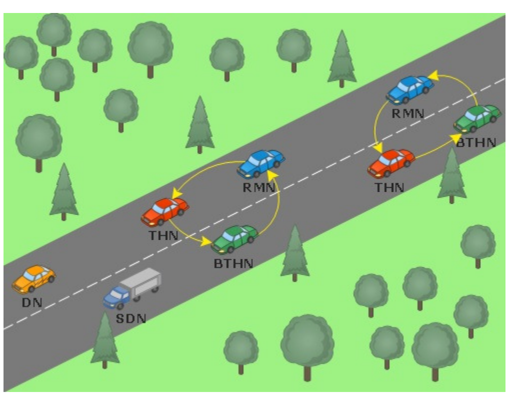

Figure 1. An illustrative example of the virtual ring.

Each node starts as an individual entity, a Dissociative Node (DN). Through beacon receptions nodes are notified about the presence of other nearby nodes and attempt to join available rings in their neighborhood. They then become a Semi-Dissociative Nodes (SDNs). As a SDN is

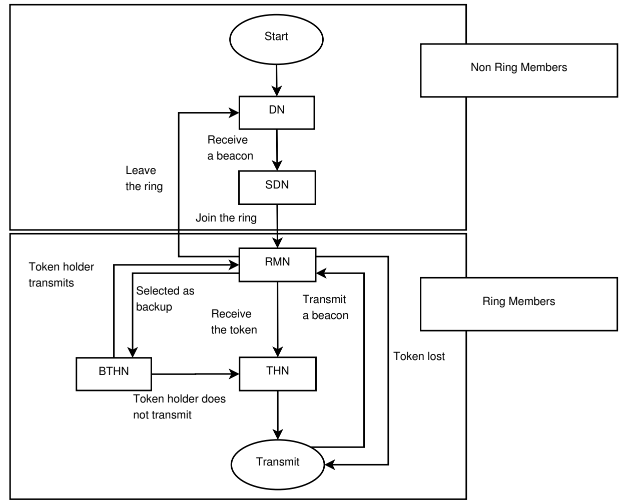

Figure 2. State transition diagram of DTB-MAC.

not a member of a ring yet, it will not get the right to use the channel through token possession, having instead to gain channel access using the IEEE 802.11p standard's CSMA/CA random access protocol. It thereby competes with other SDNs for channel access with potential packet collisions as a consequence. After receiving a beacon, the SDN waits a predefined time, T_{THN}. If the Token Holder Node (THN) does not grab the channel to send its beacon during this time, and if the channel is still idle, the SDN starts a randomized timer, T_{DIFF}:

$$T_{DIFF} = \alpha \times C \quad (1)$$

where C is a random number of time slots between 0 and T_{rem} (a measure of the "urgency" of the beacon transmission), and alpha is a value between 0 and 1 that allows fine tuning the behavior of our protocol in order to regulate the DTB-MAC delay. A high alpha value decreases the number of collisions between SDN nodes trying to access the channel. A low alpha, on the other hand, lowers the probability of a new node getting a chance to join the ring. Moreover, T_{DIFF} decreases with decreasing T_{rem} values. Once the SDN transmitted its beacon, it becomes a Ring Member Node (RMN). The process of joining a virtual ring is illustrated by the upper part of Figure 2, while timing details are shown in Figure 3.

A vehicle that has left the communication range of a virtual ring needs to be removed from the neighbor list of the remaining ring members. Removing old entries is necessary to avoid unwanted delays and degraded efficiency of the DTB-MAC protocol. A ring member therefore removes a node from the neighbor list if it has not received a beacon from that node for a predefined period T_{old}. T_{old} should be adapted according to node mobility, where a decreased T_{old} value allows a faster adaptation to topology changes. For the simulation study, we chose an optimized static parameter. A proper mechanism to dynamically adapt T_{old} to the actual node mobility level is left as future work.

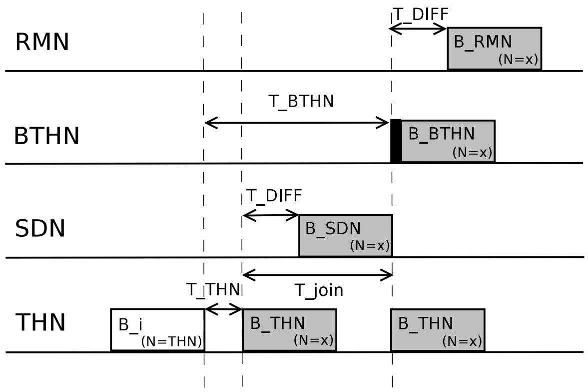

Figure 3. Transmission scheduling in DTB-MAC.

3.2. Token Management

It is vital for the success of any token passing protocol to keep the token alive, and to always choose the most suitable node as the next token holder. Therefore, a vehicle has certain responsibilities as a virtual ring member depending on its current role in the ring (Figure 2 illustrates the transition between those states):

- Maintaining a list of ring members: In order to make an informed choice of which node to hand the token to, each node maintains a neighbor list based on T_{rem} values received in earlier beacons along with the address of its sender. Upon each beacon reception, existing T_{rem} values are updated and, if necessary, a new source address is added or an outdated post is removed.
- Selecting next token holders: Before each beacon transmission, a node selects the next Token Holder Node (THN) and a Backup Token Holder Node (BTHN) from its neighbor list, where the node with the lowest and second lowest T_{rem} values are chosen as THN and BTHN, respectively. Hereby, priority is given to the node with the most pressing deadline, i.e. the node that should get access to the channel first to avoid packet drops. The node sends along its own T_{rem} value in the beacon. As expired beacons are dropped once a new beacon is generated, a vehicle will always have at most one safety message to transmit.
- Transmitting the beacon: A node chosen as THN has a beacon transmission opportunity. It transmits its beacon with a probability P_{RMN}, after a short waiting time, T_{THN}. The beacon transmission is further delayed by T_{join} with a probability of 1-P_{RMN}. This is to give potential SDNs a chance to access the channel and join the virtual ring. Only if the channel remains idle after T_{join} is the THN allowed to send its beacon. A BTHN acts as a backup in case the THN does not take the opportunity to send its beacon, thereby keeping the token alive. It only transmits its beacon if it finds the channel idle for one slot time after the waiting time T_{BTHN}, where

$$T_{BTHN} = T_{THN} + T_{join} \tag{2}$$

- Recovering from a lost token: After beacon reception, ring members that are not selected as THNs or BTHNs monitor the channel during a predefined time period T_{BTHN} (see Figure 3). If no activity is detect, token loss has occurred. This situation can be due to a problem in the previous beacon reception, causing the selected nodes to miss their THN/BTHN status notification. In order to determine which RMN should regenerate the token, each RMN randomly chooses a T_{DIFF} value (see Equation 1). If the channel is free after T_{DIFF}, the node sends its beacon, defining the new THN and BTHN according to its neighbor list.

4. Simulation Settings

Highway and urban scenarios have different characteristics. The one-dimensional and far more predictable traffic pattern of a highway scenario has been the focus of most protocol proposals and evaluations, while two-dimensional scenarios have been less thoroughly explored. Statistics [16] show, however, that a substantial portion of traffic accidents occur in urban settings. We therefore evaluated the performance of the DTB-MAC protocol in a typical old European city, represented by the 2.6 km x 2.6 km area of downtown Milan, using OMNeT++ [17] and SUMO [18] simulators.

Table 1 summarizes the general simulation parameters, while Table 2 shows the parameters specific to DTB-MAC. These parameter values were chosen based on extensive simulations where different parameter combinations were evaluated to obtain the best performance in the selected simulation scenario. For instance, T_{THN} was obtained so that each beacon is received by all neighboring nodes before a new beacon transmission.

TABLE 1. THE SIMULATION PARAMETERS.

Simulation Parameters	Value
Transmission Range	500 m
Propagation model	Sommer et. al obstacle based model with Shadowing + Nakagami small scale fading
Beacon frequency	1, 5 and 10 Hz
Packet length	500 bytes
Frequency	5.9 GHZ
Data Rate	6 Mbps
Simulation time	300 s

TABLE 2. DTB-MAC PROTOCOL PARAMETERS.

Parameter	Value
T_{THN}	0.25 ms
T_{old}	0.1 s
T_{join}	3 ms
α	0.1

The evaluation is based on widely-used parameters: (a) Beacon Delivery Ratio (BDR), defined as the ratio between the number of beacons successfully received by nodes within transmission range and the number of beacons transmitted; (b) dropped beacon ratio, calculated as the number of beacons that are dropped (due to an expired deadline) divided by the total number of beacons; and (c) channel utilization, comparing the time the channel is used for successful transmissions, failed transmissions and idle time.

5. Simulation results and analysis

Figure 4 compares the beacon delivery ratio (BDR) for DTB-MAC and the standard IEEE 802.11p for different network densities. (Note that a dropped packet due to a missed deadline is considered a packet loss.) In both cases, increased network density leads to lower BDRs since more nodes are sharing a limited resource. At increased vehicle densities, in IEEE 802.11p, packets did not find the channel idle before their deadline expired, while in DTB-MAC, vehicles did not receive the token in time to send the beacon prior to their deadline. While IEEE 802.11p benefits from low node densities, DTB-MAC suffers from interrupted token circulation when too few nodes are present. From a node density of 10 vehicles/km^2 and upwards, however, enough nodes are available to successfully run the token passing scheme, and so in those situations DTB-MAC outperforms IEEE 802.11p by up to a factor of 2.

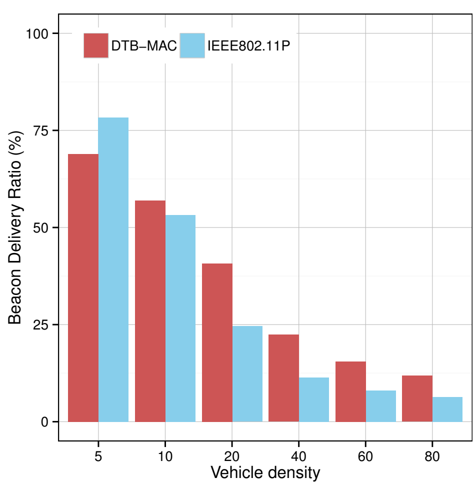

Figure 4. Beacon delivery ratio for the urban scenario.

This behavior is confirmed by the dropped beacon ratio in Figure 5, where increasing the vehicle density first shows a decrease in beacon drops (due to improved clustering and token maintenance capabilities), before increasing again due to the growing effects of resource limitations. Note, however, that despite the experienced increase of the dropped beacons ratio at high node densities, the overall beacon delivery ratio still improves, as can be seen in Figure 4.

Figure 6 provides a comparison of the BDR for various beacon sending rates, showing that DTB-MAC outperforms

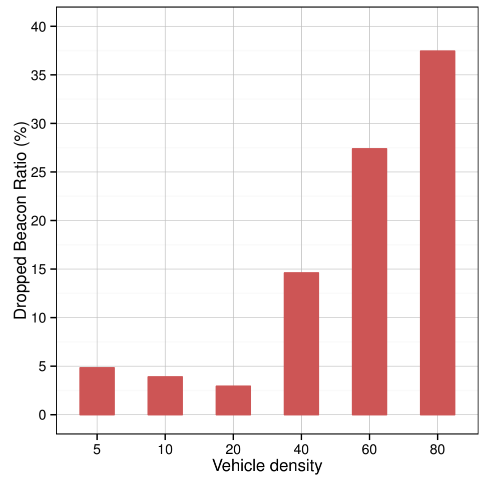

Figure 5. Dropped beacon ratio for the urban scenario.

IEEE 802.11p independently of the sending rate. The DTB-MAC algorithm automatically chooses the node closest to its deadline as the next token holder. This prioritization mechanism works independently of the node and packet density, thus providing to our protocol an edge over the 802.11p random access scheme at any sending rate.

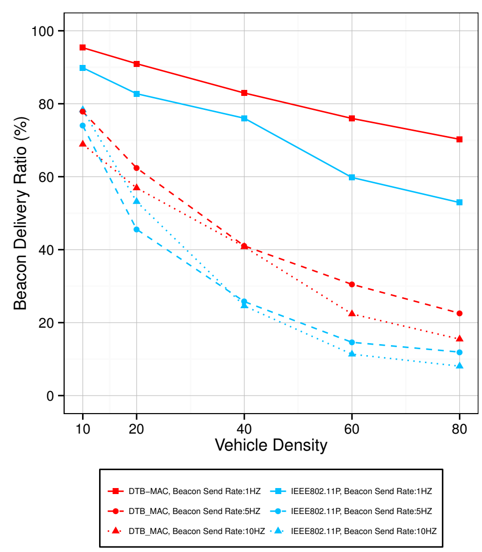

Figure 6. Beacon delivery ratio for different beacon sending rate in the urban scenario.

DTB-MAC was also evaluated in terms of channel utilization (see Figure 7). As expected, DTB-MAC introduces a slightly higher idle time than IEEE 802.11p because ring members have to wait for the token. IEEE 802.11p, on the other hand, wastes a larger portion of its bandwidth on unsuccessful transmissions (colliding packets). While the percentage of the channel used for successful transmissions remains low for 802.11p, it increases considerably for DTB-

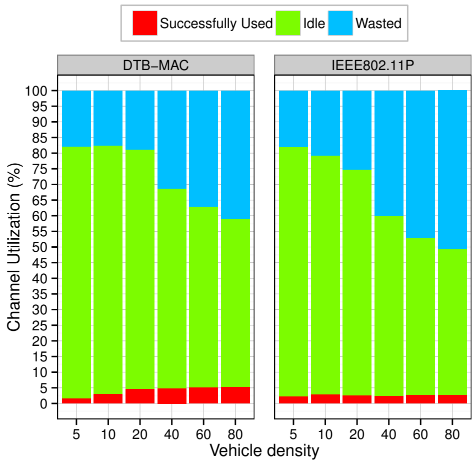

Figure 7. Channel utilization for the urban scenario.

MAC with increased vehicle density (and thereby increased possibilities of successfully forming clusters and maintaining the token).

6. CONCLUSIONS

In this paper, we propose our token-based MAC protocol, which is called Dynamic Token-Based (DTB-MAC). This protocol is decentralized, not requiring synchronization or any extra overhead for control traffic while still using standard IEEE 802.11p hardware. Vehicles that temporarily reside in each other's vicinity form different groups (rings), and they try to keep the token circulating between ring members as much as possible to clarify who has the privilege to access the channel. The node holding the token transmits its beacon and selects another ring member as the token holder by accounting for its transmission urgency, measured as time proximity to the beacon delivery deadline for that node. During that process, other ring members remain merely listening to beacon transmissions to find out when their turns to transmit beacons takes place; this is detected based on the received token data, which is piggybacked on the beacon itself. Simulation results show that the DTB-MAC protocol outperforms IEEE 802.11p in terms of beacon delivery ratio, and that the improvement ratio is increased as the vehicle density and beacon generation increase. Moreover, although DTB-MAC slightly increases idle times, the percentage of the channel used for successful transmissions shows significant improvements compared to IEEE 802.11p.

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