Chapter 2
Overview of Safety Message Broadcast in Vehicular Networks

In vehicular networks, safety-related applications usually operate based on wireless broadcast since warning messages (e.g., accident, blocked street, traffic congestion, etc.) need to be delivered to all nearby vehicles. Sometimes vehicles that have detected emergency events only need to broadcast the emergency messages to nearby vehicles within the transmission coverage, and a single-hop packet broadcast may be acceptable for this type of applications. In such a case, the MAC protocol will become the dominant component that determines the transmission efficiency of an emergency message. However, the design of a MAC protocol for emergency message disseminations is very challenging in the distributed vehicular networks due to the constantly moving nodes in the network. For example, emergency messages may experience unpredictable delays due to medium access contention [1], and long medium access delay is intolerable for safety applications in vehicular networks. Besides delay, packet loss is another serious problem for emergency message disseminations at the MAC layer in the vehicular networks [2], where a single message loss due to packet collisions could result in the loss of life.

Apart from the MAC layer issues, the network layer plays a vital role in the end-to-end delay performance in vehicular networks. Since the transmission range of a vehicle is quite limited, multi-hop broadcast of safety messages is usually employed because the alert information is required to assist remote drivers to make early driving decisions [3]. Consequently, such alert information has to be relayed hop by hop to reach the remote drivers. Whereas, how to quickly select a forwarding node to relay the emergency message is very important to decrease the end-to-end delay since a postponed message may be useless for some safety applications. In the following subsections we investigate various kinds of MAC and network layer broadcast schemes in performance improvement for safety services.

This chapter is organized as follows. In Sect. 2.1, we first survey the MAC layer broadcasting proposals. In Sect. 2.2, the network layer broadcasting proposals are introduced. In Sect. 2.3, we investigate some cross-layer solutions. Finally, Sect. 2.4 closes the chapter with conclusions.

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2.1 MAC Layer Broadcast

2.1.1 CSMA/CA-Based Broadcast

The dedicated short range communications (DSRC) standard is a widely accepted wireless technology to support ITS applications, and has become a key enabling technology for the next generation vehicular communications [4]. In 1999, the US federal communications commission (FCC) allocated 75 MHz of licensed spectrum in the 5.9 GHz band to DSRC which adopts IEEE 802.11p as its physical and MAC layers as shown in Fig. 2.1. On the top of IEEE 802.11p, several standards are defined by the IEEE 1609 Working Group for DSRC networks [5], e.g., 1609.4 for Multi-Channel communications, 1609.3 for Network Services including the WAVE short message protocol (WSMP), and 1609.2 for Security Services. IEEE 802.11p is derived from IEEE 802.11e to adapt to the vehicular environment, and the channel access mechanism of broadcast messages adopts the enhanced distributed channel access (EDCA) transmission mode [6, 7]. When the channel is idle for distributed inter-frame space (DIFS) interval, the backoff timer of a node will start and conduct the decrement operation. When the value of the timer is decreased to 0, the node broadcasts the packet immediately. Whereas, IEEE 802.11p is not suitable to be applied to safety message broadcast due to the following disadvantages [8, 9].

- Reliability - Different from the EDCA transmission mode in unicast packet communications, the receiving nodes of a broadcast message need not to send back an ACK frame to the sender. Therefore, the sender are unable to determine whether the message is successfully received by its neighboring nodes or not, and additionally timeout retransmissions are not supported by IEEE 802.11p broadcast

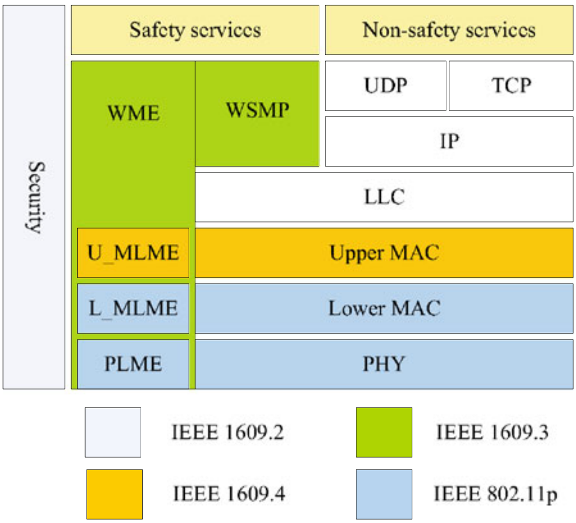

Fig. 2.1 The architecture of DSRC

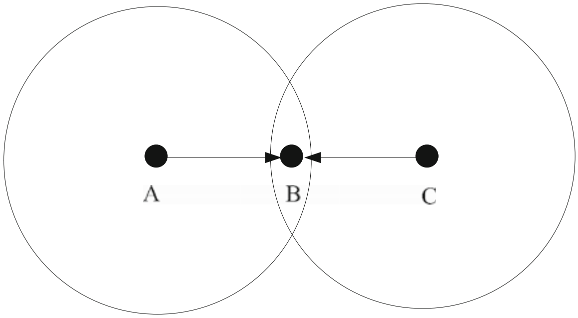

Fig. 2.2 The hidden terminal problem

protocol [10]. As a result, a neighboring node without receiving the emergency message may lead to a terrible tragedy.

- Hidden Terminal Problem - In IEEE 802.11p, since the carrier sense multiple access with collision avoidance (CSMA/CA)-based EDCA is adopted as the medium access mechanism, it may result in the hidden terminal problem in traditional ad hoc networks [11]. As shown in Fig. 2.2, node C and node A are not in the sensing range of each other, but both of them want to send packets to node B. When node A is transmitting packets to node B, since node C cannot detect the transmission from node A, it may send packets to node B, which leads to packet collisions at node B. For message broadcast in IEEE 802.11p, there is no request to send (RTS)/clear to send (CTS) handshake mechanism to alleviate packet collisions due to the hidden terminal problem in the multi-hop vehicular networks. Especially under the condition of large node density, the broadcast safety message collisions become more severe.
- Exposed Terminal Problem - The exposed terminal problem is caused by the carrier sense mechanism in IEEE 802.11p [12]. As shown in shown in Fig. 2.3, the nodes A and C are without the transmission range of each other, but within the sensing range of each other. When node A is transmitting packets to node B, node C will postpone its packet transmissions to node D since it senses the busy channel, although these two transmissions can be conducted simultaneously. As a result, exposed terminal problem brings unnecessary timer freeze in IEEE 802.11p, which prolongs the medium access delay for real-time safety messages.
- Random Access Delay - There is a number of real-time applications with tight delay requirements in vehicular networks. For example, the emergency information that is life-critical should be delivered to remote nodes as soon as possible, and out-of-date information is considered to be invalid. However, IEEE 802.11p adopts the contention-based CSMA/CA mechanism, and the medium access delay is not bounded [13, 14]. As a result, the broadcast message may suffer from large transmission delay in case of high node density, which is unacceptable for the safety applications with tight latency requirement.

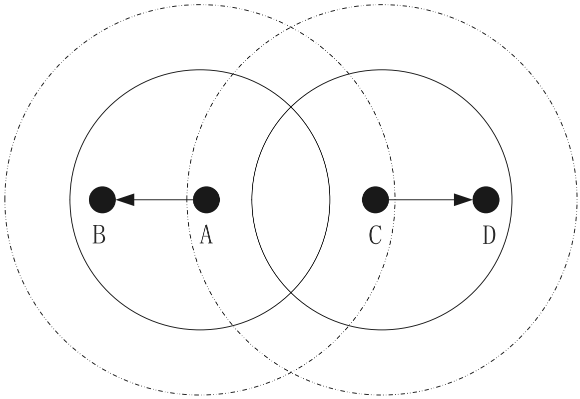

Fig. 2.3 The exposed terminal problem

In order to increase safety message reliability and improve transmission efficiency, some IEEE 802.11 based MAC protocols that utilize additional control packets are proposed [15, 16]. The broadcast medium window (BMW) protocol [16] uses RTS/CTS mechanism to address the hidden terminal problem in message broadcast as normal unicast packet transmissions, and all the receivers send back ACK frames to the transmitter to guarantee reliable broadcast transmissions. However, in BMW the time elapsed in the control packet exchanges is proportional to the number of neighboring nodes, and the long contention time usually leads to frequent timeouts, which greatly degrades the broadcast efficiency. In [17], a directional MAC (DMAC) protocol is studied in the vehicular ad hoc networks. Compared with IEEE 802.11, DMAC protocol achieves to improve network performance in terms of throughput and end-to-end delay in city roads and highways.

In [18], an efficient MAC scheme is proposed to effectively support emergency message disseminations in vehicular networks. The basic approach of the proposed MAC scheme is the intelligent use of a single control channel that carries only pulses. A node keeps sensing the control channel all the time except when they are transmitting the pulse in the channel. In addition, the emergency level of a message and the number of its duplicate copies are put in the packet header at the application layer. As a result, by eliminating the hidden terminal problem, the proposed MAC scheme achieves low and stable medium access delay, and provides multiple levels of strict priority for emergency packets in a fully distributed vehicular network. In [19], a MAC layer scheme is proposed to retransmit emergency messages to improve reliability. This scheme includes two retransmission schemes, e.g., the sequential scheme and the batch scheme. In the first one, every emergency message is retransmitted a fixed number of times at the MAC layer to mitigate against duplicate collisions. This scheme is compatible with the EDCA mechanism and hence can easily be deployed. In the batch scheme, multiple copies of an emergency message are transmitted sequentially by separated SIFS, which is achieved using the TXOP feature of EDCA. A MAC protocol that is designed for emergency message broadcasting is studied in [20], where a node broadcasts emergency messages several times to increase the transmission reliability. However, repeatedly broadcasting messages cannot guarantee the successful reception of broadcast messages, but may increase the contention level and waste the scarce wireless channel resources.

2.1.2 TDMA-Based Broadcast

TDMA-based MAC protocols have received an extensive attentions from the networking research community, and this kind of protocols can be used as control channel access in the distributed vehicular networks. The fundamental task of designing a TDMA-based scheme is to divide time into a series of superframes, each of which consists of a number of time slots. In a superframe, each node may reserve one or more dedicated time slots to transmit packets, but can only receive packets in the time slots reserved by other nodes [13]. Compared with the IEEE 802.11p protocol, the advantages of using TDMA-based MAC protocols can be summarized as follows [21, 22]: (i) All nodes have the same opportunity to access the wireless channel, (ii) Since each node has deterministic time slot allocations, packet collisions are avoided, which can improve channel resource utilization, (iii) The reliability of packet transmissions can be improved, and (iv) Medium access delay is bounded.

In [23], a dual cluster-based MAC protocol (D-CBM) is proposed, in which clusters are formed by electing stable cluster heads (CHs) to achieve high reliability and low or predictable delay. In order to achieve such design goal, vehicles are distributed to different clusters based on their position, direction of movement, and moving lane, etc. In addition, time slots are assigned to different vehicles to increase the message reliability. In [24], a multi-behavior and reliable broadcast (MRB) protocol is proposed to meet the QoS requirements of vehicular safety applications. MRB adopts either a reliable or a disseminating approach according to the type of the emergency messages. In addition, a nonuniform distance-based and time-based segmentation are proposed by taking into account headway time and collision probability to select the probe node, which makes the protocol more robust. In [25], Space-Orthogonal frequency-time medium access control (SOFTMAC) protocol is proposed for vehicular networks by combining CSMA, TDMA, space division multiple access (SDMA), and orthogonal frequency division multiplexing access (OFDMA) techniques. SOFTMAC utilizes the TDMA mechanism to ensure contention-free medium access, while OFDMA and SDMA to perform simultaneous packet transmissions, and the frequency bands and slots are preassigned according to the vehicle locations. Even though SOFTMAC meets diverse QoS requirements and improves throughput compared with IEEE 802.11, the combination of SDMA, CDMA, and OFDMA schemes make SOFTMAC very expensive and complex, and improper choices of parameters may degrade the network performance.

In [26], dedicated multi-channel MAC with adaptive broadcasting (DMMAC) is designed to support an adaptive broadcasting in vehicular ad hoc networks (VANETs). For safety applications, DMMAC provides two transmission modes, e.g., collision-free and delay-bounded transmissions, under various traffic scenarios.

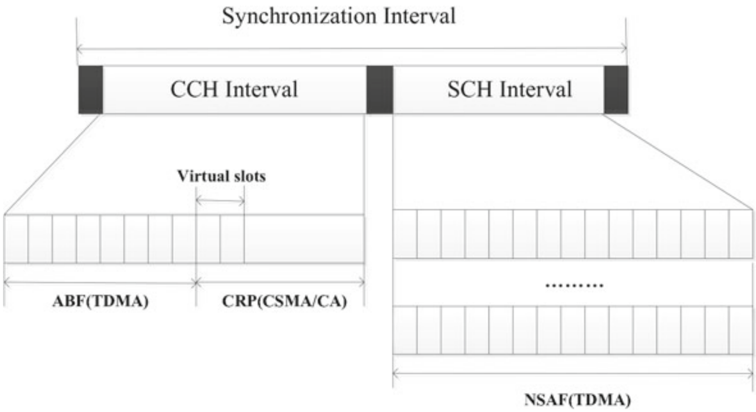

Fig. 2.4 The structure of a synchronized interval

As shown in Fig. 2.4, the DMMAC architecture is similar with that of IEEE 802.11p except that the CCH Interval is divided into an adaptive broadcast frame (ABF) period and a contention-based reservation period (CRP). During the ABF period the TDMA mechanism is utilized, and time is divided into a series of time slots, each of which is dynamically reserved by vehicles for collision-free safety message or other control message transmissions. During the CRP, the CSMA/CA mechanism is adopted as the medium access scheme, and vehicles contend for resources on SCHs for non-safety applications.

In [27–30], vehicular ad hoc networks MAC (VeMAC) is proposed as a contention-free multi-channel MAC protocol for vehicular networks, and supports both one-hop and multi-hop broadcast services on the control channel. In VeMAC, each node is equipped with two transceivers, the first one operates on the control channel while the other may be tuned to any service channel. Synchronization between nodes is performed using the GPS in each vehicle. VeMAC fully utilizes the DSRC seven channels, and assigns disjoint sets of time slots to moving vehicles in opposite directions, which efficiently decreases the possibility of packet collisions. In order to address the collisions under unbalanced traffic conditions in VeMAC, adaptive TDMA slot assignment [31, 32] dynamically doubles or shortens the superframe length based on the binary tree algorithm, by which the slot allocation information of two-hop neighbors of a vehicle is mapped into a binary tree. In [33], a novel multi-channel MAC protocol named CSMA and self-organizing TDMA (CS-TDMA) is proposed to improve broadcast performance in vehicular networks. Similar with SOFTMAC, CS-TDMA combines CSMA with TDMA and SDMA, and utilizes the same MAC frame structure as that in SOFTMAC. In CS-TDMA, the CCH and SCH intervals can be dynamically adjusted based on traffic density. For example, when the density of vehicles is low, the CCH interval is decreased to achieve higher throughput for normal data applications. Otherwise, the CCH duration is prolonged to guarantee a bounded delay for safety applications. However, in vehicular networks, nodes are usually moving fast, and the network topology can change frequently. Two remote vehicles may move into the coverage of each other, which may cause packet collisions.

2.2 Network Layer Multi-hop Broadcast

For real-time safety-related applications, a delayed emergency message may cause a terrible traffic accident, and thus the latency of the emergency message should be minimized. However, in vehicular networks multi-hop emergency message transmissions are indispensable due to the limited wireless communication range, and how to quickly select a remote forwarding node to relay emergency messages is a nontrivial task. In addition, even though neighboring nodes receive alert information by one broadcast message, an uncontrolled rebroadcast mechanism usually leads to the broadcast storm problem [34], which imposes severe message redundancy, medium contention, packet collisions, etc., and significantly wastes the limited channel resource in vehicular networks. A relatively naive broadcast control approach is simple flooding, where a receiver of the broadcast message only rebroadcasts it once. But simple flooding is still confronted with heavy message redundancy, which makes it not suitable for the high mobility vehicular scenario. In order to address the aforementioned issues, a number of network layer broadcast solutions have been proposed.

2.2.1 Neighbor Knowledge-Based Broadcast

In [35], a multipoint relaying scheme is proposed to reduce the number of duplicate retransmissions in message broadcasting. The multipoint relaying scheme works in a distributed manner, and each node computes a small set of neighboring nodes called multipoint relays independently. The scheme aims to achieve the maximum performance by selecting an optimal set of forwarding nodes and reduce duplicate broadcast messages. In [36], the relative degree adaptive flooding broadcast (RDAB) algorithm is proposed to efficiently reduce the broadcast overhead in the network. In RDAB, a node calculates the relative degree of its neighboring nodes, and decides which nodes need to retransmit and which nodes only need to receive. For example, the higher the neighbor node's relative degree, the node can cover more neighboring nodes, and it should be selected to rebroadcast packets in the networks.

2.2.2 Cluster-Based Broadcast

In [37], a new cluster-based emergency message dissemination algorithm is proposed for vehicular networks. The mathematical model named analytical hierarchy process (AHP) is utilized to calculate the weight value for each node by considering the metrics including relative speed, distance-considered connectivity, and reciprocal mean expected transmission count, etc., and the node with the smallest weight value is chosen as the cluster head in the neighborhood. After the cluster formation, the emergency message dissemination mechanism is introduced to support safety applications. In [38–40], a cluster-based multi-channel scheme is proposed to reduce channel congestion and meet the QoS requirements of broadcast services in a DSRC-based V2V communication network. In the scheme, vehicles moving in the same direction are grouped into clusters. In the intercluster communication protocol, the transmissions of the messages among clusters occur through two IEEE 802.11 MAC-based channels, while the intra-cluster coordination and communication protocol use a multi-channel MAC for each cluster head to communicate within its own cluster.

2.2.3 Topology-Based Broadcast

In [41], a vehicular multi-hop network is modeled as an evolving graph, and the problem of optimal data disseminations over the network is formulated in terms of minimum number of transmissions in a dynamic vehicular network. In the scheme, the calculation of the minimum broadcasting structure is proven to be an NP problem, and then an easy-to-implement approximation algorithm is presented by considering the number of different subgraphs and the harmonic number of the degree of the evolving graph, which enables the proposed algorithm to benchmark a state-of-the-art communication protocol. In [42], a stable connected dominating set (CDS)-based routing protocol is proposed to select the routing paths with low end-to-end delay. The protocol takes advantage of the global network topology, and builds stable backbones over road segments by considering vehicle speed and spatial distribution. At intersections, the backbones are connected via bridge nodes that keep an up-to-date network topology. The protocol eliminates the local maximum problem and balances data traffic among all possible routing paths.

2.2.4 Location-Based Broadcast

In [43], the broadcast control unit (BCUnit) is presented for reliable and low latency safety applications in vehicular networks. In BCUnit, a receiver independently calculates the backoff time to reduce packet collisions after receiving a broadcast emergency message. The computing of the backoff time is based on receiver's speed and its distance to the transmitter without the exchange beacon message. As a result, the overhead due to control or coordination among vehicles is eliminated, and the independent BCUnit can be feasibly integrated into DSRC devices. In [44], an event-driven broadcast algorithm is presented for cooperative collision avoidance in the two-way multilane highway scenario. The scheme tries to select an appropriate forwarding node for message retransmissions by exploiting the position, direction, and velocity information of nodes based on positioning devices, such as global positioning system (GPS), and wireless devices, such as Wi-Fi, and finally enables a forwarding node to rebroadcast the emergency or traffic information to other nodes quickly and reliably. A similar proposal [45] uses curb strategy to reduce the redundancy and forwarding strategy to choose the next suitable forwarding node using the position of the vehicles. In [46], the position-based multi-hop broadcast (PMB) protocol is proposed by considering the differences of transmission range among vehicles, and supports warning message disseminations with the help of nodes from different lanes. In order to reduce the number of forwarding nodes to rebroadcast warning packets, PMB selects a rebroadcast node based on additional coverage area of adjacent nodes by taking the transmission ranges of nodes and the inter-vehicle spacing into account. In addition, it guarantees the reliability of warning message disseminations by adaptively adopting the implicit ACK and explicit ACK mechanisms.

2.2.5 Distance-Based Broadcast

In [47], a new distance-aware safety-related message broadcasting algorithm is presented. In the scheme, the lengths of backoff times are computed based on the distances between the source node and its forwarding nodes, and the farthest forwarding node has the highest probability to forward messages. The scheme operates without the need of RTS/CTS exchange and packet acknowledgment in broadcasting. In addition, it adopts the synchronization intervals in the wireless access in vehicular environments (WAVE) standard and does not need additional waiting time, which makes it compatible with IEEE 802.11p and WAVE standard. In [48], the distribution-adaptive distance with channel quality (DADCQ) protocol is proposed to address some challenging issues in multi-hop broadcast of vehicular networks. DADCQ utilizes the distance method to select the forwarding nodes, and constructs a decision threshold function that takes the number of neighbors, the node clustering factor, and the Rician fading parameter into account. The optimum value of the decision threshold greatly depends on node density, spatial distribution pattern, and wireless channel quality, which enables DADCQ achieve high reachability and low bandwidth consumption under various road scenarios. In [49] the dynamic search-assisted broadcast (DSAB) protocol is presented to save the network resource and increase the packet delivery ratio. DSAB dynamically adjusts the transmission power of control messages to estimate the network density and adopts the n-way search to find the farthest node. As a result, the best vehicle in the farthest possible segment is chosen to relay the emergency messages in the network.

2.2.6 Probability-Based Broadcast

In [50], a position and mobility information assisted epidemic broadcast with attractor selection routing protocol is proposed to adapt to the highly dynamic nature of vehicular networks. By utilizing the real-time information on vehicle position and mobility, the protocol proposes an adaptive probabilistic infection and an adaptive limited time forwarding for the epidemic broadcasting, and makes a trade-off between message reachability and message efficiency, which enables the proposed scheme to achieve the efficiency and strength in terms of message reachability, delivery latency and routing cost. In [51], a neighbor coverage-based probabilistic rebroadcast protocol is proposed to reduce routing overhead. By exploiting the neighbor coverage knowledge, a novel rebroadcast delay is calculated to determine the rebroadcast order, and then accurate additional coverage ratio is obtained. In the proposal, a connectivity factor is defined to provide the node density adaptation. Thereafter, a reasonable rebroadcast probability is obtained by combining the additional coverage ratio and the connectivity factor. The proposed approach takes advantage of the neighbor coverage knowledge and the probabilistic mechanism, and significantly reduces the number of retransmissions. To efficiently utilize the wireless resource, three adaptive multi-hop broadcast proposals are designed in [52], which assign a broadcasting probabilities to mobile nodes according to the network parameters (e.g., the degrees of the nodes, distance of the nodes from each other). As a result, the presented novel 3-phase handshake gossiping protocols including distance-based handshake gossiping, valency-based handshake gossiping, and the average valency-based handshake gossiping generate less duplicates.

2.3 Cross-Layer Broadcast

In [53], a cross-layer scheme dynamic backbone-assisted MAC (DBA-MAC) is proposed as a general solution to support vehicular communications on highways. DBA-MAC combines elements from both reactive and proactive approaches, and aims to guarantee fast and efficient messages delivery to the zone of interest. DBA-MAC dynamically creates a virtual backbone of vehicles by considering the stability and channel quality of each link. Then messages are quickly forwarded over the multi-hop backbone by utilizing a novel forwarding scheme which provides contention-free access for backbone members. A black-burst-based [54] ad hoc multi-hop broadcast protocol is proposed for emergency message dissemination in [55]. A neighboring node sends a channel jamming signal (black-burst) with the time duration that is proportional to its distance from the sender. Thus, the farthest neighboring node sending the longest jamming signal wins the contention and becomes the next hop relaying node. Nevertheless, the largest jamming duration that is used by the relay candidate causes a long delay for emergency messages.

In the position-based multi-hop broadcast protocol [56], the farthest neighboring node waits the shortest time duration to reply the broadcast node. However, the farthest node usually suffers from a large path loss and a high PER, which may cause MAC layer retransmissions and a longer link delay. A cross-layer routing and MAC design for millimeter-wave wireless networks is studied in [57], which uses geographic position to maximize the channel resource utilization. However, the scheme selects paths or relays based on channel conditions or geographic information, and it does not consider the specific characteristics of VANETs, e.g., high mobility.

A cross-layer broadcast scheme is proposed for safety-related message dissemination in [58]. The scheme divides safety-related messages in VANETs into three categories and assigns them different priorities. As the class-three message, beacon messages are periodically exchanged among neighboring vehicles, which include the positions, speeds, travel time, and moving directions of these vehicles. However, repeatedly broadcasting hello or beacon messages induces a great deal of signaling overhead, and consumes many of wireless channel resources. In [55], a trinary partitioned black-burst-based broadcast protocol is presented to support time-critical message dissemination in VANETs. In order to quickly select a forwarding node, the protocol utilizes the mini-DIFS mechanism and iteratively partitions the target range into three sectors. In [59], the cross-layer broadcast protocol selects a forwarding node according to a novel metric considering the distance, relative velocity, and packet error rate, achieving a low latency and high reliability in a highway scenario. However, those approaches are lack of multidirectional broadcast support at intersections in urban scenarios.

In order to alleviate message redundancy and reduce message latency, some integrated proposals have been presented by taking into account emergency message broadcast at intersections in an urban scenario. In [60], ad hoc multi-hop broadcast (AMB) and urban multi-hop broadcast (UMB) are designed to address the broadcast storm, latency, and reliability issues. They utilize the directional broadcast to select remote forwarding nodes by the request to broadcast (RTB)/clear to broadcast (CTB) handshake on straight roads. At intersections, UMB adopts the repeater to broadcast emergency messages, while AMB enables a hunter vehicle to select the closest vehicle to the intersection to forward emergency messages in each road direction. Following the RTB/CTB handshake mechanism, a binary partition-assisted broadcast (BPAB) protocol is designed to support multi-hop emergency message dissemination in urban VANETs in [61]. BPAB utilizes different broadcast strategies according to the positions of emergency message senders. On a road, the directional broadcast scheme is adopted to iteratively divide the transmission range to select the furthest neighboring node. At intersections, the broadcast scheme selects a forwarding node in the inner region. However, the RTB/CTB handshake may be interrupted, and additionally the directional broadcast is sequentially adopted in different road directions, which increases the emergency message transmission delay.

2.4 Summary

In order to support safety-related applications in vehicular networks, a number of broadcast schemes have been proposed to address the challenging issues in single-hop or multi-hop broadcast. In this chapter, we have surveyed MAC layer, Network layer, and cross-layer solutions for safety message broadcast, and give evaluations to these proposals in the vehicular environment.

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