A Multi-Hop Broadcast Protocol for Emergency Message Dissemination in Urban Vehicular Ad Hoc Networks

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Abstract—In vehicular ad hoc networks (VANETs), multi-hop wireless broadcast has been considered a promising technology to support safety-related applications that have strict quality-of-service (QoS) requirements such as low latency, high reliability, scalability, etc. However, in the urban transportation environment, the efficiency of multi-hop broadcast is critically challenged by complex road structure, severe channel contention, message redundancy, etc. In this paper, we propose an urban multi-hop broadcast protocol (UMBP) to disseminate emergency messages. To lower emergency message transmission delay and reduce message redundancy, UMBP includes a novel forwarding node selection scheme that utilizes iterative partition, mini-slot, and black-burst to quickly select remote neighboring nodes, and a single forwarding node is successfully chosen by the asynchronous contention among them. Then, bidirectional broadcast, multi-directional broadcast, and directional broadcast are designed according to the positions of the emergency message senders. Specifically, at the first hop, bidirectional broadcast or multi-directional broadcast conducts the forwarding node selection scheme in different directions simultaneously, and a single forwarding node is successfully chosen in each direction. Then, directional broadcast is adopted at each hop in the message propagation direction until the emergency message reaches an intersection area where multi-directional broadcast is performed again, which finally enables the emergency message to cover the target area seamlessly. Analysis and simulation results show that the proposed UMBP significantly improves the performance of multi-hop broadcast in terms of one-hop delay, message propagation speed, and message reception rate.

Index Terms—Urban vehicular ad hoc networks, emergency message, directional broadcast, bidirectional broadcast, multi-directional broadcast.

I. INTRODUCTION

WITH the rapid development of the wireless communication technology, VANETs are dedicated for Vehicle-to-Vehicle (V2V) communications and extend the communication coverage area by information exchange among vehicles in a distributed manner [1]–[7]. As a result, VANETs are considered as a promising technology to support safety related applications in urban transportation system, which enables moving vehicles to quickly and accurately collect real-time road traffic information and notify neighboring vehicles of potential dangerous events quickly [8]–[12].

In urban VANETs, 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 related vehicles. In addition, due to the limited transmission range of an On-Board Unit (OBU) in vehicles, multi-hop transmissions of warning messages are usually employed because such kind of alert information is indispensable to assist remote drivers to make early driving decisions [13]. For example, in case of traffic accidents or jams, a remote driver expects to get knowledge of such events as early as possible, and then chooses an alternate driving route to avoid traffic jams in the urban transportation environment. However, such alert information has to be forwarded hop by hop to remote drivers.

To efficiently achieve the aforementioned research goals, the following challenging issues have to be addressed: i) 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 urban VANETs multi-hop emergency message transmissions are indispensable due to the limited wireless communication range [14], and how to quickly select a remote forwarding node to relay emergency messages is a non-trivial task; ii) even though neighboring nodes receive alert information by one broadcast message, an uncontrolled rebroadcast mechanism usually leads to the broadcast storm problem [15]–[18], which imposes severe message redundancy, medium contention, packet collisions, etc., and significantly wastes the limited channel resource in VANETs; and iii) message reliability is another challenging issue since the loss of an emergency message may lead to terrible casualties [19]–[22]. However, in urban VANETs without Point Coordinators (PCs) to control the medium access of vehicles, distributed medium access is definitely adopted at the Medium Access Control (MAC) layer [23]. Consequently, the

loss of an emergency message due to packet collisions can not be neglected when safety related services co-exist with other multimedia services.

In traditional mobile ad hoc networks, there exist several broadcast protocols which can be classified into *flooding based*, *probability based*, *area based* protocols [24], etc., but they can hardly be applied in urban VANETs directly due to the diverse QoS requirements of safety related services such as low latency, high reliability, low redundancy, etc. Some recent proposals take the characteristics of VANETs such as vehicle density, moving velocity, position, etc., into account to improve broadcast performance. However, most of these adaptive approaches only focus on directional broadcast in the highway scenario but neglect bi-directional and multi-directional emergency message dissemination in the complex urban environment.

In order to efficiently address the aforementioned challenging issues in urban VANETs, we propose an Urban Multi-hop Broadcast Protocol (UMBP), which takes the road layout of the urban transportation system into account. The contributions of the paper include:

- An efficient forwarding node selection scheme is presented to quickly select a remote neighboring node by utilizing iterative partition, mini-slot, black-burst, and asynchronous contention mechanisms, which greatly lowers emergency message transmission delay and reduces message redundancy.
- Based on the forwarding node selection scheme, three broadcast strategies such as bi-directional broadcast, multi-directional broadcast, and directional broadcast are then designed to quickly select a single forwarding node in each road direction to disseminate emergency messages.
- A closed-form analytical model is developed to study the performance of UMBP in terms of one-hop delay and message propagation speed.

The remainder of this paper is organized as follows. We give a brief overview of the related works in Section II. After introducing the system model, three broadcast strategies of the proposed UMBP are illustrated in Section IV. An analytical model is developed to study the performance of the proposed scheme in terms of one-hop delay and message propagation speed in Section V. Simulation results are given in Section VI, followed by concluding remarks in Section VII.

II. Related Work

There has been a number of broadcast schemes proposed to support safety related applications in VANETs recently. In [25], a street-based broadcast scheme is presented, and each vehicle periodically broadcasts the hello message which contains its position information to neighboring vehicles. In case of a traffic accident, a vehicle broadcasts an emergency message, and the farthest neighboring vehicle serves as the relaying node to forward the emergency message. A cross-layer broadcast scheme is proposed for safety related message dissemination in [26]. 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 [27], 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 [28], the Cross Layer Broadcast Protocol (CLBP) 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 the highway scenario. However, those approaches are lack of multi-directional broadcast support at intersections in urban scenarios.

Recently, some broadcast schemes are designed specifically for urban vehicular networks. In [29], an enhanced Street Broadcast Reduction (eSBR) scheme is presented to address the broadcast storm problem in urban VANETs. On receiving an emergency message, a vehicle checks whether the message has already been received or not by searching the message ID list. It keeps the emergency message if the message is received at the first time, and then decides to rebroadcast the message if its distance to the sender is larger than the threshold. In [30], Profile-driven Adaptive Warning Dissemination Scheme (PAWDS) focuses on safety related message dissemination in real urban environments. PAWDS operates in different modes including full dissemination, standard dissemination, and reduced dissemination based on the vehicle density, and utilizes eSBR scheme in the urban environment. Even though eSBR and PAWDS alleviate redundant messages to some extent, they are unable to guarantee a single forwarding node at each hop, and massive message redundancy still exist.

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 the urban scenario. In [31], Ad hoc Multihop Broadcast (AMB) and Urban Multihop 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 multihop emergency message dissemination in urban VANETs in [32]. 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.

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III. SYSTEM MODEL

UMBP aims at emergency message broadcast in an urban vehicular network with roads and intersections, and the network consists of a number of moving vehicles without roadside infrastructure support. Vehicles can move in two opposite directions on urban multi-lane roads, and they may cross intersections directly, or turn right/left. A vehicle is equipped with an OBU, which is responsible for detecting traffic accidents and then broadcasts emergency messages to neighboring vehicles. A wireless communication interface is installed on each OBU, and the basic IEEE 802.11 protocol is adopted at the MAC layer. However, different from traditional IEEE 802.11, several additional parameters are applied to safety services specifically in UMBP:

- **mini-slot**—the length of a mini-slot is set $\tau = 2\delta + t_{\text{swich}}$, where δ is the maximum signal propagation delay in the transmission range R, and t_{swich} is the radio switch delay between the reception mode and transmission mode [33]–[35].
- **BIFS**—Broadcast InterFrame Space (BIFS) is similar with Distributed InterFrame Space (DIFS) in IEEE 802.11, and an emergency message sender is obliged to sense the idle wireless channel for BIFS before accessing the medium. To avoid interrupting ongoing Request to Send (RTS)/Clear to Send (CTS)/DATA/ACK handshakes of neighboring nodes and guarantee the priority of emergent services over other multimedia services, the length of BIFS needs to satisfy the condition $T_{\text{SIFS}} < T_{\text{BIFS}} < T_{\text{DIFS}}$, where T_{SIFS} is the interval of Short InterFrame Space (SIFS), and T_{DIFS} is the interval of DIFS.
- **mini-CW**—Mini-Contention Window (mini-CW) is used to avoid emergency message collisions when multiple emergency message senders access the wireless channel asynchronously, and it is represented as

$$\text{mini\_CW} = \left\lfloor \frac{T_{\text{DIFS}} - T_{\text{BIFS}}}{\tau} \right\rfloor. \tag{1}$$

In addition, the OBU makes use of the Global Positioning System (GPS) to acquire the position information of the vehicle, and a digital map with the position information of intersections is also available for each OBU [36].

IV. THE PROPOSED UMBP

A traffic accident may occur either on a road or at an intersection in the urban environment, which triggers the initialization of an emergency message in UMBP. At the first hop, the emergency message is bi-directionally broadcast to neighboring nodes if the source node locates on a straight road, and a single relaying node is selected to forward the message in either direction of the source node. However, the emergency message has to be multi-directionally broadcast if the source node locates in an intersection area, and a single relaying node is selected to forward the message in each road branch. From the second hop, the message is directionally broadcast and only one relaying
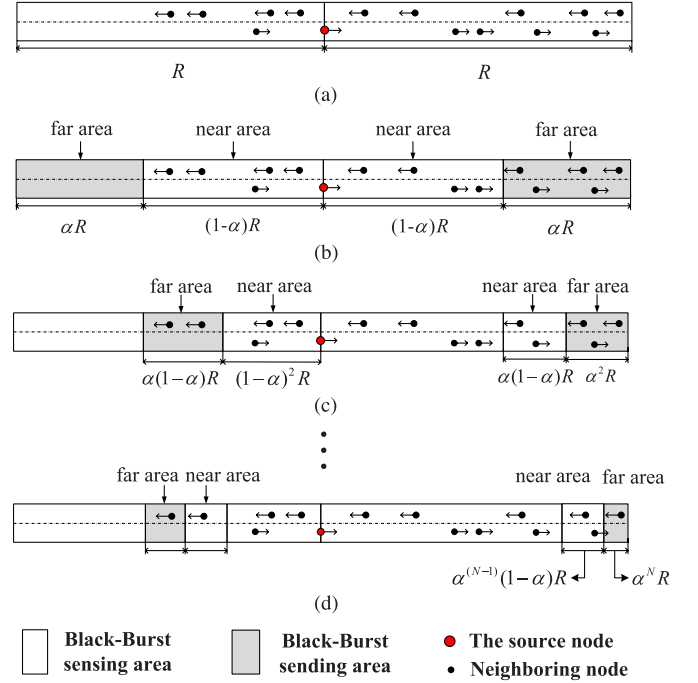

Fig. 1. The partitions of the transmission range R. (b) The first partition. (c) the second partition. (d) The N'th partition.

node is selected in the message propagation direction, except that the forwarding node locates in an intersection area. In the following subsections, we illustrate each broadcast strategy separately.

A. Bi-Directional Broadcast

On a road, some traffic accidents involve vehicles in two opposite directions, and all nearby vehicles should be aware of such potential dangerous events. For example, the red vehicle travels from left to right as shown in Fig. 1(a), and suddenly detects a dangerous event. It should quickly notify its neighboring vehicles in its *front direction* (e.g., the vehicles on the right side of the red vehicle as shown in Fig. 1(a)) and those in its *back direction* (e.g., the vehicles on the left side of the red node as shown in Fig. 1(a)) within its transmission range R.

In order to enable warning messages to propagate bi-directionally and reduce message redundancy, UMBP adopts bi-directional broadcast to select a single forwarding node in either direction of the source node. In [31], [32], the proposed schemes utilize the enhanced RTS/CTS handshake to select a forwarding node at the MAC layer in directional broadcast. However, the enhanced RTS/CTS handshake can hardly be applied to select more than one forwarding node simultaneously in bi-directional broadcast. For example, according to the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism in IEEE 802.11, when the sender transmits an RTS to neighboring nodes, a delayed CTS needs to be transmitted within DIFS interval, or else the RTS/CTS handshake may be interrupted. As a result, two candidate forwarding nodes from two opposite directions replying CTSs to the same RTS sender during DIFS interval definitely leads to a CTS collision.

To address the above issues, UMBP develops a novel approach to achieve efficient bi-directional broadcast at the first hop, which consists of the following three steps: i) the source node directly broadcasts the emergency message; ii) the black-burst mechanism is utilized to conduct candidate forwarding node selection in each direction; and iii) candidate forwarding nodes in each direction contend to serve as the forwarding node by sending an enhanced RTS (eRTS). The design details of each step are illustrated as follows.

On detecting an emergent event, the source node immediately broadcasts the emergency message directly according to the CSMA/CA medium access mechanism. Specifically, as soon as the idle wireless channel is sensed, the source node randomly selects a mini-slot from mini-CW and starts the backoff timer. If the wireless channel keeps idle until the timer overflows, the source node broadcasts the emergency message directly. On receiving the emergency message, the iterative candidate forwarding node selection process starts after SIFS interval for neighboring nodes in the *front direction* and the *back direction* simultaneously, and they decide how to conduct the iteration process according to their locations.

1) Neighboring Nodes in the Front Direction: In the first iteration which lasts two mini-slots, the transmission range R is partitioned into a Far Area (FA) and a Near Area (NA) in the *front direction* of the source node, and the ratio of the FA to R is denoted as $\alpha \in (0, 1)$ as shown in Fig. 1(b). During the first mini-slot, the neighboring nodes in the FA $((1 - \alpha)R, R]$ send black-burst, while the neighboring nodes within the NA $(0, (1 - \alpha)R]$ keep listening. Thereafter, in the second mini-slot of the iteration, the NA is further partitioned into the FA $((1 - \alpha)^2 R, (1 - \alpha)R]$ and the NA $(0, (1 - \alpha)^2 R]$ if the residing nodes did not hear black-burst in the first mini-slot as shown on the left side of Fig. 1(c); Otherwise, the NA is not further partitioned, and the residing nodes give up the opportunity to serve as candidate forwarding nodes and keep listening in the following iterations. On the other hand, the FA $((1 - \alpha)R, R]$ is directly partitioned into the FA $((1 - \alpha^2)R, R]$ and the NA $((1 - \alpha)R, (1 - \alpha^2)R]$ if there are some neighboring nodes locating within this FA in the first mini-slot as shown on the right side of Fig. 1(c); Otherwise, this FA is not further partitioned. During the second mini-slot, the neighboring nodes in the new FA have to turn their radios into the transmission mode if their were sensing black-burst in the first mini-slot, and similarly the neighboring nodes in the new NA have to turn their radios into reception mode if they were transmitting black-burst in the first mini-slot. Since the radio switch delay usually exists in each iteration, UMBP allocates two mini-slots to one iteration, the first one of which is used for black-burst transmitting or sensing, and the second one is used for radio switch. As a result, the black-burst transmissions or receptions of the neighboring nodes in the next iteration can operate correctly.

The second iteration starts from the third mini-slot. A neighboring node in the FA sends black-burst for one mini-slot, while a neighboring node in the NA senses black-burst during the same mini-slot. In the next mini-slot, the FA or the NA is further partitioned with the same principle used in the first iteration, and some neighboring nodes may switch their radios
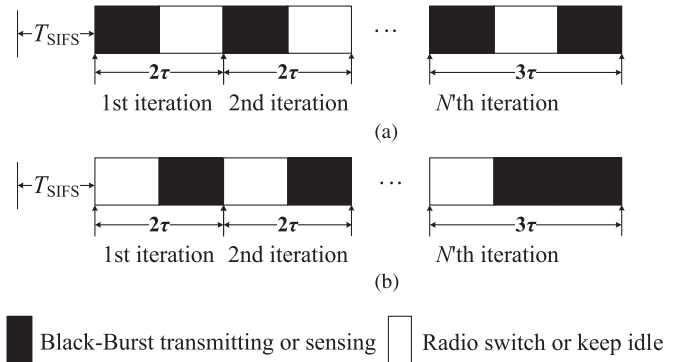

Fig. 2. The actions of neighboring nodes in two opposite directions. (a) The actions of neighboring nodes in the *front direction*. (b) The actions of neighboring nodes in the *back direction*.

during this mini-slot. The candidate forwarding node selection process continues until the iteration time reaches N as shown in Fig. 1(d), the value of which is limited to the condition

$$N \leqslant \left\lfloor \frac{T_{\text{DIFS}} - T_{\text{SIFS}} - \tau}{2\tau} \right\rfloor. \qquad (2)$$

In the N'th iteration which lasts three mini-slots, the neighboring nodes in the FA send black-burst in the $2N - 1$'th mini-slot, and then successfully become the candidate forwarding nodes in the *front direction*. However, if no neighboring nodes locate in the FA, the neighboring nodes in the NA become the candidate forwarding nodes. In the third mini-slot, the candidate forwarding nodes send black-burst to reserve the wireless channel resource. As a result, on hearing the black-burst, remote nodes that do not locate within the coverage R of the source node will keep idle for at least DIFS interval according to the CSMA/CA mechanism, and will not interfere with the following eRTS transmissions of the candidate forwarding nodes within that interval.

2) Neighboring Nodes in the Back Direction: In the *back direction*, the neighboring nodes should not transmit black-burst simultaneously with those in the *front direction*. Or else black-burst interference among the neighboring nodes in different directions of the source node cannot be avoided. For example, as shown in Fig. 1(b), the neighboring nodes in the left NA may hear the black-burst from the neighboring nodes within the right FA in the first iteration. Consequently, the neighboring nodes in the left NA give up the opportunity to serve as candidate forwarding nodes, and the emergency message will not propagate along this direction. Since the aim of black-burst from the neighboring nodes in a FA is to prevent the neighboring nodes in the NA of the same direction from contending to be candidate forwarding nodes, the black-burst from the neighboring nodes in the FA should not cover the sensing nodes in other direction. In order to address this challenging issue, neighboring nodes in the *back direction* conduct an alternative iteration process in UMBP. As shown in Fig. 2(a), neighboring nodes in the *front direction* transmit or sense black-burst in the first mini-slot of an iteration, and the second mini-slot is used for radio switch. Whereas, neighboring nodes in the *back direction* adopt an inverse sequence as shown

in Fig. 2(b). They switch radios in the first mini-slot of an iteration, and transmit or sense black-burst in the second mini-slot. In addition, the same partition principle in the *front direction* is utilized to obtain the FA and the NA in each iteration in the *back direction*. As a result, the iteration process is performed simultaneously in two opposite directions of the source node until the candidate forwarding nodes are successfully selected in each direction.

After N iterations, as soon as sensing the wireless channel idle for SIFS interval, a candidate forwarding node randomly selects a mini-slot from the Contention Window (CW) and starts the backoff process based on the CSMA/CA mechanism, where

$$CW = \left\lfloor \frac{T_{\text{DIFS}} - T_{\text{SIFS}}}{\tau} \right\rfloor. \tag{3}$$

If the wireless channel keeps idle until the backoff timer overflows, the candidate forwarding node sends an eRTS. Other candidate forwarding nodes that choose larger mini-slots stop their backoff timers on receiving the eRTS from the candidate forwarding node within the same final FA, and give up the opportunity to serve as a forwarding node. After successfully delivering an eRTS, a candidate forwarding node is promoted to be a forwarding node, and initiates the eRTS/eCTS handshake for directional broadcast along the emergency message propagation direction on a road, which will be illustrated in Section IV-C. It is possible that two or more candidate forwarding nodes in the same final FA select the same mini-slot, which leads to an eRTS collision. As a result, the next hop neighboring nodes in the message propagation direction are unable to correctly receive the eRTS, and the eRTS/eCTS handshake based directional broadcast cannot proceed normally. So if a candidate forwarding node cannot receive the black-burst within the interval $T_{\text{SIFS}} + 2\tau$ interval after delivering an eRTS, it indicates an eRTS collision in bi-directional broadcast. Consequently, the candidate forwarding nodes in the same final FA continue to contend to send an eRTS until an eRTS is successfully delivered, and then the bi-directional broadcast process completes.

B. Multi-Directional Broadcast

With the aid of GPS localization service and digital map, a source node and its neighboring nodes are feasible to identify that they are within an intersection area. When a traffic accident occurs within an intersection area, UMBP conducts multi-directional broadcast at the first hop, which guarantees the emergency message propagate along each road branch. In UMBP, multi-directional broadcast also consists of three steps as those in bi-directional broadcast, and the source node adopts the same operations to deliver an emergency message directly. Thereafter, the candidate forwarding node selection process is conducted in each direction simultaneously. However, the selection process in multi-directional broadcast is more complicated than that in bi-directional broadcast, since neighboring nodes from each direction need to participate in the iterative selection procedure. As a result, UMBP needs to eliminate black-burst interference among neighboring nodes in
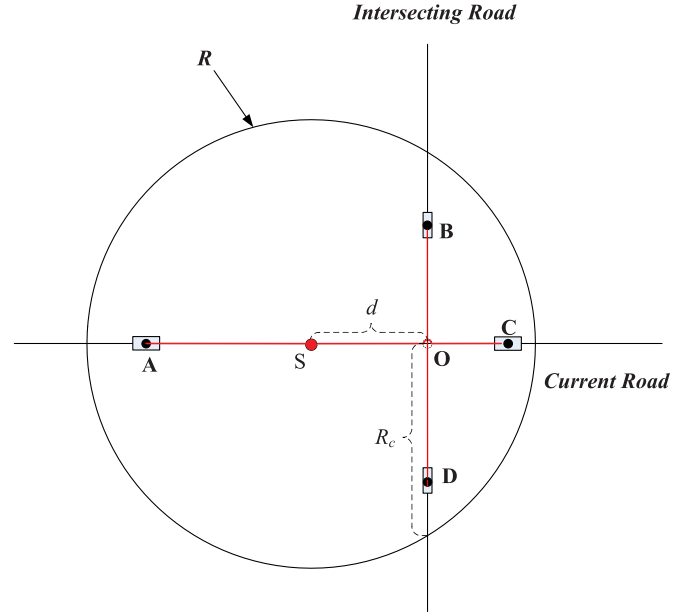

Fig. 3. Multi-directional broadcast in an intersection area.

different directions. Within an intersection area, it is impossible to prevent the black-burst transmitted by the neighboring nodes on one road from covering its intersecting road as long as the black-burst needs to reach the neighboring nodes in the opposite direction of the intersection. For example, S is the source node, and A, B, C, D are four neighboring nodes in different directions of intersection O as shown in Fig. 3. If the black-burst transmitted by node C on one road needs to reach the source node S and other neighboring nodes between S and O, the black-burst is bound to cover neighboring nodes on the another road, which leads to black-burst interference among neighboring nodes on two intersecting roads. In order to address such issue, UMBP adopts a novel approach to regulate black-burst transmissions among neighboring nodes on different roads.

On receiving the broadcast emergency message, a neighboring node decides how to transmit or sense the black-burst depending on which road it is situated on. The road where the source node is located is called the *current road*, and the road which intersects with the *current road* is named the *intersecting road*. With the position information of the source node carried by the emergency message and the position information of the intersection from the digital map, a neighboring node is feasible to identify whether it locates on the *current road* or the *intersecting road*, and starts the candidate forwarding node selection process after SIFS interval.

1) Neighboring Nodes on the Current Road: For neighboring nodes on the *current road*, such as neighboring nodes A and C as shown in Fig. 3, the iteration process is similar with that in bi-directional broadcast. In the first mini-slot of an iteration, the neighboring nodes in the *front direction* transmit or sense black-burst, while the neighboring nodes in the *back direction* may switch radios or keep idle as shown in Fig. 4(a). In the next mini-slot of the iteration, some neighboring nodes in the *front direction* may switch their radios, while some
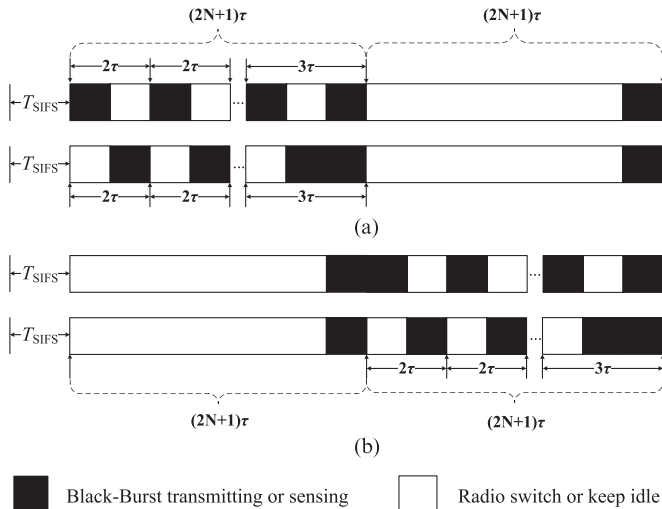
Fig. 4. The iteration process on two different roads. (a) The iteration process on the *current road*. (b) the iteration process on the *intersecting road*.

neighboring nodes in the *back direction* transmit or sense black-burst. After N iterations, candidate forwarding nodes in each direction of the *current road* are successfully selected. Thereafter, these candidate forwarding nodes keep idle for $2N\tau$ interval, and then transmit black-burst for one mini-slot to reserve the wireless channel for their following eRTS transmissions as shown in Fig. 4(a). After the transmission of black-burst, a candidate forwarding node randomly chooses a mini-slot from CW to compete to serve as the forwarding node based on the CSMA/CA mechanism.

2) Neighboring Nodes on the Intersecting Road: The iteration process of neighboring nodes on the *intersecting road* is much different from that of neighboring nodes on the *current road*. Before the iteration process, a neighboring node on the *intersecting road* needs to compute two distances: i) the distance from the source node to the intersection d; and ii) the other is the covered length of the *intersecting road* by the source node, the half of which is denoted as $R_c = \sqrt{R^2 - d^2}$ as shown in Fig. 3. The first iteration starts after $T_{\text{SIFS}} + (2N + 1)\tau$ interval on receiving the broadcast message as shown in Fig. 4(b), and R_c is initially partitioned into a FA $((1 - \alpha)R_c, R_c]$ and a NA $(0, (1 - \alpha)R_c]$ in each direction of the *intersecting road*. In the first mini-slot of the iteration, the neighboring nodes in one direction transmit or sense black-burst, and the neighboring nodes in the other direction may switch their radios or keep idle. In the second mini-slot of the iteration, the neighboring nodes that transmitted or sensed black-burst in the last mini-slot may switch their radios, while the neighboring nodes that switched their radios in the last mini-slot may transmit or sense black-burst. In the next iteration, the same principles as those in bi-directional broadcast are adopted to obtain the FA and the NA in each direction. The above procedure repeats in each iteration until the N'th iteration. Thereafter, the candidate forwarding nodes in the final FA of each direction keep idle for T_{SIFS} interval, and choose a mini-slot in CW to contend to serve as the forwarding node.

The neighboring nodes on the *current road* and the neighboring nodes on the *intersecting road* perform the iteration

process alternately as shown in Fig. 4, which eliminates black-burst interference among neighboring nodes on different roads. Through the above operations in multi-directional broadcast, a single forwarding node is successfully selected in each road direction, and then the emergency message is directionally propagated with the directional broadcast scheme. Finally, the message is able to cover the target area seamlessly in the urban environment. Note that, when the emergency message is delivered to a forwarding node within an intersection area, multi-directional broadcast is utilized. However, the neighboring nodes that locate between the current forwarding node and the former one do not participate in the forwarding node selection process.

C. Directional Broadcast

From the second hop, the emergency message is directionally broadcast as long as the forwarding node does not locate within an intersection area. In order to improve the reliability of emergency message, the eRTS/eCTS handshake is utilized to eliminate the hidden terminal problem. After sensing the wireless channel idle for BIFS, a forwarding node randomly selects a mini-slot from mini-CW, and starts the backoff process based on the CSMA/CA mechanism. It delivers an eRTS if the wireless channel keeps idle until its backoff timer overflows. On receiving the eRTS, only the neighboring nodes in the message propagation direction take part in the candidate forwarding node selection process. UMBP adopts the same principles to obtain the FA and the NA as those in the *front direction* of bi-directional broadcast. The neighboring nodes in the FA transmit black-burst but the neighboring nodes in the NA sense black-burst during the first mini-slot of an iteration. In the second mini-slot of the iteration, some neighboring nodes need to switch their radios, while some neighboring nodes keep idle. After N iterations, the neighboring nodes in the final FA become the candidate forwarding nodes, and they contend to reply an eCTS. After receiving the replied eCTS, the current forwarding node broadcasts the emergency message to its neighboring nodes. Thereafter, the candidate forwarding node that has successfully replied an eCTS serves as the forwarding node in the next hop, and repeats the forwarding node selection process and rebroadcasts the emergency message.

In UMBP, bi-directional broadcast or multi-directional broadcast is utilized at the first hop, and the forwarding node selection scheme is conducted simultaneously in different road directions. As a result, a remote neighboring node is successfully selected as the forwarding node in each road direction, which not only greatly reduces message redundancy but also decreases the transmission hops of emergency messages and lowers message transmission delay. Then, directional broadcast adopts the eRTS/eCTS handshake to choose a single forwarding node in the message propagation direction, which increases the message reliability besides reducing message transmission delay. Finally the emergency message achieves to cover the target area seamlessly in the urban environment. In summary, the emergency message broadcast strategies in UMBP are described as Algorithm 1.

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Algorithm 1 Different broadcast strategies

1: Denote i as the number of hops;
2: **if** $i = 1$ **then**
3:   **if** the source node on a road
4:     ***Bi-directionally broadcast*** the emergency message;
5:   **else**
6:     ***Multi-directionally broadcast*** the emergency message;
      // in an intersection area
7:   **end if**
8: **else**
9:   **if** the forwarding node on a road **then**
10:     ***Directionally broadcast*** the emergency message;
11:   **else**
12:     ***Multi-directionally broadcast*** the emergency message;
       // in an intersection area
13:   **end if**
14: **end if**

V. PERFORMANCE ANALYSIS

In this section, we develop an analytical model to study the performance of the proposed UMBP in terms of one-hop delay and message propagation speed. In order to enable UMBP to be tractable, the following assumptions are made.

- Vehicles are distributed on an M-lane road following Poisson process, and denote ρ as vehicle density which represents the average number of vehicles per unit distance on a lane. Due to the physical size of a vehicle and traffic safety, the value of vehicle density can not be infinite. Let $\rho_{\max}$ be the maximum value of vehicle density, and the corresponding minimum inter-vehicle distance is $L_{\mathrm{MIN}} = 1/\rho_{\max}$.
- A traffic accident occurs either on a road or within an intersection area. Only the vehicle that first detects this event initiates an emergency message dissemination, and other vehicles detecting the same event will not perform the emergency message initialization process after receiving the broadcast message.
- Packets are successfully received as long as there are not packet collisions within the transmission range R, and packet losses due to channel error are not considered [37]. The interference range is equivalent to the transmission range R.

A. One-Hop Delay

1) One-Hop Delay in Directional Broadcast: For directional broadcast, one-hop delay is defined as the interval from a forwarding node preparing to deliver an eRTS to the successful transmission of an emergency message. Whereas, for bi-directional broadcast and multi-directional broadcast, one-hop delay is defined as the interval from the arrival of an emergency message at the MAC layer to the successful transmission of an eRTS. Denote T_{O-H}^{D}, T_{O-H}^{B}, and T_{O-H}^{M} as the one-hop delays in directional broadcast, bi-directional broadcast, and multi-directional broadcast, respectively.

In directional broadcast, the one-hop delay T_{O-H}^{D} consists of the time for transmitting an eRTS, the iteration time, the contention time for replying an eCTS, and the emergency message transmission time. Since traffic accidents rarely take place, the possibility that two or more neighboring nodes select the same mini-slot to transmit an eRTS for different traffic accidents is neglected. Consequently, the time for transmitting an eRTS is mini_CW$/2 + T_{e\mathrm{RTS}}$, while the time spending in the iteration process is $T_{\mathrm{SIFS}} + (2N + 1)\tau$. In order to calculate the contention time in the eCTS replying process, the length of the final FA after N iterations and the number of candidate forwarding nodes should be obtained. Let $\mathcal{N} = 2^N$, and partition the transmission range R into $\mathcal{N}$ segments that form the state space of the final FA, which can be represented by the set

$$\mathcal{L} = \{L_0, L_1, \ldots, L_{\mathcal{N}-1}\} \tag{4}$$

where the length of the i'th segment is expressed as

$$L_i = (1-\alpha)^j \alpha^{(N-j)} R, \quad \exists j \in [0, N]. \tag{5}$$

For example, $L_0 = \alpha^N R$ is the farthest segment, $L_1 = \alpha^{N-1}(1-\alpha)R$ is the second farthest segment, and $L_{\mathcal{N}-1} = (1-\alpha)^N R$ is the nearest segment to source node as shown in Fig. 1(d). Therefore, the possibility that there are k vehicles in the i'th segment is denoted as

$$\Pr(x_i = k) = \begin{cases} \dfrac{(\lambda_i)^k}{k! \cdot \sum\limits_{n=0}^{K_i} \frac{(\lambda_i)^n}{n!}}, & k \in [0, K_i] \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

where $\lambda_i = \rho M L_i$, and $K_i = (M \cdot L_i)/L_{\mathrm{MIN}}$ is the maximum number of vehicles in the i'th segment.

If the final FA is L_i $(i > 0)$, it indicates that no vehicle locates in either of $L_0, L_1, \ldots, L_{i-1}$. Let random variable l be the final FA in directional broadcast, and random variable x be the number of candidate forwarding nodes that participate in the eCTS replying process after N iterations. Therefore, the possibility that k candidate forwarding nodes contend to reply an eCTS in the final FA L_i is expressed as

$$\begin{aligned} \Pr(x = k | l = L_i) &= \frac{\Pr(x = k \bigcap l = L_i)}{\Pr(l = L_i)} \\ &= \frac{\Pr(x_i = k)}{\Pr(x_i > 0 \bigcap x_0 = 0 \bigcap \cdots \bigcap x_{i-1} = 0)} \\ &= \frac{\Pr(x_i = k)}{\Pr(x_i > 0) \prod_{j=0}^{i-1} \Pr(x_j = 0)} \\ &= \frac{\Pr(x_i = k)}{(1 - \Pr(x_i = 0)) \prod_{j=0}^{i-1} \Pr(x_j = 0)} \end{aligned} \tag{7}$$

where $k \in [1, K_i]$, $i \in [1, \mathcal{N} - 1]$, and $\Pr(x_j = 0)$ denotes the probability that there is no vehicle in the j'th segment. Replace

$\Pr(x_i = k)$, $\Pr(x_i = 0)$, and $\Pr(x_j = 0)$ with Eq. (6), the conditional probability in Eq. (7) is obtained. Whereas, for $i = 0$, we have

$$
\begin{aligned}
\Pr(x = k | l = L_0) &= \frac{\Pr(x = k \cap l = L_0)}{\Pr(l = L_0)} \\
&= \frac{\Pr(x_0 = k)}{1 - \Pr(x_0 = 0)}, \quad k \in [1, K_0]. \quad (8)
\end{aligned}
$$

Similarly, replace $\Pr(x_0 = k)$ and $\Pr(x_0 = 0)$ with Eq. (6), the conditional probability in Eq. (8) is obtained. As a result, we have the probability

$$
\Pr(x = k) = \sum_{i=0}^{\mathcal{N}-1} \Pr(x = k | l = L_i) \cdot \Pr(l = L_i) \quad (9)
$$

With Eqs. (7) and (8), $\Pr(x = k)$ is obtained. In the eCTS replying process, a candidate forwarding node randomly selects a mini-slot from CW. Therefore, three events may take place in a mini-slot as follows

- **Idle**—no candidate forwarding node selects the mini-slot to transmit an eCTS.
- **Collision**—two or more candidate forwarding nodes select the mini-slot to transmit an eCTS simultaneously, which induces an eCTS collision.
- **Success**—only a single candidate forwarding node selects the mini-slot, and transmits an eCTS successfully.

Let p be the probability that a candidate forwarding node randomly selects a mini-slot, and we have $p = 1/\text{CW}$. Denote p_i, p_c, and p_s as the probabilities that events *idle*, *collision*, and *success* take place in a mini-slot, respectively, and they are given as

$$
p_i = \sum_{k=1}^{K_{\text{MAX}}} (1 - p)^k \cdot \Pr(x = k) \quad (10)
$$

$$
p_c = \sum_{k=1}^{K_{\text{MAX}}} \left(1 - (1 - p)^k - \binom{k}{1} p (1 - p)^{k-1} \right) \cdot \Pr(x = k) \quad (11)
$$

$$
p_s = \sum_{k=1}^{K_{\text{MAX}}} \binom{k}{1} p (1 - p)^{k-1} \cdot \Pr(x = k) \quad (12)
$$

where

$$
K_{\text{MAX}} = \max(K_i), \quad i \in [0, \mathcal{N} - 1]. \quad (13)
$$

Replace $\Pr(x = k)$ in Eqs. (10)–(12) with Eq. (9), and the probabilities p_i, p_c, and p_s are obtained. An *idle* event lasts an entire mini-slot, and then candidate forwarding nodes continue the backoff process. If an eCTS collision event occurs, candidate forwarding nodes resume the contention process after SIFS interval. But if an eCTS is successfully received, the forwarding node will broadcast the emergency message after SIFS interval. As a result, the time taken by each of these three events is given

$$
T_i = \tau \quad (14)
$$
$$
T_c = T_{e\text{CTS}} + T_{\text{SIFS}} \quad (15)
$$
$$
T_s = T_{e\text{CTS}} + T_{\text{SIFS}}. \quad (16)
$$

Before a successful eCTS transmission, the number of unsuccessful events is

$$
N_{\overline{s}} = \frac{1 - p_s}{p_s} \quad (17)
$$

and each of them is either an *idle* event or an eCTS collision. Therefore, the average time taken by an unsuccessful event is

$$
T_{\overline{s}} = \frac{p_i \cdot T_i + p_c \cdot T_c}{p_i + p_c}. \quad (18)
$$

Finally, the one-hop delay in the directional broadcast is represented as

$$
\begin{aligned}
T_{O-H}^{D} &= \text{mini\_CW}/2 + T_{e\text{RTS}} + T_{\text{SIFS}} \\
&\quad + (2N + 1)\tau + T_{\text{SIFS}} + N_{\overline{s}} T_{\overline{s}} + T_s + T_{\text{EM}} \\
&= \text{mini\_CW}/2 + T_{e\text{RTS}} + (2N + 1)\tau + 3T_{\text{SIFS}} \\
&\quad + \frac{p_i \cdot \tau + p_c \cdot (T_{e\text{CTS}} + T_{\text{SIFS}})}{p_s} + T_{e\text{CTS}} + T_{\text{EM}} \quad (19)
\end{aligned}
$$

where T_{EM} is the transmission time of an emergency message. Replace p_i, p_c, and p_s in Eq. (19) with Eqs. (10)–(12), respectively, and then the one-hop delay T_{O-H}^{D} in directional broadcast is acquired.

2) One-Hop Delay in Bi-Directional Broadcast: In bi-directional broadcast at the first hop, the one-hop delay T_{O-H}^{B} is composed of the time for transmitting an emergency message, the iteration time, and the contention time for transmitting an eRTS. Similar to those in directional broadcast, the first part of T_{O-H}^{B} takes the time $\text{mini\_CW}/2 + T_{\text{EM}}$, while the time consumed in the iteration process is $T_{\text{SIFS}} + (2N + 1)\tau$. However, the contention time for transmitting an eRTS is much different from that in directional broadcast. In directional broadcast, only the candidate forwarding nodes in the final FA of the emergency message propagation direction participate in the eCTS replying process. However, in bi-directional broadcast, the candidate forwarding nodes in the final FA of each direction contend to transmit an eRTS since the emergency message needs to propagate along two opposite directions. Consequently, if the distance between two final FAs is less than R, the contention among candidate forwarding nodes in the two final FAs can not be neglected. For a segment L_i in one direction, let

$$
\mathcal{L}_i = \{L_0, L_1, \ldots, L_{d_i}\}
$$

be the set of segments beyond the range R of L_i in the opposite direction. Denote

$$
\overline{\mathcal{L}_i} = \{L_{d_i+1}, L_{d_i+2}, \ldots, L_{\mathcal{N}-1}\}
$$

as the complementary set of $\mathcal{L}_i$. So the distance from each segment in $\overline{\mathcal{L}_i}$ to L_i in the opposite direction is less than or equal to R. As a result, for segment L_i in one direction, the probability that there is a segment within the range R in the opposite direction is

$$
q_i = \frac{\mathcal{N} - d_i - 1}{\mathcal{N}}. \quad (20)
$$

Let random variables l_f and l_b be the final FAs in the *front direction* and the *back direction*, respectively, x_f and x_b be the

number of candidate forwarding nodes in the two final FAs, and $x_c = x_f + x_b$ $(x_f \geqslant 1, x_b \geqslant 1)$ be the total number of contending neighboring nodes when l_f and l_b are within the transmission range R. As a result, we have the conditional probability

$$\Pr(x_c = k | l_f = L_i \bigcap l_b = L_j)$$
$$= \frac{\Pr(x_c = k \bigcap l_f = L_i \bigcap l_b = L_j)}{\Pr(l_f = L_i \bigcap l_b = L_j)}. \quad (21)$$

Assuming $K_i < K_j$, we have

$$\Pr(x_c = k \bigcap l_f = L_i \bigcap l_b = L_j)$$
$$= \begin{cases} \sum_{m=1}^{k-1} \Pr(x_f = m) \cdot \Pr(x_b = k - m), & k \in [2, K_i] \\ \sum_{m=1}^{K_i} \Pr(x_f = m) \cdot \Pr(x_b = k - m), & k \in (K_i, K_j] \\ \sum_{m=k-K_j}^{K_i} \Pr(x_f = m) \cdot \Pr(x_b = k - m), & k \in (K_j, K_i + K_j] \end{cases}$$
$$(22)$$

where $\Pr(x_f = m)$ and $\Pr(x_b = k - m)$ can be obtained by Eq. (6). On the contrary, if $K_j \leqslant K_i$, $\Pr(x_c = k \bigcap l_f = L_i \bigcap l_b = L_j)$ can be obtained by the similar expressions with Eq. (22).

$$\Pr(l_f = L_i \bigcap l_b = L_j)$$
$$= \Pr(x_i > 0 \bigcap x_0 = 0 \bigcap \cdots \bigcap x_{i-1} = 0)$$
$$\cdot \Pr(x_j > 0 \bigcap x_0 = 0 \bigcap \cdots \bigcap x_{j-1} = 0)$$
$$= (1 - \Pr(x_i = 0))(1 - \Pr(x_j = 0))$$
$$\cdot \prod_{m=0}^{i-1} \Pr(x_m = 0) \cdot \prod_{n=0}^{j-1} \Pr(x_n = 0) \quad (23)$$

where $\Pr(x_i = 0)$, $\Pr(x_j = 0)$, $\Pr(x_m = 0)$, and $\Pr(x_n = 0)$ can be obtained by Eq. (6).

Therefore, when L_i is the final FA in the *front direction* and the final FA in the *back direction* locates within its range R, the probability that there are k candidate forwarding nodes is denoted as

$$\Pr(x_c = k | l_f = L_i) = \sum_{j=d_i+1}^{\mathcal{N}-1} \Pr(x_c = k | l_f = L_i \bigcap l_b = L_j) \quad (24)$$

and consequently the *idle*, *collision*, and *success* probabilities are given as

$$p_i^i = \sum_{k=2}^{K_{\mathrm{MAX}}^i} (1 - p)^k \cdot \Pr(x_c = k | l_f = L_i) \quad (25)$$

$$p_c^i = \sum_{k=2}^{K_{\mathrm{MAX}}^i} \left(1 - (1-p)^k - \binom{k}{1} p(1-p)^{k-1}\right) \cdot \Pr(x_c = k | l_f = L_i) \quad (26)$$

$$p_s^i = \sum_{k=2}^{K_{\mathrm{MAX}}^i} \binom{k}{1} p(1-p)^{k-1} \cdot \Pr(x_c = k | l_f = L_i) \quad (27)$$

where

$$K_{\mathrm{MAX}}^i = \max(K_j), \quad j \in [d_i + 1, \mathcal{N} - 1]. \quad (28)$$

As a result, the one-hop delay under the condition that $l_f = L_i$ and the distance between l_f and l_b is less than R is represented as

$$T_c^i = \mathrm{mini\_CW}/2 + T_{\mathrm{EM}} + (2N + 1)\tau + 2T_{\mathrm{SIFS}}$$
$$+ T_{e\mathrm{RTS}} + \frac{p_i^i \cdot \tau + p_c^i \cdot (T_{e\mathrm{RTS}} + T_{\mathrm{SIFS}})}{p_s^i}. \quad (29)$$

When L_i is the final FA in the *front direction*, but the final FA in the *back direction* is beyond its transmission range, the candidate forwarding nodes within L_i will not interfere with those in the other direction. The probability that there are k candidate forwarding nodes contending to send an eRTS is denoted as

$$\Pr(x_f = k | l_f = L_i) = \sum_{j=0}^{d_i} \Pr(x_c = k | l_f = L_i \bigcap l_b = L_j). \quad (30)$$

Then we can obtain the *idle*, *collision*, and *success* probabilities in the situation that $l_f = L_i$ and the distance between l_f and l_b is larger than R, and the corresponding one-hop delay $\overline{T_c^i}$ is obtained. As a result, if L_i is the final FA in the *front direction*, the one-hop delay is expressed as

$$T^i = q_i \cdot T_c^i + (1 - q_i) \cdot \overline{T_c^i}. \quad (31)$$

Finally, the one-hop delay in bi-directional broadcast is denoted as

$$T_{O-H}^B = \sum_{i=0}^{\mathcal{N}-1} \left((1 - \Pr(x_i = 0)) \prod_{j=0}^{i-1} \Pr(x_j = 0)\right) \cdot T^i. \quad (32)$$

3) One-Hop Delay in Multi-Directional Broadcast: The one-hop delay in multi-directional broadcast also includes the time for transmitting an emergency message, the iteration time, and the contention time for transmitting an eRTS as those in bi-directional broadcast. The time for transmitting an emergency message is $\mathrm{mini\_CW}/2 + T_{\mathrm{EM}}$, but the iteration time is $T_{\mathrm{SIFS}} + (4N + 2)\tau$. In the contention process, since the candidate forwarding nodes on the *current road* select a mini-slot from CW to deliver an eRTS, the probability that a mini-slot is selected by a candidate forwarding node is $p = 1/\mathrm{CW}$. Assuming no contention among the candidate forwarding nodes on two intersecting roads, we can use the same procedure as that in bi-directional broadcast to derive the contention time. Consequently, the one-hop delay on the *current road* T_{O-H}^{M-c} can be obtained. Whereas, different from the transmission range R on the *current road*, the covered length in each direction of the *intersecting road* is $R_c = \sqrt{R^2 - r^2}$, where r is the distance from the source node to the intersection. Partition the length R_c

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into $\mathcal{N}$ segments that forms the state space of the final FA in each direction of the *intersecting road*, and the state space can be denoted by the set

$$\mathcal{S} = \{S_0, S_1, \ldots, S_{\mathcal{N}-1}\} \tag{33}$$

where the length of the i'th segment is denoted as

$$S_i = (1 - \alpha)^j \alpha^{(N-j)} R_c, \quad \exists j \in [0, N]. \tag{34}$$

Represent y_i as the number of candidate forwarding nodes in segment S_i, we can obtain the probability $\Pr(y_i = k)$ by the same expression as Eq. (6). Then, the contention time can be derived by the same procedure as that in bi-directional broadcast, and then we can acquire the one-hop delay on the *intersecting road* T_{O-H}^{M-i}. Finally, the average one-hop delay in multi-directional broadcast $T_{O-H}^M = (T_{O-H}^{M-c} + T_{O-H}^{M-i})/2$ is obtained.

B. Message Propagation Speed

The propagation speed of an emergency message is defined as the propagation distance per second, and it equals the distance of the final FA to the source node divided by the one-hop delay. If the final FA is L_i $(0 < i \leqslant \mathcal{N} - 1)$, it indicates that no vehicle locates in either of $L_0, L_1, \ldots, L_{i-1}$, and the probability is $(1 - \Pr(x_i = 0)) \prod_{j=0}^{i-1} \Pr(x_j = 0)$. Therefore, the average per hop propagation distance in directional broadcast is denoted as

$$D_D = (1 - \Pr(x_0 = 0)) \cdot \sum_{m=0}^{\mathcal{N}-1} L_m$$
$$+ \sum_{i=1}^{\mathcal{N}-1} \left(\left((1 - \Pr(x_i = 0)) \prod_{j=0}^{i-1} \Pr(x_j = 0) \right) \cdot \sum_{m=i}^{\mathcal{N}-1} L_m \right) \tag{35}$$

and the corresponding propagation speed is

$$V_D = \frac{D_D}{T_{O-H}^D}. \tag{36}$$

Whereas, in bi-directional broadcast, the emergency message is broadcast to neighboring nodes in two opposite directions, and consequently the propagation speed is

$$V_B = \frac{2D_D}{T_{O-H}^B}. \tag{37}$$

In multi-directional broadcast, since the covered length in each direction of the *intersecting road* is R_c, the average per hop distance in one direction is

$$D_I = (1 - \Pr(y_0 = 0)) \cdot \sum_{m=0}^{\mathcal{N}-1} S_m$$
$$+ \sum_{i=1}^{\mathcal{N}-1} \left(\left((1 - \Pr(y_i = 0)) \prod_{j=0}^{i-1} \Pr(y_j = 0) \right) \cdot \sum_{m=i}^{\mathcal{N}-1} S_m \right). \tag{38}$$

TABLE I
PARAMETERS IN SIMULATIONS

Parameter	Value	Parameter	Value
SIFS	10 μs	PLCP&preamble	192 μs
Time slot	20 μs	RTS	20 byte
DIFS	50 μs	CTS	14 byte
Basic rate	1M	DATA	512 byte
Data rate	11M	ACK	14 byte
mini-slot	5 μs	eRTS	20 byte
BIFS	15 μs	eCTS	14 byte
mini_CW	7	Emergency message	512 byte
CW	8	N	3
mini-slot	5 μs	α	1/2
δ	1 μs	Base MAC protocol	IEEE 802.11b
t_{swich}	3 μs	Transmission range	250 m

As a result, the propagation speed in multi-directional broadcast is

$$V_M = \frac{2(D_D + D_I)}{T_{O-H}^M}. \tag{39}$$

Finally, the message propagation speed in each kind of broadcasts is obtained.

VI. SIMULATION RESULTS

In this section, we implement the proposed UMBP in Network Simulator-2 (NS-2) [38], and evaluate its performance in terms of one-hop delay and message propagation speed. As a representative multihop broadcast protocol in the urban environment, BPAB [32] is utilized as the comparison protocol. Note that, since BPAB does not explicitly include the design details to support bi-directional broadcast, we utilize its multi-directional broadcast strategy to implement bi-directional broadcast in BPAB, which means the forwarding node sequentially selects the next hop relaying node in each of the two opposite directions. Both UMBP and BPAB use the same parameter values in each performance comparison, and conventional IEEE 802.11b is utilized as the base MAC protocol. The simulated urban vehicular network adopts the Manhattan mobility model that consists of a number of horizontal and vertical roads. Vehicles are randomly distributed on two-lane roads ($M = 2$) and move in two opposite directions on a road. The minimum inter-vehicle distance that represents the safety distance between two neighboring vehicles is 10 m, which means that the maximum value of vehicle density on a lane is $\rho_{\max} = 1/10$ vehicles/m. The length of a road segment between two neighboring intersections is set 1000 m. One vehicle initially broadcasts an emergency message on a road segment, and then the message propagates bi-directionally. The same simulation is conducted 50 times by each protocol, and the average simulation results are calculated for performance comparisons. The detailed parameter settings used in the simulations are tabulated in Table I.

A. One-Hop Delay

For time critical safety services, the one-hop delay of emergency messages is the most important performance metric, and it is evaluated under different scenario parameters including

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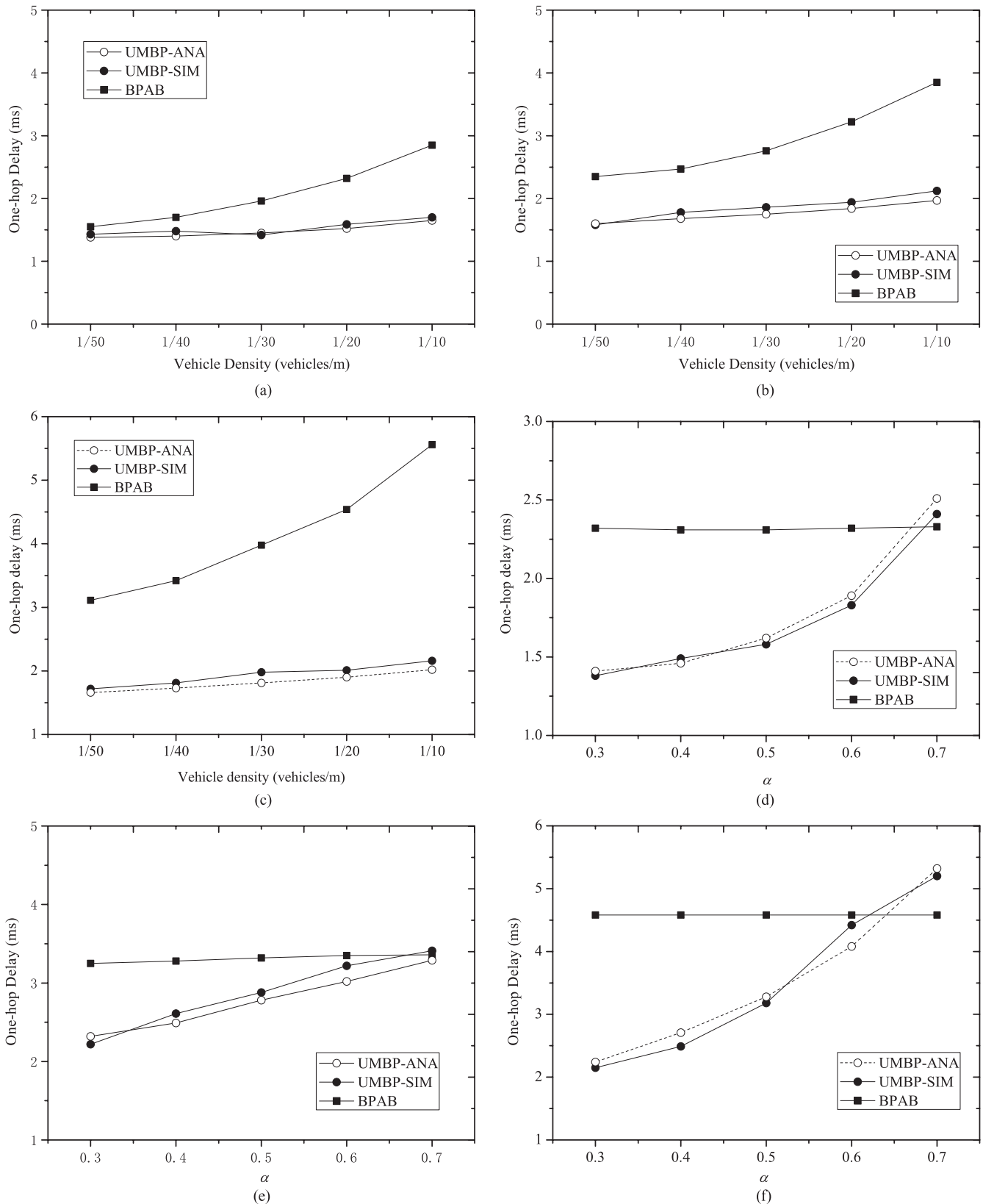

Fig. 5. Performance comparisons of one-hop delay between UMBP and BPAB. (a) The one-hop delay in directional broadcast ($\alpha = 1/2$). (b) The one-hop delay in bi-directional broadcast ($\alpha = 1/2$). (c) The one-hop delay in multi-directional broadcast ($\alpha = 1/2$). (d) The one-hop delay in directional broadcast ($\rho = 1/20$). (e) The one-hop delay in bi-directional broadcast ($\rho = 1/20$). (f) The one-hop delay in multi-directional broadcast ($\rho = 1/20$).

vehicle density ρ and ratio α in this section. In Fig. 5(a)–(c), we adopt the default value of α as shown in Table I, and obtain the values of one-hop delay by varying the values of vehicle density in directional broadcast, bi-directional broadcast, and multi-directional broadcast, respectively. From the three figures we can observe that UMBP achieves a much lower one-hop

delay than BPAB. In addition, the values of one-hop delay in both UMBP and BPAB gradually increase as the vehicle density goes up. For directional broadcast in BPAB, on receiving an RTB, candidate forwarding nodes are successfully selected by N binary partitions in the message propagation direction. Then the contention phase starts, and candidate forwarding nodes conduct the backoff process conforming to the CSMA/CA mechanism in IEEE 802.11. However, if no candidate forwarding nodes can reply CTBs within DIFS interval, their backoff timers will be frozen when one of their neighboring nodes in the message propagation direction transmits an RTS for normal data transmissions. As a result, the RTB/CTB handshake to select a forwarding node is interrupted, which prolongs the one-hop delay. However, in UMBP a candidate forwarding node randomly selects a mini-slot from CW during the contention process, and the longest backoff time $CW \cdot \tau$ is less than DIFS, which prevents the interruption of the $eRTS/eCTS$ handshake. Therefore, UMBP achieves a lower one-hop delay than BPAB in directional broadcast. At the first hop or within an intersection area, BPAB utilizes the directional broadcast in all directions, and the current forwarder sequentially selects the next hop forwarding node in each direction, which adds to the average one-hop delay. Whereas, UMBP adopts bi-directional broadcast at the first hop and multi-directional broadcast within an intersection area, and the forwarding node concurrently selects the next hop forwarding nodes in all directions, which enables UMBP to achieve a lower one-hop delay than BPAB. However, with the increase of vehicle density, there will be more CTB and $eCTS$ collisions in the contention process, and the one-hop delays in both UMBP and BPAB go up consequently.

In Fig. 5(d)–(f), with fixed vehicle density ρ, we show the one-hop delay comparisons between UMBP and BPAB by adjusting the value of parameter α. In the three figures, we set $\rho = 1/20$ which is a relatively high vehicle density in the urban environment. From the figures we can observe that the difference of one-hop delay between UMBP and BPAB gradually gets small with the increase of parameter α, and finally the one-hop delay in UMBP exceeds that in BPAB, which demonstrates that parameter α critically affects the one-hop delay performance of UMBP. In BPAB, the length of the final FA after N iterations is $R/2^N$ since it uses the binary partition in each iteration, while the length of the final FA in UMBP is $\alpha^N \cdot R$ if there are some residing nodes. As a result, the length of the final FA in UMBP is larger than that in BPAB if parameter α is greater than 1/2, and there will be more $eCTS$ collisions in UMBP than CTB collisions in BPAB during the contention process, which enlarges the one-hop delay. Therefore, in order to obtain a high one-hop delay performance, UMBP can flexibly control the length of the final FA to alleviate the contention level by adjusting the value of parameter α. However, the fixed length of the final FA in BPAB cannot reduce the contention level even through the vehicle density becomes high on multi-lane roads.

B. Message Propagation Speed

Safety services in vehicular services usually have stringent latency requirements. The longer distance the emergency message propagates within a certain interval, the more efficient the broadcast protocol is. To make a fair comparison, we use the default setting $\alpha = 1/2$ in Fig. 6(a)–(c), which means UMBP and BPAB adopt the same partition principle in each iteration, and consequently they get the same length of the final FA and contention level. We then compare the message propagation speed performance between them. From the figures we can observe that UMBP achieves a higher message propagation speed than BPAB at any time instant, which attributes to the following facts. On the one hand, the one-hop delay in BPAB is much longer than that in UMBP as illustrated in Section VI-A, which slows down the propagation speed of emergency messages. On the other hand, a forwarding node within an intersection region (a circular region of radius R/2) in BPAB has to select an intersection forwarder that is more closer to the intersection, which adds to the number of hops. Moreover, the one-hop delay in BPAB is prolonged because the intersection forwarder sequentially selects the forwarding node in each direction. But a forwarding node within an intersection region in UMBP selects a further neighboring node as the forwarding node in each direction simultaneously, which reduces the latency of the emergency message within an intersection area and enables UMBP to disseminate emergency messages quickly. Furthermore, we can also observe that the propagation speed in UMBP goes up firstly and then goes down, while the propagation speed in BPAB decreases with the increase of vehicle density ρ. In UMBP, a further segment will be selected as the final FA when vehicle density ρ increases, but the one-hop delay goes up slowly when vehicle density is low as shown in Fig. 5(a)–(c). Consequently, the propagation speed in UMBP increases at the beginning as shown in Fig. 5(a)–(c). However, when vehicle density continues to increase $eRTS$ or $eCTS$ collisions in the final FA will be incurred, which prolongs the one-hop delay in UMBP, and then the propagation speed gradually goes down. In BPAB, not only candidate forwarding nodes in the final FA but also their neighboring nodes in the message propagation direction contend to access the wireless medium in the CTB replying process, and consequently the propagation speed goes down with the increase of vehicle density.

C. Message Reception Rate

The reliability of an emergency message is another important performance metric for safety related applications, since the loss of an emergency message may induce a terrible accident. Message reception rate is defined as the ratio of the number of vehicles that successfully receive the emergency message to the number of total vehicles, and it is usually utilized to indicate the reliability performance of a broadcast protocol in vehicular networks. Fig. 6(d) shows the comparisons of message reception rate between BPAB and UMBP. From this figure, we can observe that BPAB and UMBP have the approximate message reception rate performance, but both message reception rates of BPAB and UMBP slightly drop when the vehicle density goes up. It is because that both BPAB and UMBP take the reliability issue into account and utilize two-way handshake to protect the transmission of an emergency message, which achieves to

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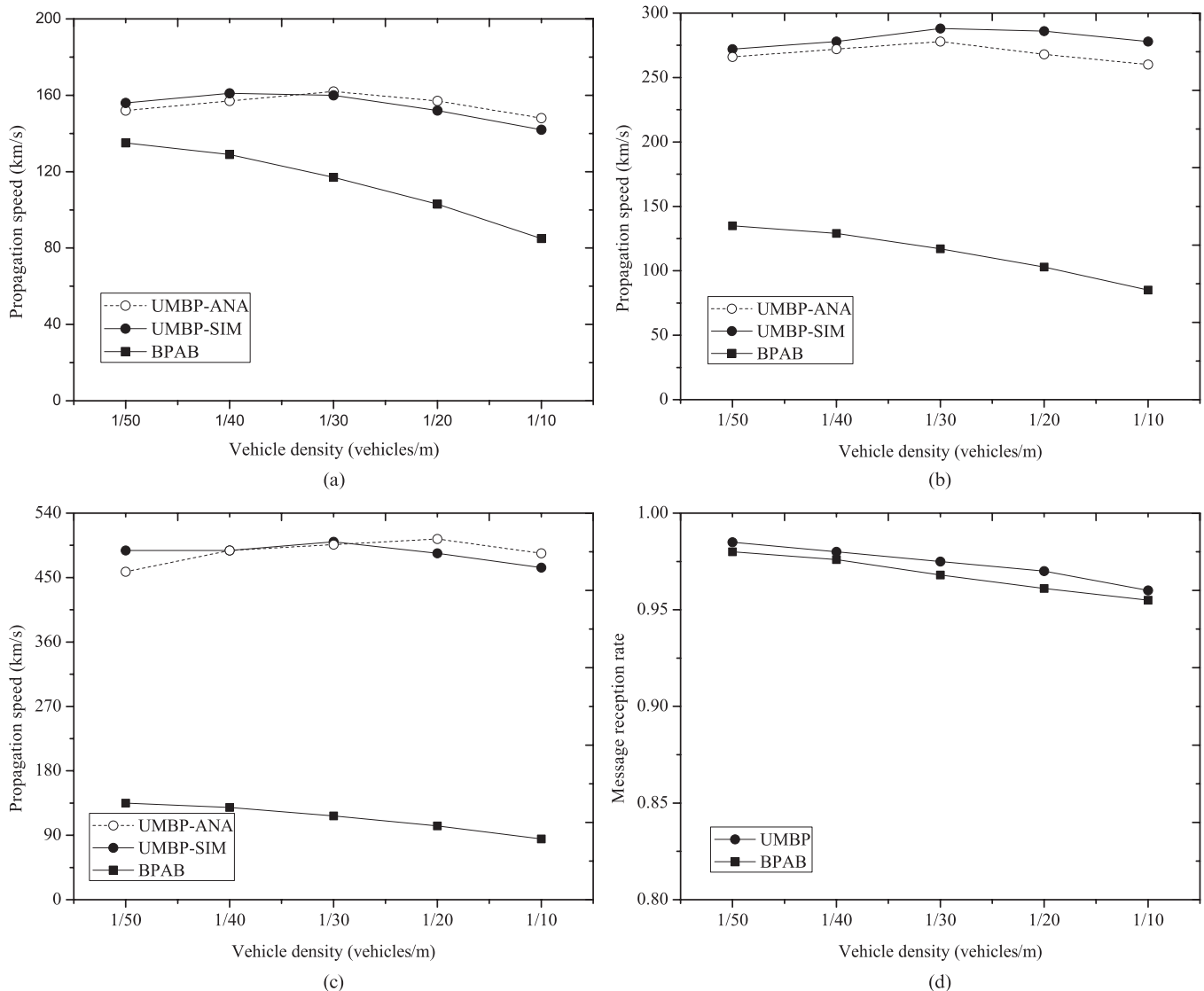

Fig. 6. Performance comparisons between UMBP and BPAB: (a)–(c) propagation speed; (d) message reception rate. (a) The propagation speed in directional broadcast. (b) The propagation speed in bi-directional broadcast. (c) The propagation speed in multi-directional broadcast.

alleviate the hidden terminal problem. As a result, they get the similar reliability performance. However, the hidden terminal problem cannot completely eliminated and becomes serious when vehicle density goes up, which degrades the message reception rate performances of both BPAB and UMBP.

VII. CONCLUSION

In this paper, we have proposed a multi-hop broadcast protocol UMBP for emergency message disseminations in urban vehicular networks. Taking the road layout of the urban transportation system into account, UMBP adopts flexible broadcast strategies according to the positions of the forwarding nodes. At the first hop, bi-directional broadcast or multi-directional broadcast utilizes an efficient forwarding node selection scheme to quickly select a remote forwarding node in each direction,

which enables the emergency message to propagate along different directions. Then, directional broadcast is adopted in the following hops, and a single remote forwarding node is successfully selected by the eRTS/eCTS handshake in each hop, which reduces message redundancy and guarantees message reliability. When the emergency message reaches an intersection area, multi-directional broadcast is adopted, and the forwarding node selection process is simultaneously conducted in multiple road directions. In addition, an analytical model is developed to study the performance of UMBP in terms of one-hop delay and message propagation speed. Analytical and simulation results demonstrate that the proposed UMBP is not only able to disseminate emergency messages quickly, but also successfully reduce message redundancy and enhance message reliability. In our future work, we will adapt the proposed UMBP to support more complex road structure in intelligent transportation system.

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