Multi-Hop Broadcast Protocol in Intermittently Connected Vehicular Networks

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Abstract — there are great challenges in vehicular networks, i.e., continuous connectivity cannot be guaranteed due to interruptions. This paper proposes a novel multi-hop broadcasting protocol with low signaling overhead in vehicular networks with frequent interruptions named as Trinary Partitioned Black-Burst based Broadcast Protocol (3P3B-DTN). The protocol operates without any infrastructure. It has low overhead supporting different Quality of Service (QoS) levels. Both analysis and comprehensive simulations show that the proposed protocol outperforms the bench mark schemes.

Index Terms— Multi-hop Broadcast Protocol, wireless ad hoc network, wireless sensor network, Vehicular Ad Hoc Networks, Intermittently Connected Networks, Land Transportation

I. INTRODUCTION

Vehicular Ad Hoc Networks (VANETs) as one sample of Mobile Ad Hoc Network (MANET) refers to the ad-hoc networks for vehicles to communicate with each other. The current standards include IEEE 802.11p and IEEE P1609.1–4 communication technologies [1-5]. Several applications have been proposed for vehicular networks based on these standards [6-11]. In [6-7], the use of road-map information for ground vehicles tracking is proposed to enhance vehicles' position prediction. In contrast to vehicle detection and tracking, papers [8-9] promote autonomous car navigation using road profile recognition along with a support from GPS. In [10], vehicular remote tolling services are proposed based on communication through vehicular network standards. Apart from these applications, there are many vehicular applications concerning safety. Some examples include emergency message dissemination, adaptive cruise control, and intersection warning systems [11].

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Due to the nature of wireless communications, implementation of any protocols in VANETs poses a number of challenges including: broadcast storm problem, the hidden terminal problem, and frequent interruptions of connections when the underlying network is sparse. In addition, provision of different QoS levels for different broadcast applications is a non-trivial problem. Lack of infrastructure support adds the complexity of the broadcast protocols due to high volume of signaling overhead among the communication peers. High level of media access control (MAC) layer collisions can also have adverse impacts on the efficiency of the protocol due to hidden terminal problem.

Here we summarize the key issues. Most of the existing broadcast protocols in the literature focus on how to select an efficient message forwarder to reduce broadcast delay and optimise network resource usage. To this end, there are some existing techniques, such as black-burst in Urban Multi-hop Broadcast (UMB) [12], contention window in Smart Broadcast (SB) [13], and binary partitioning in Binary-Partition-Assisted Broadcast (BPAB) [14]. These techniques aim to address the challenges broadcasting in ad-hoc networks. However, these solutions are not optimised for sparse networks, where there are frequent interruptions to the connectivity of the network. To address these shortcomings, authors in [18] and [19] propose Distributed Vehicular Broadcast (DV-CAST) [18] and Beaconless Broadcast (BL-CAST) protocols [19] respectively. These solutions demonstrate good performance in term of reliability even when the network is frequently disconnected. However, as DV-CAST operations are based on knowledge of the local topology information, the protocol needs periodic exchange of information among the vehicles. This incurs additional overhead and communication bandwidth resources especially in a large VANET with large numbers of vehicles in the network. BL-CAST, in contrast, takes the network overhead into consideration and operates without additional information exchange between vehicles. Nonetheless, no handshake mechanism is implemented in BL-CAST. As a consequence, this protocol is vulnerable to hidden terminal problem. In addition, the QoS provisions for different applications are not feasible in these aforementioned solutions.

Therefore, this paper proposes a multi-hop broadcast protocol namely Trinary Partition Black Burst based Broadcast Protocol (3P3B-DTN) to overcome in the problems in the existing solutions for both dense and sparse VANETs. The proposed broadcast protocol extends the research work presented in [26], including:

- 1) An effective algorithm for selection of the best message forwarder based on the concept of trinary partitioning;
- 2) A custom request to broadcast / clear to broadcast (*RTB/CTB*) mechanism to provide high packet delivery ratio (PDR), reduce the broadcasting overhead, and mitigate well-known hidden terminal problem in VANETs;

TABLE I
SUMMARY OF THE PROTOCOLS IN THE LITERATURE

Protocols	Communication Type	Deal with Broadcast Storm Problem	Deal with Hidden Terminal Problem	Deal with Disconnected Network Problem	Provide Different QoS	Require Knowledge of Local Topology
UMB	Broadcast	Yes	Yes	No	No	No
SB	Broadcast	Yes	Yes	No	No	No
BPAB	Broadcast	Yes	Yes	No	No	No
FPOR	Unicast	N/A	No	Yes	No	Yes
GeoOpps and GeoDTN+Nav	Unicast	N/A	No	Yes	No	Yes
DV-CAST	Broadcast	Yes	No	Yes	No	Yes
BL-CAST	Broadcast	Yes	No	Yes	No	No
3P3B	Broadcast	Yes	Yes	Yes	Yes	No

3) A mini distributed coordination function (DCF) inter-frame space, named as Mini-DIFS (mini Distributed Inter-Frame Space), mechanism for prioritisation of the transmission of different types of broadcast messages.

Unlike the existing works in the literature and the previously proposed 3P3B [26], 3P3B-DTN is specially designed to operate in a network with frequent interruptions. This key feature of the proposed broadcast protocol enables it to fully function in sparse VANETs, which is a non-trivial challenge. It is very crucial to maintain network reliability at the highest level, especially for safety messaging applications. The proposed adaptive disconnection management shows that it can achieve a significant improvement in term of the communication reliability and message dropping when the network gets interrupted.

Comprehensive simulations have been carried out for performance evaluation of the proposed protocol using OMNeT++ [27]. The proposed 3P3B-DTN is evaluated in term of average packet delivery ratio (PDR), end-to-end delay, and overhead, in both well-connected and interrupted networks on the highway scenarios and compared to benchmark BPAB and DV-CAST protocols. The results confirms that the proposed 3P3B-DTN significantly outperforms the benchmark protocols BPAB and DV-CAST; e.g., by achieving at least 10% and 6% higher delivery rate especially in sparse network scenarios.

The rest of the paper is organized as follows. Section II provides comprehensive review of the state of the art and related work in the literature. Section III gives the details of the proposed 3P3B-DTN. Section IV presents simulation results based performance analysis, and comparisons with the benchmark protocols. Finally, the conclusions of the paper and directions for future research are given in Section V.

II. RELATED WORK

There are a large number of papers existing on the related works in the literature; only the recent relevant and significant ones are summarized here.

Urban Multi-hop Broadcast (UMB) [12]: UMB is a broadcast protocol. It aims to maximize message progress by selecting the furthest vehicle as a forwarder. Request-to-Broadcast/Clear-to-Broadcast (*RTB/CTB*) is implemented to avoid the hidden terminal problem in this scheme. Upon a reception of *RTB*, vehicles broadcast channel jamming signal called black-burst for duration

proportion to distance from the sender. Then, the furthest vehicle that transmits the longest black-burst performs forwarding to avoid the broadcast storm problem. However, the performance analysis of this work indicates relatively high communication latency.

Smart Broadcast (SB) [13]: it is also a broadcast protocol, which aims to maximize message progress and minimize broadcast delay. By manipulating the contention mechanism of IEEE 802.11p standard, it succeeds in providing a shorter average latency compared to UMB. SB divides a communication area into sectors. Vehicles in each sector are assigned different sets of contention time slot called window. The furthest sector from the sender is assigned the shortest contention window; hence, the vehicles in this sector wait for a shorter back-off period before accessing to the communication channel. One of them will become a forwarder for the next communication hop to reduce the impact of the broadcast storm problem. The existing results indicate that SB performs better than UMB in term of average delay. Besides, SB maintains a proper message progress as it implements the same approach as UMB to select the furthest vehicles to forward the message for the next hop. However, due to the back-off process, the latency becomes larger in SB when density and size of network increase, resulting in large performance gap and delay jitter.

Binary-Partition-Assisted Broadcast protocol (BPAB) [14] aims to reduce broadcast delay and make the delay as constant as possible. BPAB maintains a good message progress by selecting the furthest forwarder as well. This protocol deploys a combination of binary partitioning as well as new contention mechanism. The binary partitioning scheme constantly divides the communication area into multiple partitions. Only vehicles in the furthest partition contend with each other during the forwarding phase. Thus, collision rate is reduced and the contention duration is stabilized. It is shown that BPAB demonstrates a good performance in terms of average dissemination speed compared to the other presented protocols.

According to these broadcast protocols, they deal with the broadcast storm problem very well by assigning only one forwarder at the time to rebroadcast messages to the next communication hop. However, they did not take interrupted network problem into account. Therefore, such protocols generally fail to achieve a good performance when the network connection becomes interrupted.

Fixed Point Opportunistic Routing (FPOR) [15]: FPOR proposes a routing protocol based on the estimations of average inter-contact time between nodes. It aims to assure performance of packet delivery in interrupted network; i.e. minimizing packet delivery time. The study also focuses on the routing properties in terms of loop-free forwarding and polynomial convergence.

GeoOpps and *GeoDTN+Nav* [16, 17]: both GeoOpps and GeoDTN+Nav protocols are DTN (Delay Tolerant Network) routing that makes use of Global Positioning Systems (GPS). GPS is assumed to provide location information of each vehicle as well as a suggested path toward a given destination. In addition, the GeoDTN+Nav scheme proposes a Virtual Navigation Interface

framework (VNI) to deal with the different content and data formats obtained from different GPSs. The protocols aims to select a carrier vehicle which is most close to the destination hence can provide quickest packet delivery. Therefore, the preferred carrier vehicle is the one that locates in the suggested path and is geographically closest to the destination.

DV-CAST [18]: DV-CAST keeps updating all vehicles position by periodically sending “hello” message. When a vehicle receives the message, it checks with its neighbour table to see if it is the last vehicle in cluster. Broadcast suppression using the slotted 1-persistence scheme [20] will be applied if the vehicle is not the last vehicle in the cluster. In case that the vehicle is the last vehicle in the cluster, but it is not connected to any other vehicles, the vehicle will hold on the message until it can forward the message to another vehicle in either the opposite or the same movement direction. However, in DV-CAST, the periodic exchange of “hello” message increases the overhead. Decrease the frequency of “hello” messages can reduce overhead but can make higher rate of communication failure due to out-of-date local topology information. In contrast, too many hello messages can make the communication more successful with larger amount of network overhead.

BL-CAST [19]: BL-CAST or Beacon-Less broadcast protocol is designed for message broadcasting in both dense and sparse networks. BL-CAST is low overhead since it does not rely on a periodic exchange of hello messages. BL-CAST implements broadcast suppression in well-connected network as implemented in DV-CAST and applies store-carry-forward in intermittently connected network. The performance shows that BL-CAST outperforms DV-CAST in term of end-to-end delay and packet delivery ratio.

To the best of our knowledge, there is no prior work that deals with all the interrupted network problem, the broadcast storm problem, the hidden terminal problem, and different QoS requirements problem in broadcast communications for highway VANET scenarios as summarized in Table I. The proposed protocol fills this gap by proposing a novel fully distributed and beaconless VANET broadcast protocol namely Trinary Partitioned Black-Burst based Broadcast (3P3B-DTN). Unlike DV-CAST and BPAB, 3P3B-DTN does not require hello messages (knowledge of local topology) as required in DV-CAST and 3P3B-DTN can successfully operate in interrupted network, which cannot be achieved by BPAB. In addition, 3P3B-DTN also provides different QoS for different classes of broadcast messages based on Mini-DIFS concept.

III. 3P3B-DTN SCHEME

This section firstly describes the system model. Then, the proposed 3P3B-DTN scheme is presented with detail.

A. System Model

The system model for vehicular sensor networks is primarily considered in a highway environment with no support of centralized infrastructure units, such as Road Side Units (RSU). Vehicles can form ad hoc network without need of cluster heads,

gateway vehicles, and periodic information exchange, such as hello messages. An opportunistic use of vehicles travelling in reverse traffic is also taken into account to extend forwarding possibility. Global Positioning System (GPS) is assumed to be equipped on all the vehicles to allow them to instantly learn their positions as well as provide time synchronization among the vehicles [12-19]. Vehicles are also equipped with On-Board communication Unit (OBU) and sensors for abnormality detection. All vehicles can communicate directly to each other via IEEE802.11p interface as long as they are in the range of point-to-point connections. Unlike some existing works [21, 22] that require a modification of communication antennas, 3P3B-DTN can fully operate using the traditional omnidirectional antenna with a consideration of signal interferences and noises, which allows the vehicles to directly communicate with each other, when the value of Signal-to-Interference-plus-Noise Ratio ($SINR$) is above the minimum $SINR$ value for acceptable signal quality ($SINR_{min}$) [23, 24].

B. Overview of 3P3B-DTN

3P3B-DTN is proposed to provide reliable message broadcasting in vehicular communications even in frequently disrupted networks. 3P3B-DTN employs three main mechanisms: a mini-DIFS mechanism; a trinary partition scheme; and a store-carry-forward mechanism.

1) Mini-DIFS

3P3B-DTN introduces mini-DIFS [26] to provide priority scheme for time-critical messages (high priority messages) and fast channel access with less contention.

The standard DIFS duration is divided into a number of mini-slots. A high priority message waits only for a small numbers of mini-slots before broadcasting. Therefore, the high priority messages will always have a preemptive channel access and be broadcasted faster than other messages. Equations (1) and (2) show how to calculate the length of mini-slot (l) and the number of mini-slots (w).

$$l = 2\rho + t_{switch} \quad (1)$$

$$w = \left\lceil \frac{T_{DIFS} - T_{SIFS}}{l} \right\rceil \quad (2)$$

where ρ is the maximum channel propagation delay in the transmission range. t_{switch} is time duration required by a transceiver to switch between transmission and reception modes. As shown in Equation (2), the minimum value of mini-slot DIFS is always greater than SIFS (Short Inter-Frame Space). Therefore, 3P3B-DTN is fully compatible with IEEE802.11p; the standard of Wireless Access in Vehicular Environments (WAVE).

After a mini-slot DIFS has expired, the sender broadcasts a Request-to-Broadcast (*RTB*). Then it waits for a Clear-to-Broadcast (*CTB*). The *RTB/CTB* is used to alleviate the hidden terminal problem in wireless communications, reduce the broadcast storm problem, and reduce network overhead. When *RTB* is received, all receivers simultaneously broadcast black-burst (B_A); a burst of jamming signals. The sender can imply a present of vehicles based on the received B_A . Then, the forwarder selection will be started using the trinary partitioning mechanism. Otherwise, the sender will restart the whole process for n times, where n is the trinary partitioning threshold. If there is no B_A received during all n trials, the sender assumes a disconnected network and starts store-carry-forward mechanism. The trinary partitioning threshold is a factor of vehicle density, communication traffic load, and channel condition. Therefore, obtaining an optimal value the trinary partitioning threshold needs further investigation and is out of the scope of this paper.

Fig. 1 Trinary partition procedure with 3 iterations ($N=3$) [26]

2) Trinary Partitioning

The trinary partitioning mechanism [26] aims to select only one message forwarder for each communication hop and reduce contention jitter. Only the furthest possible vehicle will forward messages to the next communication hop so that 3P3B-DTN achieves the largest message progress and avoids broadcast storm problem [25, 32].

Trinary partitioning is a modification of the binary partition proposed in BPAB [14]. In [26], the trinary partition has been proved to be the optimal among any n -nary partitioning mechanisms for message broadcasting in VANETs. Figure 1 illustrates how trinary partitioning operates in three iterations ($N=3$).

After the end of B_A period during the first iteration, all receivers divide the communication range (r) of the sender into three partitions (inner, center, and outer partitions) and determine their partitions. The inner partition is defined as the closest partition

to the sender, while the outer partition is the farthest partition from the sender. The vehicles of the outer partition are the most preferable as it can maximize the dissemination distance and shorten message broadcasting time. In the figure, since there are 10 vehicles in the outer partition during the first iteration, these vehicles simultaneously broadcast black-burst during the first time slot. Once the rest of the vehicles hear the black-burst, they turn to idle, because they learn that there are better forwarder candidates in the other partition. Only one time slot has been spent during the first iteration and the width of the focused partition is reduced to $r/3$.

During the second iteration, the vehicles in the focused partition re-divide such partition into three sub-partitions. The first time slot is free since there is no vehicle in the outer partition, which could broadcast black-burst in the first time slot. All four vehicles in the middle partition will broadcast black-burst simultaneously during the second time slot. The rest of vehicles imply the better forwarder candidates and turn to idle. The second iteration consumes two more time slots and the width of the focused partition is reduced down to $r/3^2$ (or $r/9$)

Fig. 2 Performance evaluation of the previously presented 3P3B in term of PDR

Fig. 3 Performance evaluation of the previously proposed 3P3B in term of end-to-end delay

A similar operation has been done during the third iteration. The vehicles in the focused partition re-divide their partition into three sub-partitions. No vehicle has been seen in both outer and middle partitions, so there is no black-burst broadcasted during the first two time slots. All four vehicles in the inner partition imply that they are the best candidates of this iteration without broadcasting the black-burst. Therefore, the third iteration consumes only two more time slots and the final focused partition has only $r/3^3$ in width. Totally, only five time slots are spent during trinary partitioning process.

In case that there are several vehicles in the final focused partition, these vehicles will randomly pick back-off values from the available contention window (cw). A vehicle whose back-off expires first broadcasts a *CTB* packet and becomes the selected forwarder. Upon the receipt of *CTB*, the sender waits for a SIFS period then broadcasts a message to all vehicles but only the forwarder will re-broadcast this message to the next communication hop.

Fig. 4 Overview flowchart of 3P3B-DTN

3) Store-Carry-Forward

As presented in [26], 3P3B is previously designed for dissemination of time-critical time critical message in only well-connected VANETs. Without taking any interruption into account, the previously proposed 3P3B fail to provide a successful

communication when interrupted. As shown in Figures 2 and 3, in the connected VANETs, 3P3B is highly reliable with more than 98% of PDR, and low end-to-end delay of about 11ms. In a dense network, most of the communication is successful for the reason that the network is well connected. Occasional failures are nonetheless occur due to collisions that can be corrected by a retransmission.

However, the performance of message broadcasting degrades significantly when network interrupted. For example, it can be seen from Figure 2, PDR notably degrades when the density of the nodes is low. This is due to the fact that the previously proposed 3P3B as well as the other existing broadcast protocols (i.e. BPAB, SB, and UMB) do not have an inherent solution for frequent network disruptions. Therefore, messages are dropped after a certain number of transmission trials. Motivated by this fact, 3P3B has been enhanced to 3P3B-DTN for an effective message broadcasting especially in disrupted networks, which is crucial in VANETs.

Therefore, in intermittently connected VANETs, instead of discarding messages after n trials, the 3P3B-DTN stores and carries the messages along the vehicle's movement path, then forwards the messages, when the vehicle finds a new connection. This store-carry-forward mechanism efficiently helps to increase PDR.

The flow chart of the 3P3B-DTN is illustrated in Figure 4. Whenever the broadcast fails up to n times; i.e. the number of retransmission attempts is over the rebroadcasting threshold, the 3P3B-DTN assumes an intermittently connected network. Then, the message forwarder switches from a broadcasting mode to a holding mode. The message forwarder carries the messages for a maximum period of τ seconds, before searching for a new connection using *RTB* retransmission. Because message rebroadcasting time is relatively smaller than the carrying time, it is recommended to rebroadcast the messages rather than carrying them through, whenever there is a chance, i.e. a new connection is founded. Therefore, the maximum carrying time before rebroadcasting, τ , is given by

$$\tau = \frac{r}{2V_{Max}}, \quad (3)$$

where r is the communication range of vehicles and V_{Max} is the maximum vehicle speed limit on the highway.

Equation (3) can be illustrated in more detail in Figure 5. At time t , both the forwarder and the receiver are not in the communication range of each other. After a period of τ , they have a new contact, which allows the rebroadcast of the messages. If the forwarder waits longer than the maximum carrying time, τ , it may miss a chance to rebroadcast the message and hence has to carry it through, which makes the delay larger.

Fig. 5 Maximum carrying time

The *RTB* will be periodically transmitted until a new connectivity is founded by receiving a B_A packet, which is a black burst packet sent by vehicles, who receive the *RTB* from the forwarder. Then, the message forwarder switches back to the broadcasting mode and start the trinary partitioning to select the furthest next-hop forwarder. The message will be dropped, when its life time is expired; i.e., the information of the message is out-of-date and no longer useful.

IV. PERFORMANCE EVALUATION RESULTS

In this section, a comprehensive set of simulations has been carried out to evaluate the performance of the proposed protocol and compare it to that of the existing benchmark protocols.

It is important to note that main focus of the paper is to enhance vehicular communications in intermittently connected networks where the vehicular network cannot be formed properly due to the limited number of vehicles. Therefore, the paper considers only a scenario containing low to medium traffic conditions, which is a highway environment. Consequently, the city scenario with high traffic condition will not be considered in the paper, since it does not reflect the problem the paper is focusing on.

A. Description of the Simulation Model

The comprehensive performance evaluation is based on the simulation package OMNeT++ [27]. The 3P3B-DTN is evaluated in term of average packet delivery ratio (PDR), end-to-end delay, and overhead, in both well-connected and intermittently connected networks on the highway environment. The average PDR is defined as the average number of packets received by all vehicles divided by the total number of packets generated and sent by all transmitters, while the average end-to-end delay is the average end-to-end delay of all first-time received packets by all vehicles in the network, and the average overhead is the average ratio between the total size of all control packets, such as *RTB* packets, and the total size of all broadcasted and rebroadcasted data packets in the network.

The 3P3B-DTN is evaluated and compared against the performance of the benchmark broadcast protocols namely BPAB [14] and DV-CAST [18]. There is no performance comparison against unicast routing protocols because the protocols are different and incomparable with broadcast protocols; i.e. there is no specific destination.

Fig. 6 Simulation scenario

The simulation scenario is illustrated in Figure 6. The simulation area is set to a straight 40km-long highway, where the vehicles are randomly placed in the simulated highway. All vehicles move with average speed varied from 60 to 100 km/hr. The number of transmitters is varied from 1 to 10 transmitters to provide different packet densities in the network, where the transmission rate of each transmitter is set to 1 message/second. There are 10 anchor vehicles placed at every 2 km following the transmitters. Therefore, the anchor vehicles cover the distance up to 20 km from the transmitters. It is note that all anchor vehicles only act as sink nodes to measure performance of 3P3B-DTN at different distances from the transmitters. They do not participate in storing, carrying, or forwarding any messages at all. To keep the distance between each anchor vehicle and transmitters constant, all of them move with the same average speed of 80 km/hr.

The performance evaluation is focused on both intermittently connected and well-connected VANETs. It is noted that the network is considered as the intermittently-connected when the vehicle density is lower than 13 vehicles per km as previously shown in Figure 2. Therefore, in the simulations, the vehicle density is varied from 0 to 60 vehicles per km to cover both scenarios. The maximum speed limit on the highway is set to be 100 km/hr [28]. The maximum carrying time, τ , of the messages

in the message holding mode is set as 16.21 seconds according to the calculation in Equation (3). Therefore, in order to observe the impact of the carrying time, the carrying time is set to 2 and 16 seconds in the simulations. The fading model used in the simulation is Rayleigh, which is one of the well-accepted fading models for vehicular communications [29, 30, 33]. The Rayleigh model generally depends on a deterministic model; i.e. free space or two-ray ground model, to which a certain variation is applied as shown in Equation (4).

$$Pr_{\text{Rayleigh}}(d) \approx \text{Rayleigh}(Pr_{\text{det}}(d)) \quad (4)$$

In this paper, the deterministic transmission power is set to 20 mW according to the standard. All other default parameter values used in the simulations are summarized in Table II.

TABLE II
DEFAULT PARAMETER VALUES OF THE SIMULATIONS

Parameters	Default Values
Standards	IEEE 802.11p/ IEEE1609.4
Communication Frequency	5.9 GHz
Propagation Model	Free Space
Fading Model	Rayleigh Model
Transmission Power	20 mW
Sensitivity	-94dBm
Bit Rate	18 Mbps
Message Size	500 Bytes
RTB Packet Size	20 Bytes
CTB Packet Size	14 Bytes
Slot Time	13 μ s
DIFS	58 μ s
SIFS	32 μ s
Max Channel-Propagation Delay	2 μ s
Transceiver's Switching Time	1 μ s
Maximum Speed Limit on the Highway	100 km/hr
Message Carrying Time in the holding mode	2 and 16s
Number of Transmitters	1, 5, and 10
Vehicle Density	0- 60 vehicle/km

B. Validation of the Simulation Results

The proposed analytical model in [31] is used to validate the results from our comprehensive simulation in term of the average PDR. There are two cases of message broadcasting in VANETs; the tradition broadcast scheme and a broadcast scheme with Store-Carry-Forward mechanism. In the first case, messages will be broadcasted only when there is a continuous end-to-end connectivity between source and destination vehicles. Otherwise, the messages will be discarded. For the second case, the messages will be broadcasted when there is a continuous end-to-end connectivity and they will be carried along the vehicle's movement path when no connection is founded. The messages will then be rebroadcasted to other vehicles as soon as a new connection has been founded. Therefore, the second case can yield higher PDR.

According to [31], the PDR of the traditional broadcast, $P_{broadcast}$, can be determined as

$$P_{broadcast} = (1 - e^{-2\lambda r})^{2\lambda L - 1}, \quad (5)$$

where λ is the density of vehicles and L is length of the highway.

In addition, the PDR based on the store-carry-forward mechanism, $P_{store-carry-forward}$, can also be calculated using the following equations.

$$P_{store-carry-forward} = \sum_{j=0}^{N-1} P_{TooFar,j} \cdot P_{reconnect,j} \quad (6)$$

$$P_{TooFar,j} = \binom{\lambda L - 1}{j} (e^{-\lambda r})^j (1 - e^{-\lambda r})^{\lambda L - 1 - j} \quad (7)$$

$$P_{reconnect,j} = (1 - \sum_{k=1}^{\lceil L/r \rceil - 1} (e^{-\lambda kr} - e^{-\lambda(k+1)r}) \left(\sum_{i=0}^{k-1} \frac{(\lambda ir)^i}{i!} e^{-\lambda ir} \right))^j \quad (8)$$

where N is the total number of vehicles and r is the communication range.

Fig. 7 The validation in term of the PDR of both the traditional broadcast scheme and the broadcast scheme with store-carry-forward mechanism

The validation in term of the PDR of both the traditional broadcast scheme and the broadcast scheme with store-carry-forward mechanism in a 20 km highway and 450 m communication range with the vehicle density varied from 0 to 60 vehicles per km is shown in Figure 7. Results of the simulation using OMNeT++, which are represented in marks, are validated against results of the analytical model, which are represented in lines. Therefore, the simulation results are validated since of both results of the analytical model and the simulation are very close.

In Figure 7, it is also observed that the broadcast with store-carry-forward mechanism gives higher packet delivery ratio than the traditional broadcast at the same vehicle density. This is because instead of dropping messages when there is no continuous end-to-end connectivity, most of such messages are rescued by the store-carry-forward mechanism and successfully delivered to following vehicles after waiting for an additional period of time.

Furthermore, both schemes achieves higher packet delivery ratio, when the vehicle density is higher. Due to the higher density of vehicles, the network becomes well connected and hence this increases the successful packet delivery ratio of the network.

C. Simulation-Based Performance Evaluations of 3P3B-DTN

1) Single-Transmitter Scenario

Single transmitter scenario means that there is only one transmitter starting transmitting urgent messages in the network which reflect low packet density scenario. In fact, this scenario seems to be a common and realistic case since most of the time there will be only one accident occur in a particular area. However, considering the worst case scenario, in the following subsection, the number of the transmitters is increased to 5 and 10 transmitters, respectively.

Figure 8 illustrates the performance comparison in term of average PDR of 3P3B-DTN and BPAB of different dissemination distances and different values of vehicle densities. The carrying time in this case is set to 2 seconds. At low vehicle density; i.e.,

(a) Vehicle density of 1.67 vehicle/km

(b) Vehicle density of 3.33 vehicle/km

(c) Vehicle density of 5.00 vehicle/km

(d) Vehicle density of 6.67 vehicle/km

(e) Vehicle density of 8.33 vehicle/km

(f) Vehicle density of 10.00 vehicle/km

Fig. 8 Performance comparison in term of PDR of 3P3B-DTN and BPAB of different dissemination distances and different values of vehicle densities where there is one transmitter in the network

Therefore, it is recommended to implement a shorter carrying time during the message holding mode to gain a high reliability with lower delay. For example, 2-second carrying time experiences much lower end-to-end delay compared to the carrying time of 16 seconds while giving approximately the same level of PDR as observed in Figure 9. However, the delays in both cases are still far lower than message life time, which normally lasts for hours until the accident has been removed from the highway.

In addition, when the density of vehicles increases, the delay decreases, because the network becomes better connected and hence most of the messages can be successfully broadcasted without need of the store-carry-forward mechanism. Figure 9(c) shows a performance comparison in term of average overhead of the dissemination distances within the first 20 km of BPAB, DV-CAST, and 3P3B-DTN and with different values of the carrying times. It can be observed that BPAB have lower overhead than 3P3B-DTN at low vehicle density but a bit higher overhead when the vehicle density increases. Due to the packet store-carry-forward mechanism at low vehicle density, 3P3B-DTN retransmits *RTB* packets several times until it finds a new connection. This leads to high number of control packet (*RTB*) transmissions and overhead.

(a) Performance comparison in term of average PDR

(b) Performance comparison in term of average end-to-end delay

(c) Performance comparison in term of average overhead

Fig. 9 Performance comparison in term of average PDR, average end-to-end delay, and average overhead of the dissemination distance within 20 km of 3P3B-DTN, DV-CAST, and BPAB where there is one transmitter in the network

In addition, 2-second carrying time faces higher average overhead compared to that of 16-second carrying time. Because for the shorter carrying time, 3P3B-DTN retransmits *RTB* more often to quickly find a new connection, this short carrying time at the same time can cause higher overhead as a side effect if it cannot find the new connection. However, due to the 20-Byte *RTB* packets are relatively small compared to the 500-Byte data packets, this overhead does not make a serious impact on the network performance.

(a) Performance comparison in term of average PDR

(b) Performance comparison in term of average end-to-end delay

(c) Performance comparison in term of average overhead

Fig. 10 Performance comparison in term of average PDR, average end-to-end delay, and average overhead of the dissemination distance within 20 km of 3P3B-DTN with different carrying times where there are 5 transmitters in the network

(a) Performance comparison in term of average PDR

(b) Performance comparison in term of average end-to-end delay

(c) Performance comparison in term of average overhead

Fig. 11 Performance comparison in term of average PDR, average end-to-end delay, and average overhead of the dissemination distance within 20 km of 3P3B-DTN with different carrying times where there are 10 transmitters in the network

By comparing to the overhead of DV-CAST, 3P3B-DTN experiences far lower overhead. DV-CAST mainly relies on hello messages for broadcasting and the amount of hello messages is directly related to network density. The overhead of DV-CAST, therefore, increases linearly as the network size increases, while the overhead of 3P3B-DTN is much more constant regardless the network size.

2) Multiple-Transmitter Scenario

Figures 10(a) and 11(a) illustrate the further performance evaluation in term of average PDR of the dissemination distance within 20 km of 3P3B-DTN with different carrying times where there are 5 and 10 transmitters in the network. The similar results can be observed here. 3P3B-DTN is able to maintain high PDR regardless the packet density. Both 2-second and 16-second carrying times also give very close results in term of the communication reliability similarly to the results of the only one transmitter.

A performance evaluation in term of end-to-end delay can be observed from Figures 10(b) and 11(b). The figures show the performance comparison in term of average end-to-end delay of the dissemination distance within 20 km of with different carrying times where there are 5 and 10 transmitters in the network. It can be seen that the 16-second carrying time experiences much higher delay compared to the 2-second carrying time in both figures. In case of the higher carrying time, forwarders normally carry messages for longer time without trying to search for a new contact. Thus, it makes the delay larger. In addition, the higher number of transmitters in the network, which reflects the higher packet density, causes higher end-to-end delay due to higher rate of channel access contention and packet collision.

Figures 10(c) and 11(c) show the performance comparison in term of average overhead of the dissemination distance within 20 km of 3P3B-DTN with different carrying times where there are 5 and 10 transmitters in the network. 3P3B-DTN with 2-second carrying time experiences the higher overhead due to more frequent transmissions of *RTB* packets. However, such overhead is considered insignificant, because the PDR of the data packet can be maintained at high value as previously presented.

V. CONCLUSION

This paper proposes a complete solution for broadcasting in vehicular sensor networks, namely 3P3B-DTN. This solution solves the broadcast storm problem, the hidden terminal problem, and service differentiation in intermittently-connected VANETs altogether. The proposed mini-DIFS and trinary partitioning mechanisms implemented in 3P3B-DTN efficiently provide priority scheme for high priority messages, selection of the furthest possible message forwarder to solve the broadcast storm and the hidden terminal problems, and reduction of contention jitter. In addition, the store-carry-forward mechanism is introduced to deal with frequent network disconnections in sparse VANETs. Comprehensive performance analysis and simulation results show that the proposed 3P3B-DTN outperforms the referenced benchmark protocols BPAB and DV-CAST in term of the PDR; e.g., at least 10% and 6% higher delivery rate especially at low vehicle density. The overall average delay of 3P3B-DTN is also lower than the referenced benchmark protocols as well, when the lost and dropped packets are taken into the comparison. The overhead of 3P3B-DTN is significantly lower, compared to DV-CAST. Nonetheless, the overhead of the proposed protocol is slightly higher than BPAB due to introduction of the carry and forward mechanism. Therefore, 3P3B-DTN becomes the current optimal solution when compared against alternative referenced benchmark protocols evaluated in this paper.

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Multi-Hop Broadcast Protocol in Intermittently Connected Vehicular Networks

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Abstract—there are great challenges in vehicular networks, i.e., continuous connectivity cannot be guaranteed due to interruptions. This paper proposes a novel multi-hop broadcasting protocol with low signaling overhead in vehicular networks with frequent interruptions named as Trinary Partitioned Black-Burst based Broadcast Protocol (3P3B-DTN). The protocol operates without any infrastructure. It has low overhead supporting different Quality of Service (QoS) levels. Both analysis and comprehensive simulations show that the proposed protocol outperforms the bench mark schemes.

Index Terms— Multi-hop Broadcast Protocol, wireless ad hoc network, wireless sensor network, Vehicular Ad Hoc Networks, Intermittently Connected Networks, Land Transportation

I. INTRODUCTION

Vehicular Ad Hoc Networks (VANETs) as one sample of Mobile Ad Hoc Network (MANET) refers to the ad-hoc networks for vehicles to communicate with each other. The current standards include IEEE 802.11p and IEEE P1609.1–4 communication technologies [1–5]. Several applications have been proposed for vehicular networks based on these standards [6–11]. In [6–7], the use of road-map information for ground vehicles tracking is proposed to enhance vehicles' position prediction. In contrast to vehicle detection and tracking, papers [8–9] promote autonomous car navigation using road profile recognition along with a support from GPS. In [10], vehicular remote tolling services are proposed based on communication through vehicular network standards. Apart from these applications, there are many vehicular applications concerning safety. Some examples include emergency message dissemination, adaptive cruise control, and intersection warning systems [11].

Due to the nature of wireless communications, implementation of any protocols in VANETs poses a number of challenges including: broadcast storm problem, the hidden terminal problem, and frequent interruptions of connections when the underlying network is sparse. In addition, provision of different QoS levels for different broadcast applications is a non-trivial problem. Lack of infrastructure support adds the complexity of the broadcast protocols due to high volume of signaling overhead among the communication peers. High level of media access control (MAC) layer collisions can also

have adverse impacts on the efficiency of the protocol due to hidden terminal problem.

Here we summarize the key issues. Most of the existing broadcast protocols in the literature focus on how to select an efficient message forwarder to reduce broadcast delay and optimise network resource usage. To this end, there are some existing techniques, such as black-burst in Urban Multi-hop Broadcast (UMB) [12], contention window in Smart Broadcast (SB) [13], and binary partitioning in Binary-Partition-Assisted Broadcast (BPAB) [14]. These techniques aim to address the challenges broadcasting in ad-hoc networks. However, these solutions are not optimised for sparse networks, where there are frequent interruptions to the connectivity of the network. To address these shortcomings, authors in [18] and [19] propose Distributed Vehicular Broadcast (DV-CAST) [18] and Beaconless Broadcast (BL-CAST) protocols [19] respectively. These solutions demonstrate good performance in term of reliability even when the network is frequently disconnected. However, as DV-CAST operations are based on knowledge of the local topology information, the protocol needs periodic exchange of information among the vehicles. This incurs additional overhead and communication bandwidth resources especially in a large VANET with large numbers of vehicles in the network. BL-CAST, in contrast, takes the network overhead into consideration and operates without additional information exchange between vehicles. Nonetheless, no handshake mechanism is implemented in BL-CAST. As a consequence, this protocol is vulnerable to hidden terminal problem. In addition, the QoS provisions for different applications are not feasible in these aforementioned solutions.

Therefore, this paper proposes a multi-hop broadcast protocol namely Trinary Partition Black Burst based Broadcast Protocol (3P3B-DTN) to overcome in the problems in the existing solutions for both dense and sparse VANETs. The proposed broadcast protocol extends the research work presented in [26], including:

- 1) An effective algorithm for selection of the best message forwarder based on the concept of trinary partitioning;
- 2) A custom request to broadcast / clear to broadcast (RTB/CTB) mechanism to provide high packet delivery ratio (PDR), reduce the broadcasting overhead, and mitigate well-known hidden terminal problem in VANETs;

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TABLE I
SUMMARY OF THE PROTOCOLS IN THE LITERATURE

Protocols	Communication Type	Deal with Broadcast Storm Problem	Deal with Hidden Terminal Problem	Deal with Disconnected Network Problem	Provide Different QoS	Require Knowledge of Local Topology
UMB	Broadcast	Yes	Yes	No	No	No
SB	Broadcast	Yes	Yes	No	No	No
BPAB	Broadcast	Yes	Yes	No	No	No
FPOR	Unicast	N/A	No	Yes	No	Yes
GeoOpps and GeoDTN+Nav	Unicast	N/A	No	Yes	No	Yes
DV-CAST	Broadcast	Yes	No	Yes	No	Yes
BL-CAST	Broadcast	Yes	No	Yes	No	No
3P3B	Broadcast	Yes	Yes	Yes	Yes	No

3) A mini distributed coordination function (DCF) inter-frame space, named as Mini-DIFS (mini Distributed Inter-Frame Space), mechanism for prioritisation of the transmission of different types of broadcast messages.

Unlike the existing works in the literature and the previously proposed 3P3B [26], 3P3B-DTN is specially designed to operate in a network with frequent interruptions. This key feature of the proposed broadcast protocol enables it to fully function in sparse VANETs, which is a non-trivial challenge. It is very crucial to maintain network reliability at the highest level, especially for safety messaging applications. The proposed adaptive disconnection management shows that it can achieve a significant improvement in term of the communication reliability and message dropping when the network gets interrupted.

Comprehensive simulations have been carried out for performance evaluation of the proposed protocol using OMNeT++ [27]. The proposed 3P3B-DTN is evaluated in term of average packet delivery ratio (PDR), end-to-end delay, and overhead, in both well-connected and interrupted networks on the highway scenarios and compared to benchmark BPAB and DV-CAST protocols. The results confirms that the proposed 3P3B-DTN significantly outperforms the benchmark protocols BPAB and DV-CAST; e.g., by achieving at least 10% and 6% higher delivery rate especially in sparse network scenarios.

The rest of the paper is organized as follows. Section II provides comprehensive review of the state of the art and related work in the literature. Section III gives the details of the proposed 3P3B-DTN. Section IV presents simulation results based performance analysis, and comparisons with the benchmark protocols. Finally, the conclusions of the paper and directions for future research are given in Section V.

II. RELATED WORK

There are a large number of papers existing on the related works in the literature; only the recent relevant and significant ones are summarized here.

Urban Multi-hop Broadcast (UMB) [12]: UMB is a broadcast protocol. It aims to maximize message progress by selecting the furthest vehicle as a forwarder. Request-to-Broadcast/Clear-to-Broadcast (*RTB/CTB*) is implemented to avoid the hidden terminal problem in this scheme. Upon a reception of *RTB*, vehicles broadcast channel jamming signal called black-burst for duration proportion to distance from the sender. Then, the furthest vehicle that transmits the longest

black-burst performs forwarding to avoid the broadcast storm problem. However, the performance analysis of this work indicates relatively high communication latency.

Smart Broadcast (SB) [13]: it is also a broadcast protocol, which aims to maximize message progress and minimize broadcast delay. By manipulating the contention mechanism of IEEE 802.11p standard, it succeeds in providing a shorter average latency compared to UMB. SB divides a communication area into sectors. Vehicles in each sector are assigned different sets of contention time slot called window. The furthest sector from the sender is assigned the shortest contention widow; hence, the vehicles in this sector wait for a shorter back-off period before accessing to the communication channel. One of them will become a forwarder for the next communication hop to reduce the impact of the broadcast storm problem. The existing results indicate that SB performs better than UMB in term of average delay. Besides, SB maintains a proper message progress as it implements the same approach as UMB to select the furthest vehicles to forward the message for the next hop. However, due to the back-off process, the latency becomes larger in SB when density and size of network increase, resulting in large performance gap and delay jitter.

Binary-Partition-Assisted Broadcast protocol (BPAB) [14] aims to reduce broadcast delay and make the delay as constant as possible. BPAB maintains a good message progress by selecting the furthest forwarder as well. This protocol deploys a combination of binary partitioning as well as new contention mechanism. The binary partitioning scheme constantly divides the communication area into multiple partitions. Only vehicles in the furthest partition contend with each other during the forwarding phase. Thus, collision rate is reduced and the contention duration is stabilized. It is shown that BPAB demonstrates a good performance in terms of average dissemination speed compared to the other presented protocols.

According to these broadcast protocols, they deal with the broadcast storm problem very well by assigning only one forwarder at the time to rebroadcast messages to the next communication hop. However, they did not take interrupted network problem into account. Therefore, such protocols generally fail to achieve a good performance when the network connection becomes interrupted.

Fixed Point Opportunistic Routing (FPOR) [15]: FPOR proposes a routing protocol based on the estimations of

average inter-contact time between nodes. It aims to assure performance of packet delivery in interrupted network; i.e. minimizing packet delivery time. The study also focuses on the routing properties in terms of loop-free forwarding and polynomial convergence.

GeOpps and *GeoDTN+Nav* [16, 17]: both *GeOpps* and *GeoDTN+Nav* protocols are DTN (Delay Tolerant Network) routing that makes use of Global Positioning Systems (GPS). GPS is assumed to provide location information of each vehicle as well as a suggested path toward a given destination. In addition, the *GeoDTN+Nav* scheme proposes a Virtual Navigation Interface framework (VNI) to deal with the different content and data formats obtained from different GPSs. The protocols aims to select a carrier vehicle which is most close to the destination hence can provide quickest packet delivery. Therefore, the preferred carrier vehicle is the one that locates in the suggested path and is geographically closest to the destination.

DV-CAST [18]: *DV-CAST* keeps updating all vehicles position by periodically sending “hello” message. When a vehicle receives the message, it checks with its neighbour table to see if it is the last vehicle in cluster. Broadcast suppression using the slotted 1-persistence scheme [20] will be applied if the vehicle is not the last vehicle in the cluster. In case that the vehicle is the last vehicle in the cluster, but it is not connected to any other vehicles, the vehicle will hold on the message until it can forward the message to another vehicle in either the opposite or the same movement direction. However, in *DV-CAST*, the periodic exchange of “hello” message increases the overhead. Decrease the frequency of “hello” messages can reduce overhead but can make higher rate of communication failure due to out-of-date local topology information. In contrast, too many hello messages can make the communication more successful with larger amount of network overhead.

BL-CAST [19]: *BL-CAST* or Beacon-Less broadcast protocol is designed for message broadcasting in both dense and sparse networks. *BL-CAST* is low overhead since it does not rely on a periodic exchange of hello messages. *BL-CAST* implements broadcast suppression in well-connected network as implemented in *DV-CAST* and applies store-carry-forward in intermittently connected network. The performance shows that *BL-CAST* outperforms *DV-CAST* in term of end-to-end delay and packet delivery ratio.

To the best of our knowledge, there is no prior work that deals with all the interrupted network problem, the broadcast storm problem, the hidden terminal problem, and different QoS requirements problem in broadcast communications for highway VANET scenarios as summarized in Table I. The proposed protocol fills this gap by proposing a novel fully distributed and beaconless VANET broadcast protocol namely Trinary Partitioned Black-Burst based Broadcast (3P3B-DTN). Unlike *DV-CAST* and *BPAB*, 3P3B-DTN does not require hello messages (knowledge of local topology) as required in *DV-CAST* and 3P3B-DTN can successfully operate in interrupted network, which cannot be achieved by *BPAB*. In addition, 3P3B-DTN also provides different QoS

for different classes of broadcast messages based on Mini-DIFS concept.

III. 3P3B-DTN SCHEME

This section firstly describes the system model. Then, the proposed 3P3B-DTN scheme is presented with detail.

A. System Model

The system model for vehicular sensor networks is primarily considered in a highway environment with no support of centralized infrastructure units, such as Road Side Units (RSU). Vehicles can form ad hoc network without need of cluster heads, gateway vehicles, and periodic information exchange, such as hello messages. An opportunistic use of vehicles travelling in reverse traffic is also taken into account to extend forwarding possibility. Global Positioning System (GPS) is assumed to be equipped on all the vehicles to allow them to instantly learn their positions as well as provide time synchronization among the vehicles [12-19]. Vehicles are also equipped with On-Board communication Unit (OBU) and sensors for abnormality detection. All vehicles can communicate directly to each other via IEEE802.11p interface as long as they are in the range of point-to-point connections. Unlike some existing works [21, 22] that require a modification of communication antennas, 3P3B-DTN can fully operate using the traditional omnidirectional antenna with a consideration of signal interferences and noises, which allows the vehicles to directly communicate with each other, when the value of Signal-to-Interference-plus-Noise Ratio (*SINR*) is above the minimum *SINR* value for acceptable signal quality (*SINR_{min}*) [23, 24].

B. Overview of 3P3B-DTN

3P3B-DTN is proposed to provide reliable message broadcasting in vehicular communications even in frequently disrupted networks. 3P3B-DTN employs three main mechanisms: a mini-DIFS mechanism; a trinary partition scheme; and a store-carry-forward mechanism.

1) Mini-DIFS

3P3B-DTN introduces mini-DIFS [26] to provide priority scheme for time-critical messages (high priority messages) and fast channel access with less contention.

The standard DIFS duration is divided into a number of mini-slots. A high priority message waits only for a small numbers of mini-slots before broadcasting. Therefore, the high priority messages will always have a preemptive channel access and be broadcasted faster than other messages. Equations (1) and (2) show how to calculate the length of mini-slot (*l*) and the number of mini-slots (*w*).

$$l = 2\rho + t_{switch} \quad (1)$$

$$w = \left\lfloor \frac{T_{DIFS} - T_{SIFS}}{l} \right\rfloor \quad (2)$$

where ρ is the maximum channel propagation delay in the transmission range. t_{switch} is time duration required by a transceiver to switch between transmission and reception

modes. As shown in Equation (2), the minimum value of mini-slot DIFS is always greater than SIFS (Short Inter-Frame Space). Therefore, 3P3B-DTN is fully compatible with IEEE802.11p; the standard of Wireless Access in Vehicular Environments (WAVE).

After a mini-slot DIFS has expired, the sender broadcasts a Request-to-Broadcast (*RTB*). Then it waits for a Clear-to-Broadcast (*CTB*). The *RTB/CTB* is used to alleviate the hidden terminal problem in wireless communications, reduce the broadcast storm problem, and reduce network overhead. When *RTB* is received, all receivers simultaneously broadcast black-burst (B_A); a burst of jamming signals. The sender can imply a present of vehicles based on the received B_A . Then, the forwarder selection will be started using the trinary partitioning mechanism. Otherwise, the sender will restart the whole process for n times, where n is the trinary partitioning threshold. If there is no B_A received during all n trials, the sender assumes a disconnected network and starts store-carry-forward mechanism. The trinary partitioning threshold is a factor of vehicle density, communication traffic load, and channel condition. Therefore, obtaining an optimal value the trinary partitioning threshold needs further investigation and is out of the scope of this paper.

Fig. 1 Trinary partitioning procedure with 3 iterations ($N=3$) [26]

2) Trinary Partitioning

The trinary partitioning mechanism [26] aims to select only one message forwarder for each communication hop and reduce contention jitter. Only the furthest possible vehicle will forward messages to the next communication hop so that 3P3B-DTN achieves the largest message progress and avoids broadcast storm problem [25, 32].

Trinary partitioning is a modification of the binary partition proposed in BPAB [14]. In [26], the trinary partition has been proved to be the optimal among any n -ary partitioning mechanisms for message broadcasting in VANETs. Figure 1 illustrates how trinary partitioning operates in three iterations ($N=3$).

After the end of B_A period during the first iteration, all receivers divide the communication range (r) of the sender into three partitions (inner, center, and outer partitions) and determine their partitions. The inner partition is defined as the

closest partition to the sender, while the outer partition is the farthest partition from the sender. The vehicles of the outer partition are the most preferable as it can maximize the dissemination distance and shorten message broadcasting time. In the figure, since there are 10 vehicles in the outer partition during the first iteration, these vehicles simultaneously broadcast black-burst during the first time slot. Once the rest of the vehicles hear the black-burst, they turn to idle, because they learn that there are better forwarder candidates in the other partition. Only one time slot has been spent during the first iteration and the width of the focused partition is reduced to $r/3$.

During the second iteration, the vehicles in the focused partition re-divide such partition into three sub-partitions. The first time slot is free since there is no vehicle in the outer partition, which could broadcast black-burst in the first time slot. All four vehicles in the middle partition will broadcast black-burst simultaneously during the second time slot. The rest of vehicles imply the better forwarder candidates and turn to idle. The second iteration consumes two more time slots and the width of the focused partition is reduced down to $r/3^2$ (or $r/9$)

Fig. 2 Performance evaluation of the previously presented 3P3B in term of PDR

Fig. 3 Performance evaluation of the previously proposed 3P3B in term of end-to-end delay

A similar operation has been done during the third iteration. The vehicles in the focused partition re-divide their partition into three sub-partitions. No vehicle has been seen in both outer and middle partitions, so there is no black-burst broadcasted during the first two time slots. All four vehicles in

the inner partition imply that they are the best candidates of this iteration without broadcasting the black-burst. Therefore, the third iteration consumes only two more time slots and the final focused partition has only $r/3^3$ in width. Totally, only five time slots are spent during trinary partitioning process.

In case that there are several vehicles in the final focused partition, these vehicles will randomly pick back-off values from the available contention window (cw). A vehicle whose back-off expires first broadcasts a *CTB* packet and becomes the selected forwarder. Upon the receipt of *CTB*, the sender waits for a SIFS period then broadcasts a message to all vehicles but only the forwarder will re-broadcast this message to the next communication hop.

Fig. 4 Overview flowchart of 3P3B-DTN

3) Store-Carry-Forward

As presented in [26], 3P3B is previously designed for dissemination of time-critical time critical message in only well-connected VANETs. Without taking any interruption into account, the previously proposed 3P3B fail to provide a successful communication when interrupted. As shown in Figures 2 and 3, in the connected VANETs, 3P3B is highly reliable with more than 98% of PDR, and low end-to-end delay of about 11ms. In a dense network, most of the communication is successful for the reason that the network is well connected. Occasional failures are nonetheless occur due to collisions that can be corrected by a retransmission.

However, the performance of message broadcasting degrades significantly when network interrupted. For example, it can be seen from Figure 2, PDR notably degrades when the

density of the nodes is low. This is due to the fact that the previously proposed 3P3B as well as the other existing broadcast protocols (i.e. BPAB, SB, and UMB) do not have an inherent solution for frequent network disruptions. Therefore, messages are dropped after a certain number of transmission trials. Motivated by this fact, 3P3B has been enhanced to 3P3B-DTN for an effective message broadcasting especially in disrupted networks, which is crucial in VANETs.

Therefore, in intermittently connected VANETs, instead of discarding messages after n trials, the 3P3B-DTN stores and carries the messages along the vehicle's movement path, then forwards the messages, when the vehicle finds a new connection. This store-carry-forward mechanism efficiently helps to increase PDR.

The flow chart of the 3P3B-DTN is illustrated in Figure 4. Whenever the broadcast fails up to n times; i.e. the number of retransmission attempts is over the rebroadcasting threshold, the 3P3B-DTN assumes an intermittently connected network. Then, the message forwarder switches from a broadcasting mode to a holding mode. The message forwarder carries the messages for a maximum period of τ seconds, before searching for a new connection using *RTB* retransmission. Because message rebroadcasting time is relatively smaller than the carrying time, it is recommended to rebroadcast the messages rather than carrying them through, whenever there is a chance, i.e. a new connection is founded. Therefore, the maximum carrying time before rebroadcasting, τ , is given by

$$\tau = \frac{r}{2V_{Max}}, \quad (3)$$

where r is the communication range of vehicles and V_{Max} is the maximum vehicle speed limit on the highway.

Equation (3) can be illustrated in more detail in Figure 5. At time t , both the forwarder and the receiver are not in the communication range of each other. After a period of τ , they have a new contact, which allows the rebroadcast of the messages. If the forwarder waits longer than the maximum carrying time, τ , it may miss a chance to rebroadcast the message and hence has to carry it through, which makes the delay larger.

Fig. 5 Maximum carrying time

The *RTB* will be periodically transmitted until a new connectivity is founded by receiving a B_A packet, which is a black burst packet sent by vehicles, who receive the *RTB* from the forwarder. Then, the message forwarder switches back to

the broadcasting mode and start the trinary partitioning to select the furthest next-hop forwarder. The message will be dropped, when its life time is expired; i.e., the information of the message is out-of-date and no longer useful.

IV. PERFORMANCE EVALUATION RESULTS

In this section, a comprehensive set of simulations has been carried out to evaluate the performance of the proposed protocol and compare it to that of the existing benchmark protocols.

It is important to note that main focus of the paper is to enhance vehicular communications in intermittently connected networks where the vehicular network cannot be formed properly due to the limited number of vehicles. Therefore, the paper considers only a scenario containing low to medium traffic conditions, which is a highway environment. Consequently, the city scenario with high traffic condition will not be considered in the paper, since it does not reflect the problem the paper is focusing on.

A. Description of the Simulation Model

The comprehensive performance evaluation is based on the simulation package OMNeT++ [27]. The 3P3B-DTN is evaluated in term of average packet delivery ratio (PDR), end-to-end delay, and overhead, in both well-connected and intermittently connected networks on the highway environment. The average PDR is defined as the average number of packets received by all vehicles divided by the total number of packets generated and sent by all transmitters, while the average end-to-end delay is the average end-to-end delay of all first-time received packets by all vehicles in the network, and the average overhead is the average ratio between the total size of all control packets, such as *RTB* packets, and the total size of all broadcasted and rebroadcasted data packets in the network.

The 3P3B-DTN is evaluated and compared against the performance of the benchmark broadcast protocols namely BPAB [14] and DV-CAST [18]. There is no performance comparison against unicast routing protocols because the protocols are different and incomparable with broadcast protocols; i.e. there is no specific destination.

Fig. 6 Simulation scenario

The simulation scenario is illustrated in Figure 6. The simulation area is set to a straight 40km-long highway, where the vehicles are randomly placed in the simulated highway. All vehicles move with average speed varied from 60 to 100 km/hr. The number of transmitters is varied from 1 to 10 transmitters to provide different packet densities in the

network, where the transmission rate of each transmitter is set to 1 message/second. There are 10 anchor vehicles placed at every 2 km following the transmitters. Therefore, the anchor vehicles cover the distance up to 20 km from the transmitters. It is note that all anchor vehicles only act as sink nodes to measure performance of 3P3B-DTN at different distances from the transmitters. They do not participate in storing, carrying, or forwarding any messages at all. To keep the distance between each anchor vehicle and transmitters constant, all of them move with the same average speed of 80 km/hr.

The performance evaluation is focused on both intermittently connected and well-connected VANETs. It is noted that the network is considered as the intermittently-connected when the vehicle density is lower than 13 vehicles per km as previously shown in Figure 2. Therefore, in the simulations, the vehicle density is varied from 0 to 60 vehicles per km to cover both scenarios. The maximum speed limit on the highway is set to be 100 km/hr [28]. The maximum carrying time, τ , of the messages in the message holding mode is set as 16.21 seconds according to the calculation in Equation (3). Therefore, in order to observe the impact of the carrying time, the carrying time is set to 2 and 16 seconds in the simulations. The fading model used in the simulation is Rayleigh, which is one of the well-accepted fading models for vehicular communications [29, 30, 33]. The Rayleigh model generally depends on a deterministic model; i.e. free space or two-ray ground model, to which a certain variation is applied as shown in Equation (4).

$$Pr_{\text{Rayleigh}}(d) \approx \text{Rayleigh}(Pr_{\text{det}}(d)) \quad (4)$$

In this paper, the deterministic transmission power is set to 20 mW according to the standard. All other default parameter values used in the simulations are summarized in Table II.

TABLE II
DEFAULT PARAMETER VALUES OF THE SIMULATIONS

Parameters	Default Values
Standards	IEEE 802.11p/ IEEE1609.4
Communication Frequency	5.9 GHz
Propagation Model	Free Space
Fading Model	Rayleigh Model
Transmission Power	20 mW
Sensitivity	-94dBm
Bit Rate	18 Mbps
Message Size	500 Bytes
RTB Packet Size	20 Bytes
CTB Packet Size	14 Bytes
Slot Time	13 μ s
DIFS	58 μ s
SIFS	32 μ s
Max Channel-Propagation Delay	2 μ s
Transceiver's Switching Time	1 μ s
Maximum Speed Limit on the Highway	100 km/hr
Message Carrying Time in the holding mode	2 and 16s
Number of Transmitters	1, 5, and 10
Vehicle Density	0- 60 vehicle/km

B. Validation of the Simulation Results

The proposed analytical model in [31] is used to validate the results from our comprehensive simulation in term of the average PDR. There are two cases of message broadcasting in VANETs; the tradition broadcast scheme and a broadcast

scheme with Store-Carry-Forward mechanism. In the first case, messages will be broadcasted only when there is a continuous end-to-end connectivity between source and destination vehicles. Otherwise, the messages will be discarded. For the second case, the messages will be broadcasted when there is a continuous end-to-end connectivity and they will be carried along the vehicle's movement path when no connection is founded. The messages will then be rebroadcasted to other vehicles as soon as a new connection has been founded. Therefore, the second case can yield higher PDR.

According to [31], the PDR of the traditional broadcast, $P_{broadcast}$, can be determined as

$$P_{broadcast} = (1 - e^{-2\lambda r})^{2\lambda L - 1}, \quad (5)$$

where λ is the density of vehicles and L is length of the highway.

In addition, the PDR based on the store-carry-forward mechanism, $P_{store-carry-forward}$, can also be calculated using the following equations.

$$P_{store-carry-forward} = \sum_{j=0}^{N-1} P_{TooFar,j} \cdot P_{reconnect,j} \quad (6)$$

$$P_{TooFar,j} = \binom{\lambda L - 1}{j} (e^{-\lambda r})^j (1 - e^{-\lambda r})^{\lambda L - 1 - j} \quad (7)$$

$$P_{reconnect,j} = (1 - \sum_{k=1}^{\lceil L/r \rceil - 1} (e^{-\lambda k r} - e^{-\lambda(k+1)r}) \left(\sum_{i=0}^{k-1} \frac{(\lambda i r)^i}{i!} e^{-\lambda i r} \right))^j \quad (8)$$

where N is the total number of vehicles and r is the communication range.

Fig. 7 The validation in term of the PDR of both the traditional broadcast scheme and the broadcast scheme with store-carry-forward mechanism

The validation in term of the PDR of both the traditional broadcast scheme and the broadcast scheme with store-carry-forward mechanism in a 20 km highway and 450 m communication range with the vehicle density varied from 0 to

60 vehicles per km is shown in Figure 7. Results of the simulation using OMNeT++, which are represented in marks, are validated against results of the analytical model, which are represented in lines. Therefore, the simulation results are validated since of both results of the analytical model and the simulation are very close.

In Figure 7, it is also observed that the broadcast with store-carry-forward mechanism gives higher packet delivery ratio than the traditional broadcast at the same vehicle density. This is because instead of dropping messages when there is no continuous end-to-end connectivity, most of such messages are rescued by the store-carry-forward mechanism and successfully delivered to following vehicles after waiting for an additional period of time.

Furthermore, both schemes achieves higher packet delivery ratio, when the vehicle density is higher. Due to the higher density of vehicles, the network becomes well connected and hence this increases the successful packet delivery ratio of the network.

C. Simulation-Based Performance Evaluations of 3P3B-DTN

1) Single-Transmitter Scenario

Single transmitter scenario means that there is only one transmitter starting transmitting urgent messages in the network which reflect low packet density scenario. In fact, this scenario seems to be a common and realistic case since most of the time there will be only one accident occur in a particular area. However, considering the worst case scenario, in the following subsection, the number of the transmitters is increased to 5 and 10 transmitters, respectively.

Figure 8 illustrates the performance comparison in term of average PDR of 3P3B-DTN and BPAB of different dissemination distances and different values of vehicle densities. The carrying time in this case is set to 2 seconds. At low vehicle density; i.e., 1.67 vehicle/km as shown in Figure 8(a), the PDR is lower compared to those in the denser networks, shown in Figures 8(b)-(f), due to a higher probability of disrupted connections in the sparse network. Similarly, the PDR also decreases when the dissemination distance becomes larger due to higher rate of packet lost and drop at the larger distance. However, the higher PDR is achieved by 3P3B-DTN against BPAB regardless the vehicle densities and dissemination distances as shown in Figures 8(a)-(f). This achievement of higher delivery ratio is due to the store-carry-forward mechanism that allows messages to be carried until a new connection is founded and hence the messages have a higher chance to be successfully broadcasted.

Figure 9 shows a performance comparison in term of average PDR, average end-to-end delay, and average overhead of the dissemination distance within 20 km of BPAB, DV-CAST, and 3P3B-DTN with different values of the carrying times. It can be observed from Figure 9(a) that 3P3B-DTN attains approximately 10% and roughly 6% higher in term of the average PDR compared to BPAB and DV-CAST, respectively, in the disrupted VANET where the vehicle density is less than 13 vehicles per km. In the well-connected VANET, all protocols perform very close to each other. However, with a close observation, 3P3B-DTN gives 3% higher PDR compared to the other two protocols in the well-

(a) Vehicle density of 1.67 vehicle/km

(b) Vehicle density of 3.33 vehicle/km

(c) Vehicle density of 5.00 vehicle/km

(d) Vehicle density of 6.67 vehicle/km

(e) Vehicle density of 8.33 vehicle/km

(f) Vehicle density of 10.00 vehicle/km

Fig. 8 Performance comparison in term of PDR of 3P3B-DTN and BPAB of different dissemination distances and different values of vehicle densities where there is one transmitter in the network

connected scenario. This confirms the significant reliability improvement accomplished by 3P3B-DTN particularly in the sparse VANETs. In addition, different values of the carrying time do not make a significant impact on the PDR, since the results of both 2-second and 16-second carrying times are very close to each other.

Figure 9(b), which shows performance comparison in term of average end-to-end delay of the dissemination distance within 20 km of BPAB, DV-CAST, and 3P3B-DTN. The end-to-end delay gained by the 3P3B-DTN is higher compared to BPAB and DV-CAST when the vehicle density is lower than

13 vehicles per km. However, this comparison can be considered unfair. Because most of the dropped and lost packets in BPAB and DV-CAST, which should experience infinity in term of delay (but they are not included in the graph), have been rescued by 3P3B-DTN with a bit higher but bounded delay (and they are included in the graph). Therefore, this increase of delay is a performance improvement rather than degradation. This increase of delay can be explained as follows. Since the carrying time is in seconds, which is far larger than the average end-to-end delay attained in the normal broadcasting mode, which is in milliseconds, the end-to-end

delay of the message holding mode is mainly dominated by the carrying time resulting in a huge increase of the delay. The longer carrying time is, the larger end-to-end delay becomes.

Therefore, it is recommended to implement a shorter carrying time during the message holding mode to gain a high reliability with lower delay. For example, 2-second carrying time experiences much lower end-to-end delay compared to the carrying time of 16 seconds while giving approximately the same level of PDR as observed in Figure 9. However, the delays in both cases are still far lower than message life time, which normally lasts for hours until the accident has been removed from the highway.

In addition, when the density of vehicles increases, the delay decreases, because the network becomes better connected and hence most of the messages can be successfully broadcasted without need of the store-carry-forward mechanism. Figure 9(c) shows a performance comparison in term of average overhead of the dissemination distances within the first 20 km of BPAB, DV-CAST, and 3P3B-DTN and with different values of the carrying times. It can be observed that BPAB have lower overhead than 3P3B-DTN at low vehicle density but a bit higher overhead when the vehicle density increases. Due to the packet store-carry-forward mechanism at low vehicle density, 3P3B-DTN retransmits *RTB* packets several times until it finds a new connection. This leads to high number of control packet (*RTB*) transmissions and overhead.

(c) Performance comparison in term of average overhead

Fig. 9 Performance comparison in term of average PDR, average end-to-end delay, and average overhead of the dissemination distance within 20 km of 3P3B-DTN, DV-CAST, and BPAB where there is one transmitter in the network

In addition, 2-second carrying time faces higher average overhead compared to that of 16-second carrying time. Because for the shorter carrying time, 3P3B-DTN retransmits *RTB* more often to quickly find a new connection, this short carrying time at the same time can cause higher overhead as a side effect if it cannot find the new connection. However, due to the 20-Byte *RTB* packets are relatively small compared to the 500-Byte data packets, this overhead does not make a serious impact on the network performance.

(a) Performance comparison in term of average PDR

(a) Performance comparison in term of average PDR

(b) Performance comparison in term of average end-to-end delay

(b) Performance comparison in term of average end-to-end delay

(c) Performance comparison in term of average overhead

Fig. 10 Performance comparison in term of average PDR, average end-to-end delay, and average overhead of the dissemination distance within 20 km of 3P3B-DTN with different carrying times where there are 5 transmitters in the network

(a) Performance comparison in term of average PDR

(b) Performance comparison in term of average end-to-end delay

(c) Performance comparison in term of average overhead

Fig. 11 Performance comparison in term of average PDR, average end-to-end delay, and average overhead of the dissemination distance within 20 km of 3P3B-DTN with different carrying times where there are 10 transmitters in the network

By comparing to the overhead of DV-CAST, 3P3B-DTN experiences far lower overhead. DV-CAST mainly relies on hello messages for broadcasting and the amount of hello messages is directly related to network density. The overhead of DV-CAST, therefore, increases linearly as the network size increases, while the overhead of 3P3B-DTN is much more constant regardless the network size.

2) Multiple-Transmitter Scenario

Figures 10(a) and 11(a) illustrate the further performance evaluation in term of average PDR of the dissemination distance within 20 km of 3P3B-DTN with different carrying times where there are 5 and 10 transmitters in the network. The similar results can be observed here. 3P3B-DTN is able to maintain high PDR regardless the packet density. Both 2-second and 16-second carrying times also give very close results in term of the communication reliability similarly to the results of the only one transmitter.

A performance evaluation in term of end-to-end delay can be observed from Figures 10(b) and 11(b). The figures show the performance comparison in term of average end-to-end delay of the dissemination distance within 20 km of with different carrying times where there are 5 and 10 transmitters in the network. It can be seen that the 16-second carrying time experiences much higher delay compared to the 2-second carrying time in both figures. In case of the higher carrying time, forwarders normally carry messages for longer time without trying to search for a new contact. Thus, it makes the delay larger. In addition, the higher number of transmitters in the network, which reflects the higher packet density, causes higher end-to-end delay due to higher rate of channel access contention and packet collision.

Figures 10(c) and 11(c) show the performance comparison in term of average overhead of the dissemination distance within 20 km of 3P3B-DTN with different carrying times where there are 5 and 10 transmitters in the network. 3P3B-DTN with 2-second carrying time experiences the higher overhead due to more frequent transmissions of *RTB* packets. However, such overhead is considered insignificant, because the PDR of the data packet can be maintained at high value as previously presented.

V. CONCLUSION

This paper proposes a complete solution for broadcasting in vehicular sensor networks, namely 3P3B-DTN. This solution solves the broadcast storm problem, the hidden terminal problem, and service differentiation in intermittently-connected VANETs altogether. The proposed mini-DIFS and trinary partitioning mechanisms implemented in 3P3B-DTN efficiently provide priority scheme for high priority messages, selection of the furthest possible message forwarder to solve the broadcast storm and the hidden terminal problems, and reduction of contention jitter. In addition, the store-carry-forward mechanism is introduced to deal with frequent network disconnections in sparse VANETs. Comprehensive performance analysis and simulation results show that the proposed 3P3B-DTN outperforms the referenced benchmark protocols BPAB and DV-CAST in term of the PDR; e.g., at least 10% and 6% higher delivery rate especially at low vehicle density. The overall average delay of 3P3B-DTN is also lower than the referenced benchmark protocols as well, when the lost and dropped packets are taken into the comparison. The overhead of 3P3B-DTN is significantly lower, compared to DV-CAST. Nonetheless, the overhead of the proposed protocol is slightly higher than BPAB due to introduction of the carry and forward mechanism. Therefore, 3P3B-DTN becomes the current optimal solution when compared against alternative referenced benchmark protocols evaluated in this paper.

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