Coordination-free Safety Messages Dissemination Protocol for Vehicular Network

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***Abstract*—Many vehicular safety applications depend on the rapid and reliable dissemination of safety messages to vehicles at risk. In order to allow sufficient reaction time for emergency events in adverse driving and road conditions, disseminating safety messages over multi-hop vehicles is often needed. However, owing to the capacity limitation of the shared control channel, disseminating safety messages in highly mobile and dynamic vehicular network conditions is challenging. In this article, a *Zero-Coordination Opportunistic Routing (ZCOR)* algorithm is proposed to deliver mission-critical life safety messages over limited target geocast regions. ZCOR is scalable and robust over dynamic VANET conditions with low rebroadcast overhead. In addition, ZCOR exploits neighbor knowledge for coordination-free opportunistic packet relay using the novel concept of *Circle of Trust (CoT)*, which defines the range of reliable local neighbor knowledge collection. The performance of ZCOR is evaluated through extensive and realistic simulations capturing time-correlated vehicular channel characteristics.**

I. Introduction

Communications between Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) have been extensively studied during the last decade to guarantee human safety and road-network efficiency. The avoidance of accidents by disseminating safety messages at intersections or highways is considered as a basic element for safety-related applications in Vehicular Ad-hoc NETworks (VANETs). Therefore, issues on the reliability and latency in disseminating safety messages over VANET environments have been thoroughly investigated by many research projects [1], [2], [3], [4], [5], [6], [7].

Most research work to enable emergency applications such as pre-crash warning relies on single-hop broadcasts of critical Life Safety Messages (LSM). Such single-hop message broadcasting, however, does not always achieve the necessary coverage for various safety applications [8]. Consider, for example, low visibility conditions on wet/icy roads and overtaking-assist applications. If it were possible to track or query the positions and speeds of the vehicles ahead, the drivers could be informed of whether or not it would be safe to pass. In such cases, the geocast range of LSMs should be extended from several hundred meters up to a kilometer depending on vehicle speed. However, even with the boosted signal strength that is allowed by current Wireless Access in Vehicular Environments (WAVE) standards [1], the necessary transmission ranges cannot be reliably obtained through single-hop communications. In urban areas, some experimental measurements data indicate a maximum range of $100 - 150\,\mathrm{m}$ even with $33\ \mathrm{dBm}$ boosted transmission power [9]. Furthermore, the range is further reduced when transmission power is lowered to improve spectrum spatial reuse.

In addition, there are a number of technical challenges to consider in designing protocols for emergency applications. Adaptation to VANET specific network environments, such as high mobility, severe channel fading, and a wide range of vehicle density, including extremely high node-density owing to rush-hour traffic in metropolitan areas, are another important aspects to consider. Typically, congested common Control CHannel (CCH) is another problem to solve. In accordance with current standards, every wireless node in VANET shares a single CCH for the exchange of various safety-related messages [10]. Therefore, this bandwidth-limited CCH is easily congested as node density grows. Although rebroadcast-suppression and message-aggregation methods are able to alleviate such congestion problems [11], these approaches come with other undesirable drawbacks, such as the loss of reliability owing to the reduced number of rebroadcasts and the latency and security problems that arise when messages are aggregated.

In this article, we propose a Zero-Coordination Opportunistic Routing (ZCOR) algorithm for VANET that aims to deliver latency-sensitive LSMs over a broader target warning area efficiently and reliably. The ZCOR algorithm exploits implicit coordination techniques in coordinating a number of possible relay nodes with minimum overhead for conflict-free coordination. Also by implicitly reserving slot time, latency-bounded transmissions for LSM packets is achieved. Moreover, the reserved slots are not tied to a particular node; instead, they utilize opportunism in relaying packets via multi-node diversity. The coordination problem for opportunistic routing under dynamic and unstable vehicular channel conditions is solved by the novel concept of *Circle of Trust (CoT)*. The CoT is defined as the range of reliable communication needed to build accurate neighbor knowledge, which is subsequently used to determine the next relay node. Hence, ZCOR does not rely on a time-consuming pre-coordination process nor on extra overhead except for low-rate heartbeat packets.

The remainder of this article is organized as follows. In Section II, we identify the characteristics of VANET. In Section III, we review the existing protocols for life safety message dissemination. In Section IV, we present the details of the ZCOR algorithm. Simulation setups and scenarios are explained in Section V with simulation results following in Section VI. Finally, conclusions are drawn in Section VII.

II. Background

Road safety messages in VANET can be classified into latency-tolerant Public Safety Messages (PSM) and latency-sensitive Life Safety Messages (LSM) [8]. PSMs are periodic

TABLE I
EVENT-DRIVEN LIFE SAFETY MESSAGES (LSM) : NHTSA & VSCC (USDOT 2006)

Class	Latency	Frequency	Range	Application	Transmitter
Low laTency High Frequency (**LTHF**)	$\leq 100\,\mathrm{ms}$	$10{-}20\,\mathrm{pkt/s}$	$\leq 150\,\mathrm{m}$	Crash and Hard-brake warning, Roll-over and control loss warning, cooperative collision warning	Vehicle
Medium laTency Medium Frequency (**MTMF**)	$\leq 200\,\mathrm{ms}$	$5-10\,\mathrm{pkt/s}$	$\leq 100-300\,\mathrm{m}$	Curve speed and stop light assistance, intersection collision warning, traffic signal violation warning	Road Side Unit
				Left turn and lane overtake assistance, extended brake signalling	Vehicle
High laTench Low Frequency (**HTLF**)	$\leq 1000\,\mathrm{ms}$	$1-2\,\mathrm{pkt/s}$	$\leq 1000\,\mathrm{m}$	Work-zone warning, low bridge warning, road condition warning	Road Side Unit
				Emergency vehicle signal preemption	Vehicle

advisory messages with less stringent requirements on their range and delivery latency. Examples of PSMs are neighbor finding heartbeats, GPS correction messages, service announcements, lane coordination, visibility enhancements, and Cooperative Adaptive Cruise Control (CACC) messages [12].

On the other hand, LSMs typically have higher priority than PSMs, as LSMs are generated for human-safety applications. In Table I, we list and characterize the VANET applications that rely on LSMs, and subsequently categorize them into three subclasses according to their latency requirements, transmission frequencies, and ranges. As further illustrated in Fig. 1, Low laTency High Frequency (LTHF) LSMs convey time-critical messages, which have short-range geocast area that can be covered by single-hop transmissions. However, HTLF LSMs are not strictly sensitive to delay targeting vehicles in longer geocast ranges up to $1-2$ km. When compared to HTLF, MTMF LSMs have a medium latency requirement of several hundreds of milliseconds for the vehicles $2-3$ hops away from the LSM source. Particularly, the messages from the latter two categories require multi-hop dissemination to achieve their desired ranges.

In this chapter, we focus on reliably disseminating latency-sensitive LSMs in the presence of background traffic packets (including PSMs) that share the same CCH. We assume that the destination of LSM is geographically defined and that their transmissions are directed along a roadway. However, reliable LSM dissemination is particularly challenging owing to a number of VANET attributes depicted in Fig. 2, that are summarized as follows:

Channel Dynamics: Similar to most mobile wireless communication channels, the vehicular communication channel suffers from reflections and signal scattering, which degrade signal strength and quality. Also, vehicular mobility adds more dynamic fading conditions combined with spatially correlated shadow fading effects. In urban areas, the correlation distance of the shadowing, caused by buildings and large vehicles, has been experimentally measured as $20\,\mathrm{m}$ [13]. In addition, strong ground reflections also produce deeply faded outage-areas between transmitters and receivers [14]. Such spatially and temporally correlated channels significantly affect the performance of wireless communications when their scale is larger than small scale fading and antenna diversity techniques are not helpful. Therefore, retransmission techniques assuring packet delivery combined with ACK (or NAK) feedback messages are widely used, although they induce more overhead and delay.

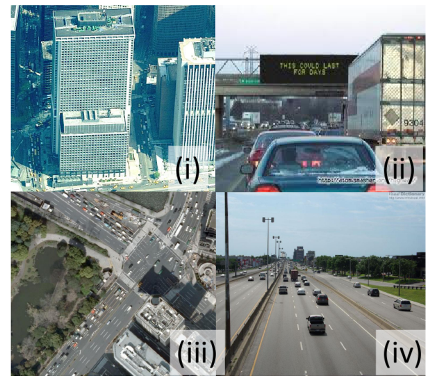
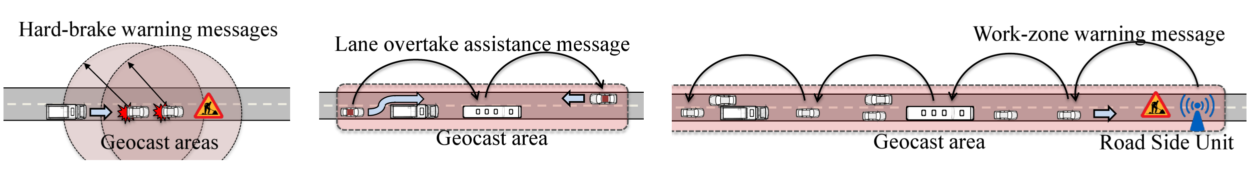


Fig. 2. VANET key attributes: (i) Shadowing due to roadside buildings. (ii) Shadowing due to on road vehicles. (iii) Dynamic mobility changes in an intersection. (iv) Velocity-density correlation of vehicles.

Mobility Dynamics: Although the mobility of vehicles is constrained by roadways, their velocity, density, and direction change dynamically over time and space. For example, a sparse road segment with a few fast running vehicles can be suddenly overcrowded with more vehicles. In such dynamically varying networks, LSM dissemination algorithms should be adaptive and scalable enough to cope with such abrupt changes of network conditions [15]. In addition, under such dynamic network conditions, nodes cannot obtain accurate neighbor knowledge. In VANETs, vehicles transmit



(a) Low laTtency High Frequency (LTHF) LSM.

(b) Medium laTtency Medium Frequency (MTMF) LSM.

(c) High laTtency Low Frequency (HTLF) LSM.

Fig. 1. Three classes LSMs categorized into three classes.

low-rate periodic heartbeat packets to broadcast their positions and movement information for basic neighborhood discovery, which are widely used for various VANET applications designed to improve the efficiency, safety, and comfort of road traffic [16]. However, the rapidly changing topology of VANETs easily renders neighbor knowledge obsolete, which may degrade the performance of LSM dissemination protocols utilizing the neighbor knowledge in controlling the size of rebroadcast overhead [17], [18], [19].

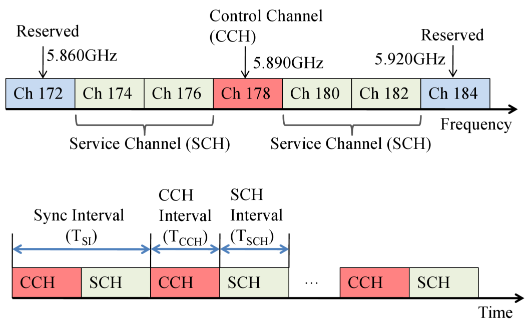


Fig. 3. Multi-channel structure in WAVE standards.

Limited Control Channel Resource: The channel structure of current WAVE standards is shown in Fig. 3. Since conventional radios only allow one channel access at a time, nodes have to be synchronized to a Synchronization Interval (SI)[1] to make time-multiplex access between the Service CHannel (SCH) and the Control CHannel (CCH) [11]. Since CCH is shared by all the wireless nodes in VANETs and is used for most safety related message transmissions (including both LSMs and PSMs), the channel is easily congested in dense traffic areas[2]. Such CCH congestion easily degrades the performance of LSM dissemination protocols. Particularly, although background packets, such as heartbeats and other PSMs, are treated with lower priority [20], background packets can still interfere with LSM transmissions inducing collisions and channel access delays.

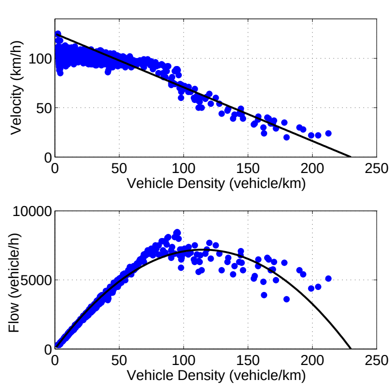


Fig. 4. Vehicle flow model

[1]Using GPS with pulse-per-second signals (available under ten dollars) is one of the cheapest methods to synchronize nodes

[2]Note that the vehicle density easily grows to hundreds of vehicles per one-hop communication range in rush-hour traffic, and CCH typically uses the lowest data rate for reliable packet delivery (i.e., $3\,\mathrm{Mb/s}$ in WAVE). For example, 200 vehicles would need $1.6\,\mathrm{Mb/s}$ bandwidth just for $100\,\mathrm{B}$ heartbeat packets with $10\,\mathrm{pkt/s}$ heartbeat rate, which already exceeds the CCH capacity (assuming CCH uses 50% of slots in SI).

Difficulties in Adaptation: The design of LSM dissemination protocols in VANET should consider the peak amount of heartbeat transmissions in relation to the accuracy of neighbor knowledge, which varies depending on road traffic conditions. However, vehicle density is strongly correlated with vehicle velocity as shown in Fig. 4, where a widely used microscopic traffic models, Greenshield linear traffic model [21], is compared with sample traffic flow data collected in I-4 Orlando, Florida [22]. Vehicles in VANET typically adjust their heartbeat transmission rate or power according to their velocity to alleviate the congestion in CCH from heartbeat packets [23], [24]. In such a case, traffic flow, that is vehicle density multiplied by vehicle velocity, equals the required bandwidth for heartbeat packets; since vehicle velocity is proportional to the heartbeat transmission rate. It is notable that nodes in VANET still experience CCH congestion at particular density conditions even when vehicles try to adapt their heartbeat transmission rate according to its velocity. Since such dynamic heartbeat transmission rate control incurs a drawback of inaccurate neighbor knowledge collection for the nodes, it is very difficult to design adaptive algorithm incorporating all the different aspects of VANET conditions.

III. Related Work

Existing prior work on safety message disseminations in VANET can be largely categorized either as flooding-based protocols or as relay-based protocols [25]. In flooding-based broadcast protocols, the decision for packet forwarding relies on individual nodes, where each node makes a decision based on its own conditions such as location, distance, Random Access Delay (RAD) timer, neighbor knowledge, or a combination of them [7], [26], [27], [28]. Depending on the decision metric, overheads from rebroadcast and reliability are determined. Such flooding-based protocols are more suitable for short-range LSM dissemination; however, they usually produce large overheads, which induce latency problems in dense networks due to contentions and collisions.

Compared to distributed flooding-based protocols, in relay-based protocols, the decision for packet relay is not distributed to receiver nodes, but given to sender nodes that relay packets [17], [6], [18], [29]. Packet forwarders use their neighbor knowledge and select a reliable and efficient next hop relay node. These protocols usually produce less redundancy than flooding-based protocols, but they are vulnerable to channel errors and node mobility, especially in sparse network conditions [30].

Many broadcast and geocast protocols use RAD timers to control rebroadcast redundancies, which are primarily built on a contention based CSMA MAC protocol. This randomness in channel access and packet routing induces not only delays but also collisions in dense network conditions [15], [31]. Therefore, a few reservation-based channel access protocols, such as Reservation-ALOHA (R-ALOHA) and Location Division Multiple Access (LDMA), have been proposed for VANET environments [32], [33], [34], [35]. R-ALOHA is robust over packet collisions through a channel reservation process [36], [37], [38], [39], [40]. However, they are mainly designed for single-hop broadcasts; therefore, reserving conflict-free slots for multi-hop delivery still remains an extremely difficult task in VANETs. LDMA was introduced for multi-hop bounded latency alerting [35], however, it still relies on out-of-band control channel for slot scheduling.

Under fading channel conditions, opportunistic routing algorithms can increase robustness and efficiency in multi-hop packet broadcasting scenarios by exploiting spatial diversity gains [41], [42]. Hence, opportunistic routing mechanisms have been applied to VANET in [43], [31], which are still relying on RAD-based timers. Recently, a time-space opportunistic routing algorithm has been proposed using a binary signaling technique to coordinate the candidates for relay nodes. However, such one-bit signaling technique is not appropriate for packet based communication systems. On the contrary, ZCOR does not require extra message exchange besides regular heartbeat packets for node coordinations in multi-hop packet relay, which can significantly reduce latency and overhead in LSM dissemination.

IV. Zero-Coordination Opportunistic Routing (ZCOR) Algorithm

In this article, we propose Zero-Coordination Opportunistic Routing (ZCOR) algorithm for efficient and reliable LSM dissemination along a linear application-determined geocast zone. ZCOR follows the multi-channel structure of the WAVE standards. Although WAVE standards are currently based on CSMA-based MAC protocols, ZCOR can be seamlessly integrated with WAVE standards since it allows non-LSM packet transmissions as low-priority messages transmitted in the same CCH. However, to avoid collisions between high-priority ZCOR packets and low-priority non-LSM (background) packets, the backoff windows for channel access are exclusively assigned to each priority type.

To reduce collisions among the packets transmitted and to improve scalability over a wider range of vehicle densities, ZCOR relies on a slot reservation mechanism. Specifically, ZCOR employs an R-ALOHA style channel reservation method; where a slot reserved by one of LSM source nodes remains reserved until they are idle again. Differently from R-ALOHA, however, as shown in Fig. 5, the reservation of slots is spatially extended over multi-hop.

To implement such reservation based MAC access, ZCOR needs just a few microseconds level time synchronization assuming 8 μs of backoff access-slot size is applied. Such microseconds level synchronization can be easily achieved either by using Network Time Protocol (NTP) disciplined clocks from RSU beacons[44] or by using commodity GPS modules.[3] Assuming the scenarios that RSUs are not widely deployed, vehicles outside RSU's beacon range need to rely on GPS PPS signal to synchronize their internal clocks in order to prevent the clocks from drifting. ZCOR radio modules, which are directly fed with GPS PPS signals, can lock their internal clocks to the PPS reference clocks to control their packet transmission properly. Also, such time critical tasks are needed to be implemented in firmware/hardware level in radio transceivers to minimize the latency and jitters across network protocol layers.

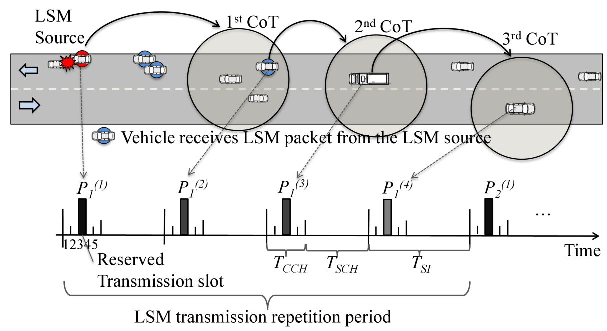


Fig. 5. The overview of ZCOR in multi-hop LSM dissemination; $P_i^{(j)}$ is jth hop LSM packet with a sequence number i.

For reliable multi-hop LSM dissemination under dynamic vehicular mobility and fading channels, ZCOR exploits multi-node diversity in receiving and relaying packets. Every packet includes coordination information for the next relayers, denoting the next-hop relay nodes. Each relayer designates an area (rather than a node) for implicit coordination, which is called Circle-of-Trust (CoT), to enable opportunistic relay to exploit multi-node reception diversity in packet receptions in each hop. However, the coordination is implicitly made without coordination-overhead besides beacon-type heartbeat packets that are considered as a basic protocol element in VANETs. The efficient and reliable multi-hop relay mechanisms of ZCOR make the protocol robust over the various VANET conditions even without relying on additional adaptive techniques.

In the following subsections, we first detail the slot reservation mechanism for LSM packets, and then explain CoT concept, which enables coordination-free opportunistic packet relay. Lastly, we extend ZCOR for multi CoTs to overcome spatially correlated shadowing effects.

A. Slot Reservations for LSM

As in current WAVE standards [46], we assume that nodes are time synchronized and simultaneously monitor CCH for a time interval T_{CCH}. After this interval, nodes access SCH until the next CCH interval begins. The time interval between the beginnings of two CCH intervals is called as a synchronization interval T_{SI}, which is typically set to $100 - 200$ ms. We propose that T_{CCH} is further divided into L transmission slots, and L is customizable to the size of a LSM packet. The transmission slots are accessed through reservations as in R-ALOHA mode. LSM source nodes randomly access any of the slots that were idle during the previous T_{CCH}. Only idle slots can be reserved, since slots that are used by other nodes are implicitly considered as reserved for the same LSM source node in the next control channel interval.

Figure 6 shows how LSMs are periodically transmitted with different periodicities according to their classes in Table I. The figure illustrates the repeat-cycle and slot assignment for each LSM class. Because the relay of each LSM packet is completed within the duration of $h \cdot T_{SI}$, where h refers to the

[3] We experimentally measured the time offsets in PPS signals from a number of Garmin GPS 18x devices[45]. Their time precisions are within $500ns$, which can be further reduced when GPS modules are integrated with radio transceiver circuits with less expensive implementation cost.

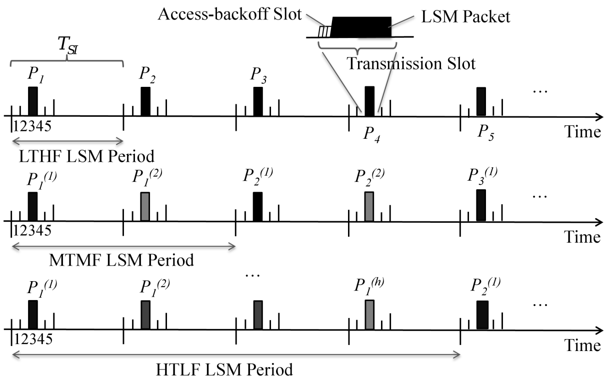


Fig. 6. Transmission slot reservation in each class of LSMs ($L = 5$); MTMF geocast has 2-hop range ($h = 2$).

number of hops from the source node, the reception latency is bounded by $h \cdot T_{SI}$. To avoid collisions between LSM packets and non-LSM packets, access-backoff slots are exclusively assigned; low order (from 0 to $K - 1$) access-backoff slots are assigned for LSM packets for implicit coordination, while high order (from K to $2K - 1$) access-backoff slots are used by non-LSM packets to avoid collisions among them.

A LSM source reserves its slot using the first LSM packet, and considers its reservation a success if its first packet is overheard in the next transmission slot. However, due to channel fading, the relayed LSM packet may not be overheard in the next transmission slot. In such a case, the node will sense busy channel status, but the node cannot demodulate the received packet; then the node cannot properly judge if its reservation has succeeded or failed due to a collision. Therefore, the source node can take a conservative choice: when the node has either received another node's LSM packet in the next transmission slot or cannot demodulate the received packet, the node considers that its reservation has failed due to a collision and therefore switches to another slot.

However, ZCOR is designed to minimize possible collision scenarios in reserving slots. We firstly consider the situation that more than two LSM sources try to reserve an identical idle slot during the same T_{CCH}. Note that such collisions rarely occur thanks to the randomness in emergency-event detections and in sensing delays in each node. However, the probability of such initial collisions can be further minimized, by exploiting the initial K random backoff slots in each transmission slot for the first LSM packets. On the other hand, LSM packets can collide with any packet transmitted from nodes in interference range. Therefore, it is necessary to sufficiently lower the carrier sensing range to avoid the transmission from the nodes in interference range; which means extending carrier sensing range to guarantee the reception of LSM packets at possible next hop relay locations (denoted as CoT in ZCOR) exploiting power capture effect [36].

After a successful hop-by-hop relay to the destination geocast area along the LSM path, the slot at each hop remains reserved. Thus, the reservation is spatially extended along the entire geocast path. By reserving packet transmission slots, LSM packets are much less interfered by background traffic in the same CCH. Moreover, such spatial and temporal slot reservation on a one-dimensional geocast area can be easily expanded over a 2-dimensional space through copying-and-forwarding multiple LSM packets to each directional road segment; however, such an expansion consumes additional transmission slots.

B. Opportunistic Relayer (Relay Node) Selection

The location of relayers significantly affects the efficiency and the reliability of multi-hop dissemination of LSM packets. However, selecting the best relayer, which usually is the farthest reachable node from the previous relayer, is a very difficult task in dynamic VANET conditions. That is because previous relayers typically have inaccurate reachability information on their edge neighbor nodes due to channel fading and mobility of nodes. Also typical velocity adaptive heartbeat rate control algorithms, which are used to alleviate heartbeat congestions, can further decrease the accuracy of neighbor knowledge.

One such problem is the *false-relayer selection problem*, which refers to the case in which a previous relayer selects a node that already moved out of its coverage range as its next hop relayer. Figure 7 illustrates an example of a two-hop LSM relay, where the current relayer node j relays packets to its relayer candidates. In this figure, node j may still falsely consider node b as its relayer candidate, because b is still in its neighbor list although b has moved away from its reachable range. Another such problem is the *hidden-neighbor problem*, which refers to the case in which better positioned nodes are not considered as candidates until their location is updated to the previous relayer. In the same figure, if j selects node c as its next relayer, then the relay fails when node c does not receive the packet to relay owing to channel fading. However, until the existence of node a is updated to node j, node a, which is a hidden-neighbor to j, cannot be used in the relay process.

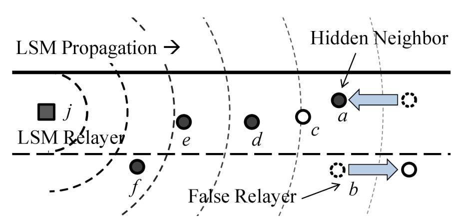
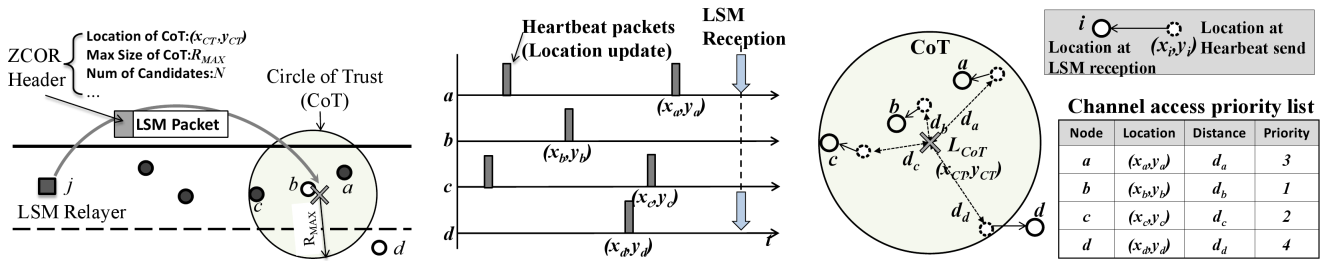


Fig. 7. LSM relayer j selects a next-hop relayer based on its neighbor knowledge collected from heartbeat packets.

Therefore, determining a relayer relying entirely on the neighbor knowledge of a single node is neither reliable nor efficient. The reliability of neighbor knowledge in VANETs, in fact, degrades rapidly according to the distance between nodes due to severe channel fading. Increasing the heartbeat packet transmission rate or power, however, easily congests CCH. To address these challenges, the LSM relayers in ZCOR select a geographic area incorporating a number of relayer candidates (instead of selecting a single node) allowing opportunistic forwarding to exploit multi-node diversity. The geography-based opportunistic relaying algorithm in ZCOR is designed to prevent both the *hidden-neighbor problem* and the *false-relayer selection problem*, which are mainly caused by imprecise neighbor knowledge.



(a) Transmission of ZCOR packet; packet header contains information for implicit coordination.

(b) Neighbor knowledge update through heartbeat packets among the candidates in CoT.

(c) Implicit coordination exploiting local neighbor knowledge.

Fig. 8. Coordination-free opportunistic LSM relay.

C. Coordination-free Opportunistic Multi-hop LSM Relay

The opportunistic relaying mechanism improves reliability in the packet relay process [41], [42] since the relay succeeds when any candidate node receives the packet from the previous relayer. Typical opportunistic algorithms, however, rely on a rather complicated coordination processes to avoid collisions among relayer candidates. Such coordination typically induces not only delay in packet transmissions, but also overhead for negotiations, which degrades the overall efficiency of the protocol. Therefore, ZCOR seeks to minimize the overhead in coordination for opportunistic relay by integrating the relayer selection mechanism with slot-based channel reservations, which virtually enables coordination-free opportunistic routing.

ZCOR exploits implicit coordination technique and obviates the need for such coordination by applying deterministic backoff on reserved slots for LSM relay. Relayer candidates receiving LSM packets access the channel according to their channel access priorities (k), which are translated into the number of access-backoff slots. Note that candidates do not need to know which other nodes have also received the LSM packets for relaying, since they can overhear higher-priority transmissions; then they cancel their own relay transmissions if the same message was already forwarded by another node. In the example scenario in Fig. 8(a), LSM relayer j adds ZCOR header containing information on the next-hop (e.g., the location and the maximum size of CoT, as well as the number of candidates) to LSM packets. The nodes receiving ZCOR packets decode the headers and determine their rebroadcast priority to relay the packet. In the example figure, among the three candidates $\{a, b, c\}$ in CoT, two candidates $\{a, b\}$ received the LSM packet from node j. If the candidates have uniquely assigned access priority, e.g, $k = \{2, 1, 3\}$ for $\{a, b, c\}$, then the node with highest priority that received LSM becomes the next relayer.

However, the access priority value should be uniquely assigned to each candidate to avoid collision among the relayer candidates. Also, the priority list should be immediately available to those candidates whenever LSM packets are received for relay. The candidates in CoT exploit their neighbor knowledge acquired from heartbeat packets, shown in Fig 8(b). Hence, the latency in establishing CoT is trivial, and LSM relayers can immediately select the location of the next CoT wherever they need to. Moreover, the candidate nodes can immediately determine their access priority using their neighbor knowledge that is previously acquired from heartbeat packets. Their access priority, k, can be simply calculated by comparing their distances to the center of CoT, L_{CoT}, with the distances of other candidates. As shown in Fig 8(c), nodes simply convert their distance rank into channel access priority, k, using the most recent location information updated from their neighbor nodes in CoT[4].

Assuming that the size of CoT is small enough to guarantee the reliable exchange of heartbeat packets, candidates can maintain identical neighbor knowledge, and then they can build an identical priority list to avoid collisions among them. Also the level of granularity in coordination outputs from current GPS modules are sufficiently fine (submillimeter levels) to avoid multiple candidates with identical distance values. Considering their typical measurement accuracy is of several meters, the digits in the coordination outputs beyond the measurement accuracy are nothing but random values, which can be used to provide enough randomness to prevent collisions among the candidates at similar distance to L_{CoT}.

D. The Size and Location of CoT

In the previous section, we simply assumed that the candidates in CoT can build reliable neighbor knowledge from heartbeat packets. However, we admit that node can collect incorrect neighbor knowledge due to errors in packet receptions caused by channel fading and the mobility of vehicles. In this section, we analyze the probability of successful packet relay (P_s) considering the heartbeat delivery rate (p_h), LSM packet delivery rate (p_r), and the number of candidates used (N).

To characterize reasonable parameter ranges for the size and location of CoT, using the two-hop relay scenario in Fig. 9, we analyze their interactions with successful relay probability, P_s. Using MATLAB, we also simulate the same scenario using a Monte Carlo method [47]. We consider that a LSM

[4]The location information used for priority determination is not the actual current location of candidates but the last location updated by heartbeat message; because the location information in heartbeat message is the common information all nodes within the CoT are sharing.

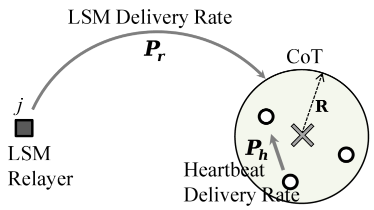


Fig. 9. Two-hop LSM relay scenario for the analyis and simulation of the implicit coordination method.

relay fails either when more than two candidates have the identical highest priority values owing to incorrect neighbor knowledge, or when the LSM packet is not delivered to any of the candidates.

Each LSM relayer sets the size and the location of the CoT for the next hop relay, and stores that information in the ZCOR packet header. The location of CoT is set as the location of the farthest reachable neighbor that contains N candidates in the circle of radius R. However, if the size of CoT R is too large, heartbeats cannot be exchanged reliably ($p_h < 1$). Then the candidates in CoT may no longer have a synchronized priority list, which may result in collisions among them. On the other hand, a smaller R may reduce spatial-diversity gains. A further tradeoff exists with respect to the distance between the CoT and the previous relayer. Let the probability of LSM delivery from the current relayer j to the next-hop candidates be denoted as p_r. If the CoT is located too far from j ($p_r \ll 1$), the relaying process may fail when none of the candidates successfully receive the LSM. If the CoT is located too close, it can increase the hop count along the path and result in additional delay. Therefore, ZCOR can flexibly trade off reliability with efficiency in LSM dissemination by controlling the location of CoT. By putting CoT away from the previous relayer, the area covered by each hop can be extended; however, the reliability can be degraded in fading channel conditions. Also, the maximum size of the access backoff, K, should be chosen considering that it limits the number of candidates used ($N \leq K$).

The LSM forwarding success probability for N nodes in CoT, $P_s(N)$, can be derived from the following equation,

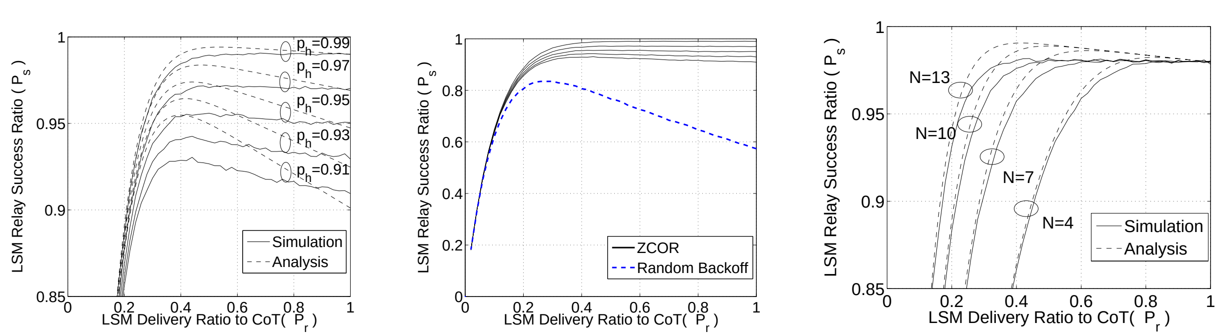
$$P_s(N) = \sum_{m=1}^{N} P_r(N,m)(1 - P_c(N,m)). \tag{1}$$

Here $P_r(N,m)$ is the probability that m out of N candidates in the CoT successfully receives LSM from node j, and $P_c(N,m)$ is the probability of any collision occurs in such a condition. Then, $P_r(N,m)$ can be computed by (2) from LSM delivery rate to the CoT, p_r.

$$P_r(N,m) = \binom{N}{m} p_r^m \cdot (1 - p_r)^{N-m}. \tag{2}$$

Also, the probability of any collision occurring when m out of N candidates in the CoT successfully receive LSM, $P_c(N,m)$, can be calculated by considering all possible priority collision cases over different combinations of receptions for N nodes. For example, when five nodes, a, b, c, d, e, have priorities of $\{1,2,3,4,5\}$ in CoT, and three of them receive LSM ($N = 5, m = 3$). One possible scenario is that node $\{a,c,d\}$ receives LSM, and node a has the highest priority. However, a collision occurs if either node c or d has the same probability as a, which is caused by any of $\{c,d\}$ having missed the heartbeat packet from a. In that case, the probability of collision can be approximated by $P_c(5,3) \approx (1-p_h)^2 + (1-p_h)^4$ assuming $p_h \ll 1$.

Figure 10(a) shows the results on the LSM relay success rate, P_s, over the reliability of heartbeat messages. The figure indicates that the size of CoT should be chosen to allow $p_h > 0.95$ to achieve more than 95% reliability in LSM relays. Note that P_s decreases in high P_r conditions owing to increased collision probability among the candidate nodes when more of them have received the packet to relay while having inconsistent neighbor knowledge. On the other hand, we compared the performance of ZCOR's deterministic priority decision method with a simple random method that each candidate randomly select its own priority. Figure 10(b) shows the CoT based method significantly reduces the probability of collision compared to the random method. In Fig. 10(c), we change the number of candidates in CoT and determine the required number of nodes in CoT for reliable LSM relays. A larger N (the number of nodes in CoT) can enhance the



(a) LSM relay rate in fixed Number of relayer candidate ($N = 10$).

(b) Comparision with random backoff method.

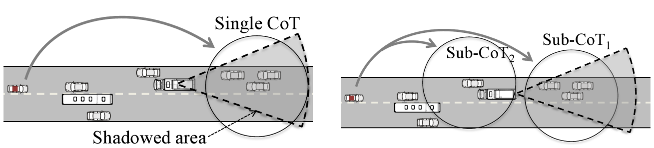
(c) LSM relay rate in fixed heartbeat delivery rate ($p_h = 98\%$).

Fig. 10. LSM relay rate in two-hop scenario.

reliability, however, which requires large K (backoff window size) to assign unique priority value to all candidates. From the figure, we can determine that $K = 10$ is large enough even for $p_r < 0.3$ assuming $p_h = 0.98$.

E. Multi-CoT Against Spatially-correlated Shadowing Effects

For reliable LSM disseminations, the effects from spatially correlated shadow-fading also needs to be addressed, which is problematic when the entire area of the CoT is shadowed as shown in Fig. 11(a). The figure illustrates an example scenario where the LSM relay fails due to showing-fading caused by a large truck blocking the signal from the previous LSM relayer. Since such shadow fading in VANET is dynamic, estimating and responding to shadowing is difficult. Enlarging the size of CoT could alleviate such a problem; however, the enlarged CoT incurs undesirable tradeoffs that produce collisions among the candidates owing to low heartbeat delivery rate. The foregoing discussion shows that, for reliable LSM relay, the size of the CoT should be smaller than the range of reliable heartbeat exchange (e.g., $p_h > 0.95$).



(a) Single CoT. (b) Multiple CoTs.

Fig. 11. Multi-CoT to cope with spatially-correlated shadow fading effects.

We address this problem by splitting a single CoT into a number of sub-CoTs, as shown in Fig. 11(b), to further exploit spatial diversity gains. The sub-CoTs have a smaller number of candidate nodes, which are separated by more than the channel correlation distance. Thus, each CoT remains sufficiently small, but owing to their spatial separation, we can still overcome shadow fading effects (each sub-CoT likely experiences independent fading). Although sub-CoT$_1$ suffers from severe shadow-fading, LSM packets can still be relayed by candidates in sub-CoT$_2$. Even if any node in sub-CoT$_1$ receives LSM, the node receiving the packet can be the next relayer. However, when all the nodes in sub-CoT$_1$ fail to receive LSM, then the candidates in sub-CoT$_2$ are automatically involved in the relay process. Therefore, the decision for the LSM relay is made dynamically for each LSM packet depending on LSM packet receptions either in sub-CoT$_1$ or in sub-CoT$_2$, which is more efficient than relying on a single CoT.

To incorporate all sub-CoTs into the relay process, channel access priorities ($\{1, 2, \cdots, K\}$) are split into a number of access priority subsets by the previous relayer, then each subset is assigned to each sub-CoT. For example, when $K = 10$ and the number of sub-CoTs is 3, three exclusive priority subsets of $\{\{1, 2, 3, 4\}, \{5, 6, 7\}, \{8, 9, 10\}\}$ can be assigned to each sub-CoT, thereby, all the nodes in the three sub-CoTs are involved in the forwarding process. Sub-CoT$_1$ is set to cover the first 3 farthest neighbor nodes from the previous relayer within a circle or radius R. Then the sub-CoT$_2$ is set to cover the next 3 nodes outside of sub-CoT$_1$ (non-overlapping over sub-CoT$_1$), and sub-CoT$_3$ is set to cover the rest 4 nodes. If the network is sparse and cannot find a sufficient number of nodes in a circle of radius R, then the CoT is split until the sub-CoTs include a total of K nodes. Initially, node j finds the farthest neighbor node l_k and sets the center of the first sub-CoT (sub-CoT$_1$) at the location of its neighbor node, which puts node l_k within the range R, and the first n_1 priorities are assigned to sub-CoT$_1$. Then, the second sub-CoT is located at least $2R$ away from the sub-CoT$_1$, and the next n_2 priorities are assigned to sub-CoT$_2$. The process continues until all K priories are assigned to all sub-CoTs.

Input:
j: Current LSM relayer node index
U_j: Neighbor node set of node j in LSM propagation path
K: Maximum access-backoff size
M: Minimum number of CoTs created
R: The size of CoT
Output:
l_{CoTm}: The center location of CoT$_m$
$l_0 = (x_j, y_j)$: The location of node j
$l_k = (x_k, y_k)$: The location of node k for $k \in U_j$
l^m_{CoT}: The center of sub-CoT$_m$
n_m: The number of nodes in CoT$_m$
$\tilde{n}_m$: The number of nodes in range R centered at l_i
Begin:
$m = 1$
Find node $k \in U_j$ that maximize $|l_0 - l_k|$
Find node $i \in U_j$ that minimize $(|l_i - l_k| - R)$
$l^1_{CoT} = l_i$
$n_1 = min(\lfloor K/M \rfloor, \tilde{n}_1)$
while $\sum n_m \leq K$ **do**
    $m = m + 1$
    Find node $i \in U_j$ that minimize $(|l_i - l^{(m-1)}_{CoT}| - 2R)$
    $l^m_{CoT} = l_i$
    $n_i = min(\lfloor K/M \rfloor, \tilde{n}_i)$
end

Algorithm 1: Algorithm selecting the locations for CoTs.

Besides the gains from additional spatial diversity, using multiple CoTs brings several additional benefits. In sparse network conditions, using multiple CoTs prevents the size of CoT from growing too large to incorporate enough number of relayer candidates, which may result in inaccurate neighbor knowledge collection among the candidates. Also, in dense network conditions, the multi-CoT algorithm prevents all candidates from being selected at the edge of the previous relayer node, which results in a high delivery failure rate caused by low LSM reception rate (p_r) for the candidates in the CoT.

V. Performance Evaluation

We implement ZCOR using Network Simulator (NS) 2 version 2.33 [48]. In this section, we explain the details of the simulation setup, channel models, and two baseline protocols to be compared with ZCOR.

A. Baseline Message Dissemination Protocols

Many broadcasting protocols for safety message dissemination have been developed to meet the various requirements for on-road human safety applications. However, it is virtually impossible to compare all broadcasting protocols side by side under the same network conditions, since each protocol is optimized assuming different scenarios under heterogeneous network conditions. Hence, we pick two representative baseline protocols for LSM dissemination, which are typically addressed as short-to-medium range geocast protocols in Adhoc networks.

1) CFG (Controlled Flooding-based Geocast): CFG is based on a controlled flooding type broadcasting protocol. To prevent the "broadcasting storm" problem [49], CFG uses Scalable Broadcast Algorithm (SBA) algorithm [50] that suppresses redundant rebroadcast using two-hop neighbor knowledge. In the SBA algorithm, the nodes receiving LSM packets, put the received packets in their transmission queues, then set their RAD timers and observe channel. However, the packets in the queues for rebroadcast are discarded if their two-hop neighbors are already covered by other nodes' rebroadcast. Such a distributed decision mechanism in CFG increases reliability in severely faded channels by inducing large rebroadcast overhead. Moreover, in dense network conditions, such RAD-timer based redundancy suppression mechanisms cannot efficiently work owing to the latency between the decision on the rebroadcast and the actual attempt of rebroadcast of the packet [51]. Since SBA does not consider the directivity of message propagation, for a fair comparison, RAD values are weighted according to the distance from the previous relayer to give higher priority to edge nodes [51].

2) MRG (Multicast Relay-based Geocast): MRG is based on a relay-based routing protocol, and next-hop relayers are deterministically selected by previous relayers. Compared to most flooding-based broadcasting algorithms, such centralized deterministic methods are more efficient since the amount of redundant rebroadcast can be easily controlled by the previous relayers depending on the network conditions. Considering the reliably in LSM disseminations, we choose Double Cover Algorithm (DCA) [52], which selects one next relayer covering the target geocast region twice at least. Moreover, to cope with erroneous channel conditions, ACK-based retransmission scheme is adopted with seven maximum retransmission attempts.

Compared to slot-based access in ZCOR, both baseline protocols use contention-based 802.11 CSMA MAC. For a fair comparison, however, 802.11e style prioritized transmission is applied to penalize low priority background PSM packets that share CCH with LSM packets. Hence, queues in MAC, the size of contention windows (CW_{min}), and backoff slots are differentiated according to the priority of the packet. Similarly, ZCOR uses exclusively differentiated backoff slots for LSM packets ($0 \leq k \leq K-1$) and PSM packets ($K \leq k \leq 2K-1$).

B. VANET Simulation Model

Path-loss in wireless communications is usually decomposed into distance-based path-loss, terrain dependent shadow-fading X_σ, and small-scale fading Y_r due to multi-path and mobility of mobile nodes. The aggregate path-loss L is represented in (3) at transmitter-receiver distance d with path-loss exponent γ. In V2V communications, where both transmitter and receivers have high mobility, shadow-fading is more dynamic [53], and spatially correlated [13], which is implemented by a 2-D shadowing model [54] using Sum-Of-Sinusoids (SOS) functions as shown in Fig. 12(a). The autocorrelation value for spatial correlation is set as $20\,\mathrm{m}$ according to the empirically measured value for peer-to-peer communications in urban areas [13]. We used the Rayleigh channel model for small scale fading considering the frequent non-line-of-sight conditions in VANET, and the packet receptions rate over distance due to small scale fading is shown in Fig. 12(b).

$$L = L_0 + 10\gamma log_{10}\frac{d}{d_0} + X_\sigma + Y_r\,[\mathrm{dB}]. \quad (3)$$

NS-2 simulation scenarios are created by using *VanetMobiSim* [55] with *Intelligent Driver with Intersection Management model* to model realistic car-chase and lane-changing behaviors of vehicles. Figure 12(c) depicts the road network where vehicles are running total $10\,\mathrm{km}$ track of 8 bi-directional lanes. For analytical simplicity, the locations of HTLF and MTMF sources (e.g., RSUs) are fixed, but single-hop LTHF sources are randomly selected among running vehicles.

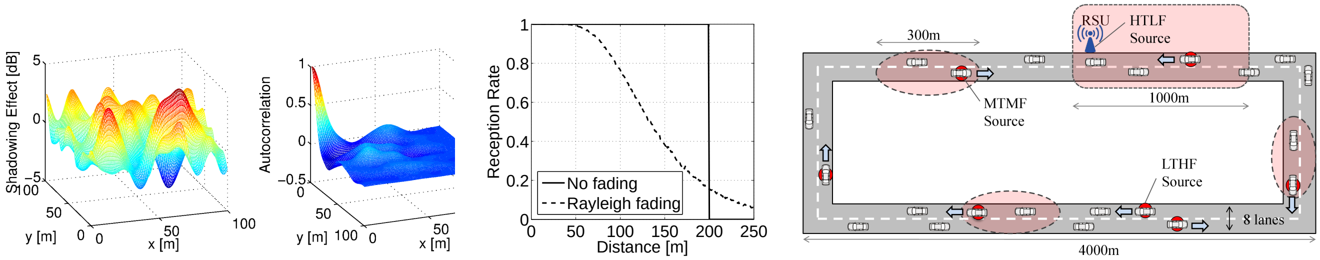
We consider two types of PSM packets which are sharing CCH with LSM. They are heartbeat packets and various types of background PSM packets that are transmitted upto $25\,\mathrm{pkt/s}$ depending on the vehicle's speed [56]. These PSM packets are basically velocity (v) adaptive to prevent the CCH congestion problem. Considering that the accuracy of most GPS-based location finding devices installed in vehicles are around $5\,\mathrm{m}$, vehicles update their location in every $5\,\mathrm{m}$ movement by transmitting heartbeat packets ($0.2v\,\mathrm{pkt/s}$), and the background PSM packets transmission is also set as ($0.2vq\,\mathrm{pkt/s}$) for a background congestion factor q. The details of configuration are shown in Table. II.

TABLE II
PROTOCOL PARAMETER

Protocol Parameters: Common	
T_{SI}	100 ms
T_{CCH}	30 ms
Number of Tx slots in T_{CCH}	30
LSM packet size	300 Bytes
Heartbeat packet size	250 Bytes
Heartbeat transmission interval	5 m/pkt
LTHF LSM (150 m) latency bound	100 ms
MTMF LSM (300 m) latency bound	200 ms
HTLF LSM (1000 m) latency bound	1000 ms
Protocol Parameters: ZCOR	
Transmission slot size	1 ms
Access-backoff slot size	8 μs
First LSM access-backoff	$[0-9]$
Heartbeat packet access-backoff	$[10-19]$
The size of CoT: R	20 m
Protocol Parameters: CFG and MRG	
CWmin for LSM	7
CWmin for heartbeat packet	31
Random backoff slot size	8 μs
Maximum RAD (CFG)	10 ms
Maximum number of retry (MRG)	7

C. NS-2 Parameters and Evaluation Metrics

A number of parameters in NS-2 are adjusted to set the communication range without channel fading as $200\,\mathrm{m}$ when considering field measured data on the communication range



(a) 2-D shadowing model: $d_{corr} = 20\,\text{m}$, maximum fading=± 5[dB]

(b) Path-loss model ($\gamma = 4$) with Rayleigh fading

(c) Highway scenario, 8-lane bi-directional roads

Fig. 12. VANET simulation channel models and scenarios.

for 802.11g based radio systems in [57]. Vehicle density is measured by the number of vehicles in a $200\,\text{m}$ circular communication range. To minimize interference from the nodes out of carrier sensing range, the carrier sensing threshold is set to guarantee packet receptions at $200\,\text{m}$ distance from the transmitter even when another packet transmitted outside of the carrier sensing range interferes with the packet. Because path-loss in vehicular networks is high, in actual network environments, throughput loss due to enlarged carrier sensing range will be small. Other parameters for simulation are presented in Table III.

In evaluating the performance of protocols, we use reliability and overhead. Reliability is measured by LSM delivery ratio for the nodes in the geocast area. Since LSMs have strict latency requirement, packets arriving later then the latency requirement of each LSM class are silently discarded along with out-of-sequence packets. Overhead is measured by the number of rebroadcast packets for each LSM covering its geocast area. We do not consider heartbeat packets as protocol overhead because the heartbeat transmission is considered as a basic network protocol element in VANETs which is widely used for many applications.

TABLE III
SIMULATION PARAMETER

Transmission power	$20\,\text{dBm}$
Reception threshold	$-87\,\text{dBm}$
Carrier sensing threshold	$-102.3\,\text{dBm}$
Capture threshold	$6\,\text{dB}$
Path loss exponent γ	4
Data rate	$3\,\text{Mbps}$
Frequency	$5.89\,\text{GHz}$
Shadow channel correlation distance: d_{corr}	$20\,\text{m}$
Maximum shadow effect	$\pm 5\,\text{dB}$
CCH duration	$30\,\%$ of SI
Minimum number of CoTs in splitting: M	2
Background congestion factor: q	2

VI. Result

For simulations, fifty topologies are created with random initial positions of vehicles. The reliability and the size of the overhead are then measured for each protocol.

A. Reliability and Overhead Comparison

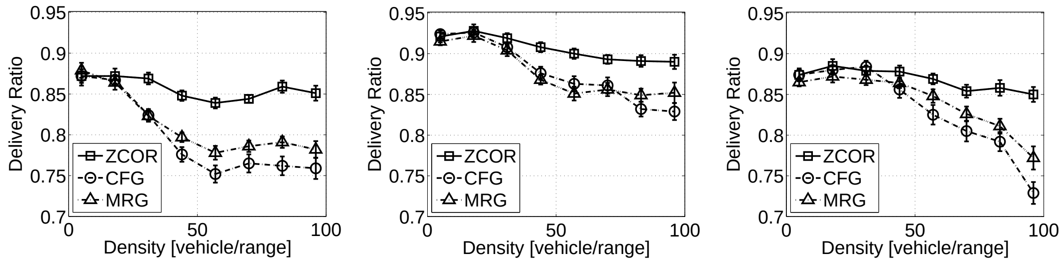
In Fig. 13, we show the reliability and overhead of ZCOR compared with CFG and MRG under different vehicle density conditions. The number of LSM sources for MTMF and HTLF are fixed as 10 vehicles while $20\,\%$ of the vehicles in the networks are randomly selected as single-hop LTHF LSM sources.

Figure 13(a)$-$13(c) compares the reliability of each protocol. As vehicle density increases, the reliability of CFG and MRG degrades owing to packet collisions and transmission delays caused by the increased amount of background packets (including heartbeat packets), rebroadcast LSM packets, and the number of LTHF LSM sources. In congested networks, although LSM packets have higher priority for channel access over background packets in MAC layer, collisions and interference are unavoidable for CFG and MRG in congested networks. When compared to those protocols, ZCOR achieves a higher delivery ratio under overall vehicle density conditions by reserving channels for the duration of the LSM transmission. ZCOR only experiences minor reliability degradation in high density conditions owing to the interference from outside the carrier sensing rage.

Although all three protocols adopted the velocity-adaptive heartbeat rate adaptation method, CCH can still be congested in mid-density network conditions where the number of background packet transmission per unit area peaks as discussed in Section II. Hence, as shown in Fig. 13(a), the reliability degrades at mid-density conditions. Figure 13(b) and 13(c) show the delivery ratio of MTMF and HTLF LSMs respectively. Compared to LTHF, MTMF LSM shows better reliability thanks to the rebroadcast LSM packets from the second-hop relay nodes. However, the reliability of HTLF LSMs is lower than MTMF as the target geocast region extends over a large area, because target nodes many hops away from LSM sources are easily disconnected.

Figures 13(d) and 13(e) compare the rebroadcast overhead for LSM dissemination to cover 300 m (MTML) and 1 km (HTLF) geocast area. As discussed in Section V, we find that as the network is congested, CFG relying on RAD based rebroadcast suppression mechanism, cannot suppress redundant rebroadcast enough, which further congests the network. Compared to flooding based CFG, ZCOR prevents the channel from being extremely congested even in high vehicle density conditions by limiting the number of rebroadcast packets at each hop.

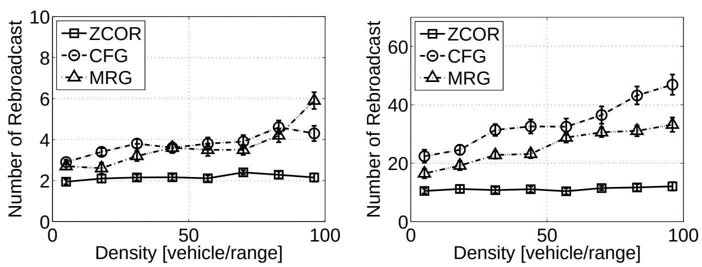
On the other hand, although MFG can efficiently control



(a) Reliability of LTHF: LSM Delivery ratio.

(b) Reliability of MTMF: LSM Delivery ratio.

(c) Reliability of HTLF: LSM Delivery ratio.



(d) Overhead of MTMF: Rebroadcast overhead.

(e) Overhead of HTLF: Rebroadcast overhead.

Fig. 13. Reliability and overhead under various vehicle density conditions.

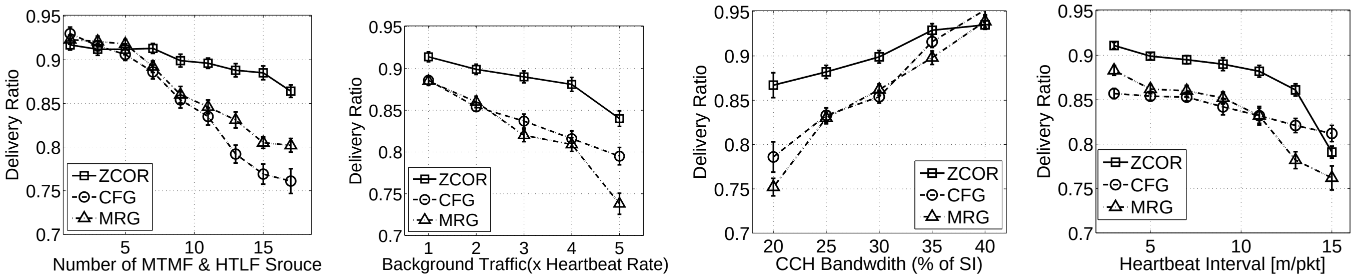
the rebroadcast overhead by selecting a single next-hop relay node, the overhead from packet retransmission usually increases in unreliable fading channel conditions. Since the centralized next-hop selection method of MFG is inefficient and unreliable in erroneous VANET channel conditions, ZCOR overcome such a problem through the opportunistic LSM forwarding mechanism. Compared to those two protocols, the overhead in ZCOR is scalable over the number of hops and the ranges of geocast as a result of the gains from multi-node diversity. We can find that ZCOR can efficiently eliminate redundant rebroadcast, which in turn produces reliable message dissemination in congested network conditions.

B. The Performance of ZCOR in VANET Conditions

We measured the reliability of MTMF and HTLF LSMs under various VANET conditions considerable in real-road conditions. Figure 14 shows the results over four different network configurations. Firstly, Fig. 14(a) shows the result when we changed the number of MTMF and HTLF LSM sources. As the number of LSM source increases, CCH is more congested and the reliability of CFG and MRG degrades quickly. In Fig. 14(b), we can also find similar results when we increase the amount of non-emergency background packets sharing CCH with LSM. Compared to CFG and MRG, as long as CCH has enough slots for assignment to each LSM source, the reliability of ZCOR is not significantly affected by the network congestion status. However, the capacity of reservation-based MAC is hard bounded, which is limited by the number of slots. Therefore, when the number of LSM sources exceeds the number of available slots for a given CCH bandwidth, the LSM sources must reduce their LSM transmission rate by increasing their LSM update cycle; otherwise, a new LSM source cannot find its transmission slot until one of the existing LSM sources finishes its transmission. Hence, LSM source nodes need to monitor the occupied number of slots in CCH to adjust its LSM period according to CCH utilization.

Therefore, the bandwidth saved by ZCOR can be used to increase the utility of SCH, which is useful for various applications designed for VANET. In Fig. 14(c), we measure reliability under various CCH over SI ratio conditions. Because the rebroadcast redundancy in ZCOR is small, its reliability does not degrade much even with small CCH over the SI ratio as long as transmission slots are not fully occupied by LSM sources.

In Fig. 14(d), we increase the interval between heartbeat packet transmissions to measure the impact from the accuracy of neighbor knowledge. As the interval between heartbeat packets increases, the overhead from heartbeat packets reduces, but the information on neighbor nodes' existence and location becomes incorrect. As MRG mainly relies on neighbor knowledge to select the next forwarder, its performance is more vulnerable to the change of heartbeat transmission rate compared to CFG. As the update from heartbeat packets is delayed owing to network congestions, relayers tend to have incorrect neighbor knowledge, and relayers are likely to fail in choosing the best next-hop relayer. However, CoT based ZCOR is less dependent on neighbor knowledge, and is more resilient to the change of heartbeat transmission rate.



(a) Various number of sources (MTMF & HTLF LSMs) conditions.

(b) Various background packet transmission rate conditions.

(c) Various CCH bandwidth conditions.

(d) Various heartbeat packet rate conditions.

Fig. 14. The reliability of MTMF and HTLF LSMs under various VANET conditions; vehicle density is 55 [vehicle/coverage].

C. The Performance of Multi-CoT Against Shadow Fading

In Fig. 15, we show how much the multi-CoT algorithm improves the reliability of LSM dissemination in severe shadow fading conditions. In the simulation, we fix the number of candidates as 10 and increase the maximum shadow-fading level upto $9\,\mathrm{dB}$. We then compare the reliability of ZCOR when different numbers of sub-CoTs are used. The results show that it is important to increase the number of sub-CoTs in severe shadowing conditions since reliability severely degrades when Single-CoT is used. However, using three CoTs (Triple-CoT) does not significantly improve the performance of ZCOR. As the nodes in the network experience deeper shadow-fading, which is spatially correlated over several tens of meters, using only a single CoT is less reliable since the nodes in a single CoT will experience similar fading. Therefore, in such conditions, it is important to use multiple CoTs to fully exploit spatial diversity gains.

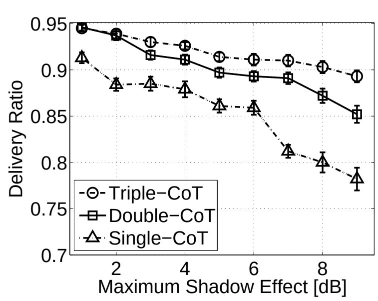


Fig. 15. Gains from multi-CoT against shadow fading; vehicle density is 55 [vehicle/coverage].

VII. Conclusion

We proposed *ZCOR* , an algorithm for mission-critical safety-related message dissemination in VANETs, which are characterized by dynamically changing network environments. *ZCOR* is a novel location-based opportunistic packet relay algorithm based on implicit coordination technique. Although *ZCOR* requires tight time-synchronization among nodes, it enables efficient and scalable multi-hop packet dissemination with significantly reduced overhead for the coordination of relayer candidates for opportunistic relay. Through extensive simulations, the performance of *ZCOR* is proved to meet the strong latency restrictions of safety-related messages over a wide variety of network conditions in VANET. Compared to the existing message dissemination algorithms, *ZCOR* showed similar or better reliability with much less rebroadcast overhead (up to 55% reduction). Such a bandwidth saving can be exploited to increase the utility of the service channel from 50% to 80% by reducing the size of control channel.

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