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Receiver Consensus: On-Time Warning Delivery for Vehicular Ad-Hoc Networks

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ABSTRACT To improve safety, a warning message in VANETs should be delivered both reliably and urgently. Existing solutions either tend to compromise propagation delay or do not reach high reliability due to *broadcast storm* problem caused by excessive retransmissions. We propose Receiver Consensus, which exploits geographical information to help nodes autonomously achieve agreement on forwarding strategies. Each forwarding candidate ranks itself and its neighbors (who affirmatively or potentially received the message already) by distance to the centroid of neighbors in need of message, to assign different priority in forwarding among neighboring nodes and remarkably suppress unnecessary retransmission, while enabling best nodes to transmit the packet without waiting. The effectiveness and efficiency of this method are validated through extensive simulations under 802.11p settings. The results demonstrate that the proposed protocol achieves the high reliability of leading state-of-the-art solutions, while at the same time significantly enhances timeliness, dedicating itself to disseminating emergency messages in 2D vehicular networks. Our solution is also superior to all existing solutions in 1-D scenarios. The algorithm is also generalized for vehicles with heterogeneous transmission ranges as follows. Candidate neighbors are ranked using d–r instead of d for ranking, where d is the distance to the ideal forwarding location and r is the communication range of a node.

INDEX TERMS VANET, location-assisted, routing, mobile computing.

I. INTRODUCTION

Vehicular Adhoc Networks (VANETs) are special Mobile Adhoc Networks (MANETs), in which networked nodes are vehicles equipped with wireless communication capability. They cooperate to deliver data without centralized administration. VANETs raise new challenges to the design of data communication protocols due to the high dynamicity of the underlying topology, the intermittent connectivity, and fast changing density. Low message reception rate, and periodical beacon exchange among neighbor nodes require specialized strategies different from those in MANETs.

Broadcasting is the message delivery task from a source node to all other nodes in a network. Many important VANET services, ranging from safety applications to location-based advertisement, rely on the reliability and efficiency of underlying broadcast protocols. Applications have different requirements on broadcast protocol design. Location-based advertisement emphasizes reliability in order to achieve higher coverage of vehicles, while warning delivery, which broadcasts emergent information to approaching vehicles, requires both low propagation delay and reliability.

Generally, a broadcast in a network begins with transmission from a source node. In *blind flooding* solution, all receivers relay the message upon its reception and ignore the subsequent copies of the same message [1]. Because of shared wireless channel, blind retransmissions lead to contention and collision in transmissions among neighboring nodes [2], which degrades reliability. Existing solutions to this *Broadcast Storm* problem for MANET cannot be directly applied in VANET contexts due to their unrealistic assumption on full connectivity and high message reception rate, and time inefficiency [3].

Current approaches addressing this problem in VANETs can be categorized into two classes. In *receiver-oriented* approaches, receiving nodes negotiate on forwarding the message, while in *sender-oriented* approaches, sender decides which of its neighbor(s) should act as the next-hop forwarder and piggybacks this decision to the transmitted message.

Existing receiver-oriented approaches are based on local timers, which differentiate the broadcast time of each node by setting different timeout. A node starts a timer after it receives a broadcasted message, and may retransmit it when the timer expires. The duration of waiting time is tuned according to local knowledge such as the cardinality of neighbors that did (did not) receive same message so far, the CDS (connected dominating set) status, or the distance from the source node. Timeout differentiation resolves the broadcast storm problem. However, delay at every hop slows down the propagation and hence the timeliness degrades. This limits the use of timer-based approaches for e.g., time-critical warning delivery.

Sender-oriented approaches [4]–[7] potentially achieve instant retransmissions. Sender dedicates one or more neighbors as forwarders, which are then able to retransmit immediately. This appears promising approach for warning delivery. However, sender-oriented approaches suffer from low message reception rates in VANETs. The dedicated forwarder may not receive the request to forward (farther nodes normally have lower packet reception probability), or may not be even a neighbor anymore. Even with perfect message reception up to certain transmission range (ideal unit disk graph model), this approach does not guarantee delivery in 2D scenarios.

In both approaches, generally, the farthest neighboring node is forwarder to accelerate the message propagation. In 2-D scenarios (urban areas), selecting farthest nodes has a "jump over intersection" issue. In Fig. 1, after transmission by *A*, *C* is the next-hop forwarder. However, if *B* does not retransmit, node *D* will never receive the message. In sender-oriented approach, vehicle *A* may not be aware of vehicle *D* and will not instruct *B* to retransmit. Therefore receiver oriented approaches will allow vehicle *B* to recognize the need to serve *D*. In [8], this is achieved by the lack of acknowledgment for the circulated message in the next beacon of *D*.

Due to high packet loss rate in VANETs, additional retransmissions might be needed to assure that all vehicles, between two successive forwarders, eventually receive the message. Further, temporary disconnection, which is frequent in VANETs, requires the addition of mechanism to restart message propagation upon discovery of new neighbors.

The knowledge of geographical information and neighboring knowledge at receivers' side is an excellent starting point to select immediate forwarders. We first consider the case of homogeneous VANET (transmission ranges of all vehicles are same), and later allow heterogeneous transmission ranges.

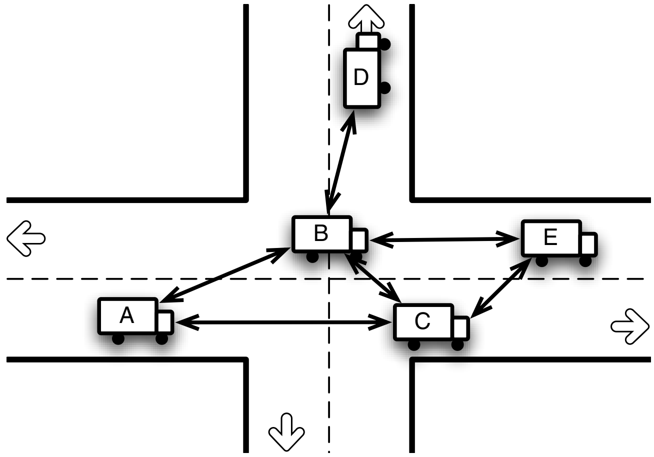

FIGURE 1. **Vehicle *C* as farthest forwarder of *A* does not cover vehicle *D* on another road. Receiver-oriented decisions may allow vehicle *B* to retransmit before *C* and cover *D* and *E*, or additionally after *C*'s retransmission to cover *D*.**

The major challenge is how to coordinate receivers to make message forwarding rapidly and orderly.

We propose a broadcasting scheme based on **Re**ceiver **C**onsensus (*ReC*), which is a fully distributed and effective warning delivery algorithm suitable for VANETs with all mobility and density scenarios. The key idea behind *ReC* is that receiving node retransmits immediately if it considers itself as the best forwarder. Rather than selecting proper forwarders by the sender, we adopt flexible receiver consensus, which can be applied in 2-D or even 3-D scenarios. Once a node receives a broadcast message, based on its local knowledge, it ranks the potential (and known) forwarders according to their geographical locations. Ranking is based on distance to an ideal forwarder, located at the centroid of (remaining) neighboring vehicles believed to need the message. In essence, time delays are computed but not run by nodes; instead, all known candidates are instantly ranked by these timers resulting in zero forwarding delay. Each potential forwarder picks up a time slot according to its ranking.

The best forwarder retransmits immediately after it receives the packet, while other nodes would take action if better ones fail to fulfill their duties. Otherwise they will update the reception information and reassess the need for further retransmissions. *ReC* demonstrates its inherent advantages and great potentials in assuring reliability and timeliness. To the best of our knowledge, this is the first broadcast protocol in VANETs solving broadcast storm and aiming at perfect timeliness in 1D, 2D and 3D scenarios. It is the first receiver-oriented approach with instant retransmission, previously possible only for sender-oriented approaches. To address scenarios with different transmission ranges at each vehicle, candidate neighbors can be ranked using d–r instead of d for ranking, where d is the distance to the ideal forwarding location and r is the communication range of a node.

The remainder of this paper is organized as follows. Section II presents literature review. In Section III we give insight onto the proposed protocol and describe it in detail. We also discuss algorithm under heterogeneous communication radius. We conduct extensive simulation-based evaluations and present the performance results and related discussions in Section IV. Finally, Section V concludes the paper. Preliminary conference version of this article appeared in [9].

II. LITERATURE REVIEW

A plethora of existing VANET broadcasting protocols are described in several surveys [3], [8], [10], [11]. Here we describe only protocols most relevant to our proposal.

A. RECEIVER-ORIENTED APPROACHES

Osafune et al. [12] proposed Multi-hop Vehicular Broadcast (MHVB) scheme. A threshold distance is set such that nodes further than this threshold do not compete to retransmit. Each receiver sets a timer based on its distance to the source, so that further nodes wait less time before retransmission. When a node receives multiple copies of the same message, it checks if it is inside a circle with any two senders as the diameter. If so, it cancels the retransmission. MHVB detects congestion by short-range sensors, and expands the waiting time of congested vehicles (inversely proportional to the number of vehicles around). This increases the time delay and contradicts the MHVB original motivation of fast retransmission.

A *Broadcasting from Static to Mobile (BSM)* scheme was proposed in [11] and [13]. BSM is based on *connected dominating set (CDS)*. In a graph, a set is said to be *dominating* if every node either belongs to it or has a neighbor belonging to it. It is normally sufficient to run broadcast task on nodes in CDS in order to cover the whole network, thus the number of retransmissions can be highly reduced. A node's CDS status can be locally computed on the fly using the algorithm described in [14] and only 1-hop neighbor information (obtained from periodical DSRC beacons) is needed. To further suppress retransmission, BSM applies *neighbor elimination*. Each node maintains two lists: R and N lists of current neighbors that received (did not receive, respectively) the message so far. Initially, all neighbors are in N list. Whenever node x receives a message from y, it adds y and its neighbors to its R list, and eliminates them from its N list. It then sets a timeout to wait before possible retransmission, as inversely proportional to the number of non-informed neighbors, and nodes in CDS always wait shorter than non-CDS nodes. While waiting, a node keeps updating its R and N lists along with timeout based on the received traffic and retransmits at timeout expiration if N is then non-empty. If a new neighbor is discovered later, the timeout is restarted as N becomes non-empty. BSM does not recognize transmission error due to the lack of acknowledgement mechanism. Besides, retransmissions to new neighbors may not be always needed, as they might be aware of the message already.

ABSM [8] extends BSM to overcome above-mentioned weak points. It adds identifiers of circulated broadcast messages into periodical beacons as acknowledgement. After retransmission by itself or a neighboring node, all neighbors of transmitter (within a range of likely reception) are placed in R list. They are moved to N list if they later do not acknowledge the receipt of the message in their beacons (within an ACK timer). In this way, transmission failure can be detected and retransmission will be scheduled, and new neighbors who already know the message will not trigger retransmission. The waiting time ($W/|N|$ for CDS nodes and $W+W/|N|$ for non-CDS nodes) has a parameter W (the longest waiting time of a node) with unclear tuning. It also does not include distance to sender, and needs further adjustments because some non-CDS nodes may retransmit before some CDS nodes.

Emergency Message Dissemination with ack-Overhearing based Retransmission (EMDOR) [15] tries to remove timers on each receiver and use probabilistic method to suppress broadcast storm. After an originator broadcasts an emergency message, a relay node immediately retransmits it. Relay node is selected using the p-persistence method [2]. In that method, a forwarding area is divided into slots, and nodes apply a probability p to relay, starting from the farthest slot, with a certain inter-slot delay before nodes in the next slot consider transmitting. Note that there could be collisions among few nodes in the same slot if both decide to retransmit, or failure to transmit when some nodes indeed exist in a slot. After retransmitting, the relay node sends an ACK to reply to the originator. It serves for other nodes to learn about the message if they receive ACK but not the message (they can then send a request to the relay node to retransmit again). A possible failure is when a node does not receive a message and also the acknowledgment related to that message. Although this protocol achieves higher reliability than other protocols, it suffers from high overhead because every message is encapsulated with additional information such as a message originator's address, a broadcast identifier and a relay node location.

In [16], emergency messages are given higher priority to forward than other safety-related messages, while regular beacons have the lowest priority level. DIFS is mini-slotted so that emergency messages are retransmitted almost instantly (with delay only corresponding to some physical layer constraints such as switching from receiving to transmitting mode, and one-hop channel propagation delay). Transmitting nodes add multi-frequency busy tones that do not affect data transmissions but prevent any transmission by two-hop neighbors. The nodes hearing the busy tone inhibit all their transmission attempts of beacon messages or other lower priority messages until the specified number of copies of such a message has been received. These ideas are orthogonal to our *ReC* warning delivery protocol, and can be incorporated into it as part of a transport layer addition. In [16] source node collects acknowledgments from neighbors by hearing their retransmissions of same warning message. Our REC protocol is based on beacon based acknowledgments but it also makes use of full warning message serving as acknowledgment. Receiving nodes apply time delay inversely proportional to distance from the sender, before attempting retransmissions (as in [4], plus a random component). When a node receives warning message, it continuously pushes to retransmit it until it receives *Nc* copies of same warning message from its neighbors (its own retransmissions do not count). Message lifetime (a parameter) needs to expire between two such retransmissions, and subsequent retransmissions are not subject to competing with neighbors (as per flow chart in [16]). Only the first retransmission is subject to competing with neighbors by time delay function. Thus competition can be repeated following reception of each new copy of received message, until the node is the winner and retransmits for the first time. This algorithm has several drawbacks. A node may receive *Nc* copies and never win to retransmit, so its neighbors do not get acknowledgment from it. In this case neighbor do not know if the node ever received the warning message. *Nc* is a parameter with unclear tuning. It may force additional retransmissions even if all neighbors already acknowledged the message (e.g., when *Nc* value is higher than number of neighbors). *Nc* value also could be too low, since retransmissions may stop prematurely, before certain neighbor ever retransmitted message, and consequently they could still be in need of receiving warning delivery message. Next, message lifetime is a parameter timer between two retransmissions, which adds to delay in spreading warning when the second copy by same node is essential for some neighboring cars to receive the message. Its role appears to be similar to the time between two beacons in other existing algorithms, including our *ReC*. Finally, algorithm forces all nodes to retransmit warning as part of their acknowledgment process. In dense networks, when all nodes might already heard the message, this may cause unnecessary collisions of many messages attempted in short time following original reception (slotted nature of delay function, despite random component, will infer them) and further delays.

B. SENDER-ORIENTED APPROACHES

A sender-oriented protocol is proposed in [4]. To retransmit a message, a node classifies its neighbors into three groups according to their relative position: same road ahead, same road behind, and different road. The farthest node in each group is selected as forwarder. The sender then broadcasts the message together with the IDs of forwarders. Only these selected forwarders will rebroadcast the message.

Li et al. [5] proposed a relay selection algorithm. As in [4], the farthest node is selected as forwarder for fast propagation. The extension is that it would also choose the node closest to the middle between the sender and the forwarder as a makeup node. These makeup nodes would also retransmit to increase reliability in case some neighbors fail to receive the packet. Without acknowledgments, this algorithm cannot terminate. In our simulations, we consider ACK based variant of this Forwarder Selection algorithm. Nodes attach their ACKs in beacons, and the selected relays would only retransmit upon the discovery of neighbors without ACKs. It is not clear how to extend this algorithm to 2-D scenarios.

The Distributed Fair Power Adjustment Protocol (D-FPAP) is proposed in [6]. Using information gathered from beacons, each node applies the ‘‘water filling’’ approach, increasing its power as long as the minimal beaconing load condition is satisfied. These power levels are then exchanged with neighbors. The node then selects the smallest power level among the locally computed and those by the surrounding vehicles. Then, [6] discussed the Emergency Message Dissemination for Vehicular environments (EMDV) algorithm. A sender node reduces the communication range and allows only neighbors within the smaller forwarding range to retransmit. It pre-selects its next hop that retransmits immediately (if it has received a message), as the furthest vehicle within its forwarding area. All receivers enter contention with time delay according to their distance from the sender. The contention will restart after each node has received a copy of the same message, according to the distance from the latest sender. There are no acknowledgments. The combination of D-FPAP and EMDV enhance their performance because D-FPAP ensures that the channel busy time is kept to a level on which EMDV can operate efficiently. A problem in this protocol is large message overhead caused by the large size of beacons or the need for sending additional beacons. In addition, this method may unnecessarily cause failures of alert messages when the forwarding area is empty and there are still vehicles within the communication range of the sender.

Amoroso, Marfia and Roccetti [7] considered 1D warning delivery problem. They assume asymmetric communication model: each car communicates its transmission range with its beacons. Therefore receiving vehicle B may not be able to respond to sender A directly, but could do so via intermediate nodes, which is envisioned during beacon period, so that A learns about its receivers (directed neighbors). Dedicated forwarding is applied. Among all directed neighbors of A, A preselects the one which maximizes $d + R$, where d is its distance from A, and R is its transmission radius. Selected neighbor B recognizes in the message that it is dedicated forwarder, and retransmits further. This algorithm (called AMR here) received some media attention (http://www.bbc.co.uk/news/technology-14125245). We observe that adding neighborhood information (to inform sender node about its directional neighbors, possibly several hops away) to regular beacons would increase beacon length and consequently beacon reception failure rate which adversely depends on packet length. Further, it dedicated forwarder orientation suffers from the drawback already discussed in this article. Finally, the algorithm does not address 2D scenarios (this could be resolved in principle by selecting one dedicated forwarder along each road known to sender node, in desired road directions; however this may require road map knowledge as additional input).

Note that, other approaches based on the road side infrastructure (e.g. [17]) also act as possible options for message delivery. In this study, we are interested in the currently realistic case when road side units are sparsely deployed and not able to assist warning delivery process.

III. PROTOCOL DESIGN

A. OVERVIEW

We propose a warning delivery scheme *ReC*, which determines forwarders according to REceiver Consensus. *ReC* is parameter-less, fitting all mobility and density conditions, and applicable to 1D, 2D and 3D scenarios.

We assume that vehicles are GPS-enabled. Following DSRC/WAVE standard [18], each vehicle periodically (e.g., every 300 ms) broadcasts a beacon containing basic information including geographic position. Nodes also use one bit in their beacons to exchange their CDS status so that a node's CDS status can be locally computed on the fly using the algorithm described in [14].

We use *a round* to refer to the period between two consecutive beacons. Nodes send beacons (and start their round) at different times to avoid collisions. Each round is divided into T time slots; one slot suffices to fit warning message.

ReC consists of two components: location-based ranking and acknowledgement-based neighbor elimination. The former enables fast propagation without unnecessary waiting time latency at every hop, and the latter guarantees reliability while reducing the number of retransmissions considerably. In both components, receivers utilize local knowledge to achieve consensus on forwarding strategies. Figure 2 summarizes the complete algorithm.

B. NEIGHBOR ELIMINATION COMPONENT AND STATUS UPDATES

Neighbors' geographic positions, local topology and CDS are updated by beacons. The topology can also be modified dynamically between beacons by estimating speed and direction of movement based on last two beacons. Beacons also include acknowledgement of warning messages. For each warning message *m*, each node divides its neighbor nodes into three sets, according to their reception status: *R* (affirmatively received, nodes that attach ACK in their beacons), *P* (potentially received), and *N* (not received, nodes without ACK in their beacons). Potentially received is a transient status before receiving ACK. Receiver node computes each neighbor's distance to the sender. Neighbors whose distances to sender are less than sender's communication radius, are marked as potentially received and moved into set *P*.

Node *A* updates the three sets in the following cases.

1) A node (can be *A* itself) broadcasts *m*: in this case all nodes in *N* covered by the sender are moved into *P*. Also the sender is moved into *R*.
2) A beacon from a node *B* (can be newly discovered neighbor) is received: if *ACK*(*m*) is attached, *B* is moved into *R*, otherwise (missing *ACK*(*m*) in the beacon) *B* is moved into *N*.
3) Beacons from a known neighbor *B* have not been heard for a period of time: it is possible that *B* moves away from *A*. *B* is removed from local neighbor list and the three sets in this case.

ReC at each node c for a message m

Initialize: P, N, R are empty
event *beacon received from neighbor* n
    update CDS status **if** $ACK(m)$ *attached in beacon* **then**
        add n to R and remove n from P, N
        if *broadcast of* m *is scheduled* **and** $N = \emptyset$ **then**
            cancel scheduled broadcast
    else
        add n to N and remove n from P
        if *broadcast of* m *is not scheduled* **then**
            perform `ideal_location_ranking`

event *message received from neighbor* s *or generated by this node* $s = c$
    add s to R and remove s from P, N
    add nodes in N within communication range of s to P and remove them from N
    add other neighboring nodes of c (not already in R) to N
    if $c = s$ **then**
        forward message via IEEE 802.11
    else
        if N *is not empty* **then**
            perform `ideal_location_ranking`
        else
            cancel scheduled broadcast

function `ideal_location_ranking`
    $\mathcal{I} \leftarrow$ centroid of nodes in N
    rank nodes in $P + R$ based on distance to $\mathcal{I}$ and current CDS at c
    if c*'s ranking is* $\#1$ **then**
        forward message via IEEE 802.11 in the next (1-th) slot
    else
        $r \leftarrow c$'s ranking
        schedule broadcast at the r-th following timeslot

event *beacon not received from* n *for a while*
    if N *contained only* n **then**
        cancel timer
    remove n from N and from neighbor set

FIGURE 2. **Pseudocode for *ReC* algorithm.**

Each warning message has its duration. Upon expiration of *m*, the corresponding acknowledgment will not be attached in future beacons. This finalizes our acknowledgement-based neighbor elimination component.

Whenever *N* becomes empty from non-empty, retransmission (if scheduled) of *m* is cancelled immediately. Reversely, if *N* becomes non-empty from empty, retransmission of *m* will start, using location-based ranking algorithm.

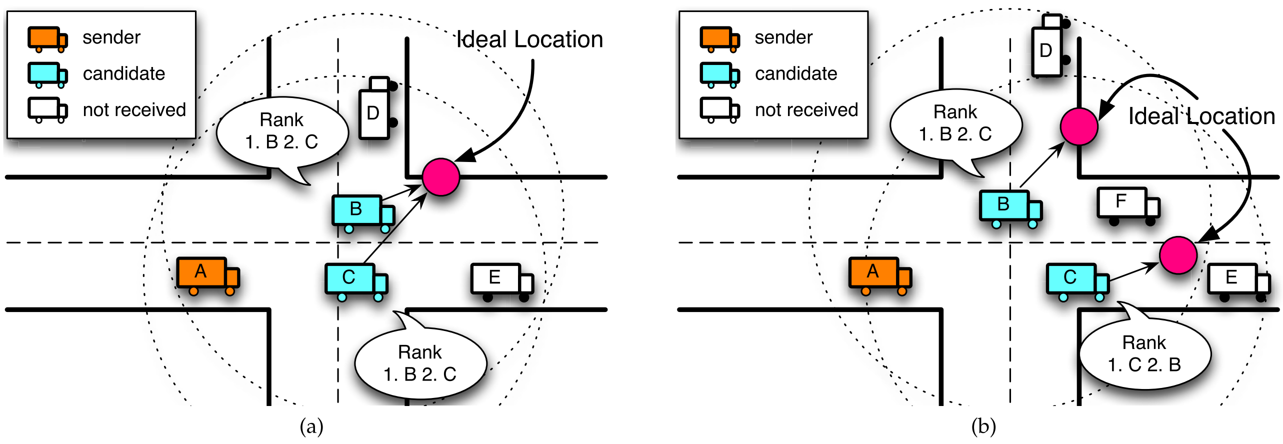

FIGURE 3. Ranking examples.

C. LOCATION-BASED RANKING

All neighbors that affirmatively or potentially received the message are ranked in the order of the distance to the "ideal" location. The node then picks up r-th upcoming slot (where r is its ranking) to retransmit the message. Thus if the node ranks itself first, it retransmits m immediately (in the next slot). If all neighbors believed to have lower ranking remain silent in previous slots, node will retransmit in r-th slot. All nodes in N are moved into P after retransmission. While waiting for its time slot, node keeps listening on the channel. Neighbors' reception status and ranking are updated upon the detection of successive broadcasts. If no more neighbors are in need of the message, the node cancels its retransmission.

The "ideal" location for the next hop forwarder is the centroid I of all nodes in N (the point having average coordinate values of "not received" neighbors). Thus it can be computed as follows:

$$\begin{cases} x(I) = \frac{\sum_{A \in N} x(A)}{|N|} \\ y(I) = \frac{\sum_{A \in N} y(A)}{|N|}. \end{cases} \tag{1}$$

All candidate nodes that are (based on local knowledge) in CDS are ranked before all the nodes that are not in CDS. Within each CDS and non-CDS candidate neighbors, further ranking is performed as follows. The node ranks all nodes in $R \cup P$ according to their distances to the ideal forwarding location I. The smaller the distance is, the higher the ranking. In case of ties, we prefer node with larger distance to the source node (whose coordinate is attached in the warning message). The x-coordinate and y-coordinate can be used for final resolution, if needed.

In 2-D case, the centroid covers large number of nodes in need of forwarding. In 1-D scenarios, it will select the farthest forwarder candidate, which is optimal in propagation efficiency (see Property III-D in Section III-D).

Fig. 3 shows two examples of location-based ranking. In Fig. 3(a), both B and C make consensus that B is closer to the ideal location (and thus B ranks 1). Consequently B retransmits immediately. Conflicts will happen in cases like Fig. 3(b), where both B and C declare themselves as #1, which leads to conflict at F. However, D and E can successfully receive the package despite collision, possibly experienced at F only. In our design, MAC layer competition follows network layer one. Thus B and C enter immediately MAC layer competition in 802.11 style, with high probability of starting their retransmission at different mini-slots. When they are neighbors, retransmission by one of them will prevent retransmission by the other.

Following lack of acknowledgment from F, B and C would compete again and will make consensus that closer of the two, C, will have then rank 1 and retransmit.

For rare cases, it may take a very long time to resolve a conflict. For example, B and C are neighbors of A but B and C are not aware of each other. Both of B and C would rank themselves to be 1st when forwarding message m to A, and thus causing collisions again and again. To resolve this, we introduce an 'invitation' mechanism. Following above example, actually A can learn that B and C both have message m which is needed by A, thus A can actively select the one closer to itself, say B, as the forwarder of m, and put this information in its beacon. When B and C receive A's next beacon, they know that A does not receive m due to collision, and this time only B should broadcast the message.

Fig. 4 shows an example on behavior of our broadcasting algorithm, assuming ideal message reception unless there is a collision. Nodes in bolder circles (A, B, D, E, H) have declared themselves to be in CDS by their beacons.

1) At the beginning, the source node S broadcasts a message to A and B.
2) A and B have mostly different neighborhood. Each of them assigns rank 1 to itself (A is closer to centroid

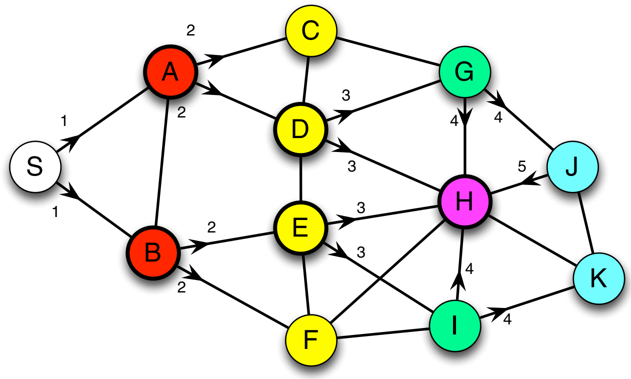

FIGURE 4. An example on behavior of ReC. Arrows show the transmission of each round.

of C and D than B; B is closer to the centroid of E and F than A). They both retransmit in the 1st slot.

3) C and F know from beacons that D and E are in CDS, so they rank themselves after D and E. D is closer to centroid of G and H, while E is closer to centroid of H and I. So both of them retransmit immediately. Their messages are received properly by neighbors G and I, but collide at H. D and E are not aware of this collision at this moment.
4) G and I assume H has received the message. Since H is in CDS, G and I assign rank 1 to H and assign rank 2 to themselves. G and I retransmit in the second slot, causing again collision at H. J and K receive the message successfully.
5) Later, H broadcasts its beacon and invites its closest neighbor J to retransmit in the first slot afterward. Other nodes remain silent so H receives the message successfully.

All nodes have received message, and all but one got it in very short time. The overall number of transmissions appears increased, compared to the ABSM algorithm [8].

D. ANALYSIS

There are several possible reasons for a neighboring node B with higher ranking not to transmit in its corresponding time slot, as observed by node A. Most commonly, B may not have the copy of message due to packet loss. Next, B could retransmit but the packet may not be received by A. B may not be located where assumed by A, causing even disconnection from A. Finally, since each node ranks its neighbors based on its local knowledge, diversity in neighboring knowledge among nodes may lead to inconsistency among local rankings. For instance, in node A's local ranking (calculated based on A's neighbor set), A ranks 2nd and B ranks 1st. But in node B's local ranking, B itself may not rank 1st because it may have different neighbor set. This *loop waiting* may lead to loss of efficiency since no node devotes itself to transmit in the first time slot after reception.

In this theoretical analysis, we assume that no packet loss occurs during transmission, and ignore the mobility of nodes. First, we discuss the *loop waiting* issue. *ReC* is *loop waiting free*, meaning that in a set of forwarder candidates $\{F_1, F_2, \ldots, F_k\}$, there exists at least one node F_i who ranks itself 1st in its local ranking, and will retransmit immediately after reception of the message. Here we provide a proof for the simplest case of two nodes. For two nodes A and B (both received the message m), we will show that it is not possible that B ranks higher than A in A's local ranking, while A ranks higher than B in B's local ranking.

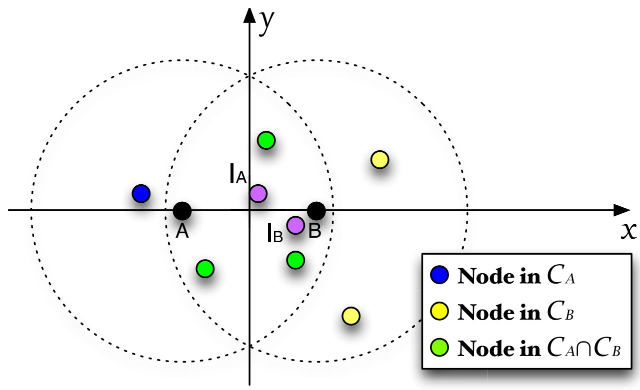

FIGURE 5. Reference figure for Property III-D.

Property 1: If nodes A and B have equal communication range, share same common nodes in need of message, and B ranks higher than A in A's local ranking, then B also ranks higher than A in B's local ranking.

Proof: Refer to Fig. 5. For simplicity, we set the origin at the mid-point of A and B, and set $\overrightarrow{AB}$ as x-axis. Thus $x(A) = -x(B)$. Suppose the ideal location computed by A is I_A, and the ideal location computed by B is I_B.

$\|\overrightarrow{BI_A}\| < \|\overrightarrow{AI_A}\|$ since B ranks higher than A in A's local ranking. All nodes closer to B than A lie on the same side of symmetry line $x = 0$ as B. Since $x(B) > 0$, this means $x(I_A) \geq 0$. To prove B ranks higher than A in B's local ranking, we only need to prove $x(I_B) \geq 0$.

Define $\odot A$ as the communication range of A, and $\mathcal{C}_A$ as the set of nodes who do not receive the message and covered by A's communication range. By definition we have

$$x(I_A) = \frac{\sum_{i \in \mathcal{C}_A} x(i)}{|\mathcal{C}_A|} = \frac{\sum_{i \in \mathcal{C}_A - \mathcal{C}_B} x(i) + \sum_{i \in \mathcal{C}_A \cap \mathcal{C}_B} x(i)}{|\mathcal{C}_A|}.$$

Thus

$$\begin{aligned} x(I_B) &= \frac{\sum_{i \in \mathcal{C}_B} x(i)}{|\mathcal{C}_B|} \\ &= \frac{\sum_{i \in \mathcal{C}_B - \mathcal{C}_A} x(i) + \sum_{i \in \mathcal{C}_A \cap \mathcal{C}_B} x(i)}{|\mathcal{C}_B|} \\ &= \frac{|\mathcal{C}_A| x(I_A) - \sum_{i \in \mathcal{C}_A - \mathcal{C}_B} x(i) + \sum_{i \in \mathcal{C}_B - \mathcal{C}_A} x(i)}{|\mathcal{C}_B|}. \end{aligned}$$

Since the origin is at the mid-point of $\overrightarrow{AB}$, and $\odot A$ have same radius as $\odot B$, we have

$$\forall i \in \mathcal{C}_A - \mathcal{C}_B, x(i) \leq 0$$
$$\forall i \in \mathcal{C}_B - \mathcal{C}_A, x(i) \geq 0.$$

Therefore $x(I_B) \geq 0$. In short, suppose that centroid of nodes in need of message and in neighborhood of A is closer to B than to A. The neighborhood of B is obtained by eliminating some nodes closer to A than B (blue nodes), and adding some nodes closer to B than A (yellow nodes). Afterwards, new centroid could only be even more closer to B than to A, i.e. $\|\overrightarrow{AI_B}\| > \|\overrightarrow{BI_B}\|$.

Note that this property may not hold if A and B do not have common neighbor set from the intersection of their communication areas. In our example, adding few nodes near A which are in the need message set of B but not known to A, would provide a counterexample.

Property III-D only guarantees that at least one node ranks itself first. It is possible that several nodes rank themselves first. At the beginning of time slot scheduled for retransmission, a node would send the packet to MAC layer. Carrier sense and random backoff mechanisms included in 802.11p MAC layer protocol are used to solve collision problems when two or more neighboring forwarder candidates pick up the same time slot. To simplify our description, we assume that MAC layer competition is done within same slot, by selecting starting mini-slot within it. We now discuss the behavior of our algorithm in 1-D scenarios.

Property 2: In 1-D scenario *ReC*, after sender S retransmits message m, the farthest node from the source, among those that received m from S, will retransmit m in the next slot.

Proof: Let $x(source) = 0$. Consider the part $x > 0$, and let the communication range be r. $A_1, A_2, \ldots, A_k$ are nodes which received the message from S and are farther form source than S, that is, $x_S < x_{A_1} < x_{A_2} < \cdots < x_{A_k} < x_S + r$. By declaring all nodes with $x_S \leq x \leq x_S + r$ as potential receivers of message and therefore outside local N sets, we conclude that, for $A_1, A_2, \ldots, A_k$, all nodes in their local N sets have only nodes with $x \geq x_S + r$. According to the ideal location calculation formula, the ideal location coordinate should be larger than $x_S + r > x_{A_k}$ for each node in $A_1, \ldots, A_k$. Thus, A_k should rank first in each node's (including A_k's) local ranking, since it is closest to the ideal location. Thus A_k will retransmit immediately after reception.

E. HETEROGENEOUS COMMUNICATION RANGE

If communication ranges are asymmetric among vehicles, the efficiency of *ReC* would suffer. For example, node A might consider a neighbor B to be "best forwarder" and give up the chance of immediate retransmission. However B might have a smaller communication range, and therefore cannot cover all neighbors of A who are in need of the message. Reliability could be fixed later when A observes some nodes not receiving the message. However the propagation speed decreases in such scenarios.

A timeout based broadcasting algorithm for heterogeneous transmission radii can be designed as follows. Each node waits for a timeout inversely proportional to $r - d$ (its own communication radii minus its distance to the ideal forwarding location). Upon expiry of timeout, node will retransmit if it has neighbor(s) in its 'need message' neighborhood set. Message acknowledgments will be sent using own transmission radius, without propagating them (via beacons of neighbors) further. This shortens the length of beacon and needs no exchange of communication ranges.

To design an algorithm that addresses warning delivery with the chance of immediate retransmissions, ranking function can be designed as follows.

Candidate neighbors are ranked using d–r instead of d for ranking, where d is the distance to the ideal forwarding location and r is the communication range of a node. It gives higher priority to nodes with larger communication ranges, which can cover more neighbors. Neighbors need to exchange their communication ranges, which increases the length of beacons and induces some overhead.

IV. EVALUATION

A. EVALUATION SETUP

We have performed different tests to assess the performance of *ReC*. In our conference version of this work [9], the simulation work has been done with *The Network Simulator ns-2*, version 2.34, competing with ABSM [8], Forwarder Selection algorithm [4], [5], and Hyper Flooding. To better understand our performance under different scenarios, such as homogeneity of communication range, mobility of vehicles (static, low speed, or high speed), and collisions, we have done additional experiments in this paper. We also implemented AMR algorithm [7] as a competitor algorithm (as a substitute for Forwarder Selection), under same beacon length assumption (which favours AMR [7]). When r is same for all vehicles, AMR would always dedicate the furthest node to retransmit. Since ACK mechanism is missing from AMR algorithm, its reception ratio is very low, so we implemented similar ACK mechanism for fair comparison of the main ideas in corresponding protocols. We design different scenarios, categorized in the following aspects.

- **layout (1D/2D)**: We use line layout for 1D (2 km highway) scenario, and grid layout for 2D scenario. The grid layout has 2 latitudinal and 2 longitudinal 3 km lanes.
- **homogeneity of communication radius (homogeneous/heterogeneous)**: For homogeneous scenarios, all nodes share the same communication range of 250 meters. For heterogeneous scenarios, the communication range of a node can be 200, 250 or 300 (randomly selected).
- **physical layer model (UDG/TRG)**: In the *unit disk graph* (UDG) model, if node u is within the communication range of node v, then packets from v can always be

delivered to u. For *two-ray-ground* propagation model [19], however, signal strength varies with distance, and u may suffer packet loss.

- **node mobility (static/slow/fast)**: For static case, all nodes are stationed in fixed positions. For 'slow' and 'fast' cases, nodes are moving at the average speed 60 km/h and 120 km/h respectively.
- **collision**: We have measured the performance for collision-free cases in our conference version [9]; here we only consider scenarios with collisions.
- **traffic density:** The traffic density is measured by the number of vehicles injected into each road (from each side of the road) every minute. Vehicles are injected into a road, and they exit when they drive out of the simulation region. We take measurement 5 minutes after the beginning so the network is 'stable' (i.e. the number of vehicles exiting per minute approximates the number of vehicles entering). In example 1D scenario, when traffic density is 15, about every 4 seconds there is a car entering the road from each side of the road, thus there are 30 cars entering the network every minute. The number of vehicles in network is about 60 for slow mobility and about 120 for fast mobility.

We focus on the following metrics.

- *Reception Ratio*. The ratio between the number N_{recv} of vehicles that received the broadcast message before the message expired, and the total number N_{total} *that could possibly receive it*. It reflects the reliability of a protocol. Some nodes may remain partitioned from the source. We calculate the number of nodes that have received the message by Hyper Flooding (HF) protocol under ideal MAC/PHY layers (no collisions) as the upper bound of N_{total}.
- *Delivery latency*. The delay for a certain node is the time since the source issues the message until this node receives the message. We also consider the average delay per node and also the delay of the last receiver. To better reflect the timeliness, we only consider nodes which are already in the network when the message is issued.
- *Usability*. It is desirable to keep the moving distance of vehicles small, during geocast, to avoid subsequent accidents. Therefore, we measure the distance travelled before receiving message.
- *Number of transmissions*. To study the workload of vehicles, we measure the total number of transmissions per vehicle, which is expected to be independent on the number of cars. We also measure the number of vehicles that get involved as forwarders.

B. RELIABILITY PERFORMANCE

Fig. 6 shows the reliability performance under different mobilities. *ReC* has high reception ratio under all scenarios. AMR can only achieve high reception ratio when using UDG model and assuming all nodes are static. In TRG model, farther nodes tend to have higher packet loss rate, and mobility leads to unstable links. If the dedicated forwarder misses the packet, the packet propagation may break and thus AMR suffers low reception ratio. For Hyper Flooding, the low reception ratio is caused by heavy collisions. Fig. 7 and Fig. 8 shows the impact of homogeneity and PHY model on reception ratio. The homogeneity does not significantly affect the reception ratio, while the PHY model has larger impacts on AMR algorithm. Our *ReC* protocol shows high reliability under all circumstances.

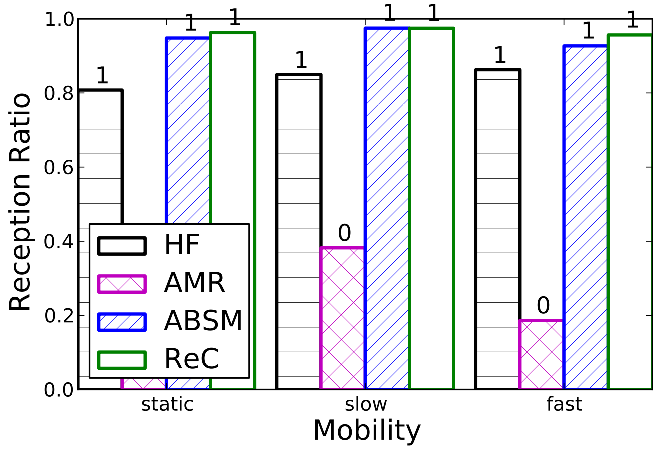

FIGURE 6. Reception ratios under different mobility (TRG).

C. DELAY PERFORMANCE

We measure the delay in 1-D and 2-D scenarios and Fig. 9 shows the result in 2-D scenarios (static mobility, homogeneous communication range). For 1-D case, AMR performs best using UDG model, but our *ReC* can approximate its efficiency. ABSM is a timer-based protocol and therefore adds an extra delay on each hop, and thus its delivery latency is much longer than *ReC* and AMR. For 2-D case, it is much more difficult for AMR to select proper forwarders (the direction is not unique). Using TRG model, AMR protocol

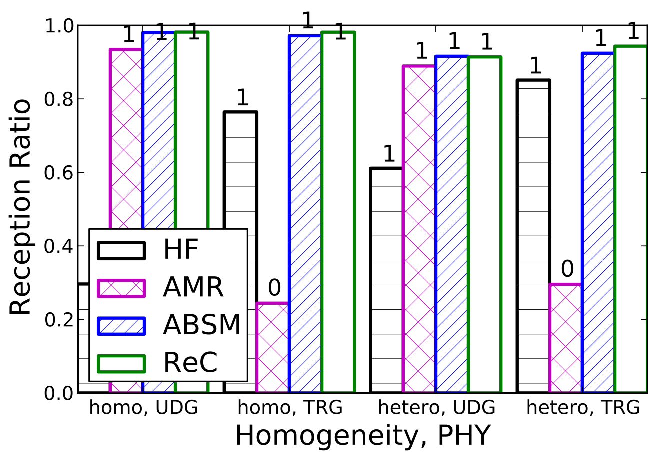

FIGURE 7. Reception ratios vs. homogeneity (TRG, static scenario).

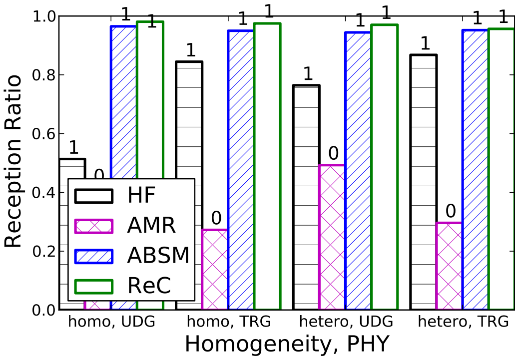

FIGURE 8. **Reception ratios vs. homogeneity (TRG, moving scenario).**

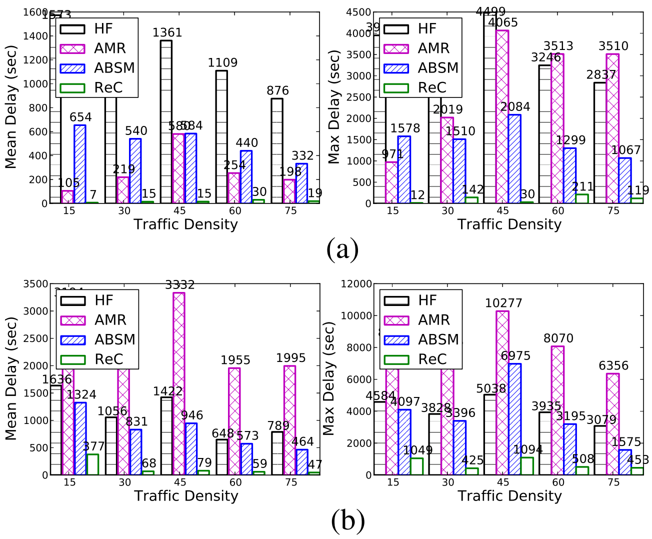

FIGURE 9. **Delay performance in 2-D scenarios (static, homogeneous). (a) Mean delay and max delay under UDG model. (b) Mean delay and max delay under TRG model.**

has considerably larger delay, because of frequent failures of reaching dedicated forwarder, and waiting for the next beacon to select another one. The broadcast storm caused by Hyper Flooding degrades its reliability and increases its delay. As the number of vehicles decreases, frequent dis-connectivity increases latency. Our experiment results show that *ReC* is adaptable and achieves good delay performance under different density, mobility and homogeneity scenarios.

We measure the reception ratio at different times during the simulation. The reception ratio of AMR rises very quickly at the beginning, but after some point it gets slow when packet loss occur on dedicated forwarder. In TRG model its reception ratio only reaches around 60% after two seconds (with the help of ACK mechanism). ABSM can always reach 80% reception ratio after 2 seconds but within 1 second it can only reach 50% reception ratio. However we notice that for most cases *ReC* is capable to spread the message to over 80% nodes within 1 second. This is very important when sending emergency messages.

We measure the relationship between delivery latency and the distance from source to destination. For AMR protocol, the propagation will stop at some distance, and vehicles will only get the message when they come close to the sender. Results show the hamper effect of ABSM's timer mechanism, which adds latency at every hop. The latency has a trend of linear growth as the distance increases, in both homogeneous and heterogeneous networks. The increase in distance has less significant impact on delays for *ReC* protocol than on the other two competitors. Besides, the homogeneity does not significantly affect the efficiency of *ReC*.

D. USABILITY

On average about 80% vehicles would move less than 100 meters before they receive the warning message. In denser scenarios the message propagates faster, and thus most vehicles have smaller moving distances. In 2-D scenarios the situation is complicated. A fraction of vehicles get warning message instantly. For the others, the moving distance is distributed evenly.

E. NUMBER OF TRANSMISSIONS

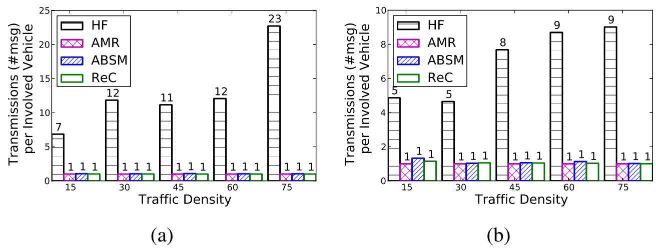

FIGURE 10. **Number of transmissions per vehicle involved. (a) 2-D homogeneous case. (b) 2-D heterogeneous case.**

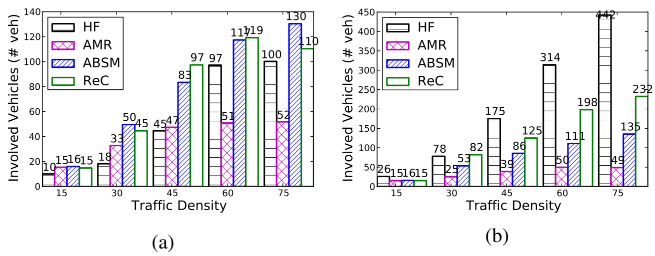

FIGURE 11. **Number of vehicles involved. (a) 2-D homogeneous case. (b) 2-D heterogeneous case.**

We study the workload for each vehicle during geocasting. Fig. 10 shows the average number of transmissions made by each node. We found that in dense scenarios, Hyper Flooding putS a heavy transmission load on each node. On contrast, our *ReC* protocol keeps the workload low for each node. Fig. 11 shows the number of cars acting as forwarders during propagation. HF gets almost every vehicle involved in passing the message. However, *ReC* can free most of vehicles because only the dedicated forwarder need to carry on the message propagation task. In heterogeneous networks, *ReC* tends to

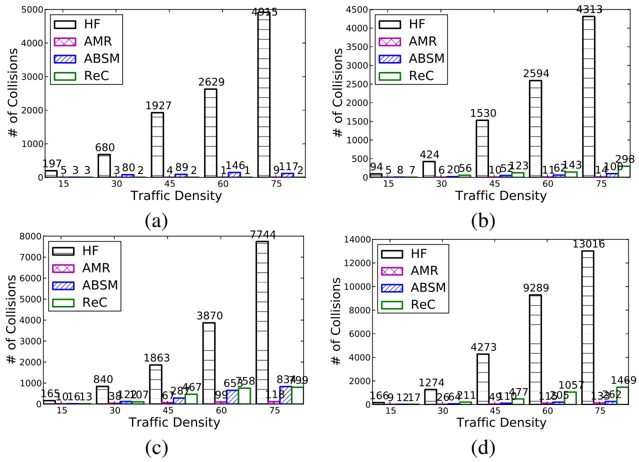

FIGURE 12. Number of reported collisions. (a) 1-D homogeneous case. (b) 1-D heterogeneous case. (c) 2-D homogeneous case. (d) 2-D heterogeneous case.

use more vehicles as forwarder. The 1st place forwarder may not cover all nodes because its communication range is not large enough; the 2nd or even the 3rd forwarder may need to rebroadcast the message afterwards, to cover all neighbors in need of the message.

Generally, *ReC* transmits slightly more than ABSM. This can be mainly attributed to the inconsistency of nodes' local neighborhood knowledge. It is possible that two neighboring nodes both rank themselves as best forwarder and compete to transmit immediately after receiving the message. This increases the number of transmissions of *ReC* protocol. However, the results show that this situation is rare. The AMR has a very small number of transmissions as each sender dedicates its furthest neighbor to be the only next hop retransmitter.

Fig. 12 shows the total number of reported collisions. One broadcast may cause multiple collisions at multiple nodes. *ReC* generates slightly more collisions than ABSM. The number of collisions in heterogeneous networks is larger than in homogeneous ones due to misunderstanding of communication range among nodes (more nodes would claim itself as 1st forwarders).

F. SUMMARY

A main objective of *ReC* is supressing broadcast storm, thus reducing collisions and enhancing reliability. Simulation result shows that the number of transmissions is greatly cut down compared with Hyperflooding and comparable with forwarder selection strategy AMR [7]. Meanwhile, *ReC* can deliver a message to over 90% vehicles for all cases, which guarantees *ReC*'s reliability as a warning delivery protocol.

Warning messages need to be delivered to nodes as soon as possible, therefore we study the latency performance of *ReC*. The result shows that *ReC* can propagate a message to 80% within 1 second, which is much quicker than AMR, ABSM and Hyper Flooding. The 'max delay' (the time when the last node receives a message) of *ReC* is much lower than the competitors. The usability performance also proves *ReC* to be a promising warning delivery protocol for VANETs. In future, geocasting and routing ideas in ad hoc networks may be helpful to further improve the performance [24]–[26].

V. CONCLUSION

We design *ReC* protocol to address both reliability and delivery latency in VANETs warning delivery. Nodes make consensus based on their local knowledge. Such mechanism provides a prospective direction of forwarder coordination. Geographical information is used to select an ideal location for forwarding, and neighbors are ranked and assigned priority to broadcast accordingly, based on their distance to the ideal location.

Our experiments show that collisions are not frequent, and we resolve this issue by applying retransmissions following lack of acknowledgments. This causes some delays. It may be possible to modify the protocol by adding communication steps between colliding vehicles. We leave this as future work, which will address medium access isssues more closely.

Our *ReC* algorithm can benefit from the transport layer ideas presented in [16], which are independent from its network layer behavior. It can also incorporate retransmissions from the source, as proposed in [20]. By transmitting different bits with different coding schemes, as proposed in [21], vehicles near the accident site (or the point-of-interest location) can receive guaranteed, detailed messages to take proper reaction immediately (e.g., slow down or change lanes), while vehicles further away have a high probability to be informed and make location-aware decisions accordingly (e.g., detour or reroute), with the assistance of reverse traffic when possible and necessary. Finally, identity-based authentication scheme [22] can be incorporated to provide security for safety messages. Finaly, we observed that reliability of *ReC* remains high compared to other solutions which are designed for non-safety messages (e.g. ABSM [8]) and it can be considered for adaption in other tasks, such as video geocasting [23].

The protocol will work in 3D scenario if the 3D location information becomes available. In theory, this is possible if 4 or more linearly independent satellites are visible. 3D data dissemination was not specifically studied in the literature and remains an interesting topic for the future work. If road side units are available in the neighborhood of the event, they could be used to assist warning delivery, by acting as a vehicle with same or larger transmission radius, or by contacting other road side units by wired or wireless transmisison to speed up the dissemination process. The details of such protocol, and merging our protocol with some exisiting ones e.g. [17] remains for future work.

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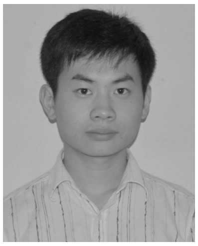

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