OppCast: Opportunistic Broadcast of Warning Messages in VANETs with Unreliable Links

Ming Li and Wenjing Lou
Dept. of ECE, WPI, U.S.A.
Email: {mingli,wjlou}@ece.wpi.edu

Kai Zeng
Dept. of CS, UC Davis, U.S.A.
Email: kzeng@cs.ucdavis.edu

Abstract

Multi-hop broadcast is a key technique to disseminate important information such as time-sensitive safety warning messages (WMs) in Vehicular Ad hoc Networks (VANETs). Due to the fact that the implementation of broadcast at the link layer uses unreliable transmissions (i.e., lack of positive ACKs), highly reliable, scalable, and fast multi-hop broadcast protocol is particularly difficult to design in VANETs with unreliable links. Schemes that use redundant network layer broadcasts have been proposed. However, the balance between receiving reliability and transmission count in such schemes needs to be carefully considered.

In this paper, we propose the opportunistic broadcast protocol (OppCast) that aims at minimizing the number of transmissions while achieving high network packet reception ratio (PRR) and fast multi-hop message propagation simultaneously. A double-phase broadcast strategy is proposed to achieve fast message propagation in one phase and to ensure high PRR in the other. The idea of opportunistic forwarding is exploited at each hop to minimize the propagation latency. An opportunistic forwarding protocol is designed accordingly as a MAC-layer broadcast coordination function, that allows multiple nodes to agree on the actual relay nodes in a distributed fashion. The proposed function also alleviates the hidden terminal problem. Theoretical analysis is carried out to optimize and design both broadcast phases. Extensive simulation results show that, compared with existing competing protocols, OppCast achieves close to 100% PRR and fast dissemination rate under a wide range of vehicle densities, while using significantly smaller number of transmissions.

1. Introduction

Communication in Vehicular Ad Hoc Networks (VANETs) is an active research area in recent years. VANET is a multi-hop mobile network designed to provide a wide range of road applications such as safety warning, congestion avoidance or mobile infotainment. One of the most important applications of VANET is the broadcast of warning messages (WMs) like accident and hazard warning. For example, when two vehicles collide with each other on a highway, or traffic congestion happens because of heavy rain or snow, the upcoming vehicles need to be notified immediately, not only to prevent possible accidents, but also to enable the vehicles located several kilometers behind the accident or hazard spot to make a detour as early as possible. While the Dedicated Short Range Communication [1] (DSRC) specifies that the data transmission range of vehicles can be up to a few hundreds of meters, single broadcast is not sufficient to provide the required vehicular coverage. Therefore, multi-hop broadcast is necessary to disseminate time-sensitive warning messages in VANETs.

The main performance goals of WM broadcast are high reliability, fast dissemination and high scalability. Scalability means having small overhead when the network is dense, since unnecessary transmissions waste precious bandwidth resource. However, in real VANETs these goals are hard to achieve simultaneously. The major challenge comes from unreliable wireless links [2], [3], which undermine the reliability of one-hop broadcast. According to studies on the DSRC [4], the one-hop broadcast reception rate is low. The packet loss is due to both channel fading and collisions with hidden terminals. There is no channel resource reservation mechanism in 802.11 for broadcast, which incurs severe packet collisions in a dense network with congested channels. Unlike unicast, it is infeasible to acknowledge the reception of each broadcast message at each recipient, because of the ACK implosion problem. Therefore, there is no reception guarantee for one-hop link layer broadcast.

Since it involves high complexity to enhance the reliability of broadcast from link-layer, most previous works have focused on redundant network layer broadcast strategies. The blind flooding leads to the well-known *broadcast storm* problem [5] where packet collisions could arise due to uncoordinated simultaneous rebroadcasts. Then various methods were proposed to mitigate this problem, such as probability-based methods [6] and timer-based methods [7]–[10]. Although these schemes enjoy high reliability when the channel load is moderate, the amount of redundant transmissions becomes prohibitively large under heavy message load. This, heavily degrades the broadcast performance, and limits their scalability to be deployed in a real VANET.

In this paper, we adopt a more practical approach. Instead

978-1-4244-5113-5/09/$25.00

of trying to guarantee "all vehicles receive all the broadcasted WMs", we ensure the expected percentage of nodes that receive a WM (packet reception ratio, PRR) to be larger than a given threshold which is close to 100%. Our main contributions can be summarized as follows.

First, we put forward the *opportunistic broadcast protocol* (OppCast), a fully distributed protocol that simultaneously achieves high reliability and fast dissemination while incurring small overhead. The broadcast scheme involves two types of broadcast phases, where one phase quickly propagates the WM using relatively long hops, and the other phase uses additional make-up transmissions to ensure a certain PRR. The design of both phases is optimized to minimize the total number of transmissions.

Second, we propose a distributed *opportunistic broadcast coordination function* (OBCF), an underlying MAC-layer broadcast primitive for the recipients of a single broadcast to agree on who will be elected as the actual relay nodes. OBCF exploits the idea of opportunistic forwarding to minimize one-hop broadcast delay. Moreover, OBCF effectively alleviates the hidden terminal problem in a lossy environment.

Third, we carry out extensive NS-2 simulations to evaluate the performance of OppCast. Results show that OppCast outperforms two other protocols by achieving close to 100% PRR and faster dissemination under a wide range of scenarios, while the overhead is much smaller. The tradeoff between reliability, dissemination rate and overhead is characterized. To the best of our knowledge, this is the first work that studies this tradeoff under realistic physical layer model in VANETs.

2. Related Work

Earlier works on broadcast in VANETs have assumed the ideal physical layer propagation model, i.e., the packet reception is "1" or "0" in or out of a fixed transmission range. The traditional protocols are relay-designated, i.e., try to find out the furthest receiver in the transmission range and designate it as the relay node to maximize the one-hop progress [11] or minimize one-hop broadcast delay [12].

As shown by empirical studies, however, the physical channel in VANETs is far from perfect [13]. Instead, channel fading is the primary challenge and has a major impact on broadcast reception rates [3], [4]. The suggested realistic propagation model on the highway is the *Nakagami model* [2], where the packet reception probability of single broadcast decreases with the distance. The "broadcast storm" problem becomes severer in VANETs with unreliable links.

The *probability-based methods* [5] simply let each node rebroadcast a packet with a fixed probability. However, this doesn't solve the broadcast storm problem. Later, [6] proposed a family of probability-based methods for VANETs, where a receiver that is farther from the sender rebroadcasts a packet with higher probability. In these methods, the probabilistic forwarding leads to redundant rebroadcasts.

Opportunistic Forwarding. A promising way to deal with unreliable links in multi-hop wireless networks is *opportunistic routing* (OR), which was proposed in the routing literature to enhance the routing throughput [14], [15]. It exploits the "forwarding opportunity" presented by the spatial diversity of wireless medium, so that each transmission is useful, the routing delay and the number of transmissions can be reduced.

The concept of OR is also adopted in the VANET broadcast. The timer-based schemes, including contention-based dissemination (CBD) [9], contention-based forwarding [3] and OB-VAN [16], opportunistically select the "best" relay nodes by maximizing the hop progress among the nodes that have received the broadcast packet. Receiver nodes located nearer to the sender backoff longer times and quit contention whenever they hear one rebroadcast (or ACK signal) from a node that has larger progress. The counter-based method [7] generalizes this to allow nodes quit contention after hearing more than one duplicate packets.

However, under the presence of unreliable links, the above schemes suffer from two problems. One is that they make forwarding decisions based on heuristic guesses of whether neighbors have received the same packet or not. The PRR of the network is not considered, and no optimizations have been made so far. Second, the signaling/coordination mechanisms during relay selection are subjected to losses and collisions, which undermines the foundation of the forwarding decision making. In this paper, we solve these two problems by explicitly considering the contribution to PRR as one of the relay node election criteria, and designing a more effective broadcast coordination mechanism.

Reliability in VANET broadcast. Elbatt *et. al.* [17] studied one-hop periodic broadcast in cooperative collision warning applications. They characterized the tradeoffs between the packets' inter-reception latency, application broadcast rate and transmission range. For multi-hop WM broadcast applications, Resta *et. al.* [18] analyzed theoretically the tradeoff between vehicles' probability to receive a WM within time t and the link level reliability. But their channel model is oversimplified, and no distributed protocol has been proposed. Our work differs from the above in that we cast insight on the application-level tradeoff between packet reception performances and the overhead, under a realistic channel model.

Disconnected VANETs. VANETs turn out to be disconnected sometimes, which falls into the delay-tolerant network (DTN) paradigm. Leontiadis *et. al.* [19] proposed an opportunistic event dissemination protocol that employs cache and periodic replay mechanisms to keep a message alive in an area. In [20], the authors proposed a routing protocol, which uses local routing in connected clusters and store-carry-forward at cluster boundaries in order to reduce latency and overhead. While our work focus on broadcast in connected parts of the network, it can be easily incorporated into a DTN-compatible broadcast scheme.

3. Problem Statement

3.1. Model and assumptions

In this paper, we consider warning message (WM) broadcast in the highway scenario. Fig. 1 shows the system model, which is a line-topology highway that may have multiple lanes. The VANET consists of vehicles equipped with on board units (OBUs) that can communicate with each other. Suppose a safety-related event (e.g. an accident) happens somewhere, where the source vehicle's OBU begins to broadcast WMs towards the interested region (IR). The IR is defined as the road segment of length $\mathscr{L}$ along the message dissemination direction, which is opposite to the driving direction. The source is called the *origin of IR*, and the other side of IR is called the *end of IR*. Since the width of the highway is far less than the length of IR, for simplicity we model the vehicles to be located in one-dimension.

We assume vehicles are GPS-capable. Each vehicle obtains its location in real-time. When GPS is not available (e.g. in tunnels), there are complementary methods to estimate a vehicle's location, such as using vehicle's speed. Also, vehicles are aware of the existence and locations of all neighboring vehicles, as they broadcast one-hop beacon messages every $100ms$ [1]. These beacons are routine safety messages, and warning messages are event-driven. They share the control channel [21].

We adopt the probabilistic radio propagation model. That is, the *pairwise packet reception probability* $P_r(u, v)$ that a node (OBU) v receives a broadcast packet directly from u (vice versa) can be expressed by a decreasing function with the distance between u and v: $P_r(u, v) = P_r(d(u, v))$. This function accounts for channel fading; it can either be derived from a propagation model or measured from practice[1]. In addition, the packet reception at each vehicle is assumed to be independent.

Now, the *network of interest* is modeled as an undirected graph $G(V, E)$, where V is the set of nodes within the IR. Each link $l = (u, v) \in E$ is associated with a $P_r(u, v)$, and the links are symmetrical. For node u, its one-hop neighbor set $N_1(u)$ include only the nodes v that $P_r(u, v) \geq P_0$, where $P_0 \ll 1$ is a small enough threshold. Then we regard $P_r(u, v) = 0$ for all other nodes $v \in V, v \notin N_1(u)$. Therefore, the *communication range* R_c is defined as: $R_c = P_r^{-1}(P_0)$. In addition, we define a *transmission range* (R_{tx}), which equals to the equivalent transmission range calculated under the free space signal propagation model, given the same transmission power. Also, we let $R_c > R_{tx}$.[2]. The network is said to be "connected" if the underlying graph G derived under R_c is connected.

3.2. Objectives

Since it is impractical to be 100% sure that every node has received a WM, we aim at providing reliable broadcast service that ensures the *packet reception ratio* (PRR) of the network of interest to be larger than a threshold P_{th} ($\gamma_s(G) \geq P_{th}, P_{th} \in (0, 1)$). This is called the *network PRR requirement*.

Definition 1 (Packet reception ratio $\gamma_s(G)$): . Given a network G and a source s, $\gamma_s(G)$ is defined as the expected percentage of nodes that can receive a WM from s.

In the meantime, it is also very important for vehicles to be warned in a timely manner. Since the broadcast reception delay ($t_{v,m}$) of WM m at each vehicle v relates to v's distance to the source (d_v), we define the individual dissemination rate as $d_v/t_{v,m}$. The *dissemination rate* is then defined as the individual dissemination rates averaged among all WMs sent and vehicles in the IR. Therefore, another goal is to reach high dissemination rate. The PRR and dissemination rate capture the application level performances.

Finally, in WM broadcast it is desirable to minimize the broadcast overhead, which is defined as the average number of transmissions of each WM. Unnecessary transmissions take up bandwidth, increase the channel access delay and the chance of packet collision. This, in turn, degrades the broadcast performance.

4. Overview of OppCast

The OppCast consists of two types of broadcast phases: *fast-forward-dissemination* (FFD) and *makeup-for-reliability* (MFR). Basically, the FFD phase uses relatively long hops to advance the WM toward the end of IR for fast propagation. The FFD phase is done via relaying the WM by one node each hop. These relay nodes thus divide the IR into several *one-hop zones*. Due to the independent reception assumption, vehicles within these one-hop zones may have not received the packet. Thus we use additional make-up transmissions in MFR phases to ensure the PRR of the network. There is only one FFD phase, which starts from the source till the message front reaches the end of IR. There are multiple MFR phases, which are independent from each other: each MFR phase is triggered right after the WM traverses another hop in FFD, and terminates by itself. Multiple MFR phases run in parallel, as long as the relay nodes don't interfere with each other.

---

[1] E.g., [2], [13] show that the Nakagami fading model is suitable to characterize the reception probability of one-hop broadcast packets in real VANETs.

[2] These ranges are defined for theoretical convenience. E.g. $P_0 = 0.1, R_c = 500m, R_{tx} = 250m$.

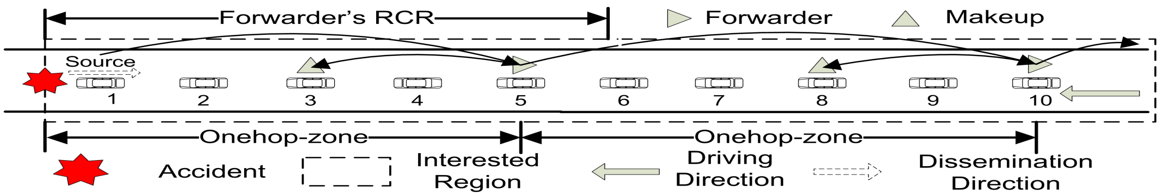


Figure 1: VANET model and overview of the broadcast scheme.

The relay nodes in FFD and MFR phases are called *forwarders* and *makeups*, respectively. The network PRR requirement is satisfied by these phases together. (1) During the dissemination of each WM, the protocol **guarantees that one forwarder at each hop is elected** (by feedback and retransmissions), which is a necessary condition for the PRR requirement of the whole network to be met. The forwarders form a dynamic backbone, which is responsible to deliver a WM to the IR from near to far. (2) After each forwarder (F_k) rebroadcasts, a one-hop zone Z_k is formed between F_k and its previous forwarder (F_{k-1}). Then makeups are elected from nodes in Z_k, **until the PRR requirement of the sub-network in Z_k is met**. The design of both phases are optimized to minimize the total number of transmissions.

The opportunistic forwarding concept is exploited by OppCast at each transmission event to minimize the broadcast latency. The underlying broadcast primitive, OBCF elects each relay node distributively and opportunistically. Upon receiving a WM from u, each node becomes a relay candidate if it is located in the *relay candidate region* (RCR) of u, and the relay candidate with the highest priority is always elected[3] to be a relay node. By utilizing the spatial diversity, the probability of at least one relay candidate receives the WM is greatly improved, especially when the network is dense. Therefore, the WM can be propagated with minimal delay at each hop. To actually achieve such small delay, the OBCF is carefully designed to avoid packet collisions.

The high-level protocol flow-chart is given in Fig. 2. Each node v, upon receiving a WM for the first time from u, decides whether to contend to be one type of relay nodes distributively. If u is a source or forwarder and v is located in the road segment starting from u towards the end of IR, v will engage in the FFD phase. If u is a forwarder or makeup and v is located in the current one-hop zone specified in the WM, v will go through the MFR phase. After that, v determines u's RCR according to v's potential relay type. If v is within that RCR, v becomes a relay candidate and contends to be the particular type of relay node.

We use a simple example to illustrate the broadcast process. Fig. 1 shows a vehicle chain where the id of nodes increase one-by-one from 1 (the source), and the distance between successive vehicles is fixed to 1. Node 1 broadcasts a WM that should be propagated to the east, and suppose nodes 2 and 5 receive the packet. If we set the length of each forwarder's RCR to be 5, then node 5 which is farthest within this range from 1 will become a forwarder and rebroadcast first. Assume the transmission of node 5 is received by nodes 3, 4, 6, 7, 8, 10. An one-hop zone is formed, whose left and right boundaries are nodes 1 and 5. Node 3 becomes a makeup since it is closest to the center of the one-hop zone among the receiver set. And node 10 becomes the next forwarder, and so on.

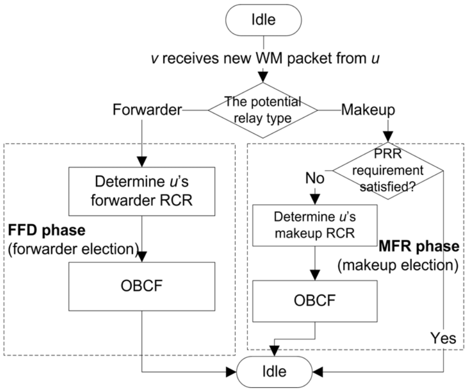


Figure 2: The high-level flow chart of OppCast.

5. OppCast: main design

5.1. Methodology and rationale

First, we answer the question of how can the network PRR requirement be met. It is known from reliability theory that to compute PRR (also called network reachability) is a NP-hard problem [22], [23]. In this paper, we transform the PRR requirement into the *LPRP requirement*: ensure the *local packet reception probability* (LPRP) of each node to be also larger than P_{th}.

Definition 2 (Local packet reception probability): $\xi_s(v)$. Given a node v in a network G and the source s, $\xi_s(v)$ is the cumulative probability that v can receive the broadcast message from v's neighborhood.

Definition 3 (LPRP requirement): For all node $v \in G$ that is not a relay node, the LPRP condition is satisfied if $\xi_s(v) \geq P_{th}$.

---

[3] A relay is "elected" after it actually sends a *broadcast acknowledgement* (BACK) to suppress other candidates.

For a particular instance of the whole process of source s broadcasting a WM m, $\xi_s(v)$ is calculated as:

$$\xi_s(v) = 1 - \prod_{u \in N_1(v) \cap T(s)} (1 - P_r(u,v)).$$

where $T(s)$ is the instance of relay node set (nodes that have rebroadcasted) for source s and WM m.

Definition 4 (OppCast broadcast strategy): . (1) It is ensured by FFD that at each hop one forwarder is elected, until the end of IR is reached. (2) Once two successive forwarders form an one-hop zone, the MFR phase tries to guarantee that every other node in this one-hop zone is covered with LPRP no less than P_{th}.

Proposition 1: The OppCast broadcast strategy satisfies the network PRR requirement, given the LPRP requirement is satisfied.

Proof: Omitted due to space limitations. □

Note that (2) in the OppCast broadcast strategy is equivalent to satisfy the LPRP requirement. Whether there are enough number of makeups to guarantee it depends on two factors: the vehicle density and the makeup election algorithm (MFR phase). It can be shown that the LPRP requirement (and thus the network PRR requirement) is satisfied whenever the vehicle density is larger than a critical value. We characterize this critical density theoretically and validate it by simulation. The result is that, for OppCast protocol the critical density is around 40 vehicles/km. Due to space limitations, the theoretical part is not presented here. When the network is sparser than the critical density, it can be dealt separately by a DTN broadcast strategy (like store-carry-forward) and will be studied as future work.

Note that the LPRP requirement guides our MFR phase design. In order to use least number of makeups to satisfy it, we optimize the elect algorithm of makeups so that each of them contribute most to the LPRP.

5.2. Fast-Forward-Dissemination

Intuitively, the longer the distance between two successive forwarders is, the faster a message can be disseminated. However, this may lead to a larger overhead, since a longer one-hop zone requires more makeups to satisfy the LPRR requirement. And more transmissions in turn slows down the overall dissemination rate. Therefore, balancing these goals, we focus on minimizing the total number of transmissions, including those from both forwarders and makeups.

A forwarder's RCR is a road segment from that forwarder towards the end of IR, with a length called *boundary range* (BR). Only nodes within BR from the previous forwarder are eligible to become forwarder candidates. Under such constraint, the priority of the forwarder candidates increases with the hop-progress (their distance to the previous forwarder), in order to maximize the dissemination rate. The forwarder candidate that is farthest to the previous forwarder becomes the next forwarder. Thus, the one-hop zone length is bounded by BR.

To minimize the expected total number of transmissions $E[NT]$, we formulate the following parameter optimization problem: find the BR,

$$Min \qquad E[NT]. \tag{1}$$

$$s.t. \quad \forall v \in G, \xi_s(v) \geq P_{th}. \tag{2}$$

Since $E[NT]$ is also related to the makeup selection algorithm, we present the results afterwards.

5.3. Makeup-For-Reliability

Once a one-hop zone is formed, makeups are elected to enhance the reception probability in that zone. The idea is, always elect the node that maximizes the minimum LPRP of the nodes in a one-hop zone. Heuristically, the LPRP requirement is satisfied with a minimal number of makeups.

Initially, for each one-hop zone Z, we already have the left and right forwarders broadcasted. Since the pairwise packet reception probability decreases with distance, the middle of Z is covered with the least LPRP. Intuitively, electing a node v_1 in the middle (or nearest to the middle) is most helpful to increase the minimum LPRP of other nodes in Z. After v_1 broadcasts, it divides Z into two sub-zones. Similarly, the middle points of these sub-zones have the least LPRP, and again new makeups closest to the middle points are elected. Continue this process, until the minimum LPRP of all nodes in all sub-zones are larger than P_{th}. The algorithm is illustrated in Fig. 3.

The makeups form a binary tree, which is indexed by level ℓ and branch λ. A makeup is denoted as $M_{\ell,\lambda}$, $\lambda \in [0, ..., 2^{\ell-1} - 1]$. The depth of the tree is bounded by a maximum level[4]. At level ℓ, the makeups divide the one-hop zone into 2^ℓ sub-zones, denoted as $Z_{\ell,\mu}$ ($\mu \in [0, ..., 2^\ell - 1]$). Each ℓ^{th} level sub-zone $Z_{\ell,\mu}$ is defined by scanning the one-hop zone from left to right, and assigning two consecutive relay nodes of level $l \leq \ell$ as its left and right boundaries ($x_L^{\ell,\mu}, x_R^{\ell,\mu}$). The one-hop zone is regarded as $Z_{0,0}$, which is bounded by $x_L^{0,0}$ and $x_R^{0,0}$, coordinates of the left and right forwarders (F_L and F_R). The right forwarder is regarded as the 0^{th} level makeup.

For each node u in $Z_{\ell,\mu}$, upon receiving WM m, the *local visited nodes* by m consists of relay nodes which are on the tree branch leading to u: $\{F_L, F_R, M_1, ..., M_\ell\}$. Based on this, u estimates[5] the LPRP of each neighbor node v within $Z_{\ell,\mu}$ iteratively and distributively:

$$\begin{aligned} \xi_0(v) &= 1 - (1 - P_r(F_L, v))(1 - P_r(F_R, v)) \\ \xi_\ell(v) &= 1 - (1 - P_r(M_\ell, v))(1 - \xi_{\ell-1}(v)) \end{aligned} \tag{3}$$

---

[4] This will not cause broadcast storm since the maximum level needed is small, and OBCF greatly reduces packet collisions.

[5] We have ignored the contribution from the broadcast of relay nodes in other branches of the tree, which yields a conservative estimation.

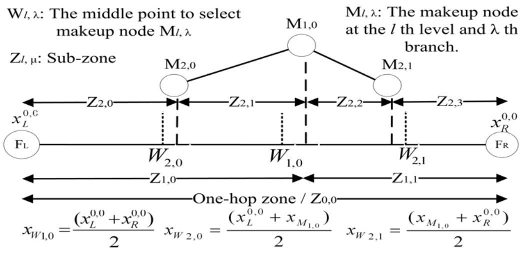


Figure 3: A makeup election tree, maximum level=2.

If the minimum LPRP: $\min_{v \in Z_{\ell,\mu}} \xi_\ell(v) \geq P_{th}$, then u knows the LPRP requirement is satisfied. Otherwise, it determines the RCRs of M_ℓ, becomes a makeup candidate and starts the OBCF based on its priority.

The priority of u is same as the rank of the *updated minimum LPRP* of nodes in $Z_{\ell,\mu}$ after u rebroadcasts m, which is denoted as $\xi^*|u$. This can be calculated by doing another iteration on Eq. (3). Let $\Phi_{\ell,\mu}(x)$, $x \in [x_L^{\ell,\mu}, x_R^{\ell,\mu}]$ denote the *LPRP function* over each sub-zone, such that $\Phi_{\ell,\mu}(x_v) = \xi_\ell(v)$.

Proposition 2: Function $\Phi_{\ell,\mu}(x)$ is concave. If it is symmetric w.r.t the middle point $W_{\ell+1,\mu}$ of sub-zone $Z_{\ell,\mu}$, then for any sequence of nodes $\{i_0, i_1, ..., i_n\}$ within $Z_{\ell,\mu}$ such that $d(i_0, W_{\ell+1,\mu}) < d(i_1, W_{\ell+1,\mu}) < \ldots < d(i_n, W_{\ell+1,\mu})$, we have

$$\xi^*|W_{\ell+1,\mu} > \xi^*|i_0 > ... > \xi^*|i_n.$$

Proof: Omitted due to space limitations. □

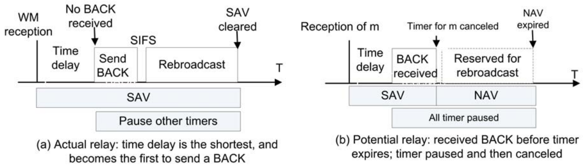
Note that, the above optimality is derived under the assumption that $\Phi_{\ell,\mu}$ is a symmetric function. In reality, $\Phi_{0,0}$ is strictly symmetrical; with the level of broadcast increases, $\Phi_{\ell,\mu}(x)$ deviates from being symmetrical gradually because of the impact of the broadcasts of other lower-level relay nodes. However, the deviation degree is small if the level is small (e.g., $\ell \leq 2$).

Therefore, the RCRs to elect a $\ell + 1^{th}$ level makeup $M_{\ell+1,\lambda}$ are simply the left and right halves of the ℓ^{th} level sub-zone $Z_{\ell,\lambda}$. For forwarder F_R, its makeup RCR is the one-hop zone $Z_{0,0}$.

5.4. MAC-layer Coordination in OppCast

The MAC-layer coordination is achieved by OBCF, whose goal is to let the relay candidates agree on the actual relay nodes in a distributed way, and for the elected relays to perform collision-free broadcast. The OBCF consists of the following: (1) A process for the relay candidates to contend for the relaying opportunity; (2) A resource reservation mechanism to avoid collision and suppress hidden terminals; (3) A retransmission mechanism to prevent the WM from dying out. Its process is as follows.

(i) When a node v receives a WM m for the first time (from node u), if v is in the RCR of u, v becomes a relay candidate. Then v sets a broadcast backoff timer (BBT) for m and calculates m's backoff delay. Also, v sets a *self allocation vector* (SAV) at MAC layer. The SAV suspends the transmission of other types of packets from v itself until there are no ongoing OBCF processes. This design provides packet-level priority access for WMs, since the WMs have the highest priority in VANETs.



(a) Actual relay: time delay is the shortest, and becomes the first to send a BACK

(b) Potential relay: received BACK before timer expires; timer paused and then canceled

Figure 4: Time domain illustration of OBCF.

(ii) If v senses a busy signal from physical layer, v will pause all its BBTs that are still counting down, in order to prevent collision and to keep its BBTs synchronized with that of other nodes. When the physical layer indicates idle again, v will resume all the paused BBTs.

(iii) If the BBT for m expires without receiving a broadcast acknowledgement (BACK), node v becomes a relay node for packet m, and sends a short MAC-layer BACK **at the base rate** to suppress other candidates. After the BACK has been transmitted, and after a short inter-frame space (SIFS), the WM is sent immediately at the data rate (higher than the base rate). The BBTs for other WMs are also paused during transmission.

(iv) If v receives a BACK for packet m from another node w before its own BBT expires, if w is a relay node that contends for the same relaying opportunity with v, v will cancel the BBT. After that, v clears the SAV, and sets a *network allocation vector* (NAV) to reserve the time period for the WM that follows the BACK to suppress hidden terminals. Also, v pauses all its BBTs.

(v) The OBCF process for m finishes when the NAV for m expires, or v finishes broadcast of m as a relay node. The SAV of v is cleared only if there are no OBCF processes going on, or when a NAV is set.

(vi) Each source or forwarder F_k sets a recurring retransmission timer upon transmitting m for the first time. This timer expires after every period of $MAX\_WAIT\_TIME = (T + \delta) \cdot \rho$ (the maximum delay of receiving a BACK from a forwarder, see below). This timer is only canceled when F_k receives a BACK that acknowledges the reception of m from a forwarder or makeup in the front of F_k. Otherwise, whenever this timer expires, F_k retransmits m until the maximum allowed number of retransmissions MAX_RETX is reached.

The time line of events are shown in Fig. 4.

A key element of OBCF is the delay function in BBT. A higher priority implies a smaller backoff delay. Observe that, for both types of relays, the RCR is a road segment, and the priority of nodes in a RCR increases/decreases

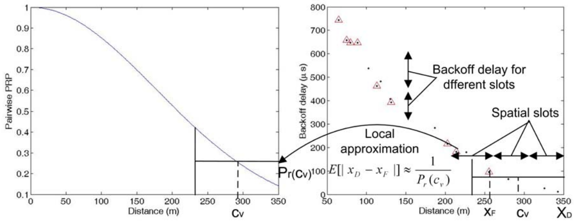


Figure 5: Left: the pairwise PRP function used in this paper. Right: an instance of the delay-distance function. $BR = 350m, R_{tx} = 250m, \rho = 50, T + \delta = 100\mu s$. "●": nodes; "△": relay candidates.

monotonically from one end to the other. So the delay can be expressed by a function of the distance.

In this paper, we propose an *enhanced slotted delay function*, where the RCR is divided into multiple equal-length spatial slots. The length of the spatial slot adapts to the local vehicle density, which results in one node per slot on average. A random jitter is used to separate multiple spatially-close nodes in the same slot to prevent collision. Naively, the average backoff delay of each slot is linear to the the slot number. However, to make the one-hop delay independent of the length of RCR, we scale the backoff delay of each spatial slot by the locally approximated average distance from the farthest relay candidate to the boundary of the RCR.

Let x_I denote the boundary towards which the delay should increase, and x_D denote the boundary towards which the delay should decrease. For a node v located in u's RCR, v's backoff delay Δt_v is:

$$S_v = \lfloor \frac{|x_v - x_D|}{L} \rfloor, L = 1000/\rho, x_v \in [x_I, x_D], \tag{4}$$

$$\Delta t_v = \begin{cases} [S_v \cdot (T+\delta) + T \cdot Rand(0,1)] \cdot P_r(c_v), \\ \qquad x_v \in [x_I, x_D]; \\ \infty, \qquad \text{otherwise,} \end{cases} \tag{5}$$

where S_v is the slot number of v, L is the spatial slot length (ρ is the vehicle density in # of vehicles/km which can be estimated distributively), T is the maximum delay range of a slot, δ is a safe interval which is used to separate two neighboring slots. And $c_v = |x_I - x_D| - \frac{S_v \cdot L + L/2}{2}$. The delay function is illustrated in Fig. 5.

The OBCF has several advantages. First, the redundant transmissions are eliminated more effectively. Because the BACK is transmitted at the base rate which requires lower SINR than using data rate, it can be received by most of the relay candidates. Also, the one-hop delay is small. Because BACK is very short (its transmission takes less than $100\mu s$), T can be set small (e.g. $80\mu s$). Third, BACK is also used to suppress the hidden terminals. As illustrated in Fig. 6, the transmission range of BACK is larger than twice that of the WM, which means most of the hidden terminals to the WMs are avoided.

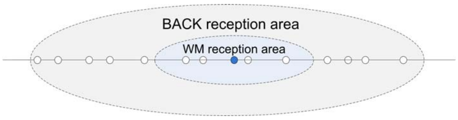


Figure 6: BACK suppresses hidden terminals.

5.5. Parameter optimization

We first introduce the centralized solution to find the optimal BR, then propose a distributed, locally optimized version. The global solution takes as input the average vehicle density ρ of IR, and approximates the $E[NT]$. Since $E[NT]$ has no closed form expression, the optimal BR that minimizes $E[NT]$ is sought out by sampling and searching.

5.5.1. Expected total number of transmissions. Let us consider a one-dimensional VANET where the IR length $\mathscr{L}$ is sufficiently large. Assume there are no redundant transmissions and no packet losses. Further, we assume there are enough relay candidates so that the PRP requirement can always be satisfied. Finally, the Rayleigh fading model is used for pairwise PRP function: $P_r(d) = exp(-\frac{P_{rxth}}{P_{ref}} d^2)$, where P_{rxth} is the reception threshold power, P_{ref} is the reference receive power at distance 1m by free space propagation model.

Next we briefly give the method and results of the derivation. Approximately,

$$E[NT] = E[X](E[M] + E[\omega] + 1), \tag{6}$$

$$\mathscr{L} = E[X] \cdot E[Y], \tag{7}$$

where $E[X]$ is the average number of one-hop zones, $E[M]$ is the average number of makeups in each one-hop zone, $E[Y]$ is the average one-hop zone length, $E[\omega]$ is the average actual retransmission count of each forwarder.

We then approximate $E[Y]$ and $E[M]$ by fixing the inter-space between successive vehicles to[6] $L = 1000/\rho$.

$$E[Y] = \sum_{k=1}^{N} kL \cdot P_F(k, L), N = \lfloor \frac{BR}{L} \rfloor, \tag{8}$$

where $P_F(k, L) = P_r(kL) \prod_{j=k+1}^{N} (1 - P_r(jL))$. From Fig. 7, we can see the above equation yields a good approximation to the average one-hop zone length. Similarly,

$$E[M] = \sum_{k=1}^{N} M(kL) \cdot P_F(k, L), \tag{9}$$

where $M(kL)$ is the number of makeups needed in an one-hop zone of length kL, under the ideal case where each makeup locates in the middle of its parent's sub-zone.

---

[6] The uniform distribution of vehicle positions is adopted in performance evaluation.

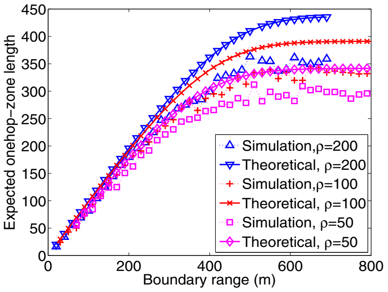


Figure 7: Numerical validation of $E[Y]$.

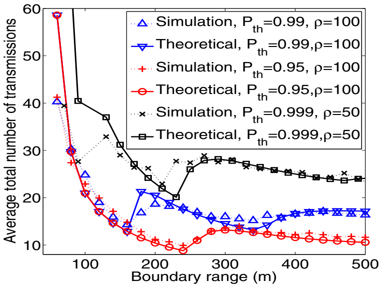


Figure 8: Numerical validation of $E[NT]$. $\mathscr{L} = 2km$.

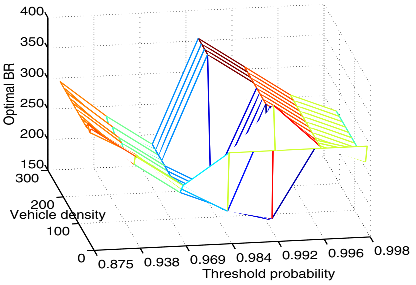


Figure 9: Optimal boundary range. $\mathscr{L} = 5km$.

For each forwarder, the expected number of retransmissions to be made is:

$$E[\omega]' = \frac{1}{1 - \prod_{i=1}^{\lfloor \frac{BR}{L} \rfloor} [1 - P_r(iL)]}, \tag{10}$$

and $E[\omega] = min\{E[\omega]', MAX\_RETX\}$.

Finally, the expected total number of transmissions is obtained by Eq. (6). $E[NT]$ is a function of both BR and ρ; however, it has no closed form solution. Under a fixed ρ, the optimal BR that minimizes $E[NT]$ can be obtained by searching BR from L to R_c (e.g. 500m), by setting the sampling interval to a small enough value, e.g., 10m.

5.5.2. Theoretical insights. First, we carry out simulations to verify the above results. An idealized version of the protocol (referred to as IDEAL) is implemented in NS2, where the BACK can be reliably received by all nodes in the network. Global vehicle density is used in IDEAL.

Fig. 8 compares the theoretical value of $E[NT]$ to the average number of transmissions in IDEAL. The theoretical values are close to the simulated values for all shown vehicle densities and P_{th}, the same for the optimal points of BR.

Interestingly, the optimal BR also exhibits an opportunistic behavior, depending on the required PRR and vehicle density. In Fig. 9, the optimal BR increases and decreases recurringly as the P_{th} increases. The reason is twofold. (1) Using some particular "longer hops" reduces the number of transmissions. Note that the $E[NT] \sim E[Y]$ function has multiple local minimas[7]. Using a farther minimal point not only reduces the number of hops, but also contributes to the LPRP of the other nodes. (2) On the other hand, the longer a hop is, the less possible it is for a WM to reach that far. The $E[Y]$ is upper-bounded when ρ is fixed.

For example, when $R_{tx} = 250m$, $E[Y]$ is always less than 350m. For $P_{th} = 0.95$, the first two local minimal points are $E[Y] = 220$ and 450, which implies the BR corresponding to the first one is optimal. In conclusion, the results indicate that *the best strategy is to opportunistically use long hops, but only when that long hop is feasible to reach statistically.*

5.5.3. Distributed algorithm. In OppCast, a distributed algorithm is used to set the BR since global vehicle density information is not available. Each node calculates its own optimal BR based on the local vehicle density estimated from its direct neighbor nodes' locations. A node is considered to be a neighbor as long as a beacon is heard from it within 1 second. Let the current forwarder be v and its furthest neighbor in the dissemination direction be u, then the local estimation of vehicle density is:

$$\widehat{\rho(v)} = \frac{\text{Number of neighboring vehicles between v and u}}{d(v,u)}. \tag{11}$$

To make the receivers of each broadcast agree on an unified RCR, we include the local optimal BR of the current node in every broadcast packet, and each node that receives the packet uses the estimation in the packet instead of its own. The protocol implementation details of OppCast are not presented due to space limitations.

6. Performance Evaluation

In this section, we evaluate the performance of OppCast. The compared protocols are: (1) Slotted p-persistence broadcast [6] (*Slotted-p*). Upon receiving a packet from j, a node i rebroadcasts the packet with a fixed probability q after the backoff delay T_{ij}, if it receives the WM packet for the first time and has not received any duplicates during the delay. Otherwise, it drops the packet. The delay-distance function is slotted and linear. *Slotted-p* is shown to be the best among the probability-based protocols [6]. We set $\tau = 5ms$, $N_S = 5$, $q = 0.5$ and $R = 250m$ in the simulations.

(2) Contention based dissemination (CBD) [9], a typical broadcast protocol also based on opportunistic forwarding. It does not differentiate between relay nodes. A node will set a backoff timer upon receiving a WM for the first time; it cancels the timer only if it receives duplicates during the delay, otherwise it rebroadcasts. The delay-distance function is continuous and linear. We set the maximum backoff delay to be 10ms and $R = 250m$.

Meanwhile, the IDEAL protocol is also compared, which can be regarded as a lower-bound to the broadcast overhead

---

[7] Because as $E[Y]$ increases beyond these local minima points, number of makeups per hop will first increase and then remain fixed.

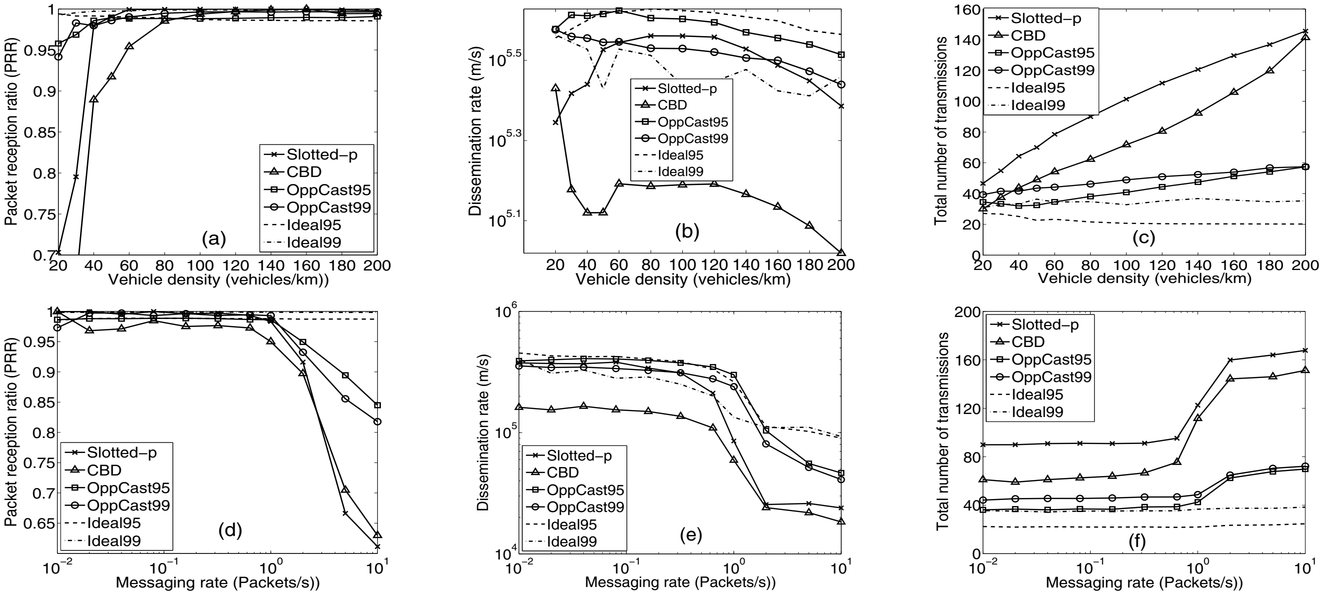


Figure 10: Simulation results. (a)-(c): fix $r = 0.1$, change ρ. (d)-(f): fix $\rho = 80$, change r.

since it has no collisions and redundant transmissions. The proposed protocols are named by appending the threshold PRR to the protocol type, e.g., for OppCast95, $P_{th} = 95\%$.

6.1. Simulation Setup

OppCast is implemented in NS-2.33 [24], which supports probabilistic propagation models. The parameters are summarized in Table. 1. The other PHY and MAC layer parameters follow the default settings of IEEE 802.11p. The Rayleigh fading model is used.

Table 1: Parameter Settings

Maximum time slot length, safe interval	80μs, 20μ s
R_{tx} for WM and BACK	250m, 628m
Transmission rates for WM and BACK	12 Mbps, 3 Mbps
Tx power, CSThresh, Noise floor	10, -96, -98dBm
WM, Beacon and BACK length	292, 72, 14 Bytes
MAX_RETX	3
Vehicle density	20-200 cars/km
Average vehicle speed	90km/h
Road length, IR length	6 km, 4-5 km (2 lanes)
Maximum makeup level	2

Each vehicle generates 10 beacons/s for routine safety applications. Each vehicle located between 1km and 2km generates urgent event-driven WMs at a messaging rate of r packets/s. Each simulation run lasts 10s, and a random scenario is generated where vehicles are uniformly distributed. Fig. 10 shows the average data from 5 repetitive runs.

6.2. Results

We first fix $r = 0.1$, and change ρ. In Fig. 10 (a), when $\rho = 60 \sim 200$, OppCast99 maintains average PRR of above 99%, and that of OppCast95 is higher than 98%. This shows OppCast indeed satisfies the PRR requirement when the network is well connected. When the network is sparse, i.e., $\rho = 20 \sim 50$, the PRR of OppCast protocols is still larger than 90%, which is much larger than Slotted-p and CBD. The advantage is primarily because the FFD phase tries to guarantee the forwarders span the whole network. The PRR in this case is lower than required, since there may not be enough makeups, and the maximum number of retransmissions is limited.

From Fig. 10 (b), it can be seen that the dissemination rate of OppCast95 is the highest except for IDEAL95, for all the vehicle densities shown. This is mainly attributed to the opportunistic forwarding concept in OBCF, which always utilizes the farthest forwarder candidate so that the one-hop delay is minimized. Also, the relay coordination mechanism in OBCF is carefully designed so that the hop-delay as small as order of $10\mu s$ can be achieved.

OppCast is more resource-efficient and scalable. In Fig. 10 (c), as vehicle density increases to 200, the number of transmissions used by OppCast95 and OppCast99 is about 40% of that of CBD. More importantly, the overhead increases slower with respect to vehicle density than in Slotted-p and CBD. This is because the relay node election mechanisms are optimized, and the OBCF is effective in reducing redundant transmissions and packet collisions under the presence of unreliable links. In CBD, because of channel fading the broadcast of relays cannot be heard by many other potential relays, which leads to large amount of redundant transmissions. On the other hand, in OppCast, we exert fine-control over the election of makeups, which turn out to be less than 3 per one-hop zone.

Next, we fix $\rho = 80$, and vary r from 0.01 to 10 packets/s. The PRR requirement in OppCast is always satisfied when r is small to moderate. The decrease of PRR only happens when message generation is very dense, i.e., $r > 1$. However, the PRR of OppCast is still much larger than Slotted-p and CBD in this case, while OppCast uses much less overhead. Similar results can be observed for the dissemination rate. This again shows the high reliability and fast dissemination is achieved in an resource-efficient way.

It is remarkable that in both simulation sets, the dissemination rate of OppCast95 even exceeds that of Slotted-p, which is essentially based on flooding. Also, the PRR of OppCast is much higher than the other protocols when the vehicles and messages are dense. Since the minimum hop-delay in Slotted-p is as low as 0, its decreased dissemination rate shows that redundant transmissions indeed undermine broadcast performance.

6.2.1. The Tradeoff. The OppCast95 achieves competitively high PRR and the highest dissemination rate using the smallest number of transmissions. The OppCast99 achieves higher PRR than OppCast95, but uses more transmissions and leads to slower dissemination. This reflects the fundamental tradeoff: the higher the reliability, more transmissions is needed, which in turn causes larger broadcast latency. Also, when the PRR is already close to 1, a marginal gain in PRR would demand noticeably more transmissions, and even a big decrease in the dissemination rate, as is in the case of OppCast99. *Thus, using a lower PRR goal, such as 95% is better than 99% in this sense.*

7. Conclusions

In this paper, we propose a fully-distributed opportunistic broadcast protocol (OppCast) for warning message dissemination in VANETs with unreliable links, which achieves high reliability and fast dissemination in a resource-efficient way. OppCast is composed of two types of broadcast phases, which are optimized so that the number of transmissions is minimized to satisfy a given PRR goal. The underlying MAC-layer broadcast primitive, OBCF, employs the idea of opportunistic forwarding to minimize the one-hop delay. The coordination mechanism between broadcast relay candidates is also carefully designed so that packet collisions are reduced effectively. Extensive simulations show that OppCast outperforms the other two state-of-the-art protocols in terms of reliability and dissemination rate under various vehicular and message densities, while having significantly smaller overhead. The results also reveal the fundamental tradeoff between reliability, dissemination rate and overhead, and provide valuable guidelines to VANET designers. We leave the extension of OppCast to different kinds of road topologies and disconnected networks as future work.

8. Acknowledgements

This work was supported in part by the US National Science Foundation under grants CNS-0746977, CNS-0716306, and CNS-0831628.

References

[1] *DSRC and IEEE 1609 standard family, http://www.standards.its.dot.gov/Documents/advisories/ dsrc_advisory.htm.*

[2] M. Torrent-Moreno, M. Killat, and H. Hartenstein, “The challenges of robust inter-vehicle communications,” *IEEE VTC 2005*, vol. 1, pp. 319–323, 28-25 Sept., 2005.

[3] M. Torrent-Moreno, F. Schmidt-Eisenlohr, H. Fussler, and H. Hartenstein, “Effects of a realistic channel model on packet forwarding in vehicular ad hoc networks,” in *IEEE WCNC*, 2006, pp. 385–391.

[4] M. Torrent-Moreno, D. Jiang, and H. Hartenstein, “Broadcast reception rates and effects of priority access in 802.11-based vehicular ad-hoc networks,” in *VANET ’04*. ACM, 2004.

[5] S.-Y. Ni, Y.-C. Tseng, Y.-S. Chen, and J.-P. Sheu, “The broadcast storm problem in a mobile ad hoc network,” in *IEEE/ACM MobiCom*, 1999, pp. 151–162.

[6] N. Wisitpongphan, O. Tonguz, J. Parikh, P. Mudalige, F. Bai, and V. Sadekar, “Broadcast storm mitigation techniques in vehicular ad hoc networks,” *IEEE Wireless Communications*, vol. 14, no. 6, pp. 84–94, December 2007.

[7] S. Oh, J. Kang, and M. Gruteser, “Location-based flooding techniques for vehicular emergency messaging,” in *IEEE MobiQuitous*, July 2006, pp. 1–9.

[8] R. Mangharam, R. Rajkumar, M. Hamilton, P. Mudalige, and F. Bai, “Bounded-latency alerts in vehicular networks,” in *MoVE*, May 2007, pp. 55–60.

[9] M. T-Moreno, “Inter-vehicle communications: Assessing information dissemination under safety constraints,” in *WONS*. IEEE, January 2007, pp. 59–64.

[10] H. Alshaer and E. Horlait, “Optimized adaptive broadcast scheme for inter-vehicle communication,” in *IEEE VTC*, May 2005, pp. 2840–2844.

[11] G. Korkmaz and E. Ekici, “Urban multi-hop broadcast protocol for inter-vehicle communication systems,” in *Proceedings of VANET ’04*. ACM, 2004, pp. 76–85.

[12] E. Fasolo, A. Zanella, and M. Zorzi, “An effective broadcast scheme for alert message propagation in vehicular ad hoc networks,” *IEEE ICC*, vol. 9, pp. 3960–3965, June 2006.

[13] V. Taliwal, D. Jiang, H. Mangold, C. Chen, and R. Sengupta, “Empirical determination of channel characteristics for dsrc vehicle-to-vehicle communication,” in *VANET ’04*. ACM, 2004.

[14] S. Biswas and R. Morris, “Exor: opportunistic multi-hop routing for wireless networks,” *SIGCOMM Comput. Commun. Rev.*, vol. 35, no. 4, pp. 133–144, 2005.

[15] K. Zeng, W. Lou, and H. Zhai, “On end-to-end throughput of opportunistic routing in multirate and multihop wireless networks,” in *IEEE INFOCOM 2008*, April 15-17, 2008.

[16] B. Blaszczyszyn, A. Laouiti, P. Muhlethaler, and Y. Toor, “Opportunistic broadcast in vanets (ob-van) using active signaling for relays selection,” in *ITS Telecommunications, 2008*, Oct. 2008, pp. 384–389.

[17] T. ElBatt, S. K. Goel, G. Holland, H. Krishnan, and J. Parikh, “Cooperative collision warning using dedicated short range wireless communications,” in *VANET ’06*. ACM, 2006, pp. 1–9.

[18] G. Resta, P. Santi, and J. Simon, “Analysis of multi-hop emergency message propagation in vehicular ad hoc networks,” in *ACM MobiHoc*, New York, NY, USA, 2007, pp. 140–149.

[19] L. Ilias and M. Cecilia, “Opportunistic spatio-temporal dissemination system for vehicular networks,” in *MobiOpp ’07*. ACM, 2007, pp. 39–46.

[20] M. Abuelela, S. Olariu, and I. Stojmenovic, “Opera: Opportunistic packet relaying in disconnected vehicular ad hoc networks,” in *IEEE MASS ’08*, 2008, pp. 285–294.

[21] D. Jiang, V. Taliwal, A. Meier, W. Holfelder, and R. Herrtwich, “Design of 5.9 ghz dsrc-based vehicular safety communication,” *IEEE Wireless Communications*, vol. 13, no. 5, pp. 36–43, October 2006.

[22] L. G. Valiant, “The complexity of enumeration and reliability problems,” *SIAM Journal on Computing*, vol. 8, no. 3, pp. 410–421, 1979.

[23] Y. Liu, Q. Zhang, and L. Ni, “Opportunity-based topology control in wireless sensor networks,” *IEEE ICDCS*, pp. 421–428, 2008.

[24] “Ns2,” *http://www.isi.edu/nsnam/ns*.