ROFF: RObust and Fast Forwarding in Vehicular Ad-Hoc Networks

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Abstract—Many safety applications rely on multi-hop broadcasting to disseminate safety messages. In most existing multi-hop broadcasting protocols, one next forwarder is selected through contention among forwarder candidates based on their different waiting times. In this paper, we first analyze the latency and collision of the existing protocols, and point out two problems: 1) unnecessary delay occurs in the contention process due to the lack of considering the distribution of vehicles and 2) the short difference between waiting times of forwarder candidates may allow redundant broadcasts to collide with each other. Secondly, we propose a new multi-hop broadcast protocol called RObust and Fast Forwarding (ROFF) to mitigate both problems. ROFF solves the first problem of unnecessary delay by allowing a forwarder candidate to use the waiting time which is inversely proportional to its forwarding priority. A forwarder candidate acquires its forwarding priority using the novel concept of ESD bitmap, which describes the distribution of empty spaces between vehicles. In addition, ROFF prevents the waiting time difference from being shorter than the predefined lower bound in order to avoid collisions, thus solving the second problem. Our extensive simulations reveal that ROFF achieves faster and more reliable broadcasting as compared to the other protocols.

Index Terms—Intelligent transportation systems (ITS), vehicular ad-hoc networks (VANET), multi-hop broadcasting

1 Introduction

A lot of safety applications over vehicular ad-hoc networks (VANET) rely on emergency message dissemination (EMD) through multi-hop broadcast. In EMD, a certain vehicle (i.e. source) issues an emergency message when a dangerous situation such as vehicle collision has been detected. Since the emergency message includes time-sensitive life-critical information, it should be disseminated to all vehicles in the target region as quickly and reliably as possible. Commonly, the target region is a road segment that is up to several kilometers long in the opposite direction of the source. Since the one-hop communication range of a source cannot cover the target region fully, multi-hop broadcasting should be used to disseminate the emergency message [1].

Until now, many broadcast schemes have been proposed to meet the requirements on the timeliness and reliability of EMD. The reliability can be improved by retransmitting the original copy of the emergency message or removing interference from hidden nodes [2], [3]. However, retransmissions and control messages exchanged for the interference avoidance increase the latency of the message dissemination. Apart from reliability issues, for fast message dissemination, the vehicle (called farthest vehicle) farthest from a forwarder in the message dissemination direction should be designated as a next forwarder. However, since the farthest vehicle can fail to successfully receive the message due to an inherently lossy wireless channel, the explicit designation of the farthest vehicle as the next forwarder may cause the multi-hop forwarding to be suspended. In most forwarding mechanisms [1], [4], therefore, vehicles (called forwarder candidates) which have received the broadcast message and are farther away from the previous forwarder contend to become a new forwarder in a distributed manner. Eventually, the forwarder candidate (called farthest forwarder candidate (FFC)) farthest from a forwarder is opportunistically selected. In particular, since retransmissions can help to increase the reliability of dissemination, each of contentions for transmission should be completed as quickly as possible in order to minimize the latency of the overall dissemination process. Note that achieving conflicting both goals simultaneously is a challenging issue [5].

The common idea behind existing forwarding mechanisms is to differentiate each waiting time (WT) of forwarder candidates. The waiting time ranges from 0 to the predefined upper bound (PUB). A forwarder candidate selects a point in the time range and uses it as the waiting time. In particular, in order to maximize the hop progress of the message in each forwarding, each forwarder candidate uses its waiting time that is inversely proportional to the distance from itself to the previous forwarder. Hence, the farthest forwarder candidate uses the shortest waiting time and then forwards the message first. The other forwarder candidates detect the transmission from the newly selected forwarder and suppress their scheduled transmissions.

We reveal two problems of existing fast forwarding schemes in this paper. First, existing schemes tacitly assume the perfect suppression of redundant transmissions, which means that all forwarder candidates can successfully receive the message from FFC within their waiting times. However, due to the short difference between waiting times of forwarder candidates, some forwarder candidates may start their transmissions before detecting the transmission from FFC and such redundant transmissions can collide with the transmission from FFC. The waiting time

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Manuscript received 29 Jan. 2014; revised 13 July 2014; accepted 28 Aug. 2014. Date of publication 21 Sept. 2014; date of current version 1 June 2015.
For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org, and reference the Digital Object Identifier below.
Digital Object Identifier no. 10.1109/TMC.2014.2359664

difference between two forwarder candidates is affected by PUB and the difference between distances from the previous forwarder to the forwarder candidates. The distance difference depends on the spatial vehicle distribution. In addition, under a given distribution of vehicles, a smaller PUB allows the next forwarder to be selected earlier, but results in a higher probability of collisions caused by the short waiting time difference. However, existing schemes simply regard PUB as a system parameter without considering the relationship between the selected PUB and collision probability (CP) under dynamically changing vehicle distributions. Second, the vehicle distribution is not uniform and continuously changing due to dynamic VANET traffic conditions. Hence, various scales of empty space with no vehicle can be present between vehicles. However, in existing schemes, waiting times of forwarder candidates are only affected by the locations of forwarder candidates without considering such an empty space. Therefore, given two vehicles separated by a large empty space, one closer to the previous forwarder should delay its forwarding necessarily for a long time even though there exists no vehicles farther than itself when it becomes FFC.

In this paper, we therefore propose a RObust and Fast Forwarding scheme (ROFF) as a solution to collision and latency-related problems mentioned above. Given two adjacent forwarder candidates A and B where A is farther from the previous forwarder than B, A's forwarding priority will be always higher than B's one, regardless of the size of the empty space between A and B. Hence, ROFF allows forwarder candidates to use waiting times which are inversely proportional to the forwarding priority in order to avoid unnecessary delay caused by the large empty space. In addition, ROFF finds out the minimum difference between waiting times of two adjacent vehicles (called $minDiff$) required for the successful suppression. $minDiff$ is affected by the latency in MAC and PHY layers (Refer to Section 3 for detailed description of $minDiff$). Based on $minDiff$, ROFF sophisticatedly adjusts the waiting times of forwarder candidates for guaranteeing that the waiting time difference between any two vehicles is larger than $minDiff$. Our main contributions are twofold. First, we highlight and analyze the collision and latency problems which existing forwarding schemes overlooked. Second, we propose a practical solution called ROFF in order to tackle the above-mentioned problems we indicated.

The remainder of this paper is structured as follows. Related works on forwarding mechanisms for EMD services are presented in Section 2. In Section 3, we analyze the collision and latency problems and present directions to solve the problems. Section 4 gives the detailed description for our proposed ROFF scheme. The ROFF scheme is evaluated in Section 5. Finally, some conclusions with future work are drawn in Section 6.

2 Related Works

In this section, we review the existing mechanisms by dividing them into two classes: waiting time-based and probability-based mechanisms.

Briesemeister and Hommel [6] first introduced a waiting time-based forwarding mechanism for VANETs. In [6], each of forward candidates determines its waiting time depending on its distance (d) to the previous forwarder according to Equation (1), where $MaxWT$ and $Range$ are the predefined maximum waiting time (i.e., PUB) and transmission range, respectively. The waiting time is mainly affected by both of $MaxWT$ and $Range$. However, the authors assumed a fixed transmissions range and did not mention about how to calculate $MaxWT$. They simply set $MaxWT$ and $Range$ to $40\,ms$ and $600\,m$, respectively in their simulations

$$WT(d) = -\frac{MaxWT}{Range} \cdot d + MaxWT. \tag{1}$$

Similar to [6], distance defer transfer (DDT) [7] and multi-hop vehicular broadcast (MHVB) [8] also allow forward candidates to select their waiting times inversely proportional to their distances between themselves and the previous forwarder. However, DDT and MHVB did not introduce any equations for calculating the waiting time. Urban multi-hop broadcast (UMB) [9] was proposed to address hidden nodes problems as well as the forwarder selection problem. UMB employed a concept of RTS/CTS signaling [10], where RTS/CTS packets were renamed as RTB/CTB (i.e. Request-To-Broadcast and Clear-To-Broadcast) packets. A forwarder broadcasts an RTB packet before forwarding an emergency message. On receiving the RTB packet, forwarder candidates participate in a segment-based contention phase where one of forwarder candidates is finally selected as the next forwarder. In this phase, the area inside the transmission range is divided into a certain number of segments. Each forwarder candidate sends a channel jamming signal (black-burst) with the duration proportional to the distance of its segment from the forwarder. Finally, a forwarder candidate with the longest black-burst wins the contention and sends the CTB message to the sender of the RTB message. After successfully receiving the CTB message from the newly selected forwarder, the current forwarder can start the transmission of an emergency message. Note that this RTB/CTB handshake can be repeated several times because of packet loss. In addition, similar to the way of differentiating a waiting time of each forwarder candidate, the duration of black-bust is mainly affected by the predefined maximum duration (i.e. PUB) as well as a transmission range. However, the authors assumed a fixed transmissions range and there is no information on how to calculate such the PUB.

Binary-partition-assisted broadcast (BPAB) [3] is a kind of improved UMB. It also relies on the RTB/CTB handshake. The strategy of BPAB for selecting a relay is similar to that of UMB in terms of the black-burst emission and area segmentation. However, BPAB introduces an enhanced segmentation method (called binary-partition) to address the latency problem resulting from the relay selection strategy of UMB.[1] In both UMB and BPAB protocols, although the RTB/CTB handshake helps to mitigate the interference from hidden nodes, it causes the delay on the dissemination of an

1. As stated in [3], this latency problem is more serious in denser networks. On the other hand, the frequent appearance of large empty spaces in sparse networks leads to long latency in timer-based protocols. Hence, both UMB and BPAB cannot be a direct solution to the drawbacks of existing timer-based protocols.

emergency message. In particular, the probability that the CTS packet transmitted from the newly selected forwarder may arrive at the current forwarder is quite low, because both BPAB and UMB aim to allow a vehicle located as far as possible from the current forwarder to be designated as a new forwarder. Hence, the repetitions of the handshake are unavoidable in error-prone vehicular networks, leading to unpredictable delays on the message dissemination. Furthermore, unicasting in 802.11 does not use the RTS/CTS handshaking when the size of a unicast message is under a certain threshold value (i.e. the default threshold value of 2347 bytes). Therefore, using control messages is considered ineffective for transmitting a small-sized emergency message.

In position-based adaptive broadcast (PAB) [11], the impact of vehicle speed on selecting a forwarder was investigated. PAB calculates the waiting time based on position and speed of a sender and receiver pair. Cut-through rebroadcasting (CTR) [12] also gives the higher rebroadcasting priority to vehicles which are farther within the transmission range, but operating in a multichannel environment. In addition, optimized dissemination of alarm message (ODAM) [13], Steet-Cast [14], Urban Vehicular BroadCAST (UV-CAST) [15] and Opportunistic broadCast (OppCast) [16], which have been proposed recently, also take a similar approach to [6].

However, aforementioned protocols do not address the collision and latency problems briefly mentioned in Section 1. They simply regard such parameters like as a controllable system parameter without careful consideration. On the other hand, fast multi-broadcast protocol (FMBP) [17] has been proposed recently to reduce the delay caused by using the fixed transmission range. FMBP allows each vehicle to estimate its actual transmission range and to use the estimated transmission range instead of the ideal transmission range (i.e. $Range$ in [6]) when calculating its waiting time. However, the estimation of actual transmission cannot be perfect in a fast fading environment such as VANETs. In addition, FMBP doest not address how to set the optimal $MaxWT$ value which is related to both of the possible collisions caused by simultaneous transmissions and the absolute duration of a waiting time of each forwarder candidate under the estimated $Range$.

Network Topology p-Persistence (NTPP) [19] also finds the proper transmission range based on the analysis on the relationship between transmission range and vehicle density. As stated in [19], the accurate estimation of the proper transmission range can be achieved when parameters such as vehicle density, transmission frequency of packets and transmission power are synchronized among vehicles. However, NTPP leaves an algorithm to synchronize such parameters as a future work. Hence, NTPP is still impractical. In addition, like FMBP, NTPP also set $MaxWT$ to a fixed value without careful considerations on collisions caused by the short difference among waiting time, and did not solve the problem on the latency caused by large empty spaces between vehicles.

Waiting time-based mechanisms can be subdivided into timer-based and contention window-based mechanisms. The aforementioned mechanisms belong to the timer-based mechanisms because a node usually defers its transmission using a timer whose timeout period is set to the selected waiting time. On the other hand, contention window-based mechanisms allow a forwarder candidate to defer its forwarding by adjusting the contention window rather than using a timer. In smart broadcast (SB) [18], the larger the distance from the previous forwarder becomes, the smaller contention window can be set. The actual waiting time is equal to the product of the slot time and integer value selected randomly within the given contention window. This approach aims to statistically allow the farthest forwarder candidate to win the contention. The BPAB protocol described previously is also a contention-based protocol. Contrary to SB, forwarder candidates within only the specific region (called farthest narrow segment) participate in the contention process using contention window. The farthest narrow segment is determined through the iterations of binary-partition phase. Other contention-based schemes can be found in [1], [4] and they work similar to SB and BPAB. In general, timer-based approaches have shown superiority over the contention window-based ones due to following reasons. First, the waiting time derived from the contention window is also mainly affected by the distance between the previous forwarder and forwarder candidates and the maximum waiting time is bounded to PUB. Therefore, contention window-based approaches suffer the latency problem as in timer-based ones. Second, in contention window-based approaches, the farthest forwarder candidate is not always selected as the new forwarder, which reduces the hop progress of the message in each forwarding. Third, contention window-based approaches restrict the forwarding to be initiated at certain times, which increases channel contention. In conclusion, we focus on the timer-based approach in this study and note that the contention means the timer-based contention in the rest of this paper.

Probability-based mechanisms allow only a subset of forwarder candidates to participate in the contention. The decision on the participation depends on the forwarding probability of each forwarder candidate. A forwarder candidate with a higher forwarding probability is likely to have more frequent chances to participate in the contention. Therefore, since the degree of contention for selecting a new forwarder is determined by the number of forwarder candidates, the main challenge in these mechanisms is to assign the optimal forwarding probability to each vehicle. For the best of our knowledge, Wisitpongphan et al. [20] first introduced probability-based mechanisms for VANETs. Two probability-based schemes are introduced in [20]: weighted p-persistence and slotted p-persistence schemes. In weighted p-persistence scheme, the vehicles that are farther away from the previous forwarder are given higher rebroadcast probabilities, which aims to maximize the hop progress of the message in each forwarding. In the weighted p-persistence scheme, a vehicle which decides to broadcast based on its forwarding probability directly transmits the packet without further contention. However, in the slotted p-persistence scheme, a vehicle which decides to forward a packet waits for a ceratin time before it rebroadcast a packet. A farther vehicle has a shorter waiting time as in waiting time-based mechanisms.

Those p-persistence schemes do not take the vehicle density into account when the forwarding probability is calculated. Therefore, the number of forwarder candidates participating in the contention can still be large even when the vehicle density is high. To address this problem, several protocols were proposed. Oh et al. [21] proposed a location-based flooding (LBF) protocol which allows each vehicle to adapt its forwarding probability according to the congestion level. In LBF, each node measures the inter arrival times of the received packets and quantifies the congestion level base on the times. Therefore, the nodes in the congested area lower their forwarding probabilities. IBrahim et al. [22] introduced a probabilistic Inter-Vehicle Geocast (p-IVG). In p-IVG, the forwarder candidate selects a random number between [0, 1]. If the selected number is less than the reciprocal of the vehicle density, the forwarder candidate participates in the contention; otherwise it drops the packet. Unlike location-based flooding and p-IVG, NTPP [19] takes both distance and vehicle density into account in calculating the forwarding probability. Hence, in NTPP, the farthest vehicle has a higher probability than nearby vehicles, and vehicles in sparse networks have a higher forwarding probability than vehicles in dense networks. Recently, Vegin et al. [23] also proposed a Collision-Aware REliable FORwarding (CAREFOR) protocol. CAREFOR also allows forwarder candidates to calculate their forwarding probabilities based on both of distance and vehicle density. In particular, since CAREFOR extends an existing scheme called irresponsible forwarding (IF) [24], a similar equation defined in IF is used to calculate the forwarding probability. However, the behavior of CAREFOR resembles that of NTPP in computing the forwarding probability.

The aforementioned probability-based mechanisms are obviously effective to reduce collisions caused by the simultaneous transmissions from multiple forwarder candidates. However, they cannot avoid the performance degradation with respect to one-hop progress of each forwarding, since even the forwarder candidates with high forwarding probabilities may cancel their scheduled forwarding. In this paper, we do not address how to calculate the forwarding probability. However, as stated before, all the probability-based protocols depend on the waiting time-based contention. Therefore, we note that our waiting time-based forwarding protocol proposed in this paper can be embedded into any probability-based protocols.

3 Forwarder Selection Problem

3.1 Collision Analysis

We classify collisions into two types: the first type of collision is caused by imperfect scheduling of channel access. In other words, nodes within the transmission range of each other may begin their transmissions at the same time, which results in a collision. The second type of collision is caused by the hidden node problem. Since nodes hidden from each other cannot sense each other, their transmissions can be overlapped in time. In this paper, we only focus on the first type. The second type of collision can be resolved by existing medium access schemes handling hidden terminal problem [9]. In the rest of this paper, collision means the first type.

We assume that S_f $(= \{f_i \,|\, 0 < i \leq N, i \text{ is an integer}\})$ is a set of forwarder candidates listed in ascending order of the distance between the previous forwarder and forwarder candidates, where N is the number of forwarder candidates and f_N corresponds to FFC. In existing schemes, each

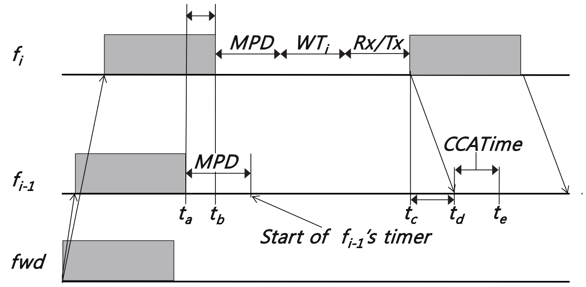


Fig. 1. Definition of the $minDiff$ between f_N and f_{N-1}.

forwarder candidate f_i suppresses its scheduled forwarding when it detects the emergency message forwarded from f_N. Hence, for the successful suppression, forwarder candidates excluding f_N should keep their interfaces staying in the receive mode until signal from f_N arrives at their interfaces. If a forwarder candidate changes the transmission mode from receive mode to transmit mode before it detects signal from f_N, it finally starts to transmit the packet and its transmission collides with one from f_N. According to existing schemes, each forwarder candidate decides its waiting time that is inversely proportional to the distance from itself to the previous forwarder. Hence, only if the timer of $f_{N\text{-}1}$ is long enough to detect the signal from f_N, all forwarder candidates including $f_{N\text{-}1}$ can successfully suppress their transmissions. However, existing schemes does not analyze the impact of the waiting time difference between f_N and $f_{N\text{-}1}$ on the successful suppression. Therefore, in this section, we find out the minimum waiting time difference between f_N and $f_{N\text{-}1}$ (called $minDiff$) required for the successful suppression.

Fig. 1 illustrates a scenario where f_i farther away from the forwarder (fwd) than f_{i-1} forwards the emergency message earlier than $f_{i\text{-}1}$. Both of f_i and $f_{i\text{-}1}$ complete the reception of the message from the previous forwarder at different times (i.e. t_a and t_b in Fig. 1) due to the difference in propagation delay. After completing the message reception, each forwarder candidate should spend additional time called MAC processing delay (MPD) in processing the message for the forwarding and then starts a waiting timer with the timeout interval being inversely proportional to the distance between the previous forwarder and itself. Once the timer expires, each forwarder candidate switches it transmission mode from receive mode to transmit mode and starts to inject the signal into the shared air medium. The time that the interface requires to change from receiving to transmitting is called Rx/Tx turnaround time (denoted by Rx/Tx). The injected signal arrives in $f_{i\text{-}1}$ at t_d, and $t_d - t_c$ is equal to the propagation delay between $f_{i\text{-}1}$ and f_i. At time t_d, although the radio interface of $f_{i\text{-}1}$ starts to receive the signal, the MAC module of $f_{i\text{-}1}$ cannot be aware of the current state of the medium before it receives an indication by the PHY module. According IEEE 802.11p, the time elapsed between t_d and the instant when the MAC module receives the indication of the change in the medium status should not be longer than the time called $CCATime$. Therefore, in this scenario, if the timer of $f_{i\text{-}1}$ expires between t_a and t_e, the transmission from f_i collides with one from $f_{i\text{-}1}$. On the other hand, if the timer of $f_{i\text{-}1}$ does not expire before t_e, the MAC module of $f_{i\text{-}1}$ can recognize that the channel status is

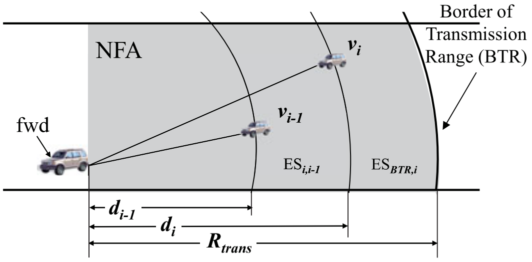


Fig. 2. The definition of empty space.

busy, and then successfully suppresses its scheduled transmission.

Since the propagation delay, MPD, Rx/Tx and $CCATime$ are not controllable parameters, the successful suppression of f_{i-1}'s forwarding can be achieved only by adjusting the difference between waiting times of f_i and f_{i-1} (denoted by WT_i and WT_{i-1}, respectively). As shown in Fig. 1, since f_{i-1} should stay in receive mode at least until the transmission from f_i is detected, MPD + WT_{i-1} should be larger than $t_e - t_a$. Therefore, $minDiff$ is equal to $(pd_{fwd,f_i} - pd_{fwd,f_{i-1}}) + pd_{f_i,f_{i-1}} + Rx/Tx + CCATime$ where $pd_{X,Y}$ indicates the propagation delay between vehicles X and Y.

3.2 Latency Analysis

In existing forwarding schemes, vehicles in the region called the forwarding area are eligible to participate in the contention. Most forwarding mechanisms define the forwarding area as the overlap region of two areas: 1) the transmission range of a forwarder and 2) the road segment that is in the opposite movement direction of a forwarder. We call this forwarding area as naive forwarding area (NFA). In VANETs, the vehicle distribution within NFA varies in time and NFA is not always filled with vehicles. In other words, there exist empty spaces of different sizes with no vehicle within NFA. We formally define the empty space as follow. We assume that S_v $(=\{v_i \,|\, 0 < i \leq M\})$ is a set of vehicles within NFA and M members are listed in ascending order of the distance between vehicles and a previous forwarder. The empty space (denoted by $ES_{i,i-1}$ in Fig. 2) between v_i and v_{i-1} corresponds to the road segment surrounded by two circles centered at the forwarder (denoted by fwd) as shown in Fig. 2. The radius of inner and outer circles are equal to distances (denoted by d_i and d_{i-1}) from the forwarder to v_i and v_{i-1} respectively. The size of empty space between v_i and v_{i-1} is equal to $d_i - d_{i-1}$. Similarly, the empty space (denoted by $ES_{BTR,i}$) between the vehicle farthest from fwd and the border of transmission range (BTR) of the previous forwarder corresponds to the road segment surrounded by two circles: one circle with radius of d_i and the other with radius of the transmission range (denoted by R_{trans}). The size of empty space between the farthest vehicle and the boarder is equal to $R_{trans} - d_i$.

The average and variance in the size of empty spaces depend on the vehicle distribution within NFA. In particular, the variance increases as the distribution becomes more uneven. In the rest of this section, we observe the negative effect of large empty spaces on the latency of the forwarder selection process through the following example. We call this problem a large empty space problem.

The broadcast delivery ratio (BDR) of 100 percent is not guaranteed in a highly lossy VANET environment. Therefore, the vehicle which is located physically farthest from the previous forwarder cannot always become the FFC. Any vehicle within NFA can become FFC according to the channel condition. Let us assume that there are two vehicles A and B within NFA where A is located farther away from the previous forwarder than B, and A has missed the broadcast message from the previous forwarder while vehicle B has received the message successfully. In this situation, if the empty space between A and B is small, B can forward the received message with a short waiting time, slightly longer than that of A. On the other hand, if the empty space between A and B is large, B will try to forward the received message after the waiting time, significantly longer than that of A even though there exists no better forwarder candidate than B.

Based on the above observations, we conclude that the performance of the existing timer-based contention schemes is affected by the distribution of empty spaces within NFA. Hence, we would like to allow waiting times not to be affected by the empty spaces in this paper. Given two adjacent forwarder candidates where one vehicle (A) is farther from the previous forwarder than the other (B), the forwarding priority of A is always higher than B's one regardless of the size of the empty space between them. Therefore, if a forwarder candidate is allowed to use the waiting time inversely proportional to its forwarding priority, not the distance from itself to the previous forwarder, the empty space cannot affect the latency of forwarding any longer. However, letting each vehicle v within NFA have a unique forwarding priority whose height is proportional to the distance from the previous forwarder to v is a challenge, which the ROFF scheme tries to address.

4 ROBUST AND FAST FORWARDING

In this section, we first give an overview of ROFF, and then its three key components are presented: construction of an ESD bitmap, forwarding priority acquisition and waiting time assignments. Our proposed ROFF protocol is designed under two assumptions: 1) each vehicle is equipped with a GPS system and a digital map. 2) In VANETs, it is assumed that each vehicle periodically broadcasts its beacon message including its current GPS position, velocity, braking/acceleration status, etc. The time interval between two consecutive beacons is called a beacon interval. The default beacon interval is approximately 100 milliseconds. Vehicles can become aware of their surroundings from periodic beacons received [25]. Note that ROFF allows each vehicle to simply utilize the information specified in the received beacon messages. Hence, ROFF does not cause any additional message overhead (MO) to collect surrounding information.

A forwarder first constructs a bitmap which describes an empty space distribution (ESD) within NFA according to a procedure introduced in Section 4.1 and broadcasts an emergency message with the bitmap. The bitmap is used to allow neighbor vehicles to decide whether or not they are allowed to participate in contention and to acquire their forwarding priorities (See Section 4.2). Selected forwarder candidates contend to be chosen as a new forwarder.

A contention resolution is done by differentiating waiting times of forwarder candidates according to our waiting time assignment algorithm (See Section 4.3).

4.1 ESD Bitmap Construction

ROFF aims to allow each node to decide its waiting time according to a forwarding priority (an integer value), not the distance from itself to the forwarder. The highest and lowest forwarding priorities are equal to 1 and the number of vehicles within NFA, respectively. In particular, since nodes with an identical forwarding priority have the same waiting time, their transmissions will collide. To avoid such collision, each node should be assigned a unique forwarding priority. Sections 4.1 and 4.2 describe how to assign forwarding priorities to vehicles within NFA. Note that each vehicle within NFA is called a potential forwarder candidate (PFC). A PFC becomes a forwarder candidate once it is allowed to participate in contention for choosing a new forwarder.

In VANETs, each vehicle can monitor a topology of its neighbors by collecting periodic beacons from neighbor vehicles. We refer to the neighborhood topology as a local view in this paper. When a PFC receives an emergency message, it can determine its forwarding priority, based on its local view and the location of the previous forwarder. However, since PFCs have different local views with each other due to packet loss and high mobility of nodes, it is possible that some PFCs have the same forwarding priority. Therefore, PFCs should determine their forwarding priorities, based on the same neighborhood topology. Therefore, ROFF utilizes the forwarder's local view as a reference.

Each vehicle manages a neighbor table (NBT) for monitoring its local view. Whenever a vehicle receives a beacon from its neighbor, it stores the neighbor information contained in the received beacon into NBT. Each entry in NBT consists of three fields: ID, location and beacon reception time. The beacon reception time is used to remove outdated information in NBT. In order to preserve the freshness of NBT, entries that are not updated every beacon interval are removed from the table. Due to the ROFF's strict constraint on the freshness of NBT, many neighbor vehicles of each vehicle v may be omitted from the v's local view, especially in an environment where a broadcast delivery ratio is low. However, as stated before, since beacons are used for many life-critical safety applications, the reliability of beacon transmission continues being improved by many researchers. In most of existing schemes, each vehicle repeatedly retransmits a beacon message several times within the beacon interval in order to allow its neighbor nodes to have redundant chances for receiving the message. ROFF assumes that its underlying beacon system adopts a repetition scheme providing the best performance in terms of transmission reliability. According to the performance measured in the previous works focusing on beacon transmissions [26], [27], we can clarify that a beacon delivery ratio of 90 percent is reasonable. Nevertheless, if there exist vehicles undiscovered by a forwarder within the beacon interval due to severely harsh channel condition, they are not regarded as neighbor vehicles of the forwarder. In addition, such vehicles cannot participate in contention for forwarding even though they received the message from the previous forwarder.

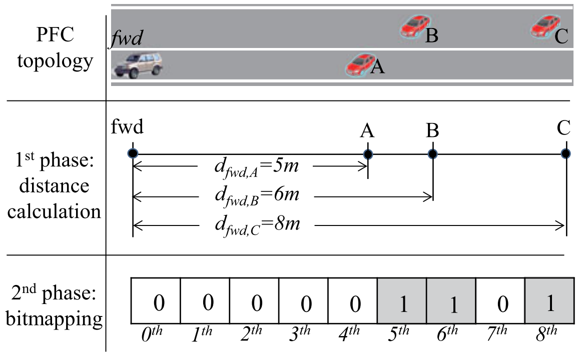


Fig. 3. ESD bitmap construction.

Based on NBT, a forwarder can acquire a topology of PFCs which is represented as a set of pairs, where each pair consists of the ID and location of a PFC. The number of pairs is equal to the number of discovered PFCs. We call this set a PFC topology. If the PFC topology is given to each of PFCs, each PFC can determine whether or not it is allowed to participate in contention and it can decide a forwarding priority. However, in dense networks, significant message overhead is required to advertise the PFC topology. As an alternative to reduce the message overhead, a list of IDs in ascending order of forwarding priority can substitute the PFC topology. Although the size of listing IDs is smaller than that of the PFC topology, it is still not negligible because the size of a vehicle ID can occupy several bytes. Particularly, in urban scenarios, hundreds of vehicles exist within their transmission range so that the message overhead can be increased significantly, implying that the approach of listing IDs is not scalable. Therefore, ROFF uses a new data structure called an ESD bitmap in order to notify PFCs of the participation in contention and to allow them to decide their forwarding priorities with the reduced message overhead.

The ESD bitmap is constructed through two phases. First, using a PFC topology, a forwarder (denoted by fwd in Fig. 3) measures its distances towards each of all the PFCs. The unit of distance measurement is meter, and the set of distances is denoted by S_{dist} in this paper. In particular, since the precision of distance measured by GPS coordination cannot be centimeter-level, all the elements of S_{dist} are non-negative integers, not floating values.[2] Fig. 3 depicts an example scenario where there exist three PFCs named A, B, and C. In this example, we assume that the distances from fwd to A, B and C are 5, 6 and 8 respectively. $d_{i,j}$ means the distance between PFCs i and j in the figure.

Second, fwd uses a bitmap (called ESD bitmap) to represent all the members in S_{dist} as shown in Fig. 3. The i-th bit set to 1 represents that there exists a PFC whose distance towards fwd ranges from $k*i$ to $k*(i+1)-1$, where k determines the distance range of PFCs identified by the same bit. According to this rule, the larger k is, the less number of bits is required to specify the presence of all the distances in S_{dist} on the bitmap. On the contrary, the probability that multiple PFCs are identified by a single bit

2. Note that our ESD bitmap construction works regardless of error in GPS coordinates. It simply utilizes GPS coordinates as an effective means of identifying each of PFCs.

increases with k. In other words, through the selection of k, there is a trade-off between the message overhead and discriminability. Although an optimal k (> 1 m) which may be effective in sparser networks can be estimated based on the distribution pattern of vehicles such as inter-distances of PFCs, we do not address the problem of finding the optimal k because the estimated value cannot be stable in dynamic vehicular environments. Therefore, in order to use each one bit to identify a single PFC as far as possible, we set k to 1 m which is a minimum meaningful value under the GPS precision, which indicates that we perform the worst-case study in terms of message overhead in this work. Furthermore, when $k == 1$, the total length of the ESD bitmap is equal to $\delta+1$, where δ is the longest distance between fwd and PFCs. In the example depicted in Fig. 3, the fifth, sixth, and eighth bits are set to 1 in order to indicate the presence of A, B and C, where δ is equal to 8.

4.2 Forwarding Priority Acquisition

The constructed ESD bitmap is piggybacked on the emergency message and broadcasted to PFCs. When a PFC receives an emergency message, it checks whether its distance toward the previous forwarder is indicated in the ESD bitmap in order to check its participation on the contention. As stated in the previous section, a forwarder uses locations of PFCs collected within the beacon interval (denoted by BI). Since the BIs of PFCs are not synchronized each other, a forwarder will not always receive the same beacon messages from a PFC within its BI. However, since a BI of each PFC can overlapped with at most two successive beacon intervals of any neighbor PFC, it will receive up to two different beacon messages from a neighbor PFC within its BI. Thus, the location of each PFC p used for the ESD bitmap construction is equal to one of two locations: 1) the location (denoted by L_t) that p advertised right before it received the emergency message at time t, 2) the location (denoted by L_{t-BI}) that p advertised right before $t-BI$. Therefore, p can decide its participation in contention according to the bit value at position $d1$ and $d2$, where $d1$ and $d2$ are the distances from the location of the previous forwarder (denoted by L_{fwd}) to L_t and L_{t-BI}, respectively. If the bit at position $d1$ or $d2$ is 1, p becomes a forwarder candidate.

After becoming a forwarder candidate, a PFC calculates its forwarding priority. In ROFF, based on the ESD bitmap, each PFC p can acquire the distances from the previous forwarder to each of PFCs who are allowed to participate in the contention. Therefore, letting L_{dist} denote the list of distances sorted in ascending order, ROFF sets p's forwarding priority to the rank of p's distance in L_{dist}, which means a higher forwarding priority is assigned to a PFC farther from the previous forwarder. Due to a low precision of distance measurements and packet loss, multiple PFCs may have the same forwarding priority. In order to avoid simultaneous transmissions from the multiple PFCs, ROFF allows them to contend and only one with the highest ID can participate in the forwarding. To enable this contention (called ID-based contention), after receiving the emergency message, each PFC p checks the existence of neighbor PFCs whose bit positions are identical to its bit position based on its NBT. If there are more than one PFC having the same bit position, p participates in the forwarding only when its ID is higher than the others.

Due to the inaccuracy of NBT caused by packet loss, the ID-based contention may fail to elect one winner as in following two cases. First, there can exist more than one PFCs considering themselves as the PFC with the highest ID. In this case, if their transmissions are not suppressed by a PFC with the forwarding priority higher than theirs, a packet collision is unavoidable. We note that since PFCs with the same forwarding priority are up to a few tens of meters far from each other, each of them can reliably track the others. Therefore, the probability that the first case happens is expected to be very low. Second, there can exist no PFC that regards itself as the PFC with the highest ID. In this case, even though a PFC has successfully received the emergency message, it is prevented from participating in the forwarding. Such a PFC is called isolated PFC in this paper. In addition, as stated in Section 4.2, a PFC also can become the isolated PFC due to its absence in the local view of the previous forwarder. In ROFF, the presence of isolate PFCs does not affect the performance of ROFF if a PFC farther away from the previous forwarder than the isolated PFCs successfully forwards the emergency message. On the other hand, if the isolated PFC is farther from the previous forwarder than the other PFCs, the non-participation of the isolated PFC may reduce hop progress of a message. However, due to the reduction of collision and latency, ROFF can outperform existing schemes in terms of the end-to-end delay, which is our main goal.

4.3 Waiting Time Assignment

ROFF allows each PFC p to be assigned the waiting time inversely proportional to its forwarding priority. In particular, for the successful forwarding, the waiting time of PFC (i)[3] should be at least longer than the waiting time of PFC (i$-$1) by $minDiff$. In Section 3.2, $minDiff$ was derived, which is the minimum difference between waiting times of two adjacent vehicles for avoiding transmission collisions caused by the short waiting time difference. Consequently, the waiting time (denoted by $WT_{PFC(k)}$) of PFC(k) is calculated by Equation (2), which means $WT_{PFC(k)}$ is the sum of $minDiff$s between PFCs whose forwarding priorities are higher than k. Note that ROFF allows PFC (1) to start the transmission without any waiting time because it has no neighboring forwarder candidates farther away from the previous forwarder than itself. Hence, Equation (2) is only applicable to PFCs whose priorities are lower than 2

$$WT_{PFC(k)} = \sum_{i=2}^{k} minDiff_{PFC(i),PFC(i-1)} (k \geq 2). \tag{2}$$

In Equation (2), $minDff$ between PFC(i) and PFC(i-1) is determined by MAC processing delay, Rx/Tx turnaround time, $CCATime$ and the propagation delays between the previous forwarder (denoted by fwd), PFC(i) and PFC(i$-$1). Rx/Tx turnaround time and $CCATime$ are fixed system parameters, but the propagation delays are dynamically changing parameters according to the distances between fwd, PFC(i) and PFC(i$-$1). While each PFC p can know the distances from fwd to each of PFCs based the ESD bitmap, it

3. We call PFC with the forwarding priority i PFC(i) in this paper.

TABLE 1
Simulation Parameters

Parameter	Value
Number of lanes	6 (three for each direction)
Lane width	5 m
Data rate	6 Mbps
Emergency message size	100 bytes
Beacon message size	100 bytes
Beacon interval	100 ms
Rx/Tx turnaround time	2 μ s
CCA time	8 μ s
N_{veh}	100, 200, 400, 800, 1,600
Margin of GPS error	$\pm$20 m

cannot calculate the distances between PFCs without any additional information such as GPS coordinates of them. However, given d_i and d_{i-1} which are distances from fwd to each of PFC(i) and PFC(i−1), respectively, p can derive the maximum distance between PFC(i) and PFC(i−1) which is equal to $\sqrt{{d_i}^2 + {d_{i-1}}^2 - 2d_id_{i-1} \cdot \cos\theta}$ where θ is determined by the location of fwd, PFC(i) and PFC(i−1). Therefore, in ROFF, the maximum distance between PFC(i) and PFC(i−1) is utilized for calculating $minDiff_{PFC(i),PFC(i-1)}$. In addition, since the physical distance between two vehicles can be different from the distance measured by GPS coordinates due to positioning errors in the GPS system, all distances between vehicles used for calculating the propagation delays are enlarged by 2*$MaxGpsErr$ where $MaxGpsErr$ is the predefined maximum position error. We note that $MaxGpsErr$ was set to 50 m in our simulations.

5 Performance Evaluation

5.1 Simulation Environments

We conducted simulations using the most recent version of the ns-2 simulator (i.e. ns-2.35) supporting realistic wireless network environments with the new IEEE 802.11 model [28]. We made parameters defined in the MAC and PHY modules of ns-2 conform to the IEEE 802.11p standard. The probabilistic Nakagami propagation model was also used as the propagation model. Measurement studies indicated that the Nakagami model fits better to VANETs than other models such as two-ray-ground (TRG), log-normal or pure Rayleigh shadowing [29]. In the Nakagami model, the distribution of signal strengths obtained by receivers can be controlled by a Nakagami fading parameter, ω. A smaller value of ω creates a more severe fading environment. In this simulation, we therefore set ω to 1 in order to create such a severe fading wireless environment. We defined three kinds of transmission power, Pt = 10.76, 15.76 and 21.76 dBm, which correspond to R_{trans} of 300, 600 and 900 m respectively under the deterministic TRG model. We generated a 4-km long straight highway scenario and allow N_{veh} vehicles to pass along the road with an average speed of 60km/h using the freeway mobility model in the USC mobility generator tool [30]. The other parameters are summarized in Table 1.

We have compared our ROFF protocol with a representative timer-based forwarding protocol [6] which is called Simple Timer-based Forwarding (STF) in this paper. As stated in Section 2, most of forwarding protocols follow the STF's approach where forwarder candidate farther away from the previous forwarder uses the smaller waiting time. It is meaningful enough to compare ROFF with STF only, since this simulation attempts to evaluate how well ROFF addresses the problems caused by both the large empty spaces and the short differences of waiting time. Other existing protocols may show their individual performances in a given simulation environment due to their different features. However, it is undesirable to compare ROFF with all those protocols one by one, since each protocol is optimized to achieve its own goal. In addition, system parameters are defined in some protocols (i.e., CAREFOR, NTPP, etc.) for their optimal operations, and they can expect good performance only by setting each of their system parameters to an appropriate value. However, most of them do not include any explicit methods to select those parameters. Hence, it is concluded that fair comparisons of ROFF with them are impossible.

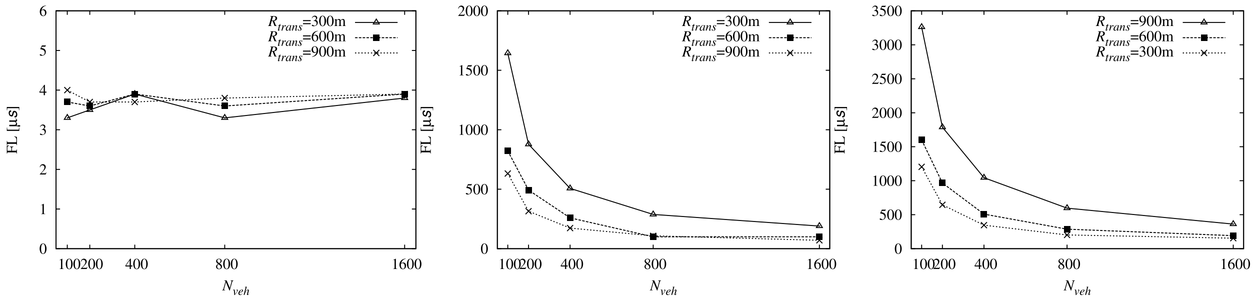
The performance of STF is mainly affected by MaxWT, the parameter of Equation (1). A smaller MaxWT allows the next forwarder to be selected earlier, but results in a higher probability of collisions caused by the short waiting time difference. Since there exists no method for calculating the optimal MaxWT, we measured the performance of STF under various MaxWTs. We name this scheme STF_x if it uses x as the MaxWT. For example, STF with MaxWT of 10ms is called STF_10ms. We implemented ROFF and STF protocols into the ns-2 simulator by modifying the existing IEEE 802.11 MAC module. A vehicle designated as a source only generates the event-driven emergency message. The target region is set to the 2-km long road segment in the opposite direction of the source. We designated the vehicle closest to the middle of the road as a source.

We evaluated the effectiveness and efficiency of the proposed ROFF protocol in terms of five metrics: 1) the forwarding latency (FL) is the time interval starting when the previous forwarder completed the packet transmission and ending when FFC successfully starts to transmit the packet. 2) the collision probability is the probability that a collision occurs between redundant transmissions caused by the suppression failure. 3) the one-hop message progress (OMP) is the additional coverage provided by the forwarder. Under our simulation environment with a homogenous transmission range and straight road scenarios, OMP can be measured as the distance between the previous forwarder and FFC. 4) the dissemination latency (DL) is the amount of time it takes all the target region to be covered by the selected forwarders. We do not consider the retransmission strategies for dealing with collisions in this study. We therefore only measured DL for scenarios where no collisions happen. Therefore, DL is mainly affected by FL and OMP. 5) the message overhead is the the ratio of the number of bytes in the information that must be sent with emergency message for the desired operations of a protocol to the total number of bytes in the emergency message.

5.2 Simulation Results

5.2.1 Forwarding Latency

First, we measured FL of the compared protocols as a function of N_{veh} and R_{trans}. Although the FL performance



(a) ROFF (b) STF_5ms (c) STF_10ms

Fig. 4. FL comparisons according to the density of vehicles.

can also be affected by BDR,[4] we used the fixed BDR of 80 percent in this simulation in order to analyze the impact of variation in N_{veh} and R_{trans} on the FL performance. The FL performance measured under different BDRs is also given later in this section. Each simulation was repeated 100 times. Depending on the topology of vehicles, both protocols may fail to successfully forward the message due to collisions. We allow outcomes with no collision to be averaged for producing the graphs within Fig. 4.

In Fig. 4, ROFF outperforms STF regardless of N_{veh} and R_{trans}. This result is the consequence of the fact that waiting times of forwarder candidates derived based on the forwarding priority are not affected by the size of empty spaces between them. Therefore, ROFF can provide low FL regardless of the distribution of empty spaces. On the other hand, in STF, FFC cannot help using long waiting time due to the presence of large empty space. In particular, the performance gain that ROFF could achieve in terms of FL as compared to STF increases as N_{veh} deceases due to the increased average size of empty spaces. On the other hand, the ROFF's gain decreases with the transmission range. This is because FL of STF is proportional to $\frac{dist(FFC,BTR)}{Range}$ where $dist(FFC, BTR)$ is the distance between FFC and BTR. Therefore, under the fixed $dist(FFC, BTR)$, a larger $Range$ results in a longer FL while FL of ROFF does not affected by both $dist(FFC, BTR)$ and $Range$.

Fig. 4 also depicts the FL performance of STF under different $MaxWT$ values. Since a smaller $MaxWT$ allows a next forwarder to be selected earlier on average, STF_5ms has a smaller FL than STF_10ms. However, there is a tradeoff between FL and CP, which means that the STF with a smaller $MaxWT$ results in having a higher CP. Therefore, although STF may provide a lower FL than ROFF when it uses a extremely small $MaxWT$, it is not desirable for STF to use a $MaxWT$ as small as possible in spite of the increase in CP. We observe the tradeoff in the next subsection.

4. In our simulations, BDR is defined as the ratio of the number of vehicles within the transmission range of a vehicle to the number of the vehicles which are discovered through beacon reception within the beacon interval. We controlled the BDR by adjusting the capture threshold ($CpTh$) value. In ns-2, a message with power equal to or higher than $CpTh$ can be successfully received in the presence of interferences. In particular, since it is impossible to let all the vehicles maintain the same BDR, we controlled the $CpTh$ value in order to allow the BDR only measured at the source to be kept around 50, 60, 70, 80, 90, and 100 percent with an error tolerance of 0.5 percent.

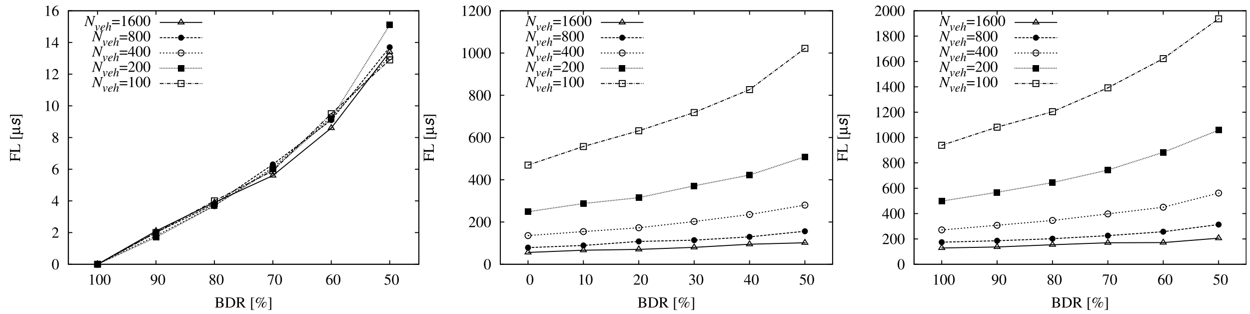
Second, we measured each FL of ROFF, STF_5ms and STF_10ms according to BDR as shown in Fig. 5. In ROFF, the probability that PFCs identified by the ESD bitmap miss the emergency message is inversely proportional to BDR. Particularly, the PFC with a higher forwarding priority is likely to miss the message more frequently, which means that the PFC with a low forwarding priority is more likely to be selected as a new forwarder in low-BDR environments. Therefore, the FL of ROFF increases as BDR decreases because the PFC with a lower forwarding priority uses a longer waiting time. Similarly, the FL of STF also increases as BDR decreases due to the increased waiting time of FFC. In STF, the waiting time of FFC is proportional to $dist(FFC, BTR)$ which increases as BDR decreases. In particular, the FL of STF increases sharply than that of ROFF because of the large empty space between FFC and BTR.

5.2.2 Collision Probability

In STF, the transmission of FFC can collide with another forwarder candidate's transmission due to the short waiting time difference between them. Given S_f $(= \{f_i \mid 0 < i \leq N$, i is an integer, N is the number of forwarder candidates$\})$ which is a set of forwarder candidates listed in ascending order of the distance between the previous forwarder and forwarder candidates, the CP of STF (denoted CP_{STF}) is equal to Equation (3) where WT_{f_i} and d_{f_i} means the waiting time of f_i and the distance between f_i and the previous forwarder respectively. In Equation (3), CP_{STF} is equal to the probability that the size of the empty space between f_N and $f_{N\text{-}1}$ is smaller than $k(= Range \cdot \frac{minDiff}{MaxWT})m$, where $Range$, $minDiff$ and $MaxWT$ are predefined parameters

$$\begin{aligned} CP_{STF} &= P(minDiff > (WT_{f_{N-1}} - WT_{f_N})) \\ &= P\left(Range \cdot \frac{minDiff}{MaxWT} > (d_{f_N} - d_{f_{N-1}})\right). \end{aligned} \tag{3}$$

Different with STF, ROFF can prevent collisions caused by the short waiting time difference. However, ROFF is not perfectly free to collision. In ROFF, a collision occurs when two events happen at the same time. The first event (e_1) is when there is more than one forwarder candidate regarding itself as the one with the highest forwarding priority. The group of forwarder candidates involved in e_1 is denoted by G. The second event (e_2) is when more than one forwarder



(a) ROFF (b) STF_5ms (c) STF_10ms

Fig. 5. FL comparisons according to broadcast delivery ratio.

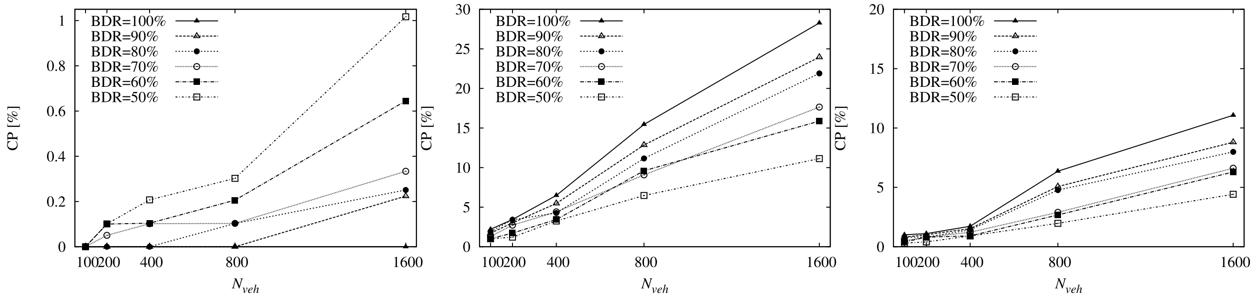
candidate within G recognize itself as the one with the highest ID. Therefore, the CP of ROFF (denoted CP_{ROFF}) is equal to the product of two probabilities P_1 and P_2 which are the probabilities that e_1 and e_2 happen, respectively.

According to the forwarding priority acquisition method in ROFF, a potential forwarder candidate becomes a forwarding candidate if only one of two locations that it advertised during last two successive beacon intervals matches with the bit set to 1. This method is called history-based method in this work, and the set of forwarder candidates selected by the history-based method is denoted by S_f^h ($= \{f_i \,|\, 0 < i \leq N$, i is an integer, N is the number of forwarder candidates$\}$). The history-based method may increase the probability that multiple nodes match with the same 1-bit as compared to the method where the matching is only done based on the single location that each vehicle has advertised recently. However, the history-based method allows a potential forwarder candidate whose location is already specified in the ESD bitmap to participate in the contention in face of packet loss. According to this operational feature, when S_f^h is determined, P_1 becomes equal to the probability that the size of the empty space between f_N and f_{N-1} is less than 1m (i.e., $d_{f_N} == d_{f_{N-1}}$).

We note that it is impossible to mathematically derive accurate CP_{STF} and CP_{ROFF} because they are affected by various factors: vehicle density, distribution pattern of vehicles, channel condition, etc. We therefore compare the performance of both protocols quantitatively. We measured each CP of ROFF, STF_5ms and STF_10ms as a function of BDR and N_{veh} as shown in Fig. 6. In this simulation, we set R_{trans} to 900 m. As expected, ROFF shows a lower CP than both STF variants regardless of BDR and N_{veh}. In addition, we also observed that STF_10ms shows a lower CP than STF_5ms (see Figs. 6b and 6c). This is because a larger $MaxWT$ derives a bigger difference between waiting times of adjacent forwarder candidates. In particular, the CP of all the compared protocols increases with N_{veh} because the average size of the empty spaces among forwarder candidates is inversely proportional to N_{veh}. More specifically, in STF, a collision occurs when the difference between waiting times of f_N and f_{N-1} is smaller than $minDiff$. Hence, STF shows a higher CP in a heavier network condition because the waiting time difference decreases with the average size of the empty space. On the other hand, in ROFF, a collision occurs when e_1 happens. The occurrence frequency of e_1 increases with the average size of the empty space.

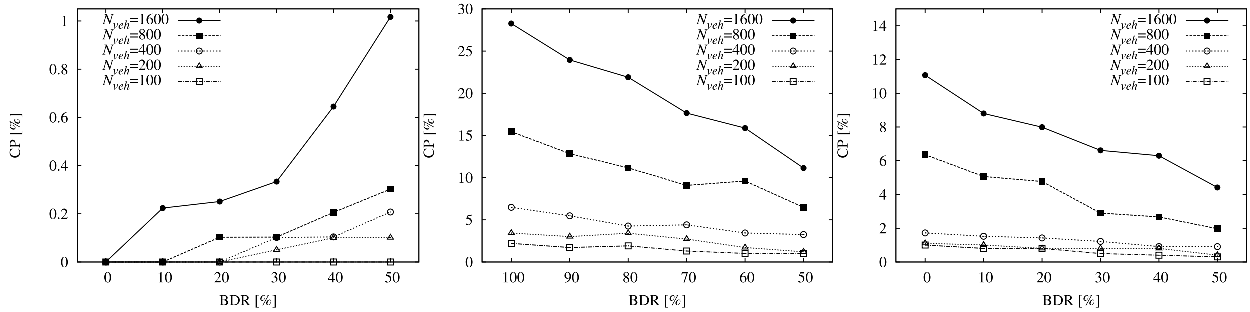
BDR is also an important parameter that affects the CP performance of the protocols. As shown in Fig. 7a, ROFF is collision-free when BDR is 100 percent. However, since the probability that multiple PFCs have the same forwarding priority is inversely proportional to BDR, the CP of ROFF increases as BDR decreases. On the other hand, the CP of STF decreases with BDR because the average size of the empty space increases as BDR decreases (see Figs. 7b and 7c).

We also measured each CP of the protocols under different R_{trans} values. As expected, we observed similar results regardless of R_{trans}. Therefore, we omitted the results of simulations using R_{trans} of 300 or 600 m in this paper. However, one interesting but expected feature is that the CP of STF increases with the transmission range due to the reduced waiting time difference between f_N and $f_{N\text{-}1}$. On the other hand, the CP of ROFF is not affected by variations in transmission range because the waiting time of each forwarder candidate is not determined depending on the distribution of empty spaces.



(a) ROFF (b) STF_5ms (c) STF_10ms

Fig. 6. CP comparisons according to the density of vehicles.



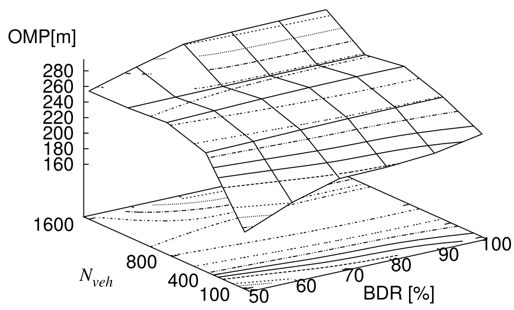
(a) ROFF (b) STF_5ms (c) STF_10ms

Fig. 7. CP comparisons according to the broadcast delivery ratio.

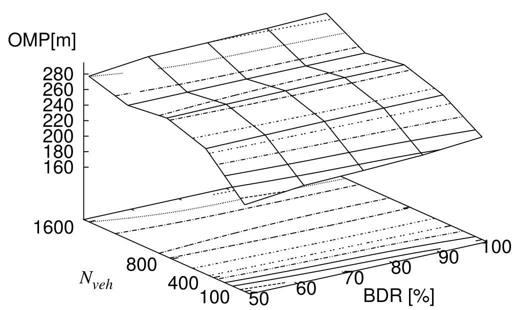
5.2.3 One-Hop Message Progress

FFC is the forwarder candidate which provides the largest OMP. In STF, FFC always becomes a new forwarder. On the other hand, ROFF may fail to select FFC as a new forwarder due to the presence of isolated PFCs, which means that ROFF cannot show a larger OMP than STF. Therefore, in order to analyze the gap between the OMP performance of both protocols, we measured the OMP of both protocols as a function of BDR and N_{veh} as shown in Fig. 8. Since $MaxWT$ and R_{trans} do not affect the OMP performance, we only measured the OMP performance of STF_10m, where R_{trans} was set to 300 m.

From Fig. 8, we can observe that the OMP of both protocols decreases with N_{veh} due to the increase in the average empty space size. In addition, since the reduction in BDR also results in the increase of the average empty space size between forwarder candidates, the OMP of both protocols also decreases as BDR increases. In particular, the presence of isolated PFCs increases the average size of empty spaces between vehicles. As stated in Sections 4.1 and 4.2, isolated PFCs appear more frequently as BDR decreases. Therefore, the OMP of ROFF decreases more sharply than that of STF as BDR increases.



(a) ROFF



(b) STF_10ms

Fig. 8. OMP comparisons.

5.2.4 Dissemination Latency & Message Overhead

DL is affected by FL, OMP, and transmission delay (denoted by d_{trans}). Previously, we analyzed the FL and OMP performance of the compared protocols, but did not measure d_{trans}. Therefore, we first analyze d_{trans} of ROFF and STF, and then measure DL of them in this section.

d_{trans} is a function of two parameters: data rate and packet size. First, d_{trans} is inversely proportional to date rate (denoted by r_{data}). However, both protocols work independent of underlying r_{data} so that r_{data} cannot derive the difference between the DLs of both protocols. Therefore, we allow the compared protocols to use the same r_{data}. Currently, IEEE 802.11p supports eight different data rates, each of which is determined by the combination of coding and modulation schemes. Among them, we used 6 Mb/s as r_{data}. Several recent measurement studies indicated that 6 Mb/s is the optimal data rate for transmitting safety messages such as beacon and emergency messages. Second, d_{trans} is proportional to the packet size (denoted by s_{pkt}). Since ROFF broadcasts the emergency message with the ESD bitmap, ROFF incurs the transmission delay longer than STF. We measured ROFF's MO against N_{veh} and R_{trans} under various BDR values. In ROFF, MO is equal to the size of the ESD bitmap. As stated in Section 4.1, the size of the ESD bitmap is equal to the distance between the forwarder (fwd) and the PFC farthest from fwd. Since the average distance between fwd and the farthest PFC increases with N_{veh}, R_{trans} and BDR, the average size of the ESD bitmap (i.e., MO) also increases with them. More specifically, MO ranges between 24 and 30 bytes in case of $R_{trans} = 300\,m$. When R_{trans} is stretched up to $900\,m$, MO gets expanded up to 86-111 bytes.

Table 2 summarizes the DL performances of ROFF, STF_5ms, and STF_10ms. We measured each DL of three protocols according to N_{veh} and BDR under different R_{trans} values. Since DL increases with the size of target region trivially, we only present results derived from simulations using target region of $2\,km$ in this paper. Each simulation was repeated 100 times. We allow outcomes with no collision to be averaged for producing the data within Table 2.

TABLE 2
DL Comparisons

N_{veh}	$R_{trans} = 300\,\mathrm{m}$			$R_{trans} = 600\,\mathrm{m}$			$R_{trans} = 900\,\mathrm{m}$		
	$ROFF$	STF_5ms	STF_10ms	$ROFF$	STF_5ms	STF_10ms	$ROFF$	STF_5ms	STF_10ms
100	0.255	1.556	2.855	0.296	0.901	1.52	0.2165	0.685	1.154
200	0.264	0.939	1.613	0.295	0.667	1.046	0.2165	0.465	0.714
400	0.268	0.679	1.091	0.293	0.492	0.689	0.2163	0.352	0.487
800	0.27	0.503	0.738	0.29	0.38	0.529	0.2161	0.295	0.383
1600	0.271	0.428	0.592	0.286	0.379	0.467	0.2156	0.272	0.345
BDR	$R_{trans} = 300\,\mathrm{m}$			$R_{trans} = 600\,\mathrm{m}$			$R_{trans} = 900\,\mathrm{m}$		
	$ROFF$	STF_5ms	STF_10ms	$ROFF$	STF_5ms	STF_10ms	$ROFF$	STF_5ms	STF_10ms
0	0.271	0.428	0.592	0.296	0.379	0.466	0.216	0.272	0.345
10	0.273	0.443	0.618	0.297	0.394	0.483	0.218	0.283	0.352
20	0.275	0.461	0.633	0.299	0.395	0.487	0.22	0.287	0.371
30	0.277	0.468	0.679	0.301	0.401	0.505	0.222	0.296	0.385
40	0.28	0.491	0.716	0.303	0.408	0.531	0.225	0.311	0.387
50	0.282	0.526	0.803	0.307	0.427	0.578	0.229	0.318	0.422

According to the simulation results observed previously, although STF is slightly superior to ROFF in terms of OMP and MO, the performance gain that ROFF could achieve in terms of FL as compared to STF is significantly high (i.e., several tens of percentages). Therefore, ROFF always outperforms STF in terms of DL regardless of N_{veh} and BDR as shown in Table 2. In particular, the ROFF's gain in DL increases with N_{veh} while it decreases with BDR. This phenomenon mainly comes from the change in the ROFF's gain in FL. Another noteworthy feature is that the ROFF's gain in DL decreases with $\frac{1}{R_{trans}}$ due to the increased transmission delay. Consequently, ROFF shows at least 27.8 and 45.5 percent less DL as compared to STF_5ms and STF_10ms, respectively in dense networks with bad channel conditions (i.e., $N_{veh} = 800$ and BDR $= 50\%$). In collision-free spare networks, we observed that ROFF shows up to 89.1 and 94.3 percent less DL as compared to STF_5ms and STF_10ms, respectively.

6 Conclusion

The RObust and Fast Forwarding protocol introduced a concept of ESD bitmap, which describes the distribution of empty spaces between vehicles within the forwarding area. Based on the ESD bitmap, forwarder candidates avoid the large forwarding latency caused by the empty spaces between vehicles by using the waiting time which is inversely proportional to its forwarding priority regardless of the size of the empty spaces between vehicles. In addition, in ROFF, the difference between waiting times of two forwarder candidates with the priority p and $p+1$ is equal to $minDiff$ which is the minimum waiting time difference between two forwarder candidates for suppressing redundant broadcasts successfully. Therefore, ROFF avoids collisions between redundant broadcasts caused by the short waiting time difference.

Through ns-2 simulations, ROFF has been evaluated against a representative existing protocol called the Simple Timer-based Forwarding protocol. Although STF is slightly superior to ROFF in terms of one-hop message progress and message overhead, the performance gain of forwarding latency and collision probability that ROFF could achieve is significantly high (i.e. several tens of percentages) as compared to STF. Particularly, in collision-free spare networks, we demonstrated that ROFF shows up to 89.1 and 94.3 percent less dissemination latency as compared to STFs with $MaxWT$ of 5ms and 10ms, respectively.

Acknowledgments

This research was supported by the Ministry of Science, ICT & Future Planning (MSIP), Korea, under the Convergence Information Technology Research Center (C-ITRC) support program(NIPA-2014-H0401-14-1004) supervised by the National IT Industry Promotion Agency (NIPA). This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2012R1A1A4A01009954).

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