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## Abstract

Rapidly and robustly disseminating safety messages is an important goal for vehicle-to-vehicle communications. When multiple vehicles receive an alert message, packet collisions may occur if they rebroadcast the message simultaneously. Due to the broadcast nature of safety messages, acknowledgement on the reception of packets is difficult, and such collision leads to non-recoverable failed delivery. The proposed Receive Power-Based Prioritized Rebroadcast (RPPR) scheme (1) minimizes the probability of packet collision during rebroadcast, and (2) maximizes the probability that a vehicle that is furthest away from the source rebroadcasts an alert message first. This improves robustness and minimizes the packet delivery time.

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# RECEIVE POWER-BASED PRIORITIZED REBROADCASTING FOR V2V SAFETY MESSAGE DISSEMINATION

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## ABSTRACT

Rapidly and robustly disseminating safety messages is an important goal for vehicle-to-vehicle communications. When multiple vehicles receive an alert message, packet collisions may occur if they rebroadcast the message simultaneously. Due to the broadcast nature of safety messages, acknowledgement on the reception of packets is difficult, and such collision leads to non-recoverable failed delivery. The proposed Receive Power-based Prioritized Rebroadcast (RPPR) scheme (1) minimizes the probability of packet collision during rebroadcast, and (2) maximizes the probability that a vehicle that is furthest away from the source rebroadcasts an alert message first. This improves robustness and minimizes the packet delivery time.

## KEYWORDS

Safety message dissemination, V2V communications, medium access control

## INTRODUCTION

One of the foreseen applications of vehicle-to-vehicle (V2V) communications relates to the dissemination of critical safety messages [1]-[4]. These messages are typically meant to inform nearby vehicles of events that may require driver intervention. Examples include the occurrence of an accident or collision, and car becoming disabled or anomaly in the roadway. These conditions may require rapid intervention by oncoming vehicles in order to avert additional collisions. With V2V communications, vehicles involved in collisions or that have detected hazardous conditions will transmit alert messages to warn other vehicles in the roadway.

The goal of safety message dissemination is to rapidly and robustly inform as many vehicles as possible regarding an event. As shown in Figure 1, due to limited range of radio signals, vehicles receiving an alert message need to rebroadcast it so that vehicles further away can also receive the same alert message. However, after vehicles B, C and D receives the original alert message, if C and D rebroadcasts the message at the same time, a packet collision occurs, and vehicles E, F and G cannot decode any of the packets. It is important that a safety message rebroadcast scheme be designed so that (1) the probability of collision during rebroadcast is minimized; and (2) the delivery time of alert message is minimized.

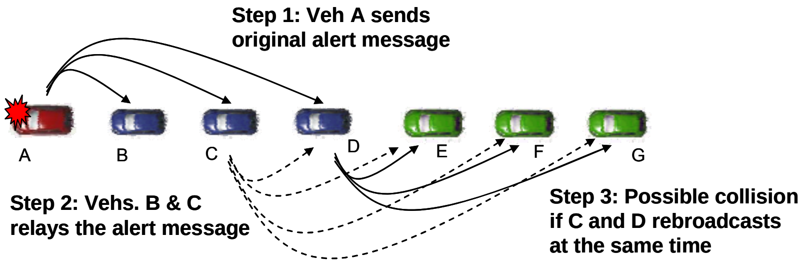


**Figure 1 Rebroadcasting safety message**

Generally, in wireless networks, collision avoidance is typically done via random back-off before transmission. For example, in existing IEEE 802.11p standard [5], each vehicle that has a message to transmit must first wait for a random amount of back-off time after channel is busy. Once the back-off time expires, the vehicle transmits its packet if the channel is free. Otherwise, it repeats the back-off process with another random back-off time. This process has a major drawback: the back-off time for messages with same priority is chosen from an identical distribution. Specifically, the vehicles immediately next to the alert source have the same probability of selecting the same back-off time as the vehicles far away from the alert source. This in turns leads to longer alert message delivery time.

Many other safety message dissemination methods have been proposed. In [4], bounded-latency alerts are achieved through an advanced city-wide planning scheme that determines the permissible transmission time of a vehicle given its current geographical location. In [6], the maximum back-off timer value is exponentially biased towards vehicles which are far away from the source, or vehicles that receive a similar proportion of forward and backward packets. As we will see, this back-off scheme is not optimal, and historical information may not be accurate due to the rapid changes in vehicle locations. In [7] and [8], very similar back-off scheme is used so that the maximum back-off time is a function of distance. Like [6], the schemes are not optimal, and their performances depend on knowledge of transmission range of the wireless network, which can be changed rapidly depending on physical environment and background interference of vehicles. The impact of irregular transmission range is evaluated in [9], but no specific methods were presented to address the issue.

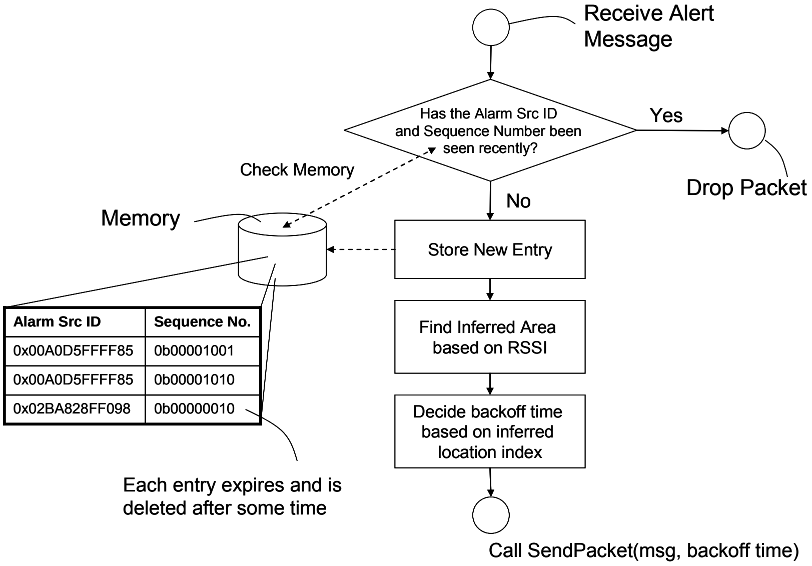
We propose the Receive Power-based Prioritized Rebroadcast (RPPR) mechanism for V2V safety message dissemination. The RPPR does not require any advanced planning, location information or historical information. Instead, the back-off timer is set using the receive power of a transmission, so that vehicles further away from the alert source has a higher priority in rebroadcasting the message. The irregular transmission range is naturally captured, since only packets that are received above the receiver sensitivity are retransmitted. We also propose to suspend back-off timer when a vehicle overhears another transmission while it is in the back-off state. This procedure leads to fast recovery when collision occurs.

Compared to other schemes that choose backoff values from a uniform distribution, our result shows that the RPPR mechanism can significantly improve the speed of alert message dissemination. At the same time, the probability of failed reception for RPPR is also significantly lower than that of other schemes using uniform distribution.

## RECEIVE POWER-BASED PRIORITIZED REBROADCAST

The RPPR focuses on the broadcast efficiency of vehicle-to-vehicle (V2V) communications. When an alert message is broadcasted by the source, vehicles in the neighborhood decode the message, inform their drivers of the content, and decide whether to rebroadcast the message to vehicles further away. This process is repeated again for vehicles receiving the rebroadcasted message.

The alert message contains an alarm source ID that uniquely identifies the source of alert messages, and a sequence number that distinguishes between the different alert messages generated from the same source. When a vehicle receives a message, it processes the packet using the steps as described in Figure 2. The receiver first checks the received alarm source ID and sequence number against its memory to see whether the specific packet has been seen before. If it has been seen previously, it is dropped; otherwise, the alarm source ID and sequence number of the packet are stored in the memory. Each entry in the memory expires after some pre-determined time. To rebroadcast the message, the vehicle first computes its *inferred area* using the receive power of the message, which in turns is used to decide the back-off time that the vehicle waits before rebroadcasting the message.



| Alarm Src ID | Sequence No. |
|---|---|
| 0x00A0D5FFFF85 | 0b00001001 |
| 0x00A0D5FFFF85 | 0b00001010 |
| 0x02BA828FF098 | 0b00000010 |

**Figure 2 Decision routine for processing a received alert message**

### Computing Inferred Area

We assume that all alert messages are transmitted using the same transmit power. Let $P_0$ (dBm) be the receive power at 1 meter away from the transmitter, and the channel path exponent is $\alpha$. Using a basic log-distance path loss model, when a vehicle receives an alert packet at power $P_r$ (dBm), the distance between the transmitter and receiver is $POW((P_0 - P_r)/10\alpha)$, where $POW(x) = 10^x$. Furthermore, the alert messages are assumed to be encoded using a fixed modulation and coding, which can be decoded only if the receive signal power is above $P_{min}$, the minimum receiver sensitivity. This implies a maximum transmission distance of $POW((P_0 - P_{min})/10\alpha)$.

The RPPR divides vehicles receiving a packet into $m \geq 2$ inferred areas. The index to the inferred area, i, can be computed using

$$i = \left\lceil \frac{POW\left(\frac{P_0 - P_r}{10\alpha}\right) - 1}{POW\left(\frac{P_0 - P_{\min}}{10\alpha}\right) - 1} m \right\rceil,$$

when $P_{\min} \leq P_r \leq P_0$. If $P_r \geq P_0$, set i = 1, and if $P_r \geq P_{\min}$, set i=m. The relationship between the inferred area index and the receive power is shown in Figure 3, assuming m = 10, $P_{\min}$ = -85 dBm and $P_0$ = 33 dBm.

Other mechanism, such as historical bit error rate, can also be used to infer the distance between a source and a receiver. However, in highly dynamic vehicular environment, reliance on historical information is difficult since the relative position of vehicle may change rapidly over time. The receive power can be measured and applied immediately at the moment a packet is received.

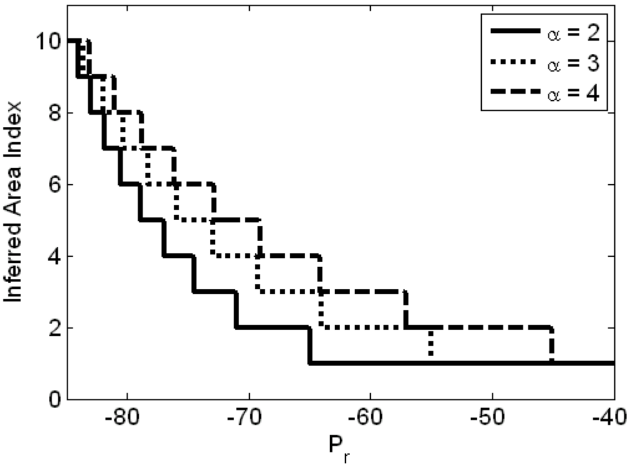


**Figure 3 Inferred area index as a function of receive power**

## Choosing Back-off Timer Value

The back-off timer should be set to achieve two key objectives: (1) to minimize the probability of packet collision during rebroadcasting; and (2) to maximize the probability of selecting a lower back-off timer value for vehicles that are further away from the alert source to rebroadcast, so to reduce latency for delivering the alert message for vehicles that are far away.

We consider $n$ integer back-off timer values $b_1 < b_2 < \ldots < b_n$. Given that a vehicle is located in an inferred area with index i, the vehicle chooses a back-off timer value $b_j$ with probability $p_{ij}$. Assuming that vehicles are uniformly distributed in a geographical area, the following theorem shows the conditional on $p_{ij}$ that minimizes the probability of packet collision during rebroadcasting:

***Theorem 1*:** When two vehicles independently select back-off timers at random to broadcast their messages, the probability of packet collision $P_{\text{collision}}$ during rebroadcasting is

$$P_{Collision} \geq \frac{1}{n},$$

with equality if and only if

$$\sum_{i=1}^{m} p_{ij} = \frac{m}{n}, \quad for\ all\ j \in \{1,2,\cdots,n\}.$$

***Proof***: Since the vehicles are uniformly distributed in a geographical area, one can readily compute the probability of collision $P_{Collision} = \sum_{j=1}^{n} \frac{1}{m^2}\left(\sum_{i=1}^{m} P_{ij}\right)^2$. The conclusion follows by noting that $\sum_{j=1}^{n} P_{ij} = 1$. ■

Many possible $p_{ij}$ values can satisfy the condition in Theorem 1. For example, as already used in the 802.11 standard [5], a uniform back-off regardless of the inferred areas ($p_{ij}$ = 1/n for all i and j) achieves minimum packet collision probability. However, schemes like that shown in [6], which chooses back-off values from uniform distribution [0, $T_{max}$], where $T_{max}$ is a function of the inferred area, are not optimal.

For the second objective, a vehicle in an inferred area with larger index should have a higher probability of choosing a lower back-off value. Also, to ensure that a far away vehicle always has priority of transmitting its packet over nearby vehicles, if a vehicle in an inferred area has a non-zero probability of selecting a particular backoff value, a vehicle at a closer inferred area should have zero probability to select a smaller backoff value. This naturally leads to the following probability filling algorithm:

```
For i = 1 to m
    For j = n to 1 with step -1
        Set $p_{ij} = \min\left\{\frac{m}{n} - \sum_{k=1}^{i-1} p_{kj}, 1 - \sum_{k=j+1}^{n} p_{ik}\right\}$
```

We show some examples of the resulting $p_{ij}$ values from the probability filling algorithm. We assume n = 4 and m ∈ [2,6]. Let $\pi_{mxn}$ be the matrix of $p_{ij}$ values,

$$P_{2x4} = \begin{bmatrix} 0 & 0 & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & 0 & 0 \end{bmatrix}, \quad P_{3x4} = \begin{bmatrix} 0 & 0 & \frac{1}{4} & \frac{3}{4} \\ 0 & \frac{1}{2} & \frac{1}{2} & 0 \\ \frac{3}{4} & \frac{1}{4} & 0 & 0 \end{bmatrix}, \quad P_{4x4} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}, \quad P_{5x4} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & \frac{4}{5} & \frac{1}{5} \\ 0 & \frac{1}{2} & \frac{1}{2} & 0 \\ \frac{1}{5} & \frac{4}{5} & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}, \quad P_{6x4} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & \frac{1}{2} & \frac{1}{2} \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ \frac{1}{2} & \frac{1}{2} & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

***Theorem 2***: The $p_{ij}$ values set by the probability filling algorithm both minimizes the probability of packet collision and maximizes the probability that a vehicle with the highest inferred area index rebroadcasts an alert message first.

The proof follows exactly the procedure shown in the probability filling algorithm, by first maximizing the probability of obtaining the smallest backoff value for vehicle is the furthest inferred area, and then giving the smallest possible backoff values to the closer inferred areas.

## State Machine

Figure 4 shows a state machine that controls alert rebroadcasting. When a vehicle receives an alert message, it transitions from listen/idle to the decode packet state. If the vehicle decides that the packet does not need to be rebroadcast, it returns to the listen/idle state; otherwise, it decides to transmit the message using a specific back-off time computed by using the procedure described in the previous subsection. It then enters the back-off state and starts decrementing the back-off time until it reaches zero, at which time it transmits the packet, and returns to the listen/idle state. While the back-off time is decrementing, other vehicles may transmit a packet, and the vehicle hears its transmission. In this case, the vehicle transitions from the back-off state to back-off suspended, and attempts to decode the packet. In the back-off suspended state, the back-off value does not change. If the packet is successfully decoded and the content of the packet is the same as the message to be sent by the vehicle, the vehicle discards the message and return to listen/idle state without sending the message. Otherwise, after the channel becomes free again, it re-enters the back-off state and continues to decrement its back-off timer.

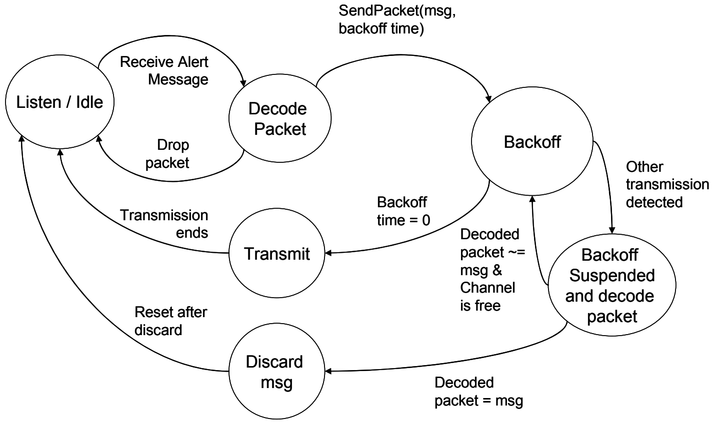


**Figure 4 State machine for alert rebroadcasting**

## Dealing with High Vehicle Density

The result in theorem 1 assumes that only two vehicles select backoff values and rebroadcast the message after the timers expire. When many vehicles are present, the collision probability increases. However, since existing WAVE communications assume that vehicles broadcast heartbeat messages every 100ms, vehicles can estimate the number of cars present in their vicinity. As vehicle density increases, the maximum number of backoff values and the corresponding maximum number of inferred areas should increase also.

In the WAVE standard, emergency broadcast may be sent after a backoff value of 0, 1, 2, or 3 slots. As a result, we will consider a case where, on average, two vehicles would choose backoff values from a set of containing 4 values. Also, we assume that $2 \le m_1 \le 4$ inferred areas are used for these 4 backoff values. Hence, for a vehicle density of $d$ vehicles per meter, and a maximum transmission distance of $\mathrm{POW}((P_0 - P_{\min})/10\alpha)$, we should set

$$m = \frac{1}{2} POW\left(\frac{P_0 - P_{\min}}{10\alpha}\right) d m_1 \text{ and } n = 2POW\left(\frac{P_0 - P_{\min}}{10\alpha}\right) d .$$

We call this setting as *Dynamic RPPR* with partition parameter $m_1$.

## SIMULATIONS

We assume OFDM transmission with transmission power of 33dBm, and minimum receiver sensitivity of -85dBm. The channel path exponent $\alpha$ = 4, and Rayleigh fading is assumed. When two packets transmit at the same time, a collision is assumed, and no vehicle can decode any message. A single alert source is located at the middle lane of a 3-lane straight horizontal highway, which define the origin of the Cartesian coordinate. Vehicles on adjacent lanes are 3.5 meters apart. For each lane, the inter-vehicle spacing follows a modified exponential variable of rate 3/*d* meters per vehicle, with a minimum value of 5 meters. We consider a highway stretch of 3km from the accident source. To focus our evaluation on the rebroadcasting protocols only, we assume that once the alert message is sent out, all other types of data and control messages of the network are suspended. The alert source sends a single message at the start of the simulation. Each packet has a transmission time of 200us. Each adjacent backoff value corresponds to an additional delay of 13 us. After carrier sensing changes from a channel busy state to channel free state, a vehicle waits for 50 us before resuming backoff. For each scenario, we run 6000 independent trials.

We first fix the maximum number of backoff values n=4 (similar to the one used for emergency messages in IEEE 802.11p standard [5]) and we consider the maximum number of zones m=2 or 4, and various vehicle density values. The results are shown in Figure 5 and Figure 6. In Figure 7, we also show the performance to the case with uniform distribution, similar to that is used in the IEEE 802.11p standard. The vertical candlesticks in the figures denote the maximum, 75-percentile, 25-percentile, and minimum delay values for vehicles in the 50 meters range. The horizontal lines in the top figures denote the median delay values. The bottom figures shows the probability of dropping failing to deliver a packet to vehicle at a certain distance away from the alert source after a single message broadcast. For every case, as the density of the network increases, the probability of failed reception at a particular distance away from the alert source also increases. This is due to the fact that a larger amount of vehicles attempts to rebroadcast and contend by picking a backoff value from a set of only four possibilities, which increases the probability of collision. In the 6000 trials, none of the protocols can send the message beyond 2200m from the alert source.

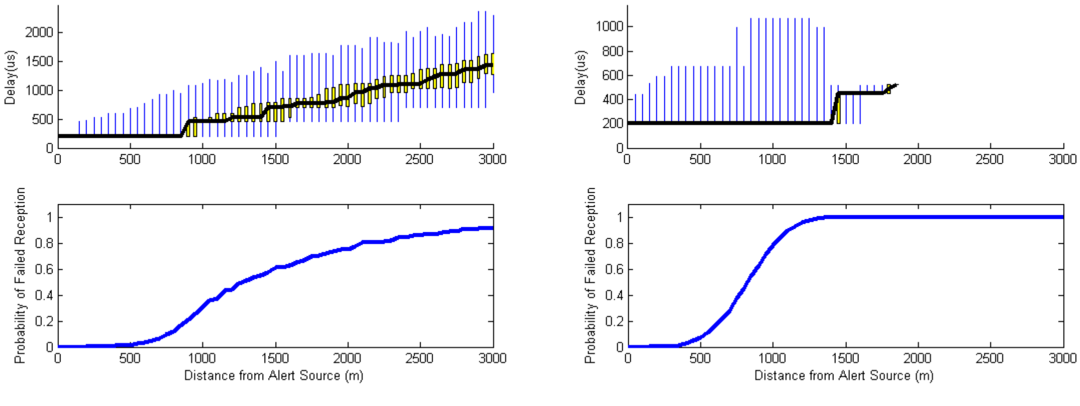


**Figure 5 Delay and Probability of Failed Reception of RPPR with m = 4 and n = 4, when vehicle density is 0.01 (left) and 0.05 (right) vehicles per meter**

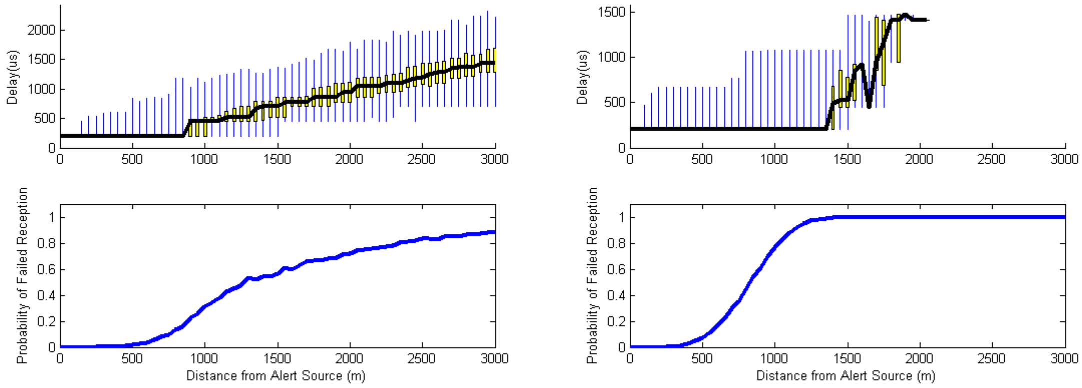


**Figure 6 Delay and Probability of Failed Reception of RPPR with m = 2 and n = 4 when vehicle density is 0.01 (left) and 0.05 (right) vehicles per meter**

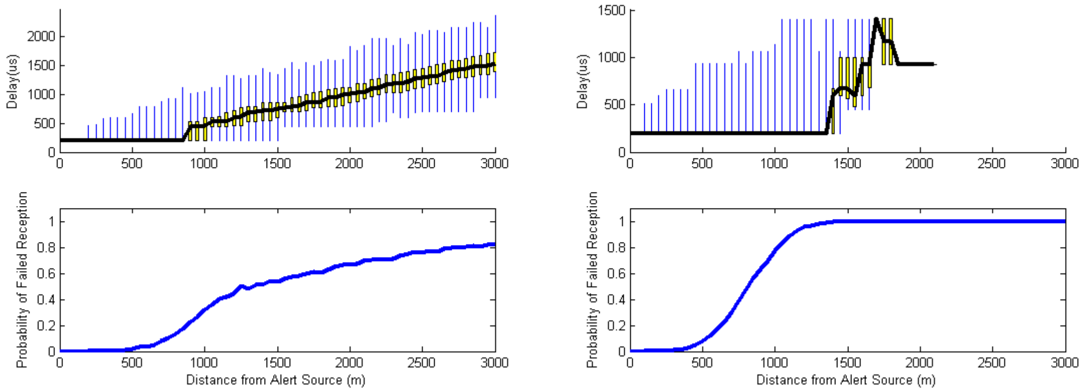


**Figure 7 Delay and Probability of Failed Reception of uniform backoff with n=4 when vehicle density is 0.01 (left) and 0.05 (right) vehicles per meter**

In Table 1, we show the average speed of dissemination and the probability of failed reception when a vehicle is located within a 50m range centered at 300m, 500m and 1km away from the alert source. We see that, given the simulation parameters, the rebroadcast protocols takes slightly more than 1us to disseminate the message for another 1m when the density is 0.01 vehicles per meter, and it takes about 1.45 us to advance 1m when the density is 0.05 vehicles per meter. Using these comparison, RPPR with m=2 and n=4 performs better than the other protocols.

**Table 1 Comparison of message dissemination speed and probability of packet drop**

| Density | RPPR: m=4, n=4 | RPPR: m=2, n=4 | Uniform: n=4 |
|---|---|---|---|
| 0.01 | 1.0492 us/m<br>0.005% @ 300m<br>0.014% @ 500m<br>30.49% @ 1km | 1.0330 us/m<br>0.002% @ 300m<br>0.018% @ 500m<br>31.01% @ 1km | 1.0263 us/m<br>0.003%@ 300m<br>0.019% @ 500m<br>32.27% @ 1km |
| 0.05 | 1.4521 us/m<br>0.005% @ 300m<br>0.077% @ 500m<br>77.76% @ 1km | 1.4503 us/m<br>0.005% @ 300m<br>0.076% @ 500m<br>76.53% @ 1km | 1.4750 us/m<br>0.008% @ 300m<br>0.078% @ 500m<br>77.38% @ 1km |

When the density of the vehicles can be estimated correctly, Dynamic RPPR can be used to further improve the performance. We consider partition parameter $m_1$ = 2 or 4. That is, for density of 0.01 vehicles per meter, we use n = 18, and m = 9 or 18. For density of 0.05 vehicles per meter, we use n = 90, and m = 45 or 90. We also compare our result to uniform distribution with n = 18 and 90. Figure 8 to Figure 10 show the performance of the Dynamic RPPR scheme and the one with uniform distribution with n = 90. We see that Dynamic RPPR with $m_1$ = 4 performs the best. As a matter of fact, the probability of failed reception is zero for the whole 3km stretch of highway. As the density decreases, the number of available backoff slots also decrease (to n=18). However, in this case (Figure 8 left), some packets are dropped. The performance of Dynamic RPPR with $m_1$ = 2 has similar, but slightly worse, performance compared to the one with $m_1$ = 4. For sufficient large number of backoff values n, we see that the performance of system using uniform distribution becomes significantly worse than the RPPR scheme. In Figure 10, even with n = 90 at low vehicle density, the probability of failed reception is significant.

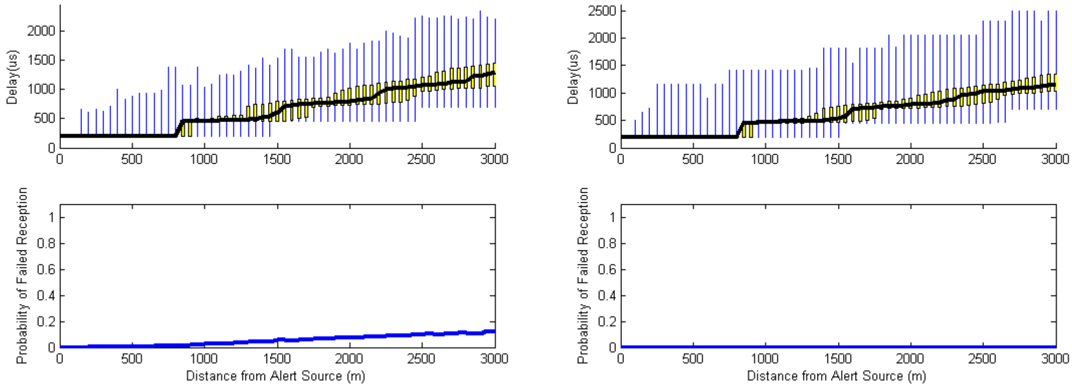


**Figure 8 Delay and Probability of Failed Reception of Dynamic RPPR with $m_1$ = 4, when vehicle density is 0.01 (left) and 0.05 (right) vehicles per meter**

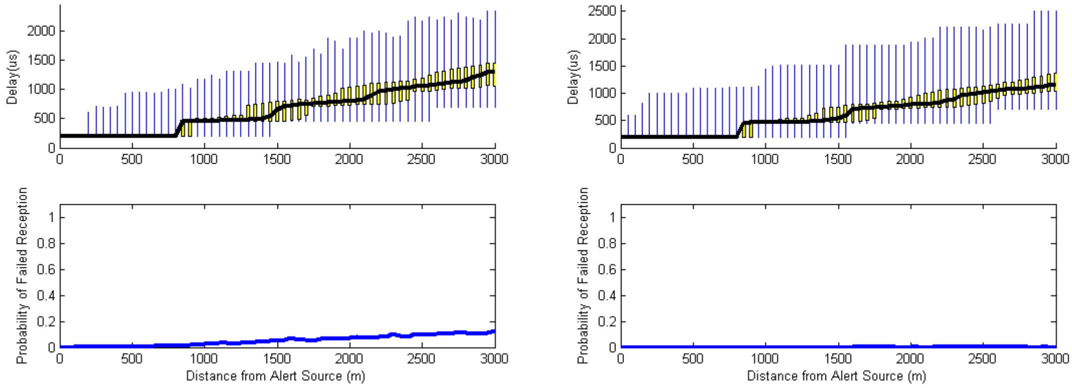


**Figure 9 Delay and Probability of Failed Reception of Dynamic RPPR with $m_1$ = 2, when vehicle density is 0.01 (left) and 0.05 (right) vehicles per meter**

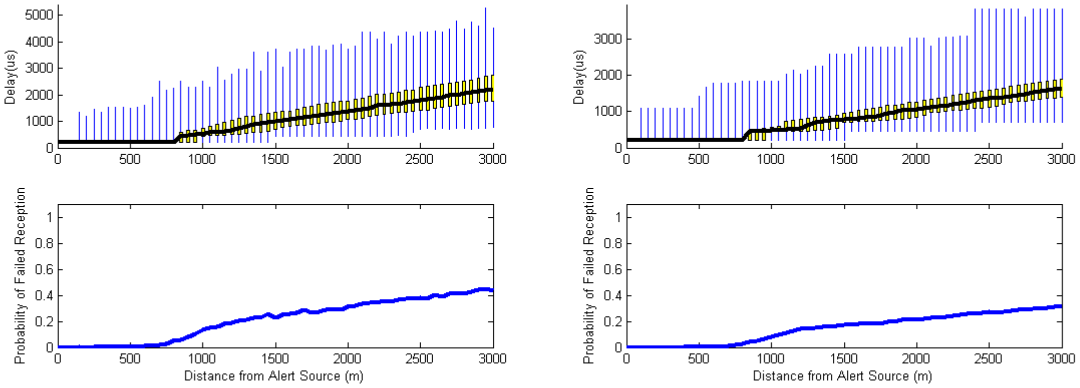


**Figure 10 Delay and Probability of Failed Reception of uniform backoff with n=90 when vehicle density is 0.01 (left) and 0.05 (right) vehicles per meter**

Table 2 shows the average speed of dissemination and the probability of failed reception of Dynamic RPPR (D-RPPR), and uniform distribution with n = 18 or 90. With dynamic RPPR, we see that the average speed of dissemination *increases* as the vehicle density increases (which is completely opposite of the case with fixed n). For density of 0.05 vehicles per meter, D-RPPR with $m_1 = 4$ sends message at about 0.7186 us per meter. This is a two-time speed up over the case with fixed n = 4. Using uniform distribution, even with n=90 (which is the same as the one used for D-RPPR), the speed of dissemination is only 0.8668 us per meter, which is 20% more than that achieved by D-RPPR. Also, note that the scheme with uniform distribution drops about 7.88% by 1km from alert source, while D-RPPR has no packet drop. We also show results for density of 0.1 vehicles per meter (here, we use n=178 and m=89 or 178). Once again, D-RPPR with $m_1 = 4$ outperforms all other schemes.

**Table 2 Comparison of message dissemination speed and probability of packet drop**

| Density | D-RPPR: $m_1$ =4 | D-RPPR: $m_1$=2 | Uniform: n=90 | Uniform: n=18 |
|---|---|---|---|---|
| 0.01 | 0.7491 us/m<br>0.0007% @ 300m<br>0.68% @ 500m<br>2.99% @ 1km | 0.7606 us/m<br>0.23% @ 300m<br>0.52% @ 500m<br>2.52% @ 1km | 1.0072 us/m<br>0.10% @ 300m<br>0.44% @ 500m<br>13.24% @ 1km | 0.8741 us/m<br>0.14% @ 300m<br>0.40% @ 500m<br>12.49% @ 1km |
| 0.05 | 0.7186 us/m<br>0.00% @ 300m<br>0.00% @ 500m<br>0.00% @ 1km | 0.7230 us/m<br>0.00% @ 300m<br>0.00% @ 500m<br>0.00% @ 1km | 0.8668 us/m<br>0.00% @ 300m<br>0.13% @ 500m<br>7.88% @ 1km | 0.9359 us/m<br>0.00% @ 300m<br>0.13% @ 500m<br>8.81% @ 1km |
| 0.10 | 0.7105 us/m<br>0.00% @ 300m<br>0.00% @ 500m<br>0.00% @ 1km | 0.7126 us/m<br>0.00% @ 300m<br>0.00% @ 500m<br>0.00% @ 1km | 0.8452 us/m<br>0.00% @ 300m<br>0.05% @ 500m<br>7.99% @ 1km | 1.1968 us/m<br>0.00% @ 300m<br>0.27% @ 500m<br>28.35% @ 1km |

## CONCLUSIONS

We introduce the Receive Power-based Prioritized Rebroadcast (RPPR) mechanism for safety message dissemination. The scheme infers the relative location of a vehicle based on the receive power of an alert message, and uses it to decide the amount of time that it waits before rebroadcasting the message. We provide an optimal probability filling algorithm to choose the back-off time, which minimizes the probability of collision during rebroadcasting, and maximizes the probability that a vehicle that is furthest away from the source rebroadcasts an alert message first. We also provide specify Dynamic RPPR which dynamically set the number of backoff values based on the vehicle density. The receive power is readily available through Receive Signal Strength Indication (RSSI) that is available to most communication devices today. It does not require any advanced planning, nor does it use any location or historical information. This is important because vehicle network changes rapidly, and outdated and inaccurate information leads to degradation of overall system performance. We compare RPPR to schemes using uniform distribution for backoff (similar to that used in IEEE 802.11p standard). We found that when the maximum number of backoff values, *n*, is sufficient large, the RPPR schemes outperformance the schemes with uniform distribution significantly.

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