Reception power quantization–based emergency message vehicle-to-vehicle multihop broadcast transmission scheme for vehicle accident prevention

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Abstract
In this article, an emergency message reception power quantization–based time-slot broadcast scheme is proposed for vehicle-to-vehicle multihop communications. The power quantization–based time-slot broadcast scheme derives the optimal reception power quantization size such that time-slot assignments can be made to minimize the average time delay to support quick multihop emergency message broadcasting. The mathematical and simulation performance analysis demonstrates that the proposed power quantization–based time-slot broadcast protocol can reduce the average time delay when compared to the infrastructure-less framework, binary-partition-assisted broadcast, and the trinary-partitioned black-burst-based broadcast schemes.

Keywords
Vehicle-to-vehicle, emergency message, multihop, broadcast

Introduction
Intelligent transportation system (ITS) services are becoming available through technologies based on IEEE 802.11p, IEEE 1609, wireless access in vehicular environment (WAVE), and dedicated short-range communications (DSRC) standards, with the objective to provide higher levels of vehicle accident prevention and various information services.¹,² Safety systems used to avoid emergency situations in vehicle traffic have very strict time-critical operation requirements. When an emergency situation occurs (e.g. car accident or road collapse), alerting approaching vehicles to avoid additional accidents (especially multiple vehicle chain collisions) is important. In alerting approaching vehicles, emergency messages (EMs) are most effective.³⁻⁵ In order to avoid a collision, the drivers reaction time to the EM alarm, as well as the EM delivery time, needs to be considered together. Due to this reason, the EM delivery time is recommended to be less than 0.1 s to provide the required time for a driver to react to the upcoming hazard and prevent an accident.⁶

In recent testing on EM vehicle-to-vehicle (V2V) relaying, in some cases, it was experienced that there was difficulty in vehicles determining their absolute and/or relative location/distance to the vehicle that sent the EM message when using global positioning satellites (GPSs) due to the margin of error and occasional loss of GPS signals. Based on this perspective, development of a V2V multihop EM broadcasting scheme that
did not rely on GPS signals was attempted, which leads to the reception power quantization–based time-slot broadcast (PQTB) scheme proposed in this article. The PQTB scheme partitions the reception power into quantization levels and assigns retransmission time-slots based on the received signal’s quantization level to avoid EM packet collision. In the PQTB scheme, among the vehicles in the communication range $R$, the vehicles farther away from the vehicle that transmitted the EM packet are assigned time-slots for earlier EM relay transmission, and vehicles closer to the vehicle that transmitted the EM packet are assigned later time-slots for EM transmission. In addition, for each relay, the multihop count is increased by 1 in the EM packet header. This way, among the vehicles in range, the vehicle farthest away from the vehicle that transmitted the EM packet will be able to relay the EM packet quickly (such that the reach of the EM will be extended farthest and fastest), and the other vehicles that detect both the former and relayed EM packet (with an increased hop count number) will withhold from relaying the EM packet to avoid packet collision with future relayed packets. In the performance analysis, the PQTB scheme was applied to the WAVE IEEE 802.11p medium access control (MAC) sublayer, where the initial contention access transmission mechanism was designed based on the distributed coordination function (DCF) and distributed inter-frame space (DIFS).

The remaining of this article is structured as follows. First, the related works are presented in section “Related works,” which is followed by section “Proposed PQTB scheme” that presents the operations of the proposed PQTB scheme and the mathematical derivations of the optimal received signal quantization step size that minimizes the average propagation delay time of multihop EM delivery. In section “Performance analysis,” the performance of the PQTB is compared to other schemes, which is followed by section “Conclusion” that presents the conclusion of the article and the references.

**Related works**

There are three fundamental ways to conduct EM broadcasting. The first method is to use V2V multihop broadcast transmission, which is a representative vehicle ad hoc network (VANET) technology. The V2V multihop scheme is very effective because the forerunning vehicle that detects an accident or a problem in the road/vehicle condition can directly broadcast an EM to approaching vehicles as soon as possible, such that approaching vehicles can slow down and take necessary precautions. Since a single vehicle’s transmission range is limited, the V2V multihop scheme must be fast and reliable for the relayed EM to cover a sufficient range. The second method would be to send the EM to a road side unit (RSU) through vehicle-to-infrastructure (V2I) communication and have the RSU broadcast the EM to approaching vehicles.1,2 This method has an advantage in providing stable EM broadcasts to all vehicles that enter the RSU’s communication range. However, the time consumed in delivering the EM to approaching vehicles via V2I is longer than the time consumed in V2V communications. In addition, a local RSU may not be available, in which V2V multihop communication may be the only option for collision prevention EM broadcasting. The third method is to use a combination of V2I and V2V communications, where V2I is used where a RSU is available and V2V multihop communication is used where the RSU’s communication range cannot reach. This third method could be effective for roads and highways that have sparsely distributed RSUs. As can be seen, V2V multihop communication plays an essential role in EM broadcasting for accident prevention, and therefore is the focus of this article.

In EM broadcasting via V2V multihop relays, a technical challenge of reliably overcoming packet collision among EM relaying vehicles exists. An EM packet collision results in a loss of all collided packets, and the V2V relaying process may stop or be seriously delayed such that the emergency information dissemination to approaching vehicles cannot be accomplished in time. In Chen et al.,3 an infrastructure-less framework (ILF) scheme that consists of a distributed warning protocol that works with a location-based backoff scheme is proposed. The ILF scheme uses a distributed warning protocol and V2V communication to form warning groups, which are sets of vehicles driving in the same direction that are within a certain distance. In a warning group, if a sudden brake event is detected then the location-based backoff scheme is used to quickly propagate warning messages among group members. In Chen and Chou,4 a lane-level, beacon-less, infrastructure-less, and GPS-less cooperative collision avoidance (BIG-CCA) scheme for vehicular sensor networks (VSNs) is proposed to prevent chain vehicle collisions. Since GPS is not used in BIG-CCA, the inaccuracy and unavailability of GPS is avoided. Like ILF, BIG-CCA uses a distributed grouping mechanism and also uses a receiver-based forwarding scheme to warn the vehicle group of sudden breaking events. In Taleb et al.,5 a cluster-based risk-aware cooperative collision avoidance (C-RACCA) scheme that avoids flooding through a cluster-based organization of target vehicles is proposed. C-RACCA uses clusters that are formed based on vehicle movement (i.e. directional bearing and relative velocity) and inter-vehicular distance and also uses a risk-aware MAC protocol to control the medium-access delay of each vehicle based on its emergency level.
In terms of multihop V2V performance, there are several schemes that have been proposed. One of the earliest optimized models is the urban multihop broadcast (UMB) scheme, which maximizes the EM multihop relaying speed by selecting the vehicle farthest away to relay the EM.\textsuperscript{7} In order to enhance the multihop speed, when V2V relaying the EM, vehicles intentionally broadcast a channel jamming signal called the black burst where the UMB scheme enables the vehicle farthest away (that transmitted the longest black burst) to perform the EM relaying. Due to using the longest black burst, the UMB scheme has a relatively high multihop latency. In Fasolo et al.,\textsuperscript{8} smart broadcast (SB) is proposed which also maximizes the EM multihop speed by minimizing broadcast relaying delay based on dividing the communication area into multiple sectors and correspondingly assigning different contention window values to minimize the average latency.

Among the existing transmission range partitioning EM broadcasting technologies, the binary-partition-assisted broadcast (BPAB)\textsuperscript{9} and the trinary-partitioned black-burst-based broadcast (3P3B)\textsuperscript{10} schemes perform the best in terms of multihop V2V relaying average time. These schemes divide the EM broadcasting range into multiple sections, where these sections are used to determine what vehicle can relay the EM to approaching vehicles while avoiding packet collision. For more effective EM broadcasting, the BPAB scheme equally divides the transmission range based on binary partitioning and selects the farthest vehicle to broadcast the EM using black burst signaling and a modified contention mechanism to effectively support vehicle transmission in the far segments. 3P3B consists of a mini DIFS-based MAC protocol (that enables time-critical EMs to more quickly access the communication channel) and a communication range trinary partitioning mechanism (that enables the vehicle farthest away to relay the EM), so the number of hops required to reach the desired broadcast range is minimized. As a result, 3P3B effectively reduces the contention period jitter and the multihop relaying average time.

### Proposed PQTB scheme

The proposed PQTB scheme is applied to vehicles equipped with WAVE or DSRC, which are based on the IEEE 802.11p and 1609 standards. The proposed PQTB scheme can operate using request-to-broadcast (RTB) and clear-to-broadcast (CTB) packets, as well as the basic IEEE 802.11 mode (which does not use RTB or CTB packets). IEEE 802.11p uses request-to-send (RTS) and clear-to-send (CTS) packets to avoid the hidden terminal problems, where in Sahoo et al.\textsuperscript{9} and Suthaputchakun et al.,\textsuperscript{10} RTS and CTS are, respectively, changed to RTB and CTB packets, which include the broadcasting message’s transmission directional information. In an RTB packet, the transmission duration is included in addition to the position and intended broadcast direction of the source node. When the vehicle that needs to send an EM needs to transmit the RTB message in multiple directions, then a new RTB packet needs to be transmitted individually in each direction.

PQTB basic mode directly transmits EM packets without using RTB/CTB before EM packet transmission and uses the relaying vehicle’s EM packet (that includes a 1 increased hop count) as its acknowledgment. An example operation of the PQTB basic mode is presented in Figure 1, where vehicle $V_1$ detects obstacles (i.e. boxes) on the road and tries to inform approaching vehicles of the obstacles through an EM. The RSU will broadcast the number of vehicles (i.e. $l$) information (step $\odot$) such that all vehicles can compute the optimal quantization size $\Delta P_r$, which is derived later in equation (6). In PQTB basic mode, after the mini-slot period expires, $V_1$ transmits an EM (with hop count $H_r = 0$) using a rear-area directional antenna (step $\oplus$) and waits for an omni-directional EM relay transmission (with $H_r = 1$). The EM relay transmission opportunity is given to the first vehicle that relays the EM among the vehicles in the farthest $S_1$ region during time-slot 1 (step $\ominus$). In PQTB basic mode, only the first vehicle needs to send the EM using a rear-area directional antenna, while all other relays will be omni-directional EM transmissions with an increased hop count. Vehicles that see an EM and a relayed EM (with an increased hop count) do not attempt relaying the EM. Any vehicle that sees an EM for the first time will check its power level segment and corresponding
time-slot and may relay the EM in its time-slot if no other vehicles does it first. In Figure 1, V_2, V_3, and V_4 receive the EM, V_1 sends (step ⊙) but V_4 relays the EM in time-slot 1 (step ⊙), and thus V_2 and V_3 do not attempt to relay the EM. Based on this multihop transmission mechanism, the EM can be quickly relayed in the rear direction to approaching vehicles without GPS information.

Applying the PQTB RTB/CTB mode to Figure 1, after V_1 transmits an RTB, V_4 in time-slot 1 will reply with a CTB, then V_1 will transmit the EM (with H_c = 0) to V_4. Next, V_4 will reply with an ACK packet and then will transmit an RTB for the vehicles behind to establish another relay of the EM (with H_c = 1).

For the opposite case where there is no vehicle to relay the EM signal in the first time-slot, the vehicles in the next farthest region S_2 have the opportunity to relay the EM signal within the second time-slot. If no relay occurs, this process is repeated until vehicles in the last region S_M are given a chance to relay the EM in the Mth last time-slot assigned to this region R. Vehicles in the same jth region S_j from V_1 will wait a randomly selected mini-DIFS backoff time internal before transmission to avoid EM packet collision within the same jth time-slot. When one vehicle (say vehicle V_2) in range R of V_1 successfully conducts an EM relay transmission, then the other vehicles in the same range will not retransmit the same EM, as these vehicles will identify that the hop count in the relayed EM is increased by one. Next, vehicles in range R of V_2 (that were not in the range of V_1) will repeat these EM relay procedures, where the relay process continues until the hop count reaches its limit value H_l.

In the following, the optimal quantization level size for PQTB will be derived. PQTB scheme consists of the following four time intervals. T_{delay} is the average time duration that the EM at the front of the transmission queue takes to be received by a single-hop receiving node. T_{init} is the average time duration from the moment the EM arrives at the front of the transmission queue until the time the RTB packet has been transmitted. T_{cont} represents the partitioning time, which is the time duration consumed by the contention access mechanism until EM packet transmission. T_{suc} represents the time duration consumed by a successful transmission.\(^9,^{10}\) The overall time delay of one EM packet relay session can be expressed as \(T_{delay} = T_{init} + T_{access} + T_{cont} + T_{suc}\). The objective of this article is to minimize the overall time delay of one EM packet relay session based on optimal reception power quantization level step size \(\Delta P_r\) control. The first-order differentiation of \(\frac{dT_{delay}}{d\Delta P_r} = 0\) is used in obtaining the optimal \(\Delta P_r\) value (i.e. \(\Delta P_r^o\)) that minimizes \(T_{delay}\), where the resulting performance is compared with ILF, BPAB, and 3P3B.

To avoid packet collision during initial access of the EM signal for vehicles that may use the same time-slot, in this article, the same mini-DIFS scheme is applied as in Suthaputchakun et al.\(^9,^{10}\) The IEEE 802.11 standards use the DCF to control transmission access, where a station can transmit a frame if the channel is continuously idle for a DIFS duration. However, if the channel is used by another station during the DIFS interval, then the station will defer frame transmission to avoid frame collision. In the mini-DIFS scheme, the DIFS is divided into mini-slots. When an EM arrives at the MAC layer, for immediate initial channel access, instead of waiting for the whole DIFS period before contending for the channel, the EM packet waits only for \(T_{init}\), which is a random number of mini-slots (i.e. \(T_{init} < T_{DIFS}\)), and therefore, the EM starts contention earlier than the other non-time-critical packets. The length of a mini-slot is \(T_i = (2 + T_{switch})\) (≈ 5 μs), which is based on the number of mini-slots \(w = (T_{DIFS} - T_{SIFS})/T_i\) and the duration required by the transceiver to switch between transmission and reception modes \(T_{switch}\), as well as the maximum communication range \((R)\) between vehicles (i.e. \(R = 300\) m) based on the IEEE 1609 standards.\(^1\) The maximum channel propagation delay \(\delta_{max}\) includes the radio ware propagation time (which is approximately 1 s for \(R = 300\) m) and the time the receiver consumes in receiving an IEEE 802.11p short frame (which is also approximately 1 μs). Therefore, \(\delta_{max}\) was set to 2 μs in the simulation experiments of the performance analysis section. After the communication channel becomes idle, a random ith mini-slot among \((0, w)\) will be selected and used in the waiting timer \(T_{wait} = T_{wait} = rT_i\) \((0 < r < w)\) by a vehicle attempting to broadcast the time-critical EM. Because mini-slot operations are conducted only between SIFS and DIFS periods, it is compatible with all inter-frame space (IFS) requirements of the IEEE 802.11 standards.\(^9,^{10}\)

In the following, the time parameter derivations for PQTB RTB/CTB mode will be provided first, which will be followed by a description of changes in time parameters required to represent the performance of the PQTB basic mode.

In the RTB/CTB mode, after the mini-slot’s period expires, the sender transmits an RTB packet and waits for the corresponding CTB packet from the next-hop forwarder. The average time duration from the moment the EM arrives at the front of the transmission queue until the time the RTB packet has been transmitted is defined as the initial time \(T_{init}\), which consists of the following three intervals. \(T_{init}^{mid}\) is the time spent during idle state, which is the length of a mini-slot \((T_i)\). \(T_{suc}^{mid}\) is the successful transmission time of an RTP packet \((T_{RTP})\) in addition, \(T_{init}^{mid}\) is the average collision time of RTP packets, which contains an RTP packet duration \(T_{RTP}\)
and a SIFS duration ($T_{SIFS}$) that directly follows every RTP packet, and a wait duration ($T_{wait}$) to avoid immediate repeated RTP packet collisions. Therefore, the three time intervals of $T_{init}$ can be expressed as $T_{idle} = T_{init}$, $T_{succ} = T_{RTB}$, and $T_{col} = T_{RTB} + T_{SIFS} + T_{init}$. The arrival process of EMs are assumed to have a Poisson distribution with a generation rate of $\lambda_{init}$.11 In addition, the probability of the three communication states can be expressed as $p_{idle} = e^{-\lambda_{init}/m}$, $p_{succ} = (\lambda_{init}/m)e^{-\lambda_{init}/m}$, and $p_{col} = 1 - p_{idle} - p_{succ}$. Using the probability generating function (PGF) of geometric distributions, the transmission failure probability can be derived as $A_{init} = \frac{1 - p_{idle}}{T_{init}}$, and using this, the average failure time

$$T_{fail} = T_{init} \frac{p_{idle}}{1 - p_{idle}} + T_{col} \frac{p_{col}}{p_{idle}}$$

can be derived. As a result, the initial contention time $T_{cont} = A_{init} T_{fail}$ can be derived, which leads to the initiating time $T_{init} = T_{RTB} + T_{cont}$. The contention time $T_{cont}$ is based on the assumption that the M-partitioning mechanism has a Poisson random distribution, with a $A$ (vehicles per unit area) generation rate and a services rate of $\mu = \lambda/M$ (vehicles per unit area). The three time intervals of $T_{cont}$ can be expressed as $T_{idle} = T_{slot}$, $T_{succ} = T_{CTB} + T_{SIFS} + T_{EM}$, and $T_{col} = T_{CTB} + T_{SIFS}$, where $T_{EM}$ is the time duration of an EM packet. In addition, the probability of the three communication states can be expressed as $p_{idle} = e^{-\mu/c_w}$, $p_{succ} = (\mu/c_w)e^{-\mu/c_w}$, and $p_{col} = 1 - p_{idle} - p_{succ}$, where $c_w$ is the contention window size. The contention window is used by IEEE 802.11 stations that conduct carrier sensing before accessing the channel, where each station will delay transmission for a backoff time duration before it accesses the channel to avoid transmission collision with other local stations. This backoff time duration is randomly selected between 0 and $c_w$. If a transmitted frame collides with a frame sent from another station, then $c_w$ is doubled, and the backoff time duration is randomly selected again between 0 and the enlarged $c_w$, which is based on the binary exponential backoff (BEB) algorithm. Doubling $c_w$ when a transmission collision is detected helps reduce the probability of retransmission collision significantly. If retransmission collisions are detected again, then $c_w$ is continuously doubled until it reaches the $c_w$ maximum limit size. If a retransmission collision occurs again after reaching the $c_w$ maximum limit size, then the backoff time duration is randomly selected again without increasing the $c_w$ size, which is repeated for a predefined number of times before forfeiting the transmission process of the given frame. Using the same derivation of $A_{init}$ and $T_{fail}$, the transmission failure probability and the average failure time can be derived as $A$ and $T_{fail}$, respectively, which result in

$$T_{cont} = A \left( T_{fail} + \frac{1}{c_w} \right)$$

where the second term represents the source retransmission delay.9,10 The successful transmission time $T_{succ}$ can be expressed as $T_{succ} = T_{CTB} + T_{SIFS} + T_{EM}$.

The PQTB basic mode (which does not use RTB and CTB) uses the same equations as the RTB/CTB mode above with only the following parameters changed. $T_{succ}$ is the successful transmission time of an EM packet ($T_{EM}$). In addition, $T_{col}$ is the average collision time of EM packets, which contains an EM packet duration ($T_{EM}$) and an initial contention duration ($T_{cont}$), in which $T_{init} = A_{init} T_{fail}$. The initiation time $T_{init}$ consists of the EM packet duration ($T_{EM}$) and an initial contention duration ($T_{col}$), as a result, the average time duration that the EM at the front of the transmission queue takes to be received by a single-hop receiving node ($T_{delay}$) is a combination of the initiation time ($T_{init}$) and the average access time ($T_{access}$). Therefore, the time intervals can be expressed as $T_{idle} = l$, $T_{succ} = T_{EM}$, $T_{col} = T_{EM} + T_{init}$, $T_{init} = A_{init} T_{fail} + T_{EM}$, and $T_{delay} = T_{init} + T_{access}$.

In order to obtain $T_{delay}$, the proposed PQTB scheme assigns time-slots based on the transmission range according to the received signal’s power level. The reception signal power is quantized into $\Delta P_r$ level sizes, where each quantization level is mapped to a time-slot of length $T_{slot}$, where the weakest power reception level is assigned the first time-slot. For the general case, the average access time $T_{access}$ for a vehicle in the range $R$ to be assigned a time-slot can be calculated as

$$T_{access} = \sum_{j=1}^{M} \left( S_j T_{slot} \right)$$

where $S_j$ is the length of each segment according to the difference in received power levels.

In this article, the PQTB analysis is conducted based on a two-ray-ground path-loss (2PL) model that includes the effect of shadowing path loss. This model is based on the parameters of transmitted power $P_t$, received power $P_r$, transmitted antenna gain $G_t$ ($\geq 1.0$), received antenna gain $G_r$ ($\geq 1.0$), transmitted antenna height $h_t$ ($\geq 1.5$ [m]), received antenna height $h_r$ ($\geq 1.5$ [m]), path-loss factor $L$ ($\geq 1.0$), and the shadowing path-loss $X_f$ random variable, which has a log-normal distribution. The difference in received power levels is expressed as

$$\Delta P_r = 10 \log_{10} \left( \frac{P_t G_t G_r h_t^2 h_r^2}{d_t^4 L} \right) - 10 \log_{10} \left( \frac{P_t G_t G_r h_t^2 h_r^2}{d_{j-1}^4 L} \right)$$

$$= 40 \log_{10} \frac{d_{j-1}}{d_j}$$

where $d_j = d_{j-1}10^{0.5}$ is the length of the $j$th communication range segment, and for notation simplification, $k$
is defined as $k = 10^{q/10}$. The length of each segment can be derived as $S_i = d_{i-1} - d_i = d_0 k^{j-1} - d_0 (k^{j-1} - k^{j-1})$. For vehicles within a distance less than 1.5 m, these vehicles are very close to vehicle that transmitted the EM, and are therefore assigned the last $M$th time-slot. Based on the 2PL model applied, $d_M = M k^{-M} T_{slot}$ represents the distance reached by the $M$th time-slot, which is considered in $T_{access} = M k^{-M} T_{slot} + k(1-k^{-1}) \sum_{j=1}^{M} k^{-j} T_{slot}$.

Applying the expansion of power series

$$M \sum_{j=1}^{M} k^{-j} T_{slot} = \frac{(k^{-1} T_{slot} + \ldots + k^{-M} T_{slot}) - (M k^{-M+1} T_{slot})}{1-k^{-1}} \quad (2)$$

and using the parameter substitutions of $x = \Delta P_r$, (dBm), $P_{r_{\text{max}}} = 13.0103$ (dBm), $P_{r_{\text{min}}} = -79.0309$ (dBm), $M = \frac{P_{r_{\text{max}}}-P_{r_{\text{min}}}}{\Delta P_r}$, $a = T_{slot} \left[ 1 - \left( \frac{10^{P_{r_{\text{max}}}-P_{r_{\text{min}}}}}{M} \right)^{-1} \right]$, and $v = \ln 10/80$ a simplified expression of $T_{access}$ is obtained in equation (3)

$$T_{access} = T_{slot}\left[ 1 - \left( \frac{10^{P_{r_{\text{max}}}-P_{r_{\text{min}}}}}{M} \right)^{-1} \right] = a \frac{e^{v c\csc(vx)}}{v x} \quad (3)$$

Applying $T_{access}$ of equation (3) to $T_{delay}$, an expression based on $x$ can be obtained for $T_{delay} = T_{init} + T_{access} + T_{cont} + T_{acc}$. The first-order differentiation of $\frac{dT_{delay}}{dP_r} = 0$ is used to derive the optimal quantization $x^* = \Delta P_r^*$ that minimizes $T_{delay}$, which results in

$$\frac{dT_{delay}}{d\Delta P_r} = -\frac{d}{\Delta P_r^3} (b + ce^2) + \frac{c}{x} e^2\Delta P_r^2 - \frac{1}{2} av[1 - \cosh(vx)]\csc(vx)e^{vx} = 0 \quad (4)$$

where for representation simplification in equation (4), the parameter substitutions of $b = T_{slot} - (T_{CTB} + T_{DIFS})$, $c = T_{CTB} + T_{DIFS} + 1/4w_2$, $q = \frac{1}{x} (P_{r_{\text{min}}} - P_{r_{\text{max}}})$, $\rho = -\frac{3}{2} (\frac{av q}{c^2} - 3)$, and $\phi = -3q^2 (q + \frac{3bq}{c^2} - \frac{a}{2vc})$ were applied. In the derivation of $x^*$, the second-order Taylor expansion based on Mathematica 10.2 was applied to equation (4) to obtain the cubic equation (5), which has an approximation error rate less than 0.0723%.

$$x^3 - q (\frac{3av q}{c} - 3)x^2 - 3q^2 (q + \frac{3bq}{c} - \frac{a}{2vc}) = 0 \quad (5)$$

Among the $x$ values that satisfy equation (5), the optimal solution $x^* = \Delta P_r^*$ is

$$\Delta P_r^* = -\frac{1}{3} \left( \frac{2\rho^3 + 27\phi}{2} \right)^{2/3} + \frac{3}{2} \left( \frac{2\rho^3 + 27\phi}{2} \right) (\frac{2\rho^3 + 27\phi}{2})^{1/3} - 4\rho^6 \quad (6)$$

where $\Delta P_r^*$ selection has to consider that the number of time-slots $M$ must be a positive integer.

**Performance analysis**

The proposed PQTB scheme is different from ILF, BIG-CCA, and C-RACCA based on the fact that it does not require group formation or clustering to execute EM broadcasting. Since vehicles change locations frequently, the additional time required in forming a group or cluster is saved in PQTB, resulting in less network structuring requirements that lead to faster EM broadcasting. However, the infrastructure-less characteristic of ILF is similar to PQTB, and therefore, ILF is included in the performance analysis of this article. In addition, in terms of optimal multihop V2V EM relaying performance, in Suthaputchakun et al., it is shown that 3P3B can outperform BPAB and can significantly outperform SB and UMB. Considering this fact, in this article, PQTB is compared with 3P3B and BPAB in terms of average EM propagation delay. In the following performance analysis, the PQTB scheme was applied to the WAVE IEEE 802.11p MAC sublayer, where the initial contention access transmission mechanism was designed based on the DIFS, and the average EM propagation delay performance of PQTB, IFL, BPAB, and 3P3B is compared.

In Figure 2, a comparison of the average delay performance of multihop EM delivery over a 1-km distance was conducted using ns2 and MATLAB simulation for PQTB RTB/CTB mode, PQTB basic mode, ILF, BPAB, and 3P3B. Simulation was based on the number of vehicles per unit area ($A$) for a transmission range of $R = 300$ m and maximum channel propagation delay $\delta_{\text{max}} = 2\mu s$, which enables the average time delay performance of ILF, BPAB, and 3P3B to be compared in an equivalent environment as in Suthaputchakun et al. The IEEE 802.11p simulation parameters are 5.9 GHz communication frequency, 20 mW transmission power, 18 Mbps bit rate, 4000 bits emergency data frame, 160 bit RTB frame, 112 bits
CTB frame, 13 μs Slot Time \( T_{\text{slot}} \), 32 μs SIFS \( T_{\text{SIFS}} \), and 58 μs DIFS \( T_{\text{DIFS}} \). BPAB and 3P3B are based on the configuration variable set \( \lambda_{\text{init}} = 5 \) and \( (n, N, c_w) \), where \( n \) is the number of partition divisions applied per iteration, \( N \) represents the number of partitioning iterations used in BPAB and 3P3B, and \( \lambda_{\text{init}} \) is the EM packet generation rate, which is assumed to be a Poisson random process.9,10 The vehicle density \( \lambda \) can be obtained and informed to the vehicles in two ways. The first way is to have the RSU send the monitored vehicle density (for a given area) periodically in its beacon packet. A second way is to have the vehicle that initially transmits the EM to include its local estimated vehicle density information in the EM, where the vehicles that receive the EM will use it in its range segment \( S_j \) computation. The first method would result in an optimal performance since the vehicle density information would be accurate compared to the second method. The analysis in Figure 2 is based on the first method. For optimal performance, BPAB was set to \( (2, 3, 5) \), 3P3B was set to \( (3, 2, 4) \),9,10 and PQTB was set to \( (M, 1, 4) \). Figure 2 shows that the average time delay performance near \( \lambda \approx 20 \) has a relation of \( \text{ILF} \geq \text{BPAB} \geq \text{3P3B} \geq \text{PQTB} \), but for \( \lambda > 75 \), the performance relation changes to \( \text{BPAB} \geq \text{3P3B} \geq \text{ILF} \geq \text{PQTB} \). In addition, when 50% background interfering traffic exists, the average time delay performance of BPAB, 3P3B, and ILF increases approximately by 2 for \( \lambda > 50 \), where the average time delay performance increases approximately by 1 for PQTB. In addition, the PQTB basic mode has the smallest average time delay performance for all cases tested and only shows an approximate 0.5 increment when 50% background interfering traffic exists, which shows that it has an advantage in heavy packet traffic environments.

Conclusion

In this article, a reception PQTB scheme is proposed for multihop V2V communications of EMs for accident prevention. Based on the performance results, it can be concluded that the proposed PQTB scheme (and especially the basic mode) provides a gain in average time delay when compared to ILF,4,5 BPAB,9 and 3P3B10 for the range of interest tested.

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