Prioritization of Basic Safety Message in DSRC Based on Distance to Danger

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Abstract—Many parties claim the technical significance of Dedicated Short-Range Communications (DSRC) in intelligent transportation system (ITS) for promotion of transportation safety. The main challenge in this key vehicle-to-everything (V2X) standard is high odds of network congestion. Furthermore, in accordance with a V2X network being inherently dynamic in key parameters such as vehicle density and velocity, the networking behavior of a DSRC system is usually highly complicated to analyze. In addition, the United States Federal Communications Commission (US FCC) recently announced the “5.9 GHz band reform,” which reduced the dedicated bandwidth for DSRC to 10 MHz from 75 MHz. Motivated from these, the necessity of “lightening” the networking load of a DSRC network has become essential to keep safety-related operations without performance deterioration. To this end, this paper proposes a protocol that prioritizes transmission of a basic safety message (BSM) at a vehicle according to the level of danger that the vehicle experiences. The proposed protocol uses the distance between a danger source and a vehicle as the metric to determine the priority for transmission. Our results show that this protocol prioritizes the transmission opportunity to dangerous vehicles, and hence results in higher performance in terms of key metrics—i.e., average delay, throughput, and inter-reception time (IRT).

Index Terms—V2X; IEEE 802.11p; DSRC; Message prioritization

I. INTRODUCTION

A. Background

1) 5.9 GHz Band for V2X: Vehicle-to-Everything (V2X) communications has the potential to significantly bring down the number of vehicle crashes, thereby reducing the number of associated fatalities [1]. The capability gave V2X communications the central role in constitution of intelligent transportation system (ITS) for connected vehicle environments. Today, the two key radio access technologies (RATs) that enable V2X communications are DSRC and cellular V2X (C-V2X). DSRC is designed to primarily operate in the 5.9 GHz band (5.850-5.925 GHz), which has been earmarked in many countries for ITS applications. On the other hand, C-V2X can operate in the 5.9 GHz band as well as in the cellular operators’ licensed carrier [2].

2) Significance of DSRC: Of the two RATs, the Dedicated Short-Range Communications (DSRC) has longer been earmarked in many countries for safety-critical applications. As such, the most important benefit for advocating DSRC as the key enabler of V2X communications is that it is a proven technology: it has been tested by car manufacturers for more than 10 years. Furthermore, DSRC is not bounded by patents, which requires no telecom subscription to use it. To take these advantages, since the 5.9 GHz band was dedicated for DSRC in United States by the Federal Communications Commission (FCC) in 1999, as of November 2018, more than 5,315 roadside units (RSUs) operating in DSRC were deployed nationwide [3]. In December 2016, the National Highway Traffic Safety Administration (NHTSA) proposed to mandate DSRC for all new light vehicles [4]. However, despite the advantages and widespread deployment, there are several key issues to resolve in order to guarantee stable operations of DSRC.

3) 5.9 GHz Band Reform by the US FCC: Out of the 75 MHz of bandwidth in the 5.9 GHz band (i.e., 5.870-5.925 GHz), in December 2019, the US FCC voted to allocate the lower 45 MHz (i.e., 5.850-5.895 GHz) for unlicensed operations to support high-throughput broadband applications (e.g., Wireless Fidelity, or Wi-Fi) [5]. While the reform is proposing to leave the upper 30 MHz (i.e., 5.905-5.925 GHz) for ITS operations (i.e., DSRC and C-V2X), it is also proposing to dedicate the upper 20 MHz of the chunk (i.e., 5.905-5.925 GHz) for C-V2X.

According to this plan, DSRC is only allowed to use 10 MHz of spectrum (i.e., 5.895-5.905 GHz). It has never been studied nor tested if 10 MHz would suffice for operation of the existing DSRC-based transportation safety infrastructure. Many states in US have already invested large amounts of fortune in the deployment of connected vehicle infrastructure based on DSRC [6]. As such, it has become urgent to understand how much impact of the FCC’s 5.9 GHz band reform will be placed on the performance of such connected vehicle infrastructure.

4) Necessity of Lightening DSRC Networking Load: According to the FCC’s 5.9 GHz band reform [5], DSRC may need to coexist with C-V2X users in the upper 30 MHz (i.e., 5.895-5.925 GHz). The key technical challenge here is that C-V2X uses a different technology standard, and hence the technology is incompatible with DSRC-based operations. Based on the author’s recent investigation [7], on average 4.63 C-V2X vehicles can corrupt a 10-MHz channel of DSRC. It implies that coexistence with 5 C-V2X vehicles may significantly degrade the performance of a DSRC system.

B. Contributions

As shall be detailed in Section II, the key limitation of the current literature can be identified as follows: despite...
being a predominant factor determining the performance of a V2X network, the length of backoff time was allocated to each vehicle without considering “semantic” contexts. We would regard it more efficient from the system’s point of view if vehicles being closer to a danger take higher chances to transmit. The rationale is that these initial BSMs will propagate through the network, which will eventually make most of the vehicles in the network able to receive the BSMs and hence promote the level of safety.

To this line, this paper proposes a V2X communications scheme where a vehicle takes the opportunity for a transmission according to the probability that it runs into a crash. Moreover, we clearly distinguish our contributions from the most relevant work [9]. While the prior work focused on the stochastic geometry of a particular coexistence scenario between military and civilian vehicles in an urban area, this paper significantly extends the scope of discussion to (i) a general two-dimensional geometry and (ii) detailed analysis on networking behaviors—i.e., an exact backoff allocation method.

The technical contributions of this paper can be summarized as follows:

1) It proposes a method prioritizing a BSM according to the level of danger to which each vehicle is exposed.
2) In order to measure the risk, it uses the “distance to a danger source,” which is a quantity that is easy to obtain using the existing techniques and apparatus.
3) Based on (i) key metrics—namely, delay, throughput, and IRT—and (ii) a generalized two-dimensional spatial model, it provides a stochastic analysis framework characterizing a DSRC network’s broadcast of BSMs.

II. RELATED WORK

A. Performance Analysis Schemes

1) Mathematical Analysis Framework: Analysis frameworks based on stochastic geometry for DSRC have been provided recently [7]-[10]. They commonly rely on the fact that uniform distributions of nodes on X and Y axes of a Cartesian-coordinate two-dimensional space yield a Poisson point process (PPP) on the number of nodes in the space [11]. This paper also applies the stochastic geometry framework for analysis of the proposed mechanism.

2) Performance Evaluation Method: A recent proposal combines a packet-level simulation model with data collected from an actual vehicular network [12]; however, the potential impacts of internal and external bandwidth contention were not studied, which forms a critical discussion point after the US FCC’s recent 5.9 GHz band reform [5]. For instance, it is assumed that safety messages and Internet packets are sent over separate DSRC channels [12], whereby no interference is generated between safety and Internet traffic. This assumption has become obsolete according to the US FCC’s recent proposition where DSRC is unable to utilize multiple channels any more [5].

3) DSRC in High Traffic Density: It has been found that a DSRC network is more constrained by packet expirations rather than collisions over the air. Thus, we put particular focus on the performance of a DSRC network in a high density of traffic. The performance of a DSRC broadcast system in a high-density vehicle environment has been studied [13], yet the assumption was too ideal to be realistic—i.e., the number of vehicles within a vehicle communication range was kept constant. Another study proposed a DSRC-based traffic light control system [14], but it limited the applicability to the traffic lights only.

4) Safety-Related Application: Furthermore, we concentrate on DSRC’s networking to support the safety-critical applications. In the related literature, a DSRC-based end of queue collision warning system has been proposed [15]. However, it discusses a one-dimensional freeway model, which needs significant improvement for application to an intersection with two or more ways.

5) External Bandwidth Contention: Lastly, the objective of our proposed protocol is to lighten the traffic load of a DSRC network to better suit in an environment of coexisting with a disparate technology (i.e., C-V2X) according to the 5.9 GHz reform [5]. The performance degradation of DSRC under interference from Wi-Fi has been studied [16]; however, it lacks consideration of coexistence with C-V2X.

B. Performance Improvement Schemes

In general IEEE 802.11 carrier-sense multiple access (CSMA), various modifications on the binary exponential backoff (BEB) algorithm have been tried as a means to improve throughput and fairness. Specifically, adjustment of the CW was often suggested to improve the performance of a vehicular communications network such as a recent work [17]. More directly relevant to our work, a distance based routing protocol has been found to perform better in vehicular ad-hoc networks (VANETs) [18]. Also, in a general ad-hoc network, reduction of the length of a header can be a solution that is worth considering [19]; however, due to being a centralized architecture, it shows a limit to be applied to a V2X network. A “subjective” user-end experience optimization is also worth consideration [20], wherein a one-bit user satisfaction indicator was introduced, which served as the objective function in a non-convex optimization.

III. SYSTEM MODEL

This section describes the system model that this paper adopts for analysis. Note that Table I lists key abbreviations that are frequently used throughout this paper. Also, mathematical notations are summarized in Table II.

| Abbreviation | Description |
|--------------|-------------|
| BEB          | Binary exponential backoff |
| BSM          | Basic safety message |
| Cat          | Category |
| CW           | Contention window |
| EXP          | Packet expiration |
| HN           | Collision by hidden node |
| IRT          | Inter-reception time |
| PPP          | Poisson point process |
| STA          | Station |
| SYNC         | Collision by synchronized transmission |

TABLE I: Frequently used abbreviations

This model will incorporate the Poisson point process (PPP) for the analysis of the proposed mechanism.
TABLE II: Key notations

| Notation | Description (unit) |
|----------|--------------------|
| $d_{\rightarrow dgr}$ | Distance of a vehicle to the danger source (m) |
| $\lambda$ | Vehicle density (vehicles/m$^2$) |
| $N_0$ | Number of slots spent for a packet failure (# slots) |
| $N_{sta}$ | Number of STAs competing for the medium (# STAs) |
| $R$ | Normalized throughput |
| $\tau$ | Probability of a transmission |
| $T_{bo}$ | Time length taken for a backoff process (sec) |
| $T_{th}$ | Time length taken for a packet collision (sec) |
| $T_{exp}$ | Time length taken for a packet expiration (sec) |
| $T_{ib}$ | Time length of the inter-broadcast interval (sec) |
| $T_{suc}$ | Time length taken for a successful packet delivery (sec) |
| $Th_i$ | Threshold on $d_{\rightarrow dgr}$ for Cat $i$ (m) |

In Figure 1, the vehicles positioned within Cats 1, 2, and 3 are marked as red, yellow, and green circles, respectively.

The vehicles that are sufficiently far are drawn as blue circles. As shall be depicted in Section IV, the proposed protocol does not allocate these vehicles not belonging to any of the three Cats. The rationale behind this is that these farthest located vehicles are within communications ranges of those belonging to Cat 3. That is, once vehicles in Cat 3 become able to transmit, the messages can be disseminated to these even further vehicles.

### IV. Proposed Algorithm

We propose a protocol that controls the value of $k$ to prioritize transmission by a vehicle at a higher crash risk as a means to improve the best knowledge in the literature and suit to supporting safety-critical messaging in DSRC, as has been discussed in Section II.

1) **Key Improvement from Conventional CSMA:** It has been noted that for contention resolution, the conventional BEB algorithm relies on the number of unsuccessful transmission attempts and Physical Layer (PHY) related constant values including packet retry limit, maximum and minimum values of CW size, header format, etc [23]. This specifically means that once the PHY specific values are fixed, the future course of the BEB algorithm would be dictated by the number of unsuccessful attempts taken by a STA to successfully transmit the packet.

We got motivated from the curiosity of why it should be mandatory to have a uniform probability of choosing a backoff time for all Txs competing for the medium. Practically, if we have 50 vehicles on the road at a certain time instant and if they try to transmit a packet at the same time, all of them will have an equal opportunity to choose for a backoff time randomly from a range of $[0, CW]$. Regardless of how close

$\mathbb{R}^2$. The crash risk is categorized by using $d_{\rightarrow dgr}$ as follows:

- Cat 1: $0 \leq d_{\rightarrow dgr} \leq Th_1$
- Cat 2: $Th_1 < d_{\rightarrow dgr} \leq Th_2$
- Cat 3: $Th_2 < d_{\rightarrow dgr} \leq Th_3$ (1)

### B. Communications

We suppose that all the vehicles distributed in $\mathbb{R}^2$ have the same ranges of carrier sensing and communication. Also, each vehicle broadcasts a BSM every 100 msec, which is denoted by $T_{bs}$—i.e., 10 Hz of the broadcast rate.

We remind that DSRC adopts distributed coordination function (DCF) as the basic access mechanism [21]. This paper assumes that the DCF operates in a saturated-throughput scenario [22]. The purpose of this assumption is to analyze a worst-case scenario (i.e., the heaviest possible network load), which can provide a conservative guideline for the performance evaluation of the proposed scheme in a DSRC network.

Lastly, in accordance with the FCC’s 5.9 GHz reform [5], this paper assumes operation of DSRC in only one channel being 10 MHz wide.

A two-dimensional space $\mathbb{R}^2$ is defined as a 2 km-by-2 km square, as illustrated in Figure 1. Once a vehicle reaches the end of the space, it bounces back into the space. This assumption is to maintain a fixed vehicle density and, hence, a same level of competition for the medium at any given time.

The distribution of the nodes follows a homogeneous PPP in $\mathbb{R}^2$. We define a general situation where a safety-critical application disseminates basic safety messages (BSMs) over a V2X network. That is, a source of “danger” exists (expressed as a large black square in Figure 1), which should be avoided by all the other vehicles. The danger source is located at the origin, i.e., the very center of $\mathbb{R}^2$.

As shall be detailed in Section IV, our proposed algorithm prioritizes transmission of a BSM as a vehicle is closer to this danger source. This necessitates to measure the distance from the danger, which is denoted by $d_{\rightarrow dgr}$. Figure 1 demonstrates an example “drop” of vehicles with the density of $\lambda = 2 \times 10^{-5}$ m$^{-2}$, which is equivalent to 80 nodes over the defined space

$\mathbb{R}^2$. As shall be detailed in Section IV, our proposed algorithm prioritizes transmission by a vehicle at a higher crash risk as a means to improve the best knowledge in the literature and suit to supporting safety-critical messaging in DSRC, as has been discussed in Section II.
Specifically, a Tx STA with a smaller distance from a danger source. Specifically, (i) each technology, it is not a difficult task to obtain a vehicle’s distance to a danger source as a key factor of an accident [25].

This makes it reasonable to consider the weather condition, road surface status, mechanical failures, etc, the selection of a danger source) will have a shorter backoff time and vice versa. The foremost key discussion in design of the algorithm is the rationale behind our selection of $d_{dgr}$ as the metric measuring the risk of a crash. While an accident can be caused by many factors including weather condition, road surface status, mechanical failures, etc, the dominating factor is the inborn reactive time limitation of the drivers [24]. This makes it reasonable to consider the distance to a danger source as a key factor of an accident [25].

2) Distance Calculation Method: The foremost key discussion in design of the algorithm is the rationale behind our selection of $d_{dgr}$ as the metric measuring the risk of a crash. While an accident can be caused by many factors including weather condition, road surface status, mechanical failures, etc, the dominating factor is the inborn reactive time limitation of the drivers [24]. This makes it reasonable to consider the distance to a danger source as a key factor of an accident [25].

Furthermore, one understands that at the current level of technologies, it is not a difficult task to obtain a vehicle’s exact distance from a danger source. Specifically, (i) each

BSM contains Global Positioning System (GPS) information; (ii) thus, each vehicle is able to exchange each other’s exact position; (iii) as such, each vehicle is able to calculate the distance from each other.

3) Backoff Allocation according to $d_{dgr}$: Now, based on the aforementioned rationale, we propose a backoff allocation algorithm according to the distance to a danger. A flowchart for the proposed mechanism is provided in Figure 2. Unlike the traditional BEB scheme, the proposed protocol allocates a smaller backoff to the group of vehicles with a smaller $d_{dgr}$. Specifically, according to the threshold distance, $T_h$, the vehicles in $\mathbb{R}^2$ are grouped in three categories--i.e., Cats 1, 2, and 3. A smaller Cat categorizes a smaller $d_{dgr}$, which, in turn, means a more urgent need for transmission.

Here is a deeper look into the Cats in relation to a CW. As presented in Section VI, this paper uses $\{300, 500, 700\} m$ for $\{T_{h1}, T_{h2}, T_{h3}\}$, representing the thresholds for Cats 1, 2, and 3, respectively, as have been shown in (1). The proposed protocol divides the entire range of CW into three chunks: for $\{T_{h1}, T_{h2}, T_{h3}\}$, the backoff time ranges of $[0, (CW-1)/3]$, $[(CW-1)/3, 2(CW-1)/3]$, and $[2(CW-1)/3, CW-1]$ are allocated. Via this modification, a Tx STA belonging to Cat 1, which is at a higher crash risk due to a shorter $d_{dgr}$, has to wait for a shorter backoff time. In contrast, a STA with a larger $d_{dgr}$ is designed to hold a bit longer before a transmission.

V. PERFORMANCE ANALYSIS

This section formulates three metrics to measure the performance of the proposed backoff allocation scheme–namely, average latency, normalized throughput, and inter-reception time IRT.

Moreover, it is worth to notice that all the three quantities are defined with a BSM transmitted at a tagged vehicle. We emphasize that such an assumption keeps generality since the type of network being considered in this paper is distributed, in which every node has an equal characteristic and hence shows a consistent networking behavior.

A. Average Latency

We remind that this paper focuses on safety-critical applications, which makes the latency the most significant metric in the performance evaluation of a DSRC network. Further, reflecting the “broadcast” nature of a DSRC network, this paper defines an average latency among all the STAs across a network.

Let $T$ denote an instantaneous total latency taken for a node to transmit a packet. Taking into account all the possible results of a packet transmission (i.e., expiration, success, and collision), an average latency can be computed as

$$E[T] = P[Tx] \cdot E[Exp] + (1 - P[Tx]) \left\{E[Success] + E[Collision]\right\}$$

$$= (1 - \tau) E[Exp] + \tau \left\{E[T_{bo}] + (1 - P_{col}) T_{suc} + P_{col} T_{col}\right\}$$

$$\approx (1 - \tau) E[Exp] + \tau \left\{E[T_{bo}] + T_{suc}\right\}$$ (2)
where \( P[\cdot] \) and \( T[\cdot] \) denote the probability and the time length of an event, respectively. Variables in (2) are defined as follows: \( \tau \) denotes the probability that a tagged vehicle is able to transmit in a certain slot within a beaconing period [7]; \( P_{\text{col}} \) gives the probability of a collision—i.e., a synchronized transmission (SYNC) or a hidden-node collision (HN) [7]; \( T_{\text{exp}}, T_{\text{col}}, \text{ and } T_{\text{suc}} \) denote the time lengths taken for an expiration, a collision (i.e., SYNC and/or HN), and a successful delivery, respectively.

**Proof of (a) in (2):** Although not presented in this paper, via a separate analysis, the authors approximated as \( P_{\text{col}} \approx 0 \) due to a DSRC system being an “expiration”-constrained system rather than a collision-constrained one. In other words, in a DSRC network, a beaconing period for a BSM is composed of quite a large number of slots (i.e., 1500 slots with a slot time of 66.7 \( \mu \)sec and a beaconing period of 100 msec), which is beneficial in avoiding a collision while detrimental in being able to transmit before an expiration. (Note that a DSRC BSM expires if it is not transmitted within a beaconing period.)

Now, each of the terms in (2) is elaborated in the following proof:

**Proof of (2):** Starting from the first term, we remind that \( \tau \) is the probability of a tagged vehicle being able to go through a backoff process before expiration and thus transmit a packet. For calculation of \( \tau \), we modified the Markov chain for a backoff process [22] in order to reflect the impacts of packet expiration, which does not occur in classical IEEE 802.11 DCF and hence was not reflected in the existing analysis models for DCF. Due to a long recursiveness in the computation process, it was more efficient to take a numerical approach to obtain \( \tau \) instead of a closed-form derivation.

The length of time taken for an expiration, \( T_{\text{exp}} \), can be given by \( E[T_{\text{exp}}] = T[\text{beacon}] E[N_{\text{fl}}] \). Notice that the number of consecutive idle beaconing periods, \( N_{\text{fl}} \), can be characterized as a geometric random variable [22]. Based on these formulations, an average time taken for an expiration can be formally written as

\[
E[T_{\text{exp}}] = E[\text{beacon}] E[N_{\text{fl}}] = T_{\text{ib}} (1 - \tau)^{-1} \tag{3}
\]

where \( T_{\text{ib}} \) is a constant denoting the inter-broadcast interval. The second term of (2) contains the length of time taken for a backoff, which is given by

\[
E[T_{\text{bo}}] = T_{\text{slot}} E[N_{\text{fl}}] \tag{4}
\]

where \( T_{\text{slot}} \) is the length of a slot [22] (i.e., 66.7 \( \mu \)sec [7]).

Also, in (4), \( N_{\text{fl}} \) denotes the number of slots spent to go through a backoff process. This quantity can be displayed as a function of the number of STAs, denoted by \( N_{\text{sta}} \), as illustrated in Figure 3. One can observe two main tendencies: (i) a larger CW spends a larger \( N_{\text{fl}} \) due to higher possibility of longer backoffs; and (ii) a higher-priority Cat consumes a smaller \( N_{\text{fl}} \) due to higher possibility of shorter backoffs.

Lastly, in (4), the number of slots that are used by a successful delivery of a packet is formulated as

\[
E[T_{\text{exp}}] = T[\text{beacon}] E[N_{\text{fl}}] = T_{\text{ib}} (1 - \tau)^{-1} \tag{3}
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where \( T_{\text{ib}} \) is a constant denoting the inter-broadcast interval. The second term of (2) contains the length of time taken for a backoff, which is given by

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\[
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\]
where \( \mathbb{E}[T] \) and \( T_{\text{suc}} \) have already been found in (2) and (5), respectively. Also, \( \tau \) has been mentioned after derivation of (2) as well.

### C. Inter-Reception Time

Lastly, we define the IRT as the time taken between two given successful packet reception events. Notice that the unit of a quantity of IRT is “the number of beaconing periods.” As such, one can multiply a beaconing time (e.g., 100 msec in this paper) when wanting to display an IRT in the unit of time (i.e., seconds).

Now, the probability that \( N_{\text{fl}} \) failures follow a successful delivery is modeled to follow a geometric distribution, which can be formally written as

\[
\text{IRT} = (1 - \tau)^{N_{\text{fl}} - 1} \tau. \tag{7}
\]

**Proof of (7):** For occurrence of an “IRT,” we suppose to start from a successful reception, and then measure how many beaconing periods are expended until the next successful reception. That is, the first beaconing period is set to have the probability of \( P_{\text{suc}} \), and thereafter the possibility is left open between \( P_{\text{suc}} \) and \( 1 - P_{\text{suc}} \) depending on occurrence of a successful delivery or a failure, respectively. This can be formulated as

\[
\text{IRT} \sim \text{Geo} (P_{\text{suc}}),
\]

\[
\Rightarrow P[\text{IRT} = N_{\text{fl}}] = (1 - P_{\text{suc}})^{N_{\text{fl}} - 1} P_{\text{suc}}
\]

\[
\approx (1 - \tau)^{N_{\text{fl}} - 1} \tau \tag{8}
\]

where (a) follows from the fact that \( P_{\text{suc}} \) gives the probability of a successful reception, which is given by

\[
P_{\text{suc}} = \tau (1 - P_{\text{col}}) \approx \tau \tag{9}
\]

since \( P_{\text{col}} \approx 0 \) as has already been mentioned in Proof of (a) in (2).

### VI. Numerical Results

In this section, we evaluate the performance of the proposed backoff algorithm compared to the traditional CSMA (i.e., BEB). As summarized in Table III, each Tx STA is assumed to have a fixed payload length of 40 bytes [26]. Also, for our numerical analysis, we set the spatial setting consistent as what has been shown in Figure 1: (i) 80 vehicles were placed following a uniform distribution with respect to both \( X \) and \( Y \) in \( \mathbb{R}^2 \) (i.e., \( \lambda = 2 \times 10^{-5} \text{ m}^{-2} \); (ii) a danger source at the origin; and (iii) the size of \( \mathbb{R}^2 \) is 2 km by 2 km.

#### A. Average Packet Delay

Figure 4 demonstrates the average delay versus the number of STAs according to the Cat and CW. We remind from (2) that \( \mathbb{E}[T] \) is composed of two parts: i.e., (i) \( T_{\text{exp}} \) and (ii) \( \mathbb{E}[T_{\text{bo}}] + T_{\text{suc}} \). As \( N_{\text{sta}} \) grows, \( (1 - \tau) \), \( T_{\text{exp}} \), and \( T_{\text{bo}} \) increase while \( T_{\text{suc}} \) remains as a constant.

This explains why the quantity of \( \mathbb{E}[T] \) ranges very large (i.e., to \( 10^{10} \)) as presented in Figure 4. In addition to the fact that \( T_{\text{exp}} \) grows faster than \( \mathbb{E}[T_{\text{bo}}] + T_{\text{suc}} \) as \( N_{\text{sta}} \) gets larger, the weight, i.e., \( (1 - \tau) \), also gets greater. This relationship leads the resulting average delay, \( \mathbb{E}[T] \), to such large numbers.
B. Normalized Throughput

As has been shown in (6), \( \tau \) and \( \mathbb{E}[T] \) are key variables to characterize, while \( T_{\text{sec}} \) has been given as a constant as formulated in (5). Hence, this subsection quantifies \( \tau \) and \( \mathbb{E}[T] \), which are displayed in Figures 5 and 6.

Figure 5 presents \( \tau \), the probability that a STA transmits in an arbitrary slot, versus \( N_{\text{sta}} \), the number of STAs competing for the medium. The figure also demonstrates comparison according to the threshold distance and CW.

Figure 5a compares \( \tau \) with respect to Cat, which depicts the impact of a threshold distance in the proposed scheme in reference to the traditional BEB algorithm. It is straightforward that a larger \( N_{\text{sta}} \) causes a lower \( \tau \). Also, the level of \( \tau \) is determined in the order of Cat 1 > Cat 2 > Cat 3. It highlights the principle of the proposed scheme: higher chances of transmissions in a backoff process are granted the vehicles that are closer to the danger source where semantic message prioritization is accomplished.

Figure 5b compares \( \tau \) according to CW. Commonly with (i) the proposed and traditional schemes and (ii) all Cats, a larger CW results in a lower \( \tau \) due to a longer backoff process. From this, one can infer that a DSRC network is a “expiration-constrained” network rather than a “collision-constrained” one; if it was a collision-constrained, a larger CW would have yielded a higher performance.

Now, Figure 6 gives \( R \), the normalized throughput, versus \( N_{\text{sta}} \) according to the threshold distance. We remind from (6) that \( R \) is directly proportional to \( \tau \), which yields that Figure 6 shows a similar overall tendency to what Figure 5 did.
C. Inter-Reception Time

Figure 7 presents the probability density function (PDF) of random variable $N_B$ according to $\text{Cat}$ and $\text{N}_{sta}$ with $\text{CW} = 15$. The figure describes that in most of the given conditions on $\text{Cat}$ and $\text{N}_{sta}$, one or two beaconing periods are consumed during a packet transmission failure. In this paper’s system model, each failed transmission takes 100 msec since an entire beaconing period is wasted without transmitting a BSM, which translates the results to consumption of 100 to 200 msec of IRT.

Figure 7 suggests that the overall tendencies in regards to $\text{N}_{sta}$ and $\text{Cat}$ are consistent with the other two metrics: (i) a $\text{N}_{sta}$ leads to a higher probability of experiencing a shorter IRT; (ii) a tighter threshold distance yields a shorter IRT.

Figure 7 also suggests that the superiority of the proposed protocol gets greater with more vehicles competing for the medium. This serves as another concrete evidence that a DSRC network is more expiration-constrained rather than collision-constrained.

VII. CONCLUSIONS

This paper proposed a protocol managing the number of messages transmitted in an entire network according to the level of danger that the vehicle experiences. Our results showed that this protocol granted higher transmission opportunities to dangerous vehicles, and hence improved a DSRC network’s performance in terms of key metrics—i.e., average delay, throughput, and inter-reception time (IRT).

This work can be extended in multiple directions. Thanks to the general model of node distribution (as opposed to previous work limiting the models to "road" environments), this paper’s findings can be applied to other types of transportation network such as unmanned aerial vehicles (UAVs) for building a stochastic geometry-based framework analyzing delay and throughput performances.

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