Coexistence of DSRC and Wi-Fi: Impact on the Performance of Vehicular Safety Applications

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***Abstract*—To adequately support high-throughput applications in next-generation WLANs, more spectrum will be needed to accommodate wider channels. To address this issue, spectrum regulators and stakeholders from the wireless industry and the intelligent transportation system communities are exploring possible band sharing approaches in the 5.9 GHz band. Such approaches include techniques that enable the harmonious coexistence of Dedicated Short Range Communications (DSRC) networks and IEEE 802.11ac networks. In this paper, we provide in-depth discussions on how the coexistence of DSRC and 802.11ac impacts the performance of DSRC applications, with a particular focus on vehicular safety applications. We propose an analytical model that provides valuable insights on DSRC network performance and its vulnerability to interference induced by other DSRC nodes as well as 802.11ac nodes. Using the analytical results derived from the model and extensive simulation results, we also propose a methodology for adjusting 802.11ac parameters that enables a DSRC network to meet the performance requirements of safety applications. Using simulations, we also analyze the throughput of the coexisting 802.11ac network.**

I. Introduction

In response to the exploding proliferation of Wi-Fi, particularly the emerging IEEE 802.11ac standard, the Federal Communications Commission (FCC) issued a Notice of Proposed Rulemaking (NPRM) 13-22 [1] in 2013 that proposed to open up 195 MHz of additional spectrum for use by unlicensed devices in the 5 GHz bands, which generally fall under the Unlicensed National Information Infrastructure (U-NII) rules of the FCC. Specifically, the NPRM proposed opening up additional spectrum in the $5.35 - 5.47$ GHz and $5.85-5.925$ GHz bands. The $5.85-5.925$ GHz band, however, overlaps exactly with the Intelligent Transportation System (ITS) band, which was allocated by the FCC in 1999. More recently, the *Wi-Fi Innovation Act* was introduced in the U.S. Senate and House [2]. This act directs the FCC to move swiftly in conducting tests to assess the feasibility of opening up the upper 5 GHz band, including the ITS band, for unlicensed use.

Dedicated Short Range Communications (DSRC) is a communications technology specifically designed to support ITS applications. The FCC's band sharing proposal would create a spectrum sharing scenario between DSRC and Wi-Fi in which the two access technologies would need to coexist harmoniously with minimal negative impact on each other (under ideal circumstances); in this case, DSRC would be the incumbent system and Wi-Fi would be the secondary system.

In August 2013, the IEEE 802.11 Regulatory Standing Committee created a subcommittee called the *DSRC Coexistence Tiger Team* to explore possible band sharing techniques that will enable the coexistence of DSRC and 802.11ac, and also help inform the regulatory process. In March 2015, the Tiger Team published their final report [3] that summarizes the issues surrounding the proposed band sharing ideas. However, the report only provides high level discussions and stressed the need for further analysis, simulations and field testing to determine an appropriate coexistence approach.

In this paper, we present the findings from our in-depth study that focused on the impact of 802.11ac on DSRC, with a particular focus on safety applications. According to our analysis, the rudimentary Dynamic Frequency Selection (DFS)-like technique discussed in the Tiger Team's report is an unnecessarily heavy-handed approach that will result in unacceptably poor 802.11ac performance when there is more than a modest density of DSRC nodes. In [4], Lansford et. al. suggest potentially more effective approaches that warrant further study. Motivated by the discussions in [4], we propose coexistence techniques that rely on adjusting the *Inter-frame Space* (IFS) value of 802.11ac. We use the terms 802.11ac and Wi-Fi interchangeably.

The main contributions of this paper are listed below.

1. To the best of our knowledge, findings presented in this paper represent results from one of the first systematic studies on the coexistence of DSRC and 802.11ac. Although the challenges of this spectrum sharing scenario were discussed in a few prior works (e.g., [4]–[6]), they provided only high-level discussions without concrete technical solutions based on rigorous analysis or simulations.

2. We propose an analytical model that enables us to quantify the impact of Wi-Fi transmissions on DSRC's performance. Moreover, the proposed model provides valuable insights on how two key Wi-Fi parameters—IFS and sensing range—influence the performance of DSRC.

3. We have validated the proposed analytical model by comparing the results derived from it with results obtained from extensive *network simulator-3* (ns-3) simulations. In our simulation model, we have implemented the *message expiration* feature, which is critical for obtaining high-fidelity simulation results. This feature enables us to simulate safety messages that have a limited lifetime, which means that they are dropped from the Medium Access Control (MAC) layer

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queue when the expiration time is reached.

II. Related Work

Recently, a few papers and technical reports that discuss the coexistence issues between DSRC and 802.11ac have been published [4]–[7]. In [6], the authors propose a method for mitigating the negative impact of 802.11ac-induced interference by controlling IFS and receiver sensitivity. However, the authors ignore the hidden node problem among DSRC nodes, limiting the practicality of their approach.

The Tiger Team report on the coexistence of DSRC and unlicensed systems [3] describes two key proposals. The first proposal prescribes a spectrum sharing approach while using the existing DSRC channelization and Clear Channel Assessment (CCA) method in 10 MHz channels. This requires all 802.11ac (and other unlicensed) devices to be equipped with a component to detect 802.11p preambles. This approach is similar to the DFS mechanism, and it requires an 802.11ac device to abstain from accessing spectrum in the $5.85 - 5.925$ GHz band for 10 seconds after it detects a DSRC preamble. This conservative coexistence approach may result in very low throughput for the 802.11ac users. The second proposal prescribes modifying the DSRC channelization scheme so that each DSRC channel is 20 MHz wide.

III. Technical Background

A. Dedicated Short Range Communications (DSRC)

The DSRC is a short to medium-range wireless communications technology that is designed to support vehicular applications. The DSRC spectrum consists of seven 10 MHz channels. Ch. 178 is the Control Channel (CCH), and Ch. 172, 174, 176, 180, 182, and 184 are Service Channels (SCHs).

The Physical (PHY) and MAC layer protocols for DSRC have been defined in the 802.11p amendment of the IEEE 802.11 standards. This amendment is referred to as Wireless Access in Vehicular Environments (WAVE). Most of the changes made in the amendment are at the MAC layer, while changes at PHY layer are minimal [4].

B. DSRC MAC Protocol

Vehicles in the DSRC system exchange two types of safety critical messages, (i) the first kind, referred to as an event-driven message, is broadcast by a DSRC node when it encounters a potentially unsafe situation. (ii) the second kind of message, known as a *Basic Safety Message (BSM)*, is broadcast periodically and conveys the senders' position, speed, acceleration, direction, etc.

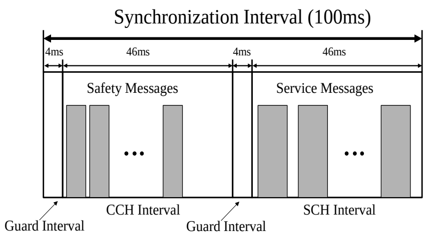


Fig. 1: The multichannel MAC scheme used by DSRC

Vehicles with a single radio use time division to operate on the CCH and SCHs. Details related to multi-channel operations are defined in the upper layer IEEE 1609.x protocols. Fig. 1 illustrates the basic time division concept defined in the IEEE 1609.4 protocol. Time is segmented into synchronized periods, the default duration of which is 100 millisecond (ms) each. Each synchronized period consists of one CCH interval followed by a SCH interval. The default division for each interval is 50 ms. Each CCH and SCH interval begins with a 4 ms guard interval, which is used by the radio to transfer control from one channel to another.

Compared to other 802.11 standards, 802.11p has a number of distinguishing features. For example, in 802.11p, a transmitter broadcasts each packet to all other nodes in the network on the CCH. In order to prevent the network from flooding with Acknowledgement messages (ACKs), 802.11p receivers do not send an ACK to the transmitter. Thus, there is no feedback mechanism provided by the receiver, and consequently, Contention Window size of the 802.11p transmitter remains fixed. If a DSRC node fails to gain access to the channel within the inter-broadcast interval, the packet is discarded at the transmitter. This is because the information contained in such packet is out of date, and a new packet containing updated information will be generated in the next time inter-broadcast interval. This is referred to as packet expiration at the transmitter. Although this is not mandated in the WAVE standards, it is required as a part of ETSI ITS architecture [8].

IV. System Model and Assumptions

In our analysis, we consider a randomly chosen pair of DSRC nodes—a transmitter (W) and a receiver (V), and the two are separated by a distance of x. The two nodes are in each other's transmission and sensing range. The main motivation for constructing the analytical model, which is described in the next section, is to calculate the probability that V can successfully receive a BSM packet from W within each inter-broadcast interval in the presence of 802.11ac interference.

The 802.11ac as well as 802.11p use the IEEE 802.11 DCF protocol. Each node in the network contends for channel access using the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. When a node has a packet to transmit, it senses the corresponding channel for an interval called the Inter-frame Space (IFS). In 802.11p, various types of IFS are used. In our analysis, we consider *PCF Inter-frame Space (PIFS), which is used to give priority access to beacons*.

The analytical model, which will be described in the next section, makes the following two assumptions. First, during each inter-broadcast interval, we assume that the DSRC nodes do not move during an inter-broadcast interval, and move to their next positions instantaneously at the start of the next inter-broadcast interval. This is a reasonable assumption considering that the change in a vehicle's position is minimal during an inter-broadcast interval. Secondly, we model the road segment as a line with zero width. According to [9], this assumption is reasonable when the transmission range of DSRC nodes is significantly larger than the width of the road.

Denote the average vehicle density as λ vehicles per kilometer. We assume that vehicles are placed on the road according to a Poisson distribution with density λ [9]. This implies that, for any road segment of length l, the probability that there are i vehicles in that segment of the road is

$$P(\text{i vehicles in length l}) = \frac{(\lambda l)^i e^{-\lambda l}}{i!}.$$

The DSRC system parameters are defined as follows. All vehicles in the network have the same transmission and sensing range R. BSM packets are broadcast periodically within every inter-broadcast interval, denoted by T_c. We define T_1 as the time required to transmit a DSRC packet and its headers.

Our model considers a single 802.11ac transmitter that has an infinite number of packets to transmit, and is *constantly* attempting to access the medium. *This assumption will maximize the influence of 802.11ac nodes on DSRC performance.* Note that in practice, a Wi-Fi transmitter contends with other Wi-Fi transmitters, and hence multiple Wi-Fi transmitters (as compared to a single transmitter that constantly attempts to access spectrum) would have less impact. We denote the IFS of 802.11ac as IFS_2, and use T_2 to denote the time required for an 802.11ac node to transmit a packet and its headers.

An 802.11ac node can transmit at a maximum power of 30 dBm, while a DSRC node can transmit at a maximum power of approximately 20 dBm in the CCH. Since 802.11ac has higher permissible transmit power than DSRC, 802.11ac's sensing sensitivity threshold (the minimum Signal to Noise Ratio (SNR) required to successfully decode the signal) is higher than that of DSRC. This difference in sensing sensitivity can lead to scenarios where Wi-Fi transmissions can interfere with DSRC node's ability to receive DSRC frames. Such interference is contrary to the rules under which unlicensed systems share spectrum with licensed users. In order to adequately protect DSRC nodes, the sensing sensitivity of 802.11ac needs to be adjusted such that its sensing range is at least as large as its transmission range. Hence, in our model, we assume that the sensing range (R_s) of 802.11ac is larger than its transmission range (R_t), i.e., $R_s \geq R_t$.

The 802.11ac transmitter is assumed to be located at the side of the road. Vertical distance between the 802.11ac transmitter and the road is d. Since we are interested in the transmission and sensing range of 802.11ac along the road, we denote $S = \sqrt{R_s^2 - d^2}$ and $S_t = \sqrt{R_t^2 - d^2}$ as the transmission and sensing distance projected along the road. The locations of the DSRC and 802.11ac nodes are shown in Fig. 2.

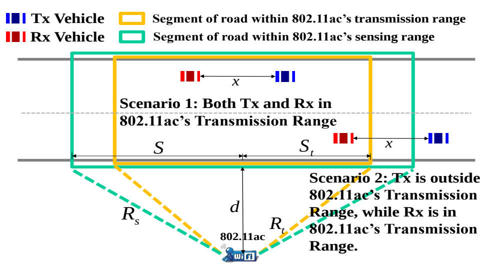


Fig. 2: Locations of the DSRC nodes and the 802.11ac node.

V. DSRC Performance Analysis

In this section, we analyze the performance of a DSRC network in the presence of 802.11ac transmissions using an analytical model. Our model ignores the PHY-layer factors that impact the DSRC network's performance (such as channel fading, shadowing, etc.) to limit the complexity of the model and ensure the feasibility of the analysis.

Most DSRC safety applications such as cooperative forward collision warning, lane change warning, etc., require the transmission of BSMs. In our model, we consider a DSRC broadcast network where each DSRC node is continuously broadcasting BSMs at a regular interval of 100 msec to all DSRC nodes within its transmission range.

When a packet sent by W fails to reach its destination, V, this can be attributed to one of the following reasons:

- *Packet expiration*. We denote the probability that a packet is successfully transmitted within an inter-broadcast interval as $P_{\text{tran}} = 1 -$ Packet Expiration Probability (PEP).
- *Concurrent transmission*. We assume that packets will collide at a receiver if two or more DSRC nodes in the receiver's sensing range begin transmitting in the same time slot. Given that a DSRC transmitter has successfully transmitted a BSM, let P_c denote the probability that a concurrent transmission will *not* occur.
- *Hidden nodes*. Given that a DSRC transmitter has successfully transmitted a BSM, let P_H denote the probability that the BSM packet will *not* collide with another packet from a hidden node.

Thus, Packet Delivery Ratio (PDR) can be expressed as

$$\text{PDR} = P_{\text{tran}} P_c P_H. \tag{1}$$

As shown in Fig. 2, 802.11ac's transmissions can impact the DSRC nodes in one of two possible scenarios:

I: W is located inside the road segment that is within the 802.11ac transmitter's transmission range. So W is not hidden to the 802.11ac transmitter. However, the presence of the 802.11ac transmitter increase the PEP.

II: W is located outside the sensing range of the 802.11ac transmitter, while V is located inside it. In this scenario, 802.11ac transmissions may not have an impact on the PEP. However, W is hidden to the 802.11ac transmitter.

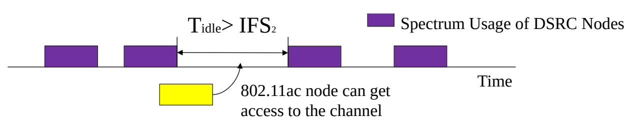


Fig. 3: A Wi-Fi node gaining access to the channel.

Before we describe how to compute the values of P_{tran}, P_c, and P_H, let us first study a scenario in which a Wi-Fi transmitter gains access to the channel before all DSRC nodes finish transmitting their BSMs; such a scenario is illustrated in Fig. 3. If the time interval between adjacent packets from two different DSRC nodes (say T_{idle}) exceeds IFS_2, an 802.11ac node will regard the channel as idle, and start transmitting its packets. During 802.11ac node's transmission, all DSRC nodes within the 802.11ac node's transmission range will cease their backoff counter. In general, an 802.11ac transmitter can transmit k packets in between DSRC transmissions if $k \cdot \text{IFS}_2 \leq \text{T}_{\text{idle}} < (k+1) \cdot \text{IFS}_2$.

Suppose $k = \lfloor \frac{\text{IFS}_2 - \text{PIFS}}{\sigma} \rfloor$, where σ is the length of one 802.11p time slot. The parameter k can be interpreted as the "virtual back-off counter" of 802.11ac. In other words, the duration of time that the 802.11ac transmitter must sense the channel before it can begin transmitting is $\text{PIFS} + k\sigma$.

The distribution of back-off counter values of DSRC nodes in the network follows ordered statistics. However, obtaining closed form expressions for discrete ordered statistics is computationally very expensive, and requires solving integrals with a large number of variables. Hence, we use a Monte Carlo sampling method (Algorithm 1) to sample P_{tran} and P_c.

Algorithm 1 Monte Carlo sampling algorithm

Input: IFS_2 of 802.11ac, PIFS, CW
Output: P_c, P_{tran}.
Define $k = \lfloor \frac{\text{IFS}_2 - \text{PIFS}}{\sigma} \rfloor$, $l = \lfloor \frac{\text{CW}}{k} \rfloor$, $\beta_1 = 2\lambda R$, $\beta_2 = 2\lambda S$
Initialize $P_{\text{tran}} = 0$,
$\gamma_1 = \min\{\beta_1, \beta_2\}$, $\gamma_2 = |\beta_1 - \beta_2|$
for $t = 1, 2, \cdots, T$ **do**
  Sample $X_1 \sim \text{Poi}(\gamma_1)$, $X_2 \sim \text{Poi}(\gamma_2)$, $N = X_1 + X_2$
  Sample $B^{(i)} \sim \text{unif}[0, \text{CW} - 1]$, $i = 1, 2, \cdots, N$
  Add $B^{(0)} = 0$, let $\mathbf{B} = [B^{(0)}, B^{(1)}, \cdots, B^{(N)}]$
  $\mathbf{B}' = \mathbf{B}[1, 2, \cdots, X_1]$
  if $\beta_1 > \beta_2$ **then**
    Find the indexes of $B^{(1)}$ in $\mathbf{B}$ and $\mathbf{B}'$, denoted as I_1 and I_2
  else
    Find the indexes of $B^{(1)}$ in $\mathbf{B}$ and $\mathbf{B}'$, denoted as I_2 and I_1
  Sort $B^{(0)}, \cdots, B^{(N)}$ in ascending order $B_0, \cdots, B_N$
  Initialize $\mathbf{Q} = [0, 0, \cdots, 0]_{1 \times l}$.
  for $j = 1, 2, \cdots, l$ **do**
    for $m = 1, 2, \cdots, N_2$ **do**
      if $k \cdot j \leq B_m - B_{m-1} < k \cdot (j+1)$ **then**
        if $m \leq I_2$ **then**
          $\mathbf{Q}(j) = \mathbf{Q}(j) + 1$
  $n_{ac} = [1, 2, \cdots, l] \cdot \mathbf{Q}^T$
  if $n_{ac} \cdot T_2 + I_1 \cdot (T_1 + \text{PIFS}) + B^{(1)} \cdot \sigma \leq T_c$ **then**
    $P_{\text{tran}} = P_{\text{tran}} + 1$
    if $B^{(1)} == B_{I_1+1}$ or $B^{(1)} == B_{I_1-1}$ **then**
      $P_c = P_c + 1$
$P_c = P_c / P_{\text{tran}}$, $P_{\text{tran}} = P_{\text{tran}} / T$

We first consider the case when $R > R_s$. Recall that R denotes the transmission range of a DSRC transmitter. We first sample DSRC nodes within 802.11ac's sensing range from a Poisson distribution with the mean value of $2\lambda R$, and let X_1 denote the number of such nodes. We then sample DSRC nodes which are outside 802.11ac's sensing range while still within W's transmission range, and let X_2 denote the number of such nodes. Thus, the total number of DSRC nodes in W's transmission range is $N = X_1 + X_2$. This is extended to the case when $R < R_s$. We sample X_1 DSRC nodes that are within W's transmission range, and then sample X_2 DSRC nodes that are inside 802.11ac's transmission range, but outside W's transmission range.

Each DSRC node chooses a random back-off counter uniformly distributed in [0, CW-1]. We sample N back-off counter values of DSRC nodes, and store these back-off counter values in matrix $\mathbf{B} = [B^{(1)}, \cdots, B^{(N)}]$, where $B^{(i)}$ is the back-off counter of the ith DSRC node. Let $\mathbf{B}' = \mathbf{B}[1, 2, \cdots, X_1]$ be the back-off counter values of DSRC nodes in 802.11ac's sensing range, and $B^{(1)}$ be W's back-off counter value. We sort $\mathbf{B}$ in ascending order and denote these values as $B_0, B_1, B_2, \cdots, B_N$, where $B_0 = 0$, $B_1 \leq B_2 \leq \cdots \leq B_N$. Suppose that the back-off counter of W is the I_1^{th} smallest among all DSRC nodes in its transmission range, and the I_2^{th} smallest among all DSRC nodes in 802.11ac's sensing range. Note that we add $B_0 = 0$ because we need to consider the scenario where an 802.11ac transmitter gains access to the channel before all DSRC nodes.

For any m, if $j.k \leq (B_m - B_{m-1}) < (j+1).k$, a Wi-Fi transmitter can send k packets before all DSRC nodes in its sensing range with a back-off counter value no less than B_m. Let n_{ac} denote the number of packets that the 802.11ac node transmits before W. We define a matrix $\mathbf{Q}$, such that $\mathbf{Q}(j)$ is the number of times that 802.11ac successfully transmits j packets between two DSRC packet transmissions. For example, as shown in Fig. 3, if 5 packets are sent out by 802.11ac transmitter between two consecutive DSRC transmissions, then $\mathbf{Q}(5)$ in increased by one. In our analysis, we focus on a particular transmitter W which is the I_2^{th} DSRC node in 802.11ac's sensing range to send its BSM. In order to check whether the BSM from W is expired, we only need to calculate the number of packets transmitted by the 802.11ac node before W, i.e., we only need to consider the case $m \leq I_2$.

Since the maximum value of the back-off counter is CW, an 802.11ac node can transmit at most $l = \lfloor \frac{\text{CW}}{k} \rfloor$ packets between two consecutive DSRC transmissions. Hence, $n_{ac} = \sum_{i=1}^{l} i \cdot \mathbf{Q}(i)$. If $\left(n_{ac} \cdot T_2 + I_1 \cdot (T_1 + \text{PIFS}) + B^{(1)} \cdot \sigma\right) > T_c$ at the instant when W wishes to transmit a BSM, more than T_c amount of time has elapsed since the generation of the packet; in this scenario, W cannot get access to the channel in the current inter-broadcast interval, and must drop its packet. Otherwise, P_{tran} is incremented by 1. We divide P_{tran} by the total number of iterations T to obtain the value of P_{tran}.

In Algorithm 1, two DSRC nodes having the same back-off counter value indicates a concurrent transmission. Given that W successfully sends its BSM, if $B^{(1)} = B_{I_1-1}$ or $B^{(1)} = B_{I_1+1}$, W has the same back-off counter value with at least one of its neighbours, resulting in a collision due to concurrent transmission. We divide the number of collisions by the number of unexpired packets to obtain P_c.

The value of P_H cannot be sampled from Algorithm 1. However, having obtained P_{tran}, using results from [9], P_H can be approximated as, $P_H = e^{-\frac{2P_{\text{tran}}\lambda x T_1}{T_c}}$. From the values of P_{tran}, P_c and P_H, we can obtain the PDR from Equation 1.

VI. Numerical and Simulation Results

A. Simulation Setting

We have generated quantitative results on the impact of Wi-Fi transmissions on DSRC performance using ns-3 simulations. The simulation setup is shown in Fig. 4. We consider a

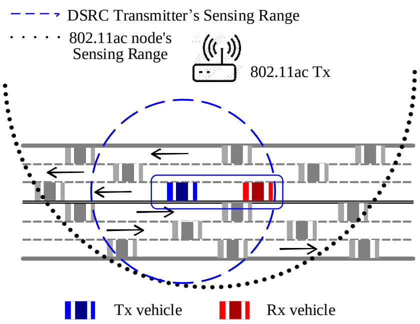


Fig. 4: Simulation scenario.

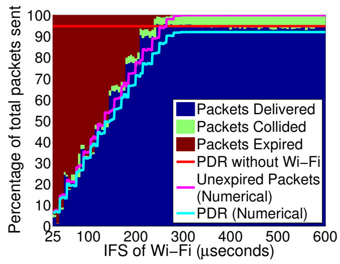
1000 meter long six-lane road with different traffic densities. The impact of 802.11ac's transmissions on DSRC performance is evaluated using a single DSRC transmitter-receiver pair as shown in Fig. 4. The simulation parameters are summarized in Table I. As pointed out in [8], the default value of CW size (CW = 7) for DSRC nodes currently proposed in the 802.11p standard for BSM packets is far from optimal. The authors suggest setting the value of CW to 127. Following this recommendation, we set the CW size of DSRC nodes to 127.

Our simulation uses the extended alternating channel access scheme with 50 ms CCH and 50 ms SCH. The DSRC transmitter broadcasts a packet once in every inter-broadcast interval over a CCH. Transmissions over SCHs are not considered (we focus on the performance of safety applications which use the CCH). Each simulation run lasts for 10 seconds. We assume that the Wi-Fi transmitter always contends for the channel. The metrics used to evaluate the DSRC performance are PDR and the Packet Expiration Ratio. These metrics are computed with and without Wi-Fi transmissions. Each computation is averaged over 10 runs with different seed values.

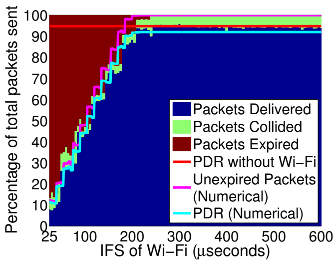
B. Impact of Wi-Fi Transmissions on the DSRC Network

Fig. 5 shows percentage of the packets delivered (in blue), lost due to collisions (in green), and expired (in brown) for different values of Wi-Fi IFS. The red line indicates the PDR of DSRC in the absence of any Wi-Fi transmissions. The solid magenta and cyan lines indicate the numerically computed values (as described in Sec. V) of the number of unexpired packets transmitted by W, and delivered to V, respectively.

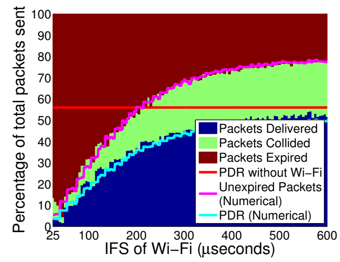
We observe that *if default IEEE 802.11ac parameters are used (i.e., IFS = 23 μs, time slot = 9 μs), performance of the DSRC network degrades significantly*. However, the PDR of the DSRC network tends to converge to fixed values as the Wi-Fi IFS increases. When the IFS of the Wi-Fi transmitter is larger than a threshold value, 802.11ac transmissions have negligible influence on DSRC network, and the performance degradation of the DSRC network is due to the contention among the DSRC nodes themselves. Moreover, any increase in the IFS of Wi-Fi beyond this threshold value yields no improvement in the performance of DSRC network. Based on Algorithm 1, given the packet size of DSRC nodes, the value of this threshold IFS depends on the number of DSRC nodes in Wi-Fi's sensing range, and the CW of DSRC nodes. The



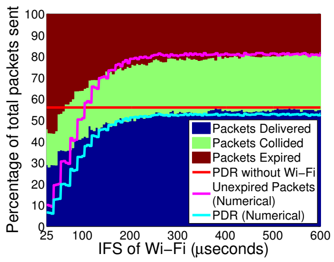
(a) 30 vehicles/km, SR = 300 m



(b) 30 vehicles/km, SR = 500 m



(c) 120 vehicles/km, SR = 300 m



(d) 120 vehicles/km, SR = 500 m

Fig. 5: Percentage of Delivered, Collided and Expired Packets

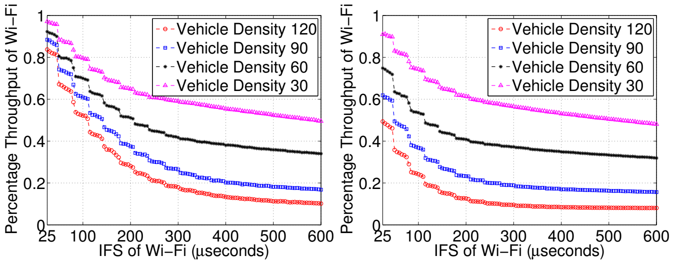
step-like pattern for the number of unexpired packets can be attributed to the virtual back-off counter value (k) of Wi-Fi.

TABLE I: Simulation parameters

Parameter	**Value**
Length of the road	1000 meters
Vehicle densities	{30,120} vehicles/km
Number of lanes	6
Lane width	3 meters
DSRC	
Gain (Tx & Rx)	7.2 dB
Transmission Range	300 meters
Sensing Range	300 meters
Packet Length	500 bytes
Data Rate	6 Mbps
PIFS	45 μseconds
Slot Duration (σ)	16 μseconds
Contention Window	127
Inter-Broadcast Interval	0.1 seconds
Distance between Tx & Rx	50 meters
IEEE 802.11ac	
Gain (Tx & Rx)	7.2 dB
Transmission Range	300 meters
Sensing Range	{300,500} meters
Packet Length	7,500 bytes
Data Rate	78 Mbps
IFS	23 to 2032μs (23 to CW $\cdot\, \sigma$)
Vertical distance from road	150 meters

Figures 5a-5d suggest that as the IFS of Wi-Fi increases, the PDR of DSRC converges to the red line faster for a larger sensing range. Thus, the sensitivity threshold of a Wi-Fi transmitter should be decreased such that its sensing range is larger than its transmission range. *Under these circumstances, we can infer from Fig. 5 that for a Wi-Fi IFS value larger than a threshold value (200 μs in our simulation setting), the performance of the DSRC network approaches its performance in the absence of any Wi-Fi transmissions.*

The effectiveness of hazard detection is heavily based on



(a) Sensing Range = 300 m (b) Sensing Range = 500 m

Fig. 6: Relative throughput of 802.11ac

how often messages can be exchanged among vehicles. Inter-reception time (IRT), introduced in [10], is defined as the time elapsed between two successive successful reception events at the receiver of packets broadcast by a specific transmitter. If no packet is lost, the average value of IRT will approximately be equal to the inter-broadcast interval. However, IRT will be increased to $N \times 100$ ms if $N-1$ consectutive packets are lost and the Nth packet is successfully delivered. Therefore, IRT follows geometric distribution. The average IRT can be approximated to $\frac{100\ \text{ms}}{\text{PDR}}$. Using this argument, and from Fig. 5, it can be inferred that the average value of IRT reduces as the IFS of Wi-Fi increases. Most safety applications discussed in [11] require the average IRT to be around 100 ms. The average IRT converges to approximately 125 ms ($\frac{100\ \text{ms}}{0.8}$) and 200 ms ($\frac{100\ \text{ms}}{0.5}$) when the traffic density is 30/km and 120/km respectively. However, this degradation in performance is due to severe contention among DSRC nodes themselves. The impact of Wi-Fi transmissions on the IRT is alleviated when the IFS value becomes larger the threshold value.

C. Wi-Fi's Performance When Coexisting with DSRC

Considering that the IEEE 802.11ac standard was developed for high data-rate applications, it is important to discuss the impact of changing IFS and sensing range on Wi-Fi performance. Fig. 6 shows Wi-Fi's relative throughput versus its IFS for sensing range values 300 and 500 m. The relative throughput is computed as a percentage of the *reference throughput*, where the reference throughput is measured with default 802.11ac parameter values (IFS = 23 μs) and no DSRC transmissions. The reduction in throughput is larger for higher vehicle densities. We observe that the throughput converges to a fixed value, corresponding to the throughput that is achieved when an 802.11ac node executes uninterrupted transmissions in the 8 ms guard period in each inter-broadcast interval.

Fig. 6b shows that for the Wi-Fi IFS value of 200 μs, the Wi-Fi throughput ranges from 15% to 60% of the reference throughput for different vehicle densities. Moreover, in our analysis, we assume the presence of a single Wi-Fi transmitter. In real-world scenarios, an 802.11ac transmitter will have to compete for the channel with other 802.11ac nodes, reducing the throughput even further. Thus, *if the 802.11ac IFS value is increased to* 200 μs*, there is a significant degradation of 802.11ac performance.* Assuming a reference throughput of 433 Mbps (the maximum PHY rate for an 80 MHz channel with one spatial stream), coexistence with DSRC nodes with a density of 120 vehicles/km results in a throughput value of 64 Mbps for a single Wi-Fi transmitter. In the presence of other 802.11ac transmitters, this throughput would decrease further. The resulting throughput may not be sufficient to support high resolution streaming applications [12]; however lower data rate applications, such as web-browsing and e-mail, can be supported [13]. On the other hand, in low vehicle density scenarios, the maximum Wi-Fi throughput ($\approx$ 250 Mbps) is sufficiently high to support most high data rate applications.

VII. Conclusions

In this paper, we provided in-depth discussions on how spectrum sharing between DSRC and Wi-Fi can impact the performance of DSRC safety applications. We proposed an analytical model to characterize the performance of a DSRC transmitter-receiver pair when it coexists with Wi-Fi nodes. Specifically, we used the model to characterize the two key parameters of Wi-Fi that have the greatest impact on the performance of DSRC—viz., IFS and sensing range. Using our model and simulations, we show that the IFS value of the Wi-Fi transmitter can be adjusted to mitigate the negative impact of 802.11ac transmissions on a DSRC network. Although this approach degrades the performance of 802.11ac networks, it represents a more viable coexistence approach compared to the Tiger Team's recent proposal, which prescribes a DFS-like mechanism in which a Wi-Fi node defers access to a channel for 10 seconds after the detection of a DSRC transmission.

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