Spectrum Requirement for Vehicle-to-Vehicle Communication for Traffic Safety

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***Abstract*—We investigate the amount of radio spectrum required for reliable vehicle-to-vehicle (V2V) communication for traffic safety. The basic feature of the traffic safety application is that it uses periodical broadcasts of status messages containing the location and velocity of transmitting vehicles. In our study we consider two dominant technologies for V2V communication, namely IEEE 802.11p and self-organizing time division multiple access (STDMA). We analyze the spectrum demand for a dense highway scenario with a stringent reliability requirement. The results indicate that more than 80 MHz bandwidth is needed to achieve 99% reliability in certain cases. This is in stark contrast to current regulatory decisions that dedicate only 10 MHz bandwidth in 5.9 GHz band for safety purposes in intelligent transportation system (ITS) in Europe and US. Our results suggests that a substantial change would be required in either spectrum allocation or in V2V communication system design to achieve the required traffic safety.**

***Index Terms*—Vehicle-to-Vehicle communication; traffic safety; IEEE 802.11p; STDMA; reliability; spectrum requirement**

I. Introduction

Wireless communication has begun to play an increasingly important role in the intelligent transportation systems (ITS). Among the emerging ITS applications is real-time vehicle-to-vehicle (V2V) communication for cooperative road safety. [1]. Future vehicles are expected to avoid possible collisions through V2V information exchange which provides safety hints to drivers or warnings about traffic situations. Two message types have been defined for this purpose: cooperative awareness message (CAM) informs other vehicles of the status of sending vehicles, e.g., location and velocity [2]; decentralized environment notification message (DENM) informs nearby vehicles of a special event such as an accident [3]. Both message types should be reliably broadcasted to vehicles within several hundred meters range with minimum delay.

Considerable standardization and research efforts have concentrated on V2V communication solutions. Most notable are the European standard ITS-G5 [4] and DSRC/WAVE standard in the US [5]. Both standards are based on IEEE 802.11p specification, which employs a simplified version of carrier sense multiple access with collision avoidance (CSMA/CA) as medium access control (MAC) protocol. Due to its best-effort nature and unbounded channel access delay, a recent ETSI proposal considered an alternative MAC, namely self-organized time division multiple access (STDMA), for future ITS-G5 system [6].

Recent studies on the performance of IEEE 802.11p-based V2V communication system have identified its scalability issue with high density of vehicles, e.g., multi-lane highway scenarios [7]–[9]. STDMA was proposed to provide a guaranteed channel access delay [10], [11]. However, packet loss due to interference and collisions in the congested network is still considered unacceptable for road safety application with strict reliability requirement.

One of the potential reasons behind the scalability issue is the insufficient amount of radio spectrum allocated to V2V communication. In the US, DSRC-based ITS services are allotted 75 MHz bandwidth in the 5.850 - 5.925 GHz band, but only 10 MHz is dedicated to critical road safety application [12]. The situation is similar in Europe, where 10 MHz control channel (CCH) out of 30 MHz bandwidth in the 5.875 - 5.905 GHz band is allocated to the critical safety messages [13]. In fact, except an initial investigation by CEPT [14], there has not been any well-established study about the spectrum requirement for traffic safety communication. Therefore, it is imperative to investigate the required amount of spectrum for satisfying the reliability and latency requirement of road safety application.

In this paper, we use packet reception failure probability as the performance metric to identify the spectrum requirement for critical road safety communication. We consider a ten-lane highway to describe a crowded environment, and perform extensive simulations with two MAC schemes, CSMA/CA in IEEE 802.11p and STDMA. Our major contribution is to identify the spectrum need for future road safety application. Our results will give insights into spectrum regulations and the design of V2V communication solutions.

The remainder of the paper is organized as follows: Section II describes the system model of V2V communication and the performance measure for reliability. The possible causes for packet reception failure are discussed in Section III. Section IV summarize the setup of the simulation scenario and Section V presents the simulation results. Finally, Section VI concludes our analysis.

II. System Model

A. V2V communication for road safety

In order to evaluate a challenging scenario, we assume all vehicles are already equipped with radio transceivers dedicated for road safety communication. As illustrated in Fig. 1, each vehicle independently generates CAMs containing its latest status information, which is updated periodically every $T = 1/f$ seconds. Then, each message is broadcasted in data

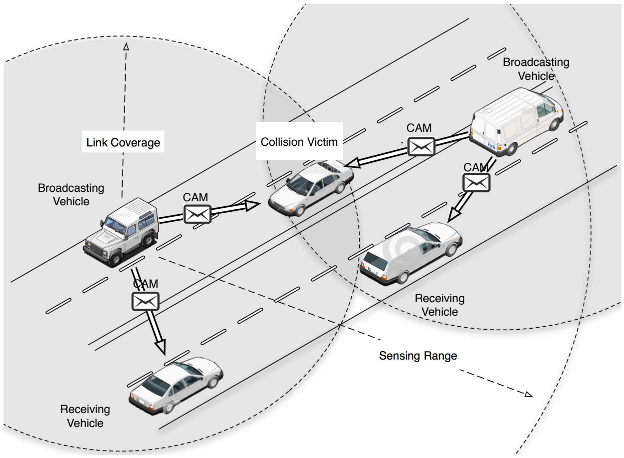

Fig. 1: System model of Vehicle-to-Vehicle communication for road safety.

packet with fixed size of m bytes to its peers within the link coverage range of R m and should be decoded by the receiving vehicles before the next message is generated. All vehicles should constantly monitor the activities on CCH within its sensing distance of D m when they are not transmitting.

If the packet is not correctly received by its intended receiver within the latency requirement for various reasons to be discussed in the next section, then that packet is considered lost and contributes to the overall packet reception failure probability (p_{fail}). As a measure for the communication reliability of the V2V communication system, p_{fail} is defined as the ratio between the number of packets that exceeds the latency constraint (N_{fail}) and the total amount of packets transmitted within the V2V communication network (N_{total}):

$$p_{fail} = \frac{N_{fail}}{N_{total}}. \quad (1)$$

Note that, we consider each packet transmitted to an individual receiver as a unique entity, although identical packets are broadcasted from the same transmitter to multiple receivers.

B. MAC layer models

In order to provide a more balanced view on the spectrum requirement issue, we implemented two types of MAC schemes that are popular for V2V communication, namely, CSMA/CA and STDMA. In both cases the MAC schemes are used to determine the channel access on only a single channel dedicated for critical road safety application.

1) CSMA/CA: The IEEE 802.11p MAC algorithm implements an exponential back-off mechanism. The transmitter can access the channel only after it has sensed the channel being idle for a certain period of time called an arbitration inter-frame space (AIFS). If the channel is busy or becomes occupied during the AIFS, the transmitter must defer its channel access for a randomized period of time defined by contention window (CW). In a typical CSMA/CA network, the channel access delay increases exponentially and becomes unpredictable as the channel load increases. However, in the V2V communication for road safety application, there is only broadcast traffic for CAMs. Thus, there is no acknowledgement and consequently no multiple back-offs that doubles the contention window size. The channel access delay is further reduced by the priority queues implemented in IEEE 802.11e.

2) STDMA: STDMA protocol was initially proposed for maritime traffic coordination [16]. It has a synchronized time slot structure and ensures a predictable channel access delay even in a congested network. When a vehicle enters the V2V communication system, it starts by listening to the channel activity for one time frame to identify which slots are occupied by transmissions from other vehicles. It then selects a few nominal transmission slots (NTS) for each packet to be transmitted during one frame. Each NTS is chosen from a group of time slots, denoted as selection interval (SI). If there were empty slots in the SI, one of them would be randomly chosen. Otherwise the slot used by the vehicle furthest away would be reused. The same NTS will be used for a few subsequent frames, until a new NTS is selected following the same procedure. The channel access delay of STDMA is therefore upper-bounded by the SI length. (more details on STDMA in [17])

C. PHY layer model

The physical layer model is based on orthogonal frequency-division multiplexing (OFDM) as specified in IEEE 802.11a. In this study, a simplification is made to keep the simulation tractable while highlighting the relationship between communication reliability and channel bandwidth. We assume that a robust modulation scheme with constant data rate is used and a minimum SINR threshold is required to successfully decode the received packet. The SINR is defined as

$$SINR = \frac{P_r}{P_n + \sum_{k=0}^{K} P_{i,k}} \geq SINR_{thres}, \quad (2)$$

where P_r is the received signal strength, P_n the noise power and $P_{i,k}$ the received interference from the kth active transmitter.

We further assume that link data rate only increases in proportion to the channel bandwidth. For instance, with QPSK modulation, a data rate of 6 Mbps can be achieved in 10 MHz channel, then with 20 MHz channel the link data rate would increase to 12 Mbps, and so on. However, this is an optimistic assumption as the Doppler fading and RMS delay in V2V channels could have a negative impact on the spectrum efficiency as the channel bandwidth increases [18].

III. Causes for Packet Reception Failure

The reliability of V2V communication is a challenging issue due to the rapidly varying link conditions and network topology. The broadcast communication for road safety application further magnifies the difficulties for predicting the amount of data traffic generated by an unforeseeable number of members of the network, since there are more passive receivers that cannot be identified without acknowledgement. Thus, packet reception failures could be the results of many potential causes, which are categorized as follow:

1) Excessive channel access delay: CSMA/CA protocol in theory has an unbounded channel access delay because it will keep backing off as long as it detects the channel as busy. Thus, there is a risk that the status information would not be sent out before the next packet arrives. This issue has been a major concern of many pervious studies for using IEEE 802.11p for road safety application. On the other hand, STDMA schedules the transmissions of all packets and can thus be designed to ensure the channel access delay is within the latency requirement.

2) Packet loss due to insufficient SINR: after obtaining channel access, the packet could still be lost during the transmission. Due to aggregate interference from simultaneously transmitting users and signal fading, the SINR at the intended receiver could be insufficient for the packet to be correctly decoded. It is worth noting that the interference may be originated from both nearby transmitters that fail to avoid the collision (see Fig. 1) and other active transmitters outside the sensing range. Packet lost during transmission is considered to have infinite end-to-end delay.

3) Inability to receive and transmit simultaneously: when vehicle A is broadcasting its status information to other vehicles, it will not be able to receive any packet simultaneously due to the limitation of half-duplex radio. Therefore if vehicle A happens to be within the communication range of another transmitting vehicle B, the packet sent from vehicle B to vehicle A would be lost. This situation will occur in both CSMA/CA and STDMA based system and cannot be alleviated by increasing the number of channels. Again, if a packet failed to reach its intended recipient, the end-to-end delay of that packet is considered to be infinite.

IV. SIMULATION SCENARIO

For the reliability performance analysis, both CSMA/CA and STDMA based V2V communication systems are implemented in MATLAB. We have investigated a urban highway environment with realistic parameter settings that are commonly used in previous literatures. The urban highway is typically considered as the worst-case scenario for V2V communication due to its high vehicle density and rapid state changes [9]. It consists of five lanes on each direction, with lane width of 5 m. Considering the link coverage range for V2V communication is typically less than 500 m, a 5 km highway segment is studied, with another 2.5 km highway segments added on both ends of it to minimize the edge effect. The arrival of vehicles on each lane is modeled as a Poisson process with 3 sec average interval[1]. To simulate the dynamics of the V2V network, each lane has a different average speed, and the speed of the vehicles on each lane follows a normal distribution with that average speed and a standard deviation of 1 m/s. The average speed of the inner two lanes are 130 km/h and the middle two lanes are 108 km/h and the outer most lane is 90 km/h. Thus, on average the traffic density is approximately 10 vehicles per km per lane.

[1]According to Swedish regulation, each vehicle should maintain a 3-second distance from the vehicle in front.

TABLE I: Simulation Parameters

Parameter	Value
Packet size (m)	300 bytes
Latency requirement (T)	100 ms
Sensing distance (D)	1000 m
SINR threshold	6 dB
CSMA/CA AIFS	58 μs
CSMA/CA CW size	3
STDMA frame length	1 s

The data traffic generated by each vehicle is periodical CAM broadcasting, where each vehicle's initial transmission time is independent and random. The ETSI recommendation for safety related message is transmitted in 800 bytes packet with repetition rate of 2 Hz, while the US standard suggests a packet size of 300 bytes with repetition rate of 10 Hz. In our simulation, we adopted the latter parameters, because most of the use cases based on CAM require a minimum update frequency of 10 Hz and a maximum latency of 100 ms [2], [15].

The channel propagation model used in the simulator is a combination of dual-slope model for distance-dependent pathloss [19] and Nakagami-m model for fading effects [20]. The dual-slope model for distance-dependent pathloss in highway environment is given as

$$P_{r,dB}(d) = \begin{cases} P_{r,dB}(d_0) - 10\gamma_1 \log_{10}\frac{d}{d_0}, & d_0 \le d \le d_c; \\ P_{r,dB}(d_c) - 10\gamma_2 \log_{10}\frac{d}{d_c}, & d \ge d_c. \end{cases} \quad (3)$$

Here $P_{r,dB}(d_0)$ is the reference power, calculated by using the free space path model at distance of 10 m. The propagation exponent γ_1 is 2.1 and γ_2 is 3.8. The critical distance is 100 m. In vehicular environment, Nakagami-m fading [21] is averaged in only the close proximity of the vehicle; slow-fading, characterized by log-normal model, can be averaged and incorporated in the slope pathless model for distance beyond 40*wavelength, i.e. 2 m [22]. Therefore, the results presented in the next section exclude the fading effect to emphasize the effect of network congestion due to insufficient channel bandwidth only.

All vehicles are assumed to have the same output power, $P_{t,dB}$ = 33 dBm per 10 MHz (the maximum allowed output power on CCH in ITS-G5A). The noise power is -99 dBm per 10 MHz and the clear channel assessment (CCA) threshold is -93 dBm per 10 MHz, corresponding to a sensing range of approximately 1 km. Note that the transmit power, sensing threshold and noise power increases proportionally to the channel bandwidth. Finally, a minimum SINR threshold of 6 dB is required for successful reception.

Regarding the MAC parameter setting, the AIFS for CSMA/CA is set to 58 μs and the contention window (CW) size is set to 3 in accordance to the highest priority of safety-related data traffic. For STDMA, the frame length is assumed to be a constant: 1 sec. The number of slots per frame increases as the data rate improves. The duration of a single slot corresponds to the transmission time of a 300 bytes packet.

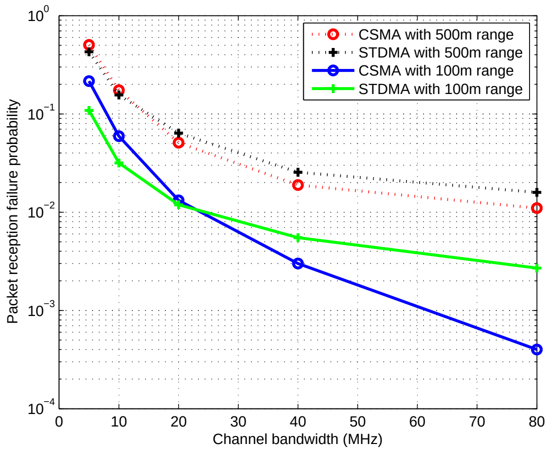

Fig. 2: Packet reception failure probability of V2V communication system with different channel bandwidth.

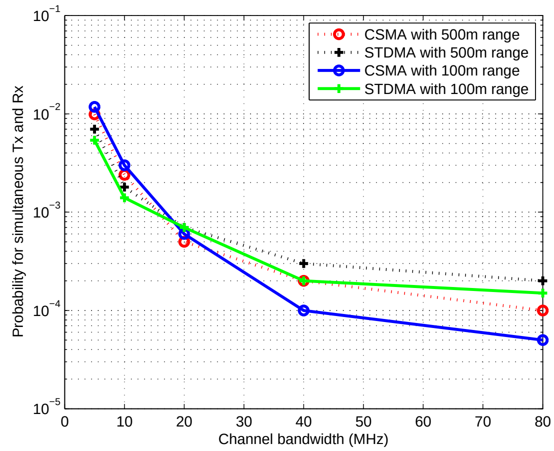

Fig. 3: Packet reception failure due to the limitation of half-duplex radio.

V. Numerical Results and Analysis

To illustrate the impact of available spectrum on V2V communication reliability, we varied the channel bandwidth of CCH from 5 MHz up to 80 MHz, effectively increasing the data rate. Vehicle traffic is generated and filled up the simulated highway segments during the initialization phase. Then the data traffic and packet reception are monitored and recorded over one-minute period. The packet reception failure rate are calculated following the definition in (1).

In Fig. 2, the dotted lines show p_{fail} values with the link coverage range of 500 m. Apparently, the packet reception failure probability is well above 10% with 10 MHz bandwidth and barely reaches 1% when the channel bandwidth increases to 80 MHz. While STDMA performs slightly better than CSMA/CA at lower bandwidth, CSMA/CA utilizes the spectrum more aggressively than the slotted STDMA and thus its performance increases faster as more spectrum become available.

Similar trends can be observed when the communication range reduces to 100 m, as depicted by the solid lines in Fig. 2. The shorter range requirement significantly decreases p_{fail}, which reaches lower than 0.1% for CSMA/CA with 80 MHz bandwidth. Recall that we have assumed a fixed sensing range of 1 km. The competition for channel access is therefore not affected and any enhancement in reliability is clearly a result of improved SINR. This theory is confirmed by tracing the causes of all failed packet receptions, where we notice that most of the packet loses are due to collisions and excessive aggregate interference from active transmitters outside the sensing range. In contrast, the channel access delay of CSMA/CA rarely exceeds the latency requirement, because there is no need to wait for acknowledgement in broadcasting and no exponential back-offs.

Fig. 3 shows the packet loss due to the inability for the half-duplex radio to transmit and receive simultaneously. These packets could have been correctly received by the intended receiver had it not been occupied for transmitting its own packet. It is interesting to notice that this effect alone causes more than 0.2% packet loss with 10 MHz band. Simply adding more frequency channels with the same bandwidth could even worsen the situation, as the actual transmission duration of each individual packet remains unchanged while the number of packets broadcasted at the same time would increase.

For some V2V applications, having one or two packets that occasionally miss the deadline may not be a serious issue. However, if consecutive packets from vehicle A failed to reach vehicle B who is within vehicle A's link coverage range, vehicle B could completely lose track of the status about vehicle A. Fig. 4 illustrates this risk of continuous interruptions in communication links by showing the instances of different numbers of consecutive packet losses in an one-minute simulation. As seen in the figure, there could be up to 50 consecutively lost packets. This corresponds to a period of 5 seconds for interrupted communication, during which time the relative distance between two vehicles could have changed by 500 m. It can also be observed that, while CSMA/CA has a higher risk for short period of continuous disruptions, it has a much lower probability than STDMA for causing extended period of communication loss.

VI. Conclusion

In this paper, we investigated the spectrum need for V2V communication for road safety application. We performed extensive simulations for CSMA/CA and STDMA MAC schemes in an urban highway scenario with realistic traffic density. Results show that more than 80 MHz is required to achieve 1% packet loss with 500 m communication range. It is significantly larger than the current spectrum allocation of 10 MHz in the US and Europe. By decreasing the communication range to 100 m, the spectrum requirement is reduced to 20 MHz, which is still twice the present day availability. If we want to achieve better reliability, i.e., packet loss of less than 1%, the spectrum requirement increases up to several hundred MHz.

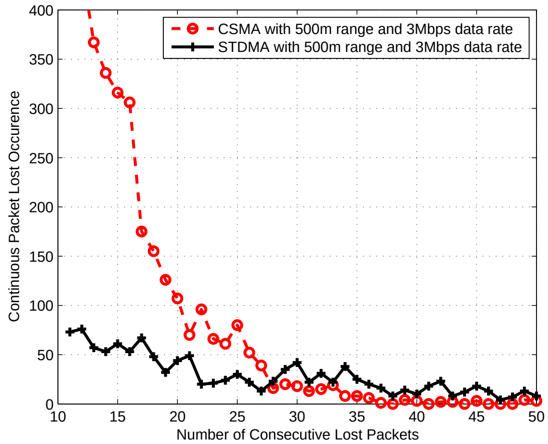

Fig. 4: Number of consecutive lost packets.

We identified that the major cause of packet reception failure is collision and aggregate interference in the congested network. We also noticed that the limitation of half-duplex radio, i.e., not being able to receive and transmit simultaneously, deserved more attention. Although it leads to 0.2% loss in 10 MHz band, this effect can only be alleviated by increasing the channel bandwidth rather than adding more channels. It was observed that STDMA performs better than CSMA/CA with limited spectrum resource. However, it has a higher risk of consecutive packet losses which is serious to the traffic safety. The performance of CSMA/CA improves fast, eventually outperforming STDMA, as the channel bandwidth increases.

Our study suggests that there must be a substantial improvement in order to fulfill the reliability requirement of critical road safety. First, spectrum allocation needs a rethinking so that a larger channel bandwidth can be available for the application. Second, MAC schemes of V2V communication can be enhanced further. For example, STDMA may utilize prediction of the worst interferer's location for deciding next transmission slots instead of relying on the current information. These remain as interesting research topics.

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