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Improving Scalability of Vehicle-to-Vehicle Communication with Prediction-based STDMA

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Abstract—Self-organized TDMA (STDMA) has been proposed as a medium access control (MAC) protocol for Vehicle-to-Vehicle (V2V) communication. Although it avoids the unbounded channel access delay faced by other CSMA-based protocols, the reliability in high traffic density is still unsatisfactory for critical road safety applications. This paper introduces an enhanced prediction-based STDMA protocol which utilizes the spatial information available in the messages exchanged for road safety applications. Thus it allocates the radio resources more efficiently and minimizes the mutual interference among different vehicles. The results show that the prediction-based STDMA offers a significant improvement in the scalability and coverage of the V2V communication system for road safety applications with strict reliability requirement. The performance enhancement of the proposed MAC protocol is achieved without adding much complexity to the existing STDMA and it has considerable potential for further improvement.

Index Terms—Vehicle-to-Vehicle communication; traffic safety; STDMA; scalability; reliability; Prediction-based; interference minimization.

I. INTRODUCTION

Traffic accidents constitute a serious problem world-wide. In 2010, the European Union saw about 30,000 fatalities and more than 1.4 million injuries from road accidents [1]. Vehicle-to-vehicle (V2V) communication can potentially decrease the number of traffic accidents by broadcasting status messages containing spatial information, e.g., the position and velocity of each vehicle [2]. Due to the ad-hoc nature of V2V communication, it has been a challenging issue to design a reliable wireless communication system that scales with high traffic density.

To meet a strict reliability requirement for high scalability, a careful design of the medium access control (MAC) protocol is crucial. Two standards have already been developed for V2V communications, the European standard ITS-G5 [3] and DSRC/WAVE standard in the US [4]. Currently both standards are based on 802.11p which employs carrier sense multiple access (CSMA). With CSMA, all vehicles must listen to the wireless channel before transmitting, and if the channel is busy, the nodes must defer their access. An evaluation of the IEEE 802.11p MAC protocol for V2V communication is discussed in [5], where the authors point out that such a MAC protocol introduces unbounded delay when the traffic density is high, thus limiting the system's scalability.

To overcome the channel access delay problem, the authors in [5] have proposed to utilize self-organizing time division multiple access (STDMA) found in [6], as a replacement

of the CSMA-based MAC. A recent ETSI proposal includes STDMA as the MAC protocol for the future ITS-G5 system [9]. STDMA has a synchronized time-frame structure and allows multiple vehicles to transmit in the same time slot thus limiting the channel access delay. When a vehicle needs to select a time slot for reuse, it selects the one that is being used by the vehicle currently located furthest away. This selection is done to minimize the mutual interference caused by simultaneous transmissions. However, once a time slot selection is made, it continues to be used for 3 to 8 frames, i.e., 3 to 8 seconds, during this time the relative distances between vehicles may change for a few hundreds meters. Consequently, a severe interference situation might occur and the reliability of communications could be seriously degraded. As indicated in the study [7], the scalability of STDMA is as limited as CSMA-based protocols.

In this paper, we propose a prediction-based STDMA protocol where future communication topologies are estimated to account for the interference situation in the entire duration of a vehicle's time slot selection. The proposed protocol utilizes vehicles current location and velocity information available in status messages, to predict the relative distances between vehicles utilizing the same resources. This prediction is performed for all the duration of the vehicles time slot selection, i.e., 3 to 8 seconds, thus considering future topology changes. The usage of the predicted information results in a minimization of future interference conditions, thus improving the system scalability for reliable V2V communications.

We consider a twelve-lane highway for the study of a worst-case scenario in terms of scalability and network topology changes. Moreover we perform extensive simulations with standard STDMA and our proposed STDMA schemes. The results show the proposed algorithm can provide higher scalability with limited added complexity to the original standard.

The remainder of the paper is organized as follows: Section 2 describes the system model; Section 3 explains our algorithm in details; Section 4 introduces the simulation scenarios and finally Section 5 presents the simulation results and analysis. In the end we give a short conclusion to our work.

II. SYSTEM MODEL

A. V2V Communication Model

In this study, we assume all vehicles are equipped with transceivers for real-time communications. The data transmissions consist of periodical broadcasting of cooperative

Fig. 1. V2V Communication Scenario.

awareness messages (CAM) to nearby vehicles. Each CAM contains status information such as position and velocity [10]. Due to the broadcast nature of transmissions, these messages are received by the all vehicles within a coverage area, as shown in Fig. 1.

This geographic coverage area has a radius defined as the distance between the transmitter and the receiver with successful packet reception at a particular signal-to-interference and noise ratio (SINR) threshold. However with the increase of traffic density, the reuse of resources causes stronger mutual interference due to simultaneous transmissions and the coverage region varies accordingly.

B. The STDMA Protocol

Self-organized TDMA is a MAC protocol where all users have guaranteed channel access, and thus offering an upper-bounded access delay. In STDMA the resources are divided into time slots and then grouped into frames. On each frame a number of equally spaced Selection Intervals (SI), comprised of a certain number of time slots, are selected by every vehicle in order to choose a nominal transmission slot (NTS). This NTS corresponds to the time slot that will be used to transmit the packet [11]. The current STDMA protocol is detailed in [9]. Fig. 2 depicts the STDMA frame structure.

Allowing simultaneous transmission is a key feature of STDMA in order to provide guaranteed channel access. Simultaneous transmission occur when a vehicle finds the SI fully occupied by other vehicles transmissions. In this case STDMA uses the available information from previously received CAMs to select the NTS that is occupied by the vehicle situated furthest away from the transmitting vehicle. However for each transmission node, there is a lifetime, which is shown in Fig. 2 as n , selected randomly between [3, 8] seconds. Meaning that for the next n seconds the node will keep transmitting in the same NTS. During this lifetime the relative distances could change up to 200-500 meters, which may cause severe interference between the vehicles transmitting in the same NTS.

Fig. 2. STDMA frame.

The predictable nature of STDMA resource allocation offers an opportunity of selecting the NTS in a more efficient way by making use of the lifetime information and conducting position estimations to decrease the amount of interference in the system.

C. PHY Layer Model

The modulation scheme used for ITS-G5A is Orthogonal Frequency Division Multiplexing (OFDM) with QPSK modulation neglecting Doppler phenomenon, specific parameters of physical layer are given in [8]. Successful communication is determined by packet reception probability based on SINR hard decision:

$$SINR = \frac{P_{ri}}{\sum_{j=1}^k P_{rj} + N_{noise}}. \quad (1)$$

Where P_{ri} is the received power from the desired transmitter i , while P_{rj} is the received power from interference transmitter j and N_{noise} is background noise which is a fixed value in the same environment. Any packet that is received with a SINR less than a given threshold is treated as lost.

D. Performance Metrics

The main performance metric here in our study is the successful packet reception probability, which offers a good insight on how the system performs in a loaded environment in terms of reliability. The failure in packet reception is mainly caused by interference. It has been mentioned that each vehicle has a transmission coverage area R m. The transmitters using the same radio resources within a certain range will cause interference for the intended receivers whenever a packet is broadcasted. This means that the SINR of the receivers may drop below the required threshold, resulting in packet reception failure. Within the V2V communication network, the successful packet reception probability is defined as the ratio between the number of successfully received packets $N_{success}$ and total number of packets transmitted, within the coverage area N_{total} :

$$P_{success} = \frac{N_{success}}{N_{total}}. \quad (2)$$

It is worth mentioning that we consider each packet transmitted to an specific receiver as a singular contribution to the total number of transmitted packets N_{total} , despite the fact that identical packets are broadcasted from a transmitter to multiple receivers [8].

III. PREDICTION-BASED STDMA PROTOCOL

In this section, we describe the proposed prediction-based STDMA protocol. Compared to the standard protocol mentioned in section II.B, the proposed version keeps the same framework but goes one step further, using not only current location information but also velocity information of the vehicles. The significant difference lies when a vehicle needs to select a time slot to reuse. With the proposed protocol, the vehicle first makes a prediction of the communication topologies for the entire lifetime of its transmission, i.e., between 3 to 8 seconds, taking into account future interference scenarios. Then it makes a selection which causes least interference within the lifetime of its transmission.

Suppose Vehicle x needs to find a NTS and there are totally N slots in its SI, allocated to Vehicle 1, Vehicle 2,..., Vehicle y separately. Note that there might be multiple vehicles in each slot. At this point of time, Vehicle x knows the allocation of the slots in its SI along with position, velocity and lifetime information of the vehicles in this SI, assuming that previous transmission were successfully received.

In order to make a selection regarding future states of the interference topology, we define a cost function for slot j considering Vehicle x :

$$C_{x_j} = \sum_{y=1}^{Y_j} \zeta_{j,y} \quad \forall j, 1 \leq j \leq N. \quad (3)$$

and

$$\zeta_{j,y} = \begin{cases} \sum_{i=1}^{\min\{L_x, L_y\}} \frac{1}{D_{j,i,y}^\alpha} & \gamma_{j,y} \geq \gamma^{th}. \\ P_{r,j,y} & \gamma_{j,y} < \gamma^{th}. \end{cases} \quad (4)$$

Where Y_j denotes the number of vehicles in j_{th} slot and $\zeta_{j,y}$ represents the cost associated with each individual vehicle depicted on (4), C_{x_j} denotes the aggregated cost of x for transmitting at j_{th} that will be used by the algorithm to select the NTS.

On (4) $D_{j,i,y}$ denotes the distance between x and y_{th} vehicle at i_{th} use of x 's NTS, α represents the propagation exponent taken from the path loss model, L_x denotes the lifetime of x 's NTS and L_y denotes the lifetime of y 's NTS. $P_{r,j,y}$ is the received power from vehicle y_{th} transmitting on slot j_{th} , $\gamma_{j,y}$ is the SINR of the received packet transmitted from y_{th} to x . γ^{th} is the SINR threshold in order to determine if the packet was successfully received or not.

When the previous packets transmitted by y_{th} vehicle are successfully received, the individual cost is selected to be proportional to the aggregated received power from vehicle y , i.e. $\frac{1}{D_{j,i,y}^\alpha}$, this way we are able to estimate the amount of interference present on slot j_{th} , during the entire transmission life time of either x or y .

In the case that previous packets transmitted by y_{th} have not been received successfully, the individual cost is set to be the received power measured on the j_{th} slot and no further estimation is performed.

Here we explain the steps on the implementation of our algorithm for vehicle x :

1. Determine the lifetime L_x , by randomly choosing an integer between [3, 8] according to uniformly distribution.
2. If x finds available time slots within its SI, it chooses one randomly among those; If not, x calculates the aggregated cost for each of the slots in its SI, i.e., $C_{x_1}, C_{x_2}, \dots, C_{x_N}$. Then choose the slot which gives the lowest cost depicted on (5).

$$s = \arg \min_{j, 1 \leq j \leq N} \{C_{x_j}\}. \quad (5)$$

In Step 2, the distances between vehicle x and other vehicles in its SI are predicted using the available position of the vehicles considering a constant velocity provided by the received CAMs. The key point in this algorithm is that, for each slot, we consider the aggregated cost among the whole lifetime of x . This means the decision will be based on the aggregated interference caused during the whole lifetime of x 's transmission, instead on just the current positions for the next transmission as in the standard.

It is important to highlight that our algorithm simply makes an intelligent use of the available information introducing only a low degree of complexity for its implementation.

IV. SIMULATION SCENARIO

Multiple simulations were conducted on MATLAB. For the scalability and reliability performance analysis, we implemented an urban highway environment with realistic parameters that are commonly found in previous literatures. This particular environment is considered to be the worst-case scenario for V2V communications since it presents rapid topology changes with high vehicular density [8]. The highway model consists of 6 lanes in each direction, vehicle velocities are taken from a Gaussian distribution with standard deviation of 1m/s and with mean velocities ranging from 70 km/h to 140 km/h. The highway is 6 km long and to avoid edge effects, data is collected only from the 3 km middle section of the highway. Vehicles broadcast periodically CAMs where the initial transmissions are selected in a random and independent way. The report rate is selected from ETSI recommendation where the messages are sent every 100 ms with a packet size of 300 bytes and a data rate of 6 Mbit/s. The channel propagation model is a two-slope model for distance dependent path loss component, as shown in (6), combined with Nakagami-m model representing fading effects [8].

$$P_{r,dB}(d) = \begin{cases} P_{r,dB}(d_0 - 10\gamma_1 \log_{10}(\frac{d}{d_0})), & d_0 \leq d \leq d_c. \\ P_{r,dB}(d_c - 10\gamma_2 \log_{10}(\frac{d}{d_c})), & d \geq d_c. \end{cases} \quad (6)$$

In (6), $P_{r,dB}(d_0)$ is the reference power on free space propagation conditions at $d_0 = 10$ m and the critical distance

$d_c = 80$ m. The propagation exponents are $\gamma_1 = 1.9$ and $\gamma_2 = 3.8$. We set all vehicles an output power of 25 dBm and the noise power is -99 dBm. The SINR threshold for correct packet reception is 8 dB as in [8].

In our simulation environment, the implementation of the improved algorithm is based under two main assumptions. The first is the realistic case where vehicles only have information about their surrounding vehicles from their last successfully received CAM. This means that when no packets are received the algorithm cannot do any prediction about that particular vehicle. The second assumption is an ideal case which assumes that the algorithm still has access to the status message information even if the CAM was not successfully received. This case is taken as an upper bound of the improved protocol's performance in order to give more concrete comparisons. It is worth mentioning that these assumptions do not make any alterations on the evaluation of the performance metrics.

V. NUMERICAL ANALYSIS AND RESULTS

In order to evaluate the performance of the proposed algorithm to improve the STDMA protocol in terms of traffic scalability, we conducted simulations for different traffic densities going from 3.1 to 20.8 average vehicles per 100 m. Each simulation was conducted for more than 100,000 arrivals of CAMs to be broadcasted. The following results show the system performance for standard and improved STDMA protocols, the later under ideal and realistic assumptions.

Fig. 3 depicts the packet reception success probability with different traffic densities for a coverage distance of 150 m. This coverage was selected to be double of the safety distance stipulated in [12] so the results could be related to a practical application metric in a conservative way. Fig. 3 shows that for both ideal and realistic assumptions the performance of the improved STDMA protocol is superior to the standard. For a packet reception success probability of 95%, in the ideal case, the improved algorithm provides an increase of 300% in supported traffic density. Under realistic assumptions still there is a significant the improvement of 87.5% for the same reliability requirement. Furthermore, with both assumptions the advantage of the improved algorithm increases when the traffic density grows, also the difference between the ideal and realistic cases becomes larger. This occurs because the improved algorithm uses current information to predict future interference conditions on the system, therefore when a packet is lost there is less information available and the prediction is less accurate, so the benefit of the algorithm is diminished.

To illustrate the reliability of communications in terms of coverage, Fig. 4 and Fig. 5 depict the packet reception success probability for different coverage distances. Additionally two traffic densities were chosen in order to stress the impact of scalability. Fig. 4 presents a low traffic density of 3.8 average vehicles per 100 m. On the ideal case the improved algorithm provides an increase in packet reception probability of up to 7% for a coverage distance of 200 m, whereas in the realistic case the enhancements is up to 5% for the same coverage. Moreover, for a target packet reception probability

Fig. 3. Packet reception success probability for a coverage of 150 m for several traffic densities.

Fig. 4. Packet reception success probability vs. distance for a low density of 3.8 average vehicles per 100 m.

of 95%, the improved algorithm offers an increase in coverage distance of 60 m and 50 m for the ideal and realistic assumptions respectively. These results show that in low density the enhancement offered by the improved protocol is limited in terms of packet reception probability, however this small improvement translates on an increase in coverage of 50% and 40% for the ideal and realistic case respectively, which becomes a more significant enhancement as this would give the vehicles further information on their surroundings.

For high density conditions Fig. 5 shows the packet reception success probability with an average traffic density of 20.8 vehicles per 100 m under different coverage distances. For the ideal case, the improvement offered by the proposed algorithm reaches up to 38% for a coverage distance of 200 m and the realistic case achieves up to 25% enhancement for the same coverage. Furthermore for a target packet reception probability of 95%, the improved algorithm reaches a coverage of 100 m approximately for the ideal case. Whereas on realistic assumptions, the enhanced STDMA protocol achieves a coverage of 50 m approximately for the same reliability requirement. From this results we can observe that the proposed algorithm

Fig. 5. Packet reception success probability vs. distance for a high density of 20.8 average vehicles per 100 m.

provides a significant improvement in performance when the traffic density is high, furthermore the algorithm is able to increase the coverage considerably compared to the standard where the range of successful transmissions is almost none existing, i.e., lower than 10 m, for 95 % packet reception probability.

Despite these advantages the improved algorithm still presents limitations when the traffic density is high and the potential gain is reduced due to the lost of packets. Therefore, the implementation of cooperative schemes where the vehicles relay information about their neighbors could make up for the lost packets, offering more scalability to the system. This we leave as a recommendation for further studies.

VI. CONCLUSION

In this paper we investigate the scalability of MAC protocol STDMA for reliable V2V communications for traffic safety applications. We introduce an improved version of the MAC protocol STDMA that minimizes the mutual interference by utilizing the status information messages in an intelligent manner and predicting future interference conditions. We have performed extensive simulations for the standard and enhanced versions of the STDMA protocol under a realistic highway scenario with several traffic densities. The results show that for a strict reliability requirement, the enhanced version of STDMA protocol provides an increase of almost double on system scalability. Furthermore a significant improvement has been accomplished on system coverage. Therefore in our study we have being able to provide an enhanced STDMA MAC protocol for V2V communications that achieves higher scalability with limited added complexity to the original standard.

It is worth mentioning that by comparing the performance of the enhanced STDMA protocol under ideal and realistic assumptions, we have found that there is room for further improvement. Therefore the implementation of cooperative solutions, where the vehicles relay information about their neighbors, combined with the enhanced version of STDMA protocol is an interesting topic for future research.

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