Study on Merging Control Supported by IEEE 802.11p Systems for Highway Environments

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Abstract—**Cooperative Adaptive Cruise Control (CACC) systems are intended to make driving safer and more efficient by utilizing information exchange between vehicles (V2V) and/or between vehicles and infrastructures (V2I). An important application of CACC is safe vehicle merging when vehicles join a main road, achieved by compiling information on the movement of individual main road vehicles. To support such road safety applications, the IEEE standardized the 802.11p amendment dedicated to V2V and V2I communications. This paper seek answers to the questions as to whether the IEEE 802.11p can support merging control and how the communications performance is translated into the CACC performance. We build an analytical model of the IEEE 802.11p medium access control (MAC) for transmissions of the ETSI-standardized Cooperative Awareness Messages (CAM) and Decentralized Environmental Notification Messages (DENM) to support merging control. We also developed a highway merging decision algorithm. Using computer simulations, packet delivery ratio (PDR), and packet inter-reception (PIR) time of IEEE 802.11p-based V2V and V2I communications and their impact on the CACC performance are investigated. Our study discloses several useful insights including that PIR and throughput provide a good indication of the CACC performance, while improving PDR does not necessarily enhance the CACC performance. Moreover, thanks to its ability to reliably provide information at constant time intervals, the V2I structure preferred over V2V as a support for CACC.**

I. Introduction

To support V2V and V2I communications for road safety and efficiency applications, the IEEE and ETSI specified the 802.11p amendment [1]. Many efforts have been made to study the IEEE 802.11p, especially radio propagation [2], MAC [3], [4], and beaconing [2] characteristics. Previous studies show that the best performance is obtained at 6 Mbps for road safety applications. The achievable transmission range is much larger in the V2I structure than in the V2V structure [5], [2]. The studies on MAC showed that the performance of the IEEE 802.11p systems can be very poor in dense networks. The previous research efforts however do not answer the question as to whether the communications technology can support actual road safety.

CACC systems greatly outperform ACC systems (which rely only on measurements from local sensors) thanks to the V2X information exchange [6]. An important application of CACC is merging control, in which information on positions and motion of main road vehicles is necessary for vehicles which intend to merge into the main road (from a minor road). The authors of [7] classified the merging maneuvers into "free", "forced", and "cooperative" and studied their impact on the traffic flow, and showed that "cooperative" merging, followed by "forced" merging, provides the greatest impact (shock) on the traffic flow. In contrast, free merging does not make any impact, and thus it should be taken whenever possible. While some studies on merging control have been carried out in the field of robotics, most of them target cooperative merging [7], especially merging maneuvers into a platoon of vehicles [6], [8]. Most importantly, the majority of the studies did not consider the communications aspects.

This paper aims to fill the gap between wireless communications and CACC. The objective of the study is to answer the questions "can the IEEE 802.11p serve CACC systems, especially for merging control?". Because merging control requires both the periodical and the event-triggered information exchange, we consider the use of the ETSI-standardized message sets, CAM and DENM [9]. We model the IEEE 802.11p MAC using a two-dimensional Markov chain for transmissions of CAM and DENM. Furthermore, in order to study the impact of the communications on the performance of CACC systems, we build a simple free-merging algorithm, which gives a decision on acceleration of merging vehicles based on the knowledge of the state of the main road. Finally, based on a distributed agent-based simulator, NetLogo [10], we investigate the performances of the IEEE 802.11p including PDR, throughput, and PIR time, and their impact on merging control for both the V2V and V2I structures. The study discloses several useful insights:

- the PDR performance does not give a good indication of the CACC performance; especially improving PDR simply by e.g., reducing message generation interval may significantly degrade the control performance;
- the PIR time and throughput can be a convincing indication of the CACC performance;
- the V2I communications structure is preferred over the V2V structure for CACC especially due to its ability to reliably provide information at constant time intervals.

The paper proceeds as follows. Sections II and III detail the IEEE 802.11p communications model and the merging control algorithm, respectively. We evaluate the performance of CACC together with that of the IEEE 802.11p communications for both V2V and V2I in Section IV. Finally, Section V concludes the paper.

II. Modeling the IEEE 802.11p MAC for Highway Merging Support

The ETSI-defined message sets, CAM and DENM [9], can be used for merging control. Specifically, individual vehicles periodically broadcast CAM packets to inform the vehicles and the infrastructure in their vicinity about their motion state. DENM packets, on the other hand, can be transmitted by main road vehicles and/or infrastructures to provide merging vehicles with necessary information, particularly the position, speed, and direction of the individual main road vehicles.

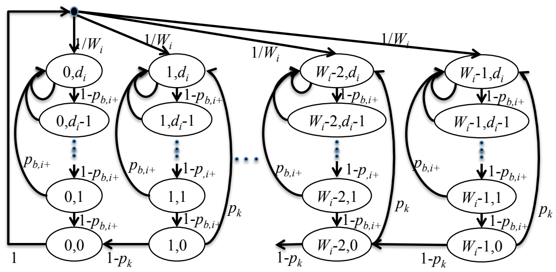

Fig. 1. 2D Markov chain.

Obviously, a DENM packet can be created based on the collected information from CAM packets. We assume that both DENM and CAM are broadcast type of packets.

Adopting EDCA of the IEEE 802.11e, the IEEE 802.11p MAC can provide differentiated channel access services to different ACs, which have different settings of contention window (CW) and arbitrary inter-frame space (AIFS). CACC application requires only two ACs: say AC_0 for CAM and AC_1 for DENM. Because broadcast packets are not retransmitted, the service differentiation is achieved based on different settings only to the minimum CW ($CW_{min}[AC_i]$) and $AIFS[AC_i]$. When a node has got a packet to transmit but the channel is sensed busy or the node just finished a transmission of a packet, it has to backoff (i.e., defer its transmission) for a random period of time, which is uniformly drawn from [0, $CW_{min}[AC_i] \times \sigma$[, where σ is the slot time. During the backoff countdown, if the channel is sensed busy, the backoff window is "frozen" until the channel gets "idle". The channel is considered to be idle if it is sensed free for $AIFS[AC_i]$. Therefore, it is obvious that for two ACs, AC_i and AC_j, if $AIFS[AC_i]<AIFS[AC_j]$ and $CW_{min}[AC_i]<CW_{min}[AC_j]$, AC_i has a greater chance to access to the channel before AC_j does.

We model the IEEE 802.11p MAC using a 2D Markov chain considering transmissions of DENM and CAM. We assume that DENM is associated with at a higher-prioritized AC than that for CAM (because DENM is event-triggered). Figure 1 illustrates the Markov chain for saturated conditions (the model will later be extended to include non-saturated conditions). The Markov chain has ($b(t)$=j,$s(t)$=k) states, where $b(t)$ and $s(t)$ are the backoff and AIFS countdown states at time t. W_i is $CW_{min}[AC_i]$ and d_i is the difference between $AIFS$ values for AC_i and AC_{i+1} in slots. The backoff countdown occurs with the probability of 1-p_k and the AIFS countdown occurs with the probability of 1-$p_{b,i+}$. p_k is the channel blocking probability i.e., the probability of the channel is sensed busy during the backoff countdown. $p_{b,i+}$ is the probability of the channel being busy during the AIFS count down. Because channel access activities at any AC at any node, excluding AC_i at the target node, contribute to p_k and activities at higher-prioritized ACs (than AC_i) contribute to $p_{b,i+}$, we have:

$$p_k = 1-(1-\tau_i)^{N_i-1}\prod_{j=0,j\neq i}^{M-1}(1-\tau_j)^{N_j}\,,\; p_{b,i+} = 1-\prod_{j=i+1}^{M-1}(1-\tau_j)^{N_j}. \quad (1)$$

Here M is the number of ACs (2 in our case). N_i is the number of the competing nodes in the sensing range and τ_i is the channel access probability for AC_i. Solving the Markov chain, i.e., $\sum_{j=0,k=0}^{W_i-1,d_i}(j,k)$=1, the channel access probability of AC_i for saturated conditions is found as

$$\begin{aligned}\tau_{si} &= b_i(0,0) = \Bigg[1 + \frac{1-(1-p_{b,i+})^{d_i}}{W_i p_{b,i+}(1-p_{b,i+})^{d_i}} + \frac{W_i-1}{2(1-p_k)} \\ &\quad + \frac{(1-(1-p_{b,i+})^{d_i})(2+3(W_i-2)p_k+(W_i-2)^2p_k^2)}{2W_i(1-p_k)P_{b,i+}(1-p_{b,i+})^{d_i}}\Bigg]^{-1}.\end{aligned} \quad (2)$$

The correctness of the model can be verified by comparing it to the well known Bianchi model [11]. The Bianchi model is built for DCF, which has a single AC, and the channel blocking probability, p_k, is not taken into account. Therefore, by setting p_k and $p_{b,i+}$ to 0, (2) deliver $\tau = 2/(W{+}1)$ coinciding with [11].

The channel access probability for non-saturated conditions can be formulated as $\tau_i = q_i \times \tau_{si}$, where q_i is the probability of having a pending packet for AC_i at the node. Assuming messages are generated following the Poisson process. the probability of a pending packet can be expressed as $q_i = 1-\exp^{-\lambda p_b T - \sigma\lambda(1-p_b)}$. Here λ is the message generation rate, T is the average time required for a transmission of a packet, and p_b is the probability of channel being busy.

The transmission of a packet is successful if the transmitted packet does not collide (i.e., no simultaneous transmission) or there is a simultaneous transmission(s), but the packet is "captured" thanks to a sufficiently large SINR. Letting P_{cf} and P_{cp} represent the former and the later probabilities, $P_{cf}[AC_i]$ and $P_{cp}[AC_i]$ are formulated considering two ACs:

$$P_s[AC_i] = (1-\tau_j)^{N_j}(1-\tau_i)^{N_i-1}$$

$$P_{cp}[AC_i] = P_0^{N_i-1}\sum_{m=1}^{N_j} P_m^{N_j}P(\gamma_m) + \sum_{k=1}^{N_i-1} P_k^{N_i-1}\sum_{m=0}^{N_j} P_m^{N_j}P(\gamma_{m+k})$$

In the previous equation, $P_k^{N_i}$ is the probability of k simultaneous transmissions from N_i competing nodes at AC_i. $P(\gamma_k)$ is the probability of SINR being larger than the capture threshold, T_{cp}, when k signals interfere with the desired signal. The probabilities P_k^N and $P(\gamma_k)$ are calculated as follows:

$$P_k^{N_i} = \binom{N_i}{k}\tau_i^k(1-\tau_i)^{N_i-k},\; P(\gamma_k) = \begin{cases} 1, & \text{if } \frac{Pwr(des)}{\sum_{l=1}^{k} Pwr(l)} > T_{cp} \\ 0, & \text{otherwise} \end{cases}$$

where $Pwr(des)$ and $Pwr(l)$ are the received powers of the desired signal and the l^{th} interfering signal, respectively. Finally, the probability of successful reception of a given packet at AC_i is calculated as $P_{cf}[AC_i]$+$P_{cp}[AC_i]$.

III. Highway Merging Control

Main road vehicles can drive up to a certain speed (the maximum speed allowed for the road) but they control their velocity such that collisions with the vehicles in front are avoided. No centralized intelligent system exists to coordinate merging maneuvers, and hence, merging vehicles take local decisions based on received information (contained in DENM packets). Targeting the above mentioned traffic situations, we develop a simple decision algorithm for safe merging. Figure 2 illustrates the algorithm. The objective of the algorithm is 1) to find an inter-vehicle gap on the main road into which the merging vehicle should enter and 2) to calculate the target acceleration/deceleration for safe merging. Let "leader" and "follower" represent the vehicles which are expected to drive in front and behind of the merging vehicle at the merging time. Safe merging is achieved if the velocity of the merging vehicle

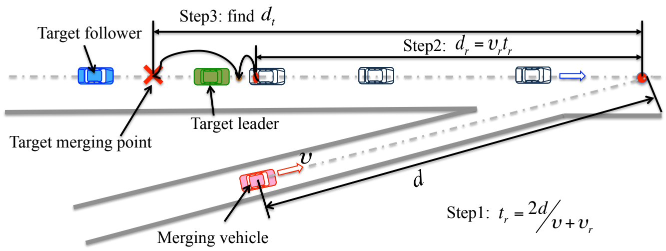

Fig. 2. Merging control.

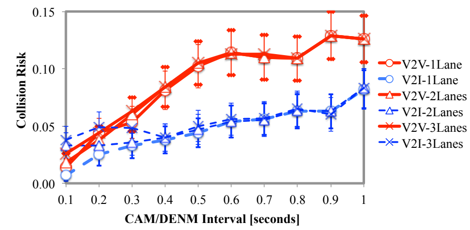

Fig. 3. Collision Risk for different CAM/DENM generation intervals.

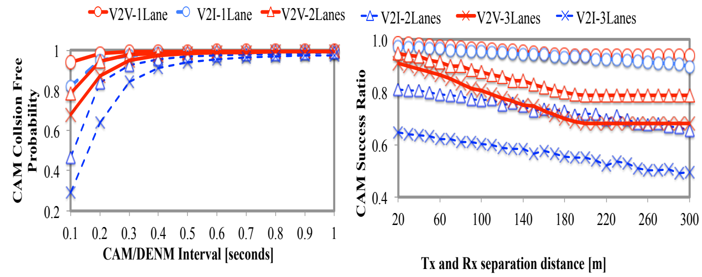

Fig. 4. CAM collision free probability and success probability.

is equal to that of its leader and the inter-vehicle gaps between the merging vehicle and the leader and the follower are larger than a certain distance (i.e., safety distance). Let v and d denote the velocity of the merging vehicle and its distance to the junction. We assume that d can be known by using e.g., a map-matching technique. Let v_r denote the target velocity for safe merging. If it is the first time a merging decision is made, v_r is initialized to the average velocity of the main-road vehicles, otherwise, it is the velocity of the leader.

The algorithm first calculates a reference time, t_r, which is required to adjust the velocity of the merging vehicle to v_r during a run of distance d: $t_r = 2d/(v + v_r)$. Then a reference distance which is run by the main road vehicle during this time is calculated: $d_r = v_r \times t_r$. The distance d_r from the junction on the main road (see Figure 2) indicates the relative point at which the merging vehicle will enter if it controls its mobility simply by taking account of the velocity requirement. However, because the vehicle has to enter into a gap where the inter-vehicle distance is sufficiently large, the next step is to find such a gap starting from the point (at distance d_r from the junction). More specifically, it searches for an inter-vehicle gap, which satisfies the following condition: $l_{gap} > 2d_s + l$, where d_s and l are the inter-vehicle safety distance and the length of the merging vehicle, respectively. While it is possible to search for the largest gap, the existing algorithm stops when it finds an inter-vehicle gap, which first satisfies the condition. Finally, by letting d_t be the distance from the junction to the center point of the target inter-vehicle gap the target acceleration value is calculated as: $a_t = v_r(v_r - v)/d_t$ Considering the mechanical limitations of the vehicle, a_t must not exceed the maximum possible acceleration and deceleration values (a_{max}, d_{max}).

IV. Performance Evaluation

Using NetLogo [10], we evaluate the performance of the IEEE 802.11p and its impact on that of merging control. Road structure is the same as that illustrated in Figure 2. The vehicle density in a lane of the main road follows the Greenshield model: $k = (v_f - v)k_j/v_f$ where v_f is the maximum allowed speed, k_j is the jam density, and v is the average speed of the vehicles. v_f, v, and k_j are set to 150 km/h, 120 km/h, and 1/6 m^{-1}, respectively. The maximum acceleration, deceleration, and acceleration jerk are 5 m/s^2, 10 m/s^2 and 2 m/s^3, respectively. On the minor road, a vehicle is set to drive towards the main road and controls its mobility based on the merging control algorithm. The initial position (i.e., the distance from the junction) and the initial speed of the merging vehicle are 300 m and 60 km/h, respectively. V2I and V2V communications are considered targeting road junctions, which are equipped or not with RSUs. The IEEE 802.11p is used with the default parameters for control channels (CCH), e.g., 10 MHz bandwidth and 6 Mbps transmission rate. According to the experimental results [5], [2], it is realistic to set the V2I and V2V transmission ranges to 1 km and 300 m, respectively. The corresponding interference range is set to the double of the transmission range. AC_{BK} and AC_{BE} are used for transmissions of CAM and DENM (see [1]). CAM has a length of 200 bytes; it is periodically broadcasted by the individual vehicles. DENM has a length of 1000 bytes; it is transmitted by the RSU for the V2I case, and by vehicles for the V2V case. It should be noted that for the V2V case, we purposely restrict DENM packets be transmitted by only the vehicles, which are in the junction area (with a length of 6 m) and hence have LOS paths with the merging vehicle.

Thousand runs are averaged for each scenario. The delivery performance of a transmitted packet is calculated following the model built in Section II at a given receiving node. We noticed that if more than 2 signals interfere with the target signal, the capture probability is nearly 0. Therefore, the capture probability is calculated considering up to 2 interfering signals. The capture threshold, T_{cp} is set to 10 dB. Focusing on the target application, CAM delivery performances are measured at the vehicles (RSU), which create DENM messages in the V2V (V2I) case. DENM delivery performances are measured at the merging vehicle. In order to evaluate the performance of the merging maneuver, we define a metric, **CollisionRisk**. Let d_l (d_f) is the distance between the merging vehicle and the leader (the follower) at the merging time. CollisionRisk is 1 if d_l or d_f is smaller than or equal to zero (i.e., already collided) or if the distance required to avoid collisions between the merging vehicle and its lead vehicle (the follower) is greater than d_l (d_f). Otherwise CollisionRisk is 0.

Figure 3 reports CollisionRisk together with the 95% confidence interval for different settings to the CAM/DENM generation interval. As can be seen in the figure, CollisionRisk is generally lower for V2I than V2V. The larger the CAM/DENM interval, the greater the collision risk is. The

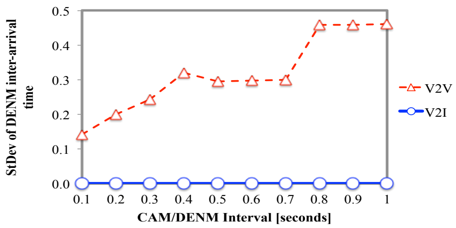

Fig. 5. Standard deviation of DENM inter-arrival time (the number of lanes is fixed to 1).

difference in the number of lanes do not deliver a significant difference in the control performance.

The corresponding communications performances are reported in Figures 4–5. Figure 4 contains comparisons of the CAM PDR performances, more precisely the average collision-free probability and the average probability of successful reception for CAM packets. Both in the V2V and V2I cases, larger message generation interval results in better PDR performance. Moreover, PDR is higher for smaller number of lanes. The reasons behind these results are obvious: a decrease of the number of contending nodes (N_i) and/or the channel access probability (τ) results in an increase of the probability of collision-free transmission (see Equation (3)). N_i is smaller for smaller number of lanes; τ is smaller for smaller message generation rate (larger message generation interval). An interesting observation, which can be made in Figure 4 is that the V2V case provides improved CAM delivery performances than those of V2I. Conceivably, this is because V2V has a much smaller interference range than that of V2I, and hence has fewer nodes contending for channel access. The right-side figure shows the message delivery performance w.r.t the separation distance between the transmitter and the receiver, when the CAM/DENM interval is 0.1 s. The result implies that the closer the transmitter and the receiver, the higher the message delivery performance is, obviously thanks to the capture effect. Finally, it should be mentioned that PDR for DENM packets was close to 1 for all the scenarios, proving that a higher-prioritized AC significantly outperforms than that with a lower priority. The perfect PDR performance for DENM is also due to the fact that there were very few nodes (vehicles/RSU), which transmit DENM packets, resulting in low contention within that AC.

Obviously, PDR does not explain the CACC performance specifically, 1) when the CAM/DENM interval is large, PDR is 1 but CollisionRisk is high and 2) V2V performs better than V2I in term of PDR but worse in terms of CollisionRisk. An important insight from 1) is that improving PDR simply by e.g., reducing message generation rate is dangerous because it can result in a very poor CACC performance due to lack of information required for the control. Thus, instead of PDR, the throughput (data rate) performance seems to provide better explanation (the throughput can easily be drawn from (Figure 3). To explain why CollisionRisk is lower for V2I than V2V, Figure 5 shows a comparison of the standard deviations of DENM packet inter-reception (PIR) time for the V2V and V2I cases when the number of lanes is 1. It can be seen in the figure that the merging vehicle receives DENM at a constant time interval in the V2I case. On the other hand, in the V2V case, the PIR time varies largely and especially when the message generation interval is large. Obviously, this is because in the V2V case, DENM packets cannot be transmitted if there is no vehicle in the junction area. Arguably, thanks to its fairly constant PIR time, V2I seems to be preferred for CACC. However, as Figure 3 shows, V2I showed higher CollisionRisk compared to that of V2V, when the message generation interval is 0.1 s and the number of lanes is 2 and 3. Conceivably, this is due to its significantly low PDR achieved for these scenarios.

V. Conclusion

We studied the impact of the V2V and V2I communications technology, the IEEE 802.11p, on the performance of CACC for merging control. We developed a MAC model and a simple merging control algorithm considering information exchange based on CAM and DENM. Our simulation evaluations delivered several useful insights, including 1) the PDR performance does not give a good indication of the CACC performance; 2) the PIR time and throughput can be a convincing indication of the CACC performance; 3) the V2I structure is preferred over the V2V structure due to its ability to reliably provide information at constant time intervals.

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