Probabilistic Communication in Car Platoons

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***Abstract*—Autonomously driving vehicles appeared on the canvas of science in the middle of the twentieth century and have since then been the subject of many generations of researchers. One application of autonomous driving is platooning, where cars autonomously follow each other in very close distance. This application is motivated by fuel savings, labor decrease, increase in road capacity and higher safety. To achieve platooning capability, vehicles require sensors, intelligent processing systems, and communication devices. This paper provides a study in which cars communicate to measure the system performance in terms of successful message transmission probability, also referred to as the integrity of wireless communication. The communication is one crucial part of the chain of the safety functionality of an orchestrated braking maneuver in a platoon, located between the car initiating the braking and all other members of the platoon. The numerical results target the influence of parameters like transmission power, channel gain, interference noise, and total number of involved vehicles.**

***Index Terms*—Vehicle-to-Vehicle, Platoon Model, Message Loss Probability, Orchestrated Braking Maneuver, Integrity of Wireless Communication.**

I. Introduction

Autonomous driving combines mechanical driving features with software. This brings car manufacturers and software developers not only together, but furthermore into a competitive relationship. Car manufacturers on a global scale like Daimler, Toyota, and Ford face software developers like Apple and Google as well as new players like Tesla in a race to provide for autonomous driving. This paper reflects on this process from a theoretical point of view by providing a method for computing the integrity of wireless communication.

One of the challenges is that different domains have different terminologies. The *integrity of wireless communication* in a scenario for providing a safety critical functionality (i.e. orchestrated braking) can also be addressed by dependability, robustness, criticality, risk or reliability, to name a few. This paper addresss the probability for a successful transmission of a safety critical message among cars in a Vehicular Ad hoc Network (VANET). The orchestrated and cooperative braking hinges on the timely propagation of relevant messages among vehicles.

The remainder of this introduction presents selected related work, reflecting upon recent advanced in inter-vehicular communication (IVC) before discussing the contributions and the structure of the paper. Autonomous driving comprises a set of functions like Green-Light-Optimized-Speed-Advisory (GLOSA) [1], [2], autonomous parking [3], [4], and platooning [5], [6]. Some surveys discuss the variety of functions [7], [8], while other articles address their performance [9]–[11].

One function of autonomous driving, to which the performance of communication among vehicles is important, is platooning. In platooning, a set of vehicles travels in very close distance (colloquially *tailgating*). Communication allows for minimizing the safety distance between vehicles if the leading vehicle can propagate messages to initiate an automatic emergency braking maneuver. Platooning comprises the phases of i) join/form/merge platoon, ii) travel, and iii) split/leave platoon. This paper selects platooning to discuss the performance of Vehicle-to-Vehicle (V2V) communication. The scenario presented considers heavy-duty-vehicles (e.g. trucks) driving at close distance for saving fuel [9], [12]. The amount of fuel saved is proportionate to the amount the safety distance is decreased [10]. Substituting the driver reaction time with an automated braking maneuver response that is communicated wireless allows for shorter inter-vehicular gaps (i.e. safety distance) while maintaining equal safety properties.

One crucial step in establishing autonomous driving functions is the communication, i) among cars and ii) with infrastructure like (Global Positioning System (GPS)). Several protocols for this cause have been developed, like IEEE 802.11p, DSRC, IEEE1609, ASTM and E2213-03 [13]. In general, communication here falls into one of two domains, either being a periodic *cooperative awareness message* (CAM) or an event driven *decentralized environmental notification message* (DENM) [14]. Selected publications discuss for instance:

- The efficiency of message dissemination based on relay selection for minimizing the error probability [15],
- a framework for the reliable exchange of messages within platoons, based on a novel dissemination policy for enhancing the reliability for a given reduced number of variable time-slots [16],
- the distinction between emergency related and other messages with a focus on safety [17],
- a smart self-driving system based on the *smarty* platooning control system for senior drivers [18], [19],
- a control strategy including path recognition focusing on urban scenarios [7],
- a probabilistic performance analysis [20] of IEEE 802.11p Distributed Coordination Function (DCF) for inter-platoon communications in a multiple platooning scenarios.

One challenge in establishing a reliable communication infrastructure among cars is the relay of messages. Popular approaches for finding optimal paths (wrt. performance and reliability) are *unicast relay sequencing*, *broadcast relay sequencing*, and their combination [21], focusing on reducing delays and fault probabilities correlated with reduced complexity. Addressing shared communication channels in *intelligent transport systems* (ITS), an analytical communication model allows for analyzing the communication reliability among platoon members [22]. Another perception of communication reliability is *network awareness* [23]. Unified models are exploited here to show the performance of a distributed controller synthesis method, tested under both uniform and non-uniform time delays. Despite safety relying on communication reliability, decreasing the safety distance based on reliable communication allows for saving on fuel by tailgating. The monetary benefits of ITS in this connection have for instance been discussed in the SARTRE project by the European Union [10]. A more theoretical focus [24] discusses the increase in safety achieved by improving the scheduling algorithm controlling the retransmission slots for failed packets. Another performance measure contrasting the importance of communication reliability is channel access delay correlated with consecutive packet drops [25],

The performance of the IEEE 802.11p MAC has been investigated in [26], pointing out its limitations in terms of packet collision probability, throughput and delayMarkov chain models can also be exploited [27] for performance and reliability evaluation of 802.11p safety relevant broadcast data in VANETs in highway scenarios. Contrary to analytical methods, the NS-2 simulator with the M/G/1/K queuing model also allows for analyzing the capabilities and limitations of the 802.11p compliant broadcast. Adjusting system parameters such as frequency, bandwidth or propagation delay allow to influence the reliability of the 802.11p broadcast. Since both CAM and DENM messages exploit a shared common communication channel, authors in [28] propose adding a dedicated service channel to comply with strict timing requirements. Little surprising, the proposed approach performs better with an added channel.

VANET applications employ either beacon or event-driven messages. Beacon messages are sent by each vehicle, containing its location and its status. Event-driven warning messages are transmitted for instance when critical situation occur. A comparative analysis of three candidate algorithms [29] discusses each algorithms benefits and drawbacks in terms of transmission rate, transmission power, and joint power with rate control with a focus on congestion situations. Drawbacks of the IEEE 802.11p protocol with MAC have been pointed out in [30], such as channel access delay and collisions on the wireless channel. To cope with these issues, the authors propose a self-organizing time division multiple access. Its simulation on highway scenario shows promising results. A brief survey of related to platooning [31] points out some challenges to be investigated, such as ability of plain IEEE 802.11p to support platooning and communication requirements for safety.

This present paper considers a platoon comprising N vehicles, each vehicle being equipped with an antenna for sending and receiving messages based on wireless communication with an exponential distribution. The communication applies Time-Division Multiple Access (TDMA). To provide for traffic safety, it is crucial that all vehicles receive communication packets *in time* (i.e., wrt. a specific timeout threshold). For measuring the safety of a platoon, the probability of a successful timely message reception is derived and computed. This computation includes the parameters of i) transmission power, ii) channel gain, iii) interference noise, and iv) the number of vehicles involved.

The paper is organized as follows: Section II presents the system model and discusses assumptions about the channel. Section III focuses on the theoretical background, and that the probability for successful transmission is based on the closed form. Section IV provides numerical examples evaluating the performance of the proposed model. Section V concludes this work.

II. SYSTEM MODEL

Consider a platoon model as shown in Fig. 1, in which N vehicles $v_1, v_2, \ldots, v_N$ communicate with each other via bidirectional wireless channels. The channel gain between vehicle v_i and v_j is denoted by h_{ij}, where $i \neq j$ and $i, j \in \{1, \ldots, N\}$. Accordingly, the channel mean gain of h_{ij} is expressed as $\Omega_{ij} = \mathbf{E}[h_{ij}]$, where $\mathbf{E}[\cdot]$ is the expected or estimated value.

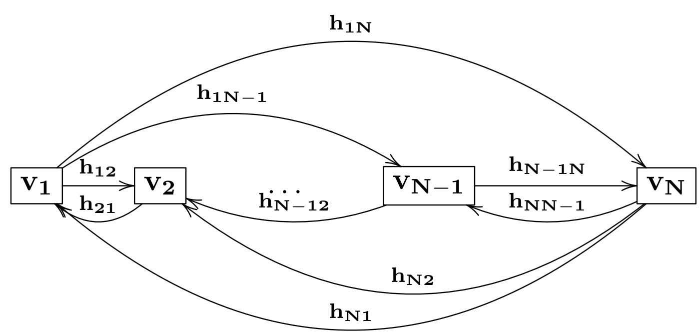

Fig. 1. A Platooning Model

The communication employs *time-division multiplex access* (TDMA), meaning that each platoon-vehicle is assigned a time slot for broadcasting messages. To guarantee safety, all vehicles have to timely receive the messages from the other platoon members to adjust their distances. Accordingly, the packet transmission time from v_j to v_i, $T_{j\to i}$, can be formulated as

$$T_{j\to i} = \frac{L}{B\log_2(1+\gamma_{ji})}, \forall j \neq i \qquad (1)$$

(cf. [32]), where L is the size of packet and B being the system bandwidth.

The parameter γ_{ji} denotes the *signal-to-interference-plus-noise ratio (SINR)* with which v_i receives the signal from the v_j. It is defined as

$$\gamma_{ji} = \frac{P_j h_{ji}}{I_i + N_0}, \forall j \neq i, \tag{2}$$

in which P_j, I_i, and N_0 are the transmit power of v_j, random interference at the v_i, and the background noise power. Generally $\gamma_{ji} \neq \gamma_{ij}$ as the transmission power of vehicles v_i and v_j can be different.

Notably, messages are propagated among all vehicles within a platoon. The maximal packet transmission time for propagating a message among all vehicles is specified as:

$$T_i = \max_{\substack{j \in \{1 \ldots N\} \\ j \neq i}} \{T_{j \to i}\}, \ \forall j \neq i, \tag{3}$$

In emergency situations, all members of the platoon have to receive all emergency messages *in time* to guarantee safe control of driving maneuvers like orchestrated braking. This implies that the maximal packet transmission time among all vehicles should not exceed the maximal admissible timeout: The event U formulates successful system communication implying safety:

$$\begin{aligned} U &= \max_{i \in \{1,\ldots,N\}} \{T_i\} < t_{out} \\ &= \max_{i \in \{1,\ldots,N\}} \left\{ \max_{\substack{j \in \{1 \ldots N\} \\ j \neq i}} \{T_{j \to i}\} \right\} < t_{out}. \end{aligned} \tag{4}$$

III. PERFORMANCE ANALYSIS

This section presents a method for computing the probability for safe communication within a platoon. In particular, the event U (cf. Eq. (4)) can be rewritten as

$$U = \frac{L}{B \log_2(1+\gamma)} < t_{out}, \tag{5}$$

with γ being defined as

$$\gamma = \min_{i \in \{1 \ldots N\}} \left\{ \min_{\substack{j \in \{1 \ldots N\} \\ j \neq i}} \left\{ \frac{P_j h_{ji}}{I_i + N_0} \right\} \right\} \tag{6}$$

Because U in Eq. (4) depends on the random variables shown in Eq. (6) (such as h_{ji} and I_i), the communication probability implying safety can be formulated as

$$O_s = \Pr\left\{ \frac{L}{B \log_2(1+\gamma)} < t_{out} \right\} = 1 - \Pr\{\gamma \leq \gamma_{th}\}, \tag{7}$$

where $\gamma_{th} = 2^{\frac{L}{B t_{out}}} - 1$. Substituting γ from Eq. (6) in Eq. (7) leads to

$$\begin{aligned} O_s &= 1 - \Pr\left\{ \min_{i \in \{1 \ldots N\}} \left\{ \min_{\substack{j \in \{1 \ldots N\} \\ j \neq i}} \left\{ \frac{P_j h_{ji}}{I_i + N_0} \right\} \right\} \leq \gamma_{th} \right\} \\ &= \Pr\left\{ \min_{i \in \{1 \ldots N\}} \left\{ \min_{\substack{j \in \{1 \ldots N\} \\ j \neq i}} \left\{ \frac{P_j h_{ji}}{I_i + N_0} \right\} \right\} \geq \gamma_{th} \right\} \\ &= \prod_{i=1}^{N} \Pr\left\{ \min_{\substack{j \in \{1 \ldots N\} \\ j \neq i}} \left\{ \frac{P_j h_{ji}}{I_i + N_0} \right\} \geq \gamma_{th} \right\} = \prod_{i=1}^{N} K_i, \end{aligned} \tag{8}$$

where

$$K_i = \Pr\left\{ \min_{\substack{j \in \{1 \ldots N\} \\ j \neq i}} \left\{ \frac{P_j h_{ji}}{I_i + N_0} \right\} \geq \gamma_{th} \right\}. \tag{9}$$

Analogously follows for Eq. (9):

$$\begin{aligned} K_i &= \prod_{\substack{j=1 \\ j \neq i}}^{N} \Pr\left\{ \frac{P_j h_{ji}}{I_i + N_0} \geq \gamma_{th} \right\} \\ &= \prod_{\substack{j=1 \\ j \neq i}}^{N} \Pr\left\{ h_{ji} \geq \frac{\gamma_{th}(I_i + N_0)}{P_j} \right\} \\ &= \prod_{\substack{j=1 \\ j \neq i}}^{N} \int_0^\infty Pr\{h_{ji} \geq \frac{\gamma_{th}(x + N_0)}{P_j}\} f_{X_i}(x) dx \\ &= \prod_{\substack{j=1 \\ j \neq i}}^{N} \int_0^\infty \exp\left[-\frac{\gamma_{th}(x+N_0)}{P_j \Omega_{ji}} \right] \frac{1}{\Omega_i} \exp\left(-\frac{x}{\Omega_i}\right) dx \\ &= \exp\left(-\gamma_{th} N_0 \sum_{\substack{j=1 \\ j \neq i}}^{N} \frac{1}{P_j \Omega_{ji}} \right) \prod_{\substack{j=1 \\ j \neq i}}^{N} \frac{P_j \Omega_{ji}}{\gamma_{th} \Omega_{I_i} + P_j \Omega_{ji}}. \end{aligned} \tag{10}$$

Finally, substituting Eq.(10) into Eq. (8) yields the closed-form expression for the communication probability implying safety:

$$O_s = \prod_{i=1}^{N} \left\{ \exp\left(-\gamma_{th} N_0 \sum_{\substack{j=1 \\ j \neq i}}^{N} \frac{1}{P_j \Omega_{ji}} \right) \prod_{\substack{j=1 \\ j \neq i}}^{N} \frac{P_j \Omega_{ji}}{\gamma_{th} \Omega_{I_i} + P_j \Omega_{ji}} \right\} \tag{11}$$

IV. NUMERICAL RESULTS

This section presents numerical results illustrating the system performance. The relevant system parameters in simulation and analysis are set to:

- bandwidth: $B = 5$ MHz;
- packet size: $L = 224$ bits;
- timeout: $t_{out} \in [10^{-4}, 3.5 \cdot 10^{-3}]$ seconds
- number of vehicles: $N = 5$

Without loss generality, we set $\gamma_j = \frac{P_j}{N_0}$ as transmission signal-to-noise ratio (SNR) and $\gamma_I = \frac{\Omega_I}{N_0}$ as average interference level. The following shows varying the transmission power in Section IV-A, varying the interference power in

Section IV-B, varying the channel mean gain in Section IV-C, and varying the number of vehicles in Section IV-D.

A. Varying the Transmission Power

The graph in Fig. 2 shows the analytical results (continuous lines) matching the simulation results (symbols). We can observe that the probability of receiving packets increases with increasing of transmission SNR, γ_j. Further, as the packet timeout threshold t_{out} is small, e.g. $[10^{-4}, 10^{-3}]$ seconds, the probability for successful communication for the whole platoon system is small, i.e., 0.5. This can be explained by the fact that as the transmission SNR of the vehicles increases, their coverage range are also increased, thus the loss of packets at each vehicle is reduced. However, reducing packet timeout threshold leads the transmitted packet to be more delay-sensitive, and thus the probability for successful communication is decreased at small value of timeout, t_{out}.

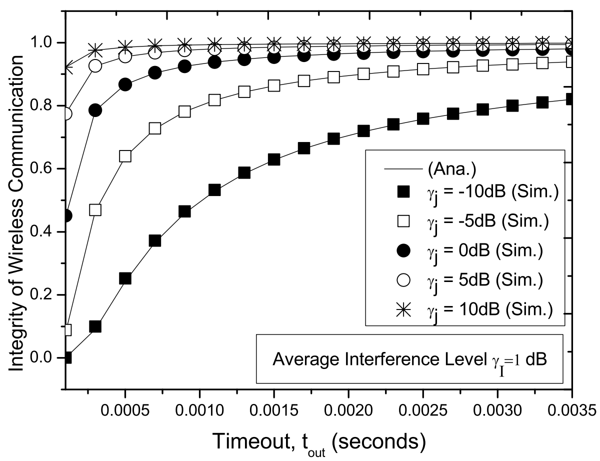

Fig. 2. Transmission Probability vs. Transmission Power over Time

B. Varying the Interference Level

Fig. 3 illustrates the probability of receiving packets in case of changing interference level at vehicles. The transmission SNR is set to $\gamma_j = 0$dB at vehicles and the average interference level at each vehicle varies from $\gamma_I \in \{0.1, 1, 5, 10\}$dB. The graph shows as expected, that smaller interference leads to a higher probability for successfully receiving the packet. It converges asymptotically to 1 over time and settles for $t_{out} \geq 1.5 \cdot 10^{-3}$ seconds. Increasing the interference power level leads to prolong the packet tranmission time, i.e., the transmitted packet is easy to be timeout. Therefore, the probability of receiving packets in a given timeout decreases. Further, the degradation is not linear and *dampens* as the interference power level linearly increases: The gap between $\gamma_I = 0.1$ and $\gamma_I = 5$ is bigger than the one between $\gamma_I = 5$ and $\gamma_I = 10$. It is to suggest that to obtain the high probability of receiving packet in case of large interference, we have to increase transmit power SNR.

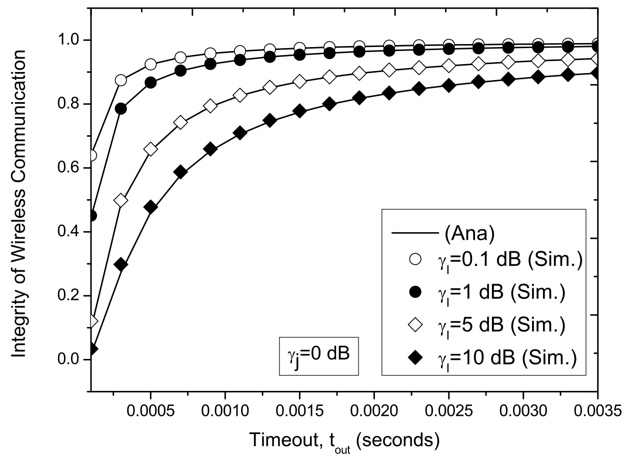

Fig. 3. Transmission Probability vs. Interference Power over Time

C. Varying the Channel Mean Gain

Plotting the channel mean gain Ω_{ji} of h_{ji} by magnitudes of $\{2, 3, 5, 10\}$, as shown in Fig. 4, allows for evaluating the performance depending on the packet timeout threshold. Same transmission SNR and better channel mean gain improved the integrity of wireless communication significantly. At 10^{-3}s timeout, the probability of successfully receiving a packet when the channel mean gain is reduced by magnitude of 10 times, is lower than 0.5. In particular for small timeouts (e.g. at high velocity or the small inter-vehicular distance as illustrated in Fig. 1), the probability of successfully receiving packets is close to 0 in worst the case of channel gain. Varying the channel gain varies significantly influences the time of successful message reception (i.e. reducing the number of necessary repetitions), thus affecting the probability of *timely* receiving the packet. Fig. 4 shows the effect of the channel gain between the devices on the integrity of the wireless

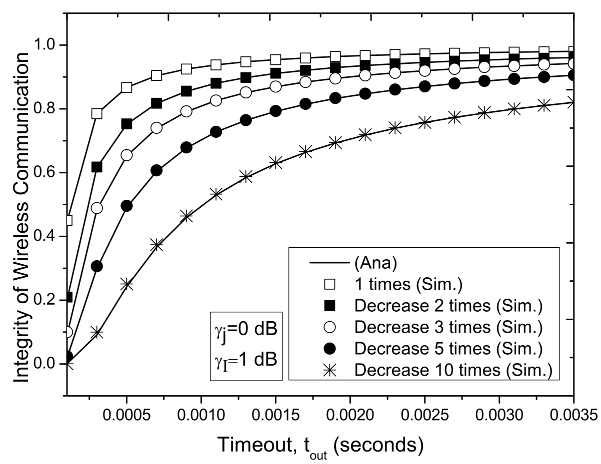

Fig. 4. Transmission Probability vs. Decreasing Channel Gains over Time

communication, and thus on the performance and safety of the system.

D. Varying the Platoon Size

Fig. 5 illustrates the impact of the number of vehicles ranging from 5 to 20 in steps of five on the system performance. The figure shows that the system works for ten

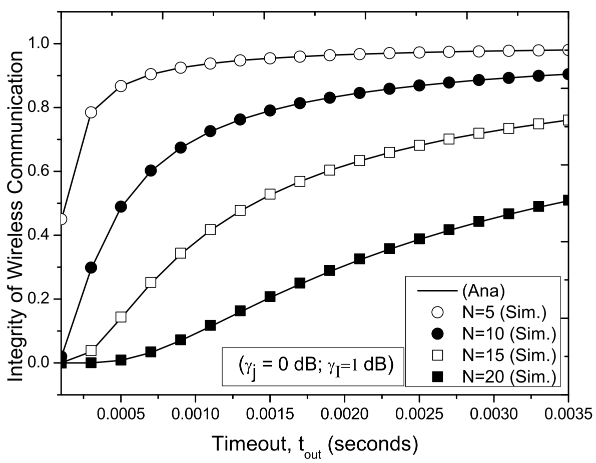

Fig. 5. Number of vehicles vs. system performance

or less vehicles. Increasing the number of vehicles increases the distance of the whole platoon model. This consequently increases the transmission times among vehicles, such that the overall probability for successfully receiving packets degrades with regards to particular timeouts.

V. Conclusions

This paper proposed a platoon system model with an exponential distribution over the channel gain for assessing the performance under varying i) transmit power, ii) interference channel gain, iii) channel gain between vehicles and iv) number of vehicles. The *integrity if wireless communication* was determined as crucial part for providing safety in cooperative maneuvers. Establishing a method for deriving the probability for a successful communication is required to achieve that goal. This paper provided an analytic and a simulation method. The results coincide perfectly, indicating the sufficient amount of simulation loops having been carried out. The simulation framework along with the analytic results can be found online[1] for sake of completeness.

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