Random Transmit Jitter Against Correlated Packet Collisions in Vehicular Safety Communications

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***Abstract*—In Vehicular Safety Communication (VSC) vehicles periodically broadcast so called Cooperative Awareness Messages (CAM) to make neighboring vehicles being aware of their current status like position, speed and heading. Such periodic transmissions on top of the Dedicated Short Range Communication (DSRC) technology can cause temporal correlated (recurring) collisions, which increase the delay between consecutive awareness updates from a certain vehicle.**

In this paper we propose to add a controlled random jitter to the nominal CAM broadcast interval at the application/facilities layer. Thus, we aim for making temporal correlated packet collisions more uncorrelated in time and by implication significantly decrease the delay between consecutive CAM updates (update delay or inter-reception time). The benefit of our approach has been demonstrated by simulating a multi-lane highway scenario at different traffic/data load conditions. By adding a random transmit jitter we were able to reduce the amount of correlated collisions by more than factor 10, and by consequence to improve the update delay performance by up to two orders of magnitude.

I. Introduction

With the introduction of Vehicular Safety Communication (VSC) vehicles are expected to go far beyond the capabilities of local radar- and vision-based sensors by providing an enhanced view of the current environment called *cooperative awareness*. Therefore, vehicles are compelled to periodically broadcast safety-related information like their current position, speed and heading to all vehicles in their vicinity via so called Cooperative Awareness Messages (CAM)[1] [1], by using Dedicated Short Range Communication (DSRC) technology [2]. Especially safety-related applications require a high up-to-dateness of the cooperative awareness, which is of higher quality the more regular CAMs are received. Consequently, the performance of such applications heavily depends on the delay between two consecutive successfully received CAM updates (update delay or inter-reception time). If too long, the VSC application is not able to detect a dangerous situation in time.

The current DSRC technology is based on the IEEE 802.11 standard [3]. Although slightly adapted to vehicular environments, the use of periodic broadcast transmissions brings it away from its original design framework: On the one hand, broadcast transmissions implicitly deactivate IEEE 802.11 collision avoidance mechanisms like the exponential increase of the contention window and the Request-To-Send/Clear-To-Send (RTS/CTS) handshake [3]. On the other hand, random channel access schemes like IEEE 802.11 have been designed for bursty data traffic patterns [4] instead of periodic ones. Although the CAM transmit policy has been enhanced by additional triggers based on mobility changes, in numerous contexts vehicular mobility is little varying and highly correlated (e.g. platooning on a highway). As a consequence, the resulting TX broadcasts are likely to be correlated as well, which may cause *correlated packet collisions*. Whereas the loss of individual CAMs only has a minor impact on the current up-to-dateness of the cooperative awareness, several consecutive losses may quickly lead to outdated information, which is not viable for safety related applications anymore.

With Decentralized Congestion Control (DCC) the VSC community tries to mitigate packet collisions in general by keeping the congestion in a controlled state (e.g. [5]–[10]). However, DCC does not address the specific problem of correlated packet collisions. A potential approach to mitigate correlated collisions may be found in the class of random repetition-based Medium Access Control (MAC) protocols (e.g. [11]). Although it can reduce correlated collisions, it also increases congestion on the channel, which is not desired. Hence, random repetition schemes have not been selected by the corresponding standardization bodies. Alternatively, Time Division Multiple Access (TDMA) approaches have been proposed (RR-ALOHA [12], MS-ALOHA [13], S-TDMA [14]) which showed to be able to mitigate this issue, but require a redesign of the DSRC chipset, which is currently not accepted by the standardization bodies as well.

In this paper, we introduce a new transmit policy at higher layers, which is able to mitigate the problem of correlated packet collisions, yet transparent to safety applications, while keeping full compatibility with the VSC reference architecture [2]. Specifically, we propose to add a random transmit jitter to the periodic CAM broadcast interval for each trans-

[1]Equivalent to the Basic Safety Message (BSM) in the US.

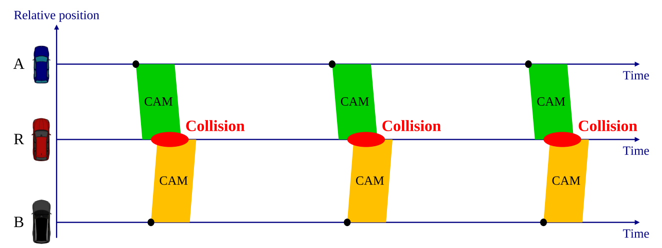

Fig. 1. Space-time schematic of three vehicles A, B and R: due to the periodic nature of CAM broadcasts in combination with slow relative speeds, a collision is likely to recur several times in a row at the same receiver R.

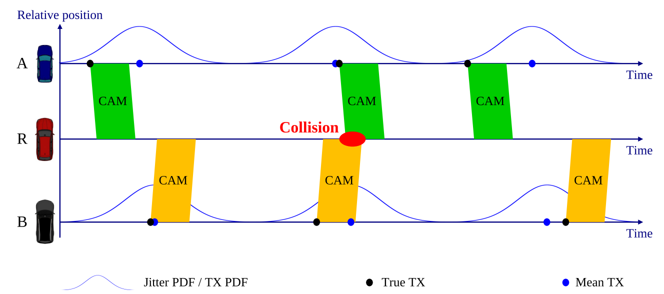

Fig. 2. Space-time schematic of three vehicles A, B and R: a random transmit jitter is indeed not able to avoid simultaneous transmissions completely, but it mitigates recurring ones at the same receiver R.

mission (i.e. not only at boot up), in order to make correlated collisions more uncorrelated in time. We evaluate our concept by simulating a multi-lane highway scenario with varying traffic/data load conditions. Especially at low traffic/data load conditions the results show significant improvements with respect to the mitigation of correlated collisions as well as the update delay.

II. Correlated Packet Collisions

Initially, CAMs have been expected to be broadcasted at a fixed rate between 1 Hz and 10 Hz. But then it has been observed, that the relevance of a CAM heavily depends on how much the vehicles status (position, speed, heading) has changed since the last CAM transmission. Accordingly, in [1] the ETSI has specified that a CAM transmission should be triggered with a fixed rate of 1 Hz *and* if the position, speed or heading have changed by a certain value. To limit the maximum TX rate to 10 Hz, the latter conditions are only checked every 100 ms.

Although the additional trigger conditions do not indicate periodic CAM transmissions anymore, it may still be observed that certain mobility conditions may not vary as much as expected for vehicular scenarios. On highways, for instance, most of the vehicles try to keep a constant velocity, especially in the case of platooning. Then their positions are changing constantly over time, again causing periodic CAM transmissions.

While DSRC has been adapted to high vehicular mobility, in numerous contexts the mutual speed between vehicles remains very low. In highway scenarios, for instance, traffic volumes and capacity tend to make vehicles converge to similar speeds per direction. In urban scenarios, traffic light controllers tend to generate synchronized flows of vehicles with similar speeds, too. If combined with quasi-periodic CAM transmissions, this results in *correlated packet collisions*. This effect is illustrated in Fig. 1 by means of a space-time scheme. Let's assume two vehicles A and B approximately transmitting at the same time (simultaneous transmission). Then, a possible receiver R in between may experience a packet collision. Due to the periodic nature of CAM transmissions in combination with slow relative mobility, the collision may recur for several subsequent transmissions at the same receiver R. The problem of recurring packet collisions is particularly significant in hidden terminal situations. Due to the broadcast mode and by implication the disabled RTS/CTS mechanism, hidden terminals are not able to detect an ongoing transmission despite carrier sensing. Furthermore, no (negative) acknowledgements are provided, which would indicate a possible collision at the receiver and the need of adapting the TX policy to avoid the next transmission colliding again.

Whereas cooperative safety applications may support the loss of individual CAMs, the loss of several subsequent CAMs may lead to outdated status information about the corresponding vehicle, which significantly lowers the application's reliability. Thus, the performance of such applications is not measured by TX-RX-metrics (end-to-end), but by pure RX-centric metrics like the update delay, which is increased significantly by (temporal) correlated packet collisions.

Correlated packet collisions are also present on radio propagation level as shown in [15]. Performing a measurement-based analysis the authors observed temporal correlated blackouts caused by persistent channel/link conditions. However, in this paper we will focus on correlated packet collisions caused by the quasi-periodic CAM TX policy in combination with slow relative mobility. Whereas changing persistent channel conditions is quite ambitious, adapting the CAM transmit policy is feasible with much less effort and is fully compatible with the current DSRC technology and DCC mechanisms.

III. Random TX Jitter to Mitigate Correlated Packet Collisions

The basic principle is illustrated in Fig. 2 by means of a space-time scheme. Assuming the same spatial situation as in Fig. 1, vehicle A and B now add a controlled random transmit jitter to their periodic broadcast interval, resulting in randomized CAM transmissions over time (see subsequent bell-shaped curves). Please note, that the Gaussian Probability Density Function (PDF) in Fig. 2 is just for illustrating the randomness of the added transmit jitter. In principle, any PDF can be used, which complies with the corresponding requirements (e.g. latency). However, we will focus on the uniform PDF for the rest of this paper. The reason for that is twofold: first, the uniform PDF is clearly limited by its interval bounds, which in turn clearly limit the delay spread around the nominal broadcast interval. Second, the uniform PDF provides the maximum randomness (entropy) among all distributions, which support the same interval [16].

By adding a random transmit jitter, we aim at avoiding recurring simultaneous transmissions and by implication temporal correlated packet collisions. Without loss of generality, let's assume the random jitter is modeled by the random variable J with zero mean and its PDF is denoted as $f_J(j)$, uniformly distributed. Let's further assume the nominal transmit times for the next CAM transmission of vehicle A and vehicle B are t_A and t_B, respectively. Then, the randomized transmissions for the next CAM of vehicle A and vehicle B can be modeled by the random variables $X = J + t_A$ and $Y = J + t_B$, respectively, and the corresponding PDFs are shifted versions of $f_J(j)$:

$$\begin{aligned} f_X(x) &= f_J(x - t_A) \\ f_Y(y) &= f_J(y - t_B) \end{aligned} \tag{1}$$

The probability of having a simultaneous transmission (i.e. at least partially overlapping packets), is the probability that vehicle A transmits at time X and vehicle B transmits at time Y, with $Y \in [X - l; X + l]$, and l defines the packet duration:

$$\begin{aligned} &\mathbf{Pr}(\text{packet overlap}) = \mathbf{Pr}(X - l < Y < X + l) \\ &= \int_{-\infty}^{\infty} \int_{x-l}^{x+l} f_{X,Y}(x, y) \, \mathrm{d}y \, \mathrm{d}x \\ &\overset{(*)}{=} \int_{-\infty}^{\infty} \int_{x-l}^{x+l} f_X(x) \cdot f_Y(y) \, \mathrm{d}y \, \mathrm{d}x \\ &\overset{(1)}{=} \int_{-\infty}^{\infty} f_J(x - t_A) \cdot \int_{x-l}^{x+l} f_J(y - t_B) \, \mathrm{d}y \, \mathrm{d}x \end{aligned}$$

The multiplication at $(*)$ is valid, as both vehicles choose their random jitter independently from each other.

It should be noted that the size of the random interval for the artificial jitter plays an important role. Assuming $t_A = t_B$ and the interval size is smaller than the packet duration itself, then the packet transmissions will always overlap, at least partially. Thus, it is necessary to choose a sufficiently large interval size (e.g. multiples of the packet duration) in order to significantly reduce the probability of overlapping packet transmissions. Please note, that the natural jitter of the clocks in vehicular communication systems is not sufficient to mitigate overlapping of subsequent CAM transmissions, as it is far below the the packet duration (e.g.: $l \approx 0.5$ ms for 300 Byte @ 6 Mbps), especially if synchronized with GPS/Galileo. Although the larger the interval size, the lower the probability of recurring packet collisions, the interval size should be strictly limited in practice. On the one hand, the delay between consecutive packet transmissions should be limited, and on the other hand an overlap of consecutive broadcast intervals should be avoided.

An important benefit of our concept is that it is fully compatible with current DSRC. Since the random transmit jitter is added on the application/facilities layer, no modification of the access layer is required, neither hardware nor software. Furthermore, our concept can be still integrated with existing DCC strategies.

Another important property of our approach is, that we are able to keep fairness with respect to the current transmit rate between neighboring vehicles. As long as the random jitter is based on random variables with the same mean, the transmissions are scheduled on average with the original broadcast interval.

IV. Evaluation by Simulation

To evaluate the concept of adding a random transmit jitter to the current broadcast interval, a straight multi-lane highway has been implemented by using the well-known simulation framework ns-3 [17]. The vehicles are generated for each lane following an Erlang distribution. Once a vehicle has been generated, it only starts transmitting its first CAM after a random waiting time between 0 s and 1 s (maximum broadcast interval). To obtain low, medium and high channel load conditions by keeping the CAM transmit policy, we adapt the number of lanes on the highway to 2, 4 and 6, resulting in 27 %, 46 % and 61 % of channel load, respectively. The most important parameters specifying the simulation setup are summarized in Table I.

Due to the additional CAM trigger conditions as specified in [1], the basic concept introduced in the previous section has to be slightly modified. If the jitter is added to the basic broadcast interval only, it will be useless, in case a change in position, speed or heading would trigger the CAM before the nominal broadcast interval has expired. Thus, in our implementation we added the random jitter to the interval, which periodically checks the corresponding changes. As this checking interval is set to 100 ms (to limit the maximum TX rate to 10 Hz), we specified the jitter to be uniformly distributed between $[-50\ ;\ +50]$ ms in order to minimize the probability of recurring simultaneous transmissions but still avoid overlapping TX intervals.

The severity of correlated collisions and the impact of adding a random transmit jitter are presented in Fig. 3. It

Traffic scenario	straight highway with 10 km length
Evaluation section	from $2.5 - 7.5$ km (to avoid border effects)
Lanes per direction Resulting channel load	2, 4 and 6 27 %, 46 % and 61 %, respectively
Vehicle generation	Erlang distributed for each lane ($\mu = 2$ s)[2]
Speed profile	20 m/s to 40 m/s (constantly increasing from outer to inner lane)
Default CAM TX policy	1 Hz + trigger conditions (see [1])
CAM packet size	300 Byte
Artificial Random Jitter	$\mathcal{U}(-50\ \text{ms}, +50\ \text{ms})$
Access technology	ITS-G5 on Control Channel
TX power	33 dBm
Radio propagation model	Log distance with exponent 2.35
Metrics	normalized collision rate, update delay (inter-reception time)

TABLE I
Most important simulation parameters.

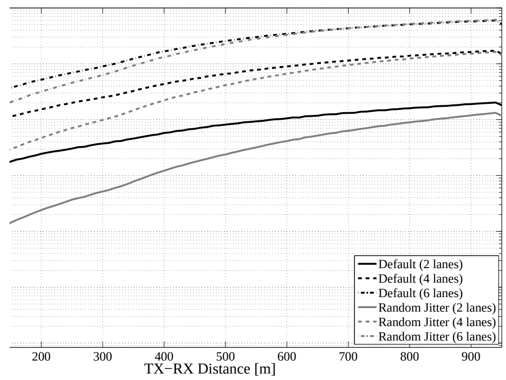

Fig. 3. Comparison of the recurring packet collision rate (normalized in time and space) for low, medium and high traffic/data load conditions (2 lanes, 4 lanes, 6 lanes).

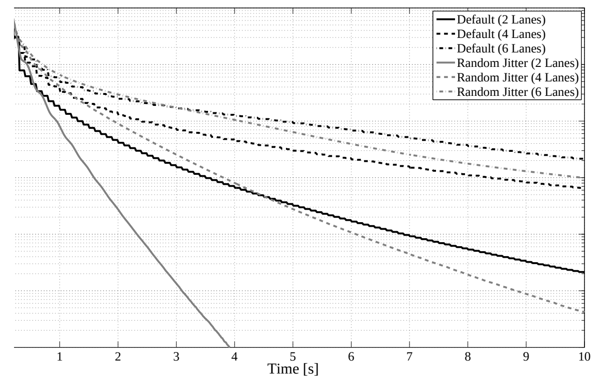

Fig. 4. Comparison of the communication performance within the entire communication range ($\approx$ 970 m) using the update delay as an RX-centric metric.

shows the absolute recurring packet collision rates (normalized in time and space) dependent on the distance between the collision inducing transmitter and the receiver, with and without the corresponding random transmit jitter. Due to the huge difference of the value ranges for the two-lanes scenario and the six-lanes scenario (approx. factor 30), the y-axis is log scaled.

The most significant reduction of correlated collisions can be observed for the low traffic/data load scenario (2 lanes). By adding an artificial random jitter the total number of recurring packet collisions at short distances (up to 200 m) can be reduced by more than factor 10. But if the traffic/data load is increased, the improvement obviously is getting less significant. In the high traffic/data load scenario (6 lanes), for instance, only up to a distance of 500 m a reduction of the amount of correlated collisions is observable. An explanation for this behavior is based on the DSRC MAC technology: since the MAC contention (backoff) procedures tend to serialize simultaneous transmission attempts, a previously added random transmit jitter at the application/facilities layer might be absorbed again, as well as its beneficial impact. As long as the traffic/data load is low, the contention on the MAC layer is low, too. Consequently, most of the added random jitter remain up to the time of physical transmission. If traffic/data load is increased, a growing number of previously added random jitters are going to be absorbed by the increasing queuing and serialization procedures, caused by DSRC MAC contention. Although the reduction of recurring packet collisions by adding a random transmit jitter is getting less significant with increasing traffic/data load, our concept does never show a worse behavior than the default approach. In the worst case, it converges to the default with increasing distance (cf. 4 and 6 lanes scenario in Fig. 3).

Next we are going to present the communication performance w.r.t. periodic CAM broadcasts. Therefore, we measured the *update delay*, which is perfectly suited to evaluate the up-to-dateness of the cooperative awareness from a communications perspective [18]. In other publications, e.g. [8], [9], [15], [19], the update delay is better known as 'Packet Inter-Arrival Time' or 'Inter-Reception Time'. However, the main difference is that we use a special representation called *Complementary Cumulative Distribution Function (CCDF)*. The advantages are twofold: First, the distribution keeps all the measured information which is not the case by focusing on average values and/or confidence intervals. Second, as we are focusing on the reliability of VSC, we are interested in probability values very close to 1. Although using a log-scaled probability axis, the CDF does not provide the necessary resolution around 1. By using the CCDF $= 1 -$ CDF, we can get (theoretically) an infinite resolution around the value we are interested in.

Fig. 4 compares the different update delay CCDFs within the entire communication range ($\approx$ 970 m). Based on the explanation above, the update delay CCDF plot provides the probability (y-axis) of exceeding a given time delay value (x-axis). An example: assuming we are interested in the probability of a vehicle remains undetected within a time frame of 4 s (corresponds to a traveled distance of 320 m at a maximum relative speed of 80 m/s), we fix the value of 4 s on the x-axis and read the corresponding probability value on the y-axis, dependent on the scenario of interest. Consequently, in the low traffic/data load scenario (2 lanes) the corresponding probability value is approx. $7 \cdot 10^{-4}$ for the default approach and approx. 10^{-6} with added random jitter. This corresponds to an improvement by approx. factor 700. In the medium traffic/data load scenario (4 lanes) the improvement has been reduced significantly, but still providing approx. factor 5. In the high traffic/data load scenario, the corresponding improvement is negligible.

Especially if we are focusing on vehicular safety, closer ranges (up to 100 m) and less time delays (up to 1 s) are much more relevant, as only close-by vehicles may pose an imminent danger regarding physical collisions between vehicles. Thus, Fig. 5 compares the different update delay CCDFs within a range of 100 m only. If we are interested in the probability of a vehicle remains without any CAM update within a time

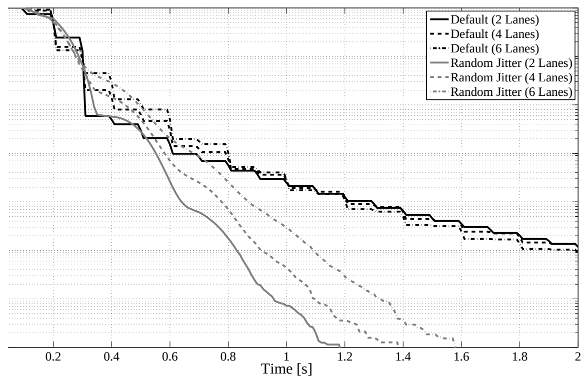

Fig. 5. Comparison of the communication performance within close range (up to 100 m) using the update delay as an RX-centric metric.

frame of 1 s for ranges up to 100 m only, we fix the value of 1 s on the x-axis again and read the corresponding probability value on the y-axis. Similar to the previous case, the lower the traffic/data load, the more significant is the improvement. In the two-lanes scenario, for instance, the default approach provides a probability of approx. $3 \cdot 10^{-4}$ compared to approx. $7 \cdot 10^{-7}$ by adding an artificial random jitter, thus providing an improvement of about factor 400. Also considering the higher traffic/data load scenarios, our random jitter approach still provides an improvement by factor 60 in the case of four lanes and factor 10 in the case of six lanes.

V. Conclusion

Correlated packet collisions significantly lower the reliability of DSRC-based cooperative safety applications. In this paper we have introduced a new technique, enhancing the current CAM transmit policy by adding a controlled random transmit jitter to the nominal broadcast interval, with no negative impact on the performance of safety applications. On the contrary, as we have provided a less periodic distribution of CAM transmissions in time, we were even able to significantly mitigate temporal correlated packet collisions as well as to improve the update delay performance, especially in low and medium traffic/data load conditions. In high load conditions most of the impact of a random jitter added at the application/facilities layer is absorbed by the increasing contention procedures at the MAC layer. As our mechanism is acting on the higher layers, it is fully compatible with current DSCR technology and DCC approaches. Consequently, a concrete integration of random transmit jitter with DCC might be a next step for future investigations. Whereas in [20] we have introduced the concept of random transmit powers to mitigate the correlated collisions in the space domain, another important future work on our road-map is to integrate random TX power (space domain) with random TX jitter (time domain).

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