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Exploiting Multi-RAT Diversity in Vehicular Ad-hoc Networks to Improve Reliability of Cooperative Automated Driving Applications

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***Abstract*—Cooperative automated driving applications require reliable and low-latency exchange of periodic control information among vehicles in proximity. Performing well at low channel loads, vehicular ad-hoc technologies suffer from performance degradation caused by channel congestion. We propose to apply Multi-RAT diversity to improve the reliability of transmissions by increasing robustness against channel congestion. Multi-RAT diversity is achieved by the redundant use of multiple access technologies in parallel. In this paper, we investigate on the potential reliability improvement by combing IEEE 802.11p and LTE-D2D mode 2. Besides explaining the basic effects and main design aspects, we quantify the potential gain in an example highway platooning scenario based on simulations and concrete requirements. The results show a high potential in the redundant use of IEEE 802.11p and PC5-based ad-hoc technologies. Significant increases in transmission range of up to four times, especially at high vehicle densities and under strict reliability requirements, are achieved.**

***Index Terms*—Multi-RAT, diversity, hybrid, heterogeneous, reliability, V2X, IEEE 802.11p, LTE-D2D mode 2, LTE-V2X, PC5, VANET, cooperative automated vehicles, truck platooning**

I. INTRODUCTION

In recent years cooperative automated driving and its potential to fundamentally change the future of mobility has raised tremendous interest. Cooperative vehicle control promises added safety in combination with increased traffic and fuel efficiency. As a well-investigated example, Cooperative Adaptive Cruise Control (CACC) in truck platoons achieves fuel savings of up to 28%, while increasing the road utilization due to reduced inter-vehicle distances [1]. However, a highly reliable, low-latency communication system is crucial to maintain string-stability and avoid crashes. Currently two candidate technologies, namely IEEE 802.11p and LTE/5G-V2X are competing for deployment. Combining these diverse technologies in a hybrid approach greatly improves the adaptivity and reliability of the communication system [2]. In this work we focus on the reliability improvements achieved by employing multiple Radio Access Technologies (RATs).

Many contributions found in literature investigate on the integration/inter-networking of cellular (LTE) and ad-hoc/short-range (IEEE 802.11p) technologies for efficient V2X message dissemination [3], [4]. Recently, the redundant use of Uu (uplink, downlink) and PC5 (sidelink) to enhance V2X communications has been investigated [5].

To the knowledge of the authors, this is the first contribution proposing to combine multiple vehicular ad-hoc technologies to increase the reliability of safety critical applications. The reason for choosing ad-hoc technologies is that they have proven in various test beds, e.g., AutoNet2030 [6], to be well suited for cooperative automated driving applications. Reasons are the ubiquitous connectivity, independent operation from cellular infrastructure, low control overhead and potentially low delays. However, it is well-known that random access schemes suffer from channel congestion resulting in packet loss and increased update times. Employing multiple ad-hoc technologies can effectively mitigate this effect by increasing the robustness against channel congestion.

In this work we investigate on the combination of IEEE 802.11p and PC5-based technologies on a system-level. Due to the missing availability of LTE-V2X models, we use LTE-D2D mode 2, the predecessor of LTE-V2V mode 4 with V2V-specific configuration. Besides showing the benefits and main design aspects when employing Multi-RAT diversity, the goal is to quantify the reliability improvement achieved in cooperative driving use cases. Therefore, we simulated a reference highway scenario with periodic, single-hop broadcast communication and evaluated the results considering the cooperative control requirements derived in [7]. It is important to mention that the study focuses on the performance gain achieved by Multi-RAT diversity rather than comparison of technologies. For realistic comparison of the base technologies interest readers are referred to [8].

The remainder of this paper is structured as follows: In Section II, we describe our Multi-RAT diversity approach for cooperative control applications in detail. Next, in Section III we explain the simulation scenario describing the RAT configurations, highway scenario and performance metrics. Section IV then discusses the achieved reliability improvements. Finally, the paper is concluded in Section V.

II. MULTI-RAT DIVERSITY

Multi-RAT diversity combines at least two diverse access technologies to improve the communication reliability. The effects causing reliability enhancements achieved are dependent on the combination of technologies and redundancy scheme applied. In this paper, we focus on the effects related to combinations of ad-hoc technologies using a packet-level redundancy scheme without additional coding. Under the assumption of technology coexistence achieved by the independent operation on exclusively allocated sets of radio resources, following effects can be identified:

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1) Robustness Against Propagation Loss: Propagation effects as attenuation, shadowing and fast fading result in degradation Signal-to-noise ratio (SNR) at the receiver. Link layer packet drops occur, if the SNR of the received packet is too low to successfully decode the packet. The redundant operation of multiple RATs reduces the probability of losing all packets by increasing the robustness against packet loss on the individual links. Due to frequency, time and space diversity each link observes an individual channel realization, reducing the probability of losing all packets due to signal fades. Frequency diversity is achieved by the use of different carrier frequencies and mitigates the effect of frequency-selective fading. The use of multiple access schemes on MAC layer leads to transmission at different time instants, increasing the robustness against time-varying channel conditions. Further, the use of multiple independent access interfaces enables space diversity based on different antenna positions.

2) Robustness Against Channel Congestion: Packet loss on MAC layer can have several reasons depending on the access scheme deployed. A major cause of packet loss for all access schemes are collisions from interference. They occur whenever the Signal-to-interference-plus-noise ratio (SINR) at the receiver is not sufficient to decode packet. Even when carrier sensing is employed, collision cannot be fully avoided due to the hidden node problem. Other causes for packet losses are queue drops and the half duplex constraint. These access related effects for packet drops become severe for high channel loads/channel congestion. Employing multiple MAC instances reduces the chance of losing all copies of the packet due to access-related effects. Further, congestion caused by unevenly distributed traffic can be avoided without the need of dynamically selecting the less congested technology.

3) Diverse Performance Characteristics: Each of the employed RATs has an unique design consisting of different PHY, MAC and higher layer protocol stack implementations. These diverse designs result in diverse performance characteristics, rendering the technologies more or less suited under certain circumstances. Since the circumstances, e.g. required transmission distance or observed channel utilization are time-varying and application dependent, the individual performance characteristics complement each other in complex V2X scenarios. As an example, one of the employed technologies may offer a better link performance, whereas the other is more robust against channel congestion. Consequently, the former technology is better suited for transmissions with high distances, whereas the latter will be superior at short ranges.

4) Impact on Spectral Efficiency: Besides the beneficial effects causing reliability enhancements also the impact on the spectral efficiency of the hybrid communication system needs to be taken into account. Each additional, redundant transmission increases the radio resource demand of the requesting application and hence increases the chance of congestion (linear dependency). Consequently, when employing Multi-RAT diversity the trade-off between increased reliability and higher resource demand needs to be carefully considered based on the application requirements. Especially, for safety-critical applications with strict reliability requirements the added cost in terms of radio resources is acceptable. Nevertheless, to minimize the impact on channel congestion, an efficient selection, deciding when to apply Multi-RAT diversity is required.

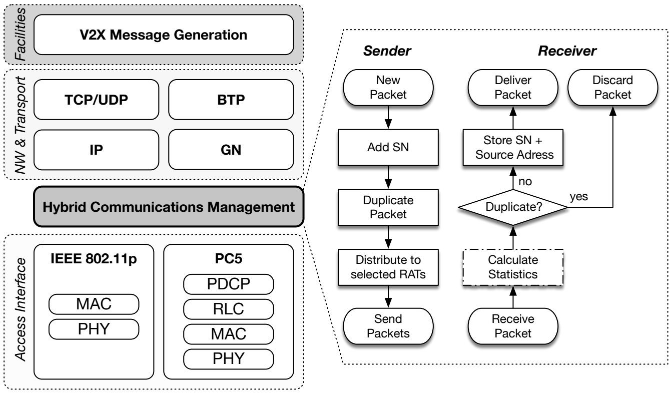

Fig. 1. Hybrid V2X protocol stack with Hybrid Communications Management enabling the redundant operation of IEEE 802.11p and PC5-based technologies, e.g., LTE-D2D mode 2. The flowchart depicts the core functionality of the Multi-RAT redundancy protocol.

A. Implementing Multi-RAT Diversity

In [2], we introduced the so-called Hybrid Communications Management (HCM) for controlling the use of multiple access technologies in parallel. It is an independent component bridging between the access interfaces and the network & transport stack as shown in Fig. 1. The HCM enables Multi-RAT coordination per packet-level and allows for easy implementation and integration into hybrid connectivity modules based on standard hardware and software components. The main functions are: RAT selection, configuration, supervision and Diversity Control (DC). In this work, we want to further specify the Multi-RAT redundancy protocol, the core element of the DC. We assume the protocol is applied for single-hop, broadcast messages with mission critical content exclusively (forwarding in the Vehicular Ad-hoc Network (VANET), e.g., using GeoNetworking (GN), is not considered). The basic idea is to increase the reception probability by sending multiple copies of the same packet over different RATs. At least one packet needs to be successfully decoded at the receiver and subsequently received copies of the packet are discarded. Applying additional redundancy codes allowing for reconstruction of packets at the receiver is out of scope of this work, since it reduces the interoperability while significantly increasing the complexity. The detailed sender-/receiver functionality of the protocol for an arbitrary number of access interfaces is depicted in the flowchart in Fig. 1.

At the sender for each network layer packet being requested for transmission a unique identifier, the Sequence Number (SN) is generated (e.g. using a sliding window approach). The SN in combination with the network layer source address (IP or GN) allows the HCM to unambiguously identify a packet. The packet including the SN is copied N times, where N equals the number of RATs selected for independent transmission. In the next step, the copies are distributed by the HCM to the different RATs, where they are queued for transmission. At the receiver the HCM collects all successfully decoded packets from the different access interfaces. For each received packet statistics including reception time, RAT configuration and channel conditions are logged. They can be used to optimize the usage/selection of diversity options. Next, the SN and source address are compared with the combinations already received, to detect whether the received packet is a duplicate or not. In case the packet was received for the first time, its identifying combination is stored and the packet is delivered to the network layer. Instead, if it has been received before, it will be discarded without further notification.

For the practical implementation of our redundancy protocol the crucial question is how to realize the duplicate detection. One feasible option is to implement the HCM as an independent layer adding own headers including a field for the SN. However, without standardization such a proprietary solution would limit the interoperability to vehicles also implementing the HCM. Alternatively, the duplicate detection available on transport layer, usually employed to enable retransmissions, can be reused. Connection-based protocols, e.g., TCP, provide the required functionality but are less suited for communication within a VANET due to their high control overhead and limitation to unicast communication. However, TCP is suited for unicast communication within a group of coherently moving vehicles, e.g. a platoon, since the network topology is less time-variant and consequently the control overhead mainly arising from the association procedure is acceptable. Unfortunately, connection-less transport layer protocols being well suited for communication within the VANET, e.g., Basic Transport Protocol (BTP), UDP, do not provide the desired functionality. A compromise, providing low control overhead and duplicate detection for both uni-/broadcast communication is to extend connection-less protocols as proposed with the Reliable Basic Transport Protocol (RBTP), an extension of the BTP protocol presented in [9].

B. Multi-RAT Diversity for Cooperative Control Applications

To understand the potential benefit of Multi-RAT diversity, we first need to identify the application-specific reliability requirements. For cooperative automated driving applications, reliability can be defined as a combination of Packet Reception Ratio (PRR), Packet Inter-Reception Time (PIR) and end-to-end delay. The PRR is used to measure the probability of successful packet reception. Whereas a single packet loss in a periodic transmission can be compensated by a robust controller, consecutive packet drops may result in platoon instabilities leading to vehicle crashes. Consequently, a constantly high PRR needs to be guaranteed. Directly related to the PRR is the PIR. The PIR is highly relevant for the exchange of periodic control information since it measures the average update interval observed at the receiver. Packet losses increase the observed update intervals reducing the controller performance respectively. Consequently, to avoid crashes, the PIR needs to fit the required controller interval (equal/lower). Otherwise, the control value need to be adapted, e.g. the inter-vehicle distance increased. In addition to the PIR, the end-to-end delay measuring the average time between generation and reception of a packet is used. It can be considered as a time offset resulting in delayed reaction of the controller. For the controller performance its relation to the actual update interval as well as its variations is important. We omitted to investigate on delay constraints since our Multi-RAT approach cannot decrease the delay beyond the values achieved by the employed technologies. Instead, the measured delay is bounded by the delay performance of the base technologies and varies depending on the individual PRR values observed.

We selected truck platooning as an example application to quantify the reliability improvement based on concrete requirements. Therefore, we derive the reliability requirements PRR_{target}, PIR_{target} from stability investigations on transmission intervals for platoons with line-topology from [7]. A line topology describes a control architecture, where each vehicle is independently controlled using status information of the preceding vehicles only. Since the line topology reflects the worst case architecture in terms of communication requirements, we consider the derived requirements as a general abstraction independent from the specific control architecture employed. As a reference scenario, we consider a typical truck speed of $80\,\mathrm{km/h}$ with a standard transmission interval of $10\,\mathrm{Hz}$. Assuming an error-free transmission and a human comfortable controller gain of $k_c = 0.5$, an inter-vehicle distance of $12\,\mathrm{m}$ can be achieved [7]. In case of 100% PRR the PIR equals the required transmission interval for packets transmitted at $10\,\mathrm{Hz}$. However, due to the shared medium the performance of ad-hoc technologies degrades under channel congestion, resulting in packet loss. Various investigations have shown that PRR target values above 99% cannot be achieved in most cases [8]. Consequently, we propose to set the target value PRR_{target} to a more realistic value of 90%. Since the 10% packets lost will lead to an increased PIR, we need to relax the PIR requirements by increasing the inter-vehicle distances (alternatively an increased message rate can be applied). Considering the non-linear dependency between PRR and PIR, we selected a PIR_{target} of $120\,\mathrm{ms}$ resulting in a inter-vehicle distance of $13\,\mathrm{m}$.

III. SIMULATION SCENARIO

We evaluate the communication performance/gain of Multi-RAT diversity based on the discrete-event simulator ns-3. Therefore, we implemented the redundancy protocol introduced in Section II-A, configured the RATs, channel model and set up a highway platooning scenario with variable vehicle density. Each simulation run has a duration of $200\,\mathrm{s}$, which is then repeated with 20 different random seeds. Parameters including the RAT configurations are summarized in Table I.

A. Radio Access Technologies

We assume perfect technology coexistence on $5.9\,\mathrm{GHz}$ carrier frequency, hence no interference between the different

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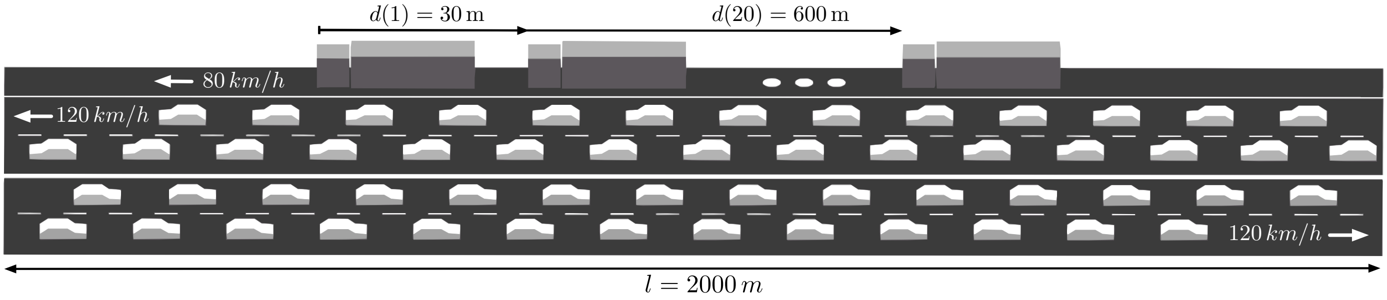

Fig. 2. Reference highway scenario: two car lanes per direction (120 km/h) with variable vehicle density, generating background traffic and a dedicated platooning lane (80 km/h) with 20 probing trucks centrally placed with 30 m spacing.

TABLE I
SIMULATION PARAMETERS

Radio Access Parameters	**LTE-D2D Mode 2**	**IEEE 802.11p**
Carrier Frequency (f_c)	5.9 GHz	5.9 GHz
System Bandwidth (B)	20 MHz	10 MHz
# Channels (N_{Ch})	4	1
Channel Bandwidth (B_{Ch})	5 MHz	10 MHz
MCS Value	8	3
Modulation Scheme	QPSK	QPSK
Code Rate / Ch. (R)	0.489	1/2
# Retransmissions (N_{Ret})	3	0
Frame Duration (T_{Frame})	40 ms	-
Repetition Pattern (k_{trp})	1 Bit	-
Channel Parameters		
Channel Model	Log-distance	
Ref. Loss at 1 m (PL_0)	52.48 dB [10]	
Loss Exponent (γ)	2, 96 [10]	
Transmit Power (P_{tx})	23 dBm	
Noise Power (P_n)	−107 dBm	−104 dBm
Noise Figure (N)	9 dB	7 dB
Message Generation		
Message Size (M)	300 Byte	
Message Periodicity (f)	10 Hz (100 ms)	
Simulation Duration (t_{sim})	20 seeds ×200 s	
Vehicle Density (ρ)	0...20 vehicles/(lane*km)	
Resolution (Δd)	30 m	

technologies is considered.[1] IEEE 802.11p is configured in a standard configuration with a single 10 MHz channel. The radio resources are accessed in TDMA fashion using the Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) access scheme. Due to the missing availability of accurate LTE-V2V models, we used the NIST LTE-D2D mode 2 implementation [11], in a customized "V2V-configuration" with an increased system bandwidth of 20 MHz. In contrast to 802.11p, the bandwidth is divided in 4 channels with 5 MHz each, enabling frequency division multiple access. Instead of using a carrier sensing based approach, the channels and the time repetition pattern k_{trp} (defining the transmission time slots) are randomly selected. The modulation and coding Scheme (MCS=3, QPSK, R=0.489) was chosen to fit a complete control message of 300 Byte into one channel within one Time Transmission Interval (TTI) of 1 ms (only 23 of 25 RBs used). Similar values have been selected for IEEE 802.11p (MCS=8, QPSK, R=0.5) to achieve a comparable link-level performance. We used the technology specific SNR/BLER curves of the ns-3 models as error models, which can be further improved by considering LTE/5G-V2X specific curves presented in [12]. We set the time repetition pattern to 1 out of 8 Bits, to fit the initial transmission plus three blind HARQ retransmissions within the lowest configurable frame duration of 40 ms. Moreover, a value of 1 Bit achieves the lowest collision probability within a frame. Further, we deactivated the error model on the control channel to model the SCI being multiplexed in frequency instead of time domain (modelled as part of the payload).

We decided on this specific configuration with doubled system bandwidth to enhance the poor access performance observed for LTE-D2D mode 2 in vehicular scenarios and hence make it comparable to LTE-V2X mode 4. The main reasons of the poor access performance being addressed with LTE-V2X are: the fixed frame structure and the random selection access scheme. Since our objective is to evaluate the potential gain of Multi-RAT diversity rather than comparing the performance of the two specific technologies, we consider the investigated configuration as reasonable. For detailed information about the mode 4 frame structure, access scheme and system-level performance interest readers are referred to [13].

B. Highway Scenario

As depicted in Fig. 2, we set up a 2 km long highway segment with two car lanes per direction and one dedicated platooning lane. The car lanes are used to generate background traffic only. Therefore, the vehicles are placed with equal distance and a variable density of up to 20 vehicles/(lane*km) moving at 120 km/h. In contrast, the platoon lane is used for evaluating the communication performance for cooperative control applications. On the platoon lane, 20 trucks are equally

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[1] A potential solution is to guarantee exclusive resource usage by allocating a distinct subset of the regionally available ITS channels for each of the RATs (regulation required). Investigations on different coexistence strategies/mechanisms are out of scope of this work.

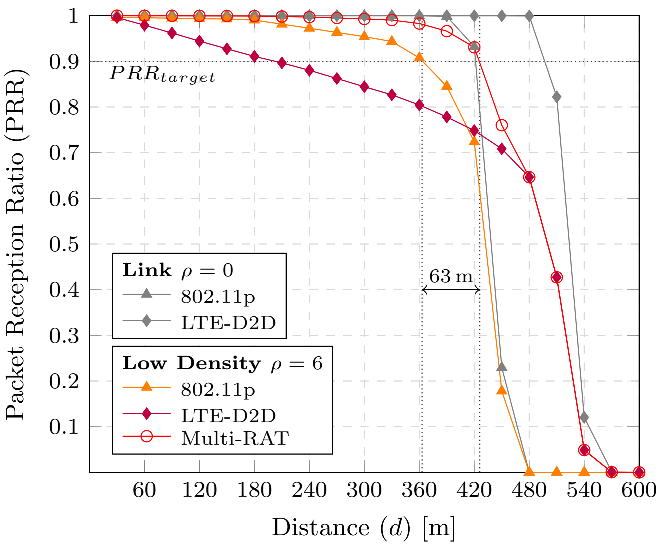

Fig. 3. Packet Reception Ratio (PRR) over distance d measured at a low vehicle density of $\rho = 6$ vehicles/(lane*km).

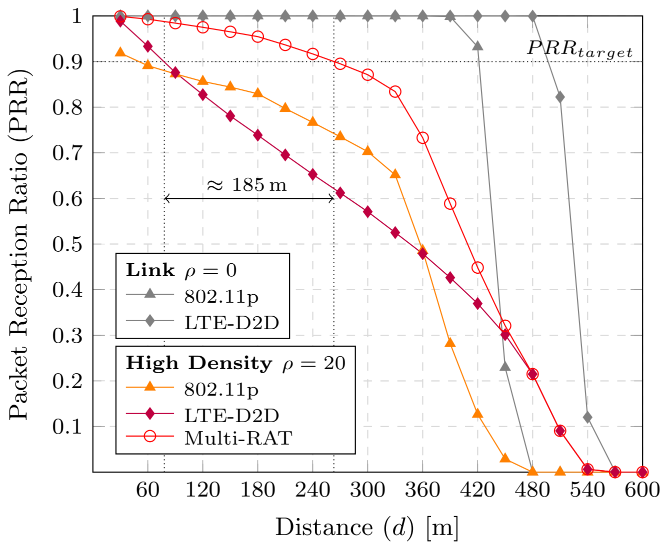

Fig. 4. Packet Reception Ratio (PRR) over distance d measured at a high vehicle density of $\rho = 20$ vehicles/(lane*km).

placed over distance: $d(i) = i \cdot \Delta d$, with a resolution of $\Delta d = 30\,\mathrm{m}$, moving at 80 km/h. All vehicles in the simulation are equipped with both radio technologies. The first truck in the platoon transmits 300 Byte control messages at 10 Hz frequency, the preceding trucks operate as receivers only. Besides, the cars broadcast status messages with the same size and frequency to emulate traffic on the channel. Each preceding truck can be considered as a probe measuring the performance metrics in a certain distance. Preceding trucks calculate the performance metrics PRR, PIR based on successful receptions of control messages sent by the first truck. This allows to evaluate the metrics not only in dependency of vehicle density, but also distance. The wireless channel is modelled with a conventional log-distance model:

$$PL(d) = PL(d_0) + \gamma \cdot 10 \log \left(\frac{d}{d_0} \right) \tag{1}$$

To obtain conservative performance results, we selected the worst case channel parameters from [10], derived from channel measurements at 5.9 GHz: a reference loss $PL(d_0)$ of 52.48 dB at 1 m and a loss exponent γ of 2.96. Both technologies transmit with 23 dBm, the noise power is calculated accordingly to the system bandwidth and the noise figure is left to the simulator default.

C. Performance Metrics

Following application-specific metrics are used to quantify the reliability improvement achieved by Multi-RAT diversity in cooperative automated driving scenarios:

1) Packet Reception Ratio (PRR): The PRR measures the probability of successful reception of packets and equals 1-Packet Error Rate (PER). We calculate the PRR for each truck i at distance $i \cdot \Delta d$. Therefore, we determine the number of successful receptions of packets sent by the first truck $N_{Rx}(i)$ and divide it by the total number of packets sent $N_{Tx}(1)$:

$$PRR(i) = \frac{N_{Rx}(i)}{N_{Tx}(1)} \tag{2}$$

2) Packet Inter-Reception Time (PIR): The PIR measures the average time between two successive receptions of packets $j, j-1$ sent from the first truck at times $t_{Rx}(i,j)$, $t_{Rx}(i,j-1)$ observed at truck i. The PIR can be calculated as follows (N_{Rx} denotes the total number of successful receptions):

$$PIR(i) = \frac{1}{N_{Rx}(i)} \sum_{j=2}^{N_{Rx}(i)} \left(t_{Rx}(i,j) - t_{Rx}(i,j-1) \right) \tag{3}$$

3) Transmission Range Gain (G_r): By comparing the results obtained for PIR and PRR with the reliability targets defined in section II-B the maximum transmission range satisfying the requirements can be determined. The range gain measures the relative improvement of the transmission range in dependency of the vehicle density ρ. Therefore, the range achieved with Multi-RAT diversity d_{MRAT} is compared to the highest range achieved by the base technologies d_{11p}, d_{D2D}. We calculate G_r as follows:

$$G_r(\rho) = 1 + \frac{d_{MRAT}(\rho) - \max\left[d_{11p}(\rho),\, d_{D2D}(\rho)\right]}{\max\left[d_{11p}(\rho),\, d_{D2D}(\rho)\right]} \tag{4}$$

IV. SIMULATION RESULTS

In this section, we present the system-level simulation results for the PRR, PIR and the range gain metric. We selected two different density scenarios for the result presentation of the PRR, PIR metrics: a low density with $\rho = 6$ and a high density scenario with $\rho = 20$ vehicles/(lane*km).

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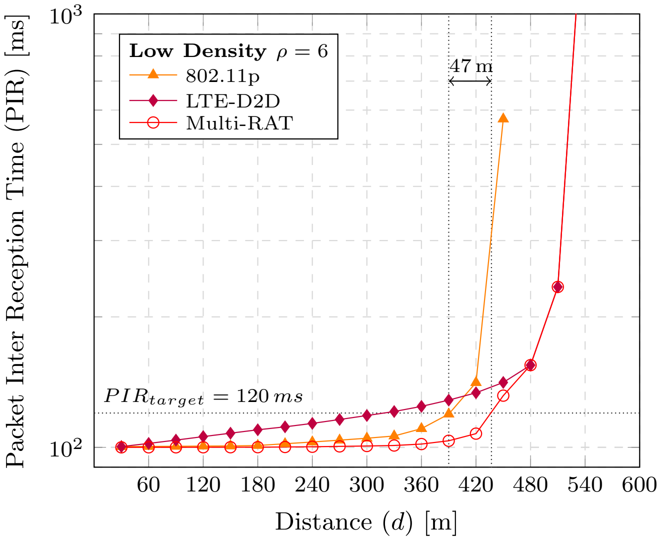

Fig. 5. Packet Inter-Reception Time (PIR) over distance d measured at a low vehicle density of $\rho = 6$ vehicles/(lane*km).

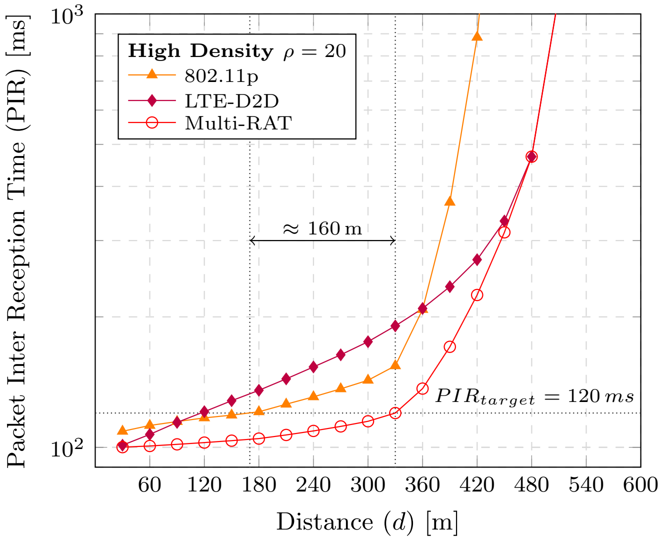

Fig. 6. Packet Inter-Reception Time (PIR) over distance d measured at a high vehicle density of $\rho = 20$ vehicles/(lane*km).

A. Packet Reception Ratio

To better differentiate between link/propagation and access related effects, we added the link performance of the base technologies to the plots. The link performance results are generated for a density of $\rho = 0$ vehicles/(lane*km) (trucks only) and can be considered as an upper bound of the PRR achievable. Since the PRR of 802.11p drops to 0% before LTE-D2D starts degrading from 100%, no performance gain is achieved on link level. To exploit increased robustness against propagation effects, the performance curves need to overlap in areas with reduced PRR values. Since fading effects flatten the curves, the authors expect to observe gains on link level when employing stochastic vehicular channel models.

In the low density case shown in Fig. 3, both technologies start at a PRR of 100%. More packets are lost at higher distances, due to the reduced SINR. Since the carrier sensing in 802.11p reduces the number of collisions (cannot be fully avoided due to hidden nodes) the loss observed is less severe than for LTE-D2D. As the performance of both technologies drops below 100%, diversity gain in terms of increased PRR starts being achieved. Packet loss on access layer dominates the PRR degradation until the link performance drops below 100% due to propagation effects ($390\,\mathrm{m}$ for 802.11p and $480\,\mathrm{m}$ for LTE-D2D). The PRR gain achieved increases until the link performance breakdown of the first technology. When the 802.11p link collapses, we still observe a high PRR gain of approximately 18%. The reason is the compensation of the better performing D2D link. After the LTE-D2D link also breaks down, the gain rapidly decreases to 0%. The crossing of both technology’s PRR curves observed at about $400\,\mathrm{m}$ shows the diverse performance characteristics of both technologies. Considering the derived PRR target value of 90%, the transmission range can be increased from $363\,\mathrm{m}$ to $426\,\mathrm{m}$, which equals an increase of $63\,\mathrm{m}$ with an equivalent range gain of $G_r = 1.17$.

As expected, for the high density case shown in Fig. 4, we observe a stronger PRR degradation due to access loss caused by channel congestion. As a result, an additional crossing of the individual PRR curves occurs at around $85\,\mathrm{m}$, indicating diverse performance characteristics on access level. The increasing loss observed results in a larger PRR gain of up to 15%, achieved by the redundant combination until the 802.11p link collapses. Due to the low downwards slope of the PRR curves in the access effect related region a moderate gain in PRR leads to a much higher gain in transmission range. For a target value of 90%, a PRR gain of around 15% increases the transmission range from $185\,\mathrm{m}$ to $263\,\mathrm{m}$ (by $78\,\mathrm{m}$), which corresponds to a significant gain of $G_r = 3.37$.

B. Packet Inter-Reception Time

In the low-density case shown in Fig. 5, the technologies show a slight PIR improvement in the access-effects dominated area, as a result of the slightly decreasing PRR. Similar to the PRR case, the increase in PIR is well compensated by our Multi-RAT approach. When the link performance of both technologies breaks down, the PIR increases towards infinity. The maximum improvement of up to $15\,\mathrm{ms}$ can be observed after the link breakdown of 802.11p. Since the PIR raises exponentially no more packets are received at high distances to be evaluated. For the required target PIR of $120\,\mathrm{ms}$ the transmission range can be increased from $390\,\mathrm{m}$ to $437\,\mathrm{m}$ (an increase of $47\,\mathrm{m}$). This equals a moderate gain of 12%.

In the high density case shown in Fig. 6, the stronger PRR degradation caused by congestion also results in a higher PIR values. Combing both technologies reduces the PIR by up to $73\,\mathrm{ms}$ by enhancing robustness against congestion. The reduction achieved also leads to a significant improvement in transmission range. From $170\,\mathrm{m}$ to $330\,\mathrm{m}$, which equals an absolute gain of $160\,\mathrm{m}$ and a gain of factor $G_r = 1.9$.

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C. Transmission Range Gain

Since the range gain is dependent on the reliability requirements, we plotted the results in Fig. 7 for a variety of different PRR and PIR thresholds. We selected target values with up to 20% deviation from the optimal values of 100% and 100 ms. For all target values a trend of increasing gain towards higher vehicle densities can be observed.[2] As an example, for the platooning scenario from Section II-B with a PPR target of 90% only a marginal gain is achieved at low vehicle densities.

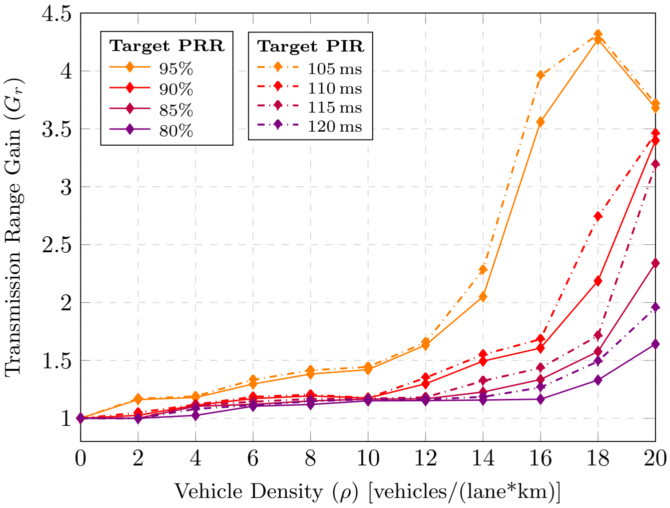

Fig. 7. Transmission range gain G_r over vehicle density ρ evaluated for different PRR and PIR target values.

In contrast, for a highly congested channel with 20 vehicles/(lane*km), a range gain of 3.4 times can is achieved. Consequently, it can be concluded that Multi-RAT diversity significantly increases robustness against channel congestion. Besides the density dependency, a trend of increased gains towards more strict reliability requirements can be observed. For the less strict requirement of 120 ms, taken from our platooning example, the maximum range gain equals a solid factor of two. In contrast, the most strict requirement of 105 ms results in a higher gain of 4.3 times the range. The reason is the less steep PRR slope of the RATs at lower distances. Since the PRR results have shown how lower distances are more prone to access related losses, this further proves the identified robustness against congestion-caused packet loss.

V. CONCLUSION

In this paper we proposed the redundant use of multiple diverse RATs to improve the communication reliability for cooperative automated control applications. We introduced the basic effects, main design aspects and quantified the performance based on an reference highway platooning scenario. The results show the high potential of the Multi-RAT diversity when combining IEEE 802.11p and PC5-based ad-hoc technologies such as LTE-D2D mode 2 or LTE-V2X mode 4. It was shown that Multi-RAT diversity can significantly increase the transmission range by increasing the robustness against channel congestion. High gains are especially observed at high vehicle densities and under strict reliability requirements. Since the achieved reliability improvement is not limited to cooperative control, the approach can also be applied for other applications, under careful consideration of the reduced spectral efficiency. Further investigations involving vehicular channel models, different message frequencies/sizes, MCS settings and a Release 14 compliant LTE-V2X mode 4 module are planned. It is expected that the combination of LTE-V2X mode 4 and IEEE 802.11p performs similarly well and leads to even better communication performance.

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[2] The decrease in gain observed for the targets of 95% and 105 ms results from crossing of the individual PRR curves with different slopes. Still, the conclusion of high densities leading to high gains is reasonable.