Wireless Digital Twin for Assessing the Reliability of Vehicular Communication Links

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***Abstract*—Digital twins are becoming a key technology in evaluating hardware and system performance in wireless communications. The explosion of new use cases in time-sensitive, safety critical scenarios and the stringent requirements for new communication standards are creating a demand for repeatable and cost-effective verification methodologies. In this paper we propose a methodology for building site-specific digital twins of wireless vehicular communication links, enabling us to obtain time-variant packet error rates and asses the link reliability in safety-critical vehicular communications scenarios. The digital twin utilizes a real-time geometry-based stochastic channel model to simulate doubly selective channel frequency responses. The frequency responses are used as input to a hardware-in-the-loop setup, to obtain time-variant packet error rates between two commercial modems. We demonstrate the functionality of the proposed approach by developing a digital twin of a multi-link vehicular scenario. Based on time-critical application requirements we use the obtained error rates to estimate the $90\,\%$ tail probability of the link level latency. In our assessment of the obtained metrics, we see how a geo-routing scenario, combining a shadowed with a relay link, can be used to increase the link reliability and reduce link latency.**

***Index Terms*—digital twin, V2X, HiL, vehicular communications, ad-hoc networks**

I. Introduction

Digital twins are virtual (software) representations of physical objects or processes. The explosion of research in the field of digital twins is powered by their envisioned role as a key technology in the digitalization of product planning and design [1]. The benefits that digital twins bring towards carbon neutrality goals have already been recognized by many industries including transportation, manufacturing, healthcare, and energy [2], [3].

The digital twin concept is also recognized as an enabling technology for future 6^{th} generation standard for mobile communications (6G) research and applications [4]–[6]. Emerging technologies such as reflective intelligent surfaces are already leveraging the digital twin approach to enable fast prototyping and affordable testing [7]. The digital twin methodology can also be applied to wireless propagation channels, to test and evaluate the performance of highly-reliable links in challenging environments.

The benefits of using digital twins in different stages of a communication network deployment process are highlighted by the authors of [6], where the network deployment process is split into three stages: (i) design and deployment, (ii) operation, and (iii) expansion. The digital twin described in this paper covers the physical layer reliability aspect of device-to-device links, and as such, provides an essential building block in a life-cycle of future vehicular networks, following the digital twin categorization from [6].

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The hardware-in-the-loop (HiL) concept is revolutionizing vehicular communication system testing by enabling repeatable and lab-based testing methodologies [8]. The authors of [9] use a geometry-based channel model (GSCM) with a real-time channel emulator to build a HiL setup for repeatable testing that can accurately emulate packet error rate (PER) and received signal power between two vehicular modems. The real-time channel emulator from [9], [10] is used in [11] to build a HiL setup and use it validate a vehicular GSCM on the link level. This is achieved by emulating a link between two commercial modems with both the measurement data and the model simulations and comparing the obtained time-variant PER curves.

Contributions of the Paper:

- We propose a novel method for building site-specific digital twins of highly-reliable wireless vehicular communication links. The presented approach combines a realistic GSCM with a hardware-in-the-loop (HiL) setup, to obtain time-variant PERs of individual links. This combination enables measuring very low error rate values in non-stationary scenarios, thus providing an affordable tool for assessing the reliability (error rate) performance of vehicular wireless links.
- To demonstrate the functionality of the proposed methodology, we develop a digital twin of a multi-link urban overtaking vehicular communications scenario, and evaluate the time-variant PERs of three communication links. We use the obtained PER values to estimate their link-level latency based on the number of required retransmissions for different reliability levels.
- We use the obtained time-variant PER and estimate time-variant latency to evaluate how combining the shadowed link with a relay link in this safety-critical scenario decreases the average error rate in obstructed LoS (OLoS) conditions from 1.2×10^{-2} to 1.4×10^{-6}, and brings down the average latency from $16.4\,\text{ms}$ to $7.9\,\text{ms}$.

II. Vehicular Communication Standards

The IEEE 802.11p vehicular communication standard [12] first offered a standardized protocol for vehicle-to-everything (V2X) communication while the long term evolution (LTE) vehicular communication standard (LTE-V2X) defined in the 3GPP Release 14 [13], provided a cellular system based alternative. More recent technology standards like the successor of 802.11p, 802.11bd [14], and 5G new radio V2X (NR-V2X), included in the 3GPP Release 16 [15], provide better performance than their predecessors [14], [16]. The LTE-V2X standard has been implemented in Cohda Wireless MK6 evaluation kits [17], while to the best of the author's knowledge, the 802.11bd and NR-V2X standards have not yet been implemented in commercial hardware.

For our digital twin we use the commercially available Cohda Wireless MK5 [18] modems, which implement the IEEE 802.11p vehicular communication standard [12]. Therefore, the links under test in this paper are using decentralized environmental notification messages (DENM), defined within the IEEE 802.11p standard, to reliably exchange delay-sensitive information [19], [20]. Vehicles use event-triggered DENM broadcast transmissions with multi-hop communication to notify other vehicles in their vicinity about a safety-relevant event or situation. The DENM messages can be used to exchange details about the event as well as vehicle kinematic information such as position, velocity, and direction. However, it's important to note that the presented framework can be directly applied to other existing and future physical layer standards.

The 5G automotive association (5GAA) defines several main use case categories (e.g., automated driving, platooning, remote driving) with stringent requirements in terms of error rate and latency [21] [22]. For most defined use cases the maximum allowed latency is $z = 10\,\mathrm{ms}$, and the minimum reliability is $r = 99.99\%$. A similar use case categorization for vehicular communications, with almost identical requirements, is defined by 3GPP 5G Rel. 16 [23].

III. Channel Model

To test high reliability levels (low error rates) many packets need to be transmitted. To measure PER values of γ at least $M_\mathrm{e} = 1/(\gamma\sigma)$ packets are needed, where σ denotes the variance. It is difficult to recreate measurement conditions (e.g., vehicle velocity, traffic conditions) in complex non-stationary vehicular scenarios. Hence, using a realistic channel model to obtain channel impulse responses by simulation is a more feasible option than using measurement data.

GSCMs are a suitable choice for modeling dynamic vehicular communication scenarios due to their ability to model the time-variant non-stationary statistics of time-variant channels with high accuracy [24]. Therefore, for the purpose of building a digital twin of vehicular communication links we use the real-time GSCM framework and the model parameters presented in [11].

Our vehicular communication scenario simulations are executed in MatLab. The GSCM environment geometry is built by parsing extracted OpenStreetMap (OSM) data, with diffuse scatterers automatically placed along buildings and vegetation. A locality sensitive hashing algorithm is used to select a subset of relevant diffuse scatterers and speed up the computations [25]. The GSCM uses (i) static discrete scatterers to represent reflective objects, such as traffic signs, and (ii) mobile discrete scatterers, with distinct reflective and penetration characteristics, to model cars and large vehicles [11].

Each simulation run is initiated with uniformly distributed random scatterer phases, allowing us to use multiple simulation runs to compute the channel statistics with uncorrelated scattering. During the simulation of multiple links we keep the initial scatterer phases to maintain correct mutual correlation properties.

Using a GSCM that models different geometries with publicly available data from OSM enables constraint-free scenario modeling. Furthermore, our geometry-based modeling approach can be easily scaled to system-level, as shown in [26].

IV. HiL Setup

The time-variant PERs are obtained using the HiL setup described in [27], where the HiL setup is used to validate a channel model. The setup uses channel frequency responses as input to the AIT real-time channel emulator [10], which uses a software defined radio (SDR) to emulate the wireless channel between two commercial modems.

To adapt the input data to the sampling rate of the emulator, the frequency responses are interpolated in time and frequency using discrete prolate spheroidal (DPS) sequences [28], [11]. The interpolated frequency responses are compressed by projecting them to a DPS sequence subspace, and then streamed in real-time to the SDR. At the SDR, the emulator convolves the channel coefficients with the signal from the transmit modem and forwards them to the receiver.

From the received packets we infer the error rate for a total of M_e transmitted packets as

$$\gamma[k] = p_\mathrm{e}[k]/M_\mathrm{e}\,, \tag{1}$$

where $p_\mathrm{e}[k] \in \{1, ..., M_\mathrm{e}\}$ is the number of erroneously received or missed packets, and the PER is bound as $\gamma[k] >= 1/(M_\mathrm{e}\sigma)$.

To measure PER values for $\gamma[k] < 1/(M_\mathrm{e}\sigma)$ we compute the combined packet error probability of K_e emulations, making $\gamma[k] >= 1/(K_\mathrm{e}M_\mathrm{e}\sigma)$. Alternatively, it is possible to calculate lower PERs by simply increasing the number of packets for which PER is computed (M_e) in (1), albeit at a cost of decreasing the PER sample resolution in time.

This approach allows testing use cases that have high reliability requirements, without performing extensive field measurements. Additionally, the presented HiL implementation allows easy and repeatable link-level testing for different modems and with different communication parameters.

V. Vehicular Communication Scenario

To demonstrate the functionality of our digital twin framework we analyze an urban overtaking scenario presented in [11], which consists of $L = 3$ vehicular wireless communication links between three cars, as depicted in Fig. 1. In the scenario, a double-decker bus obstructs the LoS connection between car 3 that intends to overtake the bus, and car 1 which is approaching from the opposite direction. Meanwhile, car 2 drives in front of the bus, with a LoS link to car 1 and an obstructed, but stable link to node 3. All the vehicles in the scenario are moving at an approximately constant speed of $\approx 11\,\mathrm{m/s}$. The scenario lasts for a total of $15\,\mathrm{s}$, during which the LoS of link $(1, 3)$ is obstructed (by the bus) between time instants $t_1 = 2.3\,\mathrm{s}$ and $t_2 = 7.9\,\mathrm{s}$.

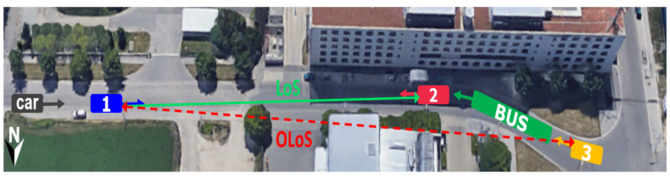

Fig. 1. Scenario diagram. Cars 1 and 2 have a line of sight (LoS) connection, while the connection between cars 1 and 3 is in obstructed LoS (OLoS). Map source: Google Maps.

A. Setup Parameters

We use the real-time GSCM described in Sec. III to model the three vehicular links and simulate time-variant channel frequency responses. The modelled links are calibrated using measurement data obtained in [11], where the model is validated by means of a qualitative and quantitative comparison of the measured and simulated time-variant channel statistics of link $(1, 3)$. In this paper we use the calibrated GSCM parameters from [11] to model all three links in the described scenario.

We emulate the channel between two commercially available Cohda Wireless MK5 [18] modems which use the IEEE 802.11p standard for vehicular communications [12]. The modems are set to use a packet length of 100 bytes and a QPSK modulation with $1/2$ convolutional coding rate. The Tx modem sends at $5\,\mathrm{dBm}$ power and with a rate of $1000\,\mathrm{packets/s}$ ($800\,\mathrm{kbit/s}$ throughput).

VI. System Model

Vehicular communication use cases described by the 5GAA and 3GPP [22] have defined thresholds for minimum required reliability and maximum latency. To reach the desired reliability level, the percentage of successfully received DENM messages can be increased by increasing the number of message retransmissions. However, increasing the number of retransmissions increases latency.

To show the practical application potential of the developed digital twin, we use the obtained time-variant PERs to compute the number of packet retransmissions needed for a certain reliability threshold. We then estimate the time-variant link-level latency that can be observed for 90% of the time of the analyzed scenario. The estimated latency values for a required reliability threshold (measured in terms of error rate) can be used to asses link performance against application scenario requirements.

The error probability of a DENM is denoted by γ. To model the probability of successfully receiving a DENM we use a Markov process with two states $\Omega = \{1, 2\}$, where the 1 denotes a successful reception and 2 denotes a lost message. By following the Chapman-Kolmogorov equation [29, (pp. 705-708)] we obtain the probability of successfully receiving a DENM after S repetitions, given that the first DENM was dropped due to an error, as

$$\mathbb{P}(X_S = 1 | X_0 = 2) = (1 - \gamma) \sum_{s=0}^{S} \gamma^s = 1 - \gamma_{a,b}^{S+1}\,, \quad (2)$$

where X is the random process of receiving a message, and S denotes the number of repetitions of a DENM required for a successful reception. Given γ we can ask how many repetitions we would need in order to achieve a specific reliability r, which presents the percentage of successfully received packets. We want to find S such that $\mathbb{P}(X_S = 1 | X_0 = 2) \geq r$ holds. We can obtain S as

$$S \geq \max\left\{0, \left\lceil \frac{\ln(1 - r)}{\ln(\gamma)} - 1 \right\rceil \right\}. \quad (3)$$

A. Latency Model

When considering time-sensitive (and often safety-critical) communications, the data has to be received within a certain time window, i.e., a latency constraint is imposed in addition to reliability. For the purpose of this paper we consider the enhanced distributed channel access (EDCA) algorithm [30] to be used for random channel access at the medium access control (MAC) layer. Therefore, we assume that the sending rates only depend on the latency induced at the MAC layer due to it being orders of magnitude larger than the the latency at the physical layer, caused by signal propagation. In this case the lowest latency corresponds to the packet sent without waiting in the buffer queue and with immediate access to the shared wireless medium.

The authors of [31] investigate the delay distribution of IEEE 802.11p transmissions and find that the latency for a transmission, when a packet becomes the head of a queue, until its successful reception can be modeled by a shifted exponential distribution. If we assume that DENMs are queued in the highest priority access category (where access categories represent different types of data traffic), we can model the latency of a successful reception by $D \sim \mathrm{Exp}(\lambda_{\mathrm{D}})$, where $\mathbb{E}[D] = \frac{1}{\lambda_{\mathrm{D}}}$ is the expected latency and λ_{D} is the distribution parameter. Sending the same frame $S + 1$ times with i.i.d. delays between the messages, we have $Y = \sum_{s=1}^{S+1} D \sim \mathrm{Erl}(S + 1, \lambda_{\mathrm{D}})$, with $\mathrm{Erl}(x)$ denoting the Erlang distribution of random variable x. The cumulative distribution function of the Erlang distribution can be expressed by the regularized gamma function

$$F_{\mathrm{E}}(Y \leq x | S+1, \lambda_{\mathrm{D}}) = \frac{\Gamma(S+1, \lambda_{\mathrm{D}} x)}{(S+1)!} = P_{\mathrm{E}}(S+1, \lambda_{\mathrm{D}} x)\,, \tag{4}$$

for which the inverse can be computed with $x \in \mathbb{R}^+$ [32]. The lower incomplete gamma function, and the lower regularized gamma function are denoted by Γ, and P_{E}, respectively.

We denote the link level latency of a link with ϕ. The maximum latency that may occur with a probability greater or equal to $\alpha \in [0,1]$ is denoted by z. We are interested in finding $z \in \mathbb{R}^+$ which satisfies $\alpha \leq \mathbb{P}(z|r) = \mathbb{P}(\phi_{1,3} \leq z|r)$.

After computing the number of repetitions S, and plugging the result into (4) to compute the inverse of the regularized inverse gamma function P_{E}^{-1}, we obtain the estimated latency z that is expected to be observed for α, as

$$z \geq \frac{1}{\xi} z = \frac{1}{\xi} P_{\mathrm{E}}^{-1}(S, \alpha_1) \tag{5}$$

where ξ denotes the DENM packet transmission rate.

B. Multi-hop Geo-routing

In the overtaking scenario, described in Sec.V, link $(1,3)$ is obstructed by a bus. Before attempting an overtaking maneuver, car 3 needs to notify other vehicles of its intention and reliably exchange its kinematic data (e.g., position, velocity, acceleration) with car 1. Meanwhile, link $(1,2)$ has unobstructed LOS conditions, as car 2 is driving in front of the bus.

Different cooperative diversity schemes at the physical layer have proven to benefit the performance of wireless links [33], [34]. Geo-routing protocols have been used to reduce wireless medium congestion by using other nodes as relays and routing messages to selected vehicles in their vicinity [35]. An overview of different reactive geo-routing protocols for ad-hoc vehicular networks is given in [36].

We want to demonstrate how our digital twin framework can be applied for analyzing the reliability and latency in such a complex vehicular scenario for novel transmission schemes. Hence, we first analyze the performance of each individual link in the overtaking scenario. We then use the obtained data to analyze the potential advantages of using a multi-hop geo-routing protocol [36] to forward packets from node 3 via node 2, to node 1 (and vice-versa). Our aim is to improve reliability and latency of link $(1,3)$. This goal is validated by comparing the performance of the shadowed link $(1,3)$ to the case when link $(1,3)$ is combined with the relay link $(1,2,3)$.

In our scenario we assume that car 3 uses geo-routing to forward its intention of overtaking and kinematic information to car 1, through a relay link via car 2. We additionally assume no packet combining scheme is implemented and, that both, the direct link and the relay link are independent and do not interfere with each other due to time multiplexing.

The relay link performance in the presented overtaking scenario can be further investigated by testing different geo-routing and relay selection algorithms, and more competitive channel access conditions (e.g., through the use of traffic and network simulators). These topics go beyond the scope of this paper, and are part of our future work.

C. Combined Link Reliability and Latency

The error probability for a single packet transmission over the direct link (link) is denoted by $\gamma_{1,3}$. The error probability of link from the source to the relay (link $(1,2)$) is denoted by $\gamma_{1,2}$, and from the relay to receiver (link $(2,3)$) by $\gamma_{2,3}$. The error probability for the multi-hop relay link is computed as

$$\gamma_{1,2,3} = 1 - (1-\gamma_{1,2})(1-\gamma_{2,3})\,. \tag{6}$$

The total error probability of the combined link then reads

$$\gamma_{\mathrm{R}} = \gamma_{1,2,3}\gamma_{1,3}\,, \tag{7}$$

when assuming a perfect and independent cooperative diversity scheme at the physical layer without using any combining algorithms. In other words, γ_{R} presents a theoretically achievable error rate of the combined link, which is used in this paper for comparison purposes. Plugging (7) into (3) yields the number of packet repetitions S_{R} needed to achieve a given reliability r through the use of the combined link.

The direct link and the relay link latency are denoted by random variables $\phi_{1,3}$ and $\phi_{1,2,3}$, respectively. With $Z = \max\{\phi_{1,3}, \phi_{1,2,3}\}$, the combined link latency must now satisfy $\alpha \leq \mathbb{P}(Z \leq z|r) = \mathbb{P}(\phi_{1,3} \leq z|r\mathbb{P}(\phi_{1,2,3} \leq z|r)$. This asks for the selection of $\alpha_1, \alpha_2 \in [0,1] : \alpha = \alpha_1\alpha_2$, $\alpha_1 \leq \mathbb{P}(\phi_{1,3} \leq z|r)$ and $\alpha_2 \leq \mathbb{P}(\phi_{1,2,3} \leq z|r)$. Since we assume an identical treatment of the two links, then we can set $\alpha_1 = \alpha_2 = \sqrt{\alpha}$.

The estimated latency of the combined link z_{R} is obtained as

$$\begin{aligned} z_{\mathrm{R}} &\geq \max\left\{\frac{1}{\xi_{1,3}} z_{1,3}, \frac{1}{\xi_{1,2,3}} z_{1,2,3}\right\} = \\ &\max\left\{\frac{1}{\xi_{1,3}} P_{\mathrm{E}}^{-1}(S_{\mathrm{R}}, \alpha_1), \frac{1}{\xi_{1,2,3}} P_{\mathrm{E}}^{-1}(2S_{\mathrm{R}}, \alpha_2)\right\} = \\ &\frac{1}{\xi_{1,2,3}} P_{\mathrm{E}}^{-1}(2S_{\mathrm{R}}, \alpha_2), \end{aligned} \tag{8}$$

where $\xi_{1,3}$ and $\xi_{1,2,3}$ denote the packet transmission rates for the direct link and the relay link, respectively. However, this only holds if we assume that the latency on the links from transmitter to relay and from the relay to the receiver are identically and independently distributed.

VII. Results

A. PER Analysis

We use the described HiL setup from Sec. IV to obtain the time-variant PERs of all three vehicular links and the combined link in the overtaking scenario. The obtained PERs are shown in Fig. 2. Before instant t_1, nodes 2 and 3 move towards node 1 and PER values drop, as expected. When node 3 is obstructed by the bus driving in front of it during the time interval Δt, $\gamma_{1,3}[k]$ has an average value of 1.2×10^{-2} while the average value of $\gamma_{\mathrm{R}}[k]$ is 1.4×10^{-6}. After instant

t_2, $\gamma_{1,2}[k]$ becomes higher than $\gamma_{1,3}[k]$, as node 2 becomes shadowed by the obstructing vehicle. These quantifiable insights obtained trough the use of our site-specific digital twin, show that utilizing a combined link in the analyzed scenario drastically increases the performance of a shadowed vehicle, reducing the error rate by a factor of 10^4 .

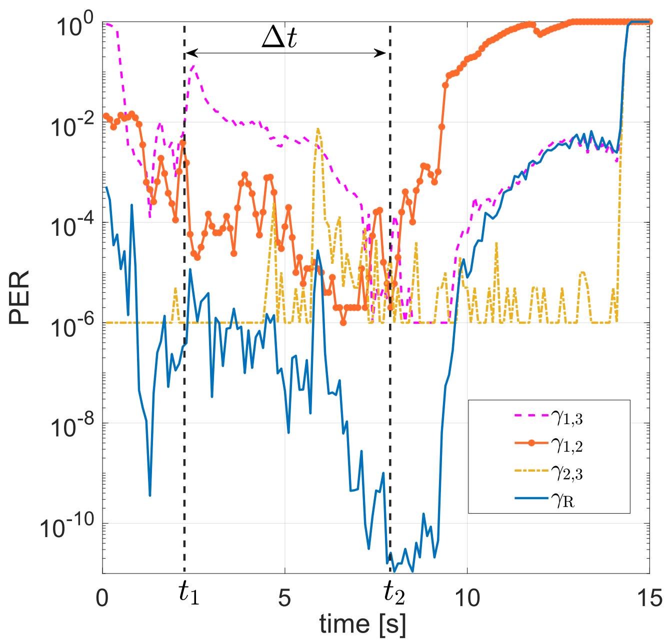

Fig. 2. The obtained time-variant PERs of the three vehicular links in the overtaking scenario. Time instants t_1 and t_2 mark the period during which link $(1, 3)$ is obstructed. The time-variant PER of the combined link is presented by the γ_R curve.

B. Latency Analysis

From (2) and (3) we obtain the required number of repetitions for the direct link. We then compute the latency of both the direct link and the combined link, for $\alpha = 0.9$, i.e. 90% of the cases of the distribution described in (4).

Fig. 3 shows the moving average over a window of 3 samples of the time-variant latency calculated for the direct and the combined link. Latency is proportional to the number of retransmissions (see (5)), and consequently, to the PER values (see (3)). Therefore, the latency values show the same behaviour as the PER values. Prior to t_1 the latency values of links $(1, 3)$ and $(1, 2)$ drop as cars drive towards each other, and they increase after t_2 as the cars drive away. During time interval Δt combining the direct link with the relay link yields an average decrease in latency from $16.4\,\text{ms}$ to $7.9\,\text{ms}$, for $r > 99.999\%$.

When comparing the obtained latency values of the direct link and the combined link for $r = 99.999\%$ (corresponding to the purple lines in Fig. 3) against the thresholds set for the advanced driving use case defined by the 5GAA in [21], we find that adding the relay link meets the reliability and latency requirements in 56.6% of the time while using only the direct link meets the requirements in only 13.2%.

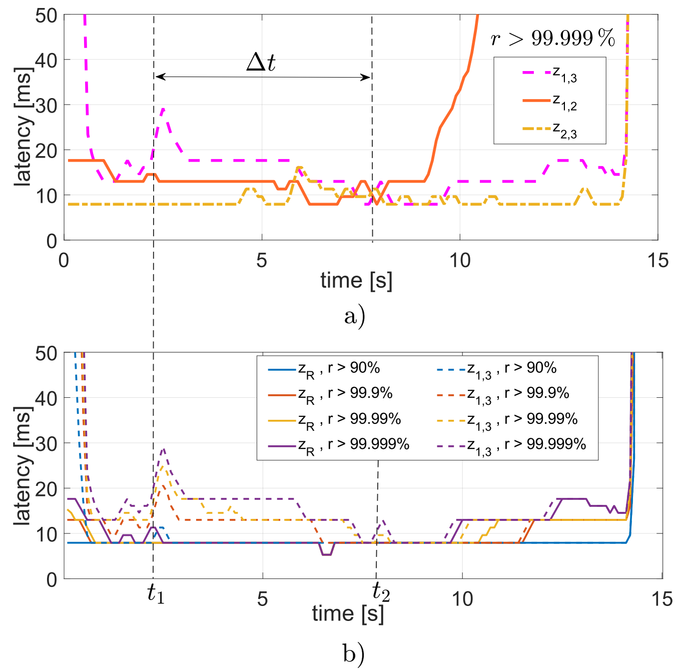

Fig. 3. a) time-variant latency values of the multi-link scenario estimated for $r = 99,999\,\%$ and $\alpha = 0.9$. The colour of each link corresponds to their respective PER curves in Fig. 2.
b) the direct link (dashed lines) and the combined link (full lines) in the overtaking scenario, plotted for different reliability constraint values r.

VIII. Conclusions

In this paper we presented a methodology for building a site-specific digital twin for reliable wireless vehicular communications. Our digital twin combines realistic GSCM simulations with a HiL setup, to asses very low error rates and estimate link-level latency in vehicular non-stationary scenarios.

We demonstrated the functionality of the proposed methodology by modeling three links in an urban overtaking vehicular communications scenario. The packet error rates of the three links are obtained by emulating links between two commercial IEEE 802.11p modems. However, the same methodology can be used for different standards and protocols such as LTE-V2X or 5G NR-V2X, with the PC5 sidelink [37], or IEEE 802.11bd. With this work, we show that our digital twin framework is a solution that can be used for affordable and efficient testing and assessment of demanding ultra-reliable low-latency communications scenarios.

The emulated error rates are used to analyze the benefits of combining a direct link with a geo-routed relay link in terms of reliability and latency. We find that combining these two links in an obstructed LoS scenario reduces the average error rate from 1.2×10^{-2} to 1.4×10^{-6}, and the average latency drops from $16.4\,\text{ms}$ to $7.9\,\text{ms}$.

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