Full Physical Layer Simulation Tool to Design Future 77 GHz JCRS-Applications

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ABSTRACT Vehicular communication systems get more and more attention with the upcoming fifth and sixth generation. Hereby, the focus lies on the development of the co-design or co-existence of communications and sensing. So called joint communications and radar sensing systems are seen as one key technology of 6G. As joint systems will have shared waveforms and hardware platforms, there is a huge benefit in cost and space which is one essential argument for the automotive industry. However, to design such a system for new applications like platooning or intersection assistance a physical layer has to be set up to represent the real physical layer properly. The proposed system design closes the lack of such a simulation tool and allows for full physical layer simulations, including e.g. the hardware non-idealities and the channel model for 77 GHz. The whole signal processing chain of the physical layer is built up and will be integrated in the higher layer state-of-the-art simulation frameworks like Veins or Artery in the next step. The communications design is developed in Simulink, whereas the sensing part is discussed.

The proposed communications architecture covers several transmission approaches (serial, parallel), a CDMA based spreading, a radio frequency representation, the channel (simulated in a 3D-Ray-Tracing-tool) and the receiver structure (e.g. the synchronisation or the channel estimation). Several design criteria are discussed, like the serial or parallel design architecture, the maximum ratio combining or the phase and frequency compensation method. The whole system architecture is freely available and in consequence, the different signal blocks and parameters can be enabled or disabled for evaluations according to future design criteria requirements.

INDEX TERMS hardware non-idealities, connected vehicles, joint communications and radar sensing, millimeter wave technology, physical layer, Simulink.

I. INTRODUCTION

Due to the emergence of vehicular networks, intelligent transportation systems and autonomous cars over the last decade, new developments of software, hardware, and communication solutions are pushed. The resulting innovative applications aim to improve the driving experience but mainly address safety like communicating potential road hazard warnings [1]. Three key components which are integrated into modern cars are an increased amount of sensors, information systems, and communication technologies to create connected vehicle networks [2]. While the sensors improve the understanding of the close environment around the vehicle, communication will allow to extend the field of view to distances kilometres in front of the vehicle as it allows to have several cars with their individual sensing systems connected [3]. Thus, vehicle-to-vehicle (V2V) communication has the potential to improve the safety of passengers, the smart management of vehicles on roads and reduce the
congestion in traffic. In consequence, the best route can be successfully found, hazards can be detected and avoided and fuel can be saved to name only some of the various advantages [4]–[7].

Summarized, intelligent transportation systems are forcing new technologies to rise. Especially, vehicular communications is widely discussed in the communities. By extending V2V towards vehicle-to-everything (V2X), connections to all forms of road users like pedestrians or cyclists, vehicles but also infrastructure like for example roadside units (RSUs) can be established. Standards like Car-Long Term Evolution (C-LTE) or IEEE 802.11p are already implemented, however potentially suffer from interference, due to e.g. large Doppler spreads resulting from highly dynamic scenarios [9]–[12]. As IEEE 802.11p is based on carrier-sense multiple access (CSMA) as its medium access control method, the system is prone to interference. The CSMA can additionally result in critical situation where the communication can experience very long channel delays [13].

This problem even increases, as the total number of vehicles on the roads are still growing and those modern cars will additionally have more sensors and communications systems included, potential interfering and distorting each other. To overcome this problem, radar based communications in the millimeter-wave frequency bands (mmWaves) is discussed [14]–[17]. Building up this additional communication link can benefit from the already established radar systems, working at just those frequencies. Radar systems even work very well in harsh conditions (rain, snow) and are meanwhile common for safety applications like adaptive cruise control or advanced driving assistance (ADAS), in modern cars [18], [19]. Thus, radar sensors are used to detect the presence of objectives, obstacles’ relative velocities and their corresponding range.

The idea of combining both radar sensing and communications is the next logical step and will have the advantages of saving money and especially hardware, as it is aimed to have both tasks on one single waveform [20]. Besides, at mmWave frequency bands, sensing as well as communication can benefit from the available bandwidth (at the 77 GHz band 4 GHz of bandwidth). Suitable waveforms for the so called joint communications and radar sensing (JCRS) technology are discussed widely. Thus, waveforms like frequency modulated continuous wave (FMCW), phase modulated continuous wave (PMCW) together with orthogonal frequency division multiplexing (OFDM) or code division multiple access (CDMA) are considered [20]–[23].

For a stable and reliable JCRS system designs however, not only the applied waveform but the entire physical layer has to be investigated, while taking into account e.g. the hardware and the channel characteristics. Full simulation systems are proposed in the literature for vehicular communications [24]–[29]. Reichardt et al. [24] designed a system at 5.9 GHz and investigated, inter alia, bit-error-rate (BER)/packet-error-rate (PER) for V2V communications for various traffic scenes. Besides, Shirude et al. [25] proposed a full transmitter and receiver design, using MATLAB/Simulink, whereas Wang et al. [26] published a vehicular ad-hoc network (VANET) simulation environment, which reconstructs the inter-vehicle-communications again for different scenarios and is designed using the MATLAB. Dakić et al. [27], on the other hand, presented a validated real-time system-level simulation for vehicular communication scenario at 5.9 GHz, using a hardware-in-the-loop simulation platform and a geometry-based stochastic channel model. Saponara et al. [28] propose a model of the IEEE 802.11p’s physical layer, using Matlab/Simulink simulations to analyse the baseband processing as well as the RF hardware parts and the physical channel for various scenarios (urban, suburban, highway). The work presented by Cabezas et al. [29] goes in the same direction. They introduced a simulation model for the IEEE 802.11p physical layer in MATLAB to obtain the PER, too. Alternatives to the legacy 802.11p standard are proposed by Triwinarko et al. [30]. The authors observed physical layer enhancements (regarding improved PER and partly higher throughput) with other 802.11 standards based on physical layer simulations done in Matlab.

In addition to the physical layer simulations, network simulations are mandatory to reconstruct an inter-vehicular communication system realistically [35]. There are different network simulators like OMNET++, ns-3, OPNET, JIST/SWANS and GloMoSim. A modular framework can be additionally used to create interaction between the two main components (network and physical layer) or even extend the network simulator to create simulation models. Veins, based on OMNET++ network simulator and SUMO traffic simulator [36], and Artery, a V2X modular framework based on ETSI ITS-G5 protocols [37], are well known examples of such tools. In [38], a realistic simulation framework integrating Gazebo with OMNET++ over Robot Operating System (ROS) which supports simulation and validation of cooperative vehicular platooning is proposed. This type of a realistic simulation environment reduces the overhead in terms of cost and complexity of validating a technology in the real world.

In [39], an existing co-simulation platform composed of SUMO and OMNET++ with realistic models of electrical vehicles (EVs), EV supply equipment and charging reservation, is extended to design a novel EV platform which assists in the pre-deployment of charging infrastructures on EV scenarios. Lekidis et al. [40] propose a new method based on OMNET++ for testing new in-vehicle features and the assessment of risks through network simulation is presented. In [41], the methods for communication between the road traffic simulator SUMO and and network simulator ns-3 is studied. The potential benefits of high data-rates in mmWave communications is also well-tapped in the vehicular communication applications. In [42], to provide a performance evaluation of V2V networks, MilliCar (the new ns-3 module based on the latest NR V2X specifications [43]) is utilized. MilliCar contains the implementation of the 3GPP channel model for V2V communications. It also includes the prop-
agitation and physical and Medium Access Control (MAC) layers in-line with the frame structure of 3GPP NR V2X. Another significant tools involved in the vehicular network simulation are Matlab/Simulink. In [44], a 5G VANETs experimental study is presented comparing the results (transfer rate and transmission delay) obtained by the ns-3 and Matlab simulations. The proposed results were able to satisfy the rigid requirements for the vehicular communication, when mmWaves are utilized for 5G networks.

In this work, the physical layer is in the focus and a complete physical layer representation is implemented in Simulink for a mmWave vehicular communications system at 77 GHz. To the best of the authors’ knowledge, there does not exist a comparable simulation environment that also considers the full physical layer at mmWaves with various signal processing blocks, integrating hardware-non-idealities and channel characteristics of a typical V2V scenario, and comparing serial and parallel pilot configuration, respectively. Indeed, a disadvantage associated with tools like Matlab/Simulink is the inability to involve complex network protocols, vehicles’ and communications models [45]. However, to overcome this problem, the proposed architecture will be integrated in the network simulator Veins in the future. Our key contributions are summarized:

- We propose a full physical layer simulation tool in Simulink for modelling the vehicular communications;
- we investigate the synchronisation, the phase/frequency compensation, a Rake receiver structure and maximal-ratio combining;
- we analyse the influence of the channel; therefore, we include channel information out of simulations done in the 3D-Ray-Tracing commercial software WinProp, Altair, for typical traffic scenarios;
- we investigate the effect of hardware non-idealities (i.e. non linearities, noise);
- we further analyse two approaches of setting up the communications via a serial as well as a parallel implementation.

The publication is organized as follows: In chapter II, several concepts of Radar-based communications (Radcom) are discussed, especially regarding the later used CDMA multiplexing technique. The general system design in Simulink is proposed in chapter III, whereas the description of the transmitter, channel and receiver is given in the chapters IV-VI, respectively. In chapter VII, the influence of the individual blocks as well as the comparison of the serial and parallel approach are depicted. Subsequently, the results are discussed in chapter VIII and the limitations are identified in chapter IX. Finally, a conclusion and outlook is given in chapter X.

II. RADAR-BASED VEHICULAR COMMUNICATION

Radar-based communication, especially the JCRS approach, aims to complete the set of already existing communication standards at the 5.9 GHz band (IEEE 802.11p and the cellular approaches like Long Term Evolution – Vehicular communication to everything (LTE-V2X)). The resulting heterogeneous network is depicted in Fig. 1 and enables cooperative decisions [46]. Applications like platooning and intersection assistance will be addressed with Radcom which is designed to provide a safe communication link to allow the implementation of such safety relevant applications.

FIGURE 1. Overview of the full set of vehicular communication approaches, including the established vehicular communication standards, as well as the proposed radar-based communications. Together, they will be interacting as a heterogeneous network to enable cooperative decisions for applications like platooning (Reprinted with permission from [8] ©IEEE 2021).

TABLE 1. Comparison of the vehicular communication standards [3], [10], [31]–[34]

|                        | IEEE 802.11p | LTE-V2X | 5G based V2X |
|------------------------|--------------|---------|--------------|
| Sustainable rate       | 3-27 Mbit/s  | 10 Mbit/s | 1 Gbit/s     |
| Peak rate              | -            | 1 Gbit/s | >10 Gbit/s   |
| Latency                | <10 ms       | 10 ms    | 1 ms         |
| Maximum speed          | 500 km/h     | 350 km/h | 500 km/h     |
| Range                  | <1000 m      | 30 km    | 30 km        |
| Bandwidth              | 10 MHz       | 10 MHz or 20 MHz | 100 MHz or 400 MHz |
safe communication link, next to the shared waveform and hardware platform are significant benefits, when compared to the established standards.

The communication standards (IEEE 802.11p and the cellular approaches) used for vehicular communication, are compared regarding their configuration in Tab. 1. IEEE 802.11p (weakened by the decision of the Federal Communications Commission (FCC) in 2020 by deallocating the 5.9 GHz bands) and C-V2X, strengthen by the FCC, will be complemented by Radcom [47], as both standards face challenges in fulfilling the traffic demands for future intelligent transportation systems regarding the throughput at the same time with ultra low latency and high reliability requirements [48]. Millimeter-wave communications, however, can enhance V2X communications [3]: It enables high throughput and allows to reuse the frequencies after short distances due to the short range/ high pathloss experienced at those frequencies. In consequence, there is less interference, which is a great advantage for the exchange of safety relevant information. Besides, the cost are getting reduced, on the one hand due to reduced antenna cost (because of the shorter wavelengths) and on the other hand due to the objective to design a JCRS based system design which uses only one waveform for sensing and communications and has both implemented on a single hardware platform.

In the following, those combined mmWave systems are discussed. First several waveform designs are discussed and the benefits of the chosen PMCW/CDMA design are highlighted. Afterwards, the state-of-the-art sensing methods are compared, whereby the general processing steps for CDMA are explained in detail.

A. JCRS WAVEFORM DESIGN

For JCRS designs, various waveforms are discussed in the literature [49]–[59]. Next to approaches using OFDM [49]–[51], Linear Frequency Modulation (LFM) [52], PCMW [53], [54] and FMCW [58]–[61] based systems are utilized.

The waveform at mmWave frequencies, typically used in modern radar sensors, is based on FMCW. It provides a fast and cost efficient signal processing via fast-Fourier transform (FFT) to detect the wanted targets parameters (velocity, range, direction of arrival). However, multiplexing is not performed in the typical radar applications. In consequence, FMCW systems are prone to interference especially when it falls in the passband of the receiver which is more likely the case in dense traffic scenarios [62], [63]. However, interference has to be minimized as it is critical for communication of safety relevant information as well as for sensing where it can result for example in ghost targets and a reduced measurement accuracy or even sensor blindness [19]. Because of these drawbacks, FMCW is not likely to be used as a communication waveform because of its non standardized, interference prone and noisy signal structure. For communication, however, a clear and distortion free signal is needed, especially for applications like platooning or intersection assistance which need a trustworthy communication link.

Thus, other waveforms are discussed in the communities, like systems that are using OFDM, LFM or PMCW. In the proposed system a PMCW waveform is chosen. It is based on direct sequence code division multiple access (DS-CDMA) and does not utilize a linear frequency ramp different to the FMCW approaches. In consequence, the processing is done via correlation receivers which allows a less complex, power efficient, robust implementation, avoiding fast frequency synthesizing and highly linear slopes [53], [64].

On the other hand, OFDM based systems have a high dynamic fluctuating in the transmitted envelope power and thus, suffer from high peak to average power ratios [65]. Additionally, PMCW is less sensitive to carrier frequency offsets than OFDM based multi-carrier systems where the high offsets are caused by the need of several local oscillators and discrete Fourier transform leakages which in turn makes it necessary to implement correction algorithms.

Besides, PMCW has the advantages of a very sharp ambiguity function, resulting in reduced range-Doppler ambiguity [66] and allows to design a MIMO radar in the code domain[64]. In consequence, a high angular resolution with fewer antennas within the same physical aperture is achievable. In addition, the proposed PMCW system can guarantee minor interference to other systems operating in the same spectral band [67]. This is due to the applied CDMA which spreads the data with orthogonal pseudorandom noise (PN) sequences at the transmitters. The receiver will only be able to successfully demodulate the data if the receiver despreads with the code sequence corresponding to the one of the intended transmitter. In consequence, the spreading secures that the transmitted signals increases the noise/distortion level only marginally and is at the same time difficult to detect and process and hence very useful in safety critical applications. This also helps in accommodating fading and multipath-channels, which makes them such beneficial for the mmWave applications as those are very susceptible to fading.

Summarized, PMCW is chosen as it has several advantages compared to other waveforms, e.g. the robustness towards interference which is essential for the addressed applications, outweighing the drawbacks of CDMA systems (e.g. the need of a high sampling rate or measuring time [68]). However, the PMCW waveform is not only applicable for communications but also for radar sensing, which is discussed next.

B. RADAR

As aforementioned, PMCW is not the typical waveform for modern radar sensors. Traditionally, FMCW is used due to its low complexity of detecting the wanted information (velocity, range, direction-of-arrival) and associated hardware costs. A rather simple signal processing, mainly 2D-Fourier-based, is necessary which is fast and cost saving [19]. However, FMCW is not advantageous as it is prone to be interfered or distorted by other sensors. In consequence, researchers were even able to introduce spoofing attacks into
a FMCW radar system with the risk to cause critical accidents by influencing the cars’ sensors [69], [70].

To solve the interference and security challenge, the system that should be addressed in this work is one that combines interference reduction and code division multiplexing together with the integration of sensing and communications to establish a secure communication path among the vehicles. PMCW based radar sensors are also well known in the literature [71]–[74]. A combined PMCW-JCRS is for example shown by K.V. Mishra et al. (2019) [54]. The general correlation based principle of PMCW radar systems are described in detail by F. Roos et al. (2019) [68]. Sensing, however, will not be further discussed as the communications model will be in the focus of the proposed work. But, the suitability of PMCW is shown and the PMCW sensing processing chain is taken into account for extending a published simplistic Simulink model by the authors (see [75]) for future integration in a JCRS Simulink model.

### III. SIMULINK MODEL

According to the previous sections, a DS-CDMA based system is designed. For the whole architecture, the authors mainly used Simulink inbuilt blocks that are validated and provided by Matlab. The corresponding direct-sequence signal is generated by first modulating the data message, Binary Phase Shift Keying (BPSK) or Quadrature Phase-Shift Keying (QPSK). Afterwards, the mapped message is spread using a sequence of pseudo-random nature known as the PN sequence. Because of the addressed safety-critical applications like platooning, BPSK is chosen for the data modulation, as this offers the most stable communication. In the next processing step, the spread signal is made radio frequency (RF)-ready. This includes e.g. up-mixing to the carrier frequency, filtering and amplification.

At the receiver, the process of multiplying the signal with the spreading code (known as despreading) causes potential interference to distribute its energy density. The data can only be correctly demodulated if the transmitter and receiver code are identical. Information of other transmitter-receiver pairs appear only as minor interference, as the sequences are designed to be orthogonal in the best case. In consequence, this approach is very suitable for applications where secrecy needs to be maintained and distortion/interference needs to be strictly limited for the exchange of safety critical information.

The proposed Simulink model is an extension of the model proposed in [8] and several design challenges were addressed: Next to the consideration of more realistic parameters (shown in Tab. 2), the model was extended by, inter alia, integrating MRC combining, channel estimation, phase and frequency compensation and a reasonable RF-representation. This full physical layer representation, addressing the various challenges of the individual processing blocks (including e.g. the realistic V2V channel, integrating hardware non-idealities, coordinating and combining all the mentioned signal processing blocks) is the key contribution of the proposed work. The entire processing chain is depicted in Fig. 2a). A PMCW signal is generated at the transmitter part, BPSK modulated, spread by PN sequences and is further processed in the RF-part. Two approaches are investigated to ensure the signal conditioning (synchronisation, phase and frequency compensation): a serial and a parallel implementation. The signals are then transmitted, propagated through the channel (to experience multipath, delay, Doppler shift, attenuation) and finally, are received. At the receiver, the RF-part is included before the further processing steps like channel estimation, synchronisation and finally, the demodulation at a Rake receiver structure follow.

### TABLE 2. Comparison between the parameters used in [8] and the extended model

| Parameter      | Previous [8] | Extended   |
|----------------|--------------|------------|
| Sustainable rate | 100 bit/s    | 5 Mbit/s   |
| $T_{\text{chip}}$ | 250 µs       | 5 ns       |
| $T_s$         | 5 µs         | 0.1 ns     |
| Bandwidth     | 8 kHz        | 400 MHz    |
TABLE 3. Comparison of the three communication “standards” [48], [76]–[78]

|                     | IEEE 802.11p | LTE-V2X     | Radcom     |
|---------------------|--------------|-------------|------------|
| Carrier frequency   | 5.9 GHz      | 5.9 GHz     | 77 GHz     |
| Sustainable rate    | 3–27 Mbit/s  | 10 Mbit/s   | 5 Mbit/s   |
| Peak data rate      | -            | 1 Gbit/s    | -          |
| Bandwidth           | 10 MHz       | 10 MHz or 20 MHz | 400 MHz |
| Modulation scheme   | BPSK, QPSK, 16-QAM, 64-QAM | QPSK, 16-QAM | BPSK, QPSK |
| Channel coding      | Convolutional coding | Turbo coding | No         |
| Multiplexing        | TDM          | TDM/FMD     | CDMA       |

As aforementioned, one major research topic is to evaluate different methods to realize the signal structure (i.e. transmitting the data and pilots in serial or parallel). The interleaved approach (same as for the previously published model [8]) was analysed, containing a preamble. The corresponding system is shown in Fig. 2b). Via this preamble, represented by a longer PN sequence compared to the short PN spreading sequence of the data, the signal conditioning, inter alia, the synchronisation and the channel estimation, is performed at the receiver. Afterwards, the data is transferred till the preamble is sent again to capture the dynamic characteristics of the channel, depending on the coherence bandwidth.

Furthermore, the parallel implementation was evaluated and is depicted in Fig. 2c). The signal conditioning and the data are simultaneously transmitted and mapped at the in-phase (I) and quadrature (Q) component, respectively. This approach has the benefit that the conditioning is monitored the whole time, resulting in a system which is capable to receive information in highly dynamic scenarios, where the channel is heavily distorted. Obviously, this comes at the price of requiring continuous and cost intensive transmission of pilots and signal processing. However, this design concept is well known in the literature, for example in 3G-Wideband-CDMA, where the dedicated physical data channel and dedicated physical control channel are transmitted in parallel in the uplink [79]. Details regarding the system design and the individual processing blocks are clarified in the chapter IV–VI.

IV. TRANSMITTER

To design a reasonable Radcom system, the applied communication parameters were extended (Tab. 2) according to the established standards IEEE 802.11p and LTE-V2X. They are compared and summarized in Tab. 3. The applied configurations, architecture (indicated in Fig. 2) and the included blocks for the baseband and RF-processing are described in detail in the subsections below. A particular focus lies on the variations of design regarding the parallel and serial setup.

A. BASEBAND

According to the rough survey of the baseband processing, given in Fig. 2, the data has to be modulated and spread by a PN sequence. The data is approximately generated randomly by a Bernoulli Binary generator, representing data provided by the higher layers, whereby the probability of a bit being either zero or one is set equally. The data rate and the sampling rate are extended, in comparison to the previously published model ([8]), to \( r_T = 5 \text{ Mbit/s} \) and \( T_{\text{data}} = 0.2 \mu \text{s} \), respectively. Thus, this data rate satisfies the IEEE 802.11p standard (see Tab. 3). In general, it is possible to increase the data rate further to 10 Mbit/s or even higher, however, this would lead to an increase in occupied bandwidth.

The bandwidth in a CDMA system is primarily defined by the applied spreading sequences. There are different types of PN sequences, with their respective advantages and drawbacks: Next to m-sequences, Gold sequences, Walsh-Hadamard codes and Kasami sequences are well-established [67], however, their behaviour is still under study for different applications and environments [80] Thus, also the optimal choice of sequences in the automotive use case is subject of the current research. Exemplary, S. Sharma et al. (2020) propose to use orthogonal variable spreading factors as spreading codes [22].

In the following, m-sequences are chosen, as they provide a simple solution with real-valued spreading outputs and in consequence, allow a parallel approach, where the quadrature component is used for transmitting the pilots. M-sequences have decent autocorrelation behaviour, resulting in a high spreading gain. This also helps to reduce the influence of the distortion and interference between unintended communication partners, as this gain lifts the desired information out of noise floor. The best design with respect to minimizing distortion and interference is to use orthogonal sequences as the cross-correlation between the interfering communication signals would be zero. Besides, ideal sequences should achieve high autocorrelation values. Summarized, under ideal conditions, the interference caused by various transmitters becomes negligible, while having a high match in despreading, which results in a high processing gain.

M-sequences are generated using Linear Feedback Shift Registers (LFSR), which provide periodic binary sequences by combing the outputs of the feedback shift registers. Different sequence lengths [127,1023] were designed by varying the number of delay flip-flops and were evaluated regarding the resulting communication performance (e.g. observed bit errors). In principle, short sequences were used for the data transfer, while for the signal conditioning long sequences were utilized. The whole LFSR is operated with a chip duration of 5 ns and a corresponding bandwidth of 400 MHz.
Due to the high demands of the communication link, the transmitted signals are BPSK modulated. Other modulation schemes can be included without significant additional effort and were already considered by the authors in [8]. However, before the data signal is transmitted, the signal conditioning has to be guaranteed. In this context, two methods of the conditioning, a serial and parallel one, are implemented. The corresponding system architectures are introduced in the following.

1) Serial

As shown in Fig. 2b, the signal conditioning and the data transfer are sequentially transmitted in the serial case. First, a pilot equal to an m-sequence of length 1023 is transmitted and received. This is mandatory to synchronize the clocks of the PN sequence generators of the transmitter and the receiver and in turn to delete errors due to varying clock offsets and guarantee an optimal communication. Due to this reason, the data sequence is transmitted after the signal conditioning has been carried out at the receiver. The system is tested for 20 µs and 40 µs (equal to 100 and 200 periods of $T_{\text{data}} = 0.2 \mu s$, respectively) after which the data is transferred. Depending on the coherence bandwidth of the channel, the signal conditioning has to be redone. A coherence bandwidth analysis is not part of this research and in consequence is not considered in the simulation. However, it can be easily included in the published Simulink model if desired.

2) Parallel

Next to the aforementioned serial approach, a second parallel approach is proposed, transferring the data and simultaneously performing the signal conditioning to keep track of the channel according to Fig. 2c. The synchronisation is again based on pilots, however, this time the pilots are transmitted over the quadrature (Q) component of the signal, while the data is modulated on the in-phase (I) component. Hereby, the pilot symbols correspond again to long PN sequences and are shifted to the Q component by applying a phase shift of 90°. On the other hand, the data symbols, spread with the short PN-sequence, are transmitted on the I component without a phase shift. At the receiver, both components are processed separately.

**B. RF-PART**

After generating, spreading and modulating the baseband signal, the physical layer representation is implemented. Therefore, a RF signal chain is built up. Realistic values are integrated exemplary and can be varied according to the demands. The architecture contains in chronological order: an up-mixer to the carrier frequency of 77 GHz, a bandpass filter, a power amplifier (PA) and the antenna representation. The antenna block models the antenna mismatch, whereas the antenna gain is not replicated as it is considered in the channel representation (described in chapter V). For each block, realistic hardware parameters are implemented according to the state-of-the-art literature of 77 GHz transmitter systems. In consequence, non-idealities, noise and realistic S-parameters are included and compared to holistic system designs [81]–[85].

The whole system design is depicted in Fig. 3. The temperature of both transmitter and receiver side is fixed to 300 K, but can be modified by adjusting the included ‘temperature block’ in the Simulink model. The functionalities of the individual blocks are briefly introduced in the following.

1) **Up-Mixer**

The up-mixer converts the baseband signal to the RF carrier frequency of 77 GHz. The S-parameters as well as the included non-idealities are summarized in Tab. 4. These are chosen according to the literature [86].

2) **Filter**

In the next step, the signal is bandpass filtered to suppress distorting signals which are generated by the mixing process. The filter parameters are set as: The 3 dB bandwidth is equal to 2 GHz at 77 GHz center frequency.

3) **Power Amplifier**

The filtered signal is then amplified by a power amplifier with S-parameters and non-idealities according to [87], [90], [91], depicted in Tab. 4. According to a rule of thumb, the third order intercept point (IP3) is assumed to be 10 dB higher than the 1 dB compression point $P_{\text{sat}}$ [92]. The saturation power $P_{\text{sat}}$ is chosen equal to 15.82 dBm [87], whereas the noise figure is approximately set to 10 dB. Besides, L.Chen et al. (2020) [87] evaluated the performance of their PA regarding temperature variations. The resulting changes are included for varying transmitter temperatures.

4) **Antenna**

Additionally, an antenna block is included according to the characteristics, published in [93]. As the subsequent chan-
V. CHANNEL MODEL

To design the entire physical layer of a Radcom communication, the channel characteristics have to be integrated in the Simulink model. Thus, channel characteristics are added to the model, as highlighted in the system overview of Fig. 2a). The corresponding parameters (like multipaths, delays, attenuation, Doppler frequency shifts, additional phase shifts) are generated by channel simulations, using WinProp, a commercial 3D-Ray-Tracing software solution from Altair\(^1\). Typical line-of-sight (LOS) and non-LOS (NLOS) traffic scenes are analysed and the corresponding channel information is integrated in Simulink. Besides, stochastic models (Rayleigh, Rice) are discussed.

A. EVALUATING SCENARIOS IN WINPROP

Two ordinary traffic scenarios are evaluated: one representing a LOS communication on a rural street and the other a NLOS link on an highway. Both scenes are displayed in Fig. 4 and are already evaluated by the authors in [94]. As WinProp is based on the Fresnel equations and the geometrical and uniform theory of diffraction, the scenarios have to be modelled in WinProp in detail. Thus, the objects as well as the corresponding frequency depending materials (permittivity, permeability, conductivity, scattering parameters) are defined at 77 GHz. The suitability of using WinProp at mmWaves is validated in the literature for 28 and 73 GHz, respectively and by the authors in [97], [98] at 60 GHz.

In the considered scenes, two communication links between two vehicles are analysed. The transmitting power at the output of the PA is set to 13 dBm at 77 GHz. A dynamic receive power range of up to 150 dB is defined, while the simulation range-resolution is set to 0.15 m, being equivalent to a RF-bandwidth of 1 GHz. The transmitting as well as the receiving antennas are mounted at the front bumper at a height of 0.5 m. For both a 2x2 patch antenna with 12.38 dBi gain, a SLL of -11.99 dB and a HPBW of 36.25° is chosen (steering in the driving direction). Further information about the directivity and the 3D-Pattern can be found in [99]. The antennas are mounted in this dynamic scenario at the TX/RX cars, which are driving with 10 m/s towards each other. The scenarios, however, differ in the LOS and NLOS characteristics of the channel, see the description below.

1) LOS

The LOS scenario considers a typical rural street, where only two cars are driving towards each other, depicted in Fig. 4a. The communication link between both is analysed: the left one acts as transmitter, whereas the right one is receiving the information. In addition to the cars, guard rails and street signs are included to enable a realistic representation of the environment. At any time, the communication link is dominated by the LOS path (green line) and few reflection paths (grey lines) like the reflection at the ground.

2) NLOS

This does not hold true for the NLOS case, where a highway scene was analysed. In this scenario, three cars and one truck are driving past each other. Again two vehicles try to communicate, as depicted in Fig. 4b). The LOS path, however, is blocked by a central guard rail between the lanes and the other vehicles, resulting in constant NLOS. Same as for the LOS scenario, additional obstacles like different kinds of street signs, are integrated in the channel simulations.

B. CHANNEL REPRESENTATION IN SIMULINK

For both scenarios, the propagation paths and their interactions with the environment, the resulting power delay profiles (PDPs) as well as propagation parameters (like direction of arrival, angle of arrival, the phase of the received signal) are investigated. Four paths are selected for each scenario, representing the most significant paths (LOS, reflection paths) next to scattering paths (more delay, and less power). The channel characteristics of these four paths are integrated into the Simulink model. This is in accordance with the literature: in [100] a two-ray model fitted the pathloss measurements at 60 and 63 GHz, respectively, and a four-ray pathloss model at 77 GHz was suggested in [101] for a rural street. Thus, for each path the following parameters are of interest: the propagation delay \(\tau\), the received power, more specific the

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TABLE 4. Transmitter RF-parameters

| Block       | S11  | S21  | S22  | IP3  | P1dB | Noise |
|-------------|------|------|------|------|------|-------|
| Up/Down-Mixer [86] | -11.4 dB | 2.1 dB | -16.1 dB | -1 dBm | -10 dBm | PN@1 MHz: -95.3 dBc/Hz |
| PA [87]     | -15 dB | 26.4 dB | -3.9 dB | -13.9 dBm | -7 dBm | NF:10 dB |
| LNA         | -25 dB | 10 dB | -20 dB | 2.2 dBm | -7.4 dBm | NF:5 dB |

PA: Power amplifier, LNA: Low noise amplifier, IP3: Third order intercept point, P1dB: 1 dB compression point, PN: Phase noise, NF: Noise figure.

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\(^1\)http://www.altair.com/resource/altair-winprop-datasheet

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### TABLE 5. Included channel parameters for the LOS and NLOS scenarios

| Paths | Delays in ns | Attenuation in dB | $\Delta\varphi$ in ° | $f_D$ in kHz |
|-------|--------------|--------------------|----------------------|-------------|
| LOS   |              |                    |                      |             |
| 1     | 67.6         | –73.4              | –                    | 5.1         |
| 2     | 72.6         | –130               | 21                   | 3.3         |
| 3     | 78.4         | –132               | 205                  | 1.9         |
| 4     | 84.1         | –132               | 101                  | 2.7         |
| NLOS  |              |                    |                      |             |
| 1     | 74.5         | –129               | 247                  | 4.3         |
| 2     | 79.5         | –143.1             | 350                  | 4.3         |
| 3     | 84.9         | –143.2             | 61.4                 | 3.8         |
| 4     | 93           | –143.8             | 212                  | 3.6         |

(a) Rural street scenario

(b) Highway scenario

**FIGURE 4.** Evaluated scenarios in WinProp (v.2021.0.3): (a) rural street (b) highway representing LOS and NLOS link, respectively. On the one hand the included materials are highlighted in various colours according to their characteristics, on the other hand the different propagation effects are coloured separately. Green dots correspond to scattering, red ones to reflections, whereas the Tx position is displayed by the blue dot.

Table 5 shows the included channel parameters for the LOS and NLOS scenarios. The table lists the paths, delays, attenuations, phase shifts, and Doppler frequencies. The LOS scenario has 4 paths with delays ranging from 67.6 ns to 84.1 ns, and corresponding attenuations and phase shifts. The NLOS scenario also has 4 paths, with delays ranging from 74.5 ns to 93 ns, and similar characteristics.

**VI. RECEIVER**

At the receiver, the multipaths are combined, using a maximum ratio combining (MRC) based on different receiving antennas. Afterwards, the combined signal is passed to the RF-blocks, before it is digitally filtered and further processed in a Rake receiver structure (synchronisation, channel estimation, phase correction, demodulation), depending on the used approach (serial, parallel). At this point, we have a look at the receiver part of the full architecture, highlighted in Fig. 2. The Rake receiver structure consists of four fingers and makes use of the multipaths by collecting the energy of the various delayed signals. All the processing steps and the corresponding blocks will be introduced in the following, respectively.

#### A. MAXIMUM RATIO COMBINING

As MRC is known to be the optimal linear combining technique (assuming the interference and noise have zero mean and are uncorrelated), a Simulink representation is built up according to the literature [67], [79]. Different to equal gain combining, the signals are multiplied by matched weighting factors and afterwards added together. Thus, the aim of MRC is to maximize the SNR in the sum-signal by optimizing the weighting factors of each branch.

In this work, the fading process of signals with different arriving directions or different delays are uncorrelated. Based on this assumption, the multipath diversity is considered, since in this case it is possible to resolve different paths and process each signal separately. Hereby, the best solution for the weighting factors is as follows:

\[
w_i = \frac{h_i}{P_{n,i}},
\]

where $P_{n,i}$ denotes the noise power of the branch, $h_i$ the channel factor and $c$ is a constant which is given by a normalization. The normalization, however, is defined so that the sum of the weighting factors is equal to the number of branches.

**C. STOCHASTIC MODELS**

In addition to the deterministic approach, using the observed propagation parameters, stochastic models (Rayleigh-, Rice-distributions) can be evaluated. Rayleigh and Rice models should be based on the observed parameters of WinProp. Thus, the parameters of Tab. 5 might be included inside the inbuilt blocks for the Rice and Rayleigh channel models. For the Rice distribution, the rural street scenario with the dominant LOS and ground reflection paths should be used, whereas for the Rayleigh distribution the NLOS scenario should be considered.
In the proposed Simulink model, the implemented MRC processes four branches separately. First, the mean values of the amplitude $A_i = \text{mean}(|r_i(t)|)$ is estimated. The channel factors are estimated by $|h_i| = A_i/\sqrt{2}$, as the channel factors correspond to the real valued path loss and the transmitted signal has a signal amplitude of $\sqrt{2}$ because its real part and imaginary part have both absolute values of 1 for the QPSK/parallel approach. For the serial approach, $|h_i|$ is equal to $A_i$. The transmitted signal is modulated by BPSK, thus its mean value is 0, the signal power is only related to its variance, which is equal to $A_i^2$. On the other hand, the applied Gaussian noise has also zero-mean and power equal to its variance. As a result, the mean of the received signal is zero and its power is equal to the variance $\sigma^2_{r,i}$, i.e.,

$$P_{r,i} = \sigma^2_{r,i} = A_i^2 + P_{n,i}. \quad (3)$$

The noise power is calculated by subtracting the useful signal power from the received signal variance. According to Eq. 2 the weighting factor $w_i$ is calculated. Since the channel parameters in the system model are real values, the estimation can be simplified. After multiplying the weighting factors to the corresponding signals, the results are summed up and forwarded to the RF-blocks.

**B. RF-PART**

In the next step, the combined received signal is amplified, filtered and mixed down to the baseband, as can be seen in Fig. 3. Additionally, an optional antenna mismatch is included and the temperature of the receiver system is set to 300 K. The blocks of antenna mismatch, the filter and the mixer are identical to the corresponding parts in the transmit chain, as the designed system represents a JCRS application where both communications and sensing is performed on one shared platform. The idea is to have a design where the transmitting and the receiving path is separated, for example by a circulator. In the receiving path, the signal is then first amplified by a low noise amplifier (LNA) before further processing (filtering, mixing). The detailed information about the characteristics of the individual blocks is described in Sec. IV-B and summarized in Tab. 4. The saturation power $P_{\text{sat}}$ and the noise figure are chosen equal to 0 dBm and 5 dB, respectively [88].

**C. DIGITAL INTERPOLATION FILTER**

An interpolation filter is installed at the input of the Rake receiver to reduce BER, see Fig. 2. The transmitted signal is up-sampled with a factor of $L = 25$ to be able to delay the signals in the ns-range and the resulting signal is transmitted through the channel, attenuated, phase shifted and delayed. Up-sampling inserts $L - 1$ zeros between each sample. In consequence, the spectrum is repeated in an interval of $[-f_s, f_s]$. At the receiver, an interpolation filter with a passband of 200 MHz recovers the original signal spectrum. Considering the signal is band-limited, while the noise is white, the filter also removes parts of the noise. The filtered signal is handed over to the Rake receiver structure, where, among other things, the synchronisation is performed.

**D. RAKE RECEIVER**

The Rake receiver design, especially the first finger, is depicted in Fig. 5. In general, the architecture differs for the serial and parallel approach. However, in both cases, two correlation detectors are included, one for the data and one for the signal conditioning path (longer PN sequences). The data correlation and demodulation of the fingers are not displayed, but the results of the demodulation are weighted and added together before the final decision regarding the transmitted bit is made. However, all fingers have the same structure of data processing, consisting of despreading and demodulation. The signal conditioning (synchronisation, channel estimation/compensation) is only performed in the first finger and the results are then included in the processing of the other three fingers. Hereby, the pilots fulfil the task of synchronisation, channel estimation and phase/frequency compensation, which are needed to process and demodulate the data properly. The individual processing steps of the signal conditioning as well as the impact on the data demodulation are described in detail in the following sections. However, the system design highly depends on the chosen approach (serial or parallel), which is discussed subsequently.

1) Serial

As introduced in section IV-A and Fig. 2b, in the serial approach, the pilots and the data are transmitted sequentially. During the prefixed pilot transmission phase, the long pilot PN sequence is correlated with the PN sequence, locally generated at the receiver. Thereafter, the output is further processed during the signal conditioning. If the signal conditioning succeeds, the signal is synchronized, phase and frequency compensated and is ready for demodulating the data correctly.

2) Parallel

In contrast to the serial approach, the pilots for the signal conditioning and the data are sent simultaneously on the Q-channel signal and on the I-channel, respectively. Only a short delay is introduced as the system nevertheless has to perform the signal conditioning before being able to demodulate the data in a sufficient manner. Of course, it is imperative that the phase of the signals has to be corrected to have a clear differentiation between the channels. After separating the data and I-Q-splitting, the signal conditioning is done in the first finger. The data symbols, received on the I-channel, are processed in every Rake finger.

**E. SYNCHRONISATION**

Any misalignment between received sequence and locally generated sequence could cause a value drop of correlation. Synchronization is used to remove this misalignment in order to recover the data from the received signal properly. The implemented synchronization architecture is designed as a
serial search in a single-dwell system and includes an acquisition, tracking and Search/Lock Control Unit (SLCU) [67]. Acquisition limits the choices of the timing offset values in a finite number, while tracking provides an accurate synchronization and is able to maintain it. Both the acquisition and tracking systems are used to regulate the clock rate. Through the changes of the clock rate, the phase or timing offset of the locally generated PN sequence at the receiver is adjusted relative to the phase or timing offset of the transmitted pilot sequence.

1) Acquisition

The first step of the synchronizer is the so-called acquisition. The received pilot (long PN sequence) is correlated with the locally generated PN sequence, utilizing a serial search method. Prior to the correlation, the received signal is downsampled to have both sampling frequency of received data, as well as the receiver PN sequence to be equal to 1 over $T_c/2$. After the correlator, the output signal is processed by an envelope detector, which uses the square law to detect the signal energy. The output signal is sent to an integrate and dump block which integrates over 4 samples to guarantee a fast tracking. The detected energy signal of the correlation output by the envelope detector. If the input value drops below the threshold, the serial search starts again.

2) Tracking

Since acquisition is completed, the sequences are roughly synchronized and the SLCU enables the tracking mode which is based on a Delay Locked Loop (DLL). During the tracking, the synchronization error is further reduced and thus, gets limited within certain bounds. The tracking subsystem is composed of two branches: The common input to the branches is the received pilot signal. For the ‘upper’ branch, the second input is the ‘early’ output of the local PN code generator (‘early’ stating that it leads in time by half of a chip duration), while the second input to the ‘lower’ branch is the output of the local ‘late’ PN output (‘late’ meaning that it is delayed by half of a chip duration).

Each branch consists of a mixer, an envelope detector and an integrate and dump block which integrates over 4 samples to guarantee a fast tracking. The detected energy from both branches are subtracted to generate an error correction which is the input of a Voltage Controlled Oscillator (VCO). The resulting frequency of the VCO controls the trigger frequency of the local PN-sequence generators. Thus, if the locally generated sequence is delayed compared to the received sequence, the signal amplitude of the upper branch is higher than the one of the lower branch. In consequence, a positive error correction is passed to the VCO and in turn, the output frequency becomes higher and the delay will be compensated. Similarly, if the locally generated sequence is earlier than the received sequence, the output frequency of the VCO is reduced.

3) Search/Lock Control System

As indicated above, the SLCU is used to monitor the current state of the synchronization, either being in the acquisition or the tracking phase. It processes three inputs: the results of the acquisition and the tracking steps and a pulse generator with a frequency of one over half a chip duration. The output of SLCU is used as clock of the PN sequence generators. As long as the acquisition is completed, the output of JK-flip-
The despread pilots are also used to estimate the phase shifts, via their phase values. In this work, these phase shifts are detected and later on compensated. Hereby, the despread pilots are averaged before the phase detection to remove the phase deviation caused by noise. A 'running mean' block is utilized if the phase shifts are constant over time, whereas for changing phase shifts, a 'moving average' with forgetting factors is preferred. However, the selection of forgetting factors greatly influences the result. In the simulation, the performance of different forgetting factors with different channel conditions is investigated.

Additionally, several frequency shift compensation methods are tested and finally, the frequency shift is determined by deriving the phase shifts according to

\[ \Delta f = \frac{1}{2\pi} \frac{\partial \phi(t)}{\partial t}. \]  

The theoretical structure of this method is depicted in Fig. 6. The upper branch calculates the frequency and the lower branch estimates the phase shift. However, before the derivative is determined, a moving average with a window length of four is used to reduce the influence of noise. The length should not be too long, since a long window could also smooth the phase jump. Furthermore, a phase jump checker has to be implemented, as the detected phase shift is continuously changing (ignoring noise), whereby the angle is always between \((-\pi, \pi]\). In consequence, if the phase crosses \(-\pi\) or \(\pi\), a phase jump occurs and supposedly, disturbs the detection. The applied phase jump checker is therefore mandatory to remove this effect, by ignoring the detected frequency when the difference between the current and previous phase exceeds a threshold. The threshold is set to 2, which is according to observations of the detected phase shift.

In the next step, the derivative is calculated, multiplied by the missing factor \(-1/2\pi\) (see Eq. 4) and used in both data despreading and phase shift compensation. The output of the discrete derivative is only enabled if the aforementioned threshold is not exceeded, otherwise the value of the previous derivative is taken. It is obvious that after the frequency shift is compensated, phase changes still remain in the signal, as small errors occur in frequency estimation. These phase shifts become especially significant after a long integration time. That is why, an additional phase shift compensator is included. The final architecture achieves a phase-frequency combined compensation, which can correct both the phase shift and frequency shift.

**G. DEMODULATION**

After the synchronization as well as the phase and frequency compensation is successfully achieved, the system is ready to process the data. The output of the data demodulation of all fingers are combined and weighted according to the MRC. Thus, the system performance is evaluated, analysing the bit error rate (BER) which is introduced in section VII-A. The advantage of the Rake receiver versus a simple receiver (corresponding to a Rake receiver with one finger) was already shown in [8]. However the performance strongly depends on the channel which is analysed. For LOS scenarios, where the direct path dominates (delay and especially amplitude-wise), the other fingers only have minor impact. However, if a NLOS scenario is evaluated and the different paths are more comparable in signal amplitude, the strength of the Rake receiver is clearly seen. The representation of this phenomenon is shown in the following results section.
VII. RESULTS

To demonstrate the potential of the proposed system, the performance of the individual blocks is described in the following. The basic structure was already presented by the authors in [8]. The influence and the improvement of a Rake receiver structure with enabled synchronisation was shown. Besides, the performance for BPSK as well as for higher modulation schemes (QPSK, 4-QAM, 16-QAM) was proven. Thus, implementing higher orders of modulation is possible with moderate effort. However, as the system should work in the context of safety relevant applications, a BPSK modulation of the data is chosen in the proposed model. To overcome the previous approximations (no Doppler shift included, knowledge of the exact despreading time delays, etc.), a channel estimation and in consequence, a phase and frequency correction is added to the model for adapted realistic parameters. Besides, digital filtering, a real RF-modelling is now part of the model. The positive impact of the newly added blocks is discussed in the following subsections individually for the parallel approach and in the context of the full architecture for both serial and parallel approaches, respectively. The Simulink model is made publicly available to the research community at [102].

A. METRICS

BER over the Signal to Noise Ratio (SNR) is an important measurement of the communication system performance. Traditionally, it is a water-fall curve: the BER decreases with an increase of SNR. To compare the performance of the proposed system, the BER-SNR curve is compared to the theoretical limit, which shows the theoretical lowest achievable BER according to

\[
\text{BER} = \frac{N_{\text{min}}}{l_d(M)} Q \left( \sqrt{\frac{d_{\text{min}}^2 E_b}{N_0}} \right),
\]

where \(N_{\text{min}}\) denotes the mean number of nearest neighboring signal points with respect to the modulation scheme. For the applied BPSK, \(N\) is equal to 1, whereas \(M\) corresponds to the total signal point of the modulation scheme which is equal to 2 for BPSK. \(d_{\text{min}}\) represents the normalized minimum quadratic Euclidean distance. In case of BPSK, its square is \(d_{\text{min}}^2 = 2\). \(E_b\) corresponds to the mean energy pro bit; \(N_0\) represents the one-side noise power density and the fraction \(E_b/N_0\) is adjusted in the Simulink model. \(Q(x)\) is the so called Q-function, given by

\[
Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-z^2/2} dz.
\]

In case of BPSK, Eq. 5 is written as

\[
\text{BER} = Q \left( \sqrt{\frac{2 E_b}{N_0}} \right).
\]

However, for the parallel approach \(d_{\text{min}}^2\) has to be modified, as the transmitted signal contains pilot and data simultaneously and thus, its constellation is similar to QPSK or 4-QAM. Nevertheless, \(d_{\text{min}}^2\) is not equal to those two modulation schemes, since the signal is a sum of the BPSK-modulated I- and Q-components instead of a QPSK/4-QAM modulated signal. Moreover, its modulation rate is \(R = 1\) bit/symbol, and the Q-components are removed before the final data demodulation, thus the \(N_{\text{min}}\) and \(M\) are same as for BPSK. In case of setting the same transmission power as for the serial approach, \(d_{\text{min}}^2\) is equal to 1 for the parallel approach. As both approaches should be compared, \(E_b\) is set to 2 W for the parallel approach instead of 1 W for the serial approach, leading to a \(d_{\text{min}}^2 = 2\). However, it has to be remarked that the noise power of the parallel approach is twice the noise power of the serial approach.

Additionally to the comparison of the BER of both approaches, the constellation diagrams are analysed at various processing steps of the full architecture which is described in detail in section VII-G.

B. MRC

Building up on the previously published model [8], the proposed model is extended by various aspects (phase and Doppler frequency shifts, varying channel models as well as an realistic RF-part). This degrades the old model’s performance to such extent that further signal processing blocks have to be considered.

To improve the previously stated performance, a maximum ratio combining is designed. The precondition is that the receiver is able to distinguish the signals through different paths and process them separately. Hereby, maximizing the SNR of the resulting signal by multiplying the signals with weighting factors is the aspired goal.

In the simulation, first the performance of MRC with equal SNR channels was tested, see Fig. 7a. The solid red line (squares) denotes the BER with (w) MRC, the blue dashed line (asterisk) represents the BER without (w/o) MRC. The BERs of the two systems are almost the same, which illustrates that the MRC has no effect on the BER when channels have the same SNR. The difference between the BERs is, however, more significant at high SNR values. This is due to the non stable weighting factors at the initialization. Because the MRC block uses the average signal and noise power to calculate the weighting factors, the system is initially non ideal and non stable causing a high BER at the beginning.

In Fig. 7b, the performance comparison with unequal SNR and equal attenuation channels is displayed for four channels. Hereby, all channels have the same attenuations of \(-82\) dB. The first channel is the reference channel with \(E_b/N_0 = 0\) dB, while other channels have progressively increased SNR. The x-axis displays the SNRs of the channels, while the difference between channels increases from left to right. The blue dashed line (asterisk) displays the BER of the system without MRC, while the red solid line (squares) corresponds to the system with MRC. With larger difference in SNR, the MRC assisted receiver clearly outperforms by reducing the BER significantly. In comparison to two channel, this even increases with more channels. In consequence, the communication system clearly benefits if MRC is applied.
especially when the multipath channels highly vary in their SNR.

C. INFLUENCE OF THE RF-BLOCKS
After multiplying the weighting factors to the corresponding signals, the results are summed up and forwarded to the RF-block whose influence is analysed in the following.

According to Fig. 3 and Table 4, realistic component values, including also non-idealities like non-linearities, noise and realistic S-parameters at the transmitter as well as at the receiver are considered. Their impact on the communication performance is analysed: starting with the influence of the temperature and further investigating the non-ideal S-parameters, the phase noise of the up-/down-mixer, the noise figure at the PA and LNA as well as the chosen non-linearities of the amplifiers. The degradation of the BER caused by the RF-block mainly comes from the joint effect of non-linearities of RF transmitter and noise figure of the LNA, while the temperature of RF transmitter, the non-linearities of RF receiver and the non-ideal S-parameters have considerably less influence.

Especially, the non-linearity of the PA showed an significant impact since for the chosen IIP3 and P1dB the PA is operated in saturation. That is why, for the subsequent investigations they are adapted to IIP3 = 17 dBm and P1dB = 0 dBm.

Moreover, the phase noise also has a high impact. If it exceeds a threshold of $-100 \text{ dBc/Hz}$ @1 MHz, the BER approaches 0.5. To decrease the BER, the phase noise level at 1 MHz has to be below $-105 \text{ dBc/Hz}$. In consequence, the phase noise level, depicted in Table 4, is too high, causing highly dynamic phase changes of the transmitted signal, deforming the rectangular shape and thus, rendering the synchronisation and data recovery impossible. That is why the phase noise level was adapted to $-105 \text{ dBc/Hz}$ for the subsequent evaluations.

In order to analyse the influence of the adapted full RF-architecture, the system performance is investigated for various channel conditions. In Fig. 8a, the BER with and without RF-blocks for different number of multipaths are depicted. Hereby, the blue solid line denotes the theoretical BER for a BPSK modulation, the red dashed (asterisk) and orange (square) ones display the performance of the systems with four and two channels and without (w/o) RF-blocks, respectively. The purple dashed (cross) and green (circle) lines represent the BER with two and four channels with (w) active RF, respectively. The BER with four channels is obviously higher than that of two channels because of the interference. However, there is a dominant increase in the BER considering the RF-blocks due to the non-idealities compared to the BER observed without. Regarding the influences of the RF-parts, it can be finally concluded that both the larger number of channels and the RF-block can increase the BER, while the latter has the larger effect. Since the RF increases the BER, it is necessary to reduce the BER in order to improve the transmission reliability. In the proposed results, the interpolation filter, described in section VI-C, assists in reducing the BER. A detailed description about its impact is given subsequently. Additionally, the previously discussed maximum ratio combining further improves the system performance. The performance of the full system is, therefore, displayed in section VII-G.

D. DIGITAL FILTER
In order to improve its performance, a interpolation filter with the passband equal to the signal bandwidth is applied to remove noise. In Fig. 8b, the previously discussed results (displayed in Fig. 8a) are now compared with and without the filtering. The results are observed for the four-channel system. The solid red (asterisk) line represents the BER with (w) integrated RF-blocks but without (w/o) digital filtering (DF), while the blue dashed line denotes the system without
different phase shifts (\(-\pi/2, \pi/2\)) into account. The signals through different paths suffer from time varying phase shifts/Doppler frequency shifts are taken into account. The compensation of these constant phase shifts is first tested, before starting by the addition of a constant phase shift. The channel is now subsequently becoming more complex, requiring system architecture like a phase/frequency compensation are required. Thus, the correct selection of the forgetting factors \(F\) is a trade-off between stability and sensitivity of the compensation system. A larger \(F\) means a slower \(\Delta T\) with \(\Delta T = 100 \mu s \ (\approx 500T_{\text{data}})\) or \(\Delta T_{\text{fast}} = 10 \mu s \ (\approx 50T_{\text{data}})\). Thus, the correct selection of the forgetting factors \(F\) is a trade-off between stability and sensitivity of the compensation system. A larger \(F\) benefits from a better performance against noise, while smaller factors achieve more flexibility due to faster responses to changing phase shifts. Moreover, varying \(\Delta T\) as well as increasing/shortening the buffer size in front of the cross-correlation are strong factors to influence the BER. Exemplary, decreasing the buffer size leads to a receiver which is more fragile to noise. However, it has simultaneously an increased update rate and thus, can track the phase shift more rapidly.

**F. COMBINED FREQUENCY-PHASE COMPENSATION**

Additional to phase shifts, the Doppler frequency shift is included and has to be compensated in the next step. In RF-blocks. Additionally, the solid yellow (circle) line depicts the system with RF-blocks and digital filtering at the same time. All curves are shaped like a water-fall for an increase in \(E_b/N_0\). However, there exists a clear difference between the system with RF but with and without filtering, which is getting even more significant for higher SNR values. In order to reduce the BER even for complexer channels (like phase and frequency shifts) further improvements of the system architecture like a phase/frequency compensation are required.

**E. PHASE SHIFT COMPENSATION**

The channel is now subsequently becoming more complex, starting by the addition of a constant phase shift. The compensation of these constant phase shifts is first tested, before time varying phase shifts/Doppler frequency shifts are taken into account. The signals through different paths suffer from different phase shifts (\((-\pi/3, -\pi/2, 3\pi/4\) and \(\pi\)), but all having the same amplitude.

Fig. 9a shows, a comparison between the phase compensated system and the system without any phase shift. The blue line represents the BER with phase shifts and compensation. The red line denotes the performance without phase shift and without compensation, whereas the orange line shows the BER of the system with phase shift compensation while the phase shifts are set to 0. The red line and orange line are almost overlapping, which indicates that the phase compensation is nearly perfectly implemented. With phase shift and compensation, however, lower BER are achieved (compare blue line). The reason for that can be found by the cross-correlation at the peak finder. Analysing the cross-correlations, it gets clear that the interference with phase shifts is significant reduced compared to the system without phase shifts. This proves that the different phase shifts can mitigate the distortion caused by inter-channel interference, and hence, the BER is lower after compensating the phase.

But it has to be mentioned that initially the estimated phase shift is non-stable and deviates from the correct result due to the lack of samples, leading to high BER at this moment. The considered ‘running mean’ block calculates the average values over the total history and thus, with increasing number of samples the BER decreases, which is depicted in Fig. 9b. The x-axis corresponds to the number of data bits, which could be considered as the time axis, whereas the y-axis denotes the BER in every time interval. The system with an ideal phase compensation is denoted by the blue line, while the red line represents the proposed phase shift compensation. Initially, the BER of the proposed compensation scheme is very high, close to 0.5. However, the BER reduces over the time and converges after a few hundred data bits to the BER of the perfect compensation.

With variable phase shifts the ‘running mean’ block has to be replaced by a ‘moving average’ block which additionally includes forgetting factors, since outdated results interfere with the current estimation. Considering the data period \(T_{\text{data}} = 200 \text{ ns}\), the phase shift changes after every \(\Delta T\) with \(\Delta T_{\text{slow}} = 100 \mu s \ (\approx 500T_{\text{data}})\) or \(\Delta T_{\text{fast}} = 10 \mu s \ (\approx 50T_{\text{data}})\).

**FIGURE 8.** Comparison between the obtained BER with (w) and without (w/o) RF and digital filter.
FIGURE 9. BER of the phase compensated system.

(a) With (w) and without (w/o) fixed phase shifts (PS) as well as with and without phase shift compensation (PSC).

(b) Time behaviour.

FIGURE 10. BER of the phase and frequency compensated system.

(a) Influence of different forgetting factors with frequency shifts but without additional phase shifts

(b) With (w) frequency shifts (FS) and with and without (w/o) phase shifts (PS).

the proposed system, the frequency shifts of the four paths are set to $\Delta f$, i.e., 10 kHz, –6 kHz, 5 kHz and –12 kHz. Fig. 10a shows the system performance with different forgetting factors in phase shift compensation. The solid blue (asterisk) line, the solid red (square) line and the dashed orange (cross) line denote the BER with varying forgetting factors of $F = 0.4$, 0.6 and 0.8, respectively. The forgetting factor of $F = 0.6$ has significantly the best performance and thus, $F = 0.6$ is chosen for later evaluations. The absolute value of frequency shift also influences the BER, the larger frequency shifts the higher the BER.

The performance of the frequency shift compensation includes BER, accuracy, reaction time, stability and complexity. The BER is the most important factor, since it is directly related to transmission reliability. In Fig. 10b, the BER for four channels with Doppler shifts according to $\Delta f$ is depicted. The blue dashed (asterisk) line shows the BER of the frequency compensated system, only applying frequency shifts, whereas the red solid (square) one displays the resulting BER for a system with both frequency and phase shifts included and compensated. The latter represents a real communication system, where both frequency and phase compensation is mandatory. Additionally to the frequency shifts of $\Delta f$, phase shifts are considered and are chosen to be randomly distributed in $(-\pi, \pi]$ and to change every 100 $\mu$s. This change of phase shift causes in turn heavy interferences on the estimated frequency. As the phase shift changes every 100 $\mu$s, it happens at the time $t = n \cdot 100 \mu$s ($n$ is a non-negative integer) that the estimated frequency shows a significant jump. However, this phase jump gets
smaller and smaller linked to a long averaging time over all previous values. This can be seen in Figs. 11, where the four corresponding frequency shifts are determined accurately (compare the predefined values of $\Delta f$). Fig. 11a displays the estimated frequency without the phase jumps, whereas in Fig. 11b the influence of the phase jumps is indicated. The negative frequencies are included as the determined frequencies are used for the compensation in the next step. Nevertheless, compared to the pure frequency compensation, errors are more prominent in case of these additional phase jumps. In Fig. 11b, it has to be remarked that at the timings at $t = n \cdot 100 \mu s$ sometimes the frequency jumps do not have an impact as the internal phase jump checker exceeds the threshold of 2 and thus, the corresponding value is deleted. On top of the frequency compensation, a phase compensation is added to remove the remaining estimation errors to further improve the system performance.

Moreover, the accuracy of estimated frequency is an important metrics, since the frequency shift is used to estimate the relative velocity between vehicles. The method based on estimating the phase derivative has short reaction times (around 50 $\mu$s) and therefore, determines the frequency shift quite fast. The estimation stability is also required. Additionally, the compensated frequency changes continuously until it approaches the final result. Afterwards the result has no obvious change in frequency any more. In consequence, the estimated frequency shifts are stable and do not suffer from dynamic changes which can negatively impact the communication performance.

G. SERIAL VS. PARALLEL IMPLEMENTATION

The positive impact of the newly added blocks has been shown in the previous subsections applying the parallel transmission (PT). In this chapter also the serial transmission (ST) is implemented and compared to the parallel one. Finally, the advantages and disadvantages of serial and parallel implemented systems are listed.

The performance of the parallel full architecture is already shown in the previous section VII-F. However, next to the BER, the constellation diagrams are analysed to evaluate the performance of the system. Fig. 12 depicts the constellation at different steps of the transmission line. At the transmitter (Fig. 12a), the signal contains an in-phase data signal and the pilot on the quadrature-phase. Therefore, its real and imaginary values have an equal absolute of 1. After the AWGN channel, the signal points are mixed and thus, it is impossible to separate them. After despreading, the useful data in Fig. 12a) is separated and can be divided by the imaginary axis (dashed red line). Due to the high sampling
Comparison of the parallel transmission (PT) and the serial transmission (ST) with a pilot length (PL) of 0.2 T and 0.4 T. A constant channel is considered, which means only delays and attenuations are included. The RF-blocks as well as the MRC are included, while digital filter and frequency and phase compensator are excluded.

In consequence, the data demodulation is reliable. The overall system parameters and settings are the same as for the parallel implemented system, except additional delay and switch blocks which guarantee the separated transmission of the pilot and data signals. Thus, after the channel conditions are estimated/compensated, the data is transmitted and in consequence, the data demodulation is reliable. The overall system performance for both implementation approaches is depicted in Fig. 13. First, their performance with included RF-blocks and MRC is tested. Since the phase and frequency shifts are not considered, the attenuations and delays are constant. However, it has to be remarked that the theoretical limits for both systems are differing, as described in section VII-A. In the proposed experiment, the serial approaches with a pilot length (PL) of 100 \( \cdot T_{\text{data}} \) (= 0.2 T) and 200 \( \cdot T_{\text{data}} \) (= 0.4 T) are tested. Their resulting BERs are compared with that of the parallel approach. The solid blue (asterisk) line, dashed red (square) line and orange line (cross) represent the BER of the parallel approach and the serial approaches with short and long pilot lengths, respectively. It can be seen that all three lines are almost overlapping due to the accurately estimated delays.

If the frequency and variable phase shifts are included, the resulting BERs indicate that the serial transmission system is easier to be affected by the dynamic systems. The settings are chosen to be identical to previous experiments: the frequency shifts are set to \( \Delta f_{\text{double}} = [20000 \text{ Hz}, -12000 \text{ Hz}, 10000 \text{ Hz}, -24000 \text{ Hz}] \) for the four multipaths and the phase shifts are set as random variables changing every 100 μs, i.e., at the beginning of each alternation period. The negative impact of the dynamic channel, especially on the serial approach is getting even more obvious, when the frequency shifts are doubled, compared to the previously chosen \( \Delta f \). In Fig. 14, the BERs for both the parallel and serial approaches are depicted for the mentioned dynamic channel. If the channel shows a higher dynamic, the BER becomes worse. This result indicates that the BER of serial approach is more sensitive to system dynamics. The serial approach in the test has longer pilot (40 μs in each alternation period). Even with long pilot, the serial approach has higher BER. Of course, it is possible to further increase the pilot length and in consequence, to reduce the BER, however, in that case the data rate is further reduced.

The previous tests are still not under realistic conditions as the phase shifts only change when the pilot transmission starts. In consequence, the serial approach can update the estimated phase rapidly. However, the phase jump can potentially occur at any time during the pilot and data transmission. If the phase changes when the data is transmitted, it is likely that all transmitted data becomes invalid till the next alternation period is started. To investigate the influence of a dynamic environment on the transmission reliability, an alternating period is set to 150 μs, while the phase still changes every 100 μs. The frequency shifts are \( \Delta f \), and the serial approach has a pilot length of 200 \( \cdot T_{\text{data}} \). Afterwards the BERs of both the serial and parallel approaches are tested.
FIGURE 15. Comparison of the parallel transmission (PT) and the serial transmission (ST) with a pilot length (PL) of 0.4 T. A highly dynamic channel is considered with $\Delta f = \{10, -6, 5, -12\}$ kHz. The signal conditioning is done every 150 µs, whereas the phase changes every 100 µs. In consequence, the phase jumps also occur during data transmission. All blocks are included, such as the RF-part, digital filter, MRC, frequency and phase compensator via phase derivative.

and shown in Fig. 15. With the non-ideal condition, the serial approach has much higher BER, even near 0.5. The diagram indicates that the parallel approach is more suitable for highly dynamic environments.

VIII. DISCUSSION

In this work, a future JCRS model is proposed, focusing on vehicular communications at 77 GHz, designed in Simulink. The sensing applicability is discussed. Various waveforms are investigated and compared. Finally, a V2V communication model based on DSSS with m-sequences as spreading sequences is proposed, which has the advantage to reduce inter-channel interference. First, a parallel transmission of simultaneous pilot and data transmission is designed, in order to guarantee the data rate even in highly dynamic environments.

The previously published model [8] is extended by realistic parameters to meet the requirements of the WLAN- and LTE-based V2X as well as various processing blocks (MRC, digital filtering, Rake Receiver, phase-/frequency compensation) to increase the communication performance of the system. These blocks are tested and evaluated successively regarding in their improvement and included in the final full architecture. Besides, interfering sources are integrated: the channel uses fast changing phase/frequency shifts, delays and attenuation; also the RF hardware blocks at 77 GHz with their corresponding non-idealities are considered. Phase shifts are estimated by directly measuring the angle of the detected maximum values. Even in the worst case with the phase changes even 10 µs, the compensator can guarantee a low BER. A frequency estimator, which is based on conducting the derivative of the phase shift, is integrated. Results show a convincing fast and accurate estimation for different channels.

Next to the parallel approach a serial is evaluated. The serial approach has almost the same BER as the parallel approach in constant channels. However, its BER becomes much higher in highly dynamic environments. Especially if the channel conditions change when the data is transmitted, the BER of the serial transmitted data becomes very high. Nevertheless, it comes also with several benefits compared to the parallel approach: less energy is consumed as well as higher modulation schemes do not lead to interference between the I- and Q-channel. A significant drawback of the serial system is that the pilot transmission also occupies time, which degrades the data rate. In consequence, the parallel approach is more suitable for highly dynamic channels and therefore, is preferred. The proposed model outperforms similar models like the one introduced by Shirude et al. [25]. Shirude et al. stated to achieve a BER of 0.4615 at an SNR equal to 10 dB, considering low disturbance, for example, representing the channel only by delay and attenuation. In the proposed model, on the contrary, constant and variable channel configurations are included and BER in the range of $10^{-2}$ are achieved at an SNR equal to 10 dB. However, it has to be remarked that the system is not optimized for low BER values yet.

The aim of proposing this model is instead to establish an open-access model (available at [102]) which the community can use for advanced processing. Next to the possibility to evaluate different signal processing blocks and their influence on the achieved communication performance, especially the non-idealities can be investigated. This allows searching in the processing chain for the weakest element as well as the impacts of parameters (minor, major, dependencies between parameters). Thus, in the proposed work, the integrated hardware blocks (phase noise of the mixers, the IIP3 and P1dB of the PA) were found to have to be adapted, as for the first configurations the system did not perform as intended. Moreover, several variants of the architecture for example the phase/frequency compensation can be compared which allows to make future design decisions and to optimize the system design, respectively. Therefore, it is simple to adapt the proposed Simulink model by commenting out processing blocks or replacing/adding blocks. This includes also adapting the communication parameters like increasing the data rate, integrating other spreading sequences, adapting the length of the sequences, or switching to higher modulation schemes like proposed by the authors in [8].

However, all the design criteria are highly dependent on the corresponding channel (dynamic, LOS, NLOS). In the proposed work, two typical traffic scenarios on a rural street (LOS) and on a highway (NLOS) are evaluated via a 3D-Ray-Tracing software WinProp, and are integrated in the Simulink model. Additionally, stochastic models like Rayleigh or Rice can be used, based on the observed channel parameters. Nevertheless, there are limitations of the model regarding the observed multipaths, which is discussed in the next section.
IX. LIMITATIONS

The proposed work has additionally some limitations which are described in the following. Future requirements and development perspectives are investigated. BPSK is chosen as modulation scheme in this work. However, standards like IEEE 802.11p and LTE-V2X utilize higher modulation schemes such as QPSK, 16-QAM and 64-QAM, while 5G uses 512- or 1024-QAM. Thus, a future research topic is expanding the modulation schemes and evaluating the limits of the Radar based communication. Initial experience in implementing higher modulation schemes is already published by the authors in [8].

A second point of criticism is that channel coding is not implemented yet. Current vehicular communications utilize channel coding schemes such as convolutional codes (IEEE 802.11p), turbo codes (LTE-V2X), polar codes and Low Density Parity Check Codes (LDPC)(5G). Thus, implementing coding is another objective for the future.

Generally, the channel configuration has to be discussed. Applying the channel parameters of the simulated typical traffic scenes, it has to be remarked that having dominant paths results in covering the other included multipaths. Thus, for the LOS, only the dominant paths with the least attenuation impact the communication performance, whereas for NLOS scenes, this is not the case. However, as the ACF of the m-sequences is not ideal and has sidelobes with maximum values larger than 100, the sidelobes exceed 1/10 of the mainlobe, marking the maximum resolvable difference of the channel attenuations. In consequence, in the considered NLOS scenario, there is still a dominant path which is covering all the other paths. Due to this reason, the individual processing blocks (phase/frequency, digital filtering, etc.) are also tested for predefined channel configuration without a dominant path as otherwise the system performance of the blocks is not possible to be validated. In future research, further channel models are mandatory to be considered.

Therefore, more complex environments, extending the rather simple rural and highway scenarios, should be investigated (for example urban scenes). Besides, the type, as well as the lengths of the spreading sequences should be examined in more detail prospectively. In consequence, it will be possible to evaluate the system performance for different channel configurations like having (non-) frequency selective channel or (non-) time selective fading to investigate the impact on the system performance.

A single carrier solution, based on direct sequence spread spectrum scheme, is proposed to reduce the inference and increase the security of the communication. In the future, a multicarrier code-division multiple access schemes should be additionally discussed, as they can outperform DSSS systems due to their inherent frequency diversity performance and less complex system design for interference cancellation compared to DSSS. The advantages should be weighted against the drawbacks of OFDM based systems, like suffering from high peak to average power ratios and being sensitive to carrier offsets.

Additionally, the proposed model will be extended to also consider Radar signal processing to meet the requirements of a JCRS system. Indeed first models already show the possibility to integrate the Radar signal processing also in Simulink [75]. However, it is planned to have the Radar signal processing implemented in Matlab as this allows to integrate traditional, as well as state-of-the-art machine learning based signal processing.

X. CONCLUSION

In this work, the authors present a simulation environment for a joint communications and radar sensing system at 77 GHz, focusing mainly on the communication side. A Simulink model, representing a CDMA solution and realistic hardware solutions as well as realistic channel parameters derived from a 3D-Ray-Tracing simulations, is introduced and made public available. Within this model, two general designs are discussed and compared: a serial as well as a parallel solution. Besides, various configurations and processing blocks (maximum ratio combining, digital filtering, synchronisation, phase-/frequency compensation) are added and evaluated regarding their improvement of the observed bit error rate. Moreover, non-idealities are integrated like hardware non-idealities of the RF-blocks at 77 GHz as well as noise and various channel configurations (constant, dynamic phase shifts, Doppler frequency shifts). The proposed model allows the community to investigate future CDMA based vehicular communication system designs, like testing critical parameters, the impact and dependencies of for example the RF hardware non-idealities. In this context, some design criteria (phase noise of the mixers, non-linearities of the PA) were found by the authors and are adapted to the model. Moreover, the introduced processing blocks can be investigated separately and different architectures can be compared. Furthermore, the model integrates various channel configurations e.g. the antenna characteristics like polarisation, mounting height, antenna direction (defined in WinProp) next to antenna matching (defined in Simulink). To summarize, the proposed work enables the full physical layer design for future intelligent transportation systems. In the future, the presented simulation environment will be further extended and integrated in state-of-the-art simulations of the higher levels like Veins or Artery. In addition, building up the setup in a measurement environment is of utmost importance and is currently being addressed in our research. Further objectives are implementing different kinds of coding, like channel coding, switching to higher modulation schemes and investigating more complex channels.

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I. Introduction

II. Theoretical Background

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