ITN-5VC

Integrated Telematics for Next Generation 5G Vehicular Communications

ITN-5VC D3.2

Performance assessment of the new protocol solution

Version v 1.0 Date: 2023/09/30

Document properties:

Grant Number:	955629
Document Number:	D3.2
Document Title:	Performance Evaluation of the New Protocol Solution
Partners involved:	CASA, FIVECOMM, UPV
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Contractual Date of Delivery:	2023/09/30
Dissemination level:	PU[1]
Version:	1.0
File Name:	ITN-5VC D3.2_v0.1

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Executive summary

The deliverable D3.2 presents the development of a novel protocol for Integrated Sensing and Communications (ISAC) in a telematics unit. It delves into the various stages of integration, scrutinizes the RRC protocol, conducts a physical layer analysis, and explores the hardware aspects of ISAC integration. Moreover, the deliverable provides an analysis of the RRC protocol in the 5G PC5 interface, which has been updated to support the integration of sensing and communications. Furthermore, we discuss the role of the PC5-RRC layer in establishing connections between devices using radio resources vehicle and consideration of possible candidate ISAC waveforms. While we present a simulation framework for the physical layer, which includes a transmitter, receiver, and channel model. The performance evaluation of the simulation platform is provided as well, while a design proposal for integrating sensing function into the physical layer is carried out.

Moreover, the deliverable discusses the integration of sensing and communication systems in telematics units, explaining different scenarios of cooperation and joint operation between the two systems. It also addresses the challenges of multi-band system integration.

Finally, we assess the performance of a new protocol solution called mmWave for ISAC in advanced automotive systems. Meanwhile, we highlight the challenges of implementing ISAC, such as the high implementation and power cost related to the number of RF chains required. The paper proposes hybrid beamforming techniques as a solution, but notes that their impact on ISAC scenarios needs further study.

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1 Introduction

The integration of communications and sensing capabilities is expected to be one of the next milestones to be achieved in wireless technologies. While mobile communications and radar have traditionally been developed separately, the evolution of both fields suggest their convergence into joint systems which would exploit the integration gains for better performance. The initial motivation to unify sensing and communications into a single system was the increase demand for spectrum. However, additional reasons have arisen like the need for a Medium Access Control (MAC) mechanism for radars, or the possibility of exploiting sensing information to improve the communication function and vice versa. This has positioned Integrated Sensing and Communications (ISAC) as a hot topic in the research community.

Different levels of integration have been studied throughout the last years, with increasing level of complexity. Initial research was mainly focus on coexistence [1], [2], where the goal is to minimise the negative impact of one function into the other. Although regulations have set restrictions to avoid mutual interference between the two functionalities, perfect isolation is difficult to achieve, hence the need for more effective solutions to alleviate performance drops. Traditionally, coexistence solutions have involved each system working separately, obtaining all the information to avoid interference by themselves. More recently, the idea of cooperation was explored as a next step in the integration process. In this case, both functionalities exchange information to coordinate operation [3] and tighter fusion is achieved. Lastly, joint operation has received most of the attention from the research community due to the possibilities to achieve greater integration gains. Joint operation implies that the same hardware and resources are exploited for communications and sensing simultaneously. Within this category, three different subcategories can be identified:

- Sensing-centric ISAC: This case implies modifying a waveform typically used for radar to also send information. The main drawback of this approach is that traditional radar waveforms are incapable of achieving high throughput.
- Communication-centric ISAC: Conversely, this approach makes use of a communication waveform to perform sensing. Due to the applicability of ISAC to mobile networks, it has been analysed extensively with Orthogonal Frequency Division Multiplexing (OFDM) as the most studied waveform [4]–[6]. The drawback lies on the lower sensing performance and the complexity of the solutions.
- Joint design: Understandably, the best approach for maximising the performance of both functionalities would require the design of new systems from the ground up with ISAC in the core of the new solution. This could imply the design of a new waveform, new physical layers procedures, and overall, represents a very complex task. Although 6G is believed to be the first generation of mobile networks conceived with tight integration of communications and sensing capabilities [7], it remains to be seen how much of current 5G technologies will be completely replaced.

In addition to redesigning the hardware to achieve ISAC, current protocols need to be adjusted to account for the different requirements of both functionalities. While communications performance is typically measured in terms of throughput, latency and reliability, sensing performance depends on resolution and accuracy. Additionally, current radars typically work in a standalone manner, without using any coordinated MAC strategy, and implementing any interference mitigation technique in isolation. However, if communications are to be deployed side by side with sensing, resource allocation becomes a critical problem in the design of the solution.

One of the target applications of ISAC that would benefit the most with its implementation is Intelligent Transportation Systems (ITS). Numerous use cases such as autonomous driving and vehicle platooning rely on accurate sensing information, and while initial implementations have worked with separated radars and communications modules, the integration would lead to better operation by increasing resource availability and easing inter-vehicle coordination. Moreover, the rise in vehicular radar density has created the need to implement a solution that avoids interference and radar blinding, which can have severe consequences for traffic safety. Even if initial efforts have presented strategies to mitigate the problem [8], they do not offer the high level of interoperability as an ISAC solution would.

The introduction of sidelink communications enables vehicles to perform sensing tasks even without network assistance, and both mono-static and bi-static setups need to be analysed to reach the full sensing potential of vehicular networks. Additionally, the possibilities of using multiple bands for ISAC opens new opportunities for better performance. While mmWave is already been used by vehicular radars, its use in mobile networks is already included in standards and implementations are increasing. The main benefit would be the availability of larger bandwidths, but also, given the characteristics of the propagation channel at mmWave, the communication channel becomes more geometrical, easing the integration with sensing.

The goal of this deliverable is to explore ISAC in the context of vehicular networks. Section two starts with an analysis of the different integration levels that can be achieved between sensing and communications as well as an overview of the benefits and challenges that each one carries. Section three deals with Radio Resource Control (RRC) changes that would be necessary to guarantee a proper operation. Section four studies the physical layer of sidelink communications and how it could be adapted to support ISAC. Section five investigates hardware aspects of ISAC implementation, looking into the current state of the art of on-board sensors and explaining requirements for an implementation of a multi-band ISAC system. In section six the conclusions for the deliverable are presented.

2 Sensor Integration Levels

As mentioned in the introduction, there are different integration levels that can be achieved between communications and sensing. In this section, we analyse the characteristics of each one, as well as the challenges and benefits of each potential integration.

2.1 Coexistence

Coexistence is the lower integration level, for which two distinct categories can be defined:

- Coexistence in non-overlapping resources: This case represents how communications and radar have been traditionally deployed. Each system gets its frequency band, and the main concern is limiting the out-of-band emissions to avoid interfering with the other.

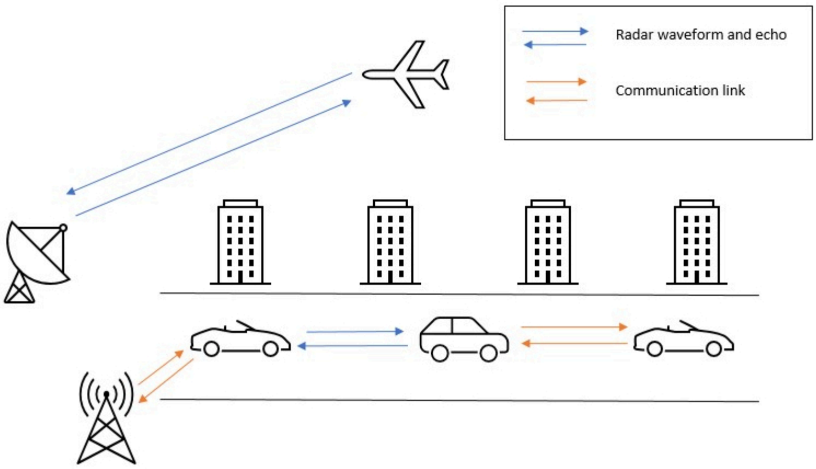

Figure 1 Classical Communications and radar coexistence.

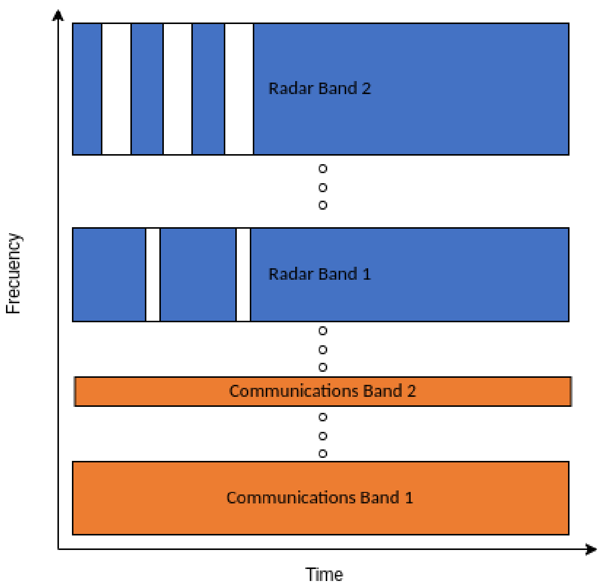

Figure 2 Coexistence without opportunistic spectrum access

- Coexistence in shared resources: For this case, typically, one of the systems intends to use resources pre-allocated to the other in an opportunistic manner. The strategy to reuse resources does not depend on exchanging information with the other system, meaning that spectrum sensing needs to be performed to detect which resources are available.

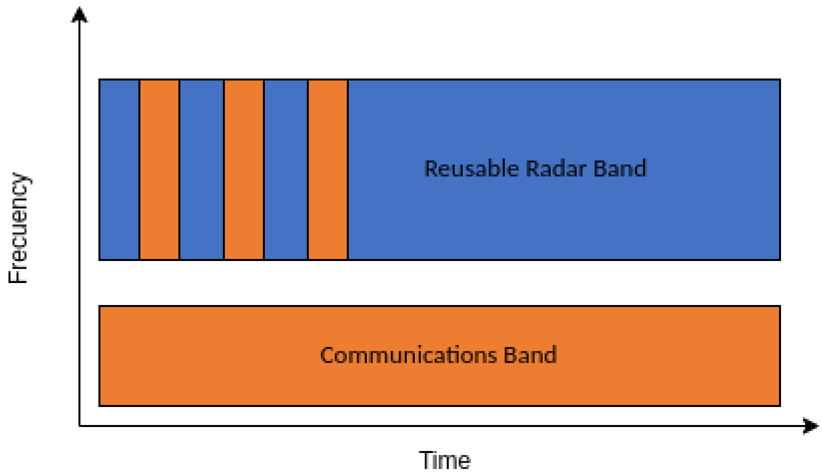

Figure 3 Coexistence with opportunistic spectrum access

The main advantage of coexistence is the simplicity of its implementation. The first level of coexistence is already deployed worldwide, and in the context of Vehicle to Everything (V2X), vehicles are already equipped with communication modules and numerous sensors. The second level of coexistence has been studied by some authors, for example in [9], and has some similarities to work done in cognitive radio. However, to our knowledge, it has not been considered for practical implementation, and the research community's interest has shifted towards more advance integration.

The obvious disadvantage of coexistence is the lower spectral efficiency since each system has its own pre-allocated bandwidth. Another disadvantage is the lack of tighter interoperability between the two functions. In vehicles, for example, the interaction between communications and sensing is mainly limited to passing the sensing information to other users.

2.2 Cooperation

Cooperation represents the first step towards ISAC. The main difference with respect to coexistence is the introduction of information exchange between the two functionalities for mutual benefit. This information can influence the decision-making involved in the operation of both systems to improve performance. Once again, focusing on the case of V2X systems, cooperation would enable not only to share sensing information between communication users but also to start sensing processes at the request of the communication entity or vice-versa. A typical example would be a vehicle that detects an obstacle in the way and classifies it as another vehicle, passing this information to the communication system, which tries to establish a V2X link with it. If the detected obstacle is another vehicle and has V2X capabilities, the link allows adding it to a list of known neighbors that exchange information periodically, or identifying which of the existing neighbors corresponds to that vehicle by comparing the estimation with received positioning information. Overall, this operation mode could significantly improve the collective perception of vehicular networks.

The cooperation would also allow to reuse resources without the need to blindly sense the spectrum. This removes the possible errors that could arise due to the spectrum sensing stage, which could be more critical in high mobility scenarios due to the fast-changing environment. With higher integration, the sensing systems could follow a MAC mechanism by exchanging information about resource availability through the communication modules.

To implement ISAC at the cooperation level, a coordination entity in charge of regulating the information exchange between the two functionalities should be used. Additionally, in the case of resource sharing, the controller would oversee distributing the available resources.

The benefits of cooperation are that while it represents an increase in implementation complexity with respect to coexistence, it is still relatively easy to implement. In terms of hardware the only new element would be the coordination controller. In terms of software, it would require creating new procedures to account for the newly available information and exploit it. The main drawback remains that the achievable spectral efficiency is low. Even if spectrum reuse is implemented, each functionality must be multiplexed in time.

2.3 Joint Operation

Joint operation is the ultimate level of ISAC and implies a unique system performing communications and sensing tasks simultaneously. This means that the same waveforms and hardware are used for both functionalities, achieving higher efficiency. The possibility of reusing spectrum that is currently being exclusively exploited by radar would enable a much higher bandwidth for communications and a better chance at achieving the Key Performance Indicators (KPIs) defined for 5G. Energy efficiency would also increase since the same transmission can be used to carry data and sense the surroundings. This, combined with the fact that the overall hardware requirements would decrease, justifies the implementation of ISAC as a greener alternative to traditional systems.

As previously stated, joint operation systems can be sensing-centric, communication-centric or joint design. Our focus will be on the latter two because of the limitations of the sensing-centric approach to fulfil current wireless communication networks' KPIs.

In the communication-centric approach, a waveform originally designed for communications, like OFDM, is also used for sensing. In principle, any waveform is suitable for radar since the goal is to listen to the echo of the emitted signal to detect and estimate targets. However, some characteristics are required to guarantee a good radar performance. The ambiguity function is the typical measurement of how suitable a waveform is for sensing, which is directly related to the ability to estimate targets' parameters from the echo. While OFDM doesn't have a good ambiguity function for typical radar processing (correlating receiver) due to the influence of the data sent, the method proposed in [4], which performs an element-wise division at the sensing receiver, has proven good results for sensing, and has become the most popular method for OFDM ISAC processing [10], [11]. The functional diagram of a communication-centric ISAC system is shown in the following figure.

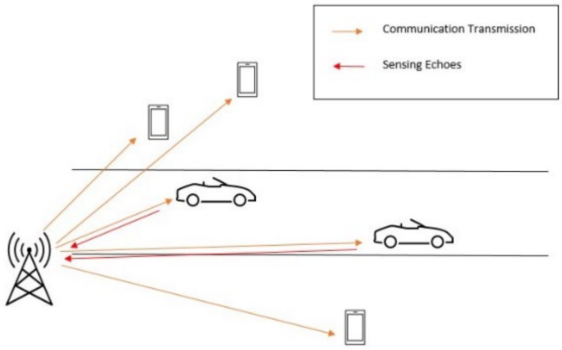

Figure 4 Joint Operation

Ultimately, authors believe that the best solution for an ISAC implementation is to design a new system from the ground up, not limited by classical preconceptions of wireless networks. This would require a new waveform. However, progress in this direction has been limited. Most literature on the new waveform design deals with signaling, and the proposed methods could be applied to OFDM. An alternative modulation scheme that has received attention recently and is a candidate for 6G is Orthogonal Time Frequency Space (OTFS). However, this would be an extension of the communication-centric approach, even though the delay-doppler mapping involved in this modulation closely relates to the sensing processing. The most likely scenario on ISAC's short and midterm future is the communication-centric scenario.

The main advantage of the joint operation approach is the complete reutilization of the spectrum. It would open the opportunity for allocating more bandwidth to the ISAC network with the corresponding gain in throughput and sensing performance. Additionally, tighter integration enables the implementation of more efficient resource allocation. No mediator entity is necessary, so the relevant information from each functionality to improve the other's performance is available in real-time.

The major disadvantage for joint operation is the high implementation complexity. To make it a reality, major hurdles need to be surpassed. Perhaps the most difficult one is the need for In-band Full-Duplex (IBFD) to support the mono-static sensing case. Current communication transceivers work in Half-Duplex mode, and moving to Full-Duplex will require effective isolation techniques that bring self-interference to the noise level. Additionally, hardware limitations need to be tackled to make use of mmWave spectrum currently used by radars and emulating their performance in ISAC. Some of these limitations come from imperfections such as phase noise which is more prominent at the targeted frequencies, mutual coupling between antenna elements and non-linear distortions [7]. While some of these impairments can be compensated through calibration, others will require dynamic compensation. Moreover, the interaction of a newly developed ISAC system with legacy technologies must be considered to ease the transition from the already deployed infrastructure.

3 RRC Protocol Analysis and Updates

This section introduces the protocol stack for the 5G PC5 interface (also known as the LTE V2X interface) used in the control plane within the higher-layer protocols, with a primary focus on Radio Resource Contro (RRC) protocol layer. This protocol stack enables communication between vehicles and other entities over the 5G network [12].

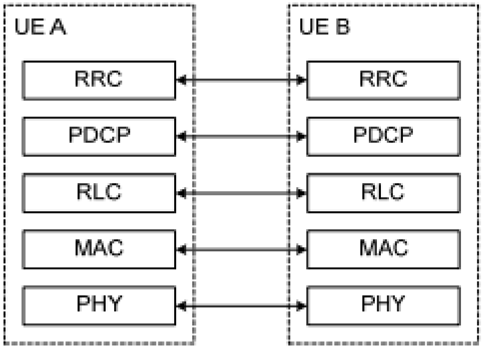

Figure 5 Control Plane Protocol Stack 5G PC5 Interface

Within the control plane, the following layers are defined: Physical Layer (PHY), Medium Access Control (MAC), Radio Link Control (RLC), Packet Data Convergence Protocol (PDCP) and RRC.

- The sidelink PHY allows physical resources to be transported over the air. Several physical channels are defined for this purpose: PSDCH, PSCCH, PSBCH and PSFCH. The PHY layer also includes features such as numerology, resource pools, bandwidths parts, and several signals such as DMRS, SL-SS, CSI-RS, and PT-ST.
- MAC layer: Within the Sidelink functionalities, the MAC layer provides radio resource selection, priority handling, Sidelink channel state information, multiplexing, Hybrid Automatic Repeat reQuest (HARQ) procedure, and logical channel management. With Sidelink, HARQ is possible to increase the reliability of each transport Block (TB) transmission because it uses forward error Correction (FEC). In addition, Sidelink HARQ uses retransmissions that include data and bit parity to avoid communication losses.
- RLC layer supports three transmission modes the Transparent Mode (TM), Unacknowledged Mode (UM) and Acknowledged Mode. RLC provides error correction and flow control to guarantee data transmission.
- PDCP layer his layer supports the functions of transfer data, header compression, ciphering and deciphering, protection and verification integrity, duplicate discarding, etc [13]
- PC5-RRC is designed to secure and establish the connection between two or more devices using radio resources. Sidelink RRC is the only layer that can modify the parameters of lower layers to find the best and most efficient process connection to ensure communication between them.

Regarding the RRC layer, in 5G NR, there are different RRC states that a device can be in, and these states help to manage the device's connection to the network efficiently [14]. The RRC states may vary slightly depending on the network and implementation. These states are defined by RRC-IDLE, RRC-CONNECTED, and RRC-INACTIVE.

In the RRC_IDLE state, the UE is not actively connected to the network and is essentially in standby mode. the UE periodically goes into a listening mode to switch from standby to connected mode. The RRC_INACTIVE state is similar to RRC_IDLE but with some additional functionality. The UE may periodically wake up to perform certain tasks, like checking for incoming calls or messages. The RRC_CONNECTED states the UE is actively connected to the network and can transmit and receive data. It can further be divided into sub-states based on the level of activity. The main purpose of RRC states is to allow a UE to efficiently manage its connection to the network.

3.1 RRC protocol updates, signalling impact and backwards compatibility.

The signaling process defined by the PC5-RRC protocol process in V2V scenarios is defined as [15]:

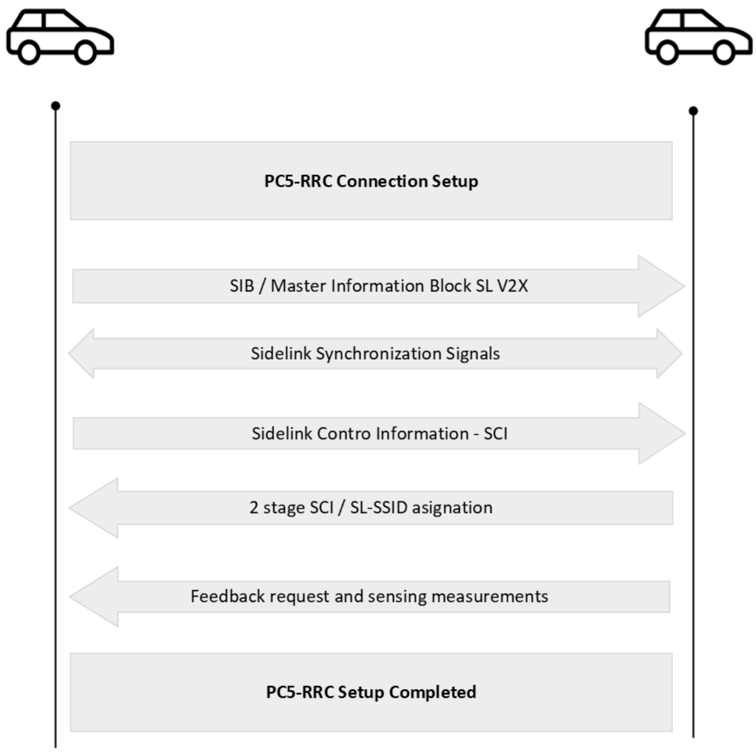

Figure 6 Signaling process 5G Sidelink V2V

The Figure 6 shows the signaling process between two vehicles, which is the first step taken by one vehicle to establish communication with another one. This signaling process is fundamental to understand which kind of information can be obtained by each vehicle. Each of these signaling procedures contains sensing information about the physical state of the communication. Obtaining information such as Received Signal Strength Indicator (RSSI), Received Signal Received Power (RSRP), and Demodulation Reference Signals (DMRS). This makes it possible to obtain constant information on sensing purposes for these types of signals.

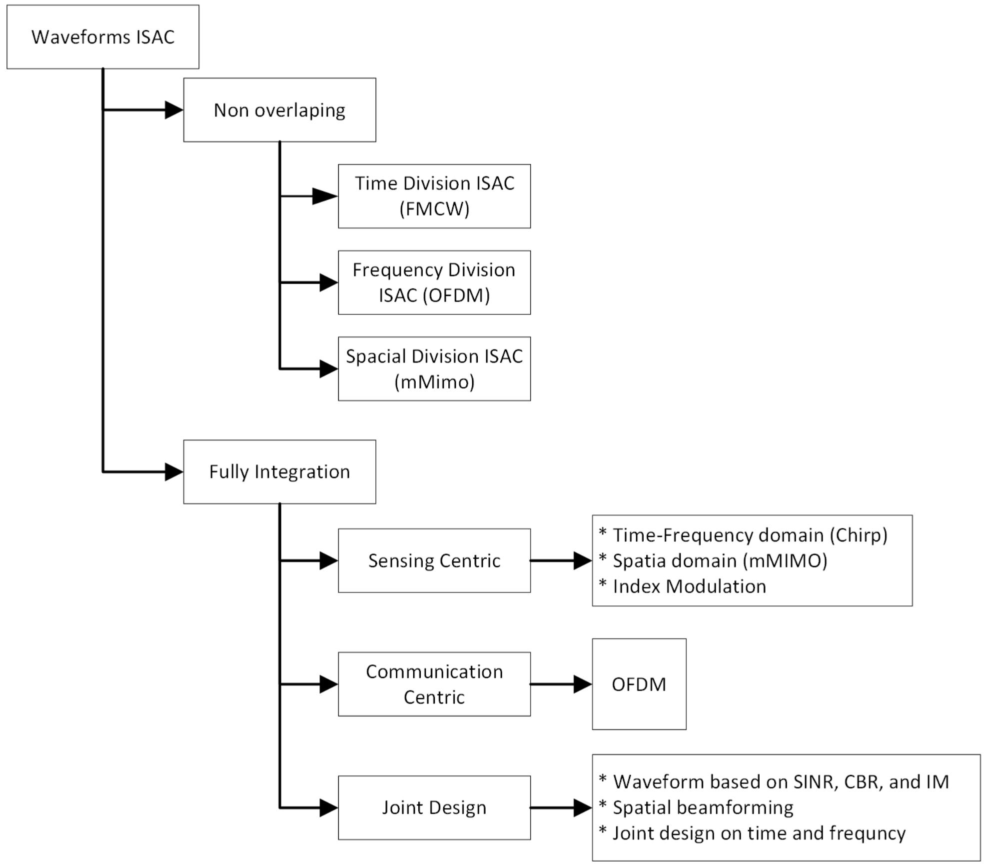

Figure 7 ISAC Waveforms candidates

As was mentioned in the previous chapter, there are several sub-categories of integration for ISAC. Each of these categories has different integration proposals with different waveforms Figure 7. In order to modify or add a new RRC protocol procedure, including sensing parameters, we will focus on communication-centric and joint waveforms.

Communication-centric aims to use the current OFDM communication waveforms. 5G V2X Sidelink physical channels and signals play a fundamental role in sensing purposes, considering that PSCCH carries SCI and is simultaneously multiplexed with the associated PSSCH. The SCI carries sensing information and sends it to the surrounding UE data, such as occupied resource blocks, resource reservation, priority data, DMRS pattern, MCS, etc. Furthermore, PSFCH provides high reliability, carrying HARQ feedback in the last OFDM symbol to guarantee the CQI. Likewise, PSBCH carries Sidelink Primari Synchronization Signal (S-PSS) and Sidelink Secundary Synchronization Signal (S-SSS), allowing nearby UEs to have the same Sidelink time reference. To approach these signals for sensing purposes, it is necessary to develop estimation, detection, and range algorithms. The advantages of OFDM are that it requires minimal changes to the communication infrastructure, all communication signals can be used for sensing, and delay and Doppler processing can be decoupled on the OFDM waveform.

Nowadays, joint waveforms are one of the current research topics due to the complexity of their design to ensure both service communication and detection in one. Some joint waveforms candidates have focused on Signal to Interference and Noise Ratio (SINR), Cramér–Rao Bound (CBR), and IP optimisation, spatial beamforming based on precoding design, multibeam optimisation, and hybrid beamforming. As well as joint design in time and frequency.

4 Physical layer of Sidelink

4.1 Simulation framework and physical Layer structure of sidelink

Since in sidelink, PSSCH is the most important channel which carries payload data, we choose to use the implementation structure of PSSCH to be able to perform detailed research.

4.1.1 Description of simulation framework

This subsection briefly introduces the simulation framework used throughout the rest of the deliverable. The Figure 8 shows the block diagram of the simulation framework. The simulation framework is built in MATLAB, and it consists of a PSSCH transmitter, receiver, and a channel model. Both the PSSCH transmitter and receiver closely follow the 3GPP standards and are explained in greater details in the following sections. TDLA, TDLB and TDLC channel models are supported and generated according to the guidelines provided by the 3GPP [16]. First, the PSSCH transmitter is configured with a set of parameters specific PSSCH and SCI2 which define the simulation. Then, the transmitter generates an OFDM baseband time domain signal corresponding to one slot of data and goes through one of the three supported channel models. Before entering the receiver, Additive White Gaussian Noise (AWGN) noise is added to the signal in order to adjust the Signal to Noise Ratio (SNR) required for the simulation. The signal is then fed into the PSSCH PHY receiver where it is OFDM demodulated and undergoes different DSP algorithms for recovering the transmitted data as explained in next section in greater detail. The number of correct PSSCH CRCs is then counted for the slot and stored. The process is repeated for a configurable number of slots and the final BLER can be obtained by dividing the total number of correctly received PSSCH CRCs by the total number of codewords generated in all the slots of the simulation.

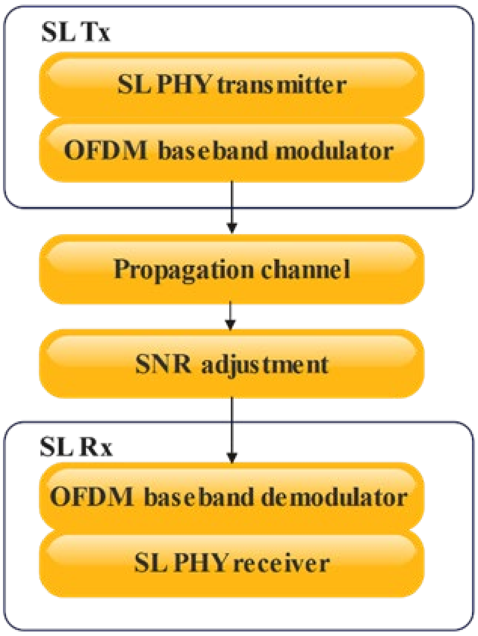

Figure 8 Simulation framework of physical layer

4.1.2 Description of transmitter and receiver design

For better illustration, the main blocks composing a 5G PSSCH transmitter according to 3GPP [17], [18] are depicted in Figure 9. First, SCI2 and PSSCH data bits are generated separately. Both streams of data undergo Polar and LDPC encoding for SCI and PSSCH respectively followed by individual rate matching. Then, the resulting bit-sequences need to be multiplexed together and sent for scrambling, modulation, and layer mapping. An identity matrix is used for precoding before mapping to the resource element grid. Once the resource element mapping is finished, it is used for generating OFDM symbols followed by CP addition. Finally, this time domain signal will be sent through the transmitter.

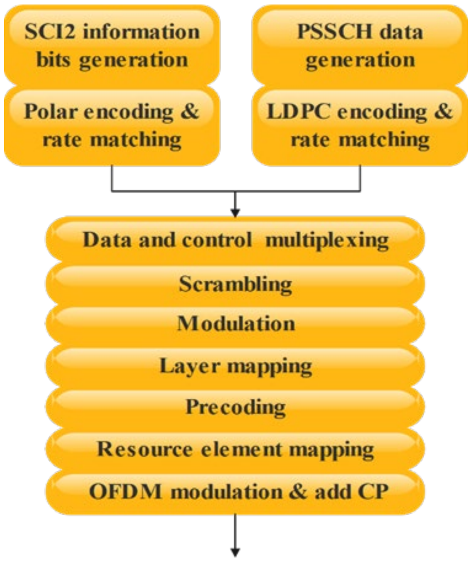

Figure 9 Workflow for transmitter

At the receiver, the received time domain signal is firstly divided into blocks of OFDM symbols, including the CP. The CP is then removed from every OFDM symbol. Then, OFDM demodulation is performed for every symbol by means of a 4K FFT. The time-frequency resource element (RE) grid is then recovered. Depending on each simulation configuration, the PSSCH data is extracted from the subcarriers carrying PSSCH information of each OFDM symbol for further processing. Figure 10 illustrates the block diagram of the SL receiver. In the following, a brief description of each block is provided.

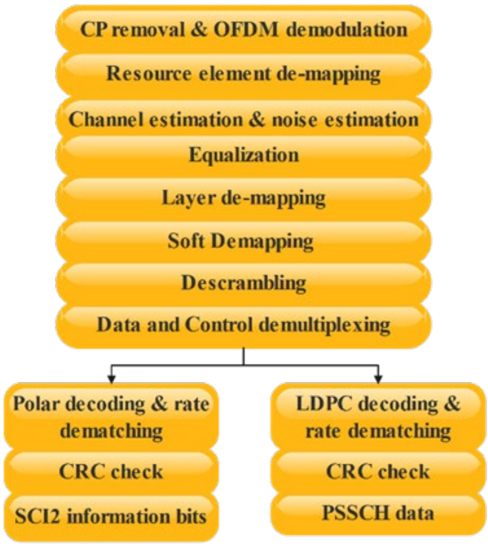

Figure 10 Workflow for receiver

- Channel and noise estimation

The channel estimation method employed in this article is achieved through the DMRS. The SL receiver has a priori knowledge of the transmitted DMRS signal and can use it to infer the disturbance introduced by the channel at each DMRS subcarrier. In the context of MIMO and spatial multiplexing, where multiple antenna ports are used both in the transmitter and receiver, each individual channel for each transmitting and receiving antenna pair needs to be estimated. Hence, the transmitted DMRS from different antenna ports need to be separable at the receiver side. This can be achieved when all transmit DMRS antenna ports use different subcarrier indices for DMRS transmission. If two different DMRS antenna ports are configured to transmit using the same subcarrier indices, an orthogonal cover code (OCC) is used to maintain the orthogonality of the DMRS signals from the different DMRS ports. In this case, orthogonality is achieved by means of code division multiplexing (CDM).

As DMRS is a known sequence for both transmitter and receiver, the estimated channel between antenna ports can be calculated by multiplying the received DMRS with the complex conjugate of original DMRS sequence. To be noticed, the estimated channel here is impaired with AWGN noise. In order to maintain a relaxed implementation complexity of the channel estimation process, we consider a rectangular fixed-size sliding window for mitigating the impact of the AWGN noise in the channel estimates.

Noise estimation is needed during the Minimum Mean Square Error (MMSE) equaliser as explained in the next subsection. The noise covariance matrix at the can be estimated by measuring the noise rejected by the rectangular filter by subtracting from the received signal.

- Equalizer

MMSE equalization provides a good performance versus complexity tradeoff and is the type of equalizer chosen for the SL signal equalization in this design. The expression of compensation matrix G for MMSE equalizer is shown below:

$$G = H^H \left(HH^H + \frac{\sigma^2}{P} I \right)^{-1}$$

Based on the knowledge from previous channel estimation and noise variance estimation, matrix G can be calculated and then multiply with received signal to restore the data.

- Following steps

After channel estimation, noise estimation and MMSE equalisation, the resulting signal shall go through layer de-mapping, soft demodulation, and descrambling as shown in Figure 10. As mentioned before, SCI2 and data on PSSCH are multiplexed together before scrambling in the transmitter. Therefore, demultiplexing before channel decoding is also necessary. After demultiplexing control information with data, SCI2 data is polar decoded whereas PSSCH needs to be LDPC decoded. Finally, to show the performance of our PSSCH receiver, the number of CRCs passed will be counted for computing the Block Error Rate (BLER).

4.1.3 Simulation results for current design

In this section, both functional test simulation results and performance test results. The following table shows parameters employed for those simulations.

Table I Simulation parameters employed

Name of simulation parameters	Configured value
Carrier frequency/GHz	3.5016
Bandwidth/MHz	100
Numerology μ	1

Subcarrier spacing/kHz	30
Number of DMRS symbols	2
Number of simulation slots	3000/500
Channel type	TDL model
Number of configured RBs	260
Number of PSSCH symbols	12
Modulation Scheme	QPSK/64QAM
Iterations of LDPC decoder	8

- Functional tests

Figure 11 shows how the estimated channel can track the actual simulated TDLC300-100 channel model for an SNR of 17dB employing a rectangular filter with length of 7 taps. From the figure, the function of channel estimation part has been proved.

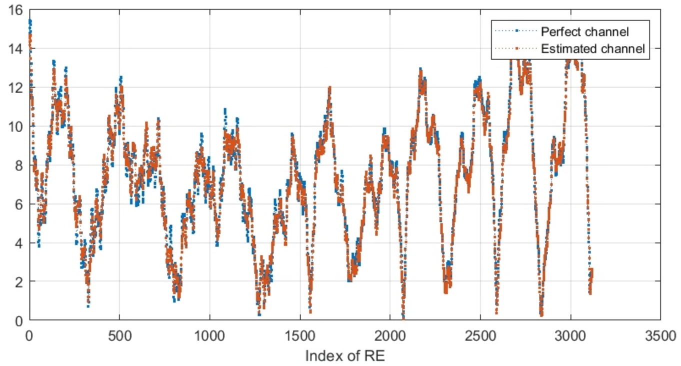

Figure 11 Comparison between estimated channel and perfect channel

Figure 12 and Figure 13 show the constellations before and after MMSE equalization for a 64QAM PSSCH signal having 17dBs of SNR. From the figures, we can perceive the correct behavior of the MMSE equalization.

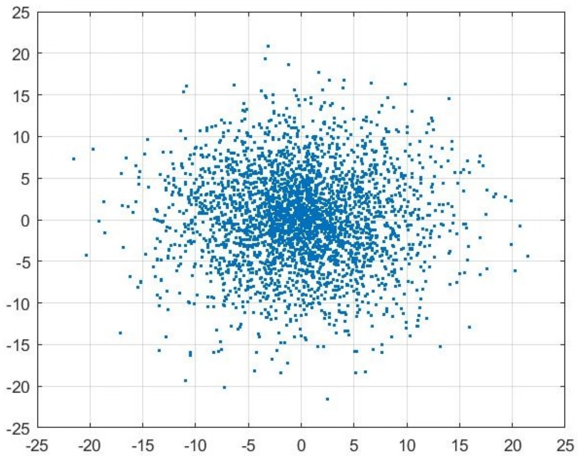

Figure 12 Constellation before equalizer

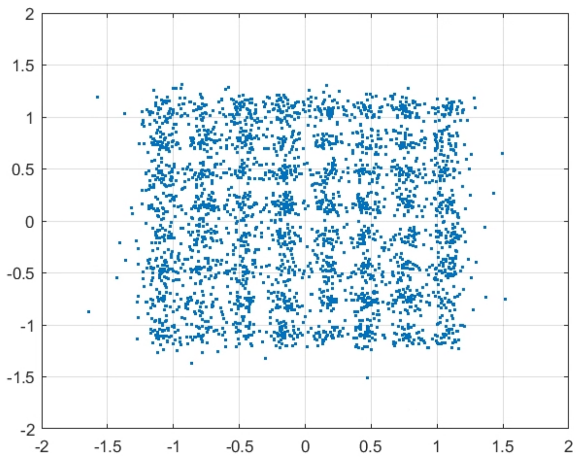

Figure 13 Constellation after equalizer

- Performance tests

Apart from functional tests, we also conduct a few performance simulations by checking BLER versus SNR graphs. Figure 14 shows the BLER versus SNR performance of the proposed PSSCH receiver under QPSK modulation scheme, MCS 0 with 0.2344 spectral efficiency under three different TDL channel models: TDLA30-10, TDLB100-400 and TDLC300-100. This simulation is measured under two transmit antennas (two layers) and two received antennas (2T2R). From Figure 14 we can observe that the proposed PSSCH receiver achieves a good performance under different channel models. BLERs below 10^{-3} can be reached for all channel models for SNRs larger than 0 dB.

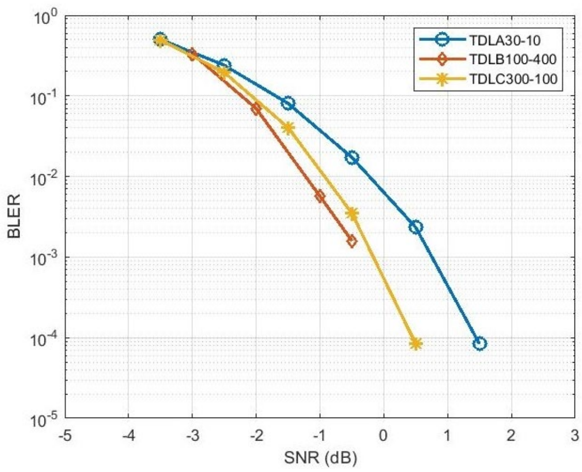

Figure 14 BLER vs. SNR for different TDL model, 2T2R, MCS0, QPSK

Figure 15 shows the BLER versus SNR performance of the proposed receiver for a 64QAM PSSCH transmission with MCS 20, having 3.3223 of spectral efficiency. The antenna configuration for this case is one transmit antenna and two receive antennas (1T2R). As expected, a much higher SNR is required to achieve the same BLER compared to MCS0 in Figure 14. It is observed that, for the TDLB100-400 case, there exists an error floor. The error floor can be explained by the 400 Hz doppler which makes the channel change faster in time and cannot be adequately tracked with only 2 DMRS symbols and current channel estimation methods. Hence, these channel estimation imperfections result in an error floor. Besides, the modulation scheme is 64QAM, and the LLR is easily wrongly decoded.

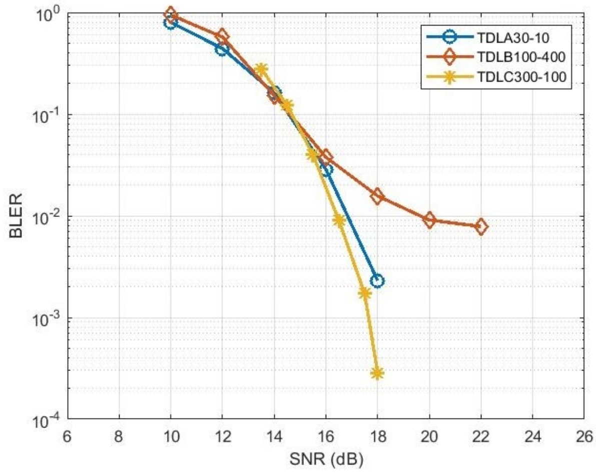

Figure 15 BLER vs. SNR for different TDL model, 1T2R, MCS20, 64QAM

4.2 Physical layer perspective for ISAC

Based on the deployment position of transmitter and receiver, the channel of ISAC system can be characterised into following types. Different types of topologies of ISAC system will lead to different physical layer receiver design.

- Monostatic ISAC

An ISAC system that is monostatic has a co-located transmitter and receiver. The broadcast signal's echoes, which contain the target's distance information, allow monostatic to detect the target. The monostatic ISAC transceivers scan in the azimuth and elevation angle domains simultaneously to rebuild the three-dimensional (3D) environment. A strong self-interference signal that the transmitter leaks into a monostatic ISAC channel, however, needs to be carefully removed. Additionally, multipath propagation may cause the intended echoes to have low signal-to-noise ratio (SNR) values [19].

- Bistatic/Multi-static ISAC

In terms of physical separation between the transmitter and receiver, bistatic/ multi-static ISAC is just like conventional communication channels. As a result, the bistatic/ multi-static ISAC design inherently avoids self-interference. Multipath signals in a bistatic ISAC channel provide rich power, distance, and angle information of the sensing target, which interacts with the original signal, in comparison to a monostatic ISAC. However, strict synchronisation between Tx and Rx is necessary because without it, the phase instability of the sensing signal could result in a loss of sensing performance. Using post-processing techniques, the information about the scatterers in the area is recovered and estimated. Eclipse wave needs be taken into account in the post-processing in order to increase sensing precision. A simple example of bistatic ISAC system is shown in Figure 16 [19].

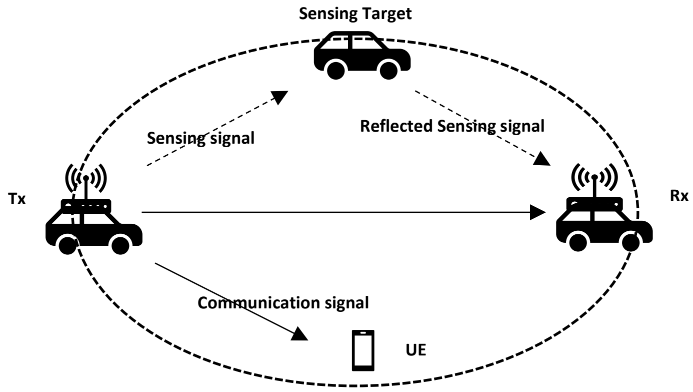

Figure 16 Simple example of bistatic ISAC deployment

4.3 Design proposal for physical layer

In this section, we take bistatic ISAC design to show the proposal of receiver for physical layer modification. As shown in Figure 16 above, signal transmitted by Tx car is collected by car which performs as a receiver, after being reflected from sensing target. Transmitted signal used for both communication and sensing can be achieved by exploiting multibeam capability.

Different from monostatic design, the range/distance estimation of bistatic design involves two parts: distance between the Tx car and the target and distance between the Rx and the target. But with propagation time τ and speed of light c, only the sum of these two distances R_{sum} can be calculated. After estimating R_{sum}via τ, the target can be located on an ellipse with a major axis equal to R_{sum}. As for velocity estimation, since only R_{sum} is known, thus only bistatic velocity can be estimated by the system. However, as the guard time of OFDM system needs to be larger than the propagation delay of scattered signal to avoid inter-symbol interference, this condition allows us to determine a maximum detectable R_{sum} and the maximum minor axis of the eclipse [20]. To be noticed, from Figure 16, when the target car is sufficiently close to baseline, it is hard to detect the position of this car and meanwhile, difficult to separate Tx-Rx path from the Tx-target-Rx one. Thus, the blind zone exists in this system and need to be further analyzed.

With the above-mentioned knowledge, a potential physical layer receiver design is shown in Figure 17. After channel estimation and noise estimation part, one of the three algorithms (i.e., MUltiple SIgnal Classification (MUSIC), root-MUSIC, and Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT)) can be chosen to estimate direction of arrival (DoA), and then for range and doppler detection, periodogram-based estimation algorithm (2D-FFT) can be employed to achieve the goal.

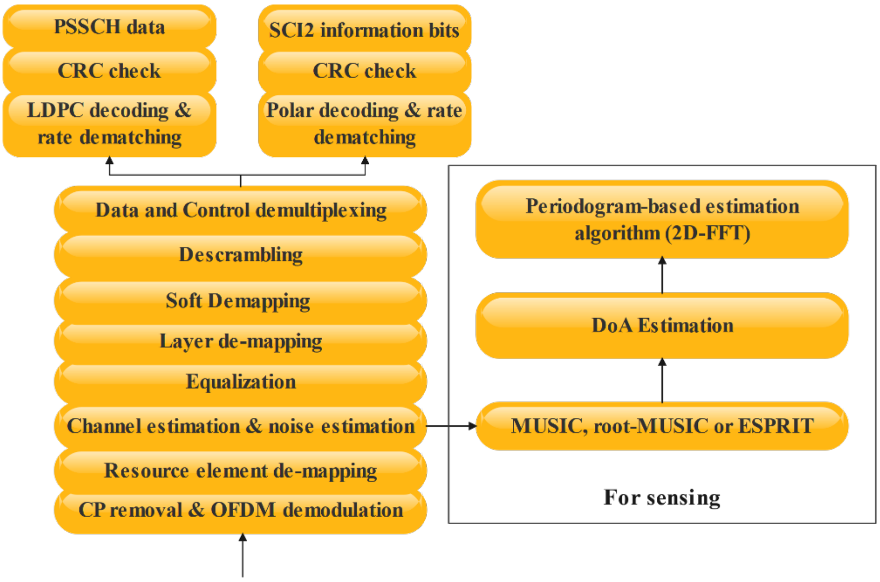

Figure 17 Potential receiver structure for ISAC

5 Hardware aspects of ISAC

5.1 State of the art of On-Board Units (OBUs) and sensors

The V2X market is evolving rapidly to support an increasing number of use cases. Accordingly, many companies compete to develop products to satisfy the existing demand. We can divide the suppliers into three main groups:

- V2X Chipset suppliers
- V2X Module suppliers
- V2X OBU suppliers

The first group is composed of chipset manufacturers. These are the cornerstone components for V2X communications. Examples of suppliers are Qualcomm, Autotalks and Huawei. The characteristics of current chipsets vary from those supporting only Vehicle to Vehicle (V2V) communications to including LTE-V2X through the Uu interface, and the more advanced ones also include 5G-V2X through Uu. Currently, there is no chipset available with the implementation of 5G-V2X PC5.

The next link in the supply chain, V2X modules, are devices which are built around the existing chipsets, adding features to ease the development of hardware solutions. Typically, more interfaces are included, such as Universal Serial Bus (USB), Reduced Gigabit Media Independent Interface (RGMII), Serial Peripheral Interface (SPI), Universal Asynchronous Receiver-Transmitter (UART) among others, including functional blocks such as the power management block, the baseband processing and the Random Access Memory (RAM), all integrated in a convenient Ball Grid Array (BGA) package. Since the module depends on the characteristics of the chipsets, the main differences between different products are given by each manufacturer's chipset. The rest of characteristics are overall very similar (interface availability, form factor, power consumption, etc). Some module providers are Quectel, SimCOM, AlpsAlpine, ZTE and Neoway.

Lastly, OBUs represent a finished product, which could be installed in vehicles or Road-Side Units (RSUs) with little or no modification. Once again, their baseline characteristics are determined by the utilised chipset or module. On top of that, each manufacturer develops its own software which must comply with applicable standards and regulations. Examples of OBUs providers are Askey, Commsignia and Harman.

Turning to sensors currently present in vehicles, multiple types of sensors are installed in modern cars, such as radars, lidars and cameras for perception. We would focus on perception-involved sensors (especially radars due to its relevance for ISAC), although there are many more such devices involved in a vehicle's functioning such as odometer, accelerometer, pressure sensors, etc. Each sensing device has its own strengths and weaknesses. Radar, for example, can work in harsh weather conditions, while lidars and cameras would be impaired. Conversely, lidars and cameras are more adequate for object classification.

Radars were the first type of these sensors to be used, and currently, millions of vehicles are equipped with multiple radars, mainly in the frequency bands of 24 GHz and the range between 76 and 81 GHz. It is worth noting that the 24 GHz Ultra-Wide Band (UWB) is being phased. On the other hand, in the band from 76 to 81 GHz, there are typically two sub-bands used [21]:

- 76-77 GHz: Used for ranges up to 250m, typically located in the front of the vehicles, with a resolution of 75cm and their main usage is for Adaptive Cruise Control (ACC) and Collision Avoidance (CA).

- 77-81 GHz: Used for ranges up to 100m, typically located in the rear and the corners of the vehicle, with a resolution of 7.5cm. Their usage is for high resolution applications such as blind spot detection, lane-change assist and rear-traffic-crossing-alert, and for detecting pedestrians and bicycles in proximity.

In these radars, the waveform is Frequency Modulated Continuous Wave (FMCW), which offers a relatively easy implementation and is a very mature technology. The following figure shows a functional diagram of a vehicular radar system.

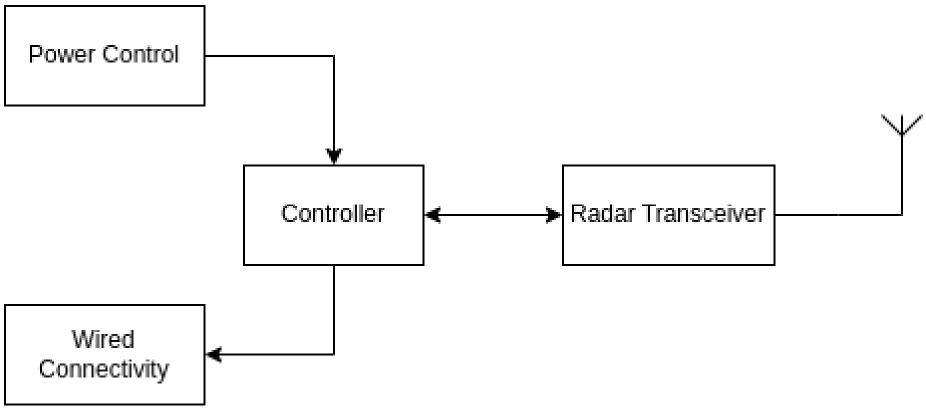

Figure 18 Functional block for vehicular radar

The controller is in charge of processing the radar information and forwarding it through the wired connectivity system to the vehicle's Controller Area Network (CAN) bus. Safety applications use the information there to perform tasks such as adaptive cruise control and forward collision warning.

Turning to Lidars, this is a relatively new application of optics with an immense potential for Autonomous Vehicles (AV). The principle is similar to radar, and even there is a FMCW variant. However, Lidar's transmitter is laser-based and the receiver consists of photodetectors. The main benefit of this technology is the high achievable precision, which enables imaging and mapping. The main drawback is the high cost of current Lidar equipment. Another disadvantage is the vulnerability to harsh weather conditions, although they are more robust than cameras, especially at night.

Lastly, cameras are becoming increasingly present in vehicles. The availability of a live video feed allows the application of state-of-the-art Artificial Intelligence (AI) algorithms for AV. Additionally, they will be indispensable for remote driving. The main disadvantage of cameras is the poor performance when visibility conditions are not good. Additionally, it is the method requiring the higher data rate and with the higher processing cost among the three analysed.

Overall, all sensing technologies must be exploited to obtain the most complete mapping of the environment possible. However, in terms of integrating sensing and communications, radar is the most relevant solution (light-based communications are not still widespread) and so it will be the one considered in the following sections.

5.2 Integration of sensing and communications into a telematics unit

When considering the integration of sensing and communications into a single telematics unit, two of the mentioned integration levels can be analysed: cooperation and joint design.

5.2.1 Cooperation

In this case, there are two distinguishable scenarios:

- Both systems have their independent transmitting and receiving blocks and share a common coordinating entity
- Both systems must share resources and RF transmitting and receiving chains.

In the first case, both functions have their own frequency band. A functional block for the solution is shown in the following figure.

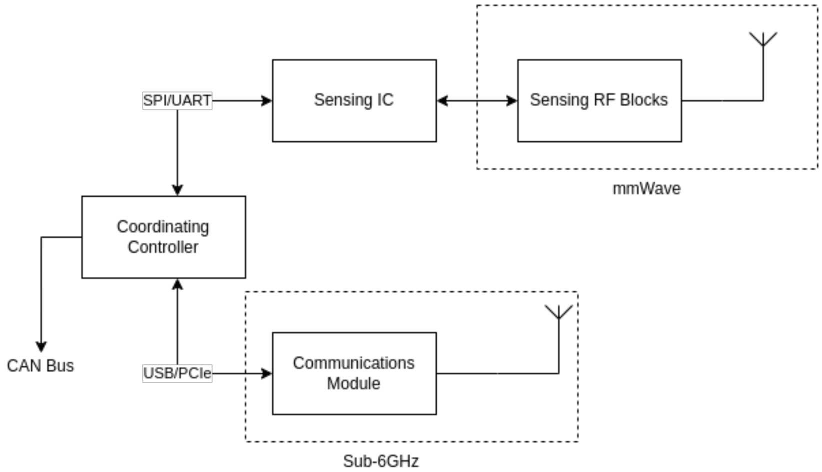

Figure 19 Functional block for cooperation solution

The controller's primary function is to use information from both systems to benefit their performance. Additionally, it is responsible for passing the collected sensing information to the vehicle's CAN bus. Current implementations in cars do not differ significantly from this scheme. However, better integration between the communications and sensing functionalities could be achieved with the use of the coordinator. Still, isolation measures between the two blocks must be kept in place, to avoid mutual interference. The Intermediate Frequency (IF) stage of radars, for example, can be extremely sensitive to external disturbances so its adequate protection remains critical for proper functioning. Additionally, power-plane and ground-plane separation must be maintained when necessary. For the communications block, this is typically eased by using a V2X module, which internally isolates its analog and digital grounds and power domain. However, radar Integrated Circuits (ICs) are normally separated for each function, so proper design rules are required.

For the second case, the transmitting front-end for the sensing block can be reused to expand the available resources for communications. A functional block for this scenario is shown in the following figure.

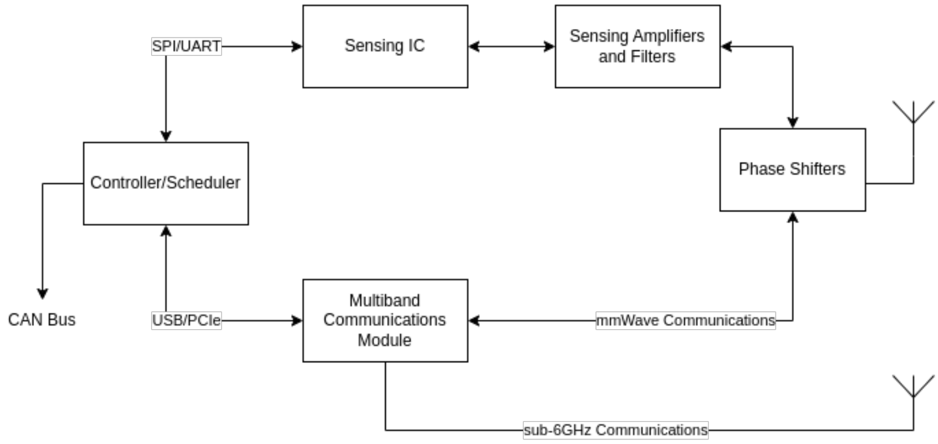

Figure 20 Functional block for cooperation with spectrum sharing

In this case, the controller not only passes the relevant information but also decides on the scheduling of the opportunistic spectrum access from the communications module into the spectrum. While the antenna arrays and phase shifters can be reused, the amplifier for each functionality must be kept separately due to the different requirements. In the case of the communications, for example, the usage of OFDM and its associated Peak to Average Power Ratio (PAPR) reduces the amplifier's efficiency, which is an adverse effect not desirable for sensing. The rules mentioned for the first case also apply here for the rest of the design. It is worth noting that currently, no communications module available in the market would allow to implement this solution. However, in the near future, the advantages of more efficient spectrum usage might motivate manufacturers to include such capabilities in their equipment.

5.2.2 Joint Operation

For the joint operation case, the functional block (shown in Figure 21) might appear simpler at first. Still, the implementation complexity is much higher due to the need to execute both functions in the same hardware and the challenges it carries. The details of the transmitting and receiving stages for an implementation based in OFDM is shown in Figure 22.

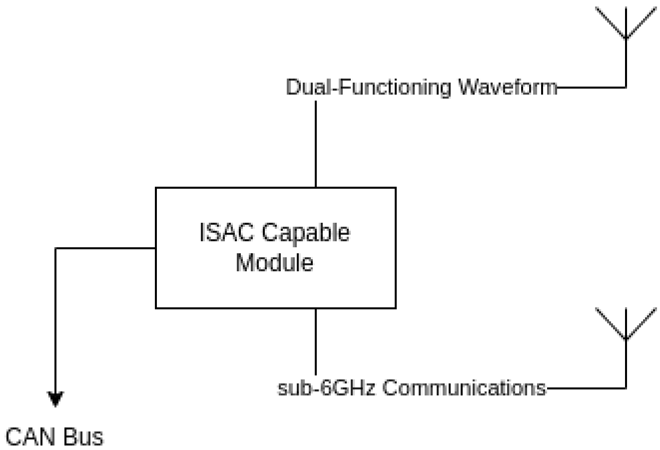

Figure 21 Functional block for Joint Operation

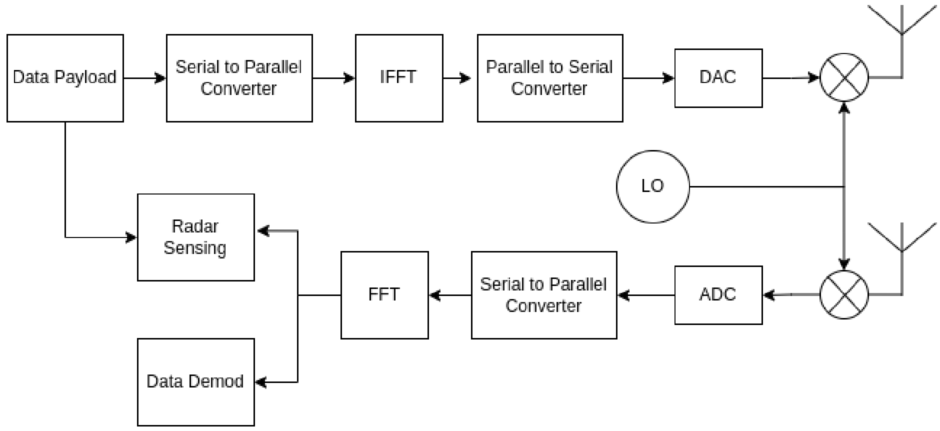

Figure 22 Detailed Joint Operation Transceiver

While using a unified waveform removes the need to multiplex resources between two systems, the different communications and sensing performance requirements impose readapting the current resource allocation mechanisms. Additionally, the need for using multiple frequency bands comes from the fact that while mmWave allows good performance for sensing and communications due to the high available bandwidth, its operation in non-line of sight (NLOS) conditions suffers. Hence, for collective perception messages that need a broader diffusion, sub-6GHz continues to be a better choice.

5.3 Challenges of multi-band system integration

Each of the explained implementations has its particular challenges. While some of them have been mentioned for clarity in their respective sections, a brief review of the most important ones is presented here.

For the cooperation case, given the relatively more straightforward hardware implementation, the challenges are more related to the software and protocol aspects of the solution. To effectively use the cooperation, algorithms that support the usage of sensing information for communications and vice versa are required. This is known in the research community as sensing-assisted communications and communications-assisted sensing. The most basic cooperation case should support MAC mechanisms to prevent radar interference by exchanging scanning parameters through the communication subsystem. For the case where resources are reutilised, the MAC protocols must be carefully revisited since the multiplexing must avoid intra-user interference and inter-user interference. Once again, exchanging radar sensing parameters of vehicles in the vicinity is required. Moreover, the placement of the different components of the solution in a car requires careful planning since it dramatically affects the radiation pattern of antennas.

For the joint operation scenario, the challenges are more significant. Starting with the requirement to suppress self-interference, the proximity of transmitting and receiving antennas puts the transmitted data at levels of over 100dB stronger than the echoes. Even though this self-interference can be considered a static target very close to the receiver, the high power could saturate the receiver with a limited dynamic range. To alleviate this, techniques such as antenna isolation and analog and digital cancellation must evolve significantly. Antenna separation is feasible for vehicles, but with a great separation, the sensing scenario turns from mono-static to bi-static and proper algorithm adjustments are required. Moreover, the transmitting and receiving gains need to be maximised to achieve good sensing performance. This demands the application of precoding and decoding techniques, which, especially in mmWave, carry a significant implementation and power cost related to the number of RF chains to employ. For this, hybrid beamforming techniques appear to be a solution, but the impact of its application to ISAC scenarios requires further study. Lastly, MAC mechanisms remain an open problem for joint operation. Once again, the need to cover the different requirements of communications and sensing demands a change in the resource allocation mechanisms. When using the same waveform for both functionalities, while radar needs high bandwidth and relatively long scanning time to achieve proper distance and velocity resolution, occupying the full resource grid is not feasible when multiple vehicles intend to use the spectrum simultaneously. Compressed sensing techniques and spectrum subsampling are two possible solutions to this problem, but both need to be carefully assessed regarding their applicability to ISAC.

5.4 Benefits and potential applications of multi-band ISAC platforms

The benefits of a multi-band ISAC solution stem from the motivations that have led to the development of this field of research. The main one would be the more efficient spectrum usage with the possibility of using the same transmission for both functionalities, enabling higher bandwidth allocations, which improve both communications and sensing performance. Moreover, the performance of localisation techniques currently implemented in mobile networks could be significantly improved since in addition to the radar capabilities, traditional localisation methods such as Time Difference of Arrival (TDOA) benefit from higher bandwidth.

In sensing-assisted communications, an area in which ISAC has significant potential is predictive beam alignment and tracking. For communications in the mmWave, highly directional links must be established to counter the propagation losses. The downside of these directional beams is the need for proper beam alignment and tracking, since, in the absence of correct steering, the received power would be insufficient for a correct demodulation. Current solutions for beam alignment require sending pilots to detect the transmitting and receiving beam pair, which offer the best performance. However, this represents a significant overhead. With sensing information, the need for pilots could be reduced, limiting the search space to the location where the ends of the communication link are located.

When analysing the use cases proposed for advanced automotive systems such as vehicle platooning, remote driving and autonomous driving, it becomes clear that a constant information exchange is required to maintain collective perception and operate safely. Using sub-6GHz spectrum exclusively is insufficient to fulfill such use cases' expected data rate and latency requirements. In consequence, a multi-band, multi-antenna system appears to be the only solution. Vehicles equipped with directional antenna arrays operating in mmWave for high data rate directional links with other vehicles in proximity and more omnidirectional antennas in sub-6GHz to exchange information with other users in NLOS would be better equipped to achieve the performance requirements of advanced use cases. Additionally, exploiting the LOS links for simultaneously sensing the environment increases efficiency and reduces the latency to acquire sensitive environmental information.

The geometrical nature of the mmWave communication channel also allows for exploiting positioning information to improve resource allocation. Typically, scheduling entities assign different time and frequency resources to different users. However, by using knowledge of the relative localization of the users, spatial orthogonality can also be exploited, improving the operation of Multi-User Multiple Input Multiple Output (MU-MIMO) systems. While typically, MU-MIMO uses Channel State Information (CSI) to multiplex users, adding sensing would reduce the need for CSI feedback and estimation. On the same line, the localization could be used to predict handovers and appropriately allocate resources in advance.

6 Section 6. Conclusions

The current deliverable has presented an overview of the multiple integration levels for communications and sensing, looking into the advantages and challenges of each solution. Additionally, current V2X protocols have been analysed with emphasis on physical layer simulation results, and ideas for required modifications to implement ISAC have been presented. Lastly, the blocks for a hardware implementation have been briefly explained and the benefits and challenges of such solutions were analysed.

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