ITN-5VC

Integrated Telematics for Next Generation 5G Vehicular Communications

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Executive summary

This deliverable reports on the progress made by the ESRs involved in WP3. It starts with a brief overview of the topic of ISAC and then touches on aspects of the NR and more specifically the V2X related protocols that will be relevant to the project. An analysis of current protocols and planned releases as well as their impact on the possible inclusion of ISAC functionality on mobile networks is included. Lastly, a description of the telematics unit's architecture and intended functionalities are offered. The described solution adopts the coexistence/cooperation integration level for ISAC.

Disclaimer: This work has been performed in the framework of the H2020 project ITN-5VC co-funded by the EU. This information reflects the consortium's view, but the consortium is not liable for any use that may be made of any of the information contained therein. This deliverable has been submitted to the EU commission, but it has not been reviewed and it has not been accepted by the EU commission yet.

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1 Introduction

1.1 Background

Radar and communications systems have traditionally been developed separately due to the different requirements for waveform, bandwidth, and operation functions. However, in recent years, many researchers have been arguing the benefits of achieving joint operations. In the literature, many terms have been used to refer to the integration of communications and sensing functionalities: Integrated Sensing and Communications (ISAC), Joint Communication and Radar Sensing (JCAS) [1]–[3], Radar-Communications (RadCom) [4], Joint Communication and Radar (JCR), Joint Radar and Communication (JRC) [5], [6] and Dual-Functional Radar-Communications (DFRC) [7]–[9]. From here we will use the term ISAC.

Intelligent Transportation Systems (ITS) are one of the fundamental use cases for ISAC and the application that more attention has received by authors [10]–[12]. Modern cars already have multiple radar modules, and Vehicle to Everything (V2X) enabled cars have also a wireless communications unit. The integration of the two functions could potentially reduce the overall costs and allow for a more efficient usage of spectrum. In addition, with the increasing number of vehicular radars, interference is expected to become a serious problem, which could be solved by using Medium Access Control (MAC) mechanisms which are already present in wireless communications systems.

There are two families of standards for vehicular communications: Dedicated Short Range Communications (DSRC) and cellular V2X (C-V2X). The former is based on the 802.11p technology and the later was firstly introduced by the 3rd Generation Partnership Project (3GPP) with Long Term Evolution (LTE) V2X in Release 14 and extended to New Radio (NR) 5G on Release 16. The focus of the ITN-5VC project is on C-V2X so DSRC will not be considered in this document.

In current C-V2X standards there is still no consideration for sensing functionalities. However, in NR 5G there are already features that could eventually facilitate the implementation of ISAC in mobile networks and that extend to V2X. In addition, there is increasing attention from the 3GPP in the topic, which has developed a feasibility study for ISAC that should be included in Release 19 [14].

This deliverable presents the proposal for a telematics unit that aims to implement ISAC for a vehicular application. A brief overview of ISAC is included, along with an analysis of current NR 5G and V2X protocols. In addition, a review of current features and potential future characteristics in 5G mobile networks that could ease the implementation of ISAC is offered. This document has been shaped by the results obtained so far in WP3, but the views exposed here as well as the intended final result of the telematic unit can be enriched with the research work to be developed in the rest of the duration of the project.

1.2 Structure of the document

The deliverable is organized as follows:

- Section 2 briefly introduces the definition and design of ISAC system, focusing on the classification of different types of ISAC system. Meanwhile, it also shows the challenges for deploying ISAC to reality.
- Section 3 makes a detailed discussion for 5G V2X protocol architecture in 3GPP standards, which includes: introduction to physical layer, resource allocation in 5G V2X, signalling 5G V2X protocol for operation mode 2 as well as the prospect of introducing ISAC to 3GPP standards.

- Section 4 presents our design for integrated telematic unit of ITN-5VC project based on the concept of coexistence in ISAC system. A detailed description of the architecture is provided. Besides, the working progress on physical layer sidelink and use cases under consideration are reviewed.
- Finally, Section 5 concludes the deliverable with the final remarks.

2 ISAC systems

2.1 Background and motivation

Perhaps the primary motivation for integrating communications and sensing into a unified system is the increased spectrum cost and the demand for more bandwidth. With a solution that could perform both functions, considerable resources could be saved. Despite the potential complexity, its overall cost should eventually become cheaper than the separated counterpart due to the reuse of functional blocks.

In addition, a current trend suggests the convergence of communications and sensing. Firstly, common technologies are being deployed in both fields, such as Multiple Input Multiple Output (MIMO) and beamforming, and common waveforms such as Orthogonal Frequency Division Multiplexing (OFDM). Secondly, there are similarities in the implementation of both systems. For example, the signal processing module of radar, traditionally implemented by analog hardware, is being replaced by digital devices [5]. Lastly, both communication and sensing are reporting increasing interest in mmWave. Many radar implementations already exploit it, and it is expected for 5G and beyond to also occupy these frequencies. In the mmWave band, channel characteristics and signal processing for sensing and communications tend to be similar. The higher propagation attenuation causes the channel to be dominated by the Line of Sight (LoS) component, and it becomes simpler to extract features from the propagation scenario's geometry. Furthermore, given the characteristics of the mmWave band, the antenna arrays can be made physically much smaller, and high gains can be achieved due to beamforming. For example, beam training and tracking in communications, are like target detection and tracking in radar. Hence, integrating both systems would enable sensing-aided communications and communications-aided sensing [8]. Future transceivers could have a dynamic nature, adapting to meet the immediate needs of transmitting information and sensing the environment [16].

Next the different levels of integration of sensing and communications will be discussed.

2.2 ISAC integration levels

An analysis of the current literature on the topic of ISAC reveals the following classifications for the integration level of communications and sensing:

- Isolated systems
- Coexistence/Cooperation
- Joint design

Isolation has been the traditional way to operate radar and communication systems. However, complete isolation between communication and sensing is difficult to achieve in practice, especially for deployments that work on adjacent bands where some interference can occur due to spectral leakage. While the regulatory entities impose restrictions to ensure proper operation, systems can experience some level of degradation. Moreover, this model is becoming obsolete with the increasing demand for spectrum.

2.2.1 ISAC Coexistence/Cooperation

In coexistence, two scenarios are distinguishable:

- Communications and Sensing in separate entities that must share spectral resources
- A unique system capable of performing communications and sensing by allocating non-overlapped resources to each function

In the first case, radar and communication systems have active transmitters using the same frequency spectrum. Hence, the problem is eliminating or mitigating mutual interference while maintaining the required performance for both functions. Concepts first introduced in cognitive radio networks, such as pilot signals for channel estimation, can be employed, and the channel information can be exchanged between the two systems. If no communication between the two entities exists, any necessary information to mitigate the other system's interference must be estimated. Blind spectrum sensing techniques, where the user scans the spectrum without any previous knowledge about frequency allocation, can be employed to inform space-time duty cycling of spectral access [16].

The optimization of signals employed to cause minimum interference has been researched for coexistence. Usually, the methodology for obtaining the optimum signal starts with determining the models for the communication and radar channels. Then, an optimization problem is solved over the variables related to the performance of the two systems.

Alternatively, with the use of MAC mechanisms, coexistence can be achieved within a single unit, where a controller decides which function will be active at a given time. Appropriate algorithms to balance both functions according to the needs for sensing and communications need to be developed. Given the status of mobile networks and radars, this could be the first step for integrating both functions in a simplified manner that could offer significant advantages over completely isolated operation.

In both cases of coexistence, cooperation can help to improve the performance of both functions. The exchange of information between communications and radar modules helps not only for resource allocation, but also for achieving communications-aided sensing and sensing-aided communications. While this is a topic that has been mostly explored on a joint design level [17], there are integrations gain that can be obtained with coexistence and cooperation.

2.2.2 ISAC Joint Design

For joint design, the focus has been on the study of waveforms that could be exploited for both functions. There are two main lines of work:

- Sensing-centric Waveforms
- Communication-centric Waveforms

Usually, adapting a waveform to a new function involves a lower performance. A third option that is gaining ground is designing from scratch a new waveform. It is argued that the waveform to be used for 6G should be designed with sensing functionalities in mind.

Given that the focus of our work is the integration of sensing functionality in mobile networks, sensing-centric waveforms are not of our interest. For Communication-centric Waveforms, a popular trend in the literature is to explore the applicability of OFDM for sensing [12], [18], [19].

Traditionally, radar processing is done via matched filtering as the delay estimator that minimizes the Cramer-Rao Bound (CRB). However, it has been shown that the ambiguity function of OFDM offers inferior performance due to the influence of transmitted data. To address this, Sturm et al. proposed a novel processing method in [20], which has been adopted by following related work and referred to as "symbol domain processing." Initially, a mono-static radar was considered, with collocated transmit and receive antennas. Once the OFDM signal is transmitted, the receiving antennas listen for echoes reflected from targets. The influence of the transmitted information is removed from the received OFDM grid by element-wise division with the original one, and the remaining matrix contains the delay and doppler information.

2.3 ISAC Challenges

Still, there are many challenges to solve to enable the applicability of ISAC on real deployments. For the completely joint solution, where the same waveform is used for both functionalities and most hardware blocks are also reused, there are two scenarios with different problems to be tackled:

- Monostatic Sensing: the main problem is the need for In-Band Full Duplex operation. The transceiver must be able to receive the echoes from the targets while simultaneously transmitting. While In-Band Full Duplex can be easier to achieve for sensing than for communication because the transmitted wave can be considered as a close target with zero doppler shift, still good self-interference cancellation techniques are required [21]
- Bi-Static / Multi-Static Sensing: the challenges in this scenario are related to achieving proper time-synchronization between the sensing transmitter and receiver, and how to efficiently fuse the information of multiple sensors to attain knowledge about the environment

While the research community has given considerable attention to the topic, still the industry has not moved towards enabling ISAC on hardware. Tests made so far use Universal Software Radio Peripheral (USRP) equipment, [18], [22]. Hence, it is reasonable to expect that the introduction of ISAC on mobile networks will occur gradually, first by achieving cooperation between sensing and communications equipment, and only later, accompanied by advances in the hardware, full integrated operation. In the context of the ITN-5VC project, while for research purposes the Joint Design approach will continue to be explored, for the implementation of the telematics unit the Coexistence/Cooperation approach will be used.

3 5G V2X protocol extension for ISAC

3.1 Brief introduction to V2X in 3GPP standard

C-V2X was firstly proposed by 3GPP based on the Long-Term Evolution (LTE) network in Rel-14 [23] as 4G enhancements. In 3GPP standards, V2X is implemented to support distinct types of vehicular communication networks, which include Vehicle to Vehicle communication (V2V), Vehicle to Infrastructure communication (V2I), Vehicle to Pedestrian communication (V2P), Vehicle to Network communication (V2N), and Vehicle-to-Road Side Unit communication (V2R). As the first step for employing the V2X concept in the cellular network, Rel-14 focused on using Evolved Packet System (EPS) to support V2V networks. With System Architecture Evolution (SAE), automotive use case verticals were put forward [24].

Later in Rel-15 [25], 3GPP firstly standardized it with NR 5G network. Its first version, specified the architecture and capabilities of 5G System (5GS). In terms of architecture, Rel-15 defined the service-based approach for the 5G Core Network (5GC), data connectivity across NR and LTE access technologies, and mobility, quality of service (QoS), traffic steering, and network slicing features. With these definitions, it extended several types of eV2X services such as: platooning, advanced driving, extended sensors, and remote driving. As a step forward in 3GPP, Rel-16 [26] provided enhancements of specifications in further completing 5G architecture and supporting new services of more specific use cases, which were vital for network topology. It specified the position of the 5G network in the advanced V2X use case and NR and LTE sidelink coexistence scenario. The Next Generation Node B (gNB) will be able to control sidelink via the Uu interface (connects user equipment (UE) to gNB) and PC5 interface (the connection between UEs). Rel-16 also supported 5GS-based V2X services; broadcast mode, groupcast mode, and unicast mode in NR PC5 interface; enhanced QoS management for NR Uu interface and simultaneous LTE PC5 and NR PC5. Recently, in Rel-17, 3GPP added some new and improved sidelink features. More specifically, it brought power management and savings, optimized resource allocation, and started to support new frequency bands. The standards also extended the use cases to the Internet of Things (IoT) and public security issues via the utilization of relay in sidelink [27].

3.2 Physical layer design in release 17 5G V2X standard

In NR 5G system, there are two different operation choices for V2X networks: communication via the PC5 interface and communication via the Uu interface. The PC5 interface supports Sidelink (SL) in V2X communication for both NR and LTE. In contrast, downlink (DL) and uplink (UL) V2X communication are supported via the Uu interface for NR Non-Standalone (NSA) and Standalone (SA) topology. Until Rel-16, only unicast communication is supported under V2X communication via the Uu interface [28]. In Rel-17, broadcast and multicast communication are discussed and enhanced in NR.

In NR V2X SL, physical layer architecture is designed according to the Rel-15 NR Uu outline. Furthermore, some definitions in LTE V2X are reused in NR V2X SL physical layer processing. In the following, there is a brief introduction to this structure.

I. **Numerology**: Theoretically, NR V2X SL should use the same frequencies as those designed for NR Uu UL and DL communications [29], which are: frequency range 1 (FR1) and frequency range 2 (FR2). For FR1, the corresponding frequency range is 410MHz-7.125 GHz. As for FR2, it is divided into two parts: FR2-1 (24.25 GHz-52.6 GHz) and FR2-2 (52.6 GHz and 71GHz). Currently, NR V2X SL is designed based on FR1. Like NR UL and DL transmissions, NR V2X SL carries on with OFDM waveform attached with a cyclic prefix (CP). The duration of one radio frame in SL frame architecture is still 10 ms. Each radio frame will be composed of 10 subframes; thus, each subframe will last for 1 ms. By using an SCS and a CP, the OFDM numerology is determined. It can be calculated with a subcarrier spacing (SCS) as $2^{\mu} \times 15$ kHz; μ is the SCS configuration factor. The value of μ can be configured as 0, 1, 2, and 3. For FR1, the available value of μ can be 0, 1, 2, and in FR2, μ can be 2, 3. As for the number of slots for each subframe, it is defined by the SCS for the OFDM waveform. For example, since the duration of a subframe is 1ms, then the duration of a slot is equal to $1/2^{\mu}$ ms, which means that a larger SCS produces a smaller duration of the slot. Like the design in NR Uu, NR V2X SL still supports two types of CP: normal CP and extended CP. Each slot has 14 or 12 OFDM symbols regarding different types of CP utilized. Notably, in NR V2X SL, only one numerology will be exploited for each carrier at one time. Unlike NR Uu UL and DL, the smallest unit of scheduling time for NR V2X SL transmissions is a slot. One thing that needs to be remembered is that mini-slot scheduling is not supported in NR V2X SL.

II. **Bandwidth part in SL**: the definition of bandwidth part (BWP) in NR Uu is a contiguous portion of bandwidth within the carrier bandwidth where single numerology is used [29]. This definition is also employed in SL. In each carrier, only one BWP of SL is used for all the terminals. Both transmission and receptions for SL are included within the BWP and exploit the same numerology, which means that all physical channels, including reference signals and synchronization signals, are sent within a BWP. Also, identical to NR Uu, this BWP of SL consists of common Resource Blocks (RBs), which are divided into 12 contiguous subcarriers.

III. **Resource pool:** for SL of NR V2X, a group of UEs is preconfigured to utilize a portion of the available SL resources for transmission. This available subset of SL transmission is named resource pool [29]. A resource pool will be composed of contiguous physical resource blocks (PRBs) and contiguous or non-contiguous slots that are predefined for SL communication within BWP. In the frequency domain, the resource pool will be composed of a predefined number L of contiguous subchannels, whose size should be defined as 10, 12, 15, 20, 25, 50, 75, or 100 PRBs. The smallest unit for SL transmitting and receiving is a subchannel. As for the time domain, the slots for the resource pool are predefined by a bitmap whose length is between 10 and 160 and will occur periodically each 10240 ms (about 10 seconds). One resource pool can be used by multiple UEs for SL communication, while a UE could be configured with several resource pools for receiving.

IV. **Physical channels and signals in NR V2X SL**: there are four different physical layer channels defined in NR V2X SL:

    1) Physical Sidelink Broadcast Channel (PSBCH): used for carrying synchronization information and sent by sidelink synchronization signal block (S-SSB).
    2) Physical Sidelink Control Channel (PSCCH): like the physical downlink control channel (PDCCH) in NR Uu, used for sending sidelink control information (SCI).
    3) Physical Sidelink Shared Channel (PSSCH): used for transmitting payload data for SL and additional control information
    4) Physical Sidelink Feedback Channel (PSFCH): used for transmitting feedback information to indicate whether the communication is successful or not. In addition, there are various kinds of signals transmitted on these physical channels, which are:
        a) Demodulation reference signal (DMRS): deployed in PSCCH, PSSCH, and PSBCH, receiver exploits it to decode corresponding SL physical channel.

b) Sidelink primary synchronization signal (S-PSS) and sidelink secondary synchronization signal (S-SSS): for receiver's synchronization usage.
c) Sidelink channel state information reference signal (CSI-RS): transmitted within PSSCH and utilized to estimate channel state information. Based on this measurement, the receiver can send feedback to the transmitter, and then the transmitter can employ it as a reference to adjust for the subsequent transmission.
d) Sidelink phase tracking reference signal (PT-RS): transmitted within PSSCH and utilized to reduce phase noise influence for higher frequency which is caused by the oscillator [29].

3.3 Resource Allocation in 5G V2X

The resource allocation in NR V2X Sidelink communications is defined in two modes [30]:

- **Mode 1:** The vehicle must be under network coverage, meaning that the gNB or eNB is in charge of managing and scheduling the radio resources. In this operation mode, the vehicle must request a sub-channel to the base station for each transport block; this process is called Dynamic Scheduling. Also, the gNB or eNB can reserve a sub-channel so that the vehicle can transmit several transport blocks. This process is called Semi-Persistent Scheduling (SPS).
- **Mode 2:** The vehicle must be outside of network coverage. In this scenario, the vehicle chooses its sidelink resources by using a channel sensing mechanism, which means it continuously senses the radio channel and averages the received signal strength values by the other nearby vehicles. This process is called sensing-based SPS.

Sensing-based SPS is a sensing procedure that identifies the resources based on decoding the 1st-stage SCI received from the surrounding vehicles, indicating the time-frequency resources in which the vehicle will transmit. Besides, the sensing procedure can perform sidelink-powered measurements, such as the Reference Signal Received Power, within the PSCCH and the PSCCH-DMRS. These procedures are used to maintain a record of resources reserved by other vehicles around them. The sensing procedure is performed during the sensing window.

The sensing window can have a duration of either 1100 ms (about 1 second) or 100 ms according to the configuration settings for each resource pool. During this time, the vehicle senses and decodes the SCIs (State Control Interface) state sent by another vehicle on the NR V2X sidelink channel. The decoded SCIs are stored together with the measurement of the RSRP to use this information to determine which resources must be excluded when a new resource selection is required [31].

Release 17 has proposed some enhancements regarding V2X sidelink communication under operation mode two, such as the power consumption, specially adapted to devices used by pedestrians and cyclist for V2X sidelink communications. Release 17 proposes to replace the first channel sensing method with a partial sensing and random resource selection scheme[32]. In addition, Release 17 introduces Inter-UE Coordination enabling vehicles to collaborate in the resource selection, focusing on avoiding collisions between vehicles and eliminating the hidden vehicle problem.

3.4 Signaling 5G V2X Protocol

This section shows the signaling 5G V2X Sidelink protocol under operation mode 2 (without coverage), aiming to understand the signaling process between two vehicles and the PC5-RRC protocol process.

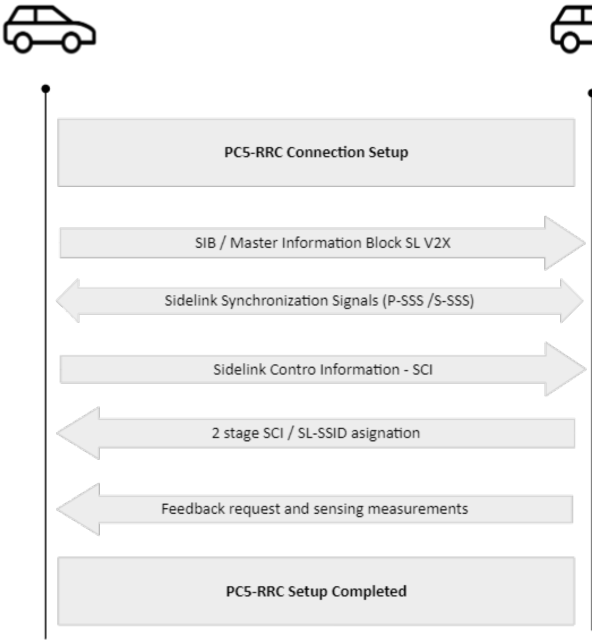
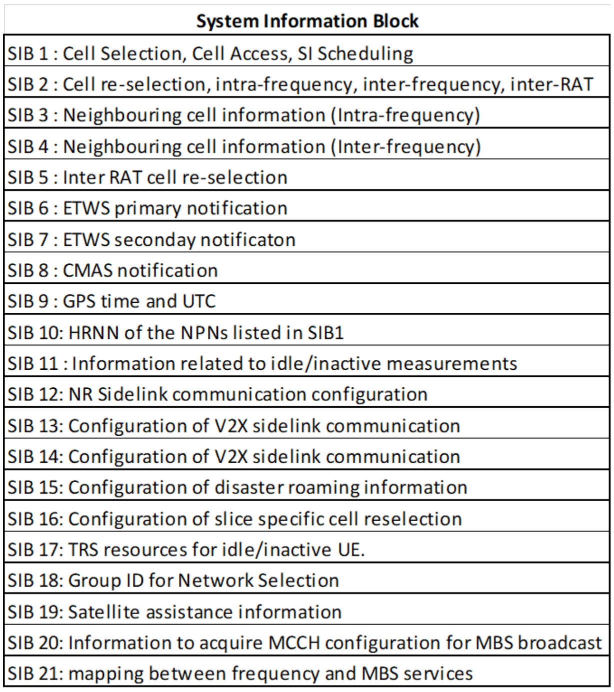


Figure 1: Signaling 5G V2X Protocol

Some preconditions need to be achieved to start the NR V2X Sidelink communication. TS 36.331 clause 5.10.1.d specifies the condition for NR V2X sidelink communication operation. In our case, the vehicle must be in RRC_IDLE Stade (without coverage). In the following, the signals associated with the setup of a sidelink communication are explained following the procedure illustrated in Fig. 1.

System Information (SI): System information is divided into two, the Master Information Block (MIB) and several System Information Block (SIB).

- Master Information Block SL – (MIB-SL): This includes the information transmitted by a vehicle and acting as a synchronization reference. MIB-SL is transmitted each 160ms and includes parameters required to acquire SIB. This parameter includes:
    a. directFrameNumber: indicate the frame number in which SLSS and SL-BCH are transmitted.
    b. InCoverage: Indicate if the vehicle is in coverage with a TRUE or out of coverage with a FALSE value.
    c. Sl-Bandwidth: Transmission of bandwidth configuration.
- System Information Block – (SIB): This contains radio resources configuration; in the protocol, there are 26 SIB, each with specific information to transmit.



System Information Block
SIB 1 : Cell Selection, Cell Access, SI Scheduling
SIB 2 : Cell re-selection, intra-frequency, inter-frequency, inter-RAT
SIB 3 : Neighbouring cell information (Intra-frequency)
SIB 4 : Neighbouring cell information (Inter-frequency)
SIB 5 : Inter RAT cell re-selection
SIB 6 : ETWS primary notification
SIB 7 : ETWS seconday notificaton
SIB 8 : CMAS notification
SIB 9 : GPS time and UTC
SIB 10: HRNN of the NPNs listed in SIB1
SIB 11 : Information related to idle/inactive measurements
SIB 12: NR Sidelink communication configuration
SIB 13: Configuration of V2X sidelink communication
SIB 14: Configuration of V2X sidelink communication
SIB 15: Configuration of disaster roaming information
SIB 16: Configuration of slice specific cell reselection
SIB 17: TRS resources for idle/inactive UE.
SIB 18: Group ID for Network Selection
SIB 19: Satellite assistance information
SIB 20: Information to acquire MCCH configuration for MBS broadcast
SIB 21: mapping between frequency and MBS services

Figure 2: Sistem Information Block[33]

SIB 12 is used when the vehicle is in coverage, and this is sent by the base station. The SIB 13 and SIB 14 are used when the vehicle is out of coverage. These SIB´s includes specific information related to receiving or transmitting SL V2X communications (TS 38.331 clause 5.8.5)

- Sidelink Synchronization signals – SLSS: There are two synchronization signals within the PSBCH named Primary synchronization signal (S-PSS) and Secondary Synchronization signal (S-SSS).

    a. S-PSS: is a set of a few common synchronization signals to facilitate the initial time in a vehicle. These signals are designed to simplify the detection of in- or out-of-coverage synchronization sources.

    b. S-SSS: together with the S-PSS, employs an accurate tuning of the reference time and recognition of the Sidelink Synchronization Signal Identification (SLSS-ID). Using this secondary signal and the Demodulation Reference Signal (DMRS) for PSBCH, the vehicle shall be measured by linear averaging over the power contribution of each Resource Element (RE).

- Sidelink Control Information (SCI): The SCI is divided into the 1-stage SCI and the 2-stage SCI; these contain information regarding physical communication and configuration parameters to achieve communication between vehicles.

  1-stage SCI is transmitted within the PSCCH and contains information related to frequency resource assignment, priority, resource reservation period, DMRS pattern, 2-stage SCI format, MCS, and time resource assignment.

  2-stage SCI is transmitted within the PSSCH and contains information related to HARQ process ID, data indicator, source ID, and destination ID.

The SL-SSID transport information regarding the synchronization source of the transmitting vehicle. The operation of this procedure is like LTE-V2X, while the difference that in NR V2X are divided in two, in-coverage (of 0 to 335 ID) and out-of-coverage (from 336 to 671 IDs) [[34].

Feedback request: this is a procedure made to guarantee the correct transition of the information between vehicles. One bit is sent under the PSFCH related to the successful or failed reception of Sidelink transmissions.

3.5 Beyond release 17 5G V2X standard including ISAC

3GPP Release 17 improves 5G systems parameters such as capacity, coverage, latency, mobility, and power consumption. Some of its main enhancements are focused on:

- Further enhanced massive MIMO
- Coverage enhancements
- Device power saving
- Spectrum expansion
- Reduced capability (RedCap or NR-Light)
- Non-terrestrial networks (NTN)
- NR Sidelink enhancements
- Broadcast / multicast expansion.
- Further enhanced URLLC, private networks, and more.

Release 17 introduces further enhancements and extensions to NR sidelink communications, covering several new use cases, such as public safety, industrial communication, positioning, and more. The most relevant features of release 17 about the NR V2X sidelink are:

- Power battery saving.
- Reliability and latency improvement.
- Enhancement or autonomous resource allocation.
- Inter-UE coordination
- Sidelink discontinuous reception
- Sidelink Relaying.
- Sidelink Positioning.

Until recently, since the topic of ISAC is under development, there was no attention from standardization organizations. However, the 3GPP has created a Work Item (WI) called “Study on Integrated Sensing and Communications”, which is expected to produce results to be included in Release 19. Nevertheless, since this is a recent development, it is still not clear the output that this WI will have on the eventual release. Moreover, even though in the WI description C-V2X is considered one of the intended use cases, it is unclear if this will translate into changes in the V2X protocols. As defined by [14], there are several ISAC applications that can improve V2X services such as:

- Infrastructure Assisted Environment Perception
- High-Definition Map Collecting and Sharing
- Tele-Operated Driving Support

It is also worth mentioning that the 3GPP sees an ISAC-enabled 5G system as a system where the sensing capabilities are provided by the same wireless communications network and infrastructure used for communications, and that the sensing information could be derived from RF-based and/or non-RF based sensors. By extending the categories of sensors, it can be expected that the future standards will not only cover the case of Joint Design ISAC but also the Coexistence/Cooperation case.

In the literature there are some works that aim to predict the future of mobile networks including ISAC. A concept that has been used to describe an ISAC-enabled network is Perceptive Mobile Network (PMN) [13], [35], [36]. The authors have described the different types of sensing that can be performed in a PMN:

- Active Downlink Sensing: A Remote Radio Unit (RRU) uses echoes from its own communication transmission to perform sensing
- Passive Downlink Sensing: An RRU uses echoes from the transmission of another RRU to perform sensing. This would be equivalent to bi-static or multi-static sensing
- Active Uplink Sensing: A UE uses echoes from its own transmission to perform sensing
- Passive Uplink Sensing: While this could mean that UEs use echoes from another UE’s transmission, the must explored case is that an RRU uses echoes derived from an uplink transmission.

The authors also suggest some of the changes that would be needed on today’s mobile networks to add these capabilities. The modifications are primarily to address some of the challenges already mentioned in section 1.2.3: full-duplex for monostatic or active sensing and clock synchronization for bi(multi)-static or passive sensing. They discuss the following possibilities:

- Dedicated static transmitter or receiver for sensing: this would be transmission/receptions points specifically used for passive sensing and synchronized with the other endpoint.
- Introduction of full-duplex radio units: this is the long-term solution, but it is not feasible in the short term.

Related to the possibility of dedicated transmitter/receiver for sensing, it could be argued that there are similarities with the introduction of Multiple Transmission and Reception Points (mTRP) on the NR specifications. While their primary function is to provide diversity for the communication link, these could be reused for passive sensing.

One of the focuses of Release 18 will be the application of Machine Learning (ML) to solve communication problems. These could later be expanded to include sensing functions, and specially resource allocation in ISAC, which is still an open problem with a high complexity given all the performance metrics and degrees of freedom involved. So far, in communications-centric ISAC, and more specifically in the context of mobile networks, three types of signals have been considered for sensing:

- Reference signals used for channel estimation: DMRS and CSI-RS.
- Synchronization signals: Synchronization Signal Block (SSB)
- Payload data

Maximizing the resources used for sensing (both bandwidth for delay resolution and time for doppler resolution) is of paramount importance for achieving a good sensing performance. Given the different requirements of sensing and communications, algorithms to balance between cell capacity and target parameters estimation need to be carefully crafted, and ML could accomplish better results in real-time applications than traditional optimization problems which tend to be non-convex.

For beyond 5G technologies, 6G is expected to be built with sensing capabilities as an intrinsic characteristic [37]. Some of the anticipated features of 6G such as increased bandwidth (with the possible extension to the terahertz band), massive antenna arrays and the channel characteristics at targeted frequencies will contribute to the inclusion of sensing. It is still unclear if OFDM will remain as the waveform for 6G but other candidates such as Orthogonal Time Frequency Space have also been tested as valid waveforms for ISAC [38], [39].

4. Design of an Integrated Telematics Unit for ISAC on a coexistence level

4.1 Architecture and Basic Functionality

Given the unavailability of a chipset in which ISAC could be done jointly, the telematics unit's aim will be a proof of concept in the coexistence and cooperation of Communication and Radar modules. Hence, the telematics unit will have separated communication and radar modules and a controller who will oversee coordinating and configuring each function's operation. The basic architecture for such a solution is shown in the following figure.

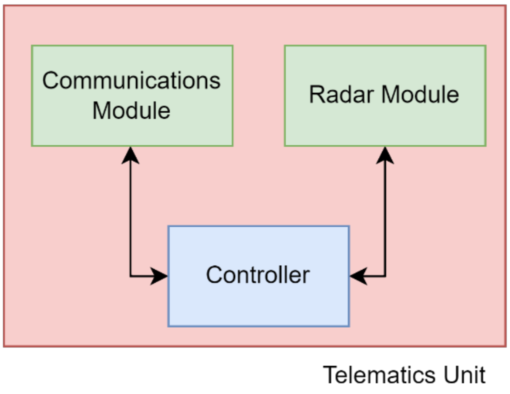


Figure 3 3: Telematic Unit Architecture

The communication between the controller and the radar module will be used to obtain information about detected targets and for the controller to configure the radars operation. On the other hand, the controller will send and receive information via the communications module and configure its operation as well.

For solutions on coexistence of radars and communications it is implied that both functions share resources, most commonly frequency. On an integrated unit, two cases for coexistence in frequency can arise:

- The communications and radar functions share the same frequency band. In this case the controller needs to schedule the operation of each function trying to optimize their performance. This scenario is illustrated in the following figure:

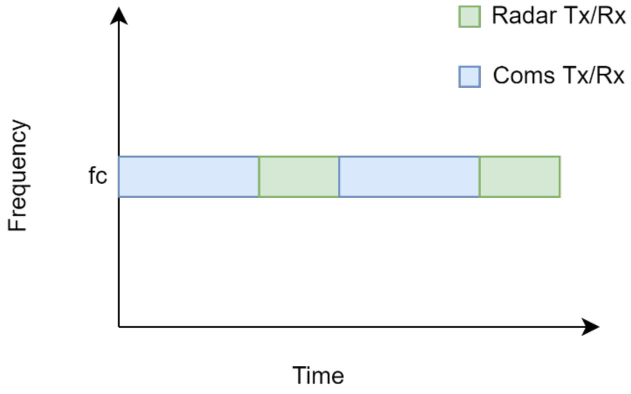


Figure 4: Radars and communication share a frequency band

The scheduling needs to be done not only considering transmissions but also reception. In the case of vehicular radars, they usually use Frequency Modulated Continuous Wave (FMCW) and achieve full duplex operation, so the transmission slot is the same as the reception slot. The transmission and reception times are different, especially in Time Division Duplex (TDD). The radar operation can be scheduled accordingly with knowledge about the communication resource allocation. However, radars from nearby cars need to be considered when operating in the same frequency band because of their interference on the communications.

- The communications module can temporarily employ carrier aggregation using the frequency band of the radar. This is illustrated in the following figure, where fc1 is the frequency used for communications and fc2 is the frequency used for radar that communications can also employ:

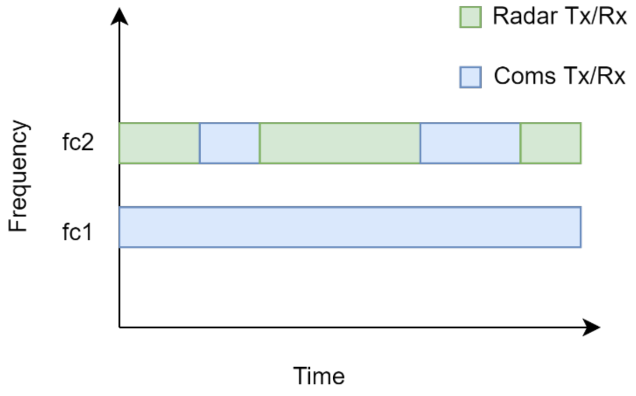


Figure 5: 5 Communications Using the Radar Frequency Band

In this scenario, due to the frequency diversity, both functions can be active for longer periods of time. Still, the possible interference on the communications because of nearby radars need to be considered.

For cooperation there are several opportunities to improve communications functionalities. Two basic solutions can be identified:

- Exploiting sensing information to improve the communication functionality
- Coordinate sensing according to information received by the communication module

4.2 Components for the Telematics Unit

Based on the architecture explained in the last section, there are three main components: the communication module, the radar module, and the controller.

Starting with the controller, a good option is to use a Raspberry Pi 4. It has support for high-speed interfaces to interact with the communication module (Ethernet / USB3) and serial interfaces for controlling the radar (UART/SPI). Due to its vast ecosystem, libraries to perform these tasks are readily available, reducing the complexity of the final software solution.

For the communication module, two options are being considered so far:

- Femto module from Casa Systems
- Custom board with commercial communications module like the RG500Q-EA from Quectel or equivalent

Both cases are functionally identical. The main difference is the way of interacting with the controller. In the case of the Femto, the interaction is via an HTTP REST interface, accessible via an ethernet connection. On the other hand, for the RG500Q-EA the controller would need libraries such as modemmanager and libqmi for setting up and managing the connection, and AT commands are also available.

Lastly, we are expecting to use a typical automotive radar unit for the radar module. A serial interface will be used to obtain the radar's measurements and to perform its configuration.

4.2.1 Sidelink implementation in communication module

Considering PSSCH is the most important physical layer channel in NR V2X sidelink, firstly, we start with the implementation of PSSCH transceiver design for communication system under sub6GHz. Following are the implementation details for transmitter part:

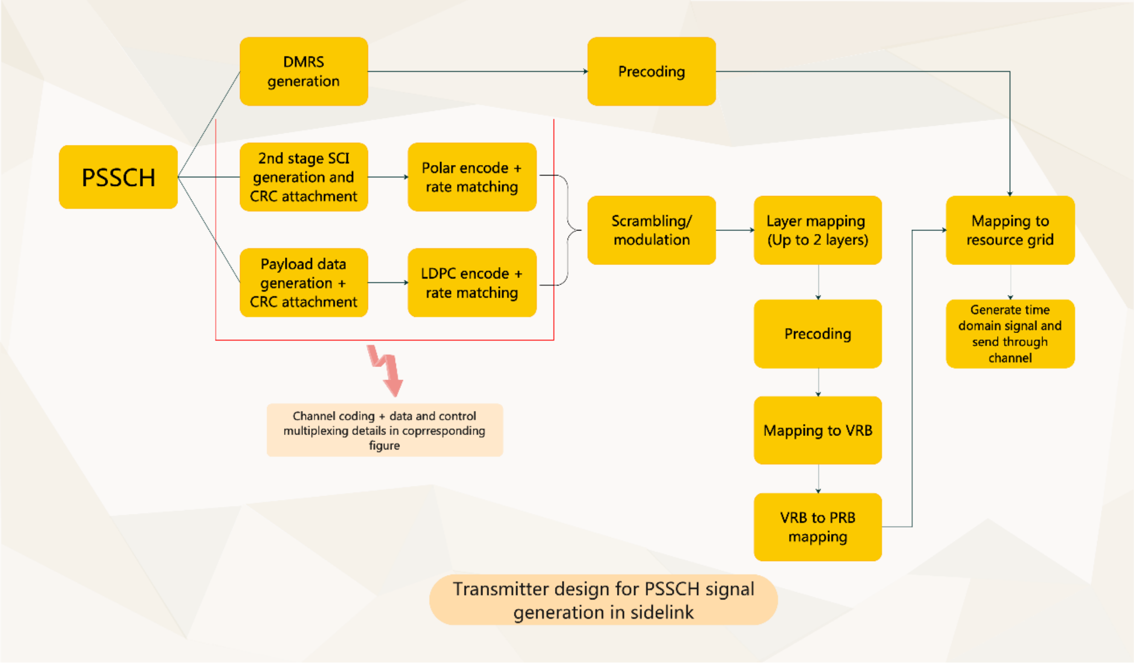


Figure 6: 6 PSSCH Transmitter Design

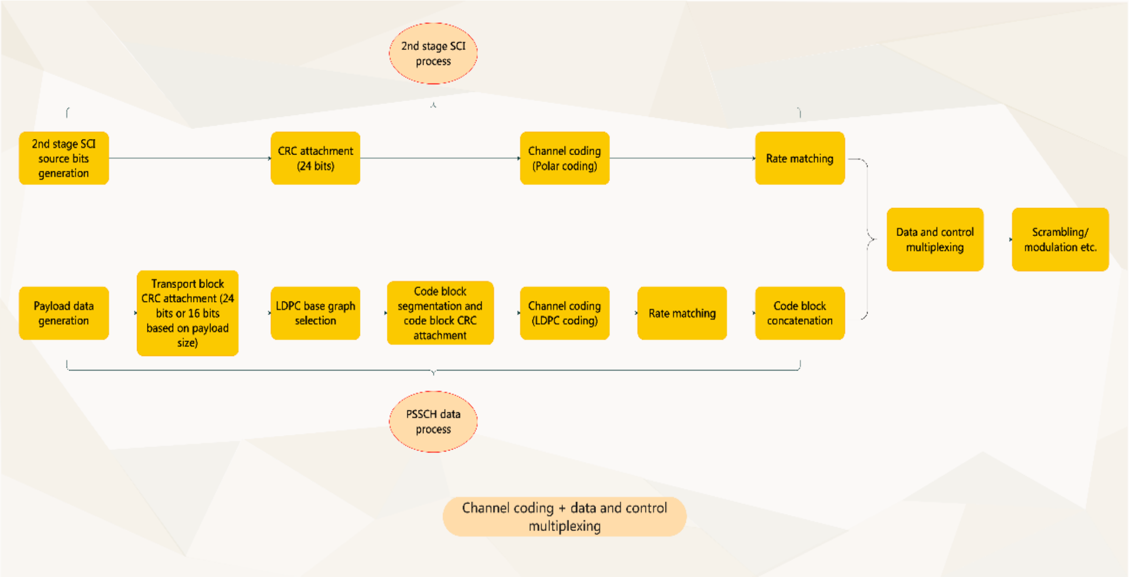


Figure 7: 7 Channel Coding and Data Multiplexing for PSSCH

4.3 Use cases being considered

With the proposed architecture it is possible to demonstrate the coexistence and cooperation between communications and radar functionalities. For the coexistence case, even if the communications and the radar modules don't share the frequency band, the controller could simulate a frequency sharing scheme, scheduling the operation of each functionality.

An example of coexistence could be a scenario where two cars are travelling in a road. The first car is ahead, and it is sending a video feed of the road to the second car, while sensing opportunistically. The controller can modify the time allocation for communication and sensing according to the existence of an obstacle on the road and the need for more accurate estimation.

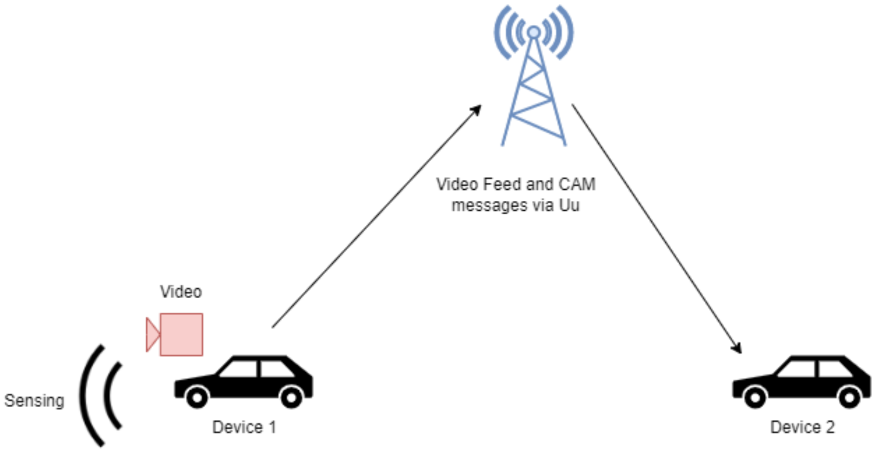


Figure 8: 8 Basic Scenario for Demonstration of Coexistence

For the cooperation case, three use cases have been identified:

- The radar detects a target, and some profiling of the echo allows to classify it. For example, the classification could be done by using values of received echo intensity and delay and defining a threshold to distinguish between weak return targets and strong ones, assuming strong return targets on the road are vehicles. When there is a possibility that the detected target is a vehicle, the controller tries to establish a V2X link with the prospective vehicle to exchange useful information (in the future this could be extended to other devices once side-link communications become more common). A flow chart of the process to follow in this use case is shown in the following figure

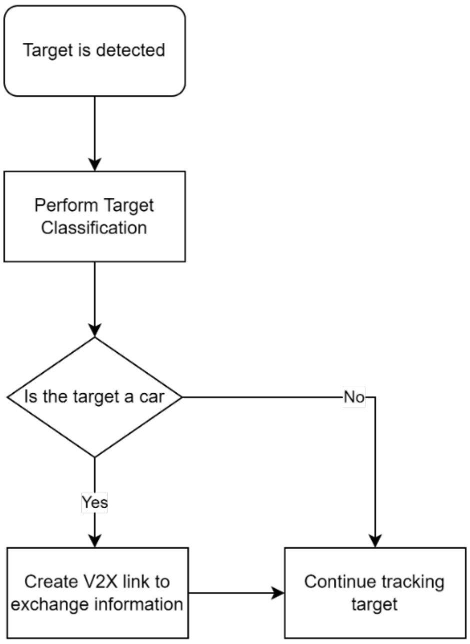


Figure 9: 9 V2X link created based on sensing results

- The communication module receives V2X messages from other vehicles in the road. The controller extracts positioning information from these messages and tries to determine if it is possible to use the radar to confirm this information. By merging information obtained by V2X and sensing a more reliable and accurate map could be obtained:

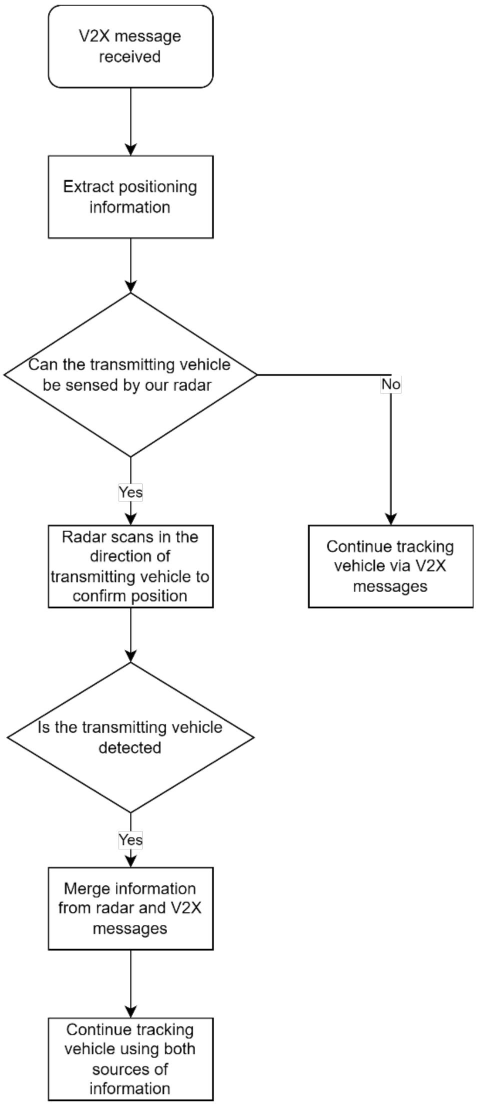


Figure 10: 10 Use of sensing to improve information on other vehicles' positioning

- There is a centralized entity coordinating the operation of radars to avoid interference. The communication module receives the radar scheduling and configuration parameters and pass them to the controller who applies the configuration to the radar. The centralized entity could be an edge server in the case of V2X mode 1 or a designated car in V2X mode 2. The first case is illustrated in the following figure:

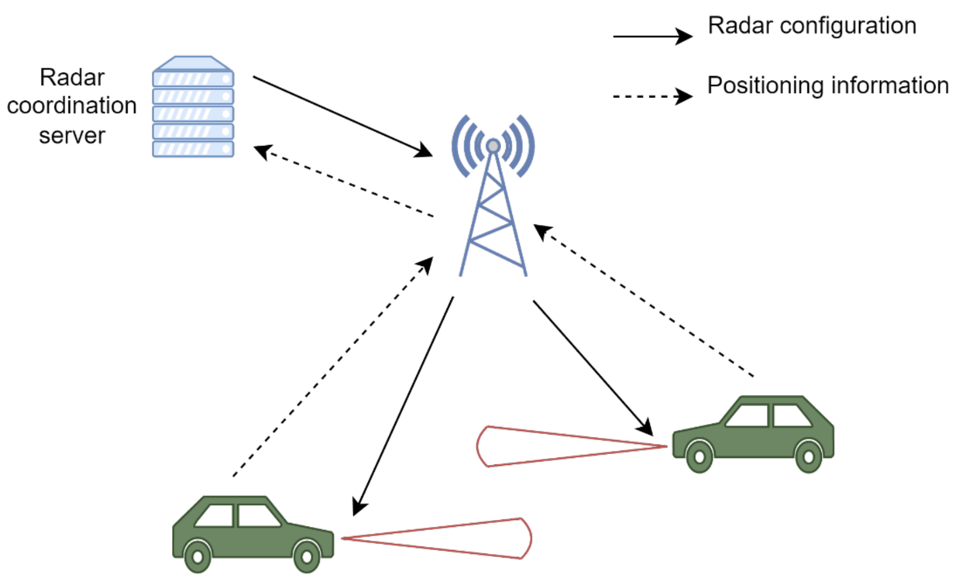


Figure 11: 11 A centralized entity to avoid interference between radars

While these are the use cases identified so far, it is possible that in the future other scenarios will be considered.

5. Conclusions

As shown in this deliverable, the integration of communications and sensing is undeniably the solution to achieve better spectrum efficiency and offers opportunities for improving the two functionalities. While in the future it is expected achieving the highest level of integration referred to as joint design, current hardware needs to evolve to overcome the challenges preventing this implementation. However, with coexistence/cooperation level integration, gains can be achieved compared to independent operations. This deliverable has presented some examples of integration gains and potential use cases that could benefit from cooperation. In addition, the state of the art of V2X protocols and resource allocation strategies were presented, as well as an analysis of features that could enable the implementation of ISAC in mobile networks and for vehicular communications. Moreover, an evaluation of characteristics that could be included in future releases with potential impact on ISAC was included. Lastly, the design of a telematics unit as a proof of concept on ISAC at the coexistence/cooperation level was explained, in addition to an overview of use cases.

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