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Waveforms

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Acronyms

2D Two-Dimensional.

5G Fifth Generation.

5G NR Fifth Generation New Radio.

6G Sixth Generation.

AoA Angle of Arrival.

BER Bit Error Rate.

CSI Channel State Information.

DD Delay-Doppler.

eLPC Enhanced Low-Power Communications.

eMBB Enhanced Mobile Broadband.

eURLLC Enhanced Ultra-Reliable Low-Latency Communications.

feMBB Further Enhanced Mobile Broadband.

FFT Fast Fourier Transform.

GSVD Generalized Singular Value Decomposition.

IFFT Inverse Fast Fourier Transform.

ISAC Integrated Sensing and Communication.

LDHMC Long-Distance and High-Mobility Communications.

LOS Line of Sight.

MIMO Multiple-Input, Multiple-Output.

mMTC Massive Machine-Type Communications.

OFDM Orthogonal Frequency Division Multiplexing.

OTFS Orthogonal Time Frequency Space.

PRS Positioning Reference Signal.

SER Symbol Error Rate.

umMTC Ultra-Massive Machine-Type Communications.

URLLC Ultra-Reliable Low-Latency Communications.

Chapter 1

Introduction

The rapid growth of wireless technologies is driving a fundamental shift in how communication networks are designed and utilized. Traditionally, communications and sensing, such as radar or localization, have been developed as separate systems with distinct hardware, spectrum, and processing methods. However, the increasing demand for spectrum efficiency, situational awareness, and intelligent services has motivated the emergence of Integrated Sensing and Communication (ISAC), a key enabler for 6G and future wireless networks.

ISAC refers to the joint design and implementation of wireless communication and sensing functionalities within a unified system [7]. Instead of treating communication signals solely as carriers of data, ISAC systems also exploit them for sensing the environment, estimating positions, and detecting objects. This integration enables devices not only to exchange information but also to perceive their surroundings, effectively merging communication and perception into a single operation.

The importance of ISAC in future wireless networks lies in its ability to maximize efficiency and intelligence. Since spectrum is increasingly scarce, ISAC makes it possible to use a single signal and bandwidth resource for both communication and sensing, avoiding conflicts between the two. It also improves positioning accuracy, motion tracking, and environmental awareness by leveraging advanced waveforms and coherent processing.

To implement ISAC, radar and communication signals have been used for both sensing and communication purposes, but due to their specialized nature, there is ongoing research on finding a multi-purpose waveform. In this deliverable we cover some of the already existing approaches to the ISAC paradigm.

Chapter 2

Considered waveforms

2.1 Orthogonal Frequency Division Multiplexing (OFDM)

Orthogonal Frequency Division Multiplexing (OFDM) is a fundamental technology to enable ISAC, due to its inherent multicarrier structure, which simultaneously supports high data rate transmission and accurate channel estimation for sensing. In order to reduce the impact of random communication data on sensing, delay and Doppler processing can be performed using the Fast Fourier Transform (FFT) and its inverse, the Inverse Fast Fourier Transform (IFFT) [8]. Additionally, the large time–bandwidth resources available in OFDM systems facilitates fine-grained target range and velocity estimation without requiring dedicated sensing signals, thus allowing spectrum reuse between communication and radar functionalities, pilot or reference signals, which are typically used for channel estimation, can be employed for radar sensing. This approach works because the pilot signals used in Fifth Generation (5G), like Positioning Reference Signals (PRS), have good auto-correlation and cross-correlation attributes, as shown in Figure 2.1, which is an important feature in radar applications. For example, PRS can be applied for the identification of objects moving near the Fifth Generation New Radio 5G NR receiver, removing the need of using specific resources to perform sensing [9].

Moreover, OFDM-based ISAC systems can be further optimized through waveform and resource allocation strategies that balance communication and sensing performance. Techniques such as subcarrier selection [10], adaptive power allocation [11], and phase coding [12] can improve radar resolution or reduce interference between the two functionalities. In particular, the orthogonality and frequency diversity inherent in OFDM enable flexible partitioning of resources, either in frequency, time, or code, allowing simultaneous yet non-disruptive operation of sensing and data transmission. These capabilities are crucial for applications such as vehicular networks, where high-throughput communication must coexist with precise object detection and localization under stringent latency and reliability requirements [13].

From a system-level perspective, OFDM current compatibility with existing communication deployments makes it highly attractive for short-term deployment of ISAC solutions. Its integration into standards such as 5G NR and the prospective Sixth Generation (6G) frameworks allows network operators to exploit their current spectrum and hardware while adding sensing capabilities via signal processing or software updates [14].

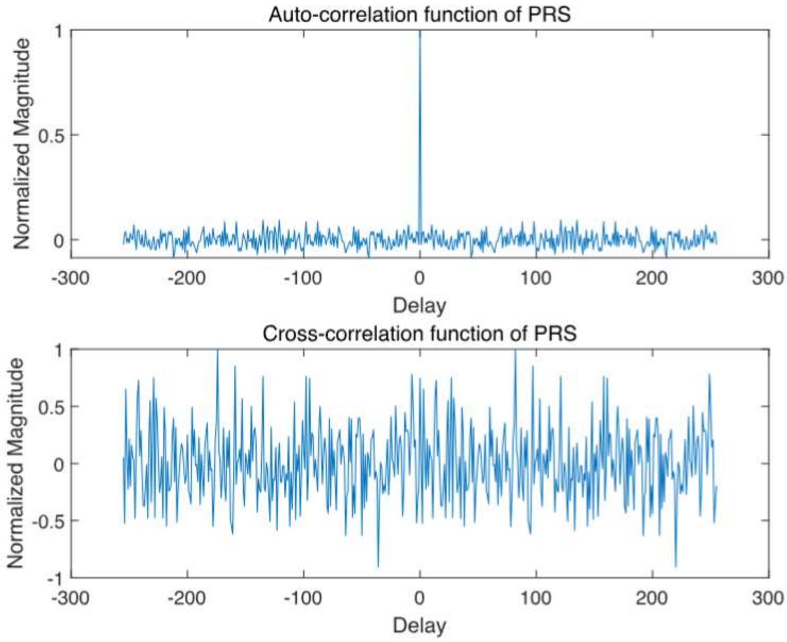

Figure 2.1: Correlation characteristics of a PRS signal [1].

2.2 Orthogonal Time Frequency Space (OTFS)

The use cases defined in 5G mobile network include enhanced Mobile Broadband (eMBB), Enhanced Ultra-Reliable Low-Latency Communications (URLLC), and massive Machine-Type Communications (mMTC). In the context of 6G mobile network, these use cases need to be further enhanced. This leads to further enhanced Mobile Broadband (feMBB), enhanced Ultra-Reliable Low-Latency Communications (eURLLC), and ultra-massive Machine-Type Communications (umMTC). In addition to these, two new use cases are introduced: Long-Distance and High-Mobility Communications (LDHMC) and enhanced Low-Power Communications (eLPC). These latter two require new investigations to design systems capable of supporting such advanced scenarios [15; 16]. Specifically, LDHMC in 6G may involve applications that exceed the current maximum mobility expectations of 500 km/h, potentially requiring communication capabilities at speeds up to 1000 km/h. This includes emerging domains such as deep-sea tourism, space tourism, and ultra-high-speed rail systems [17].

Orthogonal Time Frequency Space (OTFS) modulation, proposed in [18], is a strong candidate for high-speed environments due to its demonstrated ability to handle doubly dispersive channels. In this modulation, information symbols are mapped in the Delay-Doppler (DD) domain, where the channel is treated as time-invariant, even though it is inherently time-variant, making the system robust to extreme mobility conditions. At the receiver, the transmitted symbols are coupled with the DD channel through a two-dimensional phase-shifted convolution, which enables reliable performance even at very high speeds [19]. Since its proposal in 2017, extensive research has been conducted on the system design of OTFS. One prominent research direction is led by the authors of [2], who analyzed the complete OTFS system, including channel modeling, data detection, and channel estimation, and compared it with OFDM modulation.

As mentioned earlier, the importance of OTFS modulation comes from how the channel can be represented in this scheme. In OTFS, the time-varying channel is modeled in the two-

Dimensional (2D) DD domain [2]

$$h(\tau,\nu)=\sum_{i=1}^{P} h_i\delta(\tau-\tau_i)\delta(\nu-\nu_i), \quad 0\le\tau\le\tau_{\max}, ; -\frac{\nu_{\max}}{2}\le\nu\le\frac{\nu_{\max}}{2}. \tag{2.1}$$

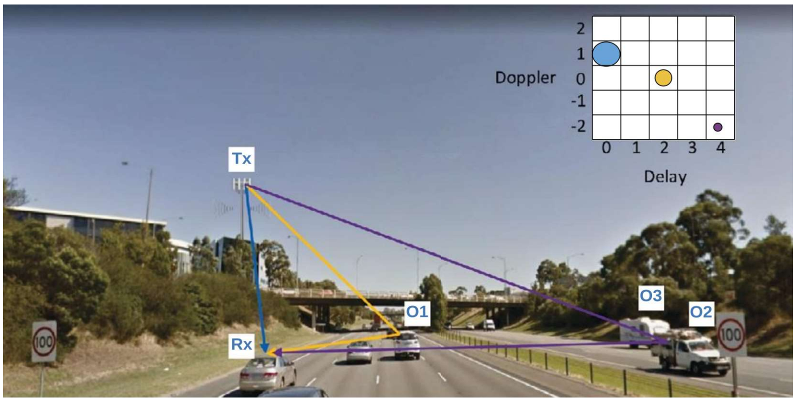

Figure 2.2: Representation of the DD channel, illustrating channel sparsity and how real-world propagation can be interpreted through it [2].

In (2.1), τ and ν represent the delay and Doppler axes, respectively. Here, P denotes the number of dominant paths between the transmitter and receiver. Outside the range $[0,\tau_{\max}]$ in delay and $[-\nu_{\max}/2,\nu_{\max}/2]$ in Doppler, the channel is effectively zero, where $\tau_{\max}$ and $\nu_{\max}$ are the maximum delay and Doppler spreads of the channel.

Even though $h(\tau,\nu)$ remains relatively constant over a large frame, it exhibits a sparse structure. This sparsity is advantageous for low-complexity channel estimation and data detection (see Figure 2.2). Moreover, the DD channel representation provides a meaningful schematic of the environment. Each channel tap h_i, along with its corresponding delay τ_i and Doppler ν_i, represents the attenuation along a specific path. The delay τ_i reflects the path length, while the Doppler ν_i indicates the relative speed of the object causing the shift (see Figure 2.2).

OTFS is an appealing waveform for ISAC [20] because it naturally maps the wireless channel into the DD domain, which is the native domain for sensing. As previously explained, in the DD domain, the channel's multipath components appear as sharp, separable impulses, where the delay corresponds to the range and the Doppler shift corresponds to the velocity of targets or channel scatterers. This inherent structure allows for unified processing of both communication and sensing information; the same channel matrix used for communication equalization directly provides the high-resolution range and velocity estimates needed for sensing [21]. Furthermore, OTFS offers resilience to high-mobility scenarios, which are often the most challenging for sensing. Finally, OTFS can be combined with Multiple-Input, Multiple-Output (MIMO) to enhance both its sensing and communication capabilities [22].

Chapter 3

Implementations of the waveforms for ISAC

3.1 Coherent

Coherent wireless systems employ pilots to perform channel estimation in order to obtain Channel State Information (CSI). This information is then used for equalization purposes. With the arrival of ISAC, the CSI carries exploitable information very valuable for sensing purposes.

Pilot-based channel estimates can be used in several ways for sensing purposes, e.g., the channel estimates from OTFS systems give inherent information about their environment due to their channel being in the delay-doppler domain, which is directly translatable to range and velocity. OTFS systems are able to map and distinguish reflectors according to their distance from the transceiver, and their radial speed, just like a radar would [23]. On the other hand, like radar, they need to take into account problems like clutter elimination or resolution at the target ranges and speeds.

It is also possible to use OFDM waveforms for sensing purposes [9]. Despite the transition to the doppler-delay domain not being straightforward, it can be done with the adequate pilot scheme and some extra signal processing overhead. The OFDM waveform might not have the desirable sensing properties that OTFS has, but its proven performance in communication and wide adoption make it a very attractive choice.

Moreover, there are other sensing paradigms, like the use of communication signals for positioning, which has received a lot of attention for precise indoor positioning [24], where Global Navigation Satellite System signals are not reliable. In these systems, the pilot-based channel estimates from several synchronized access points are classified according to their Line-of-Sight (LOS) condition, and later fed to a multilateration algorithm (e.g. Time of Arrival or Time Difference of Arrival) which determines the position [25]. A simplified diagram of this system can be found in Figure 3.1

Finally, the use of Wifi CSI for human gesture recognition has also been proposed [26]. The proposed approaches use a machine-learning approach in which patterns are found between the time-frequency CSI and the gesture being made by the user [27].

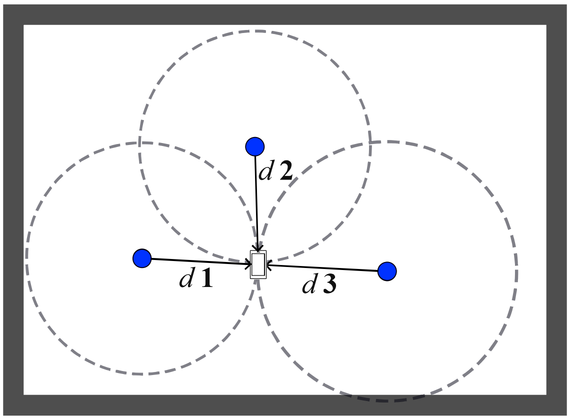

Figure 3.1: Time of Arrival based indoor location system.

3.2 Non-coherent

Despite the straightforward solution being to use pilots to obtain channel estimates which are then used for sensing, unfortunately, due to unfavorable conditions, pilot-based channel estimates are not always very accurate. This opens opportunity for non-coherent systems, those that do not rely on pilot schemes, to be used for sensing. Due to the lack of knowledge about the channel, non-coherent systems infer information about the environment directly from the received signal.

One example is the case of non-coherent MIMO systems. MIMO arrays allow the use of passive AoA estimates from several access points to locate devices through triangulation algorithms [28]. This approach is limited to the detection of radiated devices, for the detection of passive environment elements, the transmission of a waveform that illuminates them is required.

3.3 Superimposed

Superimposed pilots constitute an efficient alternative to traditional pilot schemes for joint communication and sensing, as they embed the pilot signal directly onto the used waveform rather than allocating dedicated pilot resources. This approach improves spectral efficiency since no additional physical resources are sacrificed for channel estimation, which is particularly beneficial for ISAC systems where both communication and sensing must coexist within limited bandwidth.

The embedded pilot component enables continuous channel tracking even under dynamic conditions, providing channel state information that can be exploited for both equalization and environmental sensing. Furthermore, by ensuring the pilot structure is transparent to the underlying waveform (OFDM, OTFS, for example) superimposed pilots offer a waveform-independent solution that supports diverse ISAC architectures without significant waveform redesign [3]. Figure 3.2 shows a superimposed pilots pattern where all the resources have both data symbols and pilot symbols.

From a sensing perspective, superimposed pilots provide an opportunity to extract delay and Doppler information directly from the estimated CSI without the need for separate radar signals. The persistent presence of pilots across symbols allows sensing operations such as range

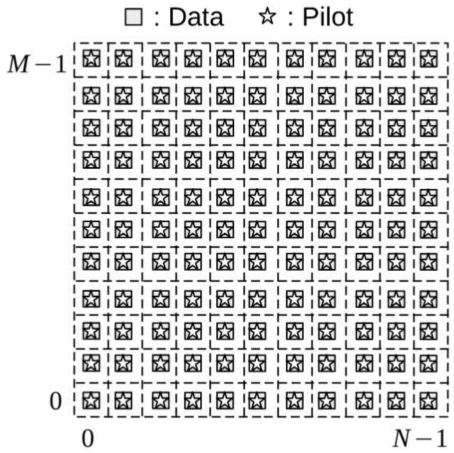

Figure 3.2: Frame structure with superimposed signals [3].

estimation or target detection to be performed seamlessly alongside communication functions. However, since the pilots are overlapped with data, interference mitigation techniques are necessary to ensure reliable channel estimation, such as power allocation strategies that balance pilot and data energy [29].

Chapter 4

Early results and discussion

The first set of results focuses on a new OTFS-based channel estimation method that uses a superimposed Zadoff–Chu pilot sequence [4]. This technique allows the system to estimate both the communication channel and sensing information (such as object range and speed) without dedicating extra resources to pilots. By embedding a constant-power Zadoff–Chu pilot directly onto the data, it maintains spectral efficiency and avoids significant signal fluctuations that can hinder transmission. Simulations show that this approach achieves accurate detection of delay and Doppler shifts (essential for sensing) while keeping the bit error rate and channel estimation error at levels comparable to more complex methods. Importantly, this design eliminates the need for computationally heavy interference cancellation techniques, instead relying on the averaging properties of the signal to filter out noise and interference.

Another key finding is the power balance between pilots and data. Adjusting this balance allows the system to prioritize either sensing accuracy or data throughput, depending on the application and scenario. Even when a larger portion of power is assigned to data, the proposed method retains reliable sensing performance. Figure 4.1 illustrates the sensing performance with different power allocation factor assigned to the data symbols (β).

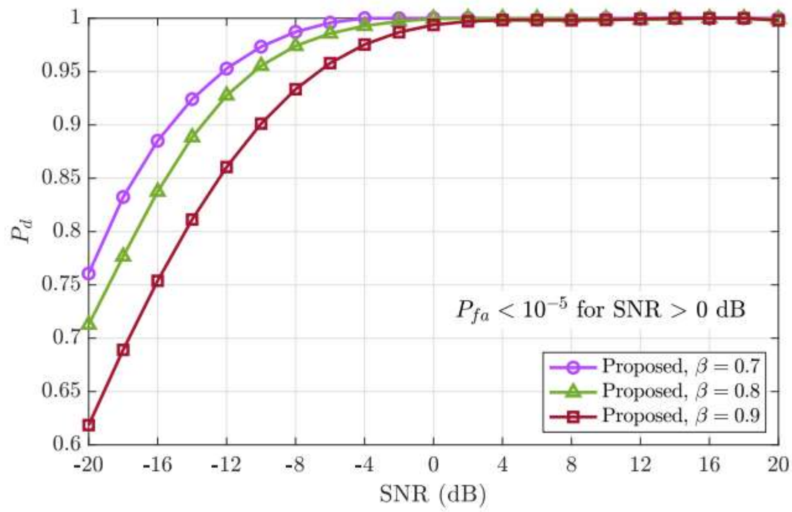

Figure 4.1: Probability of detection, P_d, and probability of false alarm, P_{fa}, vs. SNR for several β values [4].

In the OTFS field, one of the key challenges is channel estimation, more precisely the estimation of fractional delay and Doppler, which has been the focus of many research efforts. For example, in [5], the authors compared multiple methods for channel estimation in OTFS modulation and proposed a low-complexity approach that outperforms the others. The results of this comparison are illustrated in Figure 4.2.

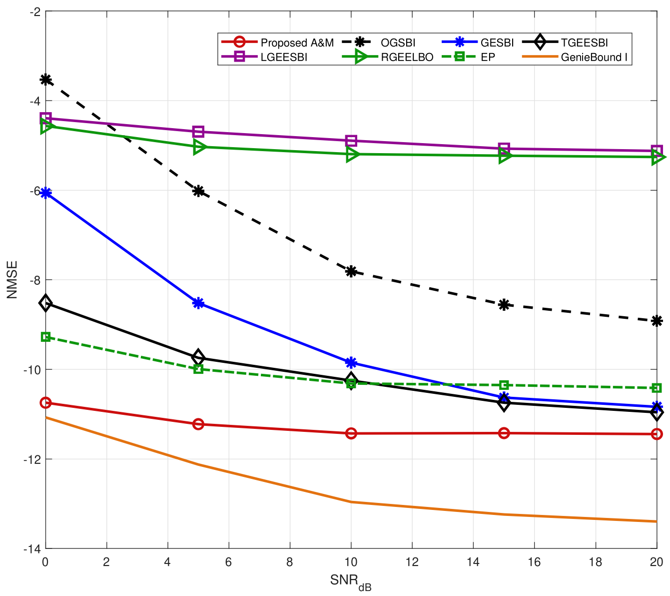

Figure 4.2: Performance comparison between different channel estimation methods in OTFS modulation [5].

In parallel, Generalized Singular Value Decomposition (GSVD) based channel decomposition techniques have been explored for multi-user OTFS systems, enabling the diagonalization of the delay-Doppler channel matrix and simplifying receiver design [30]. Both uplink and downlink studies confirm that GSVD-based precoding effectively separates private and common channels among users, mitigating inter-user interference while maintaining robustness against channel estimation errors. In the uplink scenario, the GSVD method outperforms traditional equalization algorithms in several antenna configurations, especially in coded systems and under imperfect CSI conditions. Similarly, the downlink implementation shows consistent Bit Error Rate (BER) gains across multiple deployment scenarios, including configurations where the number of base station antennas is less than or greater than twice the user antennas.

Finally, sensing information can be of great use for non-coherent MIMO communications. In [6], it is shown that AoA information can be used for the spatial filtering of non-coherent communication signals, leading to reduced interference and a consequent decrease in the Symbol Error Rate (SER). This can be seen in Figure 4.3, where the BER of a spatially filtered non-coherent waveform is close to the performance of a pilot-based coherent system. The non-coherent system using AoA information shows a significant performance improvement against a non-coherent MIMO system relying on averaging across the antennas.

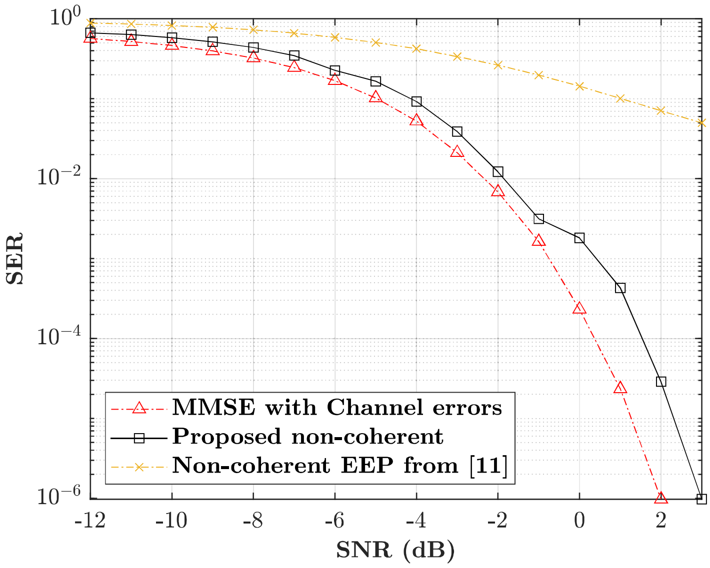

Figure 4.3: SER of a 50 antenna array in a Rician channel with a Rice factor of $K = 10$ for a scheme with channel knowledge (red), with only AoA knowledge (black), and without channel knowledge (yellow) [6].

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