Towards Integrated Sensing and Communications for 6G

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Abstract—For the next generation of mobile communications systems, the integration of sensing and communications promises benefits in terms of spectrum utilization, cost, latency, area and weight. In this paper, we categorize and summarize the key features and technical considerations for different integration approaches and discuss related waveform design issues for a future sixth generation (6G) system. We provide results on new candidate waveforms for monostatic sensing and finally highlight important open issues and directions that deserve future in-depth research.

Index Terms—sensing, integrated sensing and communications

I. INTRODUCTION

Traditionally, sensing and wireless communications have been performed individually using separated functional entities and frequency bands. For the sixth generation (6G) of mobile communications systems, the goal is to integrate sensing and communications together, so that services can be provided based on both sensing and communications functionalities. This is further motivated by the intended usage of the higher frequency bands (beyond 70 GHz) for 6G, which aims to facilitate the provisioning of sensing functionality with high-resolution capabilities.

The topic of integrated sensing and communications (ISAC) has caught researchers’ interests for at least last ten years [1]. As 6G research fully accelerates, given various global initiatives, national funded projects and academic/industrial research programs, this topic has become increasingly important and received renewed attention recently [2], [3].

The aim of this paper is to provide an overview of the key features and technical considerations of different integration approaches for 6G systems. Unlike the existing surveys, we mainly focus on the related waveform design considerations for fully integrated systems. Furthermore, initial results on a promising chirp-based waveform are presented and discussed.

The paper is structured as follows: Section II describes typical sensing and communications scenarios, followed by a discussion of different integration approaches and waveform considerations in Section III. Section IV describes open issues that deserve further in-depth research and finally in Section V the conclusions are presented.

II. SCENARIOS

In this section, we first review typical operating scenarios for sensing systems and for mobile communication systems. Subsequently, potential operating scenarios for an integrated system are presented.

A. Typical Sensing and Communications Scenarios

Sensing refers to the technology of retrieving information about an object from measurements of the emitted or reflected signals. The exemplary information of interest are distance/range, position, shape and velocity etc. Well-known sensing applications include automotive radar enabling adaptive cruise control and collision avoidance, consumer devices recognizing hand gestures and body/baggage scanning systems at airport terminals. If the object is equipped with its own receiver (Rx) and/or transmitter (Tx) for the sensing signal, the sensing system is considered to be active; otherwise it is known as passive. From a transceiver deployment point of view, a sensing system can be described as monostatic or bistatic. For the former, the Tx and the Rx of the radio signal are identical or co-located; while for the latter, the Tx and the Rx are at different locations.

The most widely used communications system is the mobile radio communications system, which consists of networked radio access nodes, i.e. base stations, and user equipments (UEs). Three types of radio links are specified, namely downlink (DL) for transmission from a base station to a UE, uplink (UL) for transmission from a UE to a base station and sidelink (SL) for transmission between two UEs. One of the key features that distinguishes current mobile radio systems from sensing systems is the centralized scheduling and coordination of the radio resource. Given the scarcity of radio spectrum, such a mechanism guarantees the performance, reliability and usability of communications services.

B. Scenarios for an ISAC system

A radio link can be described as a channel that connects a Tx and an Rx. In order to support the typical sensing scenarios in a mobile radio network, both the network nodes and the UEs may serve as the Tx or the Rx for sensing purpose. One of the goals of ISAC is to accommodate both functionalities using one system and to sense both passive and active objects. Each entity in the integrated system may adjust its role according to the operating scenario. Fig. 1 gives an overview of eight exemplary operating scenarios and their applications in an ISAC network.
It is worth mentioning that modern mobile networks provide location services, although these services have only been introduced for commercial usage recently. Considering the UE position as a sensing parameter of interest, the fifth generation (5G) mobile radio system providing location service is one form of ISAC systems. Being the target objects themselves, these UEs are actively involved in the radio transmission, with their positions being derived based on the radio link measurements obtained in the DL, UL or SL [4]. This can be seen as active sensing, since the signal is received or transmitted by the object (UE) in the sensing system.

III. INTEGRATION

In this section, we identify three integration levels for a system with both sensing and communications capability, namely,

- Application level integration;
- Spectrum level integration;
- Full integration.

We describe the characteristics of the three approaches and further examine in-depth details of the fully integrated approach.

A. Application Level Integration

The first and straightforward form of integration involves integration of a sensing system and a communications system only at the application layer. Utilizing completely different hardware blocks and frequency bands, the two systems interact with each other only at the application layer in order to assist each other’s functionality. An example of this, which has been intensively investigated, is sensor-assisted communications whereby the results of the sensing system can assist the communications system to assign specific beam directions or communications resources [5].

B. Spectrum Level Integration

The second form of integration is referred to as spectrum level integration. It allows the spectrum to be shared on a time, frequency or spatial basis for the sensing system and for the communications system. This integration level also enables partial sharing of the hardware for the two systems, leading to reduced cost, area and weight. Furthermore, the shared resource (i.e. frequency, time or space) for the two systems could be dynamically split depending upon the specific requirements for each system.

C. Full Integration

The third form, namely full integration, enables sensing and communications to be simultaneously supported by one system using the same transmitted waveform and spectral resources. In this way, latency, cost, space and power consumption are optimally reduced. This integration level offers the most benefits, but also faces most challenges. To enable this form of integration, there are three key options: 1) add communications functionality to a sensing system, 2) add sensing functionality to a communications system or 3) investigate a new waveform optimized for both sensing and communications. We describe below the technical challenges of each of these options and review the potential way forward.
1) Add communications functionality to a sensing system: The most popular waveform for sensing, as typically used in automotive radars, is frequency-modulated continuous wave (FMCW). An FMCW radar transmits a signal called a “chirp” which is a sinusoid whose frequency increases linearly with time. Specifically, an individual chirp \(s_t(t)\) is characterized by the carrier frequency \(f_c\), the bandwidth \(B\) and the duration \(T\), where the chirp slope is defined as \(\alpha = B/T\),

\[
s_t(t) = \exp\left(j 2\pi f_c t + 0.5\pi \alpha t^2\right)
\]  

(1)

A block diagram of an exemplary FMCW system is shown in Fig. 2 A series of FMCW chirps is fed to the Tx antenna and the mixer at the receiver. After mixing the transmitted signal and the received signals reflected from the target, the beat signal is generated, which has a frequency proportional to the delay corresponding to the distance between the radar and the target. The beat signal is passed through a low pass filter and analog-digital converter (ADC) for further signal processing implementation, e.g., target detection or sensing parameter estimation [6]. The main attractive feature of FMCW is its simplified hardware components and low-cost receiver. This is attributed to the low sampling-rate ADC, due to the beat frequency, and to the cheap power amplifier, due to the low peak-to-average power ratio (PAPR) of FMCW. However, FMCW has no modulation to convey communications data, rendering it difficult to be used for ISAC applications.

A modification of FMCW which has been considered for ISAC is phase coded frequency-modulated continuous-wave (PC-FMCW) which combines phase coding with traditional linear frequency modulated waveform [7]. Another alternative for communications-enabled FMCW is continuous phase modulated-linear frequency modulated (CPM-LFM) waveform, in which continuous phase modulation is combined with FMCW [8]. Both PC-FMCW and CPM-LFM are capable of communications with low to medium data rate, e.g. 8 Mbps with a bandwidth of 500MHz. However, the capability of data transmission for FMCW-based waveforms is achieved at the expense of certain drawbacks compared to normal FMCW, such as increased out-of-band emissions, high implementation complexity with high-rate ADCs, or degradation of sensing performance [8].

A further type of modified waveform based on FMCW is partial chirp modulation which has been developed in [9]. It modulates every chirp only partially during the chirp cycle. A further variation is to embed the communications symbols inside different chirp cycles using time-frequency shift modulation [10], in which different fractions of chirp are modulated with the time shift related to the modulated symbol. Both schemes have been shown to have almost no deterioration of sensing performance and no increase in out of band emissions, but can only support low data rates.

2) Adding Sensing Functionality to a Communications System: In this section, we concentrate on adding sensing capability to the orthogonal frequency-division multiplexing (OFDM) waveform since OFDM has become the dominating waveform for wireless communications systems, (i.e. LTE, 5G New Radio, IEEE Wi-Fi, etc.) in the last decade, given its robustness against multipath fading and simple receiver design. This multicarrier waveform facilitates adaptive transmission schemes and multiple access design across the subcarriers, offering flexibility in radio resource management. The investigation on OFDM for joint data communications and radar sensing dates back to a decade ago [1]. Sensing parameters such as range and velocity can be estimated using the received symbols after the discrete Fourier transform (DFT). When integrated with a communications system, these received symbols may be either pre-defined reference signals or demodulated data blocks. It has been shown that with appropriate parameterization, OFDM can achieve the same sensing performance as chirp-based waveforms in terms of delay and Doppler estimation [11]. Furthermore, estimation techniques developed for conventional sensing-only applications such as two-dimensional (2D) DFT, subspace techniques and compressed sensing can be easily exploited. With the present 5G new radio (NR) mobile communications system, a flexible air interface with configurable numerology has been developed and standardized. This potentially allows for some OFDM radar sensing utilizing the same hardware while offering high data rate out-of-the-box.

One of the issues of OFDM radar sensing, however, is that the processing bandwidth required for range estimation is much larger than that for a typical communications link if a fine resolution is desired. For example, a 15 cm range resolution requires 1 GHz bandwidth, which needs a high sampling rate ADC with correspondingly high cost and high power consumption. Alternative solutions have been developed for generating an overall large bandwidth radio frequency (RF) signal using a narrow OFDM baseband signal. In [12], an OFDM radar processing scheme with stepped carriers is proposed. The idea is to split up each wideband OFDM symbol into \(M\) sub-symbols. Each sub-symbol consists of a narrow sub-band transmitted sequentially in the baseband. This signal is up-converted to a stepped carrier frequency, generating a large RF bandwidth as shown in Fig. 3. On the receiver side, the \(M\) sub-symbols are combined to obtain the desired high resolution range profile corresponding to the large RF bandwidth. The so-called stepped OFDM scheme achieves high resolution using only a fraction of the equivalent channel bandwidth in the baseband; however, since the Doppler sampling rate is reduced by the factor \(M\), the unambiguous velocity is reduced correspondingly. A similar scheme is presented in [13], namely sparse OFDM. Inspired by the frequency hopping concept, discrete but randomly chosen frequencies are used for up-conversion of the sub-symbols. This scheme preserves the resolution and unambi-
guilty of a wideband OFDM signal and enables compressed sensing processing to reconstruct the sub-Nyquist sampled signal. However, these advanced signal processing techniques may cause significant increase of computational complexity. Another alternative scheme in [14] shows that high range resolution and maximum unambiguous velocity can be maintained at the expense of higher RF complexity. The idea is to multiply a narrow band OFDM signal with a frequency comb consisting of \( M \) carriers. Subsampling techniques are applied at the receiver side ensuring that the folded sub-bands do not overlap. Although all of these alternative solutions provide trade-offs between an improved range resolution and other limitations, they offer design flexibility for adapting the OFDM system according to the various requirements of sensing applications.

Another issue for an OFDM sensing system is that it must support full-duplex when operating in monostatic scenarios. In order to enable long distance sensing with high dynamic range, stringent Tx-Rx isolation is required in a full-duplex transceiver. Due to the high PAPR of OFDM, providing good sensing performance in monostatic scenarios is still challenging for a compact UE.

3) New waveform for both sensing and communications:

Apart from the variations of FMCW and OFDM described above, tailored to accommodate ISAC, alternative waveforms could be considered as potential candidates for providing an improved integration of the communications and sensing services especially in monostatic sensing scenarios. In this section, we review the state of the art of three such waveforms, namely orthogonal time frequency space (OTFS), orthogonal chirp-division multiplexing (OCDM) and affine frequency-division multiplexing (AFDM) and analyze the benefits and drawbacks of their potential deployment. The choice of these particular waveforms was motivated not only by their ability to overcome shortcomings of OFDM and FMCW in the sensing and/or communications domain, but also by their compatibility with OFDM. This is an important aspect for the industry, as it enables hardware reuse and backward compatibility of next generation wireless systems with their OFDM-based predecessors, allowing for dynamic switching between them.

a) OTFS: OTFS is a modulation scheme that multiplexes information symbols in the delay-Doppler domain. It can be viewed as a generalization of DFT-spread-OFDM, which spreads the information symbols both in the frequency and in the time domain. A 2D inverse symplectic finite Fourier transform (SFFT), also called OTFS transform, is first applied to transform the symbols from the delay-Doppler to the time-frequency domain. This is followed by a Heisenberg transform, which is common for all multicarrier waveforms and for OFDM is implemented by the inverse DFT (IDFT) to obtain the time-domain transmit signal. The inverse process is applied at the receiver (Wigner transform and SFFT). The block diagram of the OTFS transmitter and receiver is shown in Fig. 4. The 2D intersymbol interference in the delay-Doppler domain demands for equalizers with higher computational complexity than OFDM. Hence, a significant amount of research has been dedicated to the development of low-complexity detection schemes [15], [16]. OTFS is known for its ability to deal with high Doppler, as the time-variant channel appears constant in the delay-Doppler domain, as long as the velocity of the channel-related objects is constant. Hence, less frequent adaptation of the modulation and coding scheme is required; this can be particularly important for fast-varying channels, where even obtaining up-to-date channel state information at the transmitter can be challenging. Additionally, channel estimation and sensing are very closely related in OTFS, as it operates in the delay-Doppler domain, where radar targets are localized, and it can inherently exploit sparsity in the delay-Doppler domain [17]. Furthermore, it can support multiple-input multiple output (MIMO) and offer a lower PAPR than OFDM, but its advantage diminishes with an increasing number of symbols in the OTFS frame [18]. As far as full-duplex and ADC bandwidth are concerned, OTFS faces the same challenges as OFDM. Its sensing performance has been shown to be as accurate as that of OFDM and FMCW [15]. Additionally, delay-Doppler domain-based multiplexing of data and pilot symbols for channel estimation or multiplexing multiple users in the UL might require the introduction of guard intervals [17], [19].

b) OCDM: OCDM is a multicarrier waveform that multiplexes a set of orthogonal chirps in time and frequency. Its implementation is based on the discrete Fresnel transform (DFnT). The DFnT can be efficiently implemented with the use of the DFT. The block diagram of the OCDM transmitter and a depiction of the resulting chirps are shown in Fig. 5. \( \Lambda_{c_1} \) and \( \Lambda_{c_2} \) are diagonal matrices with entries \( \Lambda_{c_i} = \exp(j2\pi c_i n^2), \) \( c_i = 1/(2N), \) \( i = 1, 2, n = 0, \ldots, N-1. \) The chirps are shown with a different line style, with their wrapping stemming from their generation in the digital domain. Benefiting from the fact that the information-carrying
chirps span the entire bandwidth, OCDM can extract full diversity in frequency selective channels and has been shown to outperform OFDM in frequency selective channels when a non-linear equalizer is employed [20]. An important advantage of chirp-based waveforms is that, similar to FMCW, they can potentially support full-duplex operation, if the received reflected signal arrives before subsequent chirps are transmitted. However, unlike FMCW, the transmission and baseband bandwidths are the same (like OFDM), leading to the requirement of high-rate ADCs. A disadvantage of chirp-based waveforms compared to OFDM, is that, with each chirp occupying the whole bandwidth, guard bands at the spectrum edges cannot be introduced. Additional operations are required to reduce out of band emissions [21]. Techniques like MIMO, multi-user multiplexing and channel estimation (especially with scattered pilots), which are naturally supported by OFDM, are not as straightforward with OCDM. Although some works in this direction exist [22]–[24], further research effort in these directions is required. The PAPR of OCDM has been shown to be identical to that of OFDM, while its sensing performance is expected to be slightly worse due to increased sidelobe level [25].

c) **AFDM**: AFDM, which was recently proposed by [26], is based on a discretization of the generalized Fresnel transform and has an almost identical structure to OCDM. Their difference lies in the fact that, in contrast to OCDM, where chirps have a fixed slope, AFDM allows for adaptation of the chirp slope to the channel profile by optimizing $c_1$ and $c_2$. This enables AFDM to extract full diversity of linear time-variant channels, outperforming OCDM and having the same performance as OTFS, but with lower implementation complexity [26]. Due to its similarity with OCDM, it is straightforward to conclude that AFDM has the same characteristics in terms of PAPR, full-duplex and ADC bandwidth, as well as the same necessity for research in MIMO, channel estimation and multi-user multiplexing aspects. No results on the sensing performance of AFDM have been reported to date, but it is expected to be similar to that of OCDM.

To demonstrate the benefit of slope adaptation of AFDM, in Fig. 6, we plot the uncoded bit error rates (BERs) vs. signal-to-noise ratio (SNR) performance of OCDM and AFDM for frequency selective, time selective and time-frequency selective channels. Following [26], we consider the channel to have paths with delays that are integer multiples of the sampling period and Doppler shifts that are integer multiples of the subcarrier spacing. The different paths have independent and identically distributed (iid) Rayleigh fading with variance $1/P$, where $P$ is the number of paths. With $l_{\text{max}}$ denoting the maximum delay and $a_{\text{max}}$ denoting the maximum (absolute) Doppler shift, we consider three channels: a frequency selective channel with $l_{\text{max}} = 2$ (3 paths in total), a time selective channel with $a_{\text{max}} = 3$ (7 paths in total), and a time-frequency selective channel with $l_{\text{max}} = 2$ and $a_{\text{max}} = 3$ (21 paths in total). The number of chirps is $N = 64$, the number of symbols is $M = 4$, 16-QAM symbols are transmitted and a linear minimum mean square error (MMSE) equalizer is used. For the time selective channel and the frequency selective channel, OCDM and AFDM exhibit the same performance. However, for the third channel, which is time and frequency selective, AFDM clearly outperforms OCDM, which, in contrast to AFDM, fails to extract full multipath diversity.

**IV. OPPORTUNITIES AND OPEN ISSUES**

The increasing interest in ISAC has re-opened a large research area, not only because challenges for designing an integrated system are identified, but also because the topic connects two research communities which were relatively isolated from each other in the past. One of the major challenges is to bring the knowledge and experiences from both communities to work on the issues with joint efforts. Here, we provide examples of underlying challenges which deserve further study.

(a) **Air interface design aspects**: The integrated system requires a flexible air interface which offers the potential to
meet diverse requirements of both functionalities simultaneously. This includes waveform design that has been considered in this work, suitable transmission schemes, antenna arrays, multi-beam optimization, multiplexing techniques and interference management.

(b) **System design aspects**: The integration of the two functionalities raises new challenges to the system design, ranging from transceiver architecture to hardware engineering. For instance, full-duplex architectures commonly used for monostatic sensing devices have been for a long time a challenge for communications systems; a full-digital design found in most mobile radio terminals is a rather new concept for sensing devices. With respect to ISAC applications for commercial use cases, requirements on implementation complexity, power consumption and cost potentially become more stringent.

(c) **Standardization aspects**: Mobile communications networks have shown that standardization efforts are essential for efficient spectrum utilization, interoperability of devices and guaranteed quality of service. The new applications enabled by the sensing capability integrated with a communications network may significantly change the resource management strategy. Given the gap between limited resources and limitless needs, decisions must be made on how to allocate resources efficiently.

V. **Conclusion**

In this work, we summarized key operating scenarios for ISAC systems and identified three different levels for integrating the two functionalities in one system. For the full integration approach, we focused on the three design options and elaborated them in detail.

Based on the observations presented and given the almost seamless deployment of mobile radio networks, adding sensing functionality to a communications system shows clear advantages. In addition, waveforms offering enhanced sensing capability while maintaining compatibility to OFDM, are potentially interesting and worthy of further research.

As presented, adding communications data to a sensing system (i.e., using FMCW) can enable communications capability with limited data rate. Therefore, for systems which have a dedicated spectrum for sensing, e.g., the 77 GHz radar band, these schemes provide an opportunity for enabling ISAC.

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