Unlocking the Potential of Hardware Reuse in ISAC Systems with Reconfigurable Front-Ends – A Radar-Centric Approach

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Abstract—This paper investigates the potential for co-designed front-ends in specific integrated sensing and communication (ISAC) systems where the radar performance can not be compromised. In the ISAC ecosystem, communication-assisted radars, radar-assisted communications and flexible usage of these two applications have been portrayed. Even with primary focus on communication-assisted radars, this work can also apply to other topologies depending on application priorities. A step-by-step analysis of transmitter, receiver, signal processing and application-oriented design approaches are highlighted. The primary contribution lies in the inclusive approach of existing radar systems, thus mitigating the challenges of ISAC adoption in worldwide applications focused on radars.

Index Terms—ISAC, radar, front-end, transmitter, receiver

I. Introduction

In the last decade, the interest towards Integrated Sensing and Communication (ISAC) has grown manyfold. Most of the research so far has been focused on the enablement of sensing functionality in traditional communication networks or inclusion of vehicle to everything (V2X) in the future networks. The list of use-cases in the communication ecosystem is long [1] towards a sensing/radar-assisted communications. However, the need for communication-assisted radar is equally important as the coordination of automotive radars will be a must-have feature in future traffic scenarios with all cars equipped with multiple automotive radar equipments each. This coordination can be done with separate hardware and collaboration between the communication networks and radars or it can be done using reconfigurable co-designed hardware. In any case, without coordination, the interference will become the bottleneck for safe and secure roads. There has been reported research on reconfigurable hardware options [2] for ISAC as well as options for enabling ISAC in vehicles [3]. However, a systematic analysis to enable communication-assisted radars using reconfigurable approaches is missing in the literature. In the following section, more state-of-the-art literature will be presented with challenges and mitigation approaches of such systems, primarily considering mmWave frequencies. The individual transmitter and receiver blocks are

examined with respect to power consumption, performance, and area efficiency. The main contributions of this paper is given below considering primarily mono-static radars:

- options for transmitter and receiver front-ends, analog to digital converter (ADC), digital to analog converter (DAC) and transceiver architecture to enable a radar-centric approach in mmWave frequencies is investigated while using reconfigurability as the key enabler.
- pathway for deployment of communication-assisted radars and solutions to mitigate the challenges is envisioned.

Section II provides the details about the transceiver options for different blocks and the interface of physical layer controls. Section III considers the Key Performance Indicator (KPI) and standardization outlook for communication-assisted radar. Section IV concludes the paper.

II. Transceiver Options

In this section, a top-down approach is adopted, beginning with an architectural proposal for a communication-assisted radar system. Subsequently, we examine the challenges and corresponding solutions related to individual blocks, focusing on the use of a radar-centric transceiver for communication purposes. The overall architecture can lead to a near term deployment with limited performance overheads. In the following subsections, receiver front-end, transmitter front-end, DAC, ADC are discussed leading to a transceiver topology in a reconfigurable framework.

For the analyses, both Frequency Modulated Continuous Wave (FMCW) and Orthogonal Frequency Division Multiplexing (OFDM) radars are considered and associated challenges/solutions are discussed. Beamforming and multiple-input-multiple-output (MIMO) extensions are not considered in details to focus more on individual front-ends. However, an optimized single element will also lead to an optimized transceiver for a mmWave beamforming / MIMO solution.

A. Reconfigurable Front-end Architecture

Fig. 1 illustrates a multi-purpose, reconfigurable front-end that is primarily optimized for radar functionality, yet flexible enough to support communication modes. However, this also

depends on the signal processing and overall Physical Layer (PHY) architecture. The design of waveforms for ISAC is a heavily investigated subject [4]. In terms of radar signals, chirps are traditionally more common considering FMCW radars. The chirps can be generated at baseband (BB) or directly using the frequency synthesizer. The BB generation approach can be easily integrated with a communication signal processing methodology e.g. modulated chirps. The processing becomes similar for OFDM radars where communication and radar waveform choices converge. Additionally, radars today not only mean automotive radars at 76-81 GHz frequency band, but also include 60 GHz radars that are used in phones and in-cabin detection for automotive. It may mean sensing nodes to provide context awareness in communication systems. At 60 GHz bands, the bandwidth is high enough to provide good range resolution for radars, and it has a full-fledged communication ecosystem for WiFi and cellular networks that are already included in standards, thus holds the promise of an easy implementation pathway. The antenna design methodologies and the convergence of design requirements at mmWave for ISAC systems are well investigated in this paper [2].
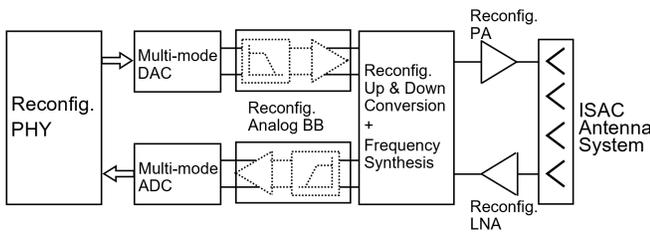

Fig. 1. A multi-purpose/reconfigurable RF front-end (Reconfig. = Reconfigurable) [2].

In terms of PHY processing, a flexible framework has already been proposed [5]. It addresses the diverse needs of radars and communications, prioritizing energy consumption for a radar-centric approach.

B. Receiver Reconfigurability

To understand the requirements of multi-mode, reconfigurable receivers, the state-of-the-art receivers are compared. Table I highlights performance differences between radar and communication receivers. The main difference in performance can be observed in linearity and noise figure. Radar systems are required to detect nearby targets accurately while preventing receiver saturation. Usually, achieving both high linearity and high gain simultaneously increases the overall power consumption. While communication receivers report very high bandwidth in literature, they generally don't use large bandwidths whereas, radar receivers require high bandwidth for better range resolution. ISAC receivers can be implemented in different ways. One such implementation is to have two separate paths for communication and radar as in [16]. The transceiver operates at 150 GHz and uses different signal processing algorithms for each mode. This is not optimal in case of area and power consumption. To

TABLE I
COMPARISON OF RADAR AND COMMUNICATION RECEIVER SPECIFICATIONS

Ref	Tech	Freq. (GHz)	BW (GHz)	Gain (dB)	NF (dB)	IP1dB (dBm)
Radar Receiver						
[6]	40nm CMOS	85	8	20-87	10	-11
[7]	40nm CMOS	85	6	20	8-9.5	-5.2
[8]	40nm CMOS	76.5	1	17	8.7-14	-7.4
[9]	45nm CMOS	78.5	5	-	13.8	-10
[10]	65nm CMOS	79	7.2	26-68	11.2-26	-7
Communication Receiver						
[11]	40nm CMOS	63-86	23	22.5	5.6-7.5	-20.5
[12]	28nm CMOS	75	27.5	30.8	7.3-9.1	-30.7
[13]	45nm SOI	67	15	27.1	4.1	-21.5
[14]	28nm CMOS	75.1	12.5	28	8.3-10	-25
[15]	130nm SiGe	73	5	70	6-7	-19.6

Note - Freq. = Frequency, BW = bandwidth, NF = Noise Figure, IP1dB = Input 1-dB compression point

optimize area and power consumption, it is only logical to implement reconfigurability in the receiver allowing the same hardware to support both radar and communication. This can be achieved while working in Time-division-duplex (TDD) scenario with same modulation schemes and signal processing algorithms. Reconfigurable ISAC receivers were already proposed in [17]. Considering a short range radar-centric approach, the receiver would primarily operate in a low gain-high linearity mode (Mode1) and switch to a high gain-low linearity mode (Mode2) when necessary. This would also mean that the power consumption can be less because the receiver works in Mode1 majority of the time. ISAC systems can use reconfigurable ADCs where the resolution can be increased based on the mode of operation.

Conventional receivers employ a low noise amplifier (LNA) first architecture where the LNA is followed by a down-conversion mixer and then the BB processing blocks. Reconfigurability can be incorporated across all these blocks to facilitate ISAC operation as follows:

- Frequency: LNA and the Mixer can be designed with tunable matching elements to facilitate frequency tunability. Topologies like switched multi-tap transformers, switched C/LC tanks, varactors are most commonly used for RF frequency tuning [18].
- Bandwidth: Radar receivers require high bandwidth when compared to communication receivers. The bandwidth can be controlled and, as needed, limited in the baseband with tunable multi-order baseband filters such as Butterworth or Rauch biquad [19].
- Gain and linearity: Gain and linearity are often inversely proportional and very high gain would usually mean low linearity. Gain and linearity can be made tunable by making all the receiver chain elements tunable. Variable biasing, back-gate biasing, tunable transistor widths, load resistor tuning are some of the commonly employed techniques in LNAs and down-conversion mixers. In the baseband, variable gain amplifier (VGA)s can facilitate this further.

However, achieving high linearity in an LNA or an active down-conversion mixer at mmWave frequencies can lead to significant power consumption [20]. In such scenarios, eliminating these power-intensive blocks allows for exploring alternative receiver architectures, such as mixer-first, which can reduce overall power requirements. Moreover, mixer-first receivers offer additional advantages for communication-assisted radar in ISAC, as their reconfigurable gain, tunable frequency selectivity, and adaptive linearity allow them to efficiently handle varying signal conditions and seamlessly switch between radar sensing and communication functions. This reconfigurability can be achieved in the following ways:

- Frequency tunability: The impedance transparency property of the passive mixers can be leveraged to tune RF impedance matching through a variable baseband impedance or frequency-translated feedback to achieve matching across a wide frequency range [21] [22]. Such reconfigurability would moreover allow multi-band operation to function as a dual-mode radar, switching between the mmWave 77 GHz radar band and 60 GHz V2X communication band by tuning the LO frequency, facilitating hardware reuse.
- Tunable bandwidth: The front-end bandwidth can be made programmable by employing tunable passive networks such as varactors at baseband, while trading off with out-of-band linearity [21].
- Gain: The gain can be made reconfigurable by tuning the feedback resistors across the baseband amplifiers as demonstrated in [23].
- Linearity: The baseband passive impedances can be made variable to tune the linearity according to the incoming signal conditions. For instance, the mixer-first receiver with feedback linearization technique proposed in [24] can switch between Mode1 and Mode2 by varying the feedback resistance around the baseband amplifier.

C. ADCs

The ADC requirements will depend on the processing architecture (e.g. matched filter, stretch). Fig. 2 shows a reconfigurable architecture, requiring two separate ADCs and DACs. The OFDM radars will require digital processing. For FMCW radars, mixing transmitted and reflected signals simplifies the sampling rate requirements of the ADC. The architecture will be sub-optimal if the same sampling rate is used for both communication and radar parts. However, using a multi-mode ADC for both radar and communication processing will reduce the routing path delays of the BB signals into two different ADCs. For the sampling rate differences between the two operations, it has to work with higher sampling rate.

Sampling rate requirements in traditional FMCW radars will be mostly below 100 MHz [26]. This may suffice the communication requirements when communication is a secondary feature with less stress on the maximum data rate. The situation will be different for OFDM radars, where the ADC needs to cover the whole bandwidth of radar signal and thus can be reused with more ease. It is important to note, in OFDM
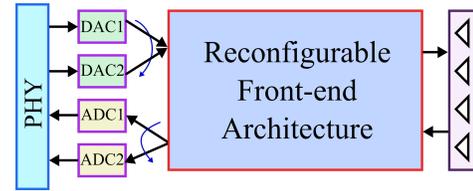

Fig. 2. Separate ADC usage in [25].

radars, there are established methods to reduce sampling rates, e.g. sub-carrier aliasing [27]. These methods would also be suitable for ISAC applications. However, impulse radar ADCs would require high sampling rates because they employ extremely short pulses for object detection.

Communication ADCs have moderate to high sampling rate depending on the modulation scheme used. Radar ADCs typically have lower resolution compared to communication ADCs, but may need a high number of bits depending on range and angular resolution. Communication ADCs have to maintain signal integrity and reduce the quantization noise. Very high linearity and high Spurious-Free Dynamic Range (SFDR) are preferred in both applications to detect weak signals in the presence of strong reflections, to minimize distortion and to maintain signal quality in case of higher order modulation schemes. The ADC for a communication-assisted radars lies in finding an optimal solution in terms of these KPIs, where the performance in radar mode does not compromise the required performance in communication mode. When it is not possible, we opt for a separate ADC solution as shown in Fig. 2.

D. Transmitter Reconfigurability

Conventional sensing and communication systems operate independently, using separate transmitters, leading to inefficiencies in power, spectrum, and hardware. In ISAC systems, transmission can occur either by switching, where separate time or frequency slots are allocated, or by simultaneous transmission, using a joint waveform for both radar and communication. Optimizing transmitter reconfigurability is key to balancing efficiency, adaptability, and performance across different ISAC applications. For example, a single transmitter can support multi-band mmWave ISAC, enabling seamless operation across all bands in 60 GHz (WiGig, V2X) or 76–81 GHz (automotive radar, smart surveillance).

1) Switching Mode Configurations: To realize an ISAC system without compromise, a simple approach would be to have distinct blocks for both communication and radar functions with no hardware reuse. Each system would require own separate components, thus increasing complexity, size, and power consumption. However, most of the blocks in the front-end are repetitive in both systems. A typical ISAC front-end is shown in Fig. 3, where a Single-Pole Double-Throw (SPDT) switch dynamically selects between radar (mixer mode) and communication mode by controlling signal routing [25]. An alternative architecture by using custom transformers and custom switches to reduce the path loss in

such switched architecture is proposed in the literature [28]. To enable reconfigurability on the transmitter side for ISAC, several changes need to be implemented, including adaptive biasing techniques. These allow for dynamic adjustments such as bandwidth reconfigurability, band switching, and power level adjustment.
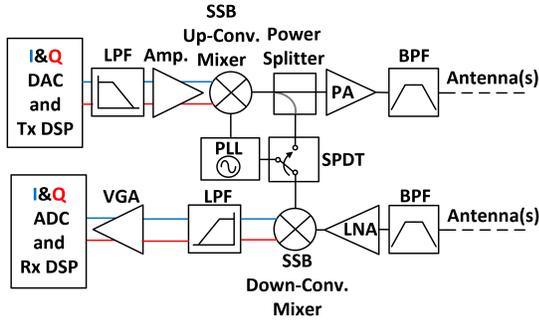

Fig. 3. ISAC front-end in [25] [28] (DSP = digital signal processing, SSB = single side band, PLL = phase locked loop, LPF = low pass filter, BPF = band pass filter).

2) Adaptive Biasing Techniques:

a) Bandwidth Reconfiguration: The transmitter bandwidth can be adjusted to suit the requirements of either function. For radar, a wideband signal is needed for high-resolution sensing, while communication systems typically require narrower bandwidths for efficient data transmission [29]. This can be achieved through adaptive biasing and tunable matching networks. For example, a Doherty power amplifier (PA) with tunable matching can be used to adapt the impedance to match the desired bandwidth [30].

b) Band Switching: Band switching adjusts the transmission frequency while keeping the same bandwidth, enabled by multi-band reconfigurable PAs such as continuous-mode Class-F PAs (which can tune across different harmonic frequencies) [31] or Varactor-Tuned PAs [32].

c) Power Level Adjustment: Power level adjustment allows switching between high-linearity Class-A/B operation for communication and high-efficiency Class-C/D/E operation for radar, often implemented with Multi-Mode PAs or Load-Modulated Doherty PAs [33]. As a result, adaptive PA design is crucial for balancing linearity, efficiency, and frequency agility in ISAC systems, ensuring optimal radar and communication coexistence.

3) Simultaneous Operating Mode: Simultaneous transmission allows radar and communication to coexist in the same time-frequency resources, requiring high-linearity PAs to mitigate interference. Table II shows the best PA architectures for various waveforms, such as OFDM, FMCW, and Hybrid OFDM-FMCW. Each of these presents unique challenges for PA design. OFDM-based ISAC requires linear PAs, while FMCW radar uses high-efficiency PAs. Hybrid OFDM-FMCW based ISAC combines the high range resolution of FMCW with the high data rate and spectral efficiency of OFDM, which requires a PA that can efficiently handle both high linearity and high efficiency across different operating conditions.

TABLE II
PA ARCHITECTURE SUMMARY FOR ISAC WAVEFORM TYPES

Waveform	Best PA Architecture	Notes
OFDM	Doherty PA, Envelope Tracking, DPD PA	Improves efficiency while handling high PAPR
FMCW	Class-AB PA, Class-F PA	Ensures phase linearity, high efficiency
Hybrid FMCW-OFDM	Doherty PA + DPD	Balances efficiency and linearity for mixed signals

a) OFDM Radars: In OFDM radar systems, the transmitter needs to support high peak-to-average power ratio (PAPR)s and handle multiple sub-carriers. To enable communication for such a system, the PA design must offer high linearity to prevent distortion of the transmitted waveform. Class-AB PAs are suitable for OFDM as they balance linearity and efficiency, although special techniques like digital predistortion (DPD) or envelope tracking improve the linearity and reduce the PAPR effect in high-frequency designs [34].

b) MIMO Radars: For MIMO radar systems, which use multiple transmit and receive elements for beamforming, the PA needs to handle the simultaneous transmission of multiple signals. The solution is to have a multi-port PA architecture, such as Doherty PAs or Distributed PAs. Such PAs can provide high linearity and can offer high efficiency at low power levels for communication while still supporting the wide dynamic range needed for radar.

c) FMCW Radars: FMCW radar uses a continuous frequency sweep (chirp signal) for range estimation. Adding Amplitude Modulation (AM) or Phase Modulation (PM) modulation to FMCW enables communication but increases PAPR, requiring high-linearity PAs and better self-interference cancellation (SIC). Phase modulation is more power-efficient but sensitive to phase noise, while amplitude modulation provides higher data rates but demands better PA efficiency. ISAC also changes chirp requirements, introducing adaptive chirp design to balance range resolution and data embedding. Communication signals can be embedded using Frequency Shift Keying (FSK), Quadrature Phase Shift Keying (QPSK), or Quadrature Amplitude Modulation (QAM)-encoded chirps, but each affects radar performance differently.

To enable ISAC, beamforming must be adapted to optimize spatial separation between radar and communication signals. Radar echoes can be distorted by communication interference, making advanced SIC crucial. Traditional constant-envelope PA is inefficient for ISAC, so high-linearity PA solutions like Doherty PA or Envelope Tracking are needed.

E. DACs

In ISAC systems, DACs face more stringent requirements than in standalone communication applications. These systems demand DACs capable of supporting wide bandwidths and high sampling rates to accommodate both high-throughput communication and high-resolution sensing waveforms. Enhanced bit resolution is often required to preserve sensing accuracy; however, this must be balanced against increased

power consumption. Superior linearity and SFDR are essential to ensure signal fidelity across dual-function operations. Low phase noise and jitter performance are critical to maintain both coherent sensing capabilities and communication link stability. Furthermore, tight synchronization across multiple DAC channels is necessary to support MIMO architectures, which are central to beamforming and spatial sensing. Reconfigurability of DAC parameters becomes vital to enable dynamic switching between communication-centric and sensing-centric modes. For communication-assisted radars, we can choose the architecture with separate DACs when radar performance gets compromised, as shown in Fig. 2.

A notable advancement in this context is the Gearbox-PHY concept, which proposes a flexible architecture that jointly adapts modulation schemes and analog front-end configurations to optimize energy efficiency [5]. This allows the system to switch between traditional modulation (e.g. QAM) and more energy-efficient alternatives such as Zero-Crossing Modulation (ZXM) and Time-Derived Zero-Crossing Modulation (TD-ZXM), each of which imposes different requirements on the DAC in terms of resolution, bandwidth, and timing precision. By enabling such adaptive modulation-front-end co-design, the Gearbox-PHY approach promotes energy-aware DAC operation, aligning hardware complexity with real-time system demands. Thus, DACs in ISAC must not only meet high-performance metrics but also support architectural flexibility to maximize energy efficiency across diverse operating conditions.

III. PERFORMANCE CO-OPTIMIZATION AND DEPLOYMENT POSSIBILITIES THROUGH EXISTING STANDARDS

The reconfigurable options for adding a communication functionality in traditional radars are described in detail in the previous section. However, it would also come with some costs/compromises:

- Power - The main challenges will be to reduce the loss in the radar mode signal flow (e.g. the splitter in Fig. 3). Any additional mode will require additional circuit blocks and control blocks. However, incorporating controllability through passive devices, such as varactors, results in a lower direct power penalty.
- Performance - Like power costs, performance degradation may occur (e.g. using noisy varactors compared to fixed capacitors). The architecture may become limited by the quality factors of passive blocks and switches. To match the performance to a stand-alone radar system, the system may consume more power.
- Area - Any new functionality means a new chip area, which also transfers to costs. However, the reconfigurable option would be better than using two separate systems in the front-end domain. Apart from that, using reconfigurable option will enable communication-assisted radars in compact user devices with very limited space for adding antennas.

From a KPI point of view, a radar front-end will be optimized for radar performances, namely, detection range, range resolution, azimuth resolution, doppler resolution, Signal-to-Noise Ratio (SNR), clutter rejection, etc. The performance matrix is also characterized by the false alarm rate and probability of detection. These system performances can be traced back to antenna performance, front-end bandwidth, transmitter conducted output power, receiver dynamic range and noise performances. However, a radar front-end optimized for these KPIs may not address equally a communication system assisting the radar, which may have KPIs like throughput, latency jitter, packet loss, round trip time, availability in overall links or more technical parameters like SNR or Bit Error Rate (BER). The good news is that communication-assisted radars may not always need to be optimized for throughput. However, the signal processing capability may become the bottleneck. A good SNR is intended for both systems. To summarize, a high-bandwidth low-noise system capable of delivering good output power with acceptable Output 1-dB Compression Point (OP1dB) at the transmitter as well as low noise figure and good/high linearity at the receiver can address both communication and radar KPIs.

As of now, ISAC systems or communication-assisted radars lack dedicated standardization documents, particularly those specifying electrical parameters such as noise levels, sensitivity, power budgets, or waveform characteristics. Current standardization efforts primarily focus on scenario definitions, which are expected to inform KPIs and, eventually, translate into constraints on electrical specifications [35]. However, existing standards from both communication and sensing domains can be effectively leveraged in the meantime. For instance, OFDM-based radar systems can refer to 3GPP 5G NR standards (Release 16 and beyond), which define power levels, spectral masks, and waveform characteristics for high-data-rate communication. Similarly, massive MIMO and beamforming specifications from these standards are directly relevant to ISAC sensing applications. Moreover, dedicated sensing standards such as IEEE 802.15.4z (Ultra wide-band (UWB)) and IEEE 802.11ad/ay (60 GHz Wi-Fi) are particularly valuable for ISAC, as they provide detailed electrical specifications related to high-precision sensing, e.g., time resolution, signal bandwidths, and ranging accuracy. Similarly, radar-based gesture recognition products, such as those using Infineon's XENSIV™ 60 GHz sensors, operate under standards like FCC Part 15.255 and demonstrate how existing wireless regulations are already enabling integrated communication and sensing applications. These can serve as practical references when designing early-stage ISAC systems. As the field matures, it is likely that a unified standard will emerge, integrating elements from both communication and sensing frameworks to support co-designed ISAC operations.

IV. CONCLUSION AND NEXT STEPS

For ubiquitous radars with access to communication via cellular networks, the key enablers would be a reconfigurable front-end and 100% connectivity of the cellular networks. A co-operative ISAC would be the first step in that vision. A reconfigurable front-end would be perfect when In-Band Full-

Duplex (IBFD) becomes a common feature in communication systems, and thus, enabling mono-static radar would only be a discussion of time slots. A band switching approach can be an interim solution going between traditional communication and radar bands as described in section II. Below 6 GHz, some basic low-resolution sensing can be achieved. However, an application-oriented approach to use non-mmWave bands (e.g. 7-24 GHz/ FR3) to accommodate new age radars will be a step in the right direction. The mmWave bands will be dedicated to high bandwidth, high resolution devices, including but not limited to V2X applications.

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