IN-BAND FULL-DUPLEX SOLUTIONS IN THE PARADIGM OF INTEGRATED SENSING AND COMMUNICATION

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ABSTRACT

The paper discusses different aspects in favor of using in-band full-duplex frontends for integrated sensing and communication (ISAC), considered for deployment of future 5G/6G infrastructure. Possible scenarios for practical utilization of the technology are discussed with additional focus on self-interference cancellation issue. An possible system implementation on abstract level is presented for cellular communication scenario. The main contribution of the paper is to highlight the hardware realization challenges and potential solutions, that can mitigate additional signal processing overheads for ISAC systems.

Index Terms— 6G communication, self-interference cancellation, radar

1. INTRODUCTION

With the introduction of 6G, the demand for data traffic will increase exponentially driven by numerous user- and machine-to-machine (M2M) centric applications [1]. While 4G/LTE communication still dominates the mobile traffic, 5G will take over with $>50\%$ share by 2028 (Fig. 1). Fixed wireless access (FWA) for communication is another expanding segment, where 5G content will have 80% share by 2028. Another growing segment is massive internet of things (IoT) communication with 18% Compound annual growth rate (CAGR). Broadband IoT will comprise 60% of the cellular IoT, with 4G still dominating. Internet of Vehicles shows 23.3% CAGR [2], which will be further boosted in parallel to the standardization of autonomous vehicle protocols [3].

Growing data traffic and the limited frequency spectrum raise new opportunities for full-duplex (FD) technology. Although FD operation is still not standardized in 3GPP releases, several companies are working on that, integrated access backhaul (IAB) being the favorable application [4].

Due to increased demands for wireless backhaul and relaying infrastructure the cost and power efficiency become an important factor. With femto-cells targeting 100$ price tag [5] and V2I (vehicle to infrastructure) gateways as low as 50$ [6], single transceiver/antenna modem solutions could be deployed among other cost-saving measures.

Location aware services provide another dimension of cost- and power-saving in 5G networks [7]. This gives several potential advantages, among those:

- channel-aware communication: channel sounding enables higher throughput utilizing multipath propagation
- energy-efficient relaying: data re-translation occurs only in the actual presence of end-user equipment
- power leveling: adjusting power level utilizing end-user location information.

This can be potentially integrated into a single frontend as a part of the ISAC concept. A comprehensive study on full-duplex applications in future networks is given in [8]. Several use-cases for millimeter-wave full-duplex systems is given in [9]. The impact of hardware impairments on FD transceivers is discussed in [10].

In this paper, different full-duplex applications are categorized in Section 2. Self-Interference issue is elaborated in Section 3. 5G NR compliant FD ISAC transceiver SNR budget is presented taking into account self-interference cancellation (SIC). Derivation of system parameters, taking into account of the hardware impairments and signal processing margins is presented. System level aspects for defining figure of merit for full-duplex SIC receivers are given in Section 4. System simulations for orthogonal frequency division multiplexing (OFDM) ISAC transceiver are discussed, followed by the conclusion.

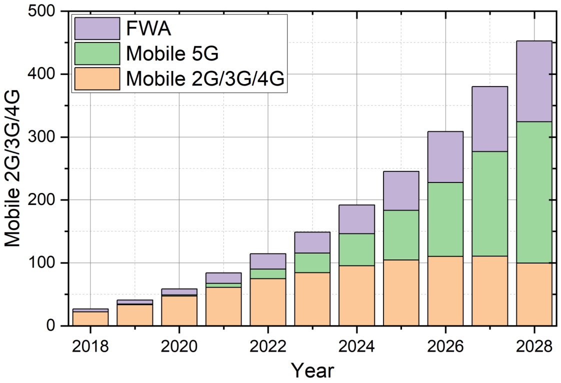

Fig. 1. Global Mobile Traffic Forecast

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2. FULL-DUPLEX APPLICATIONS

Fig. 2 shows a classification of some full-duplex applications in terms of the number of antennas and modem complexity. Some of the application areas overlap, and the categories are somehow formal. Nevertheless, it helps to define niches for the FD applications. Some of those are elaborated below.

2.1. Multiple Antenna Communications

Augmented/Virtual Reality: Augmented reality glasses or head-mounted displays will require huge channel capacity and low latency as they need to transfer 4K resolution image data with >90 Hz refresh rate to create a feeling of virtual reality. Time division duplexing (TDD) can result video stuttering. Using frequency division duplexing (FDD) is also problematic as the whole channel capacity shall be used for downlink communication. Integrated sensing capability will be required for an interaction with surrounding objects. As AR/VR applications will still cover high price segment with no limitations on the number of antennas being imposed.

Tactile Internet: The Tactile Internet will revolutionize how one interacts with others in the society and the environment [11]. Along with thorough usage of artificial intelligence and machine learning for predicting human behavior, it will require high throughput systems with less than a millisecond latency. This will require location aware full-duplex communication to mitigate those requirements.

Backhaul: With increased 5G network cell density, wireless backhaul will be an alternative solution to fiber-optic, where the installation costs are high. Full-duplex communication will be advantageous to deliver large amount of data needed for the cell operation. However, due to static line of sight (LoS) communication, no integrated sensing is required. This applies also to micro-cells/relaying stations, where FD operation can be used instead of time division duplexing, which is the default choice for 5G NR frequency bands [12].

2.2. Single Antenna Communication

Sensor Fusion/IOT: Sensor fusion or broadband internet of things (IOT) networks require low cost, low power solutions. No integrated sensing is required as large amount of data is transferred omnidirectionally. Full-duplex operation will enable data population in a much shorter time.

Mobile: Although several antennas are used on mobile phones, usually a single antenna is deployed for a communication session for certain frequency band. Full-duplex operation, along with doubling the channel capacity, shall potentially decrease the communication session time and save power.

RFID: RFID (radio frequency identification) reader is a field disturbance sensor and like most of radar-type applications, it intrinsically operate full-duplex [13]. With the shift to higher frequency bands, the reader devices become more compact. Traditionally, the size of those were defined by their ergonomic properties as the readers were handheld. With the antenna size getting smaller, the readers can be integrated into mobile devices as their NFC counterparts. Single antenna solutions will be a default choice due to the compactness.

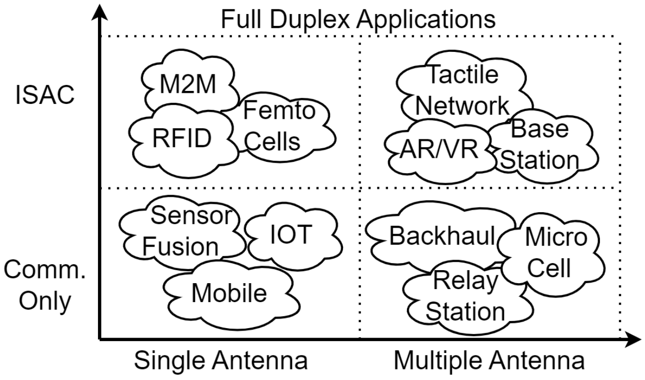

Fig. 2. Full Duplex Applications

3. SELF-INTERFERENCE CANCELLATION

During in-band full-duplex communication transmitter (TX) and receiver (RX) operate simultaneously utilizing the same frequency band. As a result, the transmitter power amplifier (PA) signal leaks to RX. That is usually several orders of magnitude higher than the received weak signal. For a single antenna TX interferer leaks into RX chain because of limited coupler isolation. In case of separate antennas, the interferer leaks through the surface waves on the shared substrate. The signal reflected of nearby objects adds up to the interferer.

To mitigate this issue, the TX to RX coupling including multipath propagation, is estimated and modeled. Known TX interferer is then equalized and subtracted from the received signal. In ideal case its power is buried in the RX noise floor.

Fig. 3 shows a typical implementation of a full-duplex transceiver. A four port electrically balanced duplexer is used for antenna coupling, where its balancing load is used to improved the isolation between the transmitter and the receiver. A single antenna can be shared also by using a dual

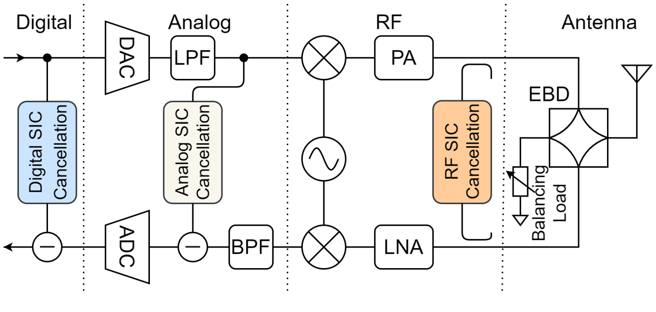

Fig. 3. Block Diagram of Single Antenna SIC Frontend

fed cross-polarized antenna [14]. For the case of separate antennas, meta-surface periodic structures can be deployed to suppress the surface wave [15]. However, high isolation levels are achieved only in a narrow frequency band. This becomes challenging for high bandwidth signal transmission over a full-duplex channel.

Passive antenna isolation is normally combined with active SIC that can be implemented in all three remaining domains. RF signal from power amplifier (PA) can be sensed through a coupler and after time or frequency domain equalization, coupled to the low-noise amplifier (LNA) input. Time domain equalization is more suitable for wideband mid-isolation applications, while frequency equalization provide high isolation for a narrowband usage.

Same or equivalent technique can be utilized in analog or intermediate frequency (IF) domain by equalizing low-pass filter (LPF) signal from TX chain and subtracting it from RX bandpass filter (BPF) output before feeding it into analog to digital (ADC) converter. Despite the potential of power saving in implementing an equalizer at lower IF, its performance is limited, as adding non-linear components before the analog to digital converter can degrade the overall performance.

Cancellation in digital domain has the highest potential for SIC as alongside with the main signal, the non-linear components and phase equalization are taken into account.

Fig. 4 shows the signal to noise ratio (SNR) budget for a FD ISAC transceiver operating at 5G FR1 band with an 100 MHz operational bandwidth (BW) and 8 dB RX noise figure (NF). The sensitivity requirement is:

$$P_{sens} = NF + 10 \cdot \lg_{10}(k \cdot T \cdot B) = -86dBm$$

On the left side, the typical values for receiver characteristics are given that comprise the receiver dynamic range (DR):

- In-band blocker: According to 3GPP standard [16], 12 dB AWGN (additive white Gaussian noise) in-band blocker should be taken into account.
- Signal to quantization noise ratio (SQNR): 10 dB is preserved to limit the SNR degradation to 0.6 dB
- Modulation SNR: 18 dB SNR should be preserved for SER = 10^{-5} (symbol error rate) OFDM modulation with 64-QAM (quadrature-amplitude-modulation)
- Peak to Average Power Ratio (PAPR): $\sim$ 12 dB should be taken into account for OFDM with 256 sub-carriers
- ADC/AGC: Non-linearity of ADC and automatic gain control (AGC) contribute 5 dB to DR
- SNR margin: 5 dB margin is usually preserved other effects, i.e. for channel fading
- Processing Gain: Digital signal processing techniques like oversampling can facilitate DR requirement by 3 dB

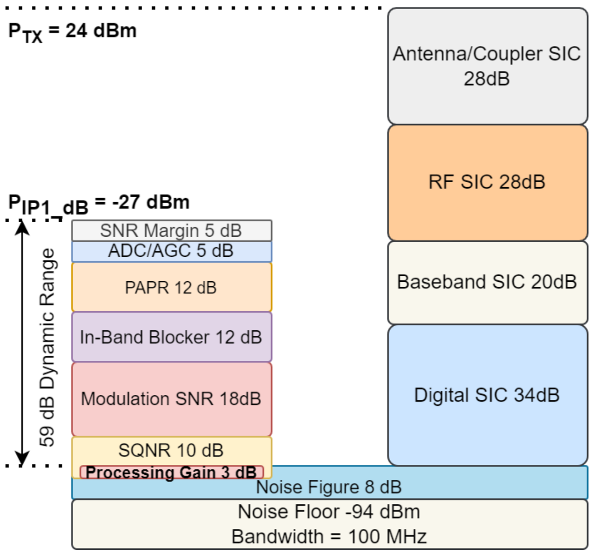

Fig. 4. Full Duplex Receiver SNR budget

3GPP specification for 5G NR local area base stations limits the transmitter output power to $\mathrm{P_{out}} = 24\,\mathrm{dBm}$ [16]. This means, that 110 dB isolation is needed to bring the TX signal into the noise floor. Here it should be noticed that the higher is the signal bandwidth, the more relaxed SIC requirements are given. This will be exactly the case for future 5G/6G applications, where even higher bandwidth requirements are imposed. From Fig. 4 it can be seen, that with insufficient SIC TX signal will appear over the noise floor. This will shift DR higher, potentially saturating receiver [21].

Table 1 gives an overview of reported SIC receivers over several frequency bands. As it can be seen, reported antenna and SIC isolation levels are much higher than those considered in the SNR budget. However, as the SIC bandwidths are relatively narrow, lower cancellation levels are taken into account in SNR budget. Power consumption of SIC circuitry gives $\sim$ 30% overhead for the receiver power budget, which is fully justified given the aforementioned benefits. Noise figure degradation is $\sim$ 2 dB, which is mainly contributed by RF cancellation circuitry at LNA input.

4. SYSTEM CONSIDERATIONS

4.1. Figure of Merit

As mentioned in Section 3, at least 110 dB isolation between TX and RX chains is needed to take the leaked TX signal below the noise floor for 100 MHz channel bandwidth. For smaller bandwidth channels more isolation will be needed, as the noise floor will decrease, while the PA power remains the same. So, product of isolation and bandwidth can be considered a figure of merit for comparing the performance of SIC systems. Carrier frequency should taken into account as well, as the fractional bandwidth scales linearly with that. How-

Table 1. Performance Comparison

	Technique	*Freq. Band [GHz]*	*BW_{SIC} [MHz]*	*SIC [dB]*	*P_{SIC} [mW]*	*P_{RX} [mW]*	*NF Deg. [dB]*
[17]	ANT+RF	0.9	80	50+23	13	51.4	1.4
[18]	EBD+BB+DIG	1.7-2.7	20	50+20+43	-	-	-
[19]	CIR+RF+BB	2.2	20	53+30+15	46	156	1.7-2.1
[20]	XANT+RF	28	1000	67+10	-	-	-
[14]	ANT+RF	60	1000	62+15	44	111	∼0+0.5

XANT = Cross-Polarized Antenna, CIR = Circulator, EBD = Electrically balanced duplexer, RF = Radio Frequency, BB = baseband, DIG = digital

ever, some benefit should be given to higher frequency implementations, because of increased power consumption and TX to RX coupling.

$$FOM = 10 \cdot \lg_{10}(\{IS_{SIC,Total} \cdot BW\} \cdot (BW/f_c) \cdot \sqrt{f_c})$$

4.2. ISAC System Simulations

It is important to analyze how the leaked signal affects radar sensing and communication performances. As OFDM modulation is becoming ubiquitous for ISAC communication [22], a transceiver including its hardware imperfections have been modeled with OFDM waveforms. For simplicity IEEE 802.11p standard have been used for waveform parameters, i.e. sub-carrier spacing, number of sub-carriers.

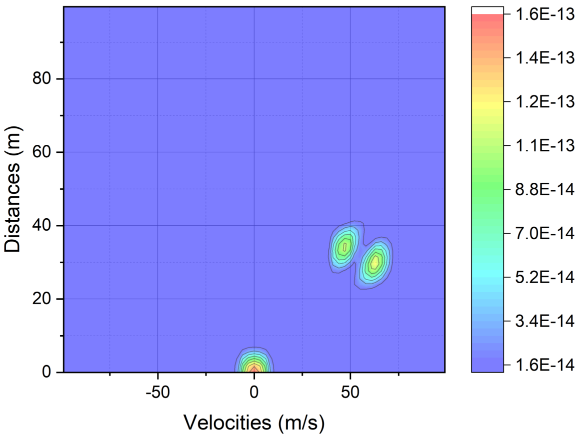

Fig. 5. OFDM Radar Range-Doppler Plot with limited SIC

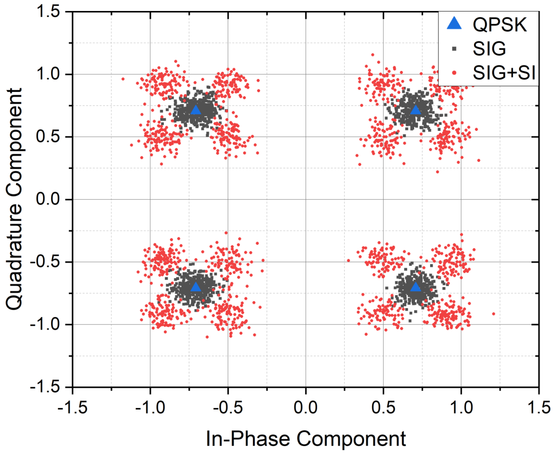

Fig. 6. OFDM RX Constellation Plot with limited SIC

4.2.1. *Sensing*

Fig. 5 shows range-Doppler plot of OFDM ISAC system with two closely co-located objects. For simplicity the detector threshold has been chosen high enough to suppress the side-lobes. As it can be seen, with insufficient SIC the leaked TX signal appeared at the range-Doppler origin – 0 m distance and 0 m/s Doppler with $\sim$ 4 dB higher power. With worse SIC·BW product the targets will potentially disappear in side-lobes. No clutter has been included so far, nevertheless self-interference cancellation algorithm deployment will be considered in future as an alternative to classical clutter removal algorithms.

4.2.2. *Communication*

RX constellations for full-duplex reception are shown in Fig. 6. Here the leaked interferer is 5 dB lower than the received signal. The leaked signal appears as superimposed constellation (red) on the received signal QPSK symbol set (gray). Although the error vector magnitude has degraded, the self-interference cancellation level is enough to sustain the symbol error rate within the specification for the current QPSK modulation. Nevertheless higher modulation schemes or lower SNR will impose stricter SIC specification to keep SER the same. It should be noted that the wideband response of TX chain significantly limits the SIC performance imposing more taps on equalizers in RF or BB domains to maintain the same cancellation levels.

5. CONCLUSION

Growing demands of data traffic and channel capacity, as well as the need of integrated sensing will further push forward the research for ISAC modems. Full-duplex operation is a prerequisite for that. State-of-art SIC techniques and algorithms can ensure sufficient suppression of transmitter leakage taking it below the noise floor. However, the existing solutions are rather narrowband, which can significantly deteriorate the performance for both communication and sensing aspects. Future improvement of $SIC \cdot BW$ will facilitate the creation of an ecosystem enabling full-duplex for future 5G/6G networks.

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