Full-Duplex Radio/Radar Technology: The Enabler for Advanced Joint Communication and Sensing

Carlos Baquero Barneto, Sahan Damith Liyanaarachchi, Mikko Heino, Taneli Riihonen, and Mikko Valkama

ABSTRACT

The use of joint communication and sensing (JCAS) systems in efficiently utilizing the scarce radio-frequency (RF) spectrum has received increased interest in the recent years. Due to the (re)use of the same resources by both functions, e.g., frequency of operation, waveforms, and hardware, various design challenges are evident in integrating communication and sensing/radar systems, and novel techniques are required to overcome them to provide both sub-systems with optimal performance. We have identified full-duplex operation as the key enabler for such JCAS systems as discussed in this paper. Furthermore, since JCAS systems usually employ large antenna arrays, novel beamforming techniques are required to efficiently manage the sensing and communication beams in addition to self-interference suppression, whereas their joint waveforms need to be optimized considering the performance metrics of both sub-systems. These requirements yield design trade-offs to address; existing and novel solutions to these aspects are explored herein from a signal processing perspective. This paper also presents experimental full-duplex sensing results through over-the-air RF measurements, showcasing the feasibility of integrating sensing systems with communication systems.

INTRODUCTION

The emerging wireless communication networks provide huge improvements in terms of data rates, traffic volumes, latency, reliability, and the number of connected devices. At the same time, radio-based sensing schemes have captured significant attention in both civilian/commercial and military applications. As a consequence, both types of systems are converging to operate around the same frequency ranges, congesting the frequency spectrum, and new techniques are required to efficiently manage the spectral resources.

A new trend referred to as the radio-frequency (RF) convergence [1] has manifested itself as an important research area that aims to solve the spectral congestion problem by designing more efficient systems that jointly exploit both communication and sensing functionalities at the same frequency bands. The possibility to use shared hardware is also accelerating this convergence.

Different concepts to jointly share the available spectrum under the umbrella of *RF convergence* can be broadly categorized into two areas, namely radar–communication coexistence and joint communication and sensing (JCAS) systems [2]. In the former, radar and communication systems treat each other as interference sources and research focuses on developing efficient interference control techniques. In contrast, the latter area co-designs systems that integrate both communication and sensing functionalities into the same device and possibly also share the same spectral resources and waveforms [3].

The integration of sensing functionalities into communication devices demands challenging system modifications. Especially, the key enabler for JCAS systems is in-band full-duplex (IBFD) operation [4], i.e., simultaneous transmit-and-receive (STAR) capability, that allows to receive reflections from the environment while simultaneously transmitting for the communication link. The major technical problem in IBFD is the self-interference (SI) between the transmitter (TX) and receiver (RX), which requires new JCAS self-interference cancellation (SIC) techniques to provide sufficient TX–RX isolation while not canceling the useful target reflections [3]. Furthermore, new JCAS beamforming strategies need to be investigated in order to satisfy the requirements for communication and sensing. As it is desired to use the same spectral resources for both functionalities, efficient allocation of the spectrum for the sub-systems needs to be also considered, which gives rise to waveform optimization for JCAS systems.

In this article, we explore the challenges in advanced JCAS systems and two major solutions that would enable a trade-off between both systems' functionalities. First, a novel multibeam solution is presented to optimize the TX and RX beamforming weights enabling multiple communication beams while a separate beam simultaneously senses the environment. The optimization minimizes the SI stemming from the direct TX–RX coupling and the clutter due to receiving reflections from the communication direction. Secondly, joint waveforms are designed to minimize the error variance of the distance and velocity estimates of the sensing system while also ascertaining satisfactory capacity for the communication system.

Furthermore, potential JCAS applications at different frequency ranges are analyzed, including mobile networks and autonomous vehicles, for which the recent research has coincidentally already enabled IBFD communication capability. Finally, we evaluate two JCAS systems through RF measurements, for vehicle detection and indoor mapping scenarios. In conclusion, the results of this paper demonstrate the feasibility of the presented advanced JCAS system, providing an optimal trade-off that would maximize the performance of both communication and sensing functions.

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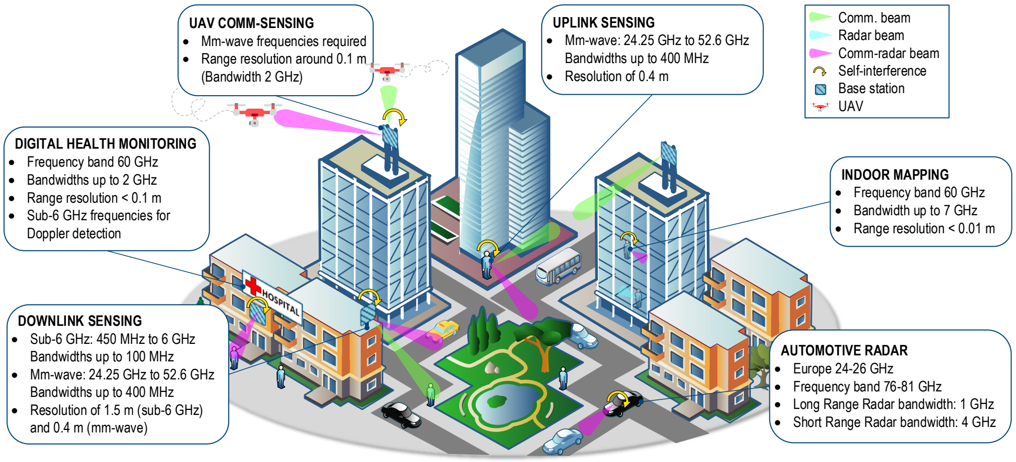


Fig. 1. Considered joint communication and sensing network architecture.

Applications and Challenges of Future Joint Communication and Sensing Systems

In this section, we describe the considered architecture and highlight different applications that can be supported by a heterogeneous JCAS network, while identifying their main specifications and requirements, as illustrated in Fig. 1.

Potential Applications

The center frequency of the system essentially defines the propagation characteristics, and consequently the potential JCAS system performance, which is basically governed by the transmit bandwidth. Wider channel bandwidths provide higher data rates from the communication perspective, but also improve the radar resolution, which is proportional to the total transmit bandwidth. Sub-6 GHz frequencies have been normally preferred for communication and long-range radar applications due to their low unity-gain path loss and penetration properties, but millimeter-wave (mm-wave) frequency bands (30–300 GHz), although having higher unity-gain path loss as well as reduced penetration and diffraction, also provide great opportunities for short-range communication and sensing applications due to the large available bandwidth and possibility to implement multi-element antenna arrays in relatively small space [5]. Traditional sub-6 GHz JCAS systems provide range resolutions in the order of meters, whereas mm-wave systems are able to achieve resolutions of few centimeters, supported by transmit bandwidths in the order of gigahertz.

One major application for JCAS technology (at both sub-6 GHz and mm-wave frequency ranges) is the mobile cellular network, which can integrate different sensing operations [6]. We identify two main operational modes depending on which transmit signal is utilized to sense the environment, i.e., the downlink or uplink one.

- In downlink sensing, the same transmit signal from a base station (BS) to multiple user equipment (UE) devices is used to sense the surroundings [3]. With this approach, a BS can operate either as a monostatic radar or a passive radar, exploiting the reflections from its own transmitted signal or the reflected signals from neighbouring BSs, respectively. It has also been demonstrated that integrating sensing information, e.g., potential user tracking, into the cellular network will improve the overall communication performance, by facilitating more efficient beam management and handover techniques [6].
- Similarly, the transmitted signal from the UE can be used for uplink sensing [7]. Mobile devices of emerging 5G New Radio (NR) networks incorporate directional antenna arrays with very small form factor allowing narrow beamwidths and beamforming for novel uplink sensing techniques. Especially, the adoption of the mm-wave technology, together with the future 5G UEs, enables new interesting applications, e.g., indoor mapping.

Automotive mm-wave radar technology is used extensively in vehicular applications, e.g., to implement adaptive cruise control and collision avoidance. The emergence of autonomous cars and the integration of JCAS systems in vehicular technology has received increasing interest in the recent years. The IEEE 802.11ad-based mm-wave technology, operating at 77 GHz band, has been investigated as a possible candidate to integrate communication and radar functionalities in the same vehicular platform [8].

Digital health monitoring, unmanned aerial vehicles, residential security and building analytics are further good examples, where JCAS can be beneficial. A mm-wave JCAS system to track the motion and actions of multiple persons in home and eldercare facility environments is presented in [9]. In this context, Wi-Fi communication signals at 2.4 GHz have been investigated to detect small body movements for signs of life detection based on Doppler detection algorithms.

It is clear that integrating sensing and communications represents a timely research area that will enable disruptive applications. This demands challenging system modifications which need to be addressed for efficient JCAS operation.

Architecture and Design Challenges

In typical JCAS architectures, a single device is used simultaneously as a communication TX and a radar transceiver. Thus, the reflected echoes of the communication signal are received by the same IBFD device. With the above applications in mind, we can identify the main research challenges for joint system design as follows.

Simultaneous transmission and reception: Due to the sensing requirements, a STAR operational mode must be adopted in order to collect the target reflections while the communication link is already established [3], [10]. Sufficient TX–RX isolation must be facilitated to prevent RX saturation and enable enough dynamic range to receive the reflections from the sensed targets. However, the reflected signal should not be canceled completely as will be discussed shortly.

Multibeam design: Existing JCAS research has mainly focused on single-beam systems, limiting the sensing and communication directions to be the same. To overcome this problem, an advanced JCAS system needs multibeam design, where the joint system integrates separate simultaneous beams for communication and sensing functionalities by considering antenna arrays with multiple elements [11].

Waveform optimization: The same waveform is ideally utilized for both radar and communication systems. In doing so, the performance of each system is proportional to the bandwidth/power allocated to it. Therefore, the joint waveform should be designed by considering the performance metrics of both systems, estimation accuracy and total power of the communication subcarriers, for the sensing and communication system, respectively. It has also been demonstrated that cyclic-prefixed single carrier and orthogonal frequency-division multiplexing (OFDM) waveforms, which are already used in LTE-Advanced, IEEE 802.11ad and 5G NR, are good candidates towards this [1], [3], and thus the same waveform can be utilized by both systems.

SYSTEM DESIGN FOR DUAL-FUNCTIONAL JOINT COMMUNICATION AND SENSING

Full-Duplex Operation

In order to integrate sensing functionalities into communication systems, some operational modifications are required. In general, a sensing RX must operate simultaneously as the TX to collect the targets' reflections, and subsequently, estimate their range and relative velocity. This STAR operation has been extensively studied under the IBFD context mainly focused on sub-6 GHz bands [4], at different communication areas which encompass wireless relays, military jammer systems, and bidirectional communication links. However, STAR operation at mm-wave frequency bands is a challenging and timely research area. This challenging operational mode can be successfully implemented only if the transmitted signal is suppressed below acceptable levels to prevent the RX chain saturation. The IBFD system normally combines different SIC techniques in antenna, analog RF and digital baseband domains to achieve typical required cancellation levels in excess of 100 dB [4].

In typical IBFD systems, the SI signal comprises all the possible coupling paths, which usually include direct and multipath reflections from different objects in the environment. From the JCAS perspective, however, only the direct coupling should be canceled, while the reflections from the true targets must be preserved. These target reflections are normally highly attenuated due to the propagation losses and do not compromise the sensing RX performance. Therefore, merging sensing to already developed IBFD communication systems does not require major changes in hardware and processing domains. A JCAS system with particular focus on the 5G NR mobile network, incorporating intelligent analog RF and digital SIC to suppress the direct coupling while preserving the target reflections is presented in [3]. It is demonstrated that moving targets are more robust against the SI, whereas limited TX–RX isolation is a concern for static target detection.

The joint operation of communication and sensing systems that support multiple beams requires new SIC techniques that consider multiple TX and RX antennas. A STAR digital phased-array architecture for communication and radar applications demonstrates that adaptive beamforming is important for future JCAS multi-antenna systems [10]. In particular, the considered TX beamformer creates a null in the TX pattern and RX beamformer rejects the remaining SI while providing a high beamforming gain in the direction of interest.

Related Multibeam Design Concepts

Conventional JCAS systems have mostly focused on single-beam approaches that are especially used in automotive applications, where the communication and sensing directions are limited to be the same. In contrast, recent studies have proposed to integrate simultaneous separate beams for each functionality to overcome this limitation [11]. Moreover, alternative beamforming algorithms need to be investigated in order to satisfy different communication and sensing requirements, some of which are having stable and high-gain beams for communication and providing direction varying scanning beams to enable sensing over the area of interest.

In [11], a multibeam JCAS framework using steerable analog antenna arrays is used for different multibeam design methods. A low-complexity method is analyzed first, which generates the communication and radar sub-beams separately, and these are combined coherently. This is presented as the preferred solution due to its flexibility to update the sensing sub-beam direction. Alternatively, joint design of the overall multibeam pattern can be also considered, but at the expense of increased complexity.

In general, two main beamforming techniques have been utilized in the radar context: phased-array and multiple-input multiple-output (MIMO) radars. The phased-array radar transmits phase-shifted copies of the same signal from each antenna element, using a single RF chain, as discussed in [10], [11]. In contrast, MIMO radars transmit independent waveforms from each antenna element using a fully digital architecture, which facilitates more degrees-of-freedom to achieve better sensing performance, at the cost of increased hardware complexity

[12]. In [2], a hybrid phased-MIMO architecture is identified as an important element for JCAS technology due to its similarities with the commonly known hybrid massive MIMO techniques used in mm-wave communication. Recent studies investigate the co-design of MIMO radar and IBFD MIMO communication systems operating at the same frequency band to optimize both functionalities' performance [12].

In JCAS systems, developing efficient interference management techniques is essential, so that communication and sensing can operate simultaneously without interfering each other. Particularly in multibeam JCAS systems, TX communication beams can produce unwanted reflections that are received by the sensing beam, known as clutter in the radar literature, that can degrade the radar performance. Thus, the impact of both beams need to be considered for efficient and robust operation.

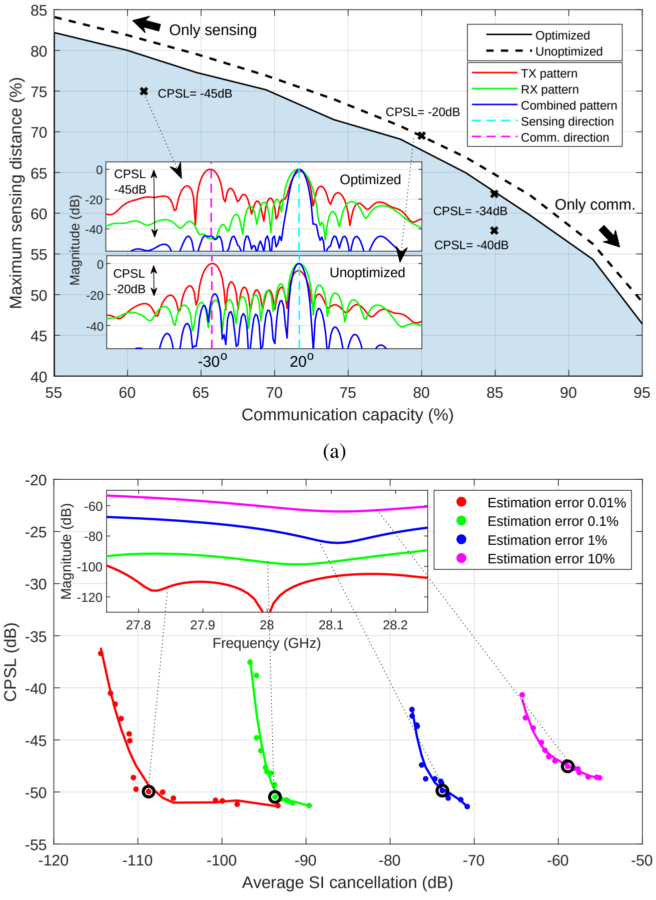
Multibeam Full-Duplex JCAS System

A novel multibeam concept is developed to overcome the challenges of integrating sensing and communication functionalities into the same device. This approach simultaneously optimizes the TX and RX beamformers to provide multiple beams for communication and a separate beam for sensing, while simultaneously suppressing the SI leakage due to the required STAR operation. To further improve the sensing performance using multiple beams, the reflections due to the communication beams, e.g., sensing clutter and false targets, are suppressed by reducing the combined peak side-lobe level (CPSL) of the effective sensing pattern, which refers to the equivalent radiation pattern for the sensing system and can be expressed by multiplying the TX and RX radiation patterns.

In general, multibeam JCAS systems sacrifice a part of the communication beamforming gain to incorporate an additional sensing beam. The amplitudes of both beams can be controlled in the design phase to jointly balance the communication and sensing performance.

Figure 2(a) shows the trade-off between both functionalities, in terms of the communication capacity and maximum sensing distance, when communication and radar beams in the directions of $-30°$ and $20°$ are considered, respectively. These metrics, expressed in percentages, represent the obtained performance in comparison with systems designed to perform communication or sensing functionalities independently using a single beam. In these results, a realistic simulated patch antenna array with 2×16 elements (where the upper and lower row are used by the TX and RX correspondingly) incorporating the mutual coupling effects operating at 28 GHz is considered, but the presented multibeam solutions can be extended to any array architecture.

An unoptimized multibeam algorithm without side-lobe suppression, similar to [11], is analyzed first. In this case, the TX is designed to provide two beams, while the RX provides a single beam in the sensing direction. This produces strong side-lobes in the effective sensing pattern, which degrade the overall sensing performance. To overcome this problem, the TX and RX radiation patterns are jointly optimized to mitigate any unwanted reflections, by reducing the CPSL of the effective sensing pattern. Adopting the effective sensing pattern, instead of the TX and RX patterns separately, is necessary for analyzing the overall sensing performance of the considered JCAS system. This approach can achieve a considerable improvement of the CPSL, at the expense of a slight degradation of the overall capacity and sensing range.



(a)

(b)

Fig. 2. (a) Trade-off between communication and sensing performance for the considered multibeam JCAS system. (b) Trade-off between CPSL of the effective sensing pattern and the average SIC for different estimation errors.

Figure 2(a) additionally illustrates the radiation patterns for the two analyzed cases. It can be observed that the optimized multibeam design substantially improves the CPSL, and consequently reduces the clutter reflections, achieving a CPSL of -45 dB that improves the detection performance, in comparison with the -20 dB of the unoptimized case. In addition, we can observe a compromise between the CPSL and the sensing range for the optimized multibeam approach. Decreasing the latter metric will provide more flexibility in choosing the TX and RX beamforming vectors during the optimization, and subsequently better CPSL for the same communication capacity, as illustrated with the two markers for a capacity of 85%.

Considering that the mutual coupling channel between TX and RX elements is measured by multichannel observation receivers, null-space projection (NSP) beamforming can be effectively implemented to suppress the SI [2], [10]. For this, the RX beamforming weights are selected such that they are projected to the null-space of the TX, and vice versa. Due to the wideband nature of JCAS waveforms, a wideband NSP constraint is jointly integrated with the multibeam approach.

Figure 2(b) shows the performance of the average SIC and the CPSL of the effective sensing pattern when the considered NSP–multibeam approach is implemented using the same phased-array architecture. The final performance is analyzed for different levels of error in estimating the mutual coupling channel between TX and RX elements, showing their Pareto frontiers that represent the optimal system performance. An efficient method to suppress the wideband SI signal is to incorporate nulls at some selected frequencies. In this case, the TX and RX beamforming vectors are optimized to null SI at 27.85 GHz and 28.15 GHz.

Finally, the SI frequency responses of selected Pareto frontiers' points illustrate the overall cancellation for different estimation errors in Fig. 2(b). It can be seen that the average SIC improves when the estimation error decreases, while the CPSL performance remains around the same level for all the considered error levels. Moreover, a trade-off between the CPSL and the SIC is observed, for all the estimation errors. This is due to the multi-objective optimization problem, which minimizes the CPSL while constraining the SIC. Therefore, it has been demonstrated that the presented JCAS design effectively addresses the multibeam and SI challenges and is a core solution for this novel technology.

Waveform Optimization for Full-Duplex JCAS Systems

Waveforms for JCAS systems are typically optimized by considering the performance metrics of both systems. For the radar system, these can be the signal-to-noise ratio (SNR) at the radar RX, range/velocity resolution, mainlobe width and integrated or peak side-lobe level of the autocorrelation function [13], detection probability and estimation performance, whereas for the communication system, they are usually the capacity or the spectral efficiency. In [14], a joint waveform is designed by maximizing the spectral efficiency of the communication system and improving the accuracy of velocity estimation. This always yields a trade-off between the two, i.e., radar performance can be improved by sacrificing the communication performance, and vice versa. The upper and lower bounds for the achievable communication rate and the radar estimation of a JCAS system are discussed in [15].

In communication systems employing OFDM as the transmit waveform, the communication TX is not fully loaded at all times and there usually exist subcarriers that are not utilized, depending on the number of communication users served by the system. For 5G NR systems, these subcarriers exist in the physical downlink shared channels. Another instance is during the synchronization signal block burst, where only a subset of OFDM symbols is used, and the rest are empty. These can be filled up with optimized symbols, so that it improves the performance of the radar system. Once filled, these subcarriers are known as *radar subcarriers*. The communication RXs will simply discard them, without affecting communication subcarriers. The radar subcarriers also become important in mm-wave JCAS systems, where the communication system may not require the entire bandwidth, and the rest could be used by the radar subcarriers. However, some power from the communication subcarriers needs to be reallocated to the radar subcarriers, and as such, communication subcarriers will experience a loss of SNR at their RX, and thus the improved performance of one is at the expense of the other.

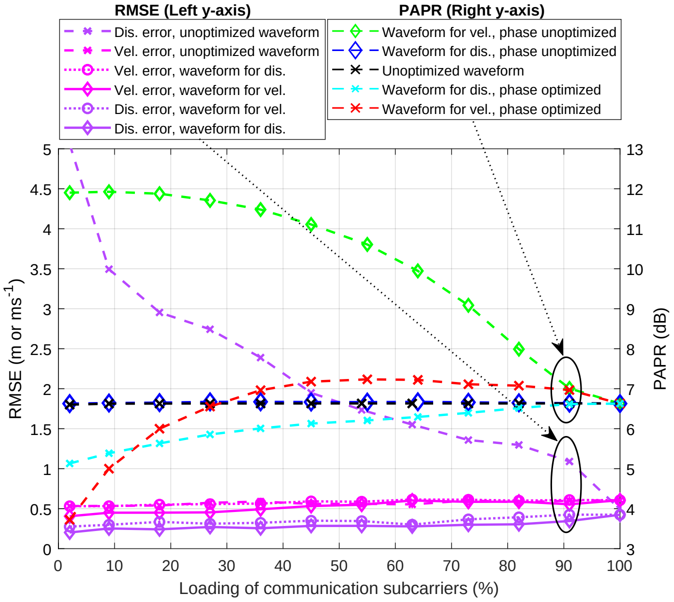


Fig. 3. The PAPR and the RMSE of the unoptimized and optimized waveforms for different loadings of the communication subcarriers.

After detecting targets, distance and velocity estimation can be performed using maximum likelihood estimation (MLE), where the variance of estimation errors is limited by the Cramer–Rao lower bound (CRLB). The symbols for the radar subcarriers can be found through an optimization procedure such that they minimize the CRLBs of either of the estimates. Total power allocated to the radar subcarriers is dependent on the proportion of them in the whole waveform, while a constraint is set to limit the power of the radar subcarriers, in frequency domain. Further, the peak-to-average power ratio (PAPR) of the waveform can be also minimized along the same process. High PAPR values are evident in OFDM systems due to the increased number of subcarriers, which degrades the efficiency of power amplification, and it is thus beneficial to minimize the PAPR.

The solution for CRLB minimization is derived analytically and it is observed that it specifies only the power values of the individual subcarriers. For the distance estimate, allocating more power to the edges of the spectrum and less to the center maximizes the root mean square bandwidth, thus minimizing the CRLB. Similarly for the Doppler estimate, the optimal solution allocates most power to a subframe's first and last OFDM symbols' radar subcarriers for minimizing its CRLB.

Modifying the phases of the subcarriers is used to minimize the PAPR in OFDM systems, e.g., in partial transmit sequences and selective mapping techniques. Conveniently, the phases of the radar subcarriers can be modified freely as this does not change their power values and will not affect the CRLBs.

The performance of the optimized waveform is evaluated for distance and velocity estimation. The optimized 5G NR waveform consists of 560 OFDM symbols and 264 physical resource blocks encompassing a bandwidth of 400 MHz with carrier spacing of 120 kHz, total transmit power of 30 dBm, and maximum power spectral densities of -103.8 and -113.3 dBm/Hz for each radar and communication subcarrier, respectively. Here, the communication subcarriers are divided into data and control. The radar and data subcarriers are randomly distributed among all the symbols in the subframe, while the control subcarriers are at fixed locations. A target with varying velocity is placed at multiple distances, and MLE is used to estimate these parameters of the target, with an SNR of -20 dB at the radar RX. Finally, by iterating this for many random realizations, the root mean square error (RMSE) is calculated for the two estimates.

Figure 3 depicts the effect of phase optimization on the PAPR minimization for the optimized waveforms for distance and velocity estimation. In the 'phase unoptimized' cases, the phases of the radar subcarriers are uniformly distributed between 0 and 2π. Through phase optimization, the phases of the radar subcarriers are chosen to further minimize the PAPR. Here, the phases of radar subcarriers of each OFDM symbol are separately optimized to minimize the PAPR. The phase optimization has allowed to reduce the PAPR of both the waveforms optimized for distance and velocity estimation. This also shows the PAPR for the unoptimized waveform, where the radar subcarriers are empty and all the power is used by the communication subcarriers.

The RMSE results are also shown in Fig. 3 for comparing the performance of the optimized and unoptimized waveforms. For both cases, the optimized waveforms perform better than the corresponding unoptimized waveforms. Therefore, the waveform optimization has allowed to decrease the errors of distance and velocity estimates, while minimizing the PAPR of the resulting waveform. The PAPR and the RMSE are dependent on both communication and radar subcarriers, and the availability of more radar subcarriers allows to improve both measures more. When the communication loading is near zero, it works as a dedicated radar—comparing with higher loading, it can be observed that this is where the radar performance is also the best as expected.

OVER-THE-AIR EXPERIMENTS AND RESULTS

We evaluate the sensing performance of two JCAS systems at different operating frequencies through RF measurements. In the measurements, STAR operation is implemented on top of a 5G NR system to sense the environment while providing a communication link, considering a single-beam configuration and a standardized 5G NR waveform.

Firstly, a similar vehicular sensing scenario as in [3] using an OFDM-based radar at the 2.4 GHz band is presented. This case represents a typical example of downlink sensing operated by a BS. In this experiment, a single horn antenna is shared between the TX and RX through a circulator. In addition, both analog and digital SIC schemes are incorporated, providing an overall isolation of ca. 100 dB. The considered JCAS system is tested in a suburban vehicular traffic scenario with four moving cars using a 5G NR waveform with 40 MHz bandwidth, which provides a distance resolution of about 4 m.

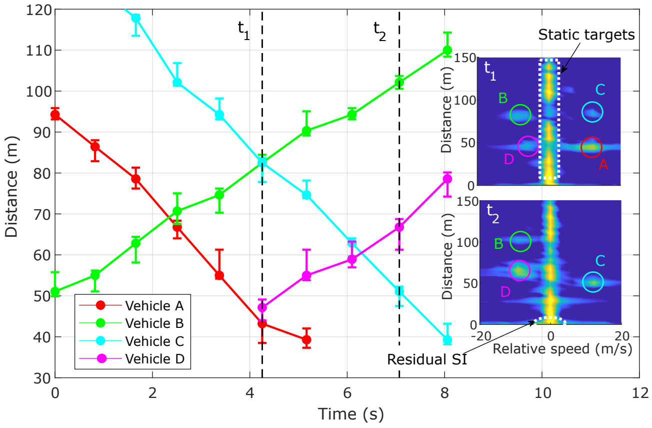


Fig. 4. Automotive radar measurements at 2.4 GHz band using a 5G signal with channel bandwidth of 40 MHz. The error bars illustrate the 3 dB variance in distance estimation from the range–velocity profiles.

Figure 4 shows the estimated range of the four vehicles in relation to time. It can be observed that all the vehicles have trajectories with similar relative velocities around ± 10 m/s. The vehicle range is estimated by applying a detection threshold test to the range–velocity profiles as illustrated at t_1 and t_2 for reference.

The considered radar processing enables to easily distinguish between moving and static targets. It can be observed that all the vehicles are sensed with different relative velocities, despite the strong reflections of the surrounding buildings and the residual SI. In summary, we have demonstrated that also sub-6 GHz frequencies are good candidates to implement JCAS functionalities when sensing relatively large objects, e.g., cars, due to the limited bandwidth and distance resolution.

Secondly, the sensing prospects of the 5G NR UE-side are investigated to demonstrate the potential for joint communication and environmental mapping [7]. The considered mobile device senses its environment by steering its beam pattern towards different directions and collecting the target reflections in order to reconstruct a map of its surroundings.[1]

Figure 5 shows the indoor uplink mapping results when a measurement setup at 28 GHz, with two horn antennas emulating the UE phased-array operation, is utilized. In this case, measurements were carried out at different locations of a corridor while the TX and RX antennas were steered from -50° to 50° with 2° steps. In this measurement campaign, a 5G NR waveform with a 400 MHz bandwidth was utilized, which provides much finer resolution of about 0.4 m compared

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[1] The sensing data are available at https://doi.org/10.5281/zenodo.3754175

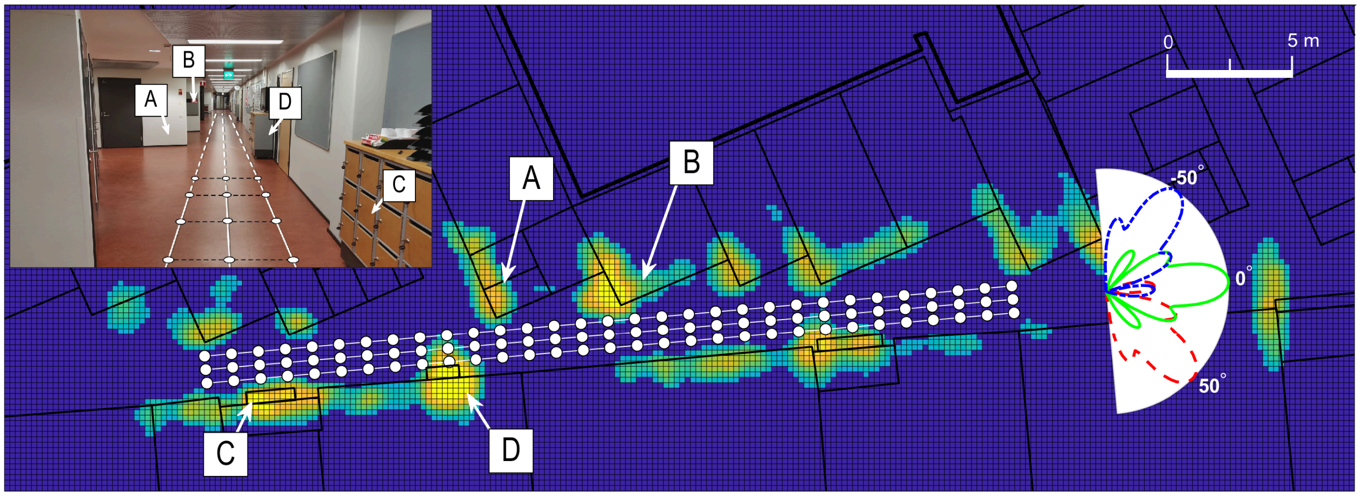

Fig. 5. Uplink indoor mapping measurements at mm-wave frequency using a 5G signal with channel bandwidth of 400 MHz.

to the previous setup. It can be seen that the considered JCAS system is able to accurately sense the fairly complex environment, making mapping reconstruction that clearly represents the main scenario layout. The obtained indoor map especially highlights the walls that are perpendicular to the sensing beams (A and B) as well as some metal lockers (C and D) due to their large radar cross section. Additional Doppler processing would be advantageous to identify between the sensed static environment and potential moving targets such as humans.

CONCLUSIONS AND FUTURE CHALLENGES

In this article, prospects and challenges for the emerging full-duplex joint communication and sensing/radar systems were investigated. The main solutions to implement highly efficient advanced JCAS systems were explored, including simultaneous transmission and reception, multibeam beamforming, and joint waveform optimization. A novel system that integrates the multibeam design while suppressing the SI leakage due to the required STAR operation was discussed. In addition, a joint communication–radar waveform was designed to simultaneously optimize both functionalities. Combining them enables the operation of MIMO JCAS systems, which is a future research challenge. Finally, proofs of different JCAS concepts were presented through over-the-air RF experiments.

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REFERENCES

[1] B. Paul, A. R. Chiriyath, and D. W. Bliss, "Survey of RF communications and sensing convergence research," *IEEE Access*, vol. 5, pp. 252–270, Jan. 2017.

[2] F. Liu, C. Masouros, A. P. Petropulu, H. Griffiths, and L. Hanzo, "Joint radar and communication design: Applications, state-of-the-art, and the road ahead," *IEEE Transactions on Communications*, vol. 68, no. 6, pp. 3834–3862, Jun. 2020.

[3] C. Baquero Barneto, T. Riihonen, M. Turunen, L. Anttila, M. Fleischer, K. Stadius, J. Ryynänen, and M. Valkama, "Full-duplex OFDM radar with LTE and 5G NR waveforms: Challenges, solutions, and measurements," *IEEE Transactions on Microwave Theory and Techniques*, vol. 67, no. 10, pp. 4042–4054, Oct. 2019.

[4] K. E. Kolodziej, B. T. Perry, and J. S. Herd, "In-band full-duplex technology: Techniques and systems survey," *IEEE Transactions on Microwave Theory and Techniques*, vol. 67, no. 7, pp. 3025–3041, Jul. 2019.

[5] K. V. Mishra, M. R. Bhavani Shankar, V. Koivunen, B. Ottersten, and S. A. Vorobyov, "Toward millimeter-wave joint radar communications: A signal processing perspective," *IEEE Signal Processing Magazine*, vol. 36, no. 5, pp. 100–114, Sep. 2019.

[6] M. L. Rahman, J. A. Zhang, X. Huang, Y. J. Guo, and R. W. Heath, "Framework for a perceptive mobile network using joint communication and radar sensing," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 56, no. 3, pp. 1926–1941, Jun. 2020.

[7] F. Guidi, A. Guerra, and D. Dardari, "Personal mobile radars with millimeter-wave massive arrays for indoor mapping," *IEEE Transactions on Mobile Computing*, vol. 15, no. 6, pp. 1471–1484, Jun. 2016.

[8] P. Kumari, J. Choi, N. Gonzalez-Prelcic, and R. W. Heath, Jr., "IEEE 802.11ad-based radar: An approach to joint vehicular communication–radar system," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 4, pp. 3012–3027, Apr. 2018.

[9] M. Alloulah and H. Huang, "Future millimeter-wave indoor systems: A blueprint for joint communication and sensing," *Computer*, vol. 52, no. 7, pp. 16–24, Jul. 2019.

[10] I. T. Cummings, J. P. Doane, T. J. Schulz, and T. C. Havens, "Aperture-level simultaneous transmit and receive with digital phased arrays," *IEEE Transactions on Signal Processing*, vol. 68, pp. 1243–1258, Jan. 2020.

[11] J. A. Zhang, X. Huang, Y. J. Guo, J. Yuan, and R. W. Heath, Jr., "Multibeam for joint communication and radar sensing using steerable analog antenna arrays," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 1, pp. 671–685, Jan. 2019.

[12] F. Liu, C. Masouros, A. Li, H. Sun, and L. Hanzo, "MU-MIMO communications with MIMO radar: From co-existence to joint transmission," *IEEE Transactions on Wireless Communications*, vol. 17, no. 4, pp. 2755–2770, Apr. 2018.

[13] F. Liu, C. Masouros, T. Ratnarajah, and A. Petropulu, "On range sidelobe reduction for dual-functional radar-communication waveforms," *IEEE Wireless Communications Letters*, vol. 9, no. 9, pp. 1572–1576, Sep. 2020.

[14] P. Kumari, S. A. Vorobyov, and R. W. Heath, Jr., "Adaptive virtual waveform design for millimeter-wave joint communication–radar," *IEEE Transactions on Signal Processing*, vol. 68, pp. 715–730, Jan. 2020.

[15] A. R. Chiriyath, B. Paul, and D. W. Bliss, "Radar–communications convergence: Coexistence, cooperation, and co-design," *IEEE Transactions on Cognitive Communications and Networking*, vol. 3, no. 1, pp. 1–12, Mar. 2017.

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