Accepted for presentation in: 2023 6th International ITG Workshop on Smart Antennas and 13th Conference on Systems, Communications, and Coding (WSA & SCC), Brunswick, Germany, February 2023.

6GEM Perspective on Joint Communication and Sensing

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***Abstract*— Joint Communications and Sensing (JCS) requires innovative new technologies and solutions in both the HW and SW domains. The key factors for JCS are very high frequencies (GHz/THz) with large bandwidths, the agility of the 6G infrastructure spectrum, and the ability to process radio signals for multiple purposes. The Innovation potential in this area is huge, but technological challenges to be solved are also demanding. In the component and hardware area, frequency-agile RF components are subject of the development to support very high bandwidths with the lowest possible nonlinearity and power consumption. The common hardware and algorithmic challenge is to ensure coherent processing of signals, sensor fusion and in particular common waveform design, novel baseband solutions, JCS supporting packet structures and efficient edge-based processing. This article provides an overview of JCS from the perspective of the 6GEM project.**

Keywords—terahertz communication, terahertz sensing, 5G and 6G technologies, JCS joint communication and sensing

I. Introduction

The activities presented in this paper are part of the funded project 6GEM [45] by the German Federal Ministry of Education and Research (BMBF). The acronym 6GEM is a made-up word from "6G" and the English word "Gem". The project is subdivided into different topics to focus on the key challenges in 6G wireless technologies. The 6GEM partners will work on the development of open mobile communication platforms for various test applications to demonstrate novel technologies and concepts with appropriate hardware and software. An overview of the technology is given in chapters II and III. Some examples are showing the integration in applications in chapters IV, V and VI.

The natural starting point for JCS development is to consider joint radar and communications processing, which are already part of various research efforts. Many of the core problems occur in radar communications, but 6GEM will not be limited to solving them. Rather, it will advance a complete 6G vision in which the entire communications infrastructure is intelligent. This also means considering other common remote sensing modes, processing methods such as radio-tomography, and feedback loops between sensing communications and applications, through concepts such as smart surfaces and components embedded in building materials. The goal is to design the key component technologies, algorithms, and protocols to enable and demonstrate the capabilities of distributed JCS in various application domains, particularly in the context of our selected testbeds and open platforms.

II. Fundamentally Significant Aspects of JCS

Joint communication and sensing (JCS) is a novel use case of 6G that incorporates radar and sensing capabilities into a unified system. It aims to maximize the performances of radar and communication systems, by sharing mutually beneficial information between them through shared hardware, shared spectrum and sophisticated signal processing facilities. This section summarizes the fundamentally significant aspects of JCS from an information theoretical perspective.

JCS has evolved from the more conventional coexisting radar-communication (C&R) systems which did not really share resources but were easier to implement in realistic scenarios since the individual systems were rather collocated but not unified. There are many ways for conveying joint C&R information through a unified system either through a single waveform for C&R or through different beams for C&R. JCS systems that aim at conveying the C&R information through a single waveform are usually also called dual functional radar communication (DFRC) systems.

The type of formulation leading to joint system design is centered around the dominant functionality. Current JCS system designs are classified into three categories based on the dominant functionality [1]: communication-centric design (JCR), radar-centric design (JRC) and finally joint design & optimization, the names defining their respective design methodology. Although all the three classes aim to utilize the shared system resources optimally, the third class can be designed with more freedom in terms of transmit waveform (joint design) and system design, leading to a more balanced optimization of C&R requirements.

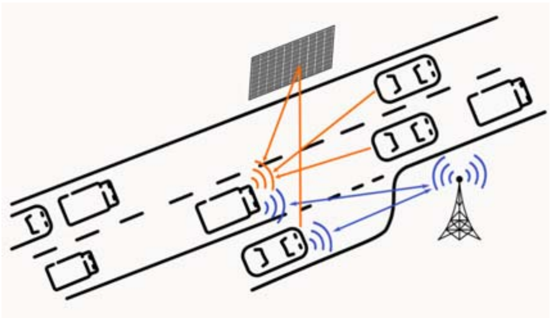

Figure 1: Car to car communication on a highway as an example for an JCS scenario.

Joint waveform design is an invigorating problem from an information theoretic point of view and has been a key research problem for JCS. Application centric performance metrics for C&R are chosen for joint optimization and consequently joint waveform design. Metrics for maximizing the performance of communication systems have been available extensively for over a decade. Optimal radar metrics for join optimization in JCS have thus gained prominence for research.

The mutual information metric, which is quite widely used for communications has also been established for radar waveform design as long ago as in the 1990s [2]. A more intuitive novel parameter in the form of radar estimation rate was formulated in [3] based on radar information rate analogous to information rate in communication. Further, [4] formulated radar estimation rate as the MI within a unit time for analyzing radar performance. Another metric used to optimize radar performance is the CRLB on the target estimation parameters.

The CRB is a lower bound on the unbiased estimators of the parameters and is jointly optimized with the communication rate in [5]. Although minimizing the variance of the estimation parameters seems to be an impressive idea, the expressions of the CRLBs have been known to be quite challenging to obtain closed form solutions.

A more general yet powerful approach for joint design in DFRC is waveform/beampattern optimization, which was jointly optimized with communication SINR in [6]. To this end, waveform/beampattern optimization is done while guaranteeing the SINR for each user in multi-user scenario. This, however, was prone to multi-user interference (MUI), which can be tackled using rate splitting multiple access for communication [8] [9].

Apart from the aforementioned spatial optimization techniques, communication signals can also be optimized across time and frequency domains while also aiming to improve sensing accuracy. For instance, [7] has parameterized a novel communication metric distortion MMSE (DMMSE) to jointly optimize the CRLB, achieving a proportional fairness in C&R.

III. JCS Systems From the Perspective of mmW-Radars

A. *System Aspects*

Literature describes a lot of millimeter wave (mmW) radars using the frequency-modulated continuous wave (FMCW) principle as their method of choice since it provides high accuracy for the measurement of both range and velocity. It uses a chirp as a waveform where the frequency changes linearly by time. Modern semiconductor technology enables the use of frequency multipliers for mmW frequencies with high dynamic range which allow to perform imaging with Millimeter resolution [10, 19]. However, the FMCW principle is not suitable for JCS purposes in the context of 6G because it cannot provide the desired data rates [11]. Instead, modern communication waveforms need to be used for simultaneous sensing, so that the system architecture of the mmW sensors rather resembles communication systems. Especially frequency multipliers cannot be used anymore since they generate intermodulation products which destroy the orthogonality in waveforms like OFDM [12]. This requires that the digital signal generation makes the bandwidth available.

In this work, a JCS frontend will be demonstrated based on the experience from mmW FMCW radars. Its architecture will be conceptualized in close alignment with the hardware component and signal processing development.

B. *Signal Design*

One challenge for JCS and future communications systems is to find a pareto optimal mode of operation for both communication and sensing. Apart from typical measurements needed for channel equalization, future systems aim for a refined user localization and perception of the environment [11]. Various waveforms are suitable to achieve the desired sensing capabilities, hence identifying and assessing waveforms for their joint sensing and communications capabilities is requisite. We will survey candidate waveforms and assess their applicability through simulations and measurements with respect to sensing and communication capabilities also with respect to different environments and scenarios (c.f. Figure 1). Moreover, we are going to evaluate the needed resources, HW-requirements, robustness of the communication link with respect to different channel impairments. Also, the integration of synchronization-methods into the signaling and self-organizing networks should be studied in the scope of this project. Finally at the end of the project a HW-demonstrator for joint communication and sensing is aimed for, to demonstrate that the developed algorithms are functional under real-life conditions.

C. *Hardware Components*

1) *Silicon Germanium*

To provide a hardware platform enabling the investigation of both system and signal processing aspects, the key is a high level of integration. Making use of a SiGe based BiCMOS process, the cointegration of digital interfaces and signal processing units as well as analog circuits working in the terahertz domain renders feasible. Future transceiver circuits will depend on reconfigurable components integrated on chip for mechanisms as carrier aggregation and the exploitation of ultra-wide bandwidth higher than 100 GHz. Furthermore, fast digital interfaces are required for both control to obtain adaptive functionality and to deliver communication signals for transmission. The mixed signal hardware concept described here makes use of ultra-wide tuning range circuits presented in [13] along with frequency multiplication. It allows for experiments on wave form phenomenons at terahertz frequencies using a completely digital setup without any high frequency interface. For that purpose, the proposed architecture makes use of on-chip antenna arrays demanding the use of terahertz frequencies for acceptable scaling levels. Finally, integrated quadrature mixers enable operation modes like OFDM radar. While it provides the highest level of integration, the target SiGe technology has its limitations in terms of output power and phase noise requiring the exploration of new materials extending those limits.

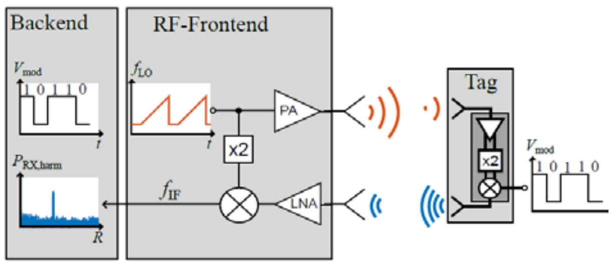

Figure 2. Block diagram of the proposed tag based joint sensing and communication system. The harmonic tag allows for reliable detection in the most demanding scenarios. Additionally, communication signals can be upconverted at the tag and sent to the radar system.

2) Graphene

2D materials have great potential for future communication and sensing applications as their mechanical flexibility makes it interesting for flexible electronics in biomedical applications or structural compliant integration in vehicles. Furthermore, they are compliant with other technologies and usable with various substrates and geometries [14]. The first ever discovered 2D material graphene exhibits an exceptionally high charge carrier mobility which promises a lot of potential in high frequency applications [15]. The nowadays existing MMIC processes for CVD grown graphene show also that wafer-scale and low-cost fabrications will be feasible in the future. While field-effect devices show low f_max due to the non-existing bandgap in graphene, metal-insulator-graphene (MIG) diodes show great performances for mmW and THz frequencies. Several devices like mixers and frequency multipliers could be demonstrated as well as power detectors and receivers [14]. So far, no radar or JCS system has been realized with Graphene based components.

We will work on a circuit design under rigid and flexible substrates of available MIG diodes [16, 17] to realise them as mmW components. The first device will be a mixer, the other ones depend on the needs of the elaborated system architecture. Therefore, the impact of the graphene devices on the frontend design compared to other utilized technologies will be investigated as well.

IV. TAG BASED FMCW RADAR AND COMMUNICATION

Frequency-modulated continuous wave (FMCW) radar sensors have the great appeal of being able to generate sensing images throughout a broad range of weather conditions. Additionally, their achievable accuracy can reach a systematic error of just a few microns, as demonstrated in [19]. They are therefore well suited for many 6G-related sensing applications like the tracking of autonomous robots and drones [20]. However, in complicated environments, such as logistics centers reliable tracking for collision avoidance can still be challenging because of the surrounding clutter.

In previous research, we have presented the benefits of a harmonic radar system detecting objects with a smaller radar cross-section reliably in the presence of clutter with the help of harmonic RFID tags [21]. Such a system sends out a fundamental FMCW waveform fLO. That waveform is reflected by every object and weighted by its respective radar cross-section, making for example small robots hard to detect. The tag however amplifies the received signal and doubles its frequency. Subsequently, after a down-conversion with $2 \cdot$ fLO only the tag's signal lies within the intermediate frequency (IF) bandwidth of the FMCW radar. Therefore the fundamental reflections of the other objects do not disturb the tracking.

Apart from allowing for the detection in a clutter-free receive channel, the active tags also enable concepts to converge radar sensing and communication. While simple backscattering based communication capabilities at 24 GHz have been implemented in [22], IQ mixers at mm-wave frequencies as presented in [23] in the tag and harmonic receiver can enable the use of arbitrary communication waveforms. This can for instance be used for status messages or to report an ID to the system for individual tracking. Therefore the accuracy of FMCW radar sensors, the clutter rejection of the harmonic approach, and communication capabilities with arbitrary waveforms are combined in one system.

V. SYNCHRONIZATION IN COOPERATIVE RADAR NETWORKS

Autonomous vehicles (cars, mobile robots, unmanned aerial vehicle (UAV), etc.) will be an essential part of the future 6G-driven infrastructure. A central role of JCS compared to existing system concepts can be expected from the networking of distributed units implemented as vehicle2vehicle, vehicle2infrastructure, and infra-structure2infrastructurenetworks. RadCom networks are particularly well suited for this approach since, as the name suggests, radars can be used both as sensors and for communication purposes. In this way, radar data can be exchanged efficiently between nodes and cooperative measurements of multiple units are enabled. This allows network-based localization to learn the relative positions of all nodes and mobile units within the wireless network, and imaging of the environment. Thereby, combining individual sensor data for cooperative understanding of the network condition and the environment is enabled.

A. Synchronization Requirements and Approaches in Communication

The benefit that can be achieved by the cooperation of distributed radars depends largely on the degree of synchronization between the individual nodes. Different applications have different requirements for synchronization of time and frequency between stations. As an example, mobile communication standards such as Long-Term Evolution (LTE) and Global System for Mobile Communications (GSM) based on time-division duplex (TDD) and frequency-division duplex (FDD) require frequency stability of ±50 ppb over a period of 1 ms [33]. Additionally, when LTE is based on TDD, the timing between base stations must be accurate to within 3 to 10 μs [24], [34]. This level of synchronization is achieved through the utilization of Global Navigation Satellite System (GNSS) receivers where feasible, as well as Physical-layerbased timing (i.e., synchronous Ethernet) and Packet-based timing (typically Precision Time Protocol (PTP) [32], or Network Time Protocol, NTP [24], [34], [35]).

B. Synchronization in Multistatic Radars

The demands on synchronization increase considerably when cooperative localization between RadCom systems is desired. On one hand, there is an inherent relation between the transmitted and received signal in monostatic measurements. Therefore, they can be used for environmental mapping without further synchronization. On the other hand, bi- and multistatic measurements are cruical for cooperative radars, enabling mutual localization between units. Common concepts for bistatic and multistatic measurements are Time of Flight (TOF) and Round-Trip-TOF (RTOF), which require precise synchronization between the nodes [40]. Typically, this is done by disciplining local oscillators to a common reference. This synchronization can be based on an electrical connection [41] or optical fibers [37], [39]. However, often wireless over the air (OTA) synchronization is preferred, especially in applications like autonomous vehicles networks where non-static RadCom systems are used. Moreover, in indoor environments, reliable reception of GNSS signals in order to discipline stable oscillators [38] cannot be guaranteed.

In [37] and [36] the 5,8 GHz LPR-System achieves a timing synchronization of 100 ps and a frequency synchronization of 10 Hz or about 2 ppb between two radar units for RTOF measurements in a master-slave setup. To do so it utilizes a sequence of Frequency-Modulated Continuous Wave (FMCW) up- and down-ramps, which are received, adapted, and re-transmitted at the slave unit.

However, the hardware effort for synchronization between two units can be reduced drastically when the radar raw data of two full duplex radar stations is processed together. In [25] and [26] a signal processing approach based on TOF is proposed, which processes highly correlated two-way full duplex receive signals of both stations. Thereby, it is capable of compensating the frequency and phase offset in a bi- or multistatic measurement. This enables a reliable estimate of the Doppler phase over consecutive measurements, which is typically only achieved with precise synchronization or in a monostatic setup. The concept has been verified with a 122 GHz radar, where a bistatic unambiguous precision of about 1mm and an ambiguous precision of 24 μm has been obtained. Unlike in a monostatic approach, the attainable phase precision is still limited here due to the uncorrelated phase noise.

The general concept of the above mentioned full-duplex method was presented in [31]. This so-called coherent full-duplex double-sided (CFDDS) principle, that is explained in more detail in [29], [30], processes the ADC raw data of two stations operating as full duplex CW radars. By estimating the unknown parameters of relative time drift, Doppler frequency, and time, phase and frequency offset, it is able to reconstruct a synthesized beat signal comparable to a monostatic primary radar response. This signal is not only carrier phase coherent but also phase-noise coherent and can, therefore be used to suppress distorting phase noise effects. The CFDDS concept has also been verified with a 5, 8 GHz radar resulting in a standard deviation for unambiguous and ambiguous range of 0.25mm and 75μm respectively. With the suggested concept, coherent operation of separate wireless radar stations with incoherent low-cost oscillators becomes feasible.

C. Opportunities for 6G-RadCom Networks

In the 6GEM subproject ”Cooperative (quasi-)coherent 6G networks for smart mobility and robotics” a high-performance method for radar-based, coherent or quasi-coherent network of autonomous vehicles is developed to form a cooperative 6G-RadCom network. The presented concepts allowing a (quasi-)coherent processing of the bistatic or multistatic radar data are investigated. New innovative localization algorithms, comparable to [28], can then be further extended to benefit from the additional information provided by the coherence signal processing. The improved achievable localization accuracy of the concept is expected to contribute to a more precise operation of unmanned vehicles, especially with respect to the 6GEM testbed with the goal of cooperative localization of rescue robots.

VI. Leveraging Mobile Network Connections for Sustainable Environmental Sensing

While the notion of joint sensing and communication (JSAC) aims to combine communication and radar functionalities, another interpretation of JSAC is to leverage wireless communication channels for sensing services. Thereby, the need for building and operating dedicated sensor infrastructures is avoided. In our recent works we have considered two example sensing services in the area of Intelligent Transportation Systems (ITS) and Smart Cities. The radio-fingerprinting-based detection and classification of vehicles [41,42] allows for the planning and control of vehicle flows to avoid congestion, whereas the small-scale motion sensing exploiting mmWave channels [43,44] serves to monitor the impact of ground movements on buildings and other critical infrastructure. The latter service is particularly motivated by a ground subsidence use case, i.e., for the

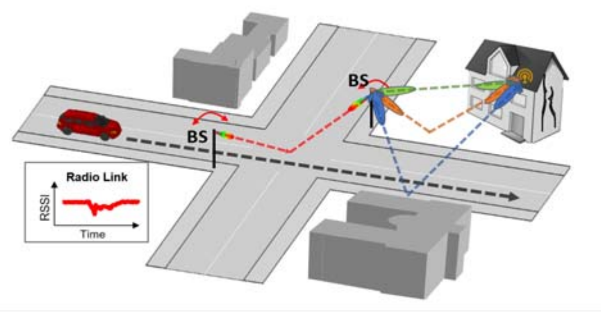

Figure 3: Leveraging mmWave channels for privacy-preserving vehicle flow detection (left) and monitoring of small-scale movements of infrastructures (right)

monitoring of a continuous gradual lowering of buildings and larger areas due to former resource extraction activities (such as coal mining in the Ruhr valley in Germany).

The basic idea of those services relies on the understanding that the numerous impacts on the wireless channel, which are typically regarded as negative interference, serve as input for sensing services. For example, a vehicle will specifically impact wireless connections depending on its movement and shape (number of axes, length, …). By analyzing such channel data patterns with machine learning (ML) methods, the vehicles' driving directions as well as vehicles' types can be detected and leveraged for false-driver detection as well as for traffic flow analysis and predictions. Unlike alternative methods (such as video surveillance), the radio-channel-based approach works in almost any weather condition and is privacy-preserving because the identity of an individual car or driver is not part of the gathered radio data. The radio-fingerprinting approach has been investigated and validated with experimental data in the sub-6 GHz range for both cars [41] as well as most recently also for bicycles [42]. Current research for 6G networks focuses on the use of mmWave channels to detect safety-critical situations to support future automated transportation systems (see figure, left).

Furthermore, the specific characteristics and capabilities of mmWave connectivity build the basis for the second service. The detection of small-scale movements in the µm-range is enabled by leveraging accurate phase shift information available through the channel state information (CSI). At the same time, the beam orientation of mmWave pencil beam antennas serves as input for the measurement algorithm as presented in [43]. For the detection process, CSI data as well as beam management information from several connections is combined to achieve an appropriate 3D motion measurement accuracy. While the approach presented in [43] uses several mmWave devices to achieve the required spatial diversity to detect and reconstruct small motions in space, the most recent work [44] leverages multipath propagation to realize a similar level of spatial diversity with just one user equipment (see figure, right). Up to now, the feasibility of the proposed subsidence sensing approach has been validated by in-depth radio propagation simulation for different antenna configurations and scenarios [43,44]. In a next step, lab experiments for validation and further investigation are planned.

VII. Conclusion

Specifically, the 6GEM project [45] will work on: the investigation of optimized waveforms (e.g. FMCW) for localization and JCS, the development of optimized waveforms and packet formats for JCS, the realization of HW components (adaptive and flexible GHz/THz wideband RF transceivers/ frontends) and distributed signal processing and algorithms through networked JCS sensors as well as adaptive signal design for JCS applications.

Acknowledgment

This work has received funding by the German Federal Ministry of Education and Research (BMBF) in the course of the 6G research hub under grant number 16KISK038.

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