Holographic Integrated Sensing and Communications: Principles, Technology, and Implementation

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Abstract—Integrated sensing and communication (ISAC) has attracted much attention as a promising approach to alleviate spectrum congestion. However, traditional ISAC systems rely on phased arrays to provide high spatial diversity, where enormous power-consuming components such as phase shifters are used, leading to the high power consumption. In this article, we introduce the holographic ISAC, a new paradigm to enable high spatial diversity with low power consumption by using reconfigurable holographic surfaces (RHSs), which is an innovative type of planar antenna with densely deployed metamaterial elements. We first introduce the hardware structure and working principle of the RHS and then propose a novel holographic beamforming scheme for ISAC. Moreover, we build an RHS-enabled hardware prototype for ISAC and evaluate its performance. Simulation and experimental results verify the feasibility of the holographic ISAC and reveal the great potential of the RHS for reducing power consumption. Furthermore, future research directions and key challenges related to the holographic ISAC are discussed.

Index Terms—Holographic integrated sensing and communication, holographic beamforming, reconfigurable holographic surfaces.

I. INTRODUCTION

Due to the explosion of wireless communication devices, spectrum congestion is becoming a severe problem, releasing increasing pressure on existing radar, communication, and other wireless systems. To cope with this issue, the concept of integrated sensing and communication (ISAC) is proposed [1]. It allows the sharing of hardware platform and spectrum between sensing and communication functions, which reduces the overall hardware cost and improves spectrum efficiency.

In ISAC systems, massive multiple-input multiple-output (MIMO) with a phased array is widely acknowledged as one of the vital techniques because it can provide the spatial diversity to improve the sensing accuracy and support high-speed communication. However, the power consumption of the phased array is relatively high due to extensive usage of complicated components such as phase shifters and power splitters, leading to insufficient performance for phased array-enabled ISAC systems given the power consumption budget [2].

Recently, holographic radio has been proposed as a new paradigm to address the above issues [3]. In the holographic radio, the antenna array is composed of a tremendous number of inexpensive antenna elements with low power consumption, tiny size, and ultra-close element spacing. Thus, by exploiting the high spatial diversity provided by numerous elements, high directive gain can be achieved for ISAC with an acceptable power consumption [4].

To fulfill this vision, reconfigurable holographic surfaces (RHSs) are viewed as a promising solution [5]. Specifically, the RHS is a type of metamaterial antenna whose subwavelength radiation elements are compactly arranged on a printed circuit board (PCB). Due to the tunability of the radiation amplitudes of RHS elements, the radiation pattern of the RHS can be customized without the use of complicated phase shifters, thus significantly reducing the power consumption and cost [6]. Besides, the feed of the RHS is embedded in the PCB, enabling the RHS to directly transmit or receive wireless signals with a low-profile structure. This is significantly different from reconfigurable intelligent surfaces (RISs), another type of metamaterial antenna [7]. Specifically, the feeds of the RIS are apart from the metasurface, which means there is an extra reflection path between the feeds and the RIS in the RIS model compared with the RHS model. Another difference in the system model is that the phase shifts of RIS elements are tunable, while the radiation amplitudes are adjusted in the RHS. As for the hardware implementation, the RIS and the feeding antenna are deployed in different locations, while the RHS is compactly integrated with the feeds and serves as an antenna.

In this article, we propose the concept of holographic ISAC where the holographic radio is used to further improve the performance of the ISAC systems. We design an RHS-enabled holographic beamforming scheme to realize the holographic ISAC and evaluate its feasibility through the experiment. Our contributions can be summarized below.

- **Working Principles of RHSs:** The RHS is a planar antenna where the surface wave is first injected through feeds and then radiated to the free space through metamaterial elements. Since the electromagnetic responses of the metamaterial elements are tunable, the RHS does not rely on phase shifters to achieve the diversity of radiation patterns.
- **Beamforming Scheme for Holographic ISAC:** To serve communication users and detect targets simultaneously, we propose a holographic beamforming scheme [8], where the digital beamforming is done at the base station (BS) and the analog beamforming is performed by the RHS. These two beamformers are carefully designed to optimize the performance metrics for ISAC.
- **Implementation of Holographic ISAC:** Different from the theoretical investigation in [8], we build a hardware prototype consisting of an ISAC transceiver module, a communication user module, and a target module to...
validate the feasibility of holographic ISAC.

- Challenges of Holographic ISAC: In addition to the holographic beamforming scheme and prototype verification, we also discuss the relevant topics including the fundamental designs for the RHS, limitations and trade-offs of holographic ISAC, and the optimization of holographic ISAC transceiver.

II. RHS: HARDWARE AND PRINCIPLES

In this section, we first introduce the hardware structure of the RHS and then present its working principle.

A. Hardware Structure

The RHS is a leaky-wave antenna with controllable radiation patterns enabled by reconfigurable metamaterial elements. After the electromagnetic wave is injected into the antenna from feeds, it propagates in the waveguide and excites the metamaterial elements embedded on the waveguide to leak the energy into the free space. The radiated signals from all the elements, which are also referred to as the object waves, can have different patterns. Through controlling the radiation amplitudes of the elements, the radiation pattern can be altered to generate desired beams.

Fig. 1 illustrates the hardware structure of the RHS. It consists of three parts, i.e., the feeds, waveguide, and metamaterial elements, which are elaborated on as follows:

- **Feed**: The feeds of the RHS are mounted at the bottom or the edge of the waveguide surface. The other side of each feed is connected to an RF chain, which will inject the electromagnetic waves, also called reference waves, into the RHS through the feed.

- **Waveguide**: The waveguide of the RHS is a planar medium where the reference wave propagates. The thickness of the waveguide is typically on the order of millimeters.

- **Metamaterial element**: The metamaterial elements are laid on the top of the waveguide. Their radiation amplitude can be independently adjusted by applying different bias voltages, enabling the RHS to control its radiation pattern.

Compared with the phased array, the structure of the RHS is much simpler because the RHS does not rely on complex feeding circuits and phase shifters. Moreover, the simpler structure also leads to lower power consumption of the RHS since power-consuming components are removed.

B. Working Principle

The working principle of the RHS is to first construct the interference pattern between the reference and object waves, and then excite the interference pattern recorded by the RHS to produce the desired radiation pattern [9]. The details of this principle are elaborated on as follows.

As shown in Fig. 1, we consider an RHS with $M$ elements and $K$ feeds. Let $x_{\text{ref},m}$ and $x_{\text{obj},m}$ denote the reference and the object waves at the location of the $m$-th element, respectively. Here, the reference wave $x_{\text{ref},m}$ is the superposition of the reference waves from all the feeds, which is determined by the locations of the feeds, the location of the $m$-th element, and the propagation vector in the waveguide. The object wave $x_{\text{obj},m}$ whose main-lobe is pointing towards direction $(\theta_0, \phi_0)$ is determined by the location of the $m$-th element and the propagation vector towards direction $(\theta_0, \phi_0)$ in free space.

Based on holographic interference principle [6], the interference pattern $x_{\text{int},m}$ at the location of the $m$-th radiation element can be expressed as $x_{\text{ref},m}^* x_{\text{obj},m}$. When the interference pattern is recorded and excited by the reference wave $x_{\text{ref},m}$, the radiated wave is in proportion to the desired object wave $x_{\text{obj},m}$, in this way the desired radiation pattern with main-lobe pointing towards direction $(\theta_0, \phi_0)$ is generated.

It should be noted that only the radiation amplitude of an RHS element can be adjusted, and thus, we only record the amplitude information of the interference wave through the RHS. The recording of amplitude information is referred to as a holographic pattern. With the holographic pattern, the generated main-lobe is also in the direction of $(\theta_0, \phi_0)$, and the corresponding information loss is low [10].
III. HOLOGRAPHIC BEAMFORMING FOR ISAC

In this section, we first introduce the holographic beamforming scheme, then discuss the performance metrics for holographic ISAC, and finally design the beamformers to optimize the ISAC performance.

A. Holographic Beamforming Scheme

As shown in Fig. 1, the proposed ISAC system consists of a BS, an RHS, a MIMO antenna array, multiple downlink users, and multiple targets [11]. The BS, RHS, and the MIMO antenna array are co-located with wired connections, unlike those in an RIS-assisted ISAC system. The BS acts as a terminal that feeds signals to the RHS for transmission and processes the echoes received via the MIMO antenna array. The signal transmission is only via the RHS, and the MIMO antenna array is used solely for the purpose of receiving the echo signals from the targets. In order to send different data streams to the downlink users and sense multiple targets simultaneously, we propose an holographic beamforming scheme for the RHS-aided ISAC system, where the BS and the RHS perform digital and analog beamforming, respectively, to transmit ISAC signals.

Specifically, we divide the timeline of the scheme into cycles, and each cycle contains two steps, i.e., transmission and reception. The block diagram in each cycle is illustrated in Fig. 2, which is further described in the following.

- **Transmission step**: ISAC beams that simultaneously serve communication users and detect targets are generated and transmitted. Specifically, L data streams and K radar waveforms are first separately precoded by the BS via different digital beamformers to generate K precoded data streams and K precoded radar waveforms. The k-th precoded data stream and radar waveform are added together, and K added signals can be produced in total. These signals are then sent to the K RF chains, and the RF chains use the input baseband signals to modulate the carrier signals and deliver the modulated signals to the feeds of the RHS. The injected signals from the feeds are converted to the radiation signals through the RF chains.

- **Reception step**: The operations of communication and sensing are performed parallel in this step. To be specific, the communication users receive the ISAC signals transmitted by the RHS to retrieve their data streams, while the BS receives the echo signals reflected by the targets via the MIMO antenna array and then performs radar signal processing.

To generate different beams toward the users and targets, we first need to create multiple holographic patterns. For each desired direction, K patterns can be generated, each corresponding to one feed. Thus, the number of the generated patterns is equal to the product of the number of the directions and the number of the feeds. Next, we can obtain the analog beamformer simply though a weighted summation of these holographic patterns [12]. The weights should be carefully optimized to maximize the ISAC performance, which will be discussed in the following. It should be noted that the number of beams can be different from the number of feeds [11].

B. ISAC Performance Metrics

Since the ISAC tasks include sensing and communication, the related performance metrics can be broadly categorized into two types, i.e., sensing and communication metrics.

**Sensing performance metrics**: Typically, the concept “sensing” involves detection, estimation, and recognition. Specifically, detection refers to the process of deciding whether a target exists or not, estimation means the judgment about the values of target parameters such as distance and velocity, while recognition refers to the act of identifying what the target is. As a result, their performance metrics vary. For example, the performance of detection can be evaluated by the detection probability (the probability of making a correct decision on the existence of a target), while the estimation performance is measured by the mean squared error (MSE, the average value of the squared error between the true and the estimated values of a target parameter).
Communication performance metrics: Similar to sensing tasks, the communication tasks also have different metrics. Two widely used metrics are the system capacity and bit error ratio (BER). System capacity is defined as the maximal mutual information that the system can provide with given bandwidth, and it is commonly modelled with the well-known Shannon formula. In contrast, the BER means the percentage of the error bits among all the received bits, which measures the reliability.

C. Holographic Beamformer Optimization

In this paper, our aim is to optimize the sensing performance given the constraints of communication. The sensing performance is optimized by minimizing the beampattern mismatch error, i.e., the difference between the transmit beampattern and a desired pattern, where the desired pattern has peaks in the target directions (as in [13]). Besides, we use system capacity to evaluate the communication performance.

This problem is challenging due to the coupling of the digital and analog beamformers. To efficiently handle this problem, we first decouple it into two subproblems, i.e., the digital and the analog beamforming subproblems, where the digital/analog beamformer is optimized given the other. Next, the digital and the analog beamforming subproblems are sequentially solved in each iteration. Specially, we first construct an initial analog beamformer with equal weights. The iteration terminates when the value difference of the beampattern mismatch errors [13] between the two adjacent iterations is less than a predetermined constant. In the following, we elaborate on the methods we use to tackle the two subproblems.

Optimization of Digital Beamformer: The digital beamformers for communication and radar sensing can be obtained by applying the zero forcing (ZF) method [14]. The basic idea is to first enforce the cancellation of the inter-user interference and the radar interference for all the communication users and then to derive the corresponding digital beamformers based on the channel information.

Optimization of Analog Beamformer: To optimize the weights in the analog beamformer, the subproblem is first transformed into a quadratic program by reformulating the objective function and the constraints in the subproblem, and the SDR technique can be applied to solve the quadratic problem.

IV. Prototype of the Holographic ISAC System

In this section, we develop a hardware prototype of the holographic ISAC system. The implementation of the RHS is first described, and then the hardware modules which comprise the ISAC system are introduced.

A. Implementation of the RHS

As shown in Fig. 3, we design an 1D RHS whose dimension is $15 \times 3 \times 0.17 \text{cm}^3$. The RHS consists of two SMA connectors,
a multi-layer substrate, and 16 metamaterial elements. One of the SMA connectors serves as the feed which joins the RHS and the RF chain together. The other SMA connector joins the RHS and a 50Ω RF load in order to absorb the energy remaining in the substrate. The substrate functions as a waveguide and is composed of four layers. The first and the third layers are made of F4B, and the second and the fourth layers are made of copper. The second layer of the substrate is the ground layer carrying a voltage of 0V. The fourth layer is the DC feed line layer. There are 16 feed lines, each connecting to a metamaterial element through a via hole. The other side of the feed line links to an output pin of the FPGA which applies a bias voltage to the element.

The type of metamaterial elements arranged on the top of the substrate is complementary-electric-resonator (CELC), and two PIN diodes (MADP-000907-14020) are laid on each metamaterial element. Since the two PIN diodes are in parallel, they have the same voltage bias, which means each element can be tuned between two states, i.e., ON and OFF states. At the 11GHz working frequency, the radiated energy of the element in the ON state is much greater than that in the OFF state, which forms the basis for the adjustment of the radiation pattern of the RHS.

B. Hardware Modules of the Holographic ISAC Prototype

The ISAC prototype is composed of three modules, i.e., the BS, user, and target modules, which are elaborated on below.

1) ISAC transceiver module: This module serves as an ISAC BS which transmits ISAC signals and receive echo signals for radar detection. To fulfill this task, an Intel NUC is implemented as the host computer. It controls the radiation amplitudes of the RHS elements via FPGA. It also connects with a USRP N210 which is able to simultaneously transmit and receive signals. Since the working frequency of the RHS (12GHz) is beyond the frequency range of the USRP (0 – 6GHz), a frequency converter is employed to up-convert the low-frequency signal transmitted by the USRP or down-convert the high-frequency signal received by the Rx antenna. The Rx antenna connecting to the frequency converter is a standard horn antenna (LB-75-20-C-SF) with a frequency range of 10 – 15GHz.

2) User module: The user module receives and decodes the ISAC signal from the ISAC transceiver module to retrieve the communication stream. Specifically, the Rx antenna first receives the ISAC signal and sends it to the frequency converter. The frequency converter down-converts the received signal and transmits it to a USRP which down-converts the signal to the baseband. The baseband signal is finally sent to the NUC via Ethernet cable for decoding.

3) Target module: This module is used to simulate radar targets by generating controllable radar echo signals [15]. It consists of an RX antenna, an antenna, a frequency converter, a USRP, and an Intel NUC. Once the Rx antenna receives the ISAC signal transmitted by the RHS, the target module is triggered, which adds delays to the ISAC signal and emits the delayed signal through the TX antenna. The value of the delayed time can be adjusted by the PC application running on the Intel NUC in order to simulate the targets located at different ranges.

V. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed ISAC system. The experiment layout is shown in Fig. 4. We deploy the proposed prototype in an anechoic chamber with a size of $4 \times 3 \times 2.5 \text{m}^3$. The ISAC transceiver module is located at the center of the chamber. The user and the target modules are placed in different directions in regard to the ISAC transceiver module, and the distance between the ISAC transceiver module and the user/target module is 1.7m. In the ISAC transceiver module, the ISAC signal transmission and the radar signal reception are performed in a time-division manner. Specifically, the BS first transmits the ISAC signal with a duration of 12µs and then listens for the echo signal to decide the presence of the target. Since there is only one RF chain in the BS, the digital beamformer is fixed as 1, and the analog beamformer is optimized to promote the ISAC performance.

Fig. 5 shows the radiation patterns of the RHS and the phased array. The phased array contains 5 antenna elements, whose relative phases can be independently tuned by phase shifters. To simultaneously detect the target and serve the communication user, the RHS or the phased array generates two beams that point towards directions 0° and −30°. We can observe that the gains of the RHS towards the directions of interest are slightly higher than those of the phased array. Besides, the power consumption of the phased array (5W) is substantially larger than that of the RHS (0.16W), which indicates that the RHS is able to support ISAC with similar performance and lower consumption compared with the phased array.

Fig. 6 illustrates the ISAC performances of the proposed platform. We place the target module in directions −50°, 0°, and 20°, respectively, to simulate the targets in different directions. The delays added to the ISAC signal by the target module are set as 20µs, 30µs, and 26.7µs which corresponds to the target in 6km, 9km, and 5km away. In order to sense the target, one of the main lobes of the radiation pattern is steered towards directions −50°, 0°, and 20° in different cycles, while the other main lobe keeps pointing toward the direction of the user module, i.e., 60°, to support downlink communication. It can be observed from Fig. 6 that the estimated range is close...
to the real range, which proves the feasibility of sensing by applying holographic ISAC. Besides, we can also observe from Fig. 6 that the communication symbol received by the user module is the same as the communication symbol transmitted by the BS, and the data rate between the BS and the user is 5M bit/s, which shows that the communication between the BS and the user can be supported when the BS performs radar sensing at the same time.

VI. FUTURE RESEARCH DIRECTIONS AND KEY CHALLENGES

In the previous sections, we have introduced the concept of holographic ISAC and shown the potential benefit of this concept compared to a traditional phased array. In this section, we introduce future research directions for RHS-based ISAC and the corresponding key challenges.

A. Fundamental Designs of the RHS

The designs of RHS layout parameters are critical in the optimization of holographic ISAC systems. In the following, we introduce the designs of two vital parameters, i.e., the RHS size and frequency band.

- **Design of RHS size:** To meet the increasing demand for communication capacity and sensing accuracy, the size of the RHS needs to be enlarged to provide higher antenna gain. However, the signal attenuation in the waveguide cannot be ignored for large-scale RHSs, which significantly decreases the efficiency of the antenna. Consequently, the size of the RHS should be optimized to balance the radiation efficiency and antenna gain.

- **Scaling to higher frequencies:** Driven by higher data rate requirements and the accommodation of more users, the communication systems are moving towards an unused spectrum with higher frequencies and larger bandwidth such as millimeter wave (mmWave). The proposed ISAC scenario also has the potential for the scaling to higher frequencies, where the RHS can be easily integrated with the mmWave circuits to reduce the profile and weight of the system. Novel designs of metamaterial structure are required to enable a high antenna gain of the RHS in the mmWave band to compensate the severe attenuation of mmWave transmission.

B. Limitations and trade-offs of Holographic ISAC

It is essential to theoretically analyze the limitations and trade-offs to further verify the superiority of holographic ISAC. To provide a general framework for the analysis, a performance bound which unifies both radar and communication is necessary.

For traditional ISAC systems, many existing works are devoted to developing closed-form expressions of the performance bounds by exploiting the inherent relation between information theory and detection theory [1]. However, due to the differences in hardware structures and working principles, the performance bounds developed for traditional ISAC systems cannot be directly applied to holographic ISAC. A new performance bound needs to be developed for RHS-based ISAC systems.

C. Optimization of Holographic ISAC Transceiver

As a metamaterial antenna, the RHS can also be utilized for a more general ISAC setting where both the TX and RX antennas of the BS are replaced by the RHSs. However, several challenges lie in designing such a scheme.

- **Channel Estimation:** Channel information is critical to the optimization of communication performances, while it is hard to be obtained due to the hybrid structure of the RHS. A straightforward method is to leverage the amplitude-controllable capability of the RHSs and estimate the channel of each element in a time division manner. Specifically, in each time slot, only one element is turned on, while the radiation amplitudes of other
elements are set as zero in order to avoid the interference. However, the time overhead of such a method is proportional to the size of the RHS, indicating the time cost could be prohibitively high for a large-scale RHS. Thus, novel methods that simultaneously estimate the channels corresponding to multiple elements should be developed to reduce the signaling burden.

- **AoA Estimation:** Considering the unique structure of the RHS where signals are first modulated by the superposition of holographic patterns and then received by the feeds, the estimation of angles of arrivals (AoAs) by using RHSs is more complicated than traditional phased arrays where the signals are directly received by the feeds. To address this issue, the maximum likelihood principle can be applied to estimate the AoAs. Specifically, for a large-scale RHS, an efficient estimation algorithm is necessary to perform multi-dimensional search and find the optimal solution of AoAs in order to further reduce the complexity.

- **Joint Design:** Due to the MIMO structure of the holographic ISAC transceiver, the beamformers at the transmitter and the combiners at the receiver are coupled, which means they need to be jointly optimized to maximize the overall performance. However, this is much more complicated than solely optimizing the beamformers or the combiners.

**VII. Conclusion**

In this article, we have introduced RHS-enabled holographic ISAC, a new paradigm for integrating sensing and communication functions. We have presented the concept of the RHS and developed a hybrid beamforming scheme for holographic ISAC based on the working principle of RHSs. In particular, we have built a hardware prototype of the RHS-enabled holographic ISAC system. Simulation and experimental results have shown that the power consumption of the RHS is lower than that of the phased array with a similar antenna gain, and unveiled the great potential for energy saving by implementing holographic ISAC. We have also discussed future research directions and key challenges of the holographic ISAC.

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