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Toward 6G Holographic Localization: Enabling Technologies and Perspectives

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Towards 6G Holographic Localization: Enabling Technologies and Perspectives

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Abstract—In the last years, we have experienced the evolution of wireless localization from being a simple add-on feature for enabling specific applications to becoming an essential characteristic of wireless cellular networks, as for sixth generation (6G) cellular networks. This paper illustrates the importance of radio localization and its role in almost all cellular generations. Also, it speculates on the idea of holographic localization where the characteristics of electromagnetic (EM) waves, including the spherical wavefront in the near-field, are fully controlled and exploited to achieve better wireless localization. Along this line, we briefly overview possible technologies, such as large intelligent surfaces, and challenges to realize holographic localization. To corroborate our vision, we also include a numerical example that confirms the potentialities of holographic localization.

Index Terms—Holographic Localization; Large Intelligent Surface; Metasurfaces.

I. INTRODUCTION

Beyond fifth generation (5G) cellular networks are endorsed by wide available bandwidths, high frequencies, and antenna arrays with a large number of antenna elements, i.e., massive multiple-input multiple-output (MIMO). These features will allow not only high-speed communication but also high-accuracy wireless positioning at an unprecedented scale [1]. For instance, massive MIMO with a considerably large distance between antenna elements (compared to the wavelength), like coordinated multipoint and cell-free massive MIMO [2], can enable extremely large aperture arrays (ELAA). Notably, thanks to their aperture, ELAA can achieve a significantly high spatial resolution that will allow them to attain accurate positioning performance.

On the contrary, we may be interested in increasing the antenna densification into compact sizes so that they can be integrated into small areas. Operating like this, in the case of extremely dense antennas, there will be the possibility to create a spatially quasi-continuous electromagnetic (EM) aperture, i.e., a holographic MIMO array [2]. A promising solution for the realization of a quasi-continuum antenna array is provided by intelligent surfaces, usually made of metamaterials [1]. While holographic communication has already received attention for the exploitation of the available degrees of freedom,

holographic localization is still at its early stage and needs yet to be explored.

In this paper, we envision holographic localization as the future of wireless positioning that will be characterized by considering ELAA and intelligent surfaces to exploit near-field and achieve the control of EM waves at an unprecedented level [3]. The term *holographic* here is intended as the ability to fully control and/or exploit the characteristics offered by different EM propagation regimes obtained by optimized control of the radiating beams and operating directly on the electric field.¹ This is particularly important when using electrically large antennas at high frequency, e.g., the millimeter wave or THz. Hence, the operating conditions may easily fall in the Fresnel radiating near-field region, where the classical plane wave propagation assumption is no longer valid. In this regime, the EM wavefront curvature offers the possibility to associate more information about the location and the antenna orientation to the wave, allowing, if fully exploited, improved localization performance. As an example, different propagation regimes of the electromagnetic fields (EMF) can be exploited to infer the position information by controlling the EM waves generated or sensed by antennas of multiple devices. Also, the features of a transmitting device, e.g., the device position and array shape and orientation, have a significant impact on the received signal. Hence, these characteristics can be inferred from the signal by considering a model that accounts for the equations governing the propagation of EM waves, rather than standard models [4].

Hence, our vision is to *fully control* and *fully exploit* the wavefront to enhance the positioning performance by considering the spherical wavefront and operating on the EM level. This opens the door for several applications that require sub-centimeter positioning accuracy such as augmented reality, virtual teleportation, and self-driving car. Towards our vision, we first overview the history of wireless positioning, emphasizing the importance of holographic localization for new applications. Then, we discuss about possible enabling technologies to control the wavefront, including large intelligent surfaces (LISs), and possible positioning algorithms together with ultimate localization to fully exploit the optimized wavefront. Finally, as a use case, we assess the performance of a reconfigurable intelligent surface (RIS)-aided localization system that optimizes the RIS phases to minimize the positioning error and make use of the spherical wavefront

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¹Holographic localization is more general than the traditional concept of *holography*, which concerns the practice of making holograms, e.g., photographic recordings of a light field to reproduce 3D images.

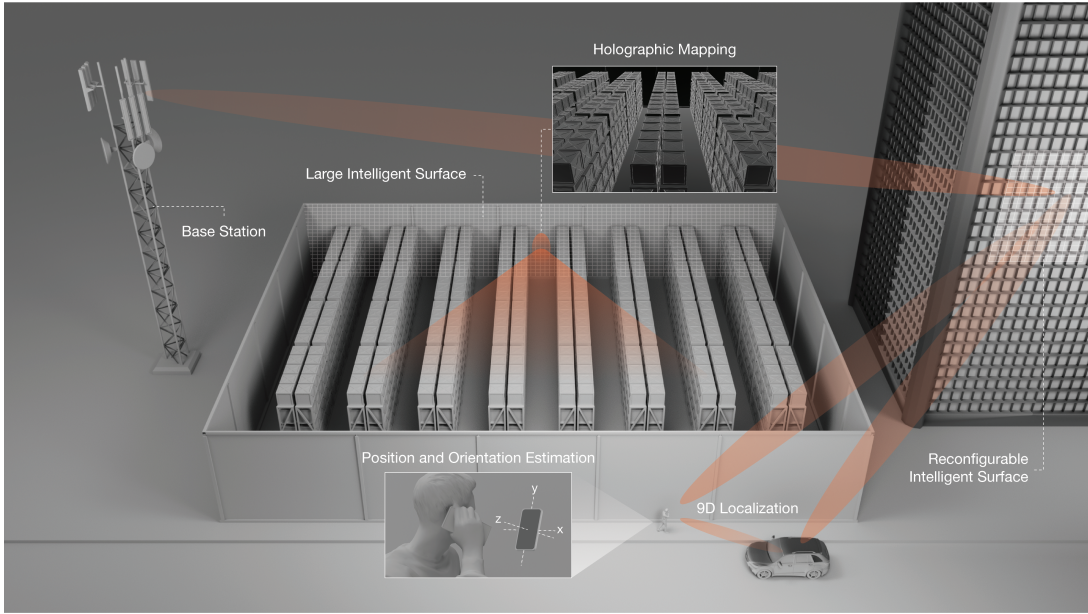


Fig. 1. A pictorial vision of possible future communication, sensing, and localization scenario for industrial internet-of-things (IoT).

through maximum likelihood estimator (MLE) considering the near-field model.

II. LOCALIZATION HISTORY AND NEW DIRECTIONS

Wireless localization has been an essential service for several applications in the last decades [5]. The position of a user equipment (UE) can be estimated either at the UE (*downlink positioning*) or at the network level (*uplink positioning*). Different types of measurements can be considered for positioning, e.g., time-of-arrival (TOA) of the radio signal, uplink time difference-of-arrival (UTDOA), time difference-of-arrival (TDOA), phase difference-of-arrival (PDOA), angle-of-arrival (AOA), angle-of-departure (AOD), and received signal strength (RSS). Another localization method is *proximity*, where a rough location of the UE is determined by the location of some reference entities (e.g., base stations (BSs) and anchors) in the proximity of the users. For instance, cellular ID (CID) and enhanced-CID (E-CID) techniques fall within this category.

A. Positioning Platforms

The positioning platforms can be classified into three main groups: (a) *ad-hoc terrestrial*, (b) *cellular*, and (c) *ad-hoc satellite* systems. In the following, we focus on the first two solutions.

a) Ad-hoc Positioning Systems: Different types of measurements can be processed to infer the user position, e.g., TOA, TDOA, AOA, AOD, and RSS [6]. Such measurements can be obtained through tailored technological solutions, spanning from ultrasounds, ultra-wide bandwidth (UWB), millimeter-waves (MM-Waves) towards visible light-based technologies, e.g., light detection and ranging (Li-DAR) and visible light positioning (VLP) technologies. To this purpose, in Table I we summarize the main characteristics of each ad-hoc technology employed for wireless positioning, as well as the related achievable localization accuracy.

b) Cellular-based Positioning: Cellular networks are designed mainly to support high-quality communications. Only recently, communication and localization have been jointly designed and this integration will be further pushed in sixth generation (6G) mobile networks. In past generations, positioning was considered as an add-on service for communications whereas now cellular systems are also conceived as a mean to provide location information for users, covering a wider area compared to terrestrial ad-hoc techniques. To this purpose, Table II displays the main features of cellular positioning for various generations, till the foreseen 6G, including the related key performance indicator (KPI). Indeed, the next 6G is expected to dramatically impact the way wireless localization is conceived in cellular-based systems.

B. Potential Applications for Holographic Localization

As previously highlighted, the advent of holographic radio will make available a larger number of degrees of freedom enhanced by the different operational EM propagation regimes (e.g., in the Fresnel region). Moreover, the possibility to fully control the EM field at both the transmitter and receiver sides, granted by the advent of new technologies, will help approaching the ultimate localization and communication performance limits. Indeed, this will open the possibility to enable new applications, in light of 6G scenarios. In fact, accurate positioning of mobile users can enhance the performance of communication systems, also called as location-aware communication. Some examples are: (i) geometric beams at the transmitters can be designed for location-based beamforming without the need to estimate the full-band channel state information (CSI); (ii) the system can adopt sophisticated spatial techniques to mitigate the interference; (iii) location information and measured radio parameters over a long time period enable the construction of radio environment maps, opening many opportunities in terms of proactive resource allocation, without the need to know the instantaneous CSI;

TABLE I
COMMON AD-HOC LOCALIZATION TECHNIQUES SUCH AS ULTRA HIGH FREQUENCY (UHF)-RADIO-FREQUENCY IDENTIFICATION (RFID), UWB, MM-WAVES, LI-DAR, AND VLP.

	UHF-RFID	UWB	MM-Waves	Li-DAR	VLP
Typical Frequency	865-868 MHz	3.1-10.6 GHz	28, 60, 77 GHz	200 THz	400-790 THz
Typical Bandwidth	200 kHz	larger than 500 MHz	larger than 2.1 GHz	-	150 MHz
Localization Technique	RSS, PDOA	TOA, TDOA	TOA, TDOA, AOA	TOA	RSS
Coverage	very small (less than 10 m)	moderate (less than 100 m)	moderate (less than 100 m)	large (less than 500 m)	tiny (less than 10 m)
Accuracy	less than 5 m	less than 10 cm	less than 1 cm	less than 1 cm	less than 15 cm
Cost	very low	moderate	moderate/high	high	very low

TABLE II
CELLULAR-BASED LOCALIZATION TECHNIQUES, FEATURES, USE CASES, AND KPI SUCH AS OBSERVED TIME DIFFERENCE-OF-ARRIVAL (OTDOA), UPLINK ANGLE-OF-ARRIVAL (UAOA), MULTI ROUND TRIP TIME (MULTI-RTT) LOCATION SERVICE (LCS), POSITIONING ELEMENT (PE), LTE POSITIONING PROTOCOL (LPP), POSITION REFERENCE SIGNALS (PRS), NR POSITIONING PROTOCOL A (NRPPA), AND EMERGENCY SERVICES (ES).

	2G	3G	4G	5G	6G
Maximum Frequency	1900 MHz	2100 MHz	6 GHz	90 GHz	3 THz
Typical Bandwidth	200 kHz	500 kHz	20 MHz	100 MHz	500 MHz
Enhanced Techniques	CID, assisted TOA, OTDOA	CID, assisted TOA, OTDOA	E-CID, UTDOA	UAoA, Multi-RTT, NR E-CID	Enhancing Previous Techniques (e.g., assisted with RIS and AI)
Localization Features	LCS	PE	LPP, PRS	NRPPa	Joint Communication & Sensing protocol
Use Cases	ES	ES	ES	ES, industry, logistics, e-Health, aerial	Holographic 9D Localization and Communications, Virtual Teleportation
KPI horizontal positioning error outdoor (indoor)	less than 100 m, 67%	less than 100 m, 67%	less than 50 m, 67%	less than 10 m (3 m), 80%	less than 10 cm, 99.9%
KPI vertical positioning error outdoor & indoor	NA	NA	less than 3 m, 67%	less than 3 m, 80%	less than 10 cm, 99.9%
Positioning latency	NA	NA	NA	less than 1 sec	less than 0.1 sec

(iv) data can be communicated with low-latency by considering proactive location-based backhaul routing; (v) the CSI can be efficiently estimated from a minimal number of pilots by considering geometric channel models when the location of the user and the scatterers can be accurately computed; and (vi) the radiation pattern of the antennas can be optimized to minimize the users' exposure to EMF based on the orientation and location estimation of the UE.

We now present some potential applications that require high-accuracy and low-latency localization. In Fig. 1, an example of a holographic localization scenario enabled by LISs is depicted. In this scenario, the intelligent surface in the outdoor acts as a passive reflector for assisting the BS in estimating the 9D location (position, orientation, and speed) of the user and vehicle. The indoor intelligent surface in the warehouse can be active and it allows holographic localization and mapping in the industrial IoT environment. Towards this vision, some use cases are reported in the following.

a) *Industrial Internet of Things*: Accurate positioning is crucial for exploiting the full potential of sensors and actuators in industrial IoT scenarios. All *things* (e.g., sensors, machines, tools, or humans) can be equipped with tags wirelessly con-

nected to provide communication services and high-accuracy positioning. For example, mobile robots require accurate information about their location and the surrounding environment to properly navigate through congested warehouses.

b) *Simultaneous Wireless Information and Power Transfer*: 6G are expected to foster systems equipped with near-pencil beam antenna arrays and high directivity. Hence, there will be the possibility not only to proficiently transfer information through the generated beams but also to energize the devices through the same communication link. Localizing with extremely high accuracy is demanded to properly focus the power transfer and reduce the amount of wasted energy.

c) *Intelligent Transportation Systems*: Accurate positioning can help in enabling better traffic routing as well as in the navigation support of autonomous cars and drones through the avoidance of collisions, enabling services such as autonomous flying taxis.

d) *Extended Reality (XR)*: Most of the XR-based systems require accurate positioning. For example, one application permits users to modify the urban design by creating and removing parts of existing buildings. The reproduced illusion requires high localization and orientation-detection accuracy

to provide the user with an immersive experience.

III. HOLOGRAPHIC LOCALIZATION ENABLING TECHNOLOGIES

To enable holographic localization, we need technologies to realize electrically large antennas and reflectors so that localization occurs in the near-field propagation regime, thus enabling holographic localization. Moreover, such technologies should allow for achieving full control of the EMF, thus moving some of the signal processing from the digital to the EM level, achieving gains in terms of flexibility, lower latency, power consumption, and complexity.

Conventional discrete antenna solutions entail the adoption of antenna elements usually spaced apart by half wavelength. In this case, each cell is equipped with an antenna and acts as an independent unit that modifies the behaviour of the wave (that can be also reflected) in the desired manner (beam-tailoring capability). Nevertheless, such a technique requires a large number of radio frequency (RF) chains for the increased number of antenna elements, leading to higher costs and bulky implementations. Also, with a half wavelength separation between antennas, if we increase the operating frequency while fixing the number of antenna elements, the users will fall easily into the far-field of the array with planar waves. Since we lose information about the curvature of the wavefront, it becomes harder to jointly estimate the range and AOA, leading to poor localization performance.

In the following, we discuss potential techniques that can enable holographic localization by allowing more users to be in the near-field of the array and exploiting the entire position information associated with the propagating EM.

A. Extremely Large Aperture Arrays

Massive MIMO with a considerably large distance between antenna elements (compared to the wavelength) can enable the realization of ELAA. These arrays have a significantly high spatial resolution, enabling accurate positioning performance due to their large apertures compared to arrays with the same number of antennas, but with smaller apertures.

Moreover, buildings coated with ELAA will extend the near-field region even for several kilometers around the array, allowing to manage more degrees of freedom which can be exploited to enhance the localization. For instance, since the UE can be likely located in the near-field of an ELAA, it will be possible to directly retrieve the distance (ranging) information from the spherical wavefront together with the AOA information [7]. In addition, antennas will experience a different received signal strength indicator (RSSI) with great probability due to the large distance between them (e.g., imagine two elements at different corners of a building), so that further location information can be gathered. In addition, it might happen that, due to the large aperture, some antennas of the ELAA might be in non-line-of-sight (NLOS) with the UE, whereas others might keep the visibility with it. Therefore, the study of the visibility region of the ELAA is of paramount importance for localization.

Another benefit is that in the near-field the signal can be focused on a point, i.e., the user location, rather than a direction. If we have a rough initial estimation for the user's location, the received signal-to-noise ratio (SNR) at the user can be boosted, and the interference to other users is reduced, even if they lie at the same angular sector. On the contrary, in far-field beamforming, users in the same angular sector, but with different ranges, cannot avoid such interference. Hence, exploiting the near-field can lead to a more accurate user position estimation.

Nevertheless, several challenges still need to be properly addressed, such as the presence of strong phase ambiguities that could dramatically affect the localization accuracy, as well as the requirement of tight synchronization among the antennas within the ELAA.

B. Intelligent Surfaces

Metamaterials have been recently proposed for coating both small and large objects with large surfaces because their reflections can be programmed and controlled to meet the application needs. Indeed, these surfaces become intelligent, that is, able to focus the power towards the desired targets, and they represent a viable and promising solution for the realization of holographic localization.

Intelligent surfaces can be employed in different functional modes: (i) in transmission mode by modulating the phases of the radiating elements and/or in reception when they are equipped with a set of RF chains; (iii) in reflection mode when they are used as passive relays of multipath components, and they control the reflections in real-time. In the following, we will discuss these modes in detail.

1) *Intelligent Surfaces as Active Antennas (LIS)*: LISs can be used as transmitters, receivers or for both purposes. In this scenario, they can be interpreted as compact and low-cost antenna arrays that might be exploitable at the BS. Such antennas can be fabricated with either tiny antennas or metamaterial radiating elements capable of actively communicating over a wireless link [8]. When a LISs is used actively and with the adoption of many tiny antennas, it represents a natural evolution of massive MIMO technology [9].

Recently, it has been investigated the possibility to adopt dynamic metasurfaces as active antennas to control the transmit/receive beam patterns with advanced hybrid A/D signal processing capabilities [8]. Compared with conventional antennas implemented by patch antennas and phase shifters, dynamic metasurface antennas operate at low power consumption and cost, while naturally implementing RF chain reduction without requiring dedicated analog circuitry but by exploiting metamaterials located within waveguides.

Another possibility is to place a reconfigurable EM lens in front of a single transmitter/receiver antenna, such that part of the signal processing is performed in the analog domain through large surfaces. In this way, there is the advantage that the digital signal processing is dramatically reduced, as it is delegated to the lens that operates in the analog domain. On the other side, the cost to be paid is reduced flexibility, as only one RF chain is connected to the antenna that collects the resulting signal after the lens processing.

2) *Intelligent Surfaces as Reflectors (RIS)*: LISs can be also employed to ease and enable the wireless localization between the BS and multiple users by acting as a method to control the multipath, and they are also referred to as RISs or digitally controllable scatterers (DCSs), since each element of the surface is treated as a local scatterer. Indeed, this is in principle different from relays that are usually active or they require more energy and sophisticated processing operations. This emerging technology exploits the possibility to dynamically and artificially adjust the physical properties, such as permittivity and permeability, of the EM waveforms to obtain some desired electrical or magnetic characteristics that in principle are not available in nature [2]. Operating like this, radio waves can be shaped in a way that the reflected signals might not obey Snell's law, but rather a generalized Snell's law. As an example, such an effect can be realized with unit cells made of metallic or dielectric patches that can be modeled as a passive scattering element. To preserve energy and cost efficiency, each unit cell can be equipped with some low-power tunable electronic circuits, e.g., PIN diodes or varactors, and sensors. An alternative is represented by metaprisms, which refers to a passive and non-reconfigurable metasurface that acts as a metamirror. Its reflecting properties are frequency-dependent within the signal bandwidth and they can be optimized at the BS by proper frequency resource allocation to increase the communication and localization coverage even in situations where the line-of-sight (LOS) is obstructed.

IV. PERFORMANCE LIMITS AND ENABLING ALGORITHMS

As previously mentioned, *holographic localization* is the capability to fully exploit the EM characteristics of the incident wavefront to infer the position information. In other words, it refers to the possibility of recording a quasi-continuum measurement profile through which the position and the orientation of a user are inferred. For example, when using an array of antennas or a metasurface whose dimension is large enough to consider the surrounding users in the near-field region, the phase profile of the impinging waveform provides sufficient information to estimate the positions. In fact, the plane wave approximation is no more valid in the near-field and the spherical characteristic of the EM wave brings all the needed information for the positioning, i.e., distance and angle information. Such models that capture the coupling between the distance and angles in the near-field can be found in [10] and [6], [11] for ELAA and RIS, respectively. Novel positioning algorithms that exploit holographic localization are required, as current far-field-based algorithms encounter an additional positioning error due to the model mismatch when the user is in the near-field [12]. To this aim, in the following, we illustrate (i) the latest contributions for establishing the localization performance limits in RIS-aided scenarios; (ii) some of the localization algorithms and their complexity.

A. Fundamental Limits

The localization performance limits provide a lower bound on the achievable estimation mean square error of any (unbiased) localization estimator. Such limits, typically based

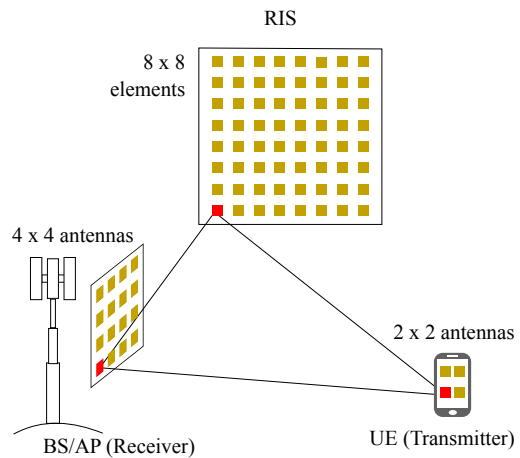


Fig. 2. Considered localization scenario.

on Cramér-Rao lower bound (CRLB), represent benchmarks for practical estimators and depend on various parameters, such as, for example, the adopted technology, the geometric scenario, the array geometry, the presence/absence of a LOS link, the accuracy and number of measurements, and the presence/absence of any prior information on parameters. Moreover, any type of collaboration between nodes should be taken into account by these limits as well as the adopted waveforms and codebooks, and the presence of synchronization and technological impairments. A survey on the CRLB for classical positioning problems can be found in [5] and, only recently, research on fundamental limits has advocated the importance of considering near-field propagation induced by the use of large surfaces where the ultimate localization and orientation fundamental limits are derived in scenarios with a RIS [1], [6] or with a LIS [9], [10]. More specifically, in the derivation of the near-field CRLB for localization, authors in [9] put together estimation theory and wave propagation, accounting for the electromagnetic field over a defined region. Indeed, the aforementioned near-field contributions have shown a performance enhancement in terms of positioning accuracy and coverage when using RISs and the possibility of using a single node and narrow-band signals for localization. Therefore, they can be considered as a first step towards the concept of holographic positioning.

B. RIS-aided Localization Approaches

Localization algorithms assisted by RISs usually are based on the assumption that a discrimination between the direct path, representing the link between the user-BS, and the reflected path controlled by the RIS is possible, for example by adopting CSI estimation approaches [13]. Usually, this entails accumulating a large number of pilot symbols and adopting random phase configurations. Subsequently, both direct positioning and two-step localization approaches can be used to localize the user. For example, in [14] where a dual RISs scenario is considered, the delay difference of the direct and reflected paths corresponding to each RIS present in the environment is calculated via the cross-correlation of the signals over the two paths and the location of the user

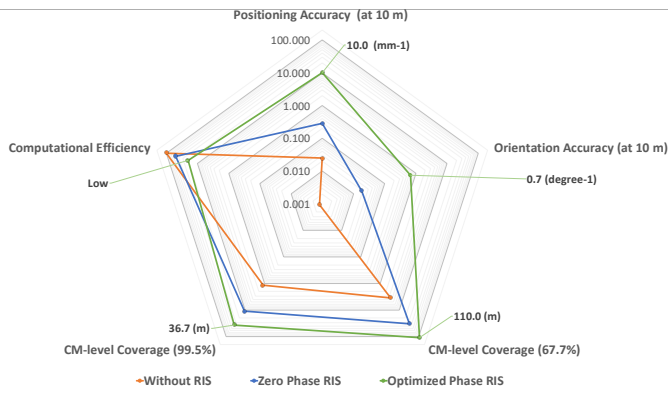


Fig. 3. Radar chart on the localization performance for various architectures without and with RISs, according to the scenario displayed in Fig. 2.

is finally estimated according to the geometric laws. In [15] an indoor positioning application is considered and, thus, the UWB technology is proposed in conjunction with the adoption of RIS for its ability to resolve multipath. On the other hand, the near-field is exploited in [11] to estimate the ranges, AOA, and AODs for the UE-RIS and RIS-BS links using a sparse recovery algorithm.

The performance of the aforementioned localization algorithms depends heavily on the RIS phase profile. In fact, the phase shift induced at each RIS element should be adequately designed to improve the localization performance, which is obtained as a solution to an optimization problem. Several performance metrics can be considered as objective functions that are optimized to improve the positioning performance such as the received SNR, CRLB on location and orientation estimation, and algorithm-tailored localization errors [6].

V. CASE STUDY

In this case study, we focus on uplink positioning which is an important add-on service in 6G communication systems. In particular, we consider a single-anchor localization scheme in RIS-assisted environment, where a BS estimates the location and orientation of a UE from the direct and RIS-reflected signals. The BS can exploit the full *holographic* profile of the impinging signal, as we account for the wavefront curvature by considering the near-field model rather than the far-field approximation that assumes a planar wavefront. The system operates with a center frequency of 28 GHz. The UE transmits an orthogonal frequency-division multiplexing (OFDM) signal with -10 dBm allocated power per subcarrier. The CRLB of this system is derived in the recent paper [6].²

To corroborate our vision, we report in Fig. 2 an example of the scenario of interest, where the RIS location is in (5,5,1) meters, while the BS is in the center. Then, in Fig. 3, we consider the performance for such a scenario accounting for the following schemes: *i) Without RIS*: single-anchor localization without the help of a RIS; *ii) Zero Phase RIS*: the RIS acts as an EM mirror obeying Snell's law, i.e., the phase shifts are all zero; *iii) Optimized Phase RIS*: the RIS is designed to

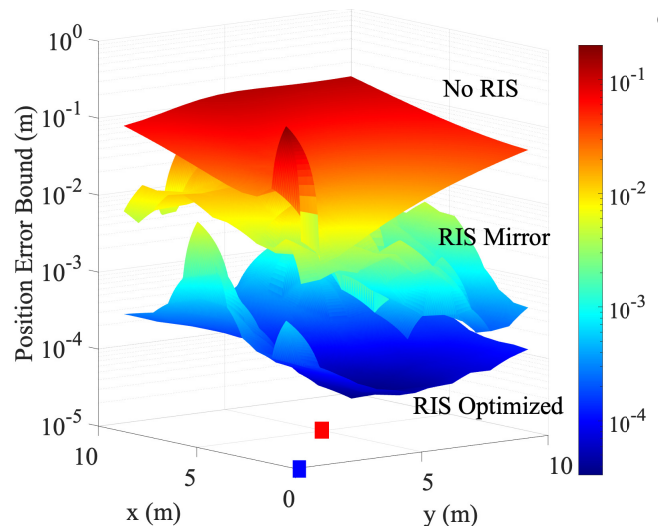


Fig. 4. The PEB vs various UE locations for scenarios with and without RIS, with blue and red markers indicating the BS and the RIS position, respectively.

minimize the CRLB on position or orientation estimation, i.e., position error bound (PEB) or orientation error bound (OEB). The performance is indicated in terms of several metrics, i.e., *i) positioning/orientation accuracy*: the reciprocal of the PEB/OEB obtained from the CRLB computed at a distance of 10 m from the BS; *ii) CM-level Coverage (67.7% or 99.5%)*: the maximum distance from the BS such that we are sure by 67.7% or 99.5% that the localization error is less than 1 cm; *iii) Computational efficiency*: the reciprocal of the computational complexity. We set the number of UE, BS, and RIS antennas to 4, 16, and 64, respectively. We can see that the optimized RIS phase leads to higher position accuracy, orientation accuracy, and coverage compared to the without-RIS scheme by factors of about 400x, 812x, and 31x, respectively, at the expense of increased computational complexity.

The impact of RIS-assisted environment for various UE locations is also evidenced in the 3D maps of Fig. 4. We can see that the error is minimal when the UE is near the RIS, which is located at (5,10,1) meters, with a localization error that is almost two and three orders of magnitude less than the scheme with non-optimized RIS and without RIS, respectively. The RIS plays a role in a twofold manner: it creates a new link between the BS and the UE, and it expands the near-field region, as the UE can be in the near-field of the RIS but in the far-field with the BS. These numerical considerations represent the first step towards holographic localization, showing that it is possible to attain a localization accuracy in the order of the millimeter, and an orientation accuracy of a fraction of a degree. Moreover, this put in evidence the need of having a proper RIS phase design, which is still challenging when RIS-assisted localization is performed. Further numerical results for holographic localization can be found in [6], [9]–[12].

VI. CONCLUSION AND FUTURE DIRECTIONS

In this paper, we have motivated our vision towards holographic localization, enabled by LISs, as an essential feature for next-generation wireless networks. There are several key research aspects that present unsolved issues, but the road ahead is promising, and it is expected to nurture new challenging studies towards the establishment of 6G. In the following,

²The results are conducted using MATHEMATICA[®], and the source code is available at <https://github.com/ahmedelzanaty/Holographic-Localization>.

some of the future directions and challenges for holographic localization with intelligent surfaces are stated.

High Complexity Iterative Algorithms The problem formulation of the RIS phase design usually requires an initial rough position estimate for the device that needs to be localized. Therefore, the localization problem often involves multiple iterations, where the estimated location of the device in the last iteration is used to compute the RIS phases for the next iteration. This process should be repeated iteratively until the algorithm converges to the actual location. Therefore, there is a great challenge of obtaining the position information with low overhead and extremely low latency.

Multi-Objective Function in 9D Localization Some 6G use cases, such as augmented reality-based applications, require accurate 9D localization, i.e., the position, orientation, and speed estimation errors should be minimized. Unfortunately, in general, it is challenging to optimize the RIS phases such that all the aforementioned errors are simultaneously minimized, as required for 9D localization. Hence, the phase design turns into a multi-objective optimization problem, requiring more sophisticated algorithms. In this sense, efficient solutions for the RIS phase design by optimizing multi-objective functions are still lacking.

Ad-hoc Waveform Design In general, for 9D localization, multiple waveforms can also be designed for different time slots in order to achieve better accuracy for the estimation of different parameters in a time-division fashion. Moreover, following a trend started by LTE Advanced, the 6G waveforms will be designed for joint communication and localization purposes. In this regard, the joint design of the RIS phases and the beamforming codebooks at the BS and UE is essential. Moreover, a distinction should be made according to the use of RIS either being a transmitter or a reflector. The joint optimization problem can be also challenging, increasing the complexity of the localization algorithms.

Holographic Simultaneous Localization and Mapping 6G can exploit holographic radio to increase ambient awareness by reconstructing the surrounding environment (*holographic mapping*) and by allowing a user to self-localize with respect to the reconstructed map. In this perspective, holographic simultaneous localization and mapping (SLAM) will allow users to improve their perception of the environment and their interaction with it.

AI for Holographic Localization Machine learning approaches can be used to assist in solving the optimization problem of the phase profile. In addition, the user's location and orientation can be inferred from the received signal with machine learning approaches, where a deep neural network can be trained by mapping the environment through a sub-sample of random location for the UE. Nevertheless, the required training data for data-driven schemes with machine learning can be massive to achieve the target accuracy. In this regard, an alternative machine learning method that does not necessitate a large amount of possible UE locations is more relevant.

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