Radio Localization and Mapping with Reconfigurable Intelligent Surfaces

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Abstract—5G radio localization at millimeter wave (mmWave) and sub-THz frequencies exploits information via both angle and delay measurements, by the virtue of increased bandwidth and large antenna arrays. When large arrays are embedded in surfaces, they can passively steer electromagnetic waves in preferred directions of space or generate shaped beams. Reconfigurable intelligent surfaces (RISs), which are seen as a transformative “beyond 5G” technology, can, thus, control the physical propagation environment. Whereas such RISs have been mainly intended for communication purposes so far, we herein state and analyze a RIS-aided localization and mapping problem.

INTRODUCTION

The interaction between the digital and physical world relies on high-definition situational awareness. Situational awareness refers to the ability of a device or agent to determine its own location, as well as the location of objects and other devices in the operating environment. Applications include automated vehicles and robots in general, as well as healthcare, highly immersive virtual and augmented reality, or new human-to-machine interfaces (HMI).

Situational awareness can be achieved by a variety of technologies, depending on the application and requirements. These technologies can be categorized as radio-based (such as satellite positioning, radar, cellular or WiFi) and others (such as lidar, inertial measurement unit, camera). Radio-based technologies are attractive as they can have a dual communication and sensing functionalities and are often less susceptible to environmental factors such as poor lighting. Since 4G, dedicated localization reference signals have been considered as part of communications system design and standardization. Those can enable location accuracy levels on the order of 10 m. With 5G, the use of larger bandwidths and higher carrier frequencies in combination with antenna arrays at user equipment (UE) and base station (BS) is expected to further improve the location accuracy to around 1 m. Within Beyond 5G systems, the trend is to operate at much higher frequencies (above 30 GHz, possibly up to 1 THz) so as to benefit from large available bandwidths and thus, achieve even better localization accuracy below 1 m.

While radio technologies at high carrier frequencies and large bandwidths can exploit multipath, they suffer from obstructions due to objects blocking line-of-sight (LOS) path between the transmitter and the receiver. The reliance on the LOS path can be reduced through multipath-aided localization by exploiting either a prior map information [1] or through joint localization and mapping [2]. Therein the locations of objects in the environment (surfaces and scatter points) are determined simultaneously with the user’s location, called radio-based simultaneous localization and mapping (SLAM). Even if these solutions make use of the multipath channel as a constructive source of information as regards to the localization problem geometry, the related electromagnetic interactions (induced by the physical environment) still remain uncontrolled and as such, largely suboptimal from a localization perspective.

Reconfigurable intelligent surfaces (RISs) represent a breakthrough technology whereby surfaces are endowed with the capability to actively modify the impinging electromagnetic wave [3]. A RIS can be implemented using a variety of technologies as discussed below and can provide significant benefits in terms of communication by guaranteeing coverage when the LOS is blocked. A RIS can operate in three distinct modes: transmission can be achieved by modulating the phases of the RIS elements [3] or by exciting a current in the surface, reception by providing the RIS with a limited number of RF chains [4] or by observing the radio signal across a continuous surface, and reflection, the most common operating mode, is achieved by real-time control of the RIS elements or current distribution [5], [6].

The potential of RIS for localization has received limited coverage in the literature and include studies where the RIS operates in the receive mode [7] and reflection mode [8]. A RIS can create anomalous reflections, i.e., the direction of the reflected wave is no longer specular according to natural reflection laws, but steerable. This property makes them relevant for localization and mapping. Hence, it is timely to delve deeper into the potential of RIS for such applications, as well as the main research questions that we should address in the coming years. Possible applications of RIS for localization are visualized in Figure 1. The aim of this paper is to describe the core technical and scientific challenges of applying RIS to localization and mapping, along with preliminary system visions, results and solutions recently put forward on related topics.

RADIO LOCALIZATION AND MAPPING

How it Works?

Any radio localization and mapping system comprises three essential parts: measurements, a reference system, and the...
Measurements: The measurements are derived from the radio signal between a transmitter and a receiver. They can typically be obtained directly from the channel estimation routine used for communication. Common location-dependent metrics include power measurements (received signal strength (RSS)), time measurements (time of arrival (TOA) and TOA-based round-trip-time-of-flight (RT-TOF) or time-difference-of-arrival (TDOA)) and phase measurements (phase of arrival (POA)), angle measurements (angle of arrival (AOA) and angle of departure (AOD)), and Doppler shift measurements. TOA and POA provide distance information, while angle measurements provide orientation information, and the Doppler measurements relate to the velocity.

Measurements can be characterized by their resolution and accuracy. The resolution refers to the ability to distinguish two signals based on their delay, phase, angle, or the Doppler shift. It depends on the signal bandwidth, carrier frequency and waveform, the number of antennas, and coherent integration time, respectively. The accuracy refers to the extent to which we can determine the parameter of interest. It depends also on the signal-to-noise ratio (SNR), as well as on the detailed properties of the signal waveform such as the time-frequency and spatial power allocation.

Reference System: The measurements are all taken in a certain frame of reference, e.g., that of the receiver. Those are spatial points with known location, sometimes called as anchor points. This frame of reference needs to be associated to the global frame of reference of the localization system. In a mono-static radar, for example, the transmitter and receiver are co-located as are their reference frames leading to relative localization. For some systems, the receiver is the reference, while for others the transmitter is the reference. There may be multiple position references, as in cellular localization or satellite positioning, which may in turn place requirements in terms of synchronization, array calibration, as well as dedicated control signals. The geometric placement of the reference plays an important role in the accuracy of a localization system, an effect commonly measured through the geometric dilution of precision (GDOP).

Localization and Mapping Algorithms: The process of generating a position estimate based on the measurements typically relies on statistical signal processing. Due to the nonlinear and noninvertible relation between positions and the measurements, common approaches can range from simple least-squares to Bayesian methods that can harness a priori information and can fuse information from different sensors. A main distinction between a communication and a localization algorithm is how the multipath is treated. In communication, multipath is used to provide diversity or spatial multiplexing, thus, decreasing error rate or increasing data rate. In localization, only the LOS has traditionally been used, as the measurements associated with that path could directly be related to the location of the user. More modern approaches also exploit measurements from non-line-of-sight (NLOS) paths, corresponding to scattered or reflected signal components. When the environment is known, this leads to multipath-aided localization, while for an unknown environment, SLAM methods can be used, in order to both localize the user and map the environment. A critical component in SLAM is the association of measurements to sources, where a source can be a transmitter or a fixed object in the environment, or clutter.

In the design aspects of the measurements, reference system, and algorithms, the fundamental performance bounds can play an important role. They allow, often in closed form, to assess the localization potential of signals or reference systems, guide the development and benchmarking of algorithms, or even be used as approximated performance indicators or real-time optimization/selection criteria in systems.

Localization and Mapping with mmWave RIS

The inclusion of RIS affects the three above-mentioned aspects of radio localization. The measurements are in general of the form of tuples of TOA, POA, AOD, AOA, and the Doppler shift, but can under near-field also include the curvature of arrival (COA). The relation between the measurements depends on the underlying channel model, which at mmWave frequencies is largely geometric: each path corresponds to a cluster of rays, depending on the electro-magnetic (EM) properties of the objects. In other words, the locations and EM properties of the environment impose a mapping from position space to measurement space.

The references include the BS and RIS, which can reasonably be assumed to have a pre-programmed known location and orientation in a common coordinate system, while users and passive object have unknown or partial location and orientation information. The signal from the BS is to a large extent controllable in the time, frequency, and spatial domains. Therefore, it can be optimized in terms of power allocation and
beamforming to optimize the accuracy of the measurements. The signals from the RIS can be shaped by the RIS controller, in order to further improve accuracy, when the RIS is acting as a transmitter or a reflector [7], [8]. The design may however be less flexible than the signal from a conventional BS, for obvious power and complexity considerations. In terms of inference algorithms, the RIS-based SLAM approach is thus to invert the mapping from position to measurements, and thereby obtain position estimates of the user and the objects, and track these over time, harnessing the flexibility of the BS signals and RIS controllability, to improve both localization and mapping coverage, but also accuracy.

**Challenges and Opportunities**

When a RIS used as a reflector, it could be interpreted in two different ways: as part of the passive environment, acting like any scatterer or reflector, or alternatively as part of the infrastructure, playing a similar role as a global reference or anchor point. These two views lead to fundamental challenges and opportunities in incorporating RIS in radio localization and mapping, as highlighted below. Many of these challenges are inter-related, but are presented as separate for reasons of clarity: RIS and channel modeling, near-field propagation, channel estimation, system architecture and signaling, RIS control, signal design, and SLAM methods.

**RIS Modeling and Channel Modeling**

**Challenge:** There are several different antenna technologies and terminologies for RIS, including classical phased arrays, reflectarrays [9], transmit arrays [10], smart, programmable or software defined metasurfaces [11], large intelligent surfaces (LISs), etc. Making their usage truly pervasive, programmable wireless environments could be created [12]. Proper models of their functionality or how they interact with EM waves still represent an active area of research. As in the case of the beamforming, RISs could be implemented as full-digital, hybrid or analogue architectures with both amplitude and phase or phase-only control. Quasi-continuous phase range or quantization could be selected as a function of the required complexity and power consumption specifications.

In the RIS model, the radiation pattern in azimuth and elevation should account for coupling of the RIS elements, which are typically located on a regular or triangular lattice with an inter-element distance between one-tenth and one-half wavelength. If the RIS is partially active, impedance matching and reflection losses can affect its performance. In the case of reflect and transmit arrays, for example, the scattering properties of the elements should be included in the model. The impact of the oblique incidence on the element performance is also an important parameter. More generally, this RIS model should be defined according to the EM properties of the chosen underlying technology (e.g., specific EM synthesis tools are needed to calculate the impedance modulation in case of metasurfaces). RIS geometry and periodicity, which impact the mutual coupling between its constituting elements, should also be taken into account and finely reflected. Finally, the method and electronics used to control the RIS beam (e.g., single frequency phase-shift, time delays, quasi continuous phase vs. quantized phase) shall be properly developed, while considering related hardware impairments (e.g., specific models for phase-shifters and other building tunable devices, including RF losses and limited resolution, active element performances). The model of the radio channel to and from a RIS, including the beamshape of signals, polarization effects, path loss, as well as joint angular and delay spread and how to control these require significant research efforts. Moreover, the interaction with new BS technologies and radio stripes is poorly understood.

An example of RIS based on transmit array technology is presented in Figure 2. This antenna is composed of a controllable flat lens with 20 × 20 elements and a spatial feed based on a 16-element Substrate Integrated Wave-guide (SIW) spatial feed [10]. (Right) Measured co-polarization beams (gain in dB) on the O°-azimuth cut-plane at broadside direction and scan angle of −20° as a function of the elevation angle and frequency.

**Opportunities:** Determining proper models requires a combination of skills, ranging from the EM theory to circuits. Since there are multiple RIS technologies and a RIS can act in transmit, receive, or reflect mode, there is no one size fits all model. What is common in all these models, however, is the dependence on location, orientation, and extent of the RIS, leading to clear opportunities to reuse the models for localization purposes, where each specific models of RIS may present different opportunities to improve localization and mapping. In addition, if models are to be used for localization and mapping, they should be spatially and temporally consistent and account for the locations and orientations of all relevant objects (both passive and active).
Near-field Propagation

**Challenge:** Beyond the Fraunhofer distance, signals are in far-field so that the plane wave assumption holds. The near-field region is proportional with the surface area of the RIS, so that a 20 cm × 20 cm RIS has an 8 meter near-field region at a wavelength of 1 cm. Hence, even at moderate distances to the RIS, near-field propagation occurs, leading to wavefront curvature, which must be properly modeled and accounted for in the communication system. This affects both RIS and channel modeling as well as RIS channel estimation and control.

**Opportunities:** As regards to near-field propagation, the wavefront curvature (see also Figure [1]) can be harnessed to reduce the need for infrastructure or synchronization. The AOA from a near-field signal provides information about both the angle and distance to the RIS, so that in combination with TOA it is possible to determine unknown clock biases and/or to improve ranging through redundancy. The TOA observable by an array of elements, possibly asynchronous and non-coherent to the transmitter itself, can also be exploited directly in terms of spherical wave localization [13]. This exploitation requires novel dedicated signal processing methods, as well as possibly new signal designs that can maximally harness the near-field properties. The specific properties of different RISs (e.g., their size) can be used in near-field multipath-aided positioning and to simplify data association in SLAM.

Channel Estimation

**Challenge:** In communication, for the purpose of detection, phase adjustment, or precoding, RIS channel estimation is needed in receive, reflect, or transmit mode, respectively. As a RIS may have limited processing capabilities and, under reflect mode, may have no or few RF chains, such channel estimation to and from the RIS is challenging [4]. For instance, in [14], a protocol is proposed to separately estimate the LOS and RIS channels, by activating the RIS with different phase patterns while sending pilots leading to delays. Channel estimation in receive mode is arguably not well understood, with, e.g., [13] analyzing the impact of channel estimation errors, but not proposing a channel estimation routine.

**Opportunities:** At high carrier frequencies, the channel response is sparse and depends mainly on the geometric configuration of UE, BS, and the environment (including the RIS). Hence, the sparse channel properties can be leveraged in the process of channel parameter estimation by resorting to compressive sensing (CS) methods [4]. The estimated channel parameters in turn help to determine the user location by following the geometrical relationship. Prior location information of the UE and the RIS location and orientation could be used as a replacement for channel state information (CSI). In other words, the geometric information could be converted to partial CSI or to CSI statistics. For instance, the end-to-end compound channel can be determined a priori as a function of the UE location through machine learning techniques. As the UE location is generally only statistically known, this uncertainty should be reflected in the CSI uncertainty accordingly. Hence, suitable Bayesian methods are needed to provide this mapping.

Nevertheless, the compound channel still needs to be estimated at the receiver side, in order to extract the AOA, AOD, and TOA of each propagation path (or cluster), as well as their respective spreads.

Signaling and System Architecture

**Challenge:** Localization can be performed in uplink or sidelink (i.e., between two UEs). Uplink localization can benefit from richer measurements and more processing power at the BS side, while downlink localization can reuse high-power downlink pilots, localize multiple users simultaneously, and requires less UE power. Sidelink signals can be used for relative localization, both in a bistatic and a monostatic configuration. No matter which modality is chosen, control and feedback signals need to be provided among all network entities. Calibration and synchronization signals are needed for maintaining the reference. For example, similarly to non-RIS based localization, multiple-way ranging protocol transactions may be needed to remove clock bias and the relative drifts and convert TOA estimates per path into absolute time of flight information. These signals can be performed over the air or via wired links between the infrastructure elements. Finally, fine a priori location and orientation information of RIS is needed to support localization.

**Opportunities:** The design of signaling protocols and the trade-offs of uplink, downlink, and sidelink RIS-aided localization are still unknown and remain largely unexplored in the research community. A possible architecture with corresponding signal flow in depicted in Figure [3] The estimated UE location information can be re-injected to refine the RIS setting and selection to further improve the next localization steps. As RISs are expected to often operate with obstructed LOS, localization and mapping methods can support communication by providing the system with prediction of the future LOS conditions.

RIS Control

**Challenge:** RIS control refers to adjusting the surface impedances to steer the beams. Efficient RIS control depends on the connection to other network elements and related communication latency constraints. The material and hardware properties will set practical limits to the accuracy and speed of the phase shift control, which is in practice often quantized to finite accuracy. This may easily lead to combinatorial optimization problems. The control mechanisms and material properties have an impact on the RIS power consumption and thereby the overall system energy efficiency. All this raises research questions on how frequent the control can and should be updated (e.g., frame level or symbol level). The RIS could be used as a type of relay (typical use), but also as a transmitter or as a receiver, all of which have distinct implications for localization. Finally, different RIS use cases of transmit/receive antenna or a reflector pose their own control challenges.

**Opportunities:** In contrast to communication, localization and mapping applications can be supported with low update rates, related to physical movements of the UE and environment, and hence infrequent RIS control. Each RIS with known
For a RIS transmitter, signal design remains an unexplored area, while for a RIS reflector, preliminary results indicate the potential of dedicated designs. Figure 4 shows the performance of different codebooks at the UE and RIS, where a hierarchical codebook brings promising performance in terms of mean squared error (MSE) with low training overhead and approaches the exhaustive search with highest resolution codebook even in the low SNR regime.

**Localization and Mapping Algorithms**

**Challenge:** Recovery of the user’s position and the map of the environment is based on the multipath signal information. As signal paths parameterized by their angles and delays have no identifier of the corresponding source, this process also involves a data association of the detected paths to RIS as a priori location, provides an additional source of information.

**Challenge:** The CSI or its proxy via location information needs to be converted to the design of precoding at the BS, beamforming at the RIS, and combining at the UE. As in standard mmWave communication, the design should be robust to account for location estimation errors, which include both position and orientation. In addition, finite quantization of the RIS phases, which enables low-power low-complexity control as mentioned above, adversely limits the flexibility of the codebooks that can be used. The signal design at the BS should also account for the presence of the RIS and availability of LOS path. Similar to standard position reference signals in LTE and 5G, dedicated signals can be designed for localization with and without RIS. Such joint designs involve both signals at the BS as well as the codebooks at the RIS, and should be sufficiently flexible to support accurate angle or delay estimation. The uncertainty in the map and UE location can be accounted for through robust designs which may explicitly encode different levels of location uncertainty. For a RIS transmitter, signal design remains an unexplored challenge.

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well as passive objects in the environment. In the presence of clutter measurements and missed signals possibly due to directional beamforming, this is not an easy task. As the state of the user contains both the 3D position and 3D orientation, as well as a clock bias, a sufficient number of resolvable signal paths must be available, which can be enabled by proper RIS control. Finally, when the user and possibly also the RIS is mobile, dedicated tracking routines must be applied that include mobility models.

Opportunities: The use of RIS has clear benefits for localization and mapping algorithms, since their location and orientation are known a priori. While data association is still needed to separate RIS signal paths from non-RIS signal paths, the a priori information reduces the number of data association hypotheses and allows better localization of passive landmarks and of users. These benefits are present in monostatic as well as bistatic configurations, not only in terms of localization accuracy but also in terms of service coverage. As for algorithm design, various solutions have been put forward for multipath-aided localization or channel-SLAM. Those could be extended to the RIS context. Among such algorithmic proposals, the solutions based on Bayesian inference over factor graphs and message-passing techniques look particularly suitable and promising, given the complexity of the new RIS-based SLAM problem (i.e., with the necessity to resolve and process signal contributions from multiple heterogeneous sources, possibly within strongly asymmetric and/or cooperative system settings) [2]. Finally, proper algorithm design should include all aforementioned challenges in RIS localization and mapping to reap the full potential of the RIS.

Comparison of RIS and Passive Objects

To conclude this section, we compare in Figure 5 the theoretical error bounds for TOA-based localization over a canonical scene as a function of the actual UE location in five distinct scenarios: one BS and one “natural” scatter point, one BS and one passive reflecting surface, two BSs (each with 50% of the bandwidth), 1 RIS with a scatter-like model per element (Model 1), and 1 RIS with a reflector-like model per element (Model 2). Both RIS models are considered in the far field regime, for simplicity. Despite the use of a single RIS in our example, it is shown that the RIS exhibiting a behavior according to model 1 already provides limited – yet interesting – gains in terms of both coverage (resp. error), when compared to a single passive reflector (resp. a single passive scatterer). The use of a more advanced RIS according to model 2 could even lead to much better performance in terms of both coverage and errors, comparable with that of 2 active BS.

Conclusions and Outlook

We have argued that RISs can be beneficial for localization and mapping in terms of improved accuracy or extended physical coverage, provided the appropriate models and algorithms can be developed. Progress in this area is somewhat hampered by the immaturity of working assumptions and models, which would need further investigation and validations. Different visions of the RIS coexist today, depending on their technological maturity, leading to distinct physical behaviors (typically, in terms of end-to-end power loss over reflected paths), and, thus, distinct advantages and drawbacks with respect to localization and mapping. Beyond this, the actual feasibility of integrating and controlling the RIS at low cost, low power, low complexity and low overhead, and, possibly, the necessity to acquire side channels or prior UE location for optimal control, are still challenged by more conventional approaches such as deploying additional BSs.

The overall aim of this paper was to provide the reader with an up-to-date overview of the relevant problem applications and formulations or RIS-based localization and mapping, and to describe the main challenges in this field. Moreover, we provide a large number of prominent research questions, along with potential avenues of research to answer these questions. As we usher in the era of beyond 5G communications, we believe it is time to also consider beyond 5G or 6G localization. RISs can be a game-changer for both these applications and deserves attention from the communication, signal processing, propagation, and antenna communities.

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