Empowering Programmable Wireless Environments with Optical Anchor-based Positioning

Dimitrios Tyrovolas, *Member, IEEE*, Dimitrios Bozanis, *Student Member, IEEE*, Sotiris A. Tegos, *Senior Member, IEEE*, Vasilis K. Papanikolaou, *Member, IEEE*, Panagiotis D. Diamantoulakis, *Senior Member, IEEE*, Christos K. Liaskos, *Member, IEEE*, Robert Schober, *Fellow, IEEE*, and George K. Karagiannidis, *Fellow, IEEE*

***Abstract*—The evolution toward sixth-generation (6G) wireless networks has introduced programmable wireless environments (PWEs) and reconfigurable intelligent surfaces (RISs) as transformative elements for achieving near-deterministic wireless communications. However, as RIS capabilities advance with the addition of more reflecting elements, the need for high-precision user localization becomes increasingly critical, since inaccurate localization could lead to erroneous configuration of RISs. In this direction, this paper investigates the integration of RISs and optical anchors in PWEs, emphasizing the crucial role of ultra-precise localization in unlocking advanced electromagnetic functionalities. Specifically, we present an in-depth analysis of various localization techniques, both RIS-based and RIS-independent, while introducing the concept of empowering PWEs with optical anchors for enhanced localization precision. Our findings highlight that accurate localization is essential to fully exploit the capabilities of RISs, paving the way for future applications. Through this exploration, we contribute to advancing PWEs in line with 6G networks and improving service quality in next-generation wireless networks.**

***Index Terms*—Reconfigurable Intelligent Surfaces (RISs), Programmable Wireless Environments (PWEs), Light-emitting Reconfigurable Intelligent Surfaces (LERISs), Visible Light Positioning (VLP), Localization**

D. Tyrovolas is with the Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece, and the Technical University of Crete, Chania, Greece (tyrovolas@auth.gr)

D. Bozanis, S. A. Tegos, and P. D. Diamantoulakis are with the Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece (dimimpoz@auth.gr, tegosoti@auth.gr, padiaman@auth.gr).

V. K. Papanikolaou and R. Schober are with the Friedrich Alexander University, 91058 Erlangen, Germany (vasilis.papanikolaou@fau.de, robert.schober@fau.de).

C. K. Liaskos is with the University of Ioannina, Greece, and with the Foundation for Research and Technology Hellas (FORTH), Greece (cliaskos@uoi.gr).

G. K. Karagiannidis is with the Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece (geokarag@auth.gr).

The work of D. Tyrovolas was supported by the EU H2020 research and innovation programme 6G TransContinental Edge Learning (6GXCEL, GA 101139194). The work of D. Bozanis and G. K. Karagiannidis was implemented in the framework of H.F.R.I call "Basic research Financing (Horizontal support of all Sciences)" under the National Recovery and Resilience Plan "Greece 2.0" funded by the European Union – NextGenerationEU (H.F.R.I. Project Number: 15642). The work of S. A. Tegos and P. D. Diamantoulakis was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "3rd Call for H.F.R.I. Research Projects to support Post-Doctoral Researchers" (Project Number: 7280). The work of Robert Schober was partly supported by the Federal Ministry of Education and Research of Germany under the programme of "Souveran. Digital. Vernetzt." joint project 6G-RIC (project identification number: PIN 16KISK023) and by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under grant SCHO 831/15-1.

I. Introduction

The transition to sixth-generation (6G) wireless networks marks a significant leap in communications, introducing a multi-band framework that fosters intelligence, unlimited connectivity, and the seamless integration of the physical and digital realms through connected sensing and artificial intelligence (AI). Aligned with these ambitions, the concept of *programmable wireless environments (PWEs)* was introduced as a transformative approach for converting propagation environments into intelligent spaces capable of delivering wireless services with near-deterministic accuracy [1]. This transformation is achieved through the utilization of reconfigurable intelligent surfaces (RISs), which are programmable metasurfaces composed of individually controllable reflecting elements designed to manipulate electromagnetic waves and perform functionalities like beam steering, splitting, or absorption [1]. Specifically, RISs are thin, planar devices that interact with impinging electromagnetic waves on a macroscopic level, while on a microscopic level, they are hardware platforms enabling the software-defined adjustment of their reflecting capabilities. The process of configuring an RIS involves precisely tuning embedded active components, such as PIN diodes, to alter the electromagnetic response of each reflecting element. This fine-tuning shapes the RIS's scattering profile, allowing it to execute specific electromagnetic functionalities that directly impact the efficiency and precision of wireless services. Consequently, the ability to control wave propagation within the PWE underscores the pivotal role of RISs in enhancing the quality of service (QoS) and advancing 6G wireless network standardization efforts [2].

In the PWE paradigm, optimizing RIS configuration is critical for enabling 6G services, highlighting the need for novel methodologies that adapt the RISs' scattering diagrams to the network demands. Among the existing methodologies, codebooks emerge as a notably practical method, comprising pre-calculated optimal RIS configurations for specific scenarios, thereby facilitating rapid adaptation to network changes without the complexity associated with iterative optimization or extensive data training [3]. However, the effectiveness of this approach relies heavily on precise localization, as accurate inputs regarding the positions of the transmitter, RISs, and receivers are crucial for selecting the correct RIS configuration. Moreover, as RIS functionalities grow more complex with an increasing number of reflecting elements, the margin

TABLE I: Comparison of Localization Methods

Localization Method	Robustness to Multipath	Low Latency	Increased Complexity	Scalability	Data Privacy
Beam-Scanning [5]			✓		✓
Diffusion [6]		✓		✓	✓
Gridding [7]		✓	✓		✓
RF-Anchors [8]		✓		✓	✓
Camera-Based [9]	✓		✓		
Optical-Anchors [10]	✓	✓		✓	✓

for error narrows, making even slight localization inaccuracies critical as they can result in improper RIS configurations and degraded service quality. This requirement extends beyond simple applications, as these advanced RIS configurations must accurately direct electromagnetic waves to deliver precise and reliable services within the PWE. Specifically, the literature highlights applications like extended reality-radio frequency (XR-RF), where RISs direct RF wavefronts to the receiver, each corresponding to specific graphical outputs on the user's device, meaning that even minor errors can severely degrade QoS [4]. Thus, the integration of methodologies for accurate localization is crucial for enabling the full utilization of RIS capabilities and adaptation to network demands.

In this paper, we study the integration of RISs and light-emitting diodes (LEDs) as optical anchors within PWEs, emphasizing their crucial role in achieving precise localization, which is essential for unlocking advanced PWE services. Specifically, we provide a thorough analysis of various localization methods, including both RIS-based and independent approaches, to reveal their capabilities and limitations in PWEs. Based on this analysis, we propose a PWE architecture that incorporates multiple ceiling-mounted LEDs and light-emitting reconfigurable intelligent surface (LERIS) units, achieving widespread LoS coverage and high localization accuracy, allowing the user equipment (UE) to accurately determine its position by utilizing the available LEDs. Importantly, a LERIS uses optical technology for localization while continuing to manipulate RF wavefronts, thus maintaining its core functionality in the RF domain and significantly increasing the localization accuracy required for sophisticated electromagnetic operations. In addition, we propose two optical-based localization methodologies, the received signal strength (RSS) method and a hybrid RSS/angle of arrival (AoA) technique, which are integrated into a comprehensive framework that effectively coordinates the available optical anchors and RISs to ensure precise localization and service delivery within the PWE. Finally, through detailed simulations, our work demonstrates the necessity of high-precision localization to offer novel PWE services, as well as the effectiveness of the proposed LED-empowered PWE architecture.

II. A Roadmap to Precise Localization for PWEs

To ensure effective PWE operation, the development of precise localization techniques becomes vital, especially as we advance the capabilities of RIS to facilitate intricate electromagnetic functions. To address this need, the development of locate-and-then-configure (LATC) schemes should incorporate advanced localization strategies to select the optimal RIS configurations from a comprehensive codebook, which is a data structure that maps RIS functionalities to specific configurations. This intricate relationship between RIS functionalities and localization precision underscores the categorization of LATC schemes into those that are based on specific RIS functionalities and those based on external localization systems, demonstrating the range of available methods for accurate localization in PWEs that also align with the dynamic requirements of 6G networks. The strengths and limitations of these methods in terms of robustness to multipath effects, latency, complexity, scalability, and data privacy are further detailed in Table I.

A. RIS-Based Localization

The strategic deployment of RISs throughout the PWE unlocks new paths for enhancing localization through RF wavefront manipulation. Guided by codebooks, the operation of RISs lays the groundwork for creating functionalities for localization that can outperform traditional systems, eliminating the necessity for direct line-of-sight (LoS) between access points (APs) and UE. Such flexibility allows the UE to employ angle of arrival (AoA), received signal strength (RSS), and time difference of arrival (TDoA) based methods for location determination exploiting RISs, with subsequent steps involving reporting their location to the network [11]. Therefore, the unique capabilities of RISs necessitate the exploration of different functionalities designed for UE localization.

- **Beam Scanning**: This functionality employs RISs to dynamically generate directional beams across the entire service area, aiming to detect UEs by sweeping the space with directional beams, thus bypassing the need for direct LoS between the AP and the UE [5]. However, beam scanning involves a trade-off between the latency induced by the highly directional beams required for scanning the whole space, and faster but less precise location estimation provided by broader beams. Furthermore, as the PWE expands, beam scanning requires additional RISs with enhanced capabilities for coordinated beam steering over larger areas, compounded by the need for advanced control systems for beam management and synchronization to adapt to UE movement and environmental changes. This increases complexity, as ensuring coherent RIS operation requires strict calibration and alignment to maintain accurate coverage and avoid overlaps or

gaps. Therefore, while beam scanning is an innovative functionality for UE localization in PWEs, its practicality is closely linked to managing the trade-off between scanning coverage and operational latency, underscoring the challenges of achieving optimal localization performance.

- **Diffusion**: In a PWE where multiple RISs are strategically deployed, we can facilitate accurate positioning by homogeneously diffusing electromagnetic waves to enable trilateration at the UE [6]. In this method, the RIS elements are configured to uniformly diffuse the incoming signals, creating a uniform wavefront distribution that the UE can use to determine its location by measuring distances from multiple known points. However, this strategy faces challenges, such as the necessity for multiple RISs with a LoS to the UE, which increases deployment costs and operational complexity. Moreover, the effectiveness of diffusion is influenced by the potential for increased multipath effects due to the wide and indiscriminate reflection of signals across the environment, ultimately reducing the precision of the localization process. Thus, while the diffusion approach offers a novel RIS-based localization strategy, its successful implementation depends on careful RIS placement and the existing scatterers.
- **Gridding**: The gridding functionality in the PWE framework leverages RISs to segment the service area into distinct grids, each characterized by unique RSS values, thereby directly correlating the UE position with the RSS value it encounters [7]. However, this innovative approach requires high precision for optimal signal distribution across grids, which is further complicated by the necessity for significant RSS differentiation between adjacent grids for accurate position identification. Moreover, ensuring uniform gridding performance in dynamic environments requires extensive coordination among multiple RIS units and regular codebook updates, in response to environmental changes. Consequently, while gridding is considered a novel strategy for localization in PWEs, its successful deployment depends on overcoming the mentioned technical challenges.

B. RIS-Independent Localization

Despite the promising capabilities of RIS-based localization strategies, their full potential in PWEs is constrained by hardware limitations that prevent precise wavefront manipulation and multipath effects arising from uncontrolled transmissions that do not impinge upon the RISs, leading to reduced localization accuracy. Consequently, independent localization systems that are dedicated to accurate positioning can prove critical for PWEs to dynamically and accurately adapt to user-specific needs, by enhancing the accuracy and robustness of RIS configurations in complex environments. To this end, it becomes imperative to explore independent systems to achieve effective localization, and thus PWE adaptability to dynamic network requirements.

Building on this, RF anchors constitute a traditional independent localization system, leveraging four RF nodes to maintain direct LoS with the UE and employing RSS-based trilateration for localization. The inherent simplicity and direct communication of this approach facilitate fast and scalable localization, which is critical for real-time applications [8]. However, its dependency on uninterrupted LoS paths poses significant challenges in environments with dynamic obstacles or dense structures. Additionally, while RF anchors operate independently of RISs, their presence in the environment can affect wave propagation and scattering, requiring carefully designed configurations to mitigate multipath effects and maintain localization accuracy, thereby illustrating the complexity of effectively integrating RF anchors into PWEs.

To fully unlock the potential of PWEs and align with the multi-band vision of 6G networks, developing localization solutions that resist multipath effects and do not rely on specific RIS configurations is crucial. In this direction, optical wireless stands out as a viable technology, promising precise localization without RF spectrum interference issues or spectrum saturation. Specifically, advances in cameras and image processing techniques over the past decade have enabled highly accurate and robust localization capabilities [9]. However, the practical application of camera-based methods faces several challenges, including the need for adequate illumination to ensure effectiveness, increased latency due to the complexity of processing image data, and privacy concerns related to the potential collection of sensitive information, as opposed to methods that process electromagnetic signals without capturing identifiable visual data. Moreover, camera-based localization exhibits significant hardware demands, like high-resolution cameras for various lighting conditions, powerful processors for real-time analysis, and adequate storage. Therefore, addressing these challenges necessitates a thorough assessment of camera-based localization requirements and the potential to create a system leveraging optical frequencies without the limitations of camera-based approaches.

III. Optical Anchors in PWEs

In the effort to incorporate accurate localization in PWEs, the use of LEDs as optical anchors emerges as a strategic approach for configuring the available RISs, offering several critical advantages. Unlike RF-based approaches, which can suffer from multipath issues, optical anchors leverage their primarily LoS channel to deliver accurate location data with minimal computation, thereby enhancing the reliability of communication in PWEs [10]. Moreover, the integration of LED-based systems into existing lighting infrastructure meets the diverse and growing needs of PWEs, providing a scalable, energy-efficient solution that supports sustainable network operations. This wide beam coverage ensures that precise localization can be maintained even when users are mobile, eliminating the need for complex real-time adjustments, while the process can be conducted for all users simultaneously. Additionally, the inherent privacy offered by optical anchor-based localization, which relies on signal strength and photodetector arrays rather than visual data collection, addresses privacy concerns that are increasingly relevant in the era of ubiquitous computing. Therefore, developing a well-defined PWE architecture that incorporates optical anchors not only addresses these critical needs but also paves the way for a holistic localization strategy that meets the stringent requirements of 6G networks.

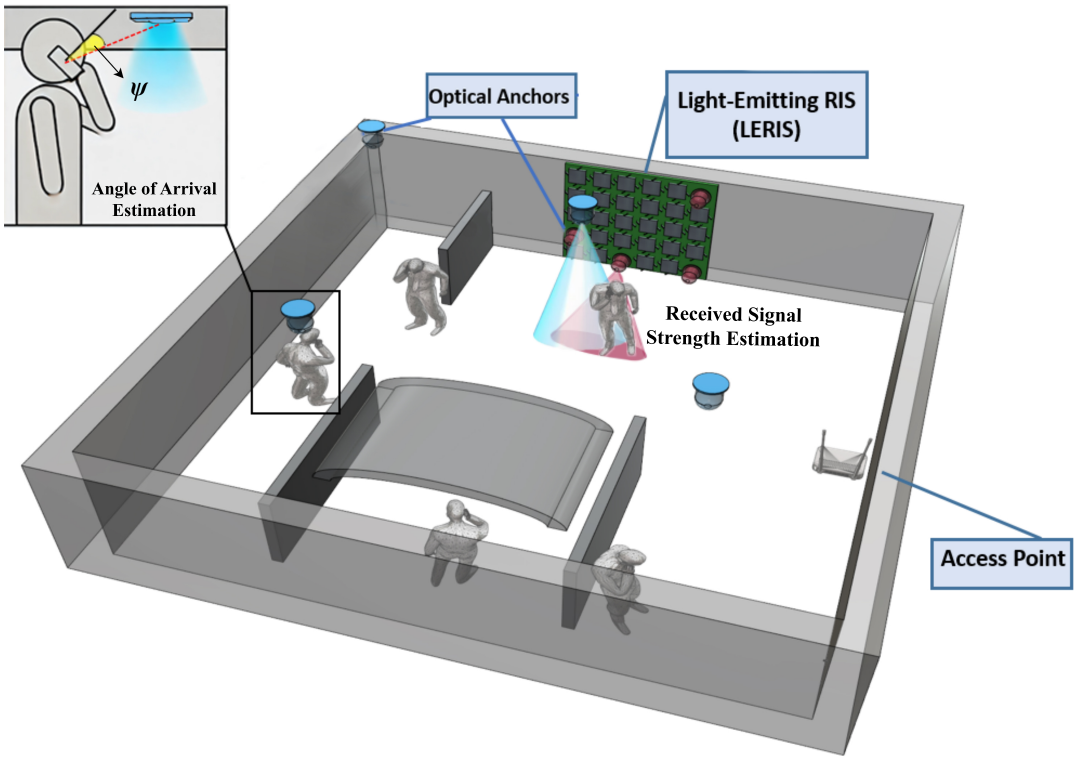


Fig. 1: Overview of an empowered PWE with optical anchors.

A. Integrating Optical Anchors in PWEs

Given that LoS between optical anchors and the UE is essential for accurate localization, achieving comprehensive LED coverage in PWEs is a significant challenge. To address this, given the need to arrange the optical anchors to accommodate different lighting conditions and receiver orientations, we propose to deploy multiple LEDs on the ceiling and on the available RISs, as shown in Fig. 1. Each LED emits at a unique frequency in the IR spectrum to minimize interference and is coordinated by a central node using contention-free multiple access protocols, wavelength division multiplexing with optical filters at the receivers to prevent inter-channel interference, or a multiple-input multiple-output (MIMO) configuration. As a result, the network adapts to UE movement by combining the received information from multiple available optical anchors, improving localization accuracy through dynamic LED selection.

By leveraging the strategic placement of RISs to provide ubiquitous functionality, an innovative solution aligning with the LED-empowered PWE is the utilization of LERISs. As shown in Fig. 1, this design involves equipping each RIS with four IR LEDs, each emitting at a unique frequency, that are directly coordinated by the RIS controller. As each LED emits an identifiable signal to the receiver, it becomes possible for the UE to accurately determine its position and orientation with respect to the RIS by using the unique emitted optical signal profiles. This eliminates the dependency on ceiling optical anchors, which may be blocked. As a result, LERIS represents a seamless integration of optical and RIS technologies, marking a significant advancement in the development of compact, efficient and accurate localization systems, perfectly aligned with the PWE vision.

Among the key localization techniques enabled by optical anchors is the RSS method, which requires the simultaneous illumination of the UE by at least four LEDs, laying the groundwork for trilateration. This approach imposes minimal computational demands on the UE, highlighting its efficiency and simplicity as a localization strategy. Furthermore, by carefully placing the LEDs in the PWE, the orientation of the UE can also be determined, reducing the need for additional receiver-side devices to acquire orientation. However, if increased localization precision is required, a hybrid approach that combines RSS with the AoA technique can be used to improve localization performance. Specifically, this approach distinguishes LoS components by their unique intensities and receiving angles using the receiver's photodetectors (PDs) to detect variations in signal strength and arrival times due to the unique signal paths between an LED and each detector. Consequently, by calculating the AoA based on the spatial distribution of the PDs, accurate UE localization is enabled by mitigating the effects of non-LoS signals even in scenarios where only a single LED maintains LoS with the UE. However, it should be emphasized that this localization method requires the receiver to be equipped with multiple PDs to ensure angular diversity.

To further clarify the capabilities of the proposed PWE architecture, we refer to Fig. 1 and delineate the discrete scenarios involving the depicted UEs, demonstrating the adaptability of the proposed architecture to different localization needs in the PWE. More specifically, the localization of UE 1 is achieved via the ceiling LEDs, while the position of UE

2 is determined through the LERIS, illustrating the innovative approach of using the LERIS for areas not covered by ceiling LEDs. Additionally, in scenarios where a UE is illuminated by more than 4 LEDs, such as UE 3 and UE 4, the flexibility of the architecture is demonstrated as the UE selects the four highest RSS values to achieve accurate localization, leveraging the strength of multiple optical anchors. Finally, UE 5, experiencing a LoS channel with only a single LED, requires the application of the hybrid RSS/AoA method, highlighting the architecture's ability to adaptively apply different localization techniques based on the UE's specific situation. This versatility highlights the ability of the proposed PWE in Fig. 1 to accurately localize users under different conditions, validating its effectiveness in adapting to the dynamic and complex requirements of 6G networks.

B. Optical Anchor-based LATC Scheme

After integrating optical anchors into PWEs, it becomes feasible to offer enhanced PWE services through an optical anchor-based LATC scheme. This innovative approach takes advantage of the unique characteristics of optical anchors to ensure precise localization and seamless interaction between the UE and the PWE, unlocking the full potential of PWEs in the evolving context of 6G networks. This strategy not only ensures optimal service delivery but also provides a solid foundation for the cooperative operation of RISs and optical anchors, thereby increasing the overall efficiency of the PWE.

The proposed LATC scheme presented in Algorithm 1 starts with the AP broadcasting a beacon signal to announce the availability of the PWE, prompting UEs within it to select their desired PWE services and define the required QoS parameters. In this context, "desired PWE service" refers to the services requested by the UEs, such as wireless charging or immersive gaming, while "required QoS parameters" include the performance characteristics necessary to satisfy the UE requests, such as data rate and latency. This initiates the localization process, where UEs calculate the number N of LoS optical anchors available to them by analyzing received optical signals, which involves interpreting the unique intensity profiles of each optical anchor, a critical step in selecting the most appropriate localization method. When $N < 4$, meaning that there are not enough LoS paths for complete RSS localization, the localization error can become large. In this case, the UE employs the combined RSS/AoA method if the receiver is equipped with more than one PD, ensuring precise localization [12]. In contrast, if $N \geq 4$, the UE is presented with the option to utilize either plain RSS or again a combination of RSS and AoA to achieve the desired level of localization precision as dictated by its chosen QoS. Subsequently, the UE reports its location p to the AP by configuring the available RISs as randomly reconfigurable surfaces to ensure broad transmission of signals across the PWE without requiring prior knowledge of the UE's location [13]. Upon receiving this information, the PWE meticulously selects the optimal RIS configuration through the available codebooks to match the reported location and the requested services.

Algorithm 1 LATC Scheme based on Optical-Anchors

```
Broadcast message to UEs advertising the existence of PWE
Select PWE service and define QoS parameters.
Calculate number of optical anchors N that can serve each UE
for Each UE do
    if N < 4 then
        Employ the RSS/AoA method.
    else
        Choose the 4 higher RSS values.
        Choose localization method based on QoS.
    end if
end for
Set RISs to operate as Randomly Reconfigurable Surfaces.
Transmit UE location p to AP.
Dynamically select optimal RIS configuration using p and requested service.
```

Following the initial configuration, the PWE can employ a dynamic feedback loop designed for real-time optimization, continuously adapting to changes in the UE position or the environment. This mechanism involves regular recalibration of the optical anchor setup and periodic updates to the codebook based on collected performance metrics. Such adjustments ensure the PWE remains responsive to dynamic user requirements and environmental variations, maintaining high levels of PWE performance.

C. Preliminary Results

As we explore enhanced electromagnetic functionalities, the need for RISs with a large number of reflecting elements, M, becomes crucial to improve the accuracy of wavefront manipulation. For instance, the beam-steering functionality shown in Fig. 2 is an example where precise localization is essential to ensure the correct delivery of demanding services like wireless charging. In more detail, Fig. 2 illustrates the variation in the scattering diagram of an RIS performing beam-steering for different numbers of reflecting elements. As can be observed, the directivity of the RIS increases with M, so that the half power beam width (HPBW) θ decreases from 18^o for an RIS with 50 elements to 10^o for 100 elements, and further to 2^o for an RIS with 1600 elements. This observation underscores the need for high-precision LATC schemes in PWEs since as the required RIS capabilities become more detailed, the margin for localization errors decreases significantly. To further emphasize this point, Fig. 3 illustrates the tolerated localization error σ_p, defined as the maximum permissible displacement of the UE in θ and is equal to the product of $\tan\left(\frac{\theta}{2}\right)$ and the RIS-UE distance. As shown, σ_p diminishes with more reflecting elements, emphasizing the critical role of precise localization in PWEs to capitalize on the advanced capabilities of larger RISs, ensuring accurate delivery of RIS electromagnetic functions to the intended UEs. This relationship between beam steering and localization accuracy is also relevant to more complex functionalities, like beam splitting, which relies on multiplexing of simpler functionalities such as beam steering [14]. Therefore, the insights provided by Figs.

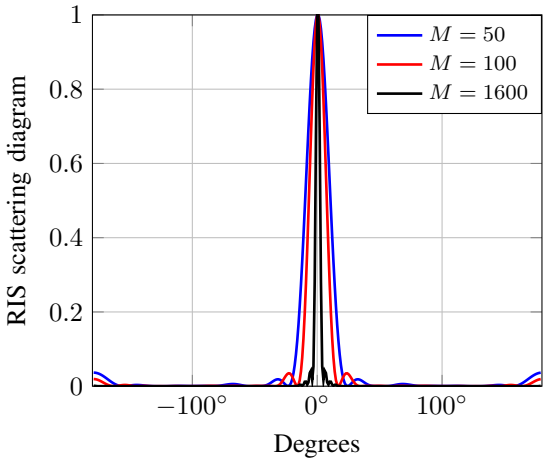


Fig. 2: Beam steering directivity versus number of reflecting elements.

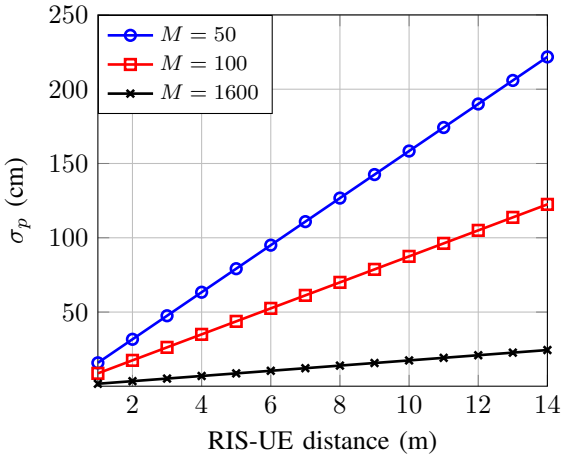


Fig. 3: Tolerated localization error σ_p versus RIS-UE distance.

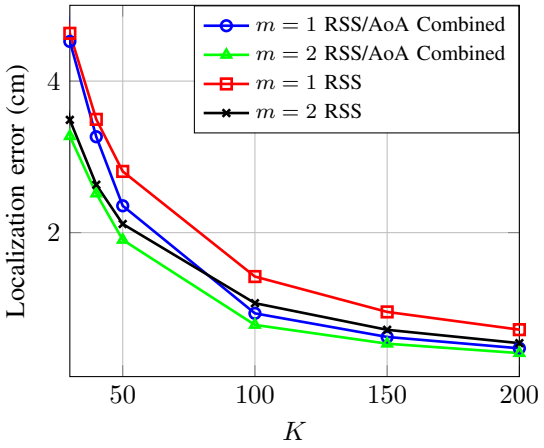


Fig. 4: Localization error of the proposed optical anchor-based methods versus K.

2 and 3 effectively demonstrate why precise UE localization is critical for both basic and advanced RIS functionalities.

Considering the pursuit of ultra-precise localization in PWEs, Fig. 4 shows the relationship between the localization error and the parameter K. Specifically, the localization error is defined as the difference between the estimated and actual position of the UE, while K is the Ricean parameter representing the ratio of the power of the LoS component to the non-LoS components in the optical channels over different Lambertian emission orders m, where m describes the directional characteristics of the emitted light. Considering that K typically exceeds 100 in practical optical channels, both the RSS and the combined RSS/AoA methods exhibit outstandingly low localization errors, exceeding the accuracy required even for RIS configurations with up to 1600 reflecting elements. This result strongly suggests that optical anchor-based localization can meet the stringent accuracy requirements of sophisticated RIS functionalities and underscores its critical role in the design of PWEs. Moreover, while increasing the directivity of optical anchors further refines localization accuracy, it is important to note that this improvement comes at the cost of reducing the illuminated areas, highlighting the need to balance anchor directivity and localization performance to optimize the PWE capabilities.

IV. Challenges and Future Directions

In the context of PWEs, the introduction of optical anchors presents both promising opportunities and significant challenges. This section explores the many challenges of seamlessly integrating optical anchors and provides insights into current limitations and potential avenues for future advancements.

A. Challenges

In the pursuit of efficiency in LED-based localization systems for PWEs, the placement of LEDs is crucial to ensure the pervasive presence of LoS signals throughout the PWE. This task entails a challenging optimization, considering multiple parameters, such as the field of view of the UEs. The situation is complicated further in scenarios lacking orientation extraction capabilities at the UE, demanding an LED deployment that provides strong LoS channels and avoids symmetries which could potentially complicate the location extraction, thereby offering both coverage and orientation information. Additionally, the integration of LEDs into the LERIS framework requires careful consideration of their compatibility with the metasurface, aiming to harmonize optical emissions with RF wave manipulation. This includes implementing advanced power routing protocols and thermal management strategies that are essential to dissipate the heat generated by the LEDs, ensuring that the heat emission does not compromise operational efficiency. By addressing these issues to fine-tune LED positioning for optimal LoS coverage, inaccuracies in UE localization that might result in suboptimal RIS configurations are minimized, ensuring the PWE maintains its service quality. Moreover, the spatial deployment of LERIS and ceiling LEDs introduces additional challenges, as their distribution must be strategically planned to ensure comprehensive coverage across all possible UE locations, particularly in complex PWEs where service requirements change dynamically.

Furthermore, misalignments in the placement of the trans-

miter and the RISs can profoundly impact performance, particularly in services requiring high directivity. Since codebooks are designed for specific location inputs, any deviation from these prescribed positions introduces a significant mismatch between the anticipated and actual signal paths. This misalignment can lead to substantial QoS degradation, as the beams fail to converge optimally toward the intended targets. To address such disparities, rigorous calibration procedures become imperative, through which, the PWE can adapt to the actual location inputs and compensate for misalignment. Thus, comprehensive calibration processes are paramount to harness the full potential of precise RIS functionalities, ensuring optimal PWE performance.

B. Future Directions

Despite current challenges, future directions aim to enhance system performance in line with 6G network demands, particularly through the synergy of RF and optical technologies, which opens avenues for improved localization precision in PWEs. Specifically, RF signals offer wide coverage and robustness to obstructions, while optical signals, with their finer spatial resolution and immunity to RF interference, can be utilized for both communication and localization, thus facilitating cost-effective solutions for hybrid localization systems and networks [15]. Finally, integrating these signals via sensor fusion techniques alongside developing new RIS configurations tailored for LED empowered PWEs, boosts the localization process centered on optical anchors. This comprehensive strategy ensures smooth transitions between localization schemes, fitting specific environmental needs or application demands, and highlights the combined potential of RF and optical frequencies in enhancing PWE efficiency.

Furthermore, central to the evolution of PWEs is the capability of AI to transcend current localization limitations. Specifically, AI can integrate RSS values from optical anchors with spatial data into a continuously updated spatial database, thus aligning RSS metrics with exact coordinates. This approach is notably effective given the LoS nature of optical frequencies, ensuring stable RSS values across locations and thus boosting PWE efficiency with optical anchors. Additionally, by utilizing advanced AI algorithms and the aforementioned spatial database, we can extract spatial information from non-illuminated areas, referred to as zero-power zones, and potentially foresee object movements or presences by extending mapping even to non-illuminated areas. Finally, exploiting historical data information in the proposed localization methods could significantly enhance performance, improving accuracy and reducing system complexity by narrowing the search domain, which reduces computational needs and maximizes efficiency and resource usage.

Finally, in PWEs, the imperative to accurately determine device positions without requiring active participation from UE necessitates the development of passive localization techniques. This need is particularly critical to support precise localization for devices with limited computational capabilities, such as IoT nodes. The complexity of this task is heightened by the challenge of discretizing the UE's antenna, especially as antennas become smaller to meet 6G requirements. Traditional localization methods, such as imaging, may struggle with smaller antennas, while RF techniques might necessitate wider beams, which could reduce the received power. To address these challenges, we propose advanced waveform manipulation as a promising solution to improve localization accuracy in these scenarios. By harnessing advanced signal processing techniques like waveform shaping and beamforming, these methods offer a pathway to achieving precise localization goals. Crucially, these techniques enable passive and simultaneous localization, ensuring seamless integration and optimal performance of PWEs across diverse UE scenarios.

V. Conclusion

In this paper, we have presented an in-depth investigation into the synergy between RIS and optical anchors in PWEs, aimed at achieving the high precision in localization required for unlocking the full potential of 6G network functionalities. Central to our exploration is the introduction of a newly proposed PWE architecture, equipped with multiple LEDs positioned on the ceiling and multiple LERISs, a design aimed at maximizing LoS signal coverage and enhancing localization accuracy across the PWE. Our results underscore the importance of precise localization, brought to the forefront by the integration of optical anchors, in improving the effectiveness of RISs across different frequency bands and, by extension, the overall performance of PWEs. This exploration not only contributes to the theoretical advancement of wireless networks but also provides a practical framework for future research in the field, paving the way for 6G networks.

References

[1] C. Liaskos, S. Nie, A. Tsioliaridou *et al.*, "A new wireless communication paradigm through software-controlled metasurfaces," *IEEE Commun. Mag.*, vol. 56, no. 9, pp. 162–169, 2018.

[2] R. Singh, A. Kaushik, W. Shin *et al.*, "Towards 6G evolution: Three enhancements, three innovations, and three major challenges," 2024.

[3] J. An, C. Xu, Q. Wu *et al.*, "Codebook-Based Solutions for Reconfigurable Intelligent Surfaces and Their Open Challenges," *IEEE Wirel. Commun.*, pp. 1–8, 2022.

[4] C. Liaskos, A. Tsioliaridou, K. Georgopoulos *et al.*, "XR-RF Imaging Enabled by Software-Defined Metasurfaces and Machine Learning: Foundational Vision, Technologies and Challenges," *IEEE Access*, vol. 10, pp. 119 841–119 862, 2022.

[5] F. Jiang, A. Abrardo, K. Keykhosravi *et al.*, "Two-Timescale Transmission Design and RIS Optimization for Integrated Localization and Communications," *IEEE Trans. Wirel. Commun.*, vol. 22, no. 12, pp. 8587–8602, 2023.

[6] A. Fascista, M. F. Keskin, A. Coluccia *et al.*, "RIS-Aided Joint Localization and Synchronization With a Single-Antenna Receiver: Beamforming Design and Low-Complexity Estimation," *IEEE J. Sel. Top. Signal Process.*, vol. 16, no. 5, pp. 1141–1156, 2022.

[7] H. Zhang, H. Zhang, B. Di *et al.*, "MetaLocalization: Reconfigurable Intelligent Surface Aided Multi-User Wireless Indoor Localization," *IEEE Trans. Wirel. Commun.*, vol. 20, no. 12, pp. 7743–7757, 2021.

[8] G. Han, J. Jiang, C. Zhang *et al.*, "A Survey on Mobile Anchor Node Assisted Localization in Wireless Sensor Networks," *IEEE Commun. Surv. Tutor.*, vol. 18, no. 3, pp. 2220–2243, 2016.

[9] V. Loscrí, C. Rizza, A. Benslimane *et al.*, "BEST-RIM: A mmWave Beam Steering Approach Based on Computer Vision-Enhanced Reconfigurable Intelligent Metasurfaces," *IEEE Trans. Veh. Technol.*, vol. 72, no. 6, pp. 7613–7626, 2023.

[10] D. Bozanis, N. G. Evgenidis, V. K. Papanikolaou *et al.*, "Indoor 3D Visible Light Positioning Analysis with Channel Estimation Errors," in *Proc. 30th Internat. Confer. on Systems, Signals and Image Processing (IWSSIP)*, 2023, pp. 1–4.

[11] T. Ma, Y. Xiao, X. Lei *et al.*, "Reconfigurable Intelligent Surface-Assisted Localization: Technologies, Challenges, and the Road Ahead," *IEEE Open J. Commun. Soc.*, vol. 4, pp. 1430–1451, 2023.
[12] H. Steendam, "A 3-D Positioning Algorithm for AOA-Based VLP With an Aperture-Based Receiver," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 1, pp. 23–33, 2018.
[13] S. A. Tegos, D. Tyrovolas, P. D. Diamantoulakis *et al.*, "On the distribution of the sum of double-nakagami-m random vectors and application in randomly reconfigurable surfaces," *IEEE Trans. Veh. Technol.*, vol. 71, no. 7, pp. 7297–7307, 2022.
[14] M. Segata, P. Casari, M. Lestas *et al.*, "CoopeRIS: A framework for the simulation of reconfigurable intelligent surfaces in cooperative driving environments," *Comput. Netw.*, vol. 248, p. 110443, 2024.
[15] D. Bozanis, V. K. Papanikolaou, A. A. Dowhuszko *et al.*, "Optimal Aggregation of RF and VLC Bands for Beyond 5G Mobile Services," in *Proc. 18th Internat. Confer. on Wireless and Mobile Computing, Networking and Communications (WiMob)*, 2022, pp. 75–80.

Dimitrios Tyrovolas (tyrovolas@auth.gr) [M] is a Post-Doctoral Research Fellow at the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece.

Dimitrios Bozanis (dimimpoz@auth.gr) [S] is a PhD Candidate at the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece.

Sotiris A. Tegos (tegosoti@auth.gr) [SM] is a Post-Doctoral Research Fellow at the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece.

Vasilis K. Papanikolaou (vasilis.papanikolaou@fau.de) [M] is an Alexander-von-Humboldt Post-Doctoral Research Fellow at the Institute for Digital Communications, Friedrich-Alexander-University Erlangen-Nuremberg (FAU), Erlangen, Germany.

Panagiotis D. Diamantoulakis (padiaman@auth.gr) [SM] is an Assistant Professor at the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece.

Christos K. Liaskos (cliaskos@uoi.gr) [M] is an Assistant Professor at the Department of Computer Science and Engineering, University of Ioannina, Greece, and the Institute of Computer Science, FORTH, Heraklion, Greece.

Robert Schober (robert.schober@fau.de) [F] is a Professor at the Institute for Digital Communications, Friedrich-Alexander-University Erlangen-Nuremberg (FAU), Erlangen, Germany.

George K. Karagiannidis (geokarag@auth.gr) [F] is a Professor at the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece.