Shedding Light on Joint Communication & Sensing

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***Abstract*—This contribution highlights the emerging importance of optical wireless communication (OWC) and optical fiber technologies focusing on their role in integrating communication and sensing functionalities in the evolution towards 6th generation (6G) wireless networks. Highlighting the transition to those technologies that not only facilitate data transmission, but also exhibit deep environmental awareness, we focus on the potential of optical wireless technology to enhance sensing and localization capabilities that are critical for the Internet of Things. The advantages of OWC, such as reduced interference, low latency, and high directivity, are outlined and its diverse applications in various sectors are discussed, such as smart cities, healthcare, industrial environments, and intelligent transportation systems. To support OWC, we envisage optical fiber as a complementary technology for joint communication and sensing, due to its unparalleled capacity for long-distance data transmission and its emerging role in environmental sensing. Addressing challenges and future research directions, the vision for adaptive and resilient networks that leverage the dual capabilities of OWC and optical fiber is presented, providing a comprehensive overview of how these technologies are pivotal in shaping the future landscape of wireless communications.**

***Index Terms*—Optical wireless communication (OWC), optical fiber, sensing, visible light positioning**

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I. INTRODUCTION

The current trajectory of wireless communication technology is steering us towards the next milestone—the sixth generation, or 6G, of networks. Historically, wireless networks have been at the forefront of providing robust mobile broadband and ever-increasing data rates. However, we are witnessing a transformative phase in the evolution of these networks—a phase that broadens the traditional focus from sheer data transmission to a multifaceted approach that includes sensing and localization functions [1]. These functions, previously on the margins of network design and capability, are now taking center stage. The era of the Internet of Things (IoT) requires networks that not only transmit data but also possess high awareness of their operating environment.

The ability to sense and localize is no longer optional but essential, especially as we progress toward interconnected environments such as smart cities and intelligent transportation systems (ITS) where autonomous interaction is key. Thus, with the introduction of 6G on the horizon, we anticipate the rise of a network ecosystem that transcends the data-centric models of the past. Based on this approach, 6G is envisioned to integrate intelligent functionalities—such as environmental sensing, precise object localization, and detailed spatial mapping—into the fabric of the network infrastructure. Such integration aims to transform passive networks into active systems capable of interacting with and adapting to their environment in real time. It is noted that this integration has already affected the standardization activities, including IEEE 802.11 [2]. In this regard, optical wireless communication (OWC) is expected to have an important role in these advanced functionalities of future communication networks.

In more detail, the integration of optical wireless (OW) and radio-frequency (RF) technology into hybrid networks offers a promising solution to the challenges of current and future communications needs [3]. OWC uses light-emitting diodes (LEDs) and lasers to transmit data and can offer advantages such as reduced interference and low latency, which are critical for real-time processing and rapid data transfer. A defining characteristic of this technology is its narrow beamwidth, which can significantly enhance angle-of-arrival measurements, making it ideal for applications that require pinpoint accuracy in localization efforts, such as indoor navigation systems, advanced robotics operations, and augmented reality scenarios. The potential applications for OWC are thus diverse and hold great promise for several sectors. In transportation, for example, it could revolutionize the way vehicles communicate with each other and with infrastructure, improving traffic flow and safety. In industrial environments, it could enable more accurate asset tracking, better process monitoring, and predictive maintenance through real-time sensing. In healthcare, the use of this technology could lead to improved patient monitoring systems, smarter management of medical devices, and improved delivery of care services. The convergence of OW and RF systems could further enhance these applications by leveraging the strengths of each technology. RF technology, with its proven long-range and obstacle penetration capabilities, complements the high speed and precision of OWC. By taking advantage of both optical and RF technologies, hybrid networks can provide robust, reliable, and highly accurate wireless communication solutions. Along with advances in wireless technologies, optical fiber has emerged as a powerful medium for joint communication and sensing (JCS), providing a complementary solution to hybrid OW and RF systems. Fiber optic technology is known for its unparalleled ability to transmit data over long distances with high bandwidth and minimal signal degradation. Beyond communications, these fibers can serve as distributed sensors capable of detecting temperature changes, pressure fluctuations and acoustic vibrations along their length.

In the context of JCS, research efforts can be categorized into two primary themes. The first theme revolves around the development of **networks that can simultaneously support communication and sensing functions**—enabling a single piece of infrastructure to handle multiple tasks, which can lead to cost savings and enhanced efficiency. The second theme is centered on **environmental-aware communications**, wherein networks use their sensing capabilities to augment their performance. By actively responding to environmental changes, these networks can maintain consistent service quality even when faced with disruptions or obstacles, making them self-optimizing and resilient.

This contribution aims to conduct a thorough examination of how the integration of OW technology with RF systems can improve the sensing and localization features intrinsic to wireless networks. We will discuss the research frontiers in simultaneous communication and sensing, as well as environment-aware communications, shedding light on the future possibilities for hybrid OW and RF technology. This integration is anticipated to reshape the landscape of wireless networks, transitioning them from passive channels of data to active entities aware of the ever-growing ecosystem.

II. COMPATIBILITY AND CONFLICT OF JCS

It is beneficial to identify the shared benefits and mutual conflicts of communications and sensing for the better understanding and designing JCS either in RF or OWC domains. The marriage of communications and sensing is justified due to many compatible benefits of them, such as [4]

- Reuse of bandwidth: The randomness in communications due to modulation spreads the spectrum and brings timing information (via the autocorrelation) for ranging. Therefore, the same bandwidth is leveraged by both functions.
- Common signal structure: The subcarrier structure of frequency spectrum in orthogonal frequency division multiplexing (OFDM) brings both flat-fading channels for communications and wideband benefit for OWC, thus making OFDM a possible common waveform shared by communications and sensing, despite new challenges such as subcarrier misalignment.
- Common benefit of multi-in-multi-output (MIMO): MIMO due to multiple antennas results in multiplexing, diversity, and beamforming for both functions.

The conflict is intensified in sensing that adaptively probes target features in different frequency bands, while the preference mismatches that of communications. The waveform preferences become more complex when other metrics of sensor, which determines the performance, are taken into account. This is due to the following reasons:

- Uncertainty: Sensing prefers carefully designed pseudo-random (deterministic) waveforms, over random waveforms. However, randomness is essential for communications, yielding a conflict on the waveform uncertainty.
- Multi-access in networks: There have been various mechanisms of multi-access, such as code-division multiple access (CDMA), orthogonal frequency-division multiple access (OFDMA) or carrier-sense multiple access (CSMA), in communications for combating interference. However, no similar regulation has been made in sensor networks. These conflicts, particularly intensified in networks, result in Pareto fronts characterizing the trade-off between communications and sensing.

III. OW 3D SENSING AND LOCALIZATION

The adoption of OW technology, particularly by leveraging the widespread use of LED lighting, has opened new horizons in the field of simultaneous communication and sensing. This innovative approach, rooted in the dual functionality of LEDs to illuminate spaces and transmit data, has been exemplified by recent studies focused on the development of centralized optical 3D positioning systems. Using visible light communication (VLC) or infrared (IR) techniques, these systems modulate the intensity of light emitted by LEDs to encode data and seamlessly integrate with the ambient lighting infrastructure to enable high-speed data transmission and accurate indoor sensing.

A characteristic example of this technology is the implementation of a centralized optical local positioning system, which underscores the system's ability to provide accurate 3D positioning [5]. This setup uses a minimum of two fixed receivers to triangulate the positions of mobile LEDs embedded in the environment, illustrating the potential for precise localization tasks. Such an architecture not only supports tracking and navigation of objects and people in indoor environments, but also enhances the robustness and scalability of the positioning system. The incorporation of geometric considerations into a non-linear least squares estimator further refines the accuracy of position estimates, demonstrating the effectiveness of the system in environments where precise navigation and object tracking are critical.

Another interesting technique in VLC-based sensing systems is the methodical altering of the color temperature of the LEDs, ranging from a warm reddish hue (2600 K) to a cool blueish light (6200 K), to detect the presence, position, and color of objects within the sensing area [6]. A key finding from this investigation is that while the color temperature of the

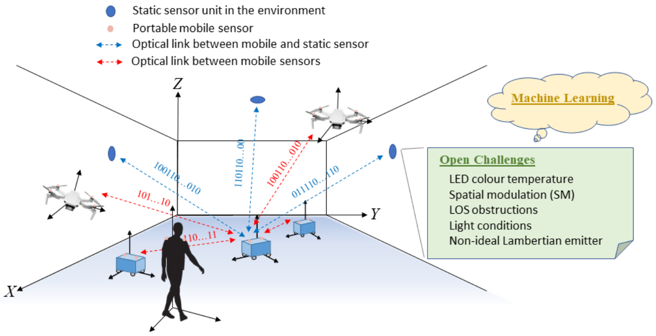

Fig. 1. Centralized optical local positioning system

LED does not significantly influence the system's capacity to estimate the position of an object, the differentiation of object color signatures markedly improves under white light with a high color rendering index. This distinction highlights the critical role that the quality of lighting plays in enhancing the performance of VLC-based sensing systems. By optimizing the color temperature for higher color accuracy, VLC systems can achieve more precise identification of object color signatures, demonstrating the potential of color temperature adjustments to refine the accuracy and reliability of OW sensing applications. This research not only contributes to the advancement of VLC technology but also opens new avenues for the application of such systems in diverse indoor monitoring and object sensing scenarios.

Also, it needs to be noted that the role of spatial modulation (SM) in JCS, particularly within the framework of OW technologies, emerges as a pivotal innovation in the proposed three-dimensional (3D) indoor visible light positioning (VLP) algorithm [7]. This novel approach significantly deviates from conventional methods by leveraging the spatial characteristics of light for both communication and precise positioning, showcasing a remarkable enhancement in efficiency and accuracy. By estimating optical channel gains between LEDs and photodetectors through a pilot-based technique, and subsequently employing trilateration algorithms for position determination, the SM-based VLP system circumvents the limitations observed in received signal strength (RSS)-based systems. Notably, this method achieves interference-free transmission and heightened spectral efficiency without necessitating demultiplexing at the receiver, marking a substantial leap in the realm of indoor positioning systems. The implementation of SM not only ensures a more accurate 3D positioning by refining distance measurements through pilot-aided channel estimation but also addresses the challenges of transmission data rate constraints, all while significantly reducing positioning errors in challenging indoor environments as validated by comprehensive computer simulations. This advancement underscores the transformative potential of SM in enhancing the synergies between communication and sensing capabilities in OW systems.

However, the use of OW technologies for communication and sensing also faces several challenges. The line-of-sight (LoS) requirement between transmitters and receivers introduces limitations in environments with potential obstructions. In addition, system performance can be affected by ambient light conditions, which can introduce noise and degrade signal-to-noise ratio (SNR). These challenges require further research and optimization of the system's design and deployment strategies to improve its reliability and efficiency in various indoor environments.

Another important challenge is that the ideal assumption of a perfect Lambertian emitter often fails in practice due to factors like imprecise LED placement and environmental conditions, impacting the accuracy of OW systems. In reality, deviations in LED alignment and emission characteristics can alter expected signal distributions, affecting localization and sensing performance. Machine learning (ML) presents a robust solution to mitigate these discrepancies by adapting to the unique behaviors of LEDs and their environments. By leveraging data on actual signal patterns and positions, ML algorithms can correct for non-ideal emitter characteristics, significantly enhancing system accuracy. This adaptability enables OW systems to dynamically adjust to real-world conditions, improving their ability to accurately triangulate positions and maintain high performance over time.

IV. SENSING-AWARE PROACTIVE RESOURCE ALLOCATION IN HYBRID NETWORKS

As it was mentioned previously, the hybrid network paradigm can benefit from both OW and RF technologies, since each offers its own advantages. In these hybrid networks, that integrate OW and RF, proactive resource allocation emerges as a sophisticated strategy to maximize network performance. In such networks, the use of OW technology for both communication and localization provides accurate knowledge of the user's position, which can be critical for efficient resource allocation. By integrating this location data, a network can proactively allocate RF and OW resources to optimize user experience and network efficiency.

This approach is particularly beneficial in scenarios where users are mobile and their channel state information (CSI) can quickly become outdated. For example, in a room where both VLC/IR and RF are deployed, the RF provides extensive coverage, while the VLC provides high-speed data transmission within a limited area. The user's mobility may cause him to move out of the VLC coverage area, which, if not proactively managed, could lead to service interruptions and suboptimal resource allocation. By predicting user movement and adjusting resource allocation in real time, the network can ensure consistent quality of service.

The concept of proactive resource allocation in such networks is based on anticipating the user's position and using this foresight to allocate resources before the CSI becomes outdated [8]. This approach is particularly beneficial at the edge of the VLC coverage area. Here, users may experience dropped service if the system relies solely on reactive resource allocation strategies based on delayed CSI. By using a proactive model, hybrid networks can dynamically adjust the allocation of VLC/IR and RF resources to where they are most needed, improving the overall reliability and efficiency of the network. This proactive resource management is critical to maintaining seamless connectivity in dynamic environments where users are constantly on the move.

To this end, RF and optical reconfigurable intelligent surfaces (RISs) can play a transformative role in addressing the challenges of proactive resource allocation in hybrid VLC/RF networks. These technologies offer novel ways to manipulate electromagnetic and optical waves, respectively, to enable more precise control of the propagation environment. This capability can significantly improve network adaptability and performance, especially in dynamic scenarios where user locations and connectivity needs change rapidly. In addition, the use of RIS technologies can contribute to the development of more sophisticated resource allocation algorithms. With the ability to gather detailed information about the propagation environment and user positions, RISs could enable more accurate and timely resource allocation decisions, further enhancing the network's ability to proactively manage connectivity for a wide variety of users and use cases.

Implementing proactive resource allocation in hybrid VLC/RF networks presents several challenges due to the dynamic nature of wireless communication environments and the complexity of integrating different technologies. One of the primary hurdles is accurately predicting user mobility in order to anticipate their future location and, consequently, their connectivity needs. This challenge is compounded by the variability of human movement patterns and the diversity of indoor environments, which can include obstacles that affect signal propagation. In addition, the need for real-time processing and decision making to update resource allocation based on these predictions increases the computational burden on the network infrastructure. There is also the issue of balancing the allocation of VLC and RF resources to optimize network performance without sacrificing quality of service for each user, especially at the edges of the VLC coverage area where the risk of service interruption is higher. Ensuring seamless handovers between VLC and RF systems and minimizing the impact of outdated CSI further complicates the resource allocation process, requiring sophisticated algorithms that can adapt to rapidly changing conditions.

A closer look at the challenges of proactive resource allocation reveals that achieving an accurate understanding of user mobility patterns is not only about tracking movement, but also about interpreting those patterns in the context of varying indoor environments. Each environment presents unique obstacles and user behaviors that can significantly impact signal coverage and thus the effectiveness of resource allocation strategies. In addition, the integration of VLC/IR and RF technologies, while beneficial, introduces the complexity of managing different types of resources that have different propagation characteristics and limitations. This requires advanced algorithms capable of making split-second decisions to dynamically reallocate resources as users move and network conditions change. These algorithms must not only be efficient, but also scalable to accommodate a wide range of network scenarios and user densities. Managing the latency between identifying the need for resource reallocation and implementing these changes is also critical to preventing data transmission delays and maintaining quality of service. Overcoming these challenges requires innovative approaches to network design and management, including the development of more sophisticated predictive models and the use of artificial intelligence (AI) to improve real-time decision making.

V. FIBER OPTICS IN LONG-DISTANCE SENSING

In the field of fiber optics, the combination of communication and sensing technologies has the potential to have a significant impact on several areas, including environmental monitoring and infrastructure security. Known for its ability to efficiently transmit data over long distances, fiber optics is now being explored for its sensing capabilities. Single-mode fiber optic cable, widely used in residential and commercial applications and even in remote areas such as Mount Everest, exemplifies the widespread use and potential of fiber optics [9]. While these fibers are primarily used for telecommunications, they can also function as sensors by taking advantage of their ability to detect environmental changes. The fibers typically operate in the 700-1800 nm wavelength range, which is a compromise between covering a wide range of applications and managing costs, highlighting the practicality of extending fiber optic applications beyond simple data transmission.

The application of AI and ML to fiber optic sensing technologies marks a significant advancement in their capabilities. AI and ML can greatly improve the accuracy and efficiency of fiber optic sensors, enabling the detection of small environmental changes or the monitoring of structural conditions with a level of precision previously unattainable. This combination not only improves sensor performance, but also expands the range of potential applications, from managing agricultural production to observing weather patterns and tracking natural phenomena such as avalanches or glacier movement. One of the key advantages of fiber optic sensors is their ability to operate without an external power source at the sensor site, making them ideal for use in hard-to-reach or unsafe locations.

In addition, the practicality of using fiber optic sensors is a significant advantage, as sensors with no moving parts are preferred for their reliability and durability, which are critical for monitoring tasks in inaccessible or challenging environments. The ability to deploy and leave these sensors without ongoing maintenance, along with their ability to operate over distances ranging from a few to over a hundred kilometers, provides a viable solution for a wide range of surveillance activities. Whether it is tracking human movement in remote areas, searching for people lost in the mountains, or monitoring the environment, fiber optics is a powerful and flexible technology that effectively combines communication with sensing to provide valuable insights into many aspects of the natural and built environment.

VI. ENHANCING URBAN MOBILITY AND AUTONOMOUS VEHICLE INTEGRATION

OWC and sensing, particularly through technologies such as VLC and IR, play a critical role in advancing traffic control systems and enhancing the capabilities of autonomous vehicles [10]. The integration of VLC into ITS aims to improve traffic efficiency and safety by facilitating vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and infrastructure-to-vehicle (I2V) communications. By leveraging the ubiquitous presence of LED-based lighting in vehicles, streetlights, and traffic signals, VLC enables the dual use of these sources for both illumination and data transmission. This approach not only increases the communication bandwidth available for vehicular networks, but also opens up the potential for highly

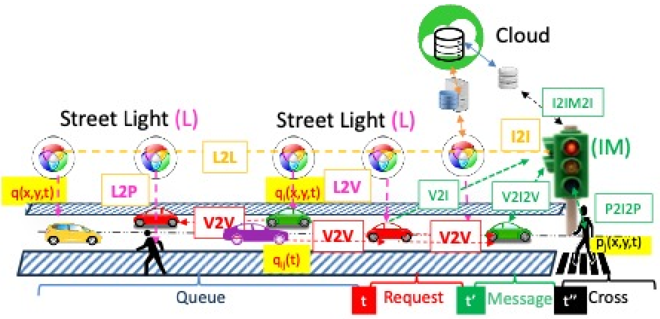

Fig. 2. OWC for adaptive traffic control

accurate, real-time positioning and navigation services critical for autonomous driving.

The implementation of adaptive traffic control strategies through cooperative communication exemplifies the benefits of OW technologies in managing complex traffic scenarios. Using data-driven insights from connected vehicles and the infrastructure, adaptive traffic control systems can dynamically adjust traffic signals to optimize traffic flow, reduce congestion, and improve road safety. These systems rely on the continuous exchange of traffic-related data, including vehicle position, speed, and intended direction, to make informed decisions about signal timing and intersection management. The real-time nature of VLC communication enables a more responsive and flexible approach to traffic control, capable of adapting to changing traffic conditions with precision.

In addition, the use of VLC enables a more granular and accurate form of vehicle localization and sensing, which is essential for autonomous vehicle navigation. By encoding and modulating data in the light emitted by LEDs and using sophisticated optical receivers, vehicles can determine their precise location relative to other vehicles and infrastructure. This capability is critical to the decision-making process of autonomous vehicles, allowing them to navigate safely through intersections, avoid collisions, and plan their routes efficiently. The high directivity and short-range nature of visible light also contributes to the reliability and security of the system, minimizing the risk of interference and eavesdropping common in RF-based communication systems.

Finally, the advancement of VLC and optical sensing technologies contributes to the broader goals of smart city development and sustainable urban mobility. By enabling more efficient traffic management and supporting the safe integration of autonomous vehicles into the urban landscape, these technologies pave the way for reduced vehicle emissions, lower energy consumption, and improved quality of urban life. The ability to transmit data through light not only complements existing wireless communication networks, but also opens new avenues for innovation in urban transportation systems, highlighting the transformative potential of OWC in shaping the future of mobility.

One of the main challenges associated with the integration of OW technology in urban mobility is the LoS requirement inherent to optical communications. While this characteristic is beneficial for safety and precision, it limits the effectiveness of VLC in scenarios where there is no LoS, such as around corners or in harsh weather conditions that can obscure light transmission. In addition, the scalability and interoperability of VLC systems with existing communications networks pose significant technical challenges, requiring robust protocols and standards to ensure seamless integration. Another concern is the potential for optical interference from both natural sunlight and artificial light sources, which can affect the reliability of data transmission. In addition, the widespread deployment of VLC-based ITS will require significant investment in infrastructure upgrades, including the installation of advanced LED lighting and sensors throughout the urban landscape. Overcoming these challenges will require concerted research, development, and policy efforts to unlock the full potential of wireless optical technologies to enhance urban mobility and autonomous vehicle capabilities.

VII. CONCLUSIONS

Concluding this contribution, we would like to highlight the important role that OWC, specifically in the range of VLC, IR, and optical fiber technologies play in the evolution towards 6G networks and beyond. Emphasizing their ability to merge communication with sensing capabilities, these technologies are presented as key drivers for the future of smart cities and the IoT. The challenges, such as the need for direct LoS for OWC and the integration of these new technologies with existing systems, set a clear agenda for future research. Ultimately, it is suggested that overcoming these challenges will enable the full exploitation of OWC and fiber, making networks more versatile, efficient, and responsive to the demands of a digitally connected world.

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