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SIMULTANEOUS LIGHTWAVE INFORMATION AND POWER TRANSFER FOR NON-TERRESTRIAL NETWORKS ENABLED SITUATIONAL AWARENESS

P. D. Diamantoulakis[1], S. A. Tegos[1], G. K. Karagiannidis[1], L. Athanasekos[2] and D. Nodaros[2]

Abstract

This paper presents an innovative approach to enhancing future public-safety capabilities by integrating simultaneous lightwave information and power transfer (SLIPT) into non-terrestrial networks for situational awareness. The shift from reliance on human observers to the use of unmanned aerial vehicles (UAVs) and CubeSats is highlighted for efficient, secure, and precise intervention. Utilizing optical wireless communication, which provides secure, high-bandwidth communication free of radio frequency pollution, we explore the concept of SLIPT, which facilitates both data transmission and energy harvesting, propose a dual-purpose system architecture for UAVs, and outline strategies for overcoming the space challenges faced by CubeSats. Finally, we discuss technical challenges related to tracking accuracy, resource allocation, and receiver weight.

Keywords

Simultaneous lightwave information and power transfer (SLIPT), Unmanned aerial vehicles (UAVs), Satellites

1. INTRODUCTION

Situational awareness is a cornerstone of military efficacy, serving as the bedrock upon which strategic decisions and tactical responses are built. In the complex theatre of operations, it encompasses the continuous, real-time acquisition, analysis, and synthesis of environmental and situational data to understand the current context and predict future states. This awareness is critical across all levels of command, from individual soldiers on the ground to high-level strategic planners. Advances in technology, including satellite surveillance, unmanned aerial vehicles (UAVs), and sophisticated communication networks, have significantly enhanced the ability of armed forces to gain a comprehensive view of the battlefield. Such technologies facilitate the detection of threats, the identification of opportunities, and the coordination of movements with unparalleled precision and speed. Moreover, situational awareness extends beyond the immediate physical environment to include cyber and electromagnetic spaces, where modern conflicts increasingly unfold. By integrating information from these diverse domains, military forces can maintain a decisive advantage, adapting to dynamic conditions and outmaneuvering adversaries with informed, agile strategies.

Also, the utilization of UAVs and CubeSats has revolutionized disaster mitigation efforts, offering innovative tools for monitoring, assessment, and response strategies. UAVs provide immediate aerial imagery and data collection in real-time, enabling rapid assessment of disaster-impacted areas without risking human lives. Their agility and ability to capture detailed visual information make them invaluable for identifying accessible routes for emergency responders, assessing

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[1] Department of Electrical and Computer Engineering, Thessaloniki, Greece
[2] Akmon S.A., Athens, Greece

structural damage, and monitoring ongoing environmental changes. CubeSats, on the other hand, extend the capabilities of disaster mitigation from space, offering a broader perspective with continuous global monitoring. These miniature satellites can track weather patterns, environmental changes, and the progression of natural phenomena such as hurricanes, floods, and wildfires over vast areas. Together, UAVs and CubeSats form a powerful synergy for early warning systems, enhancing predictive models with precise data and significantly improving the timing and efficiency of disaster response. By integrating these advanced technologies into disaster mitigation strategies, communities and emergency management agencies can enhance their preparedness and resilience against the increasingly unpredictable challenges posed by natural disasters.

Situational awareness is a critical component of public safety operations and precise intervention, encompassing the ability to identify, process, and understand the critical elements of information about what is happening in the environment. This cognitive process enables first responders and security personnel to project and anticipate future states in emergency scenarios, facilitating informed decision-making and effective action. At its core, situational awareness is the real-time collection and analysis of environmental data, communication flows, and dynamic risk assessments. These elements are critical for orchestrating coordinated responses to emergencies, optimizing resource allocation, and minimizing the impact on affected communities. Enhancing situational awareness through technological advances and training programs can significantly improve the effectiveness of public safety operations, leading to more targeted, timely, and successful interventions in crisis situations.

The unmanned aerial vehicles (UAVs) and CubeSats represent a paradigm shift in the domain of situational awareness in public-safety applications and disaster mitigation. UAVs, with their ability to loiter and conduct surveillance over hostile territories without putting human lives at risk, offer a significant enhancement in the safety and efficacy of an intervention [1], [2]. These aerial platforms can capture real-time data on enemy movements, fortifications, and equipment, feeding this information back to command centers and artillery units with unprecedented speed and accuracy. The high-resolution imagery and thermal imaging capabilities of UAVs enable the sensing of the environment with a level of detail and precision that was previously unattainable.

On the other hand, CubeSats, which are miniature satellites launched into space, extend the capabilities for precise interventions beyond the atmospheric confines [3]. These small yet powerful tools can provide continuous surveillance over broad areas, offering strategic insights into enemy positions and movements over time. With the advantage of a bird's-eye view, CubeSats can track changes in the battlefield landscape, monitor enemy reinforcements, and predict potential threats, all from the safety of orbit. This space-based perspective not only enhances situational awareness but also contributes to the strategic planning and execution of precise intervention missions.

2. MOTIVATION AND PROBLEM STATEMENT

To meet the need for robust, secure, and efficient communication and power transfer systems for UAVs and CubeSats, the exploration of innovative technologies that overcome traditional limitations is paramount. One such promising advancement is the application of optical wireless communication (OWC), which relies on the use of light to transmit information through unguided propagation media. This approach exploits the enormous bandwidth potential inherent in optical carriers, which span the infrared (IR), visible (VL), and ultraviolet (UV) spectral regions, providing a combined bandwidth of approximately 400 THz. The use of laser or LED transmitters, known for their rapid modulation capabilities, together with receivers equipped with positive-intrinsic-negative (PIN) photodiodes or avalanche PDs (APDs), enables high-speed, linear photodetection. OWC provides several attractive features, most notably intrinsic security, as light propagation can be effectively restricted within pre-defined boundaries, eliminating the risk of eavesdropping and interference commonly associated with radio frequency (RF) technologies. In addition, OWC is immune to electromagnetic interference, supports high bandwidth and efficient bandwidth reuse, and is free of RF contamination, resulting in a cleaner spectrum and increased energy efficiency. These factors not only contribute to the operational safety and performance of UAVs and CubeSats, but also underscore the environmental benefits of reduced RF pollution.

The concept of simultaneous lightwave information and power transfer (SLIPT) is emerging as a particularly innovative application of OWC, facilitating both communication and energy harvesting through a single, streamlined process [4]. Using low-complexity passive receivers, such as non-coherent receivers and solar panels, SLIPT enables passive capture of optical signals and simultaneous power harvesting, providing a sustainable solution that minimizes energy consumption and operating costs [5]. This dual functionality overcomes the logistical and financial challenges associated with traditional power methods, such as tethering or battery swapping, by providing a wireless, autonomous power source that extends the operational range and endurance of UAVs and CubeSats without compromising their mobility or incurring significant additional costs.

In addition, the use of directional SLIPT systems provides a cost-effective, flexible means of powering UAVs via a directional optical link that not only provides significant power transfer to extend the life of the device, but also facilitates communications. This approach is particularly beneficial in optimizing the energy-to-weight ratio, a critical factor for UAVs where the goal is to maximize efficiency while minimizing additional mass. The integration of advanced solar cell technologies, such as organic and perovskite solar cells, enhances this aspect by offering superior efficiency and a favorable energy-to-weight ratio compared to traditional silicon-based cells. Its flexibility and adaptability to different surface geometries further expands the potential applications of SLIPT in UAV and CubeSat systems.

However, the practical application of SLIPT in UAV-based networks requires careful consideration of the trade-offs between energy harvesting and communication efficiency, as well as the development of appropriate theoretical channel models that accurately reflect the unique challenges posed by UAV mobility and environmental factors. Existing research underscores the importance of resource optimization and the need for comprehensive studies that take into account the dynamic operational context of UAVs, including energy consumption, mass impact, and the effects of high-power laser use. The pursuit of SLIPT for UAVs and CubeSats is therefore a multifaceted challenge that goes beyond the technical realm and requires innovative solutions that balance performance, safety, and sustainability.

3. THE FUNDAMENTALS OF SLIPT

The SLIPT concept introduces a breakthrough approach to communication and power distribution that is critical to enhancing the autonomy and functionality of unmanned aerial vehicles (UAVs) and other remote applications. At its core, SLIPT exploits the inherent directivity of light beams to minimize geometric propagation losses, enabling the efficient transfer of information and power over long distances. This characteristic is particularly beneficial in scenarios requiring long-distance point-to-point exchanges, such as underwater and airborne environments, where traditional methods fall short in terms of efficiency and reliability. Within this configuration, systems often incorporate advanced beam-alignment mechanisms to counteract potential perturbations caused by environmental factors such as wind or structural movement.

In terms of the hardware required for SLIPT, the use of resonant lasers or narrow-beam light-emitting diodes (LEDs) as transmitters plays a central role. By limiting the half-power angle of these transmitters to the milliradian range, a high degree of signal directivity is achieved, ensuring that the light beams are sufficiently focused for long-range transmission. On the receiver side, the architecture can vary to meet the specific needs of the application. An option for the receivers in a SLIPT system is a combination of photodiodes (PDs) and photovoltaic (PV) cells, tailored to efficiently receive information and convert the received optical signals into electrical energy. For PD-based information receivers, adaptive convex liquid lenses are used to precisely focus incoming light onto the active area of the PD, which can be of the positive-intrinsic-negative (PIN) or avalanche PD (APD) type, depending on the system requirements. However, the improvement of sustainability and the reduction of power consumption can be effectively achieved through the careful design and deployment of low-complexity passive receivers. In this context, noncoherent receivers come into play, especially when priorities lie in cost-effectiveness, minimal energy usage, and easy implementation on the receiver’s end. To receive noncoherent optical signals passively, a solar panel is employed as the most efficient approach for simultaneously extracting lightwave information and harvesting power. Using the solar panel, compatible with intensity modulation direct detection (IM/DD), it's possible to harvest energy from the direct current (DC) component of the modulated light, unlike the alternating current (AC) component that transmits data. This method allows for the achievement of significant data transmission rates, in the range of megabits per second (Mbps), while also generating enough energy to power various wireless devices, such as unmanned aerial vehicles UAVs and CubeSats, meeting their energy needs efficiently.

When aiming to achieve both high efficiency and low weight, it becomes essential to consider the energy produced per unit weight. Silicon crystalline solar cells, while highly efficient, do not excel in terms of energy-to-weight ratio due to their thickness. In contrast, thin-film inorganic solar cells like Copper Indium Gallium Selenide (CIGS) and a Amorphous Silicon (Si) exhibit improved specific mass, offering a better energy-to-weight ratio. However, organic solar cells and perovskite solar cells outperform the others in terms of efficiency, boasting around 10 Wg-1 and 23 Wg-1, respectively. Additionally, what sets organic and perovskite solar cells apart is their ability to be manufactured on flexible substrates. This flexibility opens up exciting possibilities for easier integration into various applications due to their adaptability to curved or irregular surfaces.

SLIPT can be realized by two main methods: The first is to use identical waveforms for both downlink data transmission and power transmission, ensuring seamless integration of communication and power. This method relies on careful waveform design to encode information while maximizing power transfer efficiency. The second approach, known as the harvest-then-transmit protocol, separates the processes in time. In this case, the system first harvests energy from the incoming lightwave, stores it, and then uses the stored energy to power the transmission of data. This method provides the flexibility to manage energy and information transfer independently, allowing adjustments based on operational requirements and availability of light resources.

4. SLIPT FOR UAVS

The advent of SLIPT technology represents a significant step forward in the capabilities of UAVs, providing an innovative dual-purpose solution for data transmission and remote power supply. This technology is unique in its ability to provide both optical data and power simultaneously, ensuring that UAVs can maintain continuous operation and secure data communications even while in motion. A key component of this architecture is the situational awareness centre. Its role is critical in receiving processed data from ground stations via a secure SLIPT method, underscoring the system's focus on maintaining operational integrity and security [6], as shown in Figure 1.

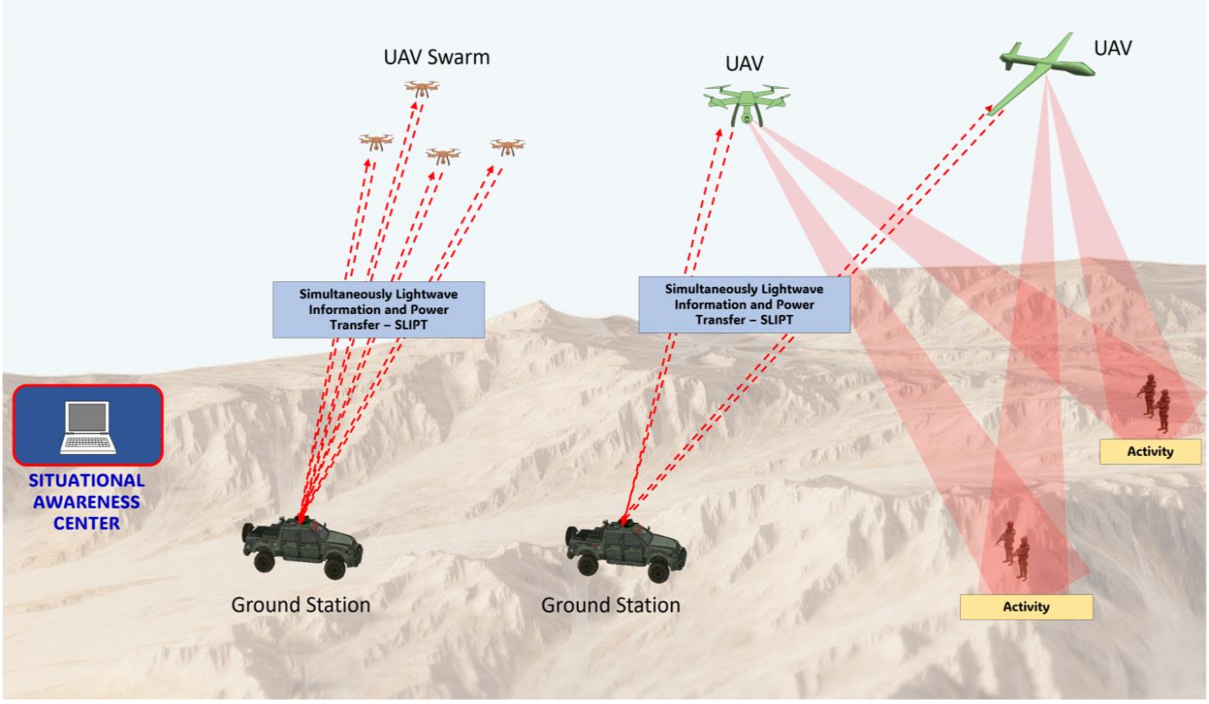

Figure 40: SLIPT for UAVs in situational awareness application.

At the heart of the proposed system is the integration of a directive SLIPT transmitter characterized by a laser array complemented by a tracking system. This system is tasked with providing the precision targeting required for effective use of the SLIPT transmitter. At the receiving end, the SLIPT receiver will incorporate solar cells along with a modified circuit designed to simultaneously process incoming information and harvest energy. This intricate design aims to significantly increase the endurance of UAVs and push the boundaries of continuous, round-the-clock operation.

Achieving the ambitious goals of this system requires overcoming several multifaceted research challenges. These include the optimal design of key components within the infrared communications (IRC) spectrum, such as lasers, solar cells, and photodiodes. A critical consideration is matching the physical dimensions of the UAV with the light collection area of the photodetector to ensure maximum efficiency in light absorption and energy conversion.

Moreover, modulating high-power lasers in SLIPT systems presents a unique set of challenges that stem from the inherent properties of high-power light sources and the physical demands of optical communication. High-power lasers can deliver the robust signal strength necessary for long-distance SLIPT links, but they require precise modulation techniques to encode data effectively without degrading the signal quality. One of the primary difficulties in modulating these lasers is managing the thermal effects associated with high-power operation. High levels of power can lead to significant heat generation within the laser diode, causing thermal lensing and changes in the refractive index, which can distort the optical beam and affect the fidelity of the transmitted signal. Additionally, the non-linear optical effects, such as self-phase modulation and stimulated Brillouin scattering, become more pronounced at higher power levels, potentially leading to signal distortion and a reduction in system performance. Implementing modulation schemes that can cope with these challenges, while maintaining high data rates and signal integrity, requires sophisticated control mechanisms and cooling strategies to mitigate thermal effects and manage non-linearities, making the modulation of high-power lasers a complex task in the development of SLIPT systems.

In addition, the system must balance the rate of data transmission with the efficiency of energy harvesting. This balance is critical and requires the formulation and application of sophisticated algorithms that take into account the energy requirements of the UAV and the desired communication bandwidth. Research and development of optical receivers capable of supporting a range of data rates, from Mbps to Gbps, is also essential. Such a diversity of capabilities will ensure that the system can meet a wide range of operational requirements, thereby increasing its applicability across different UAV platforms.

Furthermore, the comprehensive optimization and evaluation of the system architecture requires a holistic approach. This includes a thorough consideration of controllable hardware parameters and strategic deployment methodologies for SLIPT to maximize both the performance and efficiency of the system.

By addressing these challenges, the proposed system aims to revolutionize UAV operations by extending their endurance and ensuring robust and secure communication channels. The integration of SLIPT technology into UAV systems represents a forward-looking approach that promises to improve air operations and broaden the horizon for its application in various sectors.

5. SLIPT FOR CUBESATS

To address the unique challenges posed by CubeSat satellites, such as their compact dimensions and the extreme conditions of space, there is a concerted effort in the scientific community to explore and develop a number of technical strategies aimed at overcoming these obstacles and enhancing CubeSat functionality. This effort involves several critical areas of research and development, with a particular focus on advancing solar cell technologies, exploring alternative energy sources, and improving the characteristics of batteries used in space applications. The goal is to ensure that CubeSats can operate more efficiently and for longer periods of time, despite their inherent limitations [7].

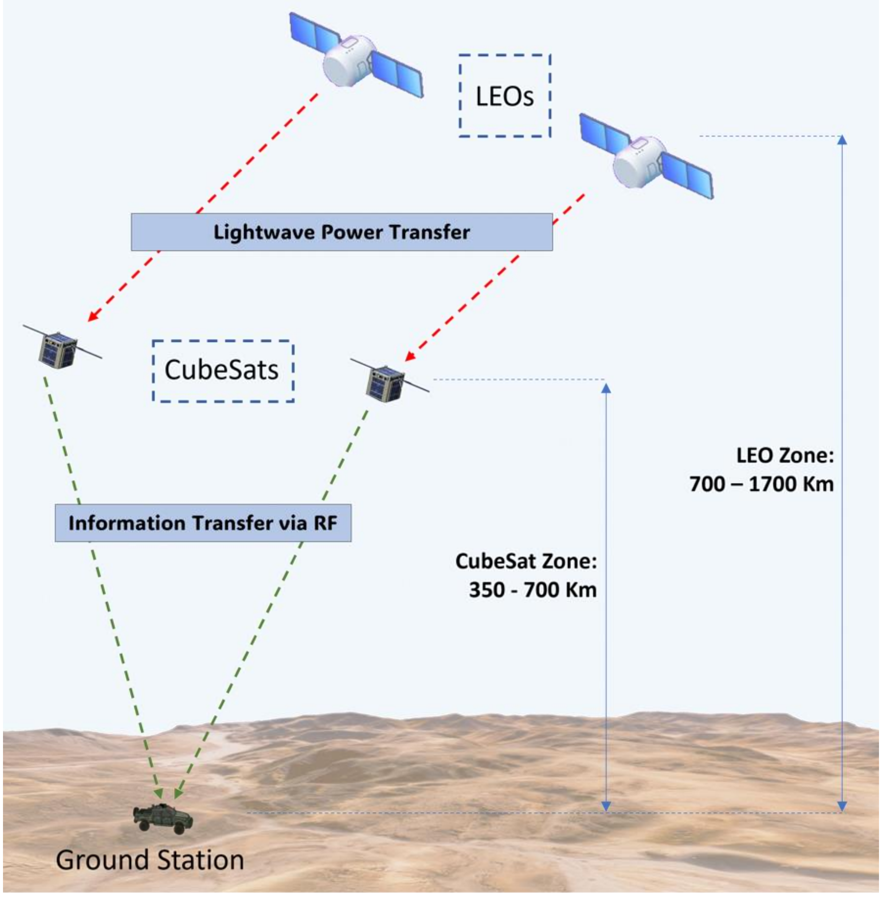

Figure 41: SLIPT for CubeSats

Another important step in optimizing CubeSat operations is the use of sophisticated energy management systems. These systems are designed to intelligently manage the energy resources available to the satellite, thereby increasing its overall efficiency and longevity. At the same time, there is an ongoing effort to develop and refine materials that have the resilience to withstand the harsh and unforgiving conditions of space. These materials must be able to withstand extreme temperatures, radiation, and the vacuum of space, making their development critical to the success of CubeSat missions.

In particular, this section focuses on the potential of SLIPT as a means of delivering power from low Earth orbit (LEO) satellites to CubeSats, achieving power delivery to the CubeSats on the order of kilowatts (kW), which is sufficient to charge their batteries [8]. This innovative approach promises not only to overcome the power limitations of CubeSats, but also to facilitate robust communication links between CubeSats and ground base stations (GBS). Preliminary results show that by using the energy delivered from LEOs, CubeSats can achieve average data rates in the order of Mbps. Establishing such links is essential for the transmission of data to Earth, allowing CubeSats to fulfil their mission objectives. The proposed system will be analysed at various intervals during the mission, allowing for a granular understanding of its operational dynamics. It is important to note that for the purposes of this analysis, the positions of both the satellites and the ground station are considered fixed during these intervals. The power derived from LEO satellites through SLIPT is specifically dedicated to communication functions, enabling the CubeSats to initiate and maintain effective communication with the GBS. This integration of wireless power transfer with data communications underscores the symbiotic nature of these processes and enhances the operational capabilities of the CubeSat.

In addition, the exploration of using satellites in higher orbits, such as medium earth orbit (MEO) and geostationary orbit (GEO), as alternative power sources open new avenues for CubeSat operations. These higher orbit satellites can potentially provide higher levels of energy that could be critical to powering CubeSats. This approach not only provides a viable solution to the energy constraints faced by CubeSats, but also expands the operational possibilities for other small satellites, particularly those used in high-demand applications. By harnessing the power of satellites in higher orbits, CubeSats could achieve greater operational efficiency and reliability, paving the way for more ambitious missions and applications in space exploration and satellite communications.

6. OPEN TECHNICAL ISSUES

SLIPT systems are at the forefront of revolutionary communication and power transfer technologies. However, their widespread adoption and integration into existing network infrastructures face several significant hurdles. These challenges span several technical and practical areas, highlighting the complexity of realizing SLIPT's full potential.

Tracking and alignment: One of the key technical issues is the precision tracking and alignment required for optimal SLIPT operation. The effectiveness of lightwave information and power transfer depends heavily on precise directional alignment between the transmitter and receiver. This requires sophisticated tracking systems capable of maintaining high accuracy in real time to counteract motion and environmental factors, which can be particularly challenging in mobile or dynamic operational scenarios such as UAVs or CubeSats in space.

Channel Modelling: Accurate statistical modelling of the channel is crucial for determining the stability needs of UAVs to sustain a specific level of link quality. This level is influenced by the requirements for communication quality-of-service and the necessary quantity of energy to be harvested when utilizing the optical wireless link for SLIPT. However, to comprehensively tackle these issues, it's essential to obtain experimental data and align the statistical parameters with the specifications of the UAVs and cubesates.

Resource allocation: Another critical issue is the efficient allocation of resources, including bandwidth and power. SLIPT systems must intelligently manage these resources to balance the dual demands of data transmission and power harvesting. This balance is critical to maximizing the efficiency and effectiveness of the transmission processes, requiring innovative solutions to optimize resource allocation under varying conditions and usage requirements.

Weight considerations: The physical characteristics of SLIPT receivers, particularly with respect to weight when airborne platforms are of interest, present a significant challenge. While it is technologically feasible to develop receivers with conversion efficiencies greater than 40%, their high cost and significant weight make them impractical for widespread mobile applications. This limitation is a barrier to the adoption of SLIPT, particularly in contexts where minimal weight is paramount. Alternatives, such as ultra-thin and lightweight film solar cells with about 20% efficiency, offer a partial solution. However, these options typically suffer from limited bandwidth, which in turn limits the data rates that can be achieved, creating a trade-off between weight and power efficiency.

Multidisciplinarity: Addressing the multiple challenges of SLIPT systems requires a multidisciplinary approach. The integration of high-speed photodetectors alongside solar cells has been proposed as a means to enhance both the energy harvesting and data transmission capabilities of SLIPT systems. While this approach aims to improve the overall performance of the system, it introduces complex issues related to the physical space allocation for both components within the receiver unit. This scenario underscores the need for innovative designs and solutions that can reconcile the requirements for high-speed data communication, efficient power transfer, and compact, lightweight construction.

7. CONCLUSIONS

The paper concludes by emphasizing the need for a collaborative, multidisciplinary effort to address the complex technical challenges of deploying SLIPT technology in public-safety applications. Highlighting the potential of SLIPT to revolutionize communications and power transfer for UAVs and CubeSats, innovative research and development is required to overcome obstacles related to tracking accuracy, resource allocation, and system architecture optimization. The integration of SLIPT into future networks is poised to significantly enhance public-safety capabilities by ensuring more secure, efficient, and sustainable operations.

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Authors

Panagiotis D. Diamantoulakis (Senior Member, IEEE) received the Diploma (5 years) and the Ph.D. degree from the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece, in 2012 and 2017, respectively. Since 2022 he is a Postdoctoral Fellow with the Department of Applied Informatics, University of Macedonia, Thessaloniki, Greece. Since 2017, he has been a Postdoctoral Fellow with Wireless Communications and Information Processing (WCIP) Group, AUTH and since 2021, he has been a Visiting Assistant Professor with the Key Lab of Information Coding and Transmission, Southwest Jiaotong University, Chengdu, China. His research interests include optimization theory and applications in wireless networks, optical wireless communications, and goal-oriented communications. He is a Working Group Member of the Newfocus COST Action “European Network on Future Generation Optical Wireless Communication Technologies.” He serves as an Editor of IEEE Open Journal of the Communications Society, Physical Communications (Elsevier), and Frontiers in Communications and Networks, while during 2018-2023 he has been an Editor of IEEE Wireless Communications Letters. He was also an Exemplary Editor of the IEEE Wireless Communications Letters in 2020, and an Exemplary Reviewer of the IEEE Communications Letters in 2014 and the IEEE Transactions on Communications in 2017 and 2019 (top 3% of reviewers).

Sotiris A. Tegos (Senior Member, IEEE) received the Diploma (5 years) and Ph.D. degrees from the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece, in 2017 and 2022, respectively. Since 2022, he is a Postdoctoral Fellow at the Wireless Communications and Information Processing (WCIP) Group, Aristotle University of Thessaloniki, Thessaloniki, Greece, and at the Department of Applied Informatics, University of Macedonia, Thessaloniki, Greece. Since 2023, he is also a Postdoctoral Fellow at the Department of Electrical and Computer Engineering, University of Western Macedonia, Kozani, Greece. In 2018, he was a visiting researcher at the Department of Electrical and Computer Engineering, Khalifa University, Abu Dhabi, UAE. His current research interests include multiple access in wireless communications, optical wireless communications, and reconfigurable intelligent surfaces. He is a Working Group Member of the Newfocus COST Action “European Network on Future Generation Optical Wireless Communication Technologies”. He serves as an Editor for IEEE Communications Letters. He received the Best Paper Award in 2023 Photonics Global Conference (PGC). He was an exemplary reviewer in IEEE Wireless Communications Letters in 2019 and 2022 (top 3% of reviewers).

Dr. Loukas Athanasekos received his degree in Physics in 2001, from University of Ioannina, Greece and MSc degree in “Photonics and Optoelectronic Devices”, from Heriot-Watt University and University of St. Andrews, Scotland, UK. He received his PhD (2014), entitled: “Development and investigation of microstructures by use of laser for photonic applications” from University of Patras, Materials Science Department. He has been working for more than 10 years in scientific research projects in National Hellenic Research Foundation (NHRF), Theoretical & Physical Chemistry Institute (TPCI) and University of Patras. He has been a post-doc fellow in N.C.S.R. "DEMOKRITOS", Institute of Nanoscience and Nanotechnology (INN) for 2 years. He is author or co-author of 13 peer-reviewed papers in scientific journals, 8 proceeding papers in international conferences, author of 1 Chapter in Book and has presence in more than 30 national & international conferences. He has an 18 years’ experience in National and European R&D project management. Currently, he serves as Senior Research Projects Manager at AKMON SA.

Mr. Dimitrios Nodaros has graduated from the Hellenic Military Academy of Evelpidon in 1984. In addition to the training during his Military Service as Artillery Officer, he has been trained by several Hellenic Military Schools and Oberammergau NATO School, and by the University of Athens in Business Administration and in Informatics. Furthermore, he has been qualified as Internal Inspector of Quality Management Systems ISO 9001: 2015 from University of Piraeus and in Project Management from GK organization. During his military career he has been awarded for the computerization/digitalization of the HQ Operations Center. During his professional career in the private sector, he serves as Director of New Technologies Domain at AKMON SA and he has served as Deputy General Director at EIGHT BELLS, Head of European/National Programs at MILTECH HELLAS S.A., HELLENIC INSTRUMENTS and

METADATA S.A. During his professional career he participated and coordinated projects in National and EU programs, since 1999. He has vast experience in EDF, EDIDP and Horizon Europe frameworks and today he has been nominated as EU – EDF Responsible for SEKPY (HELLENIC ASSOCIATION OF DEFENCE INDUSTRIES). Beyond that he participated in Multinational Space-Based Imaging System (MUSIS) project (2006-2009), as National Representative to the THALES ALENIA SPACE Consortium for the design of the MUSIS European Earth Observation System Architecture with responsibility for drafting the initial study report on the Security and Communication of the system. At the moment he is member of DRC Committee and MADIG (Military Air Domain Group) in ASD.

George K. Karagiannidis (Fellow, IEEE) is currently Professor in the Electrical & Computer Engineering Dept. of Aristotle University of Thessaloniki, Greece and Head of Wireless Communications & Information Processing (WCIP) Group. He is also Faculty Fellow in the Cyber Security Systems and Applied AI Research Center, Lebanese American University. His research interests are in the areas of Wireless Communications Systems and Networks, Signal processing, Optical Wireless Communications, Wireless Power Transfer and Applications and Communications & Signal Processing for Biomedical Engineering. Dr. Karagiannidis was in the past Editor in several IEEE journals and from 2012 to 2015 he was the Editor-in Chief of IEEE Communications Letters. From September 2018 to June 2022 he served as Associate Editor-in Chief of IEEE Open Journal of Communications Society. Currently, he is the Editor-in-Chief of IEEE Transactions on Communications. Recently, he received three prestigious awards: The 2021 IEEE ComSoc RCC Technical Recognition Award, the 2018 IEEE ComSoc SPCE Technical Recognition Award and the 2022 Humboldt Research Award from Alexander von Humboldt Foundation. Dr. Karagiannidis is one of the highly-cited authors across all areas of Electrical Engineering, recognized from Clarivate Analytics as Highly-Cited Researcher in the nine consecutive years 2015-2023.