Deployment of Optically-Powered Hybrid OWC/RF Systems Towards 6G

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***Abstract*—This paper presents the concept and deployment of an optically-powered hybrid optical wireless communications (OWC)/radio frequency (RF) system aimed to beyond fifth-generation (B5G) applications, including the sixth generation of cellular networks (6G). The proposed architecture is based on the integration of two B5G enabling technologies, free-space optics (FSO) and power-over-fiber (PoF), with a commercial 5G-New Radio (5G-NR) femtocell, as a proof of concept. Particularly, the FSO system acts as an optical/wireless fronthaul, whereas the PoF link is responsible to optically power the 5G-NR femtocell. It is demonstrated the possibility of remotely energizing B5G remote sites, by ensuring a delivered electrical power of 27 W using 100-m multimode fiber (MMF) links. Experimental performance analyses prove the stability and efficiency of PoF systems in order to use fiber-optics not only to transport high data rates (Gbps), but also to power remote radio units from the future 6G systems.**

I. Introduction

The advent of the fifth generation of mobile network (5G) represented a significant milestone in wireless communication, with the capacity to support high data rates, ultra-low latency, and a massive number of connected devices [1]. With the global commercial deployment of 5G, attention is now increasingly directed towards the beyond 5G (B5G) networks, which are anticipated to require enhanced connectivity to support a diverse range of emerging applications. These include advanced virtual reality (VR) and augmented reality (AR) experiences, high-definition holographic communications, and the massive expansion of the Internet of Things (IoT) framework [2], [3]. In this context, optical wireless communications (OWC) emerges as a promising technology, which employs light to transmit data through free space [4]. The optical frequency range offers a broader unregulated bandwidth compared to millimeter-wave (mm-wave) and terahertz (THz), presenting a compelling opportunity for complementing or even replacing traditional radiofrequency (RF) systems. In addition, OWC technologies are immune to electromagnetic interference (EMI) and provide secure communication [5], [6].

Free-space optics (FSO) is a subset of OWC that uses infrared lasers to transmit data through free space over short to moderate distances [7]. This technology offers several advantages, including straightforward installation, free licensing, cost-effectiveness, immunity to EMI, and wide bandwidth [8], [9]. Although FSO links are severely impacted by outdoor weather conditions, such as fog, dust, and rain, the technology may be an alternative to optical fiber fronthauls in B5G networks, as optical fiber implementation may be costly or impractical in some areas [10]. Several FSO-based fronthaul solutions have been report in literature. For instance, Shakir *et al.* and Zhang *et al.* implemented a hybrid fronthaul solution based on FSO and mm-wave links at 1550 nm and 60 GHz, respectively [11], [12]. The authors in [13] reported a hybrid 1550-nm FSO link and a 28-GHz RF link operating simultaneously for 5G fronthaul and backhaul applications. Furthermore, a FSO fronthaul was demonstrated in [14] for extending the optical-fiber fronthaul link in 5G networks. Nguyen *et al.* experimentally demonstrated an FSO fronthaul and mm-wave wireless transmission aimed at broadband wireless access [15]. Our previous work was based on FSO fronthauls integrated with radio-over-fiber (RoF) and wireless technologies converged into a heterogeneous network [16]. Additionally, we have demonstrated the integration of FSO with fiber-wireless (FiWi) and visible light communications (VLC) technologies as a network physical layer solution to meet the requirements for B5G scenarios [10].

A crucial consideration for the implementation of FSO-based fronthaul solutions is the seamless integration with the access network infrastructure, particularly the deployment of small cells. Small cells are expected to be essential components of B5G cellular networks, designed to enhance coverage, increase network capacity, and improve overall user experience in both urban and rural environments. In the context of the centralized radio access network (C-RAN) architecture, the FSO link aims to establish a high-speed, reliable fronthaul connection between the centralized network core at the central office (CO) and the distributed small cells. However, deploying small cells in ultra-dense networks presents challenges regarding power distribution. Traditional methods, such as power-over-Ethernet (PoE) using copper wires, face challenges regarding susceptibility to EMI, voltage fluctuations, and distance limitation [17]. Consequently, power-over-fiber (PoF) emerges as a promising technology for reliable power distribution within the C-RAN architecture. This technique involves transmitting high-power light from a high-power laser diode (HPLD) through optical fibers to a remote location, where it is converted from optical to electrical energy using a photovoltaic power converter (PPC) [18]. The use of optical fibers to transmit power ensures electrical isolation and immunity to RF, magnetic fields, sparks, and interference [19]. In the specialized literature, PoF technology has been employed in various scenarios. For instance, Altuna *et al.* demonstrated data and power transmission over a 14.43-km single-mode fiber (SMF) for 5G new radio (NR) systems [20]. Moreover, a 150-W power transmission over a double-clad fiber (DCF) achieved up to 43.7 W of converted electrical power [21]. In [22], multicore fibers (MCFs) have been employed for high-power transmission, achieving over 11 W of converted electrical power. In our previous work, we have demonstrated an optically-powered full-duplex 5G system with over 4 Gbps throughput, powering a remote antenna unit (RAU) composed of a laser, photodetector, and electrical amplifiers [23]. Recently, we have reported a PoF-based OWC system, in which different communication links based on RoF, FSO, and VLC technologies were optically powered using a standard multimode fiber (MMF) link [24].

This work presents a proof-of-concept based on an optically-powered hybrid OWC/RF network architecture aiming at B5G applications. Firstly, we implement a FSO link as the fronthaul component, establishing a high-speed 30-m optical link that enables high-bandwidth data transmission in the 5G NR context. In addition, we integrate an RF-based access network by employing a commercially available femtocell, compliant with the 5G NR standard. In order to demonstrate its operation within the proposed hybrid network setup, we perform throughput and performance tests. Furthermore, we demonstrate the use of PoF technology for powering the commercial femtocell for the first time in literature. In this context, we transmit up to 135 W of optical power using MMF links and analyze power efficiency and stability. Our main contribution is demonstrating the feasibility and potential of combining FSO and RF technologies in advanced 5G network infrastructures and offering insights into the practical implementation of PoF for powering network components.

This paper is organized as follows. Section II describes the implementation of our optically-powered hybrid OWC/RF 5G NR system. Section III reports the experimental results including the characterization and performance investigation of the FSO, femtocell, and PoF links. Finally, the conclusions and future works are outlined in Section IV.

II. Experimental Setup

The block diagram of the optically-powered hybrid OWC/RF system considered in this paper is shown in Fig. 1 (a). We utilize a centralized architecture where the 5G core, developed using *Amarisoft* software, is located at the CO. This setup provides network access for terminals and supports voice and data transmission with indoor wireless broadband coverage. The 5G core is connected to the FSO transceiver (model EL-10G ex, from EC Systems) via an Ethernet cable and small form-factor pluggable (SFP) module for Gigabit Ethernet (model ASF-GE-T 10/100/1000Base-T, from 10Gtek). The FSO transceiver is powered by a direct current (DC) 48V supply. At the other end, another FSO transceiver enables a 30-meter reach FSO communication link. An additional SFP module is connected to this FSO transceiver, allowing the insertion of the modulated 5G NR signal from the FSO link into another Ethernet cable that is connected to a commercial femtocell (Sunwave nCELL-F2240 SKU). The FSO transceiver incorporates an optical auto-tracking system, which ensures precise alignment of the receiving and transmitting apertures. The optical auto-tracking system operates using a wavelength of 785 nm, facilitating service information exchange between the pair of transceivers without impacting customer data transmission. On the other hand, the information signal from the 5G core is converted into an optical signal at a wavelength of approximately 1550 nm and then transmitted in the wireless channel. It is important to mention, that the transceivers must have direct line-of-sight visibility to each other. Fig. 1 (b) and (c) show the photography of our experimental setup. The commercial femtocell achieves a peak data rate of up to 780 Mbps for downlink and up to 140 Mbps for uplink and supports up to 128 subscribers in 5G standalone (SA) mode. Furthermore, it operates from

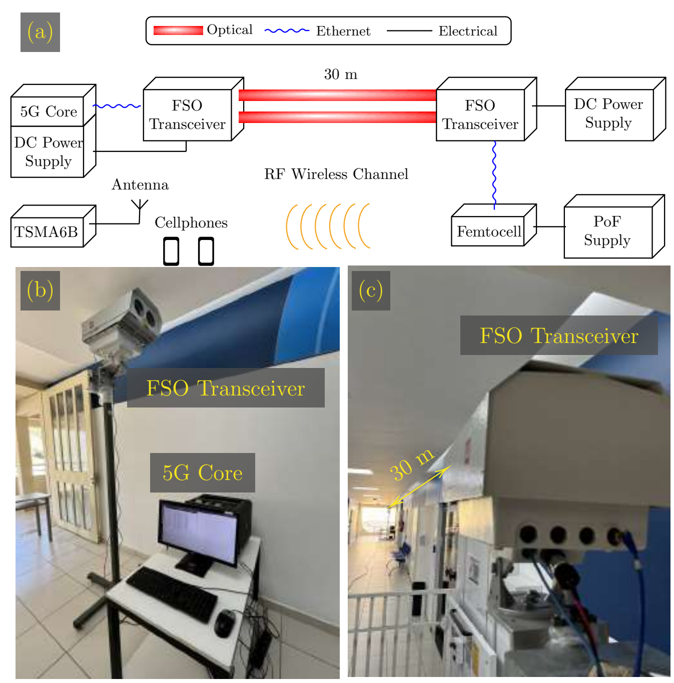

Fig. 1. Optically-powered OWC/RF 5G NR system implementation. (a) Experimental setup block diagram. (b) Experimental setup photograph of the FSO transceiver and 5G Core. (c) Experimental setup photograph of the 30-m link and FSO transceiver.

3300 to 3800 MHz (N78 band) with a maximum bandwidth of 100 MHz. The global positioning system (GPS) ensures accurate timing and coordination with the wider network infrastructure. The device employs a 2 x 2 multiple-input multiple-output (MIMO) configuration, enhancing data throughput and reliability by utilizing multiple transmission and reception paths. Considering all these features, the femtocell energy consumption remains below 45 W. In our proof-of-concept implementation, the femtocell can be powered either by a conventional DC power supply or via PoF.

Regarding the PoF setup, depicted in Fig. 2, two 100 W HPLDs centered at 976 nm (model LSM-100, from MH GoPower Company Limited) were employed and configured to transmit 80 W and 55 W optical power through two dedicated 100 m MMF links with core and clad diameters of 105 and 125 μm, respectively. Subsequently, two PPCs with maximum input optical powers of 70 W and 50 W (models YCH-H020-15 and YCH-H010-15, respectively, from MH GoPower Company Limited) were used for optical-to-electrical conversion at the end of MMF links transmitting 80 W and 55 W optical power, respectively. Due to the fiber attenuation of approximately 1 dB, the output optical power of each link was nearly 63.5 W and 43.7 W, ensuring that the optical power levels remained below the maximum input values allowed in for the PPCs. Subsequently, the outputs of each PPC were connected in parallel to the input of a DC/DC converter (model DDH1800, from MH GoPower Company Limited), which was adjusted to provide 12 V to supply the femtocell. For monitoring purposes, two multimeters were used to measure the current and voltage values at the DC/DC converter output terminals, as may be observed in Fig. 2, where PPC 1 and PPC 2 corresponds to the 50 W and 70 W models, respectively.

III. Results and Discussion

This Section describes the characterization and results of the optically-powered hybrid OWC/RF 5G NR system.

A. FSO Characterization

We initially characterized the FSO link by utilizing a pair of FSO transceivers in conjunction with a pair of Wise TSW900ETH Ethernet traffic generators. The TSW900ETH facilitates diagnostic tests on the physical medium, including both electrical cables and optical signals, and supports various configurable data traffic tests. For instance, the equipment can execute tests as outlined in RFC 2544, such as throughput and latency. To enable direct connectivity between the Ethernet traffic generators and the FSO transceivers, we employed two SFP modules for Gigabit Ethernet (model ASF-GE-T 10/100/1000Base-T, from 10Gtek) in each transceiver. This setup allowed for a comprehensive performance evaluation of the FSO transceiver in a controlled environment.

The TSW900ETH can be configured to operate in Loopback mode, facilitating the testing of both downlink and uplink transmissions. Fig. 3 presents the results of FSO link characterization in terms of throughput and latency. These measured metrics were compared with those obtained from a back-to-back (B2B) configuration, where the traffic generators were directly connected using Ethernet cables. This comparison serves as a benchmark to evaluate the potential impact of the FSO transmission link on the throughput and latency of the transmitted signal.

Throughput and latency tests were conducted using packets of various frame sizes, specifically 128, 256, 512, and 1024 bytes. The results indicate that the throughput remained the same when compared to the B2B transmission, achieving 864.69, 927.35, 962.22, and 980.25 Mbps for frame sizes of 128, 256, 512, and 1024 bytes, respectively. This suggests that the FSO link does not significantly affect the throughput, maintaining performance levels comparable to the direct Ethernet cable connection. Regarding the latency tests, the FSO link introduced approximately 1.3 μs of additional latency compared to the B2B transmission. This increase resulted in

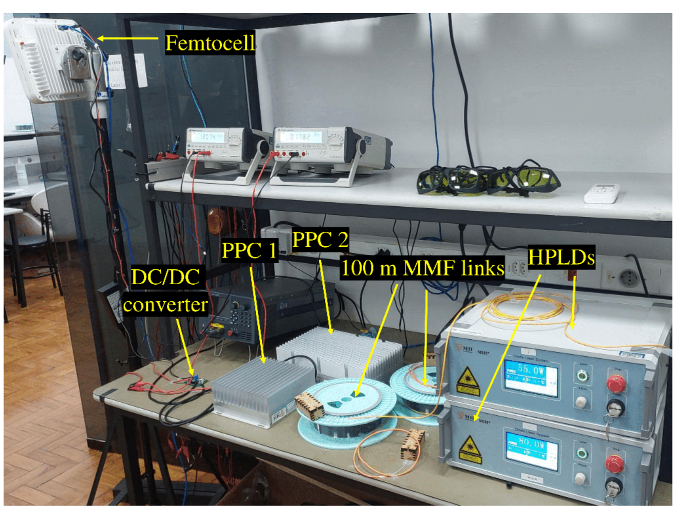

Fig. 2. Experimental setup photograph of the PoF system and femtocell.

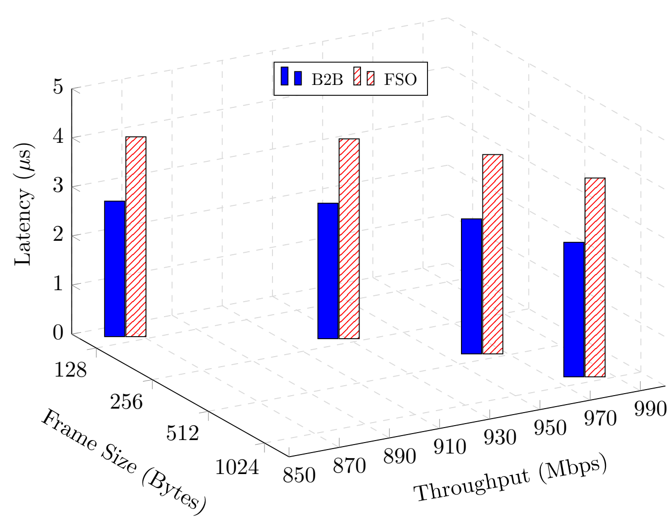

Fig. 3. FSO Throughput and Latency characterization as function of frame size.

the average latency rising from 2.7 to 4.0 μs. These results endorse the use of FSO links to extend the link distance between the 5G core and the access network, as no significant impact on performance was observed.

B. Femtocell Characterization

We have performed the femtocell characterization using a network scanner from Rohde & Schwarz, TSMA6B. This equipment demodulates 5G NR signals and conducts measurements, such as error vector magnitude (EVM), received signal strength indicator (RSSI), synchronization signal block (SSB)-RSSI, and secondary synchronization signal (SSS)-reference signal received power (RSRP). The metric EVM quantifies the degree of divergence between the received signal and the theoretical ideal signal, attributed to sources such as noise, distortion, or channel impairments [25]. RSSI represents the total received power within the channel bandwidth [26]. SSB-RSSI measures the received power of the SSB within the channel bandwidth. This metric is calculated by aggregating the power from multiple resource blocks [27]. Finally, SSS-RSRP is defined as the linear average of the power contribution of the elements carrying the SSS signal, and measures the average power received from the secondary synchronization signal [28]. The parameters align with the definitions and metrics specified in 3rd Generation Partnership Project (3GPP) technical documents for evaluating signal quality.

Table I presents the performance metrics measured at different distances between the TSMA6B equipment antenna and femtocell. The EVM penalty evaluation was conducted by measuring the EVM for each distance and comparing these values to the reference EVM value recorded at 0 m. Compared to the standard EVM, the EVM penalty highlights the relative increase in EVM caused by different factors. One may observe that the EVM penalty increased gradually by approximately 0.3 dB every 10 m from 0 to 50 m. In contrast, this metric increased sharply from 50 to 60 m, which may be attributed to an additional wall obstructing the line-of-sight and thereby degrading the quality of the TSMA6B-femtocell link. Moreover, the RSSI decreased from -36.9 dBm at 0 m to -93.1 dBm at 60 m. Similarly, the SSB-RSSI decreased from -33 dBm at 0 m to -89.9 dBm at 60 m. In both measurements, the most significant drop occurred between 0 and 10 m, with the values subsequently stabilizing beyond 20 m. Additionally, SSS-RSRP values declined with increasing distance, as the level sharply dropped from -54.18 at 0 m to -86.11 dBm at 10 m, signaling an immediate loss of signal power. This decline continues progressively, reaching -112.5 dBm at 60 m. Overall, as distance increases, there is a noticeable degradation in signal quality (higher EVM penalty) and the attenuation of signal strength (lower RSSI, SSB-RSSI, and SSS-RSRP values). This trend is expected, given that the femtocell is designed to operate effectively over short distances within indoor environments.

TABLE I
FEMTOCELL CHARACTERIZATION

Distance (m)	0	10	20	30	40	50	60
EVM Penalty (dB)	0	0.3	0. 55	0.66	1.9	2.1	7.4
RSSI (dBm)	-36.9	-69.8	-76.15	-76.6	-83.5	-83.4	-93.1
SSB-RSSI (dBm)	-33	-64.13	-72.3	-74.09	-80.6	-81.1	-89.9
SSS-RSRP (dBm)	-54.18	-86.11	-93	-96.5	-103.12	-103.8	-112.5

C. Optically-Powered Hybrid System

A PoF performance test was carried out before optically powering the femtocell. To ensure the proper functioning of the communication system, the stability of the PoF output electrical power was evaluated over a 60-minute period, as well as the stability of the femtocell power consumption using the conventional DC supply, as shown in Fig. 4. During the measurements, the femtocell was in standby mode with no users connected, resulting in an output voltage of approximately 12.1 V and an electrical current of 1.59 A, providing nearly 19.2 W of electrical power. The stability curve indicates that the implemented PoF system successfully powers the femtocell throughout the entire period, even during power consumption peaks probably caused by cyclically transmitted synchronization and control signals. These power peaks may also be observed in the conventional DC supply stability measurements. Furthermore, we have calculated the power transmission efficiency (PTE), which is defined as the power ratio between the HPLD power injected into the PoF link and the PPC output electrical power [21]. The femtocell displays increased power consumption and current draw during uplink and downlink operations. Specifically, in uplink mode, power consumption rises to 22.8 W with the electrical current increasing to 1.9 A. For downlink operations, the power consumption further increases to 27.6 W with a corresponding current of 2.3 A, respectively. We have calculated the PTE based on the maximum power consumption scenario, where the laser was set to deliver its peak power of 135 W, resulting

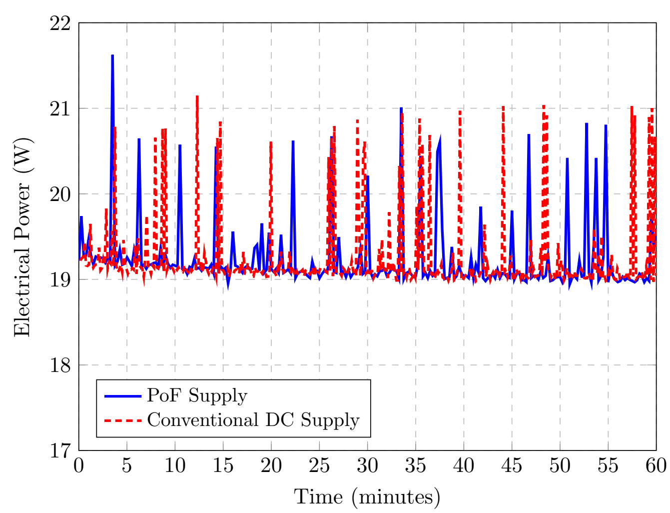

Fig. 4. PoF system output electrical power measurements over a 60-minute period.

in a PTE of 20.4%, which is comparable with previous works [23].

Throughput tests (uplink and downlink) were conducted to analyze communication performance using the PoF system to power the femtocell. The performance was compared with a B2B configuration, where the 5G core was connected directly to the femtocell without the FSO link, and with the femtocell powered by a conventional power supply with the FSO link. Fig. 5 presents the obtained throughput for uplink and downlink in the three tested scenarios. One may note that in both test scenarios, the uplink throughput present similar performance for all measurement indexes, reaching up to 115 Mbps throughput. In the downlink test, as expected, the data rate is higher than in the uplink communication, with a throughput average of nearly 658 Mbps considering all cases. However, fluctuations are observed at the beginning and end of the measurements across all three scenarios. These variations may be associated with the measurement tool used for network analysis (*iPerf*). Nevertheless, the optically-powered system performance presented no significant degradation in comparison with B2B configuration or conventional supply, validating the proposed PoF system application.

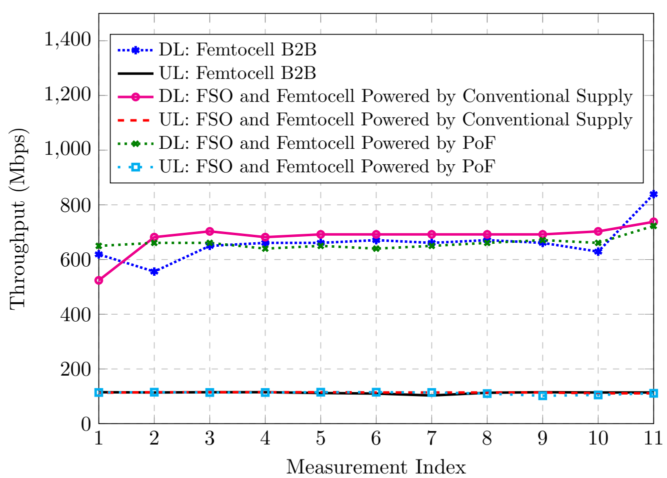

Fig. 5. Throughput measurements for uplink and downlink modes considering B2B femtocell link, femtocell powered by conventional supply with FSO, and femtocell powered by PoF with FSO.

Subsequently, the power of the radiated 5G NR signal was measured using a monopole antenna with 2.3 dBi of gain and a signal analyzer (model MXA N9020A, from Keysight). The obtained frequency spectra are presented in Fig. 6. It can be observed that all three scenarios present similar spectrum results, with slight differences in the RF power. In addition, one may note degradation in the uplink spectrum, which may be associated with multi-path suffered by the radiated signal from the cellphone antenna.

IV. Conclusions

This work has successfully demonstrated a proof-of-concept for an optically-powered hybrid OWC/RF network architecture designed for B5G applications. The integration of a FSO link

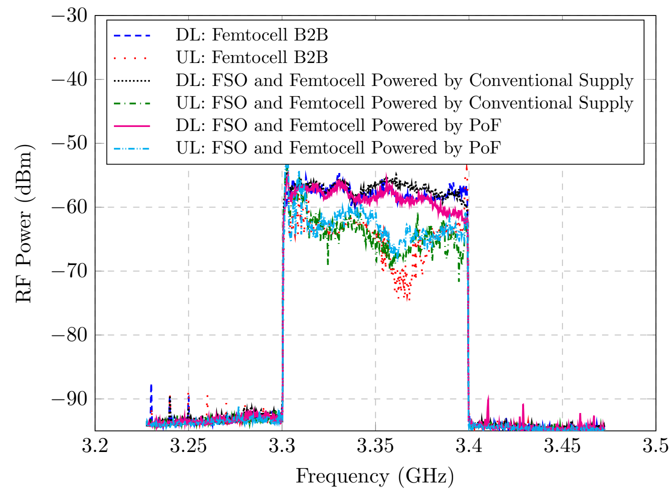

Fig. 6. RF spectra measurements for uplink and downlink modes considering B2B femtocell link, femtocell powered by conventional supply with FSO, and femtocell powered by PoF with FSO.

with a commercial femtocell supported high-bandwidth data transmission, maintaining high throughput levels and minimal latency impact. The use of PoF technology for powering the femtocell was validated, demonstrating stable performance and no significant degradation compared to traditional power supplies. The PoF system effectively delivered over 27 W of electrical power by transmitting up to 135 W of optical power, with a PTE of 20.4%. Overall, this work demonstrated the potential of combining FSO and PoF technologies to enhance B5G network infrastructures, offering a viable solution for reliable power delivery and high-performance data transmission. Future works regard the integration of other key technologies, such as RoF and VLC, to further enhance the capabilities and flexibility of the hybrid OWC/RF network architecture.

Acknowledgments

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