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Integrating Light Fidelity and Millimeter-Wave through Gigabit Passive Optical Networks

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Abstract— **This paper investigates the integration of Light Fidelity (LiFi) and millimeter wave (mm-wave) via Gigabit Passive Optical Networks (GPONs) aiming to 5G and future 6G networks. The proposed heterogeneous network (HetNet) dual-access architecture combines high-throughput mm-wave and secure, high-speed LiFi communications. Experimental results confirm the feasibility of this integration, demonstrating LiFi and mm-wave technologies operating simultaneously. We exploited the effectiveness of media converters in maintaining high data rates and the capillarity of GPON infrastructure to distribute the signals. The proposed topology presents a promising approach to meet the increasing demand for high-capacity communication in future 6G networks.**

Keywords— **5G, 6G, HetNet, LiFi.**

I. INTRODUCTION

Discussions about the evolution of the fifth-generation of mobile network (5G) into sixth-generation of mobile network (6G) are gaining attention, underscoring the need for this forthcoming system to advance with enhanced capabilities and innovative technologies [1]–[3]. The radio access network (RAN) for 6G are expected to integrate terrestrial wireless, satellite and optical-wireless communications (OWC) systems to ensure ubiquitous global connectivity [4]. These networks will leverage advanced technologies, including free-space optics (FSO) [5], visible-light communication (VLC) [6], fiber/wireless (FiWi) [7] and notably, Light Fidelity (LiFi) [8], [9]. Moreover, 6G will expand the use of artificial intelligence (AI) to optimize network operations and dynamically allocate resources, improving efficiency and reducing latency [10]. AI will also be employed in the physical layer (PHY), aiming to improve performance and/or reduce complexity [11].

The development of 6G access networks faces significant technical challenges, including the need for new infrastructure and ensuring interoperability among diverse technologies. The heterogeneous network (HetNet) topology is emerging as an interesting approach to manage the increase in traffic capacities and connection densities [12], [13]. Indoor access in HetNets is crucial to offer high-capacity wireless connectivity, which are essential to support bandwidth-intensive applications like video streaming, virtual and augmented reality, and cloud-based services. HetNets may incorporate various OWC and wireless millimeter-wave (mm-wave) technologies to enhance network performance and scalability [14]. HetNets may also leverage gigabit passive optical network (GPON) infrastructure to distribute signals between Mobile Network Operator (MNO) central office (CO) and the indoor environment, in which the access networks will be implemented. This approach simplifies the network infrastructure due to the high-capillarity of GPON. It has been demonstrated that employing this strategy does not interfere with GPON services, as it uses distinct wavelengths [15]. This approach allows us to integrate multiple access technologies within a single infrastructure.

Wireless mm-wave access networks have been under discussion for 5G since its conception. Although significant advantages of mm-wave communications, such as high spectrum availability enabling data transfer rates of multiple gigabits per second, numerous technical challenges have hindered their widespread adoption. The mm-wave range is also being considered for 6G communications, which aims to further enhance communication speeds, potentially achieving terabits per second [16]. The higher frequencies allow for the transmission of large amounts of data over short distances, making mm-wave an interesting solution for indoor access network [17]. Despite these challenges, the deployment of mm-wave technology is crucial for meeting the growing needs for wireless bandwidth and is a cornerstone of the evolution toward more capable and efficient wireless networks.

The LiFi technology is another interesting technology that might be employed to establish an indoor access network [18]. This technology utilizes light to transmit data, offering numerous benefits over traditional wireless communications, including significantly higher data rates, improved security, and reduced electromagnetic interference [19], [20]. This makes LiFi particularly advantageous in environments where the radiofrequency (RF) spectrum is congested. An additional advantage is that LiFi can simultaneously operate with Wireless Fidelity (WiFi) without any interference, making this solution a complementary option to provide Internet access [21]. However, the technology also faces substantial challenges that may hinder its widespread adoption. The requirement for line-of-sight between transmitters and receivers can be restrictive, as any obstruction can disrupt the signal. Furthermore, integrating LiFi with existing communication infrastructures presents critical challenges, including the need to enhance mobility support.

Many works have been proposed regarding the applica-

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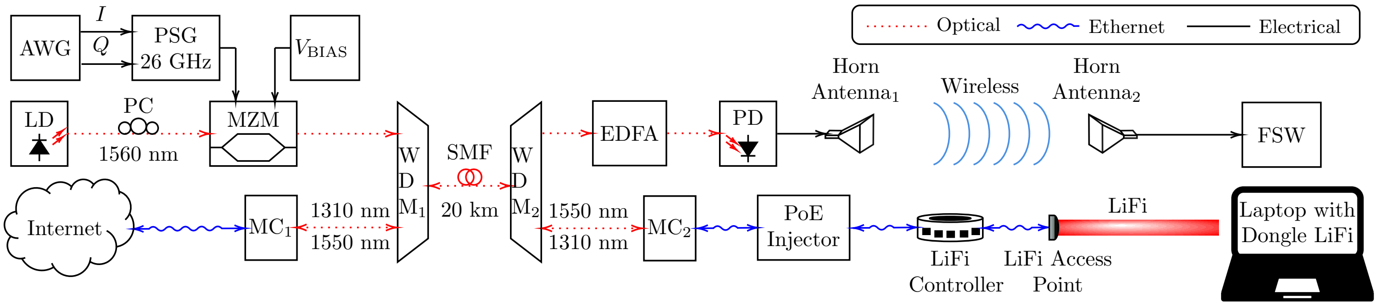

Fig. 1. Block diagram of the integrated 5G NR and LiFi system. The setup includes key components such as Horn Antennas, LiFi Controller, LiFi Access Point, WDM- Wavelength Division Multiplexers, PoE - Power over Ethernet Injector, MCs - Media Converters (MC1 and MC2), SMF - Single-Mode Fiber, and various electronic and optical devices.

tion of LiFi in 5G systems. In [22], the authors introduce LiFi as a 5G technology, demonstrating its high-throughput transmissions. It emphasizes the importance of the small cell concept and the allocation of new spectrum to advance LiFi technology. The paper discusses about moving from wireless mm-wave to LiFi communication, driven by the limited availability of RF spectrum and the exponential growth in wireless data traffic. A comprehensive overview of LiFi technology, discussing its strengths, weaknesses, opportunities, and threats, is presented in [23]. It highlights the LiFi advantages such as high-speed data transmission, enhanced security, and lower implementation and maintenance costs compared to WiFi. Hassan et. al. propose enhancements for handover processes in mobility scenarios [24]. It also discusses the potential of LiFi technology in applications such as healthcare and smart home systems, offering advantages like reliable data transmission, security, and power management. Finally, in [25], the authors discuss the benefits of VLC and LiFi for short-range indoor communication scenarios, enabled by advancements in light-emitting diodes (LEDs) for both illumination and communication. The paper proposes using VLC and LiFi to meet the demanding requirements of 5G networks, describing them as key technologies for future communication systems.

In this work, we proposed and implemented a dual-access network leveraging wireless mm-wave and LiFi technologies. The indoor wireless network utilizes mm-wave technology to facilitate high-throughput 5G New Radio (5G NR) communications at 26 GHz. Concurrently, the LiFi network provides real Internet access using established commercial LiFi technology. To extend the reach of Internet communications, we utilized a pair of media converters to transform the Internet signal from an Ethernet cable into an optical signal. This optical signal is then integrated into the GPON architecture, enabling the long-distance transport of the Internet signal. The GPON infrastructure plays a pivotal role in distributing and transporting signals from both the wireless and LiFi cells. These signals are subsequently combined using a wavelength division multiplexing (WDM) system, effectively creating two simultaneous access networks.

This paper is organized as follows. Section II describes implementation details of the proposed HetNet multiple access network, whereas Section III presents the experimental results, considering the simultaneous operation of both indoor access network. Finally, Section IV presents the main conclusions.

II. DESCRIPTION OF THE PROPOSED SYSTEM

This section describes the generation, transport, and radiation of the signals, forming a dual-access HetNet. The scenario considered in this paper is illustrated in Fig.1, which details the integration of 5G NR with LiFi by transporting two distinct signals within this HetNet architecture. The first is a real Internet signal from a local Internet service provider (ISP), and the second is a 5G NR signal at 26 GHz. It is assumed that the 26 GHz 5G NR signal is generated at the MNO CO, where the Internet signal is also available. These two signals are converted to the optical domain and transported over a 20 km fronthaul. The fronthaul link is implemented using analog radio-over-fiber (A-RoF) because it offers lower operational expenditure (OPEX) compared to the digital RoF (D-RoF) solution [26]. At the indoor access location, both signal are converted back in electrical. The 5G NR signal is radiated, creating a short-range indoor mm-wave access network and the Internet signal reaches the LiFi Access Point, giving rise to a LiFi access network.

At the transmission side, a M8190A arbitrary waveform generator (AWG) from Keysight is used to generate the I-Q samples of the base-band 5G NR signal. The generated base-band samples are upconverted to a 26-GHz signal with 0 dBm RF power, by employing a E8267D performance signal generator (PSG), also from Keysight. This signal is applied in a FTM7939EK Mach-Zehnder modulator (MZM) from Fujitsu, which modulates the optical carrier generated by a tunable laser from Golight at 1560 nm with 14 dBm optical power. The MZM is a polarization sensitive component, which means that a polarization controller (PC) is required to control the incident optical beam polarization. Additionally, a direct current (DC) power supply is used to control the MZM operating point. Specifically, 2.4 V is applied, leading the MZM to operate at the quadrature point. In parallel, the Internet signal from the local ISP is converted to optical using a media converter 1 (MC_1), which operates with downlink and uplink wavelengths of 1310 and 1550 nm, respectively. The optical signals from the MZM and MC_1 are combined by wavelength division multiplexing 1 (WDM_1) and transmitted through a 20 km single-mode fiber (SMF).

A SMF transports the signal to wavelength division multiplexing 2 (WDM_2), which demultiplexes the wavelengths. The optical carrier at 1560 nm, carrying the 5G NR signal, is amplified by an Erbium-doped fiber amplifier (EDFA). A ThorLabs DMX50AF photodetector (PD) converts the 5G NR signal from optical to the electrical, and a 24-dB RF amplification is performed before a 25-dBi horn antenna radiates the signal, creating an indoor access network. Another identical antenna is used to receive the signal, which is analyzed by a FSW Signal & Spectrum Analyzer from Rohde & Schwarz.

Regarding the Internet signal, the media converter 2 (MC_2) is used to convert the signal back to electrical to feed the LiFi Access point. This signal reaches the power over Ethernet (PoE) injector 802.3at standard with a maximum power supply capacity of 30 W, which combines the Internet data and power supply in a single Ethernet cable (CAT-6), connected to the LiFi controller, which has an Ethernet input and multiple Ethernet outputs to supply the LiFi access points. The LiFi establishes a duplex communication with symmetrical flow up to 150/150 Mbps and 1 ms latency. Regarding the coverage, the emission beam is approximately 83° at 1.8 m from the transmitter and the performance is reliable for links up to 5 m.

The LiFi communication is based on the International Telecommunication Union (ITU)-T G.vlc or G.9991 international standard. In addition, the Institute of Electrical and Electronics Engineers (IEEE) has certified the 802.11bb standard for light-based wireless communications. Therefore, there are a few companies dedicated only to provide LiFi hardware and services, such as: Oledcomm, pureLiFi and the Fraunhofer Institute for Telecommunications Heinrich Hertz Institute (HHI). In particular, we have used the LiFi equipment from Oledcomm, encompassing one LiFi controller, one access point, and a dongle. The LiFi access is fully secure, using 802.1X authentication with an advanced encryption standard of 256-bit key length (AES256), captive portal connection, and virtual local area network (VLAN) management at the dongle side. The LiFi access point complies with the International Electrotechnical Commission IEC/EN 62471 standard relating to photobiological safety. The LiFi access point is class 0 (does not present any photobiological risk) and is also equipped with an automatic optical signal cut-off mechanism when the access point/dongle link is broken (e.g., when a person looks closely and in the direction of the access point). Additionally, the LiFi access point complies with the IEC/EN 61000 standard for electromagnetic compatibility (EMC), i.e., does not cause or suffer electromagnetic interference from conventional radio equipment. The LiFi communication uses a LED operating at 940 nm (infrared), in which the spectrum of natural sunlight is at a low point and, therefore, interference from it is practically negligible. The system is also protected from other light radiation utilizing an optical filtering system integrated in the LiFi modules, making it reliable and less sensitive to natural and artificial light interference.

The hybrid access approach allows us to create two access networks: one operating at mm-wave with a 3-meter range, and the other using OWC technology, also with a 3-meter range. A LiFi dongle must be connected to the laptop USB port for full-duplex communication. This LiFi dongle has a LiFi receiver that allows the signal to be recovered and also a transmitter to perform the uplink transmission. Fig. 2 illustrates our experimental setup, divided into the TX and RX sides. One can observe the LiFi beam emission (infrared) in shades of red which is enabled by the camera view.

Fig. 2. Photography of the experimental setup.

III. EXPERIMENTAL RESULTS

This section presents the performance evaluation results for the proposed dual-access HetNet topology. The evaluation considers the simultaneous operation of both access networks: RF-mm-wave wireless and LiFi OWC. The first investigation is regarded to the mm-wave 5G NR signal. We have evaluated the received root mean square error vector magnitude (EVM_{RMS}) and compared with the 3rd Generation Partnership Project (3GPP) EVM_{RMS} requirements as a benchmark. Fig. 3 shows the EVM_{RMS} results as a function of bandwidth, considering a 3-m wireless link. Four distinct bandwidths were evaluated, namely 50, 100, 200, and 400 MHz, using 16- and 64-quadrature amplitude modulation (QAM). It is important to note that the 5G NR signal is based on the orthogonal frequency division multiplexing (OFDM) waveform, which means that QAM symbols are mapped onto the OFDM subcarriers. The bandwidths were chosen in accordance with the 5G NR frequency range 2 (FR2) specification, which defines bandwidths of 100, 200, 300 and 400 MHz [27]. Notably, all configurations meet the 3GPP EVM_{RMS} requirements for both 16- and 64-QAM, 8 and 12.5 %, respectively. Additionally, we included the constellations for 50 and 400 MHz, where no apparent distortion was detected.

We started the second investigation by testing the benchmark Internet download and upload speed. Figs. 4 and 5 show all the measurements taken during the download and upload operation. The first step was to measure the total

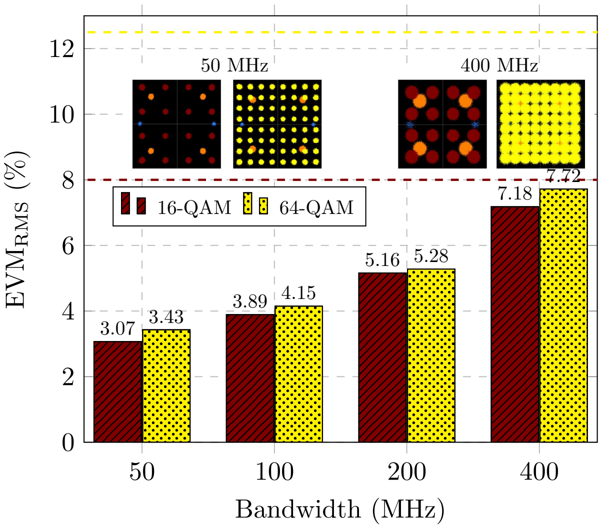

Fig. 3. $\mathrm{EVM}_{\mathrm{RMS}}$ as a function Bandwidth for the 5G NR signal at 26 GHz, considering a 3-m wireless transmission.

Internet speed, which was done by directly connecting the Ethernet cable to the laptop and conducting an Internet speed test across 10 distinct measurements. This Internet back-to-back (B2B) measurement resulted in an average download and upload speeds of 668.915 and 149.926 Mbps, respectively, which we used as the benchmark. As described in Section II, the Internet signal was converted into an optical signal for integration into the HetNet topology using media converters (MCs). We also tested the Internet download speed with only two MCs. In other words, the Internet signal from the Ethernet cable was directly connected to MC_1, which converted it into an optical signal. This optical signal was then sent to MC_2, which converted it back to an electrical signal. The output from MC_2 was connected to the laptop via another Ethernet cable, where we investigated the Internet download and upload speed. This approach enables us to verify if the use of MCs results Internet speed reduction. The achieved average speed was 683.934 Mbps for download and 140.339 Mbps for upload, which is close to the B2B measurement. These results indicate that the optical-to-electrical and electrical-to-optical conversions performed by the employed MCs do not result in any speed reduction. This endorses its use to integrate the Internet signal from a local ISP in a HetNet topology.

After performing the B2B and MC measurements, we evaluated the LiFi link performance. For this test, we directly connected the Ethernet cable to the PoE injector, which was then connected to the LiFi controller. This setup supplied power and data to the LiFi Access Point. The goal was to investigate the total download and upload speeds when using only the commercial LiFi transceiver. We conducted 10 distinct measurements, as illustrated in Figs. 4 and 5, resulting in an average download speed of 65.372 Mbps and 40.08 Mbps for upload. The speed reduction compared to the B2B measurement is due to the rate limitation of the commercial LiFi transceiver. Additionally, the MCs were used to determine if any further speed reduction would occur. The results were similar to our previous measurements when only LiFi was employed, indicating that no rate reduction is observed when the MCs are used. We achieved download speeds of 61.365 Mbps and upload speeds of 42.112 Mbps, respectively.

Finally, we investigated the Internet speed integrated into the HetNet topology. In this setup, the signal output from MC_1 was integrated into the HetNet topology using WDM_1. The average download speed achieved was 63.01 Mbps, while the average upload speed was 41.11 Mbps. It is important to note that these measurements were taken while both access networks were simultaneously operating. No perceptible interference was observed, suggesting that these networks can operate concurrently without issues. This complementary access network can enhance coverage in indoor environments, providing an improved experience for end users.

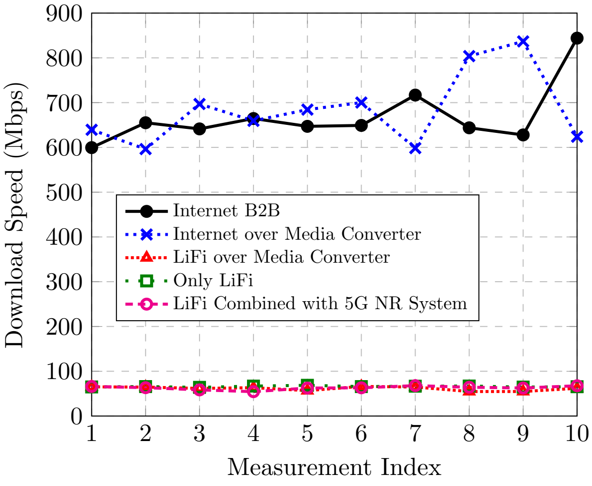

Fig. 4. Comparison of download speeds across different communication setups, including Internet B2B, Internet over Media Converter, LiFi over Media Converter, Only LiFi, and LiFi combined with 5G NR System.

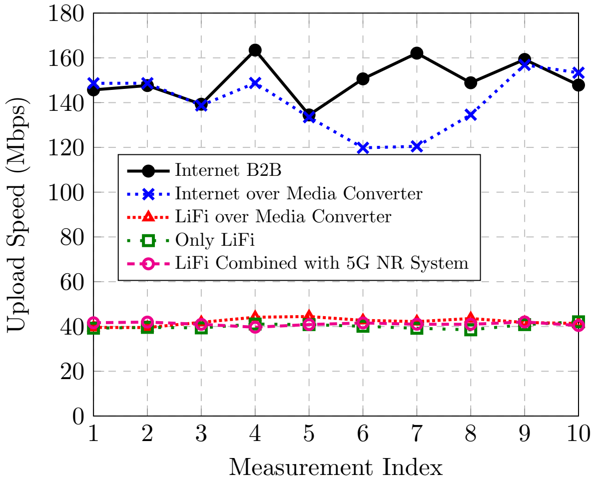

Fig. 5. Comparison of upload speeds across different communication setups, including Internet B2B, Internet over Media Converter, LiFi over Media Converter, Only LiFi, and LiFi combined with 5G NR System.

IV. CONCLUSIONS

This work demonstrated the feasibility and effectiveness of integrating LiFi and mm-wave within a GPON framework to enhance 5G and towards 6G HetNets. The proposed dual-access network successfully combined the high-throughput capabilities of mm-wave technology with the secure, high-speed data transmission of LiFi, achieving a complementary system that optimized indoor wireless connectivity.

Experimental results confirmed the viability of this integration, showing that both LiFi and mm-wave technologies can simultaneously operate. The use of MCs for electrical-to-optical and optical-to-electrical signal conversion proved to be effective, maintaining high data rates comparable to direct Ethernet connections. This allow to exploit the potential of GPON infrastructure to distribute signals enabling multiple-access networks, supported by WDM technique.

The findings also highlight the importance of addressing challenges such as line-of-sight requirements for LiFi and the technical complexities associated with mm-wave propagation. Despite these challenges, the integration of these advanced technologies within a unified GPON framework presents a promising approach to meet the increasing demand for high-capacity communication in future 6G networks.

Future work should focus on further optimizing the network architecture to enhance mobility support for LiFi systems and exploiting the scalability of the proposed solution in larger, more complex environments. Additionally, the development of efficient AI-driven resource management techniques could further improve network performance and adaptability, paving the way for the widespread adoption of integrated 6G communication technologies.

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