A Radio- and Power-over-Fiber System using Double-clad Fiber Towards B5G Networks

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Abstract—**This paper presents the integration of radio- and power-over-fiber (RPoF) for beyond-fifth-generation (B5G) systems using double-clad fibers (DCFs) to deliver data and power simultaneously. We propose a system that transmits a 5G new radio (NR) signal centered at 26 GHz and over 20-W optical power through a 250-m DCF link. In this setup, the PoF system is able to power critical components of the RoF system, including a photodetector (PD) and electrical amplifier (EA). Our experimental performance investigation is based on power efficiency and stability analysis, as well as root mean square error vector magnitude (EVM$_{\text{RMS}}$) measurements. The results demonstrate that the proposed RPoF system meets the 3$^{\text{rd}}$ Generation Partnership Project (3GPP) requirements without degradation from the high-power feed light. Additionally, a throughput of 1.6 Gbps is achieved, demonstrating the feasibility of using DCFs in RPoF systems.**

Index Terms—**B5G, double-clad fiber, power-over-fiber, radio-over-fiber.**

I. INTRODUCTION

The increasing demands for higher data rates, ultra-low latency, and extensive device connectivity are driving the evolution of the fifth-generation (5G) of mobile networks [1]. To meet these challenges, future generations, referred to as beyond 5G (B5G) networks, aim to integrate cutting-edge technologies and novel architectures, enhancing performance and energy efficiency [2]. One of these advancements is the centralized radio access network (C-RAN) architecture, which centralizes baseband processing at a central office (CO) and connects to remote antenna units (RAUs) via fronthaul links [3]. Analog radio-over-fiber (A-RoF) technology is crucial in this setup, enabling the transmission of radio frequency signals over optical fibers. A-RoF simplifies the network infrastructure, reduces power consumption, and improves bandwidth efficiency, making it an essential component for the high-performance requirements of B5G networks [4].

As the network complexity and density increase, power distribution becomes increasingly critical. In this context, power-over-fiber (PoF) is a promising solution for replacing copper-based technologies, such as power-over-Ethernet (PoE), which suffer from electromagnetic interference, voltage fluctuations, and distance limitation. This technique involves the transmission of high-power light over optical fibers and converting it into electrical power [5]. The integration of RoF and PoF technologies gives rise to a radio- and power-over-fiber (RPoF) system, enabling reliable power distribution and high-speed communication over optical fiber infrastructure. RPoF systems have been implemented in various scenarios: using a single optical fiber for both power and data with single-mode fibers (SMFs), which can suffer from non-linear effects [6], or with multimode fibers (MMFs) that handle higher power but may limit data rates [7]. Alternatively, using separate fibers for data and power reduces interference but increases cost and complexity [8]. We propose a hybrid approach using double-clad fibers (DCFs), where the single-mode core transmits data and the larger inner cladding handles high optical power.

Despite significant advancements being achieved in PoF systems based on DCFs [5], [9], no studies have yet reported their use for powering small cells or RAU components. This study aims to address this gap by evaluating the feasibility of using PoF to optically power critical components for signal reception within a C-RAN architecture. Specifically, we demonstrate the simultaneous transmission of a 5G new radio (NR) signal centered at 26 GHz and over 20 W of optical power using a 250-m DCF link. Furthermore, we evaluate the PoF system efficiency and stability and analyze the impact of high optical power transmission on 5G NR signal performance using 3$^{\text{rd}}$ Generation Partnership Project (3GPP) root mean square error vector magnitude (EVM$_{\text{RMS}}$) requirements.

II. EXPERIMENTAL SETUP

Fig. 1 illustrates the block diagram of the proposed RPoF system using a DCF link to simultaneously transmit data and power. In this setup, the CO contains the transmitters for both A-RoF and PoF systems. The 5G NR waveform is generated by an arbitrary waveform generator (AWG) with up to 400 MHz bandwidth and up-converted to 26 GHz using a vector signal generator (VSG). This signal is modulated onto an optical carrier by a Mach-Zehnder modulator (MZM), driven by a power source (PS), and transmitted by a standard SMF. In parallel, a high-power laser diode (HPLD) provides optical power for PoF transmission using a 105/125 μm MMF. The system employs a bidirectional DCF coupler to combine and route the data signal (Port A) and power (Port B) to the DCF respective core (9 μm) and inner clad (105 μm) (Port

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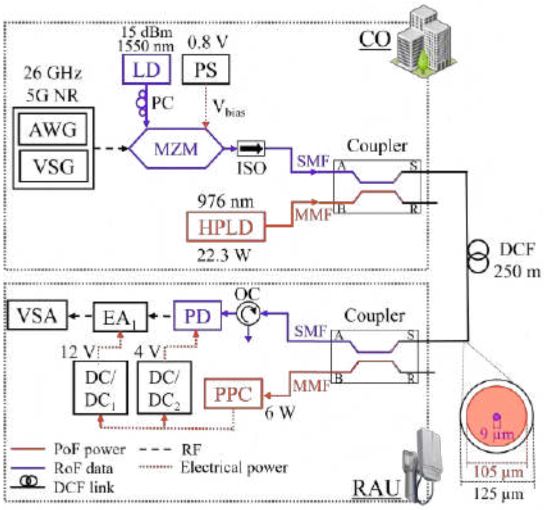

Fig. 1. Block diagram of the proposed DCF-based RPoF system.

S). The optical isolator is used to prevent damage from back reflections.

Following the transmission through the 250-m DCF link, the signals are routed through a second coupler to separate the light from the core and inner cladding. The transmission loss from Port S to Port A is about 0.5 dB, while the efficiency from Port S to Port B is less than 55%. During testing, high power leakage from Port S to Port A was observed, potentially affecting the A-RoF system performance and risking damage to the photodetector (PD) due to its power limits. To address this challenge, an optical circulator (OC) was used to route the 1550 nm A-RoF carrier while suppressing the 968 nm leakage. Alternatively, a narrow-band filter could have been used. The A-RoF optical carrier is then received by a 30-GHz PD for O/E conversion, with signal amplification by a 35-dB gain electrical amplifier (EA). Simultaneously, the PoF feed light is converted to electrical power by a photovoltaic power converter (PPC), which powers the PD and EA. The PPC has a conversion efficiency of 26-30% and an output voltage of about 18 V. Two DC/DC converters regulate the voltage for the different components (4 V to the PD and 12 V for the EA). This setup provides simultaneous powering of all the RAU active components, thereby enabling a fully optically-powered A-RoF solution.

III. EXPERIMENTAL RESULTS

Fig. 2 displays an experimental setup photograph. Our investigation into the performance of the RPoF system is based on the PoF system characterization and EVM_{RMS} measurements of the 5G NR signal. Firstly, we have calculated the PoF system power transmission efficiency (PTE) performance metric, which is defined as the ratio between the HPLD power injected into the PoF link and the PPC output electrical power [5]. For each power level injected into the PPC, an optimum load was set on an electronic load (N3300A, Keysight) to ensure the maximum power point (MPP). Our experimental results indicated an average PTE of 6.6%. This value could be attributed to the PPC low conversion efficiency (26-30%) and the optical losses. The measured losses include approximately 1 dB between the HPLD and coupler (including splices, connectors, and adapters), 1 dB (Port B to S) and 2 dB (Port S to B) in bidirectional couplers, and 1.25 dB for the 250-m DCF link. In order to ensure stable operation, we have conducted a stability analysis by measuring the voltage levels at the PD and EA input over 2 hours, as presented in Figure 3. The measured average voltage levels at the input of the PD and EA were 3.9892 V and 11.996 V, respectively. The small standard deviations associated with these measurements, i.e., 0.00093 V for the PD and 0.00042 V for the EA, indicate minimal variation in the voltage levels. We have generated enough power to supply the PD and EA, which required 1.3 W of electrical power. Considering losses in DC/DC converters and load mismatch, the PoF system required an output electrical power of approximately 1.5 W, resulting in 22.3 W of transmitted optical power for effective RPoF system operation.

In order to evaluate the impact of simultaneous feed light transmission on our 5G NR system, we have conducted a performance analysis based on EVM_{RMS} and throughput measurements in accordance with the 3GPP Release 18 [10]. Fig. 4 displays the EVM_{RMS} penalty, which is defined as the EVM_{RMS} difference between propagation with and without simultaneous 22.3-W feed light. One may notice that the EVM_{RMS} penalty is less than 0.02%, meaning that the simultaneous transmission of the 22.3 W feed light did not

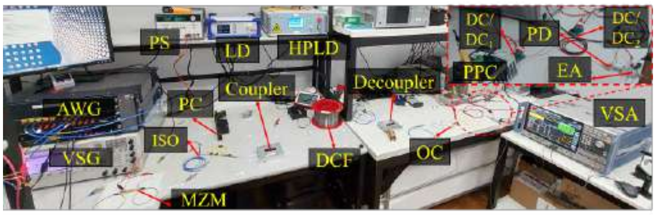

Fig. 2. Photograph of the experimental RPoF system setup.

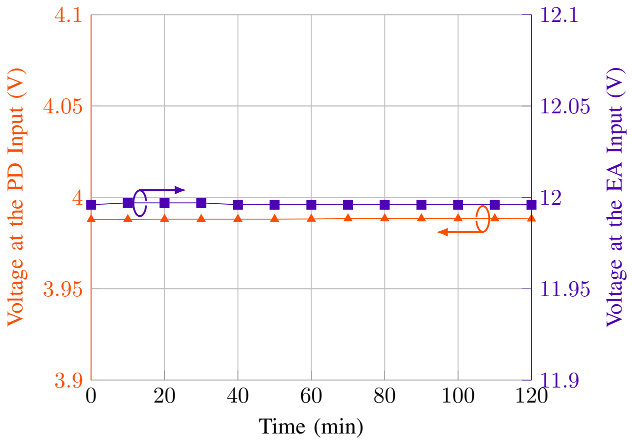

Fig. 3. Voltage level measurements at the PD and EA inputs, respectively, over a 120-minute period.

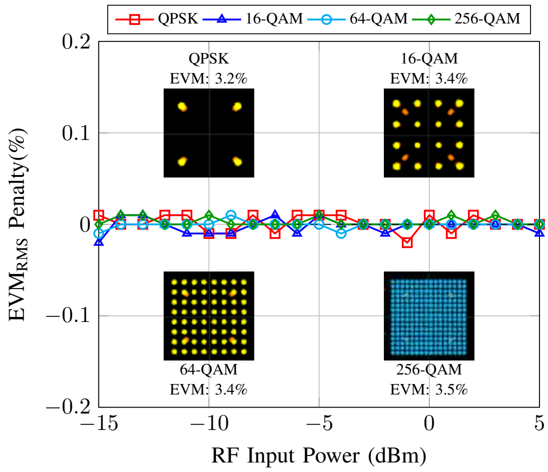

Fig. 4. $\mathrm{EVM_{RMS}}$ penalty measurements as a function of the RF input power for a 50-MHz bandwidth 5G NR signal centered at 26 GHz transmitted with and without simultaneous feed light transmission (22.3 W). The insets display the constellations and EVM values for QPSK, 16-QAM, 64-QAM, and 256-QAM at 5-dBm RF input power.

impact the integrity of the 5G NR data signal. The insets in Fig. 4 also demonstrate that the proposed RPoF system met the 3GPP requirements for all tested modulation schemes, i.e., quadrature phase shift keying (QPSK), 16-quadrature amplitude modulation (QAM), 64-QAM, and 256-QAM, for a 50-MHz bandwidth 5G NR signal centered at 26-GHz at 5-dBm RF power.

Table I presents the $\mathrm{EVM_{RMS}}$ and throughput results for the 5G NR system across different modulation schemes and bandwidths. The table lower section displays the $\mathrm{EVM_{RMS}}$ maximum values as specified by 3GPP, i.e., 17.5%, 12.5%, 8%, and 3.5% for QPSK, 16-QAM, 64-QAM, and 256-QAM respectively [10]. Both QPSK and 16-QAM modulations met the 3GPP $\mathrm{EVM_{RMS}}$ requirements for all frequency range (FR) 2 bandwidths (up to 400 MHz). For QPSK, the $\mathrm{EVM_{RMS}}$ ranges from 3.2% to 9%, with a maximum throughput of 800 Mbps. For 16-QAM, the $\mathrm{EVM_{RMS}}$ ranges from 3.4% to 9.5%, with a maximum throughput of 1.6 Gbps. On the other hand, the 64-QAM scheme meets the 3GPP limits up to 200 MHz, with $\mathrm{EVM_{RMS}}$ values ranging from 3.4% to 6.6% and throughput from 300 Mbps to 1.6 Gbps. In contrast, the 256-QAM only meets the $\mathrm{EVM_{RMS}}$ requirement up to 50 MHz, with $\mathrm{EVM_{RMS}}$ values of 3.5% and throughput of 400 Mbps.

TABLE I
$\mathrm{EVM_{RMS}}$ AND THROUGHPUT RESULTS FOR THE 5G NR SYSTEM.

BW [MHz]	Modulation scheme							
	QPSK		16-QAM		64-QAM		256-QAM	
	EVM (%)	Gbps	EVM (%)	Gbps	EVM (%)	Gbps	EVM (%)	Gbps
50	3.2	0.1	3.4	0.2	3.4	0.3	3.5	0.4
100	4.7	0.2	4.9	0.4	5	0.6	-	-
200	6	0.4	6.6	0.8	6.6	1.2	-	-
400	9	0.8	9.5	1.6	-	-	-	-
3GPP ⇒	17.5%		12.5%		8.0%		3.5%	

IV. CONCLUSIONS

This work has successfully demonstrated an RPoF system using a 250-m DCF link for transmitting over 20-W optical power and a 5G NR signal centered at 26 GHz. The proposed PoF system effectively delivered stable electrical power to critical components of the A-RoF system, namely PD and EA. Our performance analysis, considering different modulation schemes, demonstrated that the simultaneous optical power transmission did not cause any impact on the 5G NR signal performance. Overall, our RPoF system achieved a throughput of 1.6 Gbps and PTE of 6.6%. Future works will focus on the improvement of PTE by using high-efficiency PPCs and reducing optical losses.

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