Article

Demonstration of a Hybrid Analog–Digital Transport System Architecture for 5G and Beyond Networks

Konstantina Kanta 1,*, Panagiotis Toumasis 1, Kostas Tokas 1, Ioannis Stratakos 1, Elissaios Alexis Papatheofanous 2, Giannis Giannoulis 1, Ioanna Mesogiti 3, Eleni Theodoropoulou 3, George Lyberopoulos 3, George Lentaris 1, Dimitris Apostolopoulos 1, Dionysis Reisis 2, Dimitrios Soudris 1 and Hercules Avramopoulos 1

Abstract: In future mobile networks, the evolution of optical transport architectures enabling the flexible, scalable interconnection of Baseband Units (BBUs) and Radio Units (RUs) with heterogeneous interfaces is a significant issue. In this paper, we propose a multi-technology hybrid transport architecture that comprises both analog and digital-Radio over Fiber (RoF) mobile network segments relying on a dynamically reconfigurable optical switching node. As a step forward, the integration of the discussed network layout into an existing mobile infrastructure is demonstrated, enabling the support of real-world services through both standard digital and Analog–Intermediate Frequency (IF) bridge for the transmission of legacy traffic over the analog network segment. The experimental evaluation of the proposed concept was based on the dynamic optical routing of the legacy Common Public Radio Interface (CPRI), 1.5 Gbaud analog-intermediate frequency-over-fiber (A-IFoF)-based converged fiber–wireless paths. Emphasis has been placed on the implementation of a real-time A-IFoF transceiver that is employed through a single embedded fully programmable gateway array (FPGA)-based platform that serves as an Ethernet to Intermediate Frequency (IF) bridge for the transmission of legacy traffic over the analog network segment. Finally, the end-to-end proof-of-concept demonstration of the proposed solution was achieved through the delivery of 4K video streaming and Internet Protocol (IP) calls over a mobile core network.

Keywords: 5G; A-IFoF; digital signal processing (DSP); FPGA; orthogonal frequency division multiplexing (OFDM); hybrid analog/digital; transceiver; mmWaves; fiber-wireless; fronthaul

1. Introduction

With the rise of Smart Building, Smart Cities and Industry 4.0, future mobile networks will encounter the challenge of delivering enormous data rates for the interconnection of a massive number of machines and user devices. Gbit per second scale user connectivity, along with low latency reliability, dynamicity and fast service deployment times, are some of the critical requirements that drive the evolution towards the Beyond-5G (B5G) era [1,2]. In order to deliver a plethora of advanced services with much variation of the delivery of key performance indicators (KPIs), fronthaul networks should evolve to provide flexible, high-bandwidth and low-latency connectivity to the remote radio heads (RRHs), adopting...
architectural transformations that will lead to enhanced scalability and interoperability with Wireless Fidelity (Wi-Fi), fixed and cloud networks [3].

Within the already mature, digitized fronthauling environment, it is inevitable that Common Public Radio Interface (CPRI)-based links will remain the most common interface for the interconnection between the baseband units (BBUs) and the Remote Radio Heads (RRHs), despite the inherently limited bandwidth efficiency of the CPRI protocol and the flexibility limitations that have been widely discussed during the past years [4]. Nonetheless, a series of brand-new technological enablers have arisen, promising large bandwidth availability, flexibility and easy deployment, hence increased scalability. More specifically, the adoptions of large unlicensed bands at high radio frequencies (i.e., V-band, D-band) have combined to advanced radio techniques (such as cooperative beamforming and massive multiple input–multiple output (MIMO) transmission) and the embracement of photonic processing/networking solutions seems to be a promising path towards surpassing the capacity and scalability bottleneck of the current deployments. On top of that, innovative beyond-CPRI fronthaul alternatives, such as the analog radio-over-fiber (A-RoF) and sigma-delta-over-fiber (SDoF) schemes have been widely visited as possible candidates to host these technological blocks, showcasing the Gbps scale connectivity over fiber and converged wired–wireless topologies [5,6]. As such, it is essential to migrate to a network infrastructure that can efficiently integrate the various heterogenous technologies and enable the internetworking of the existing small cells and future deployment extensions.

For the implementation of such densified and versatile network deployments, cloud radio access networks (C-RAN) are highly attractive, as they offer greater network scalability, efficient transport and increased network function virtualization (NFV) [4]. The cloud-based virtual BBUs (vBBUs) can support the dynamic allocation of baseband processor platform resources based on the traffic demand. Within this centralized, reconfigurable universe the vBBUs can concurrently and interoperably accommodate heterogeneous, remotely located radio units that are equipped with different interfaces, reached via the already existing optical paths or those that are beyond-legacy, currently emerging optical transport schemes. The adaptation of the optical transport architectures, interconnecting central units (CUs), distributed units (DUs) and RUs in this ever-changing, multi-technology ecosystem has been widely discussed during the past years [7]. Specifically, the transition to hybrid topologies co-hosting inhomogeneous transceivers and protocols in a transparent manner while interconnecting BBUs and RUs in a versatile and reconfigurable way is necessary [7,8]. For this purpose, the current static point-to-point (PtP) optical interconnection of a single BBU with an RRH should evolve and be replaced with scalable, Point-to-Multi-Point (PtMP) layouts offering wavelength aggregation and the reconfigurable routing of variable types of waveforms and protocols.

The concept of evolving optical transport networks in order to support multiple traffic streams that are addressed for varying radio terminals has been explored in [9]. More specifically, the use of optical networking segments to setup and orchestrate the BBU–DU–RU interconnection has been recently discussed through the literature as a practical solution for the support of active functionalities across the optical edge of mobile networks [10–13]. At the same time, the exploitation of optical switching-enabled hybrid transport layouts that are handling standardized legacy traffic has been showcased in [3,13–15], including, for example, the concurrent transmission of multiple CPRI lanes in [13] or the coexistence of 5G, passive optical network (PON) and datacenter (DC) traffic in [3]. Inspired by these works, similar architectures could accommodate reconfigurable fiber and fiber–wireless (FiWi) transport architectures, relying on the flexible point-to-multipoint (PtMP) connectivity of both analog and digital centralized transceivers with variable radio units, located anywhere in the field.

During the past years, the adoption of new fiber transmission schemes along the standard Digital-Radio over Fiber (D-RoF) solution has been explored in lab-scale experiments targeting the demonstration of mixed analog and digital formats’ propagation over shared fiber infrastructure [9] aiming to show the benefits of hybrid A/D-RoF fronthauling.
In this direction, [12] discusses the employment of an Arrayed Waveguide Grating Router (AWGR)-enabled PtMP transport topology, aggregating and steering A-RoF traffic to the radio units. Although these experiments highlight the potential adoption of beyond-CPRI schemes in multi-tenant transport networks, the actual integration of these solutions, employing both standard and analog optical transceivers, in a mobile core network as well their seamless operation in true mobile services is far beyond their scope. At the same time, the employment of traffic-transparent optical networking units to host such hybrid transport architectures has scarcely been reported in the literature.

In this paper, we present a hybrid transport system architecture comprising both standardized and beyond-CPRI mobile transport segments via a reconfigurable wavelength aggregation optical node. The demonstrated architecture focuses on the accommodation of heterogeneous mobile traffic streams stemming not only from standard digital optical transceivers but also from a custom Fully Programmable Gateway Array (FPGA)-based A-IFoF transceiver within a transparent optical layout. The mixing of legacy and currently evolving transport technologies was achieved via a software defined networking (SDN)-enabled node supporting spatial–spectral flexible switching functionalities. The employed hybrid optical node enabled the co-integration of four individual network segments, some of them carrying real-world application services, after the integration of the demonstrated setup into the mobile network operator (MNO)’s infrastructure. The MNO’s equipment was interconnected through the CPRI interface and it enabled the delivery of services over mobile phones, including 4K video streaming and Internet Protocol (IP) calls over both fiber and converged fiber–wireless paths. Finally, the successful operation of the presented topology was verified via physical layer performance evaluation metrics including the acceptable EVM values for complex radio waveforms and error-free operation of the binary optical streams.

The remainder of the present manuscript is structured as follows: Section 2 introduces the concept of the Wavelength Selective Switch (WSS)-enabled hybrid node and the architecture of the proposed dynamically reconfigurable transport network segment, while Section 3 presents the implementation of a converged Fiber-Wireless (FiWi) fronthaul layout, based on the development of a real-time A-IFoF transceiver. Section 4 provides the transmission performance measurements of the implemented A-IFoF transceiver and presents its integration over deployed MNO infrastructure. In Section 5 the experimental demonstration of the proposed hybrid transport network segment is elaborated on. Finally, Section 6 summarizes and concludes the manuscript.

2. Concept and Proposed Architecture

The development of architectures, technologies, interfaces and networks for 5G fronthaul has gained significant attention from both academia and industry in the last few years [16]. The migration to flexible, dynamically reconfigurable transport network segments, enabled by wavelength division multiplexing (WDM) programable optical nodes, is a necessary step for the flexible interconnection of the centralized BBU pools and multiple radio units that are distributed in the field. More specifically, the standard interconnection between each single BBU with its corresponding RU has reached a bottleneck in terms of capacity growth, the adoptability of emerging technologies and the efficient utilization of centralized resources [17,18]. The above limitations are inseparably connected to the static nature of PtP fronthaul connectivity. As such, PtMP architectures have been recently investigated throughout the literature, promising flexible bandwidth steering and the dynamic management of resource allocation among edge and radio sites, based on the traffic demand [19–21].

Inspired by the legacy of WDM-PON networking [22,23], the use of optical switching and wavelength aggregation units can host the evolving heterogeneous PtMP fronthauling. Benefiting from the low-loss, protocol agnostic and SDN-compatible characteristics that they offer, WDM nodes can transparently aggregate disparate optical transmission schemes (D-/A-/SDoF) and modulation formats, enabling heterogeneous deployments.
that comprise both fiber and converged FiWi lanes. Therefore, such architectures are capable of the co-hosting of heterogeneous fronthaul segments and radio terminals in a cooperative manner, enabling the synergy of multiple BBUs to concurrently provide enhanced capacity to selected radio sites (i.e., for hot-spot use cases) or the exploitation of advanced newly deployed RRHs that are operating at the mmWaves by varying the MNO’s baseband equipment. In a few words, WDM-based transport deployment enables the adaptive transformation of baseband-to-radio hardware internetworking, based on the occurrence of a plethora of services with varying requirements [24,25].

Our proposed solution, which is schematically illustrated in Figure 1, aims to showcase a hybrid optical fronthaul architecture that can allow for the dynamic interconnection of central offices with RRHs (and vice versa) via both digital and analog paths. An optical node that is based on an SDN-compatible WSS was employed supporting WDM and space division multiplexing (SDM) functionalities for the dynamic distribution of the traffic to the radio sites. In detail, the proposed approach relies on the coexistence of the following fiber and FiWi fronthaul implementations:

- Legacy CPRI connectivity in which the data transmission is carried out by fragmenting and encapsulating the radio data using well-established standards such as IP or Ethernet. The resulting data stream can then be multiplexed with the other network traffic, switched in Ethernet switches and routed in IP routers (Long-Term Evolution (LTE)/4G).
- Broadband binary streams for digital optical links for 5G connectivity scenarios as in 5G-oriented RAN. Intensity modulation/direct detection (IM/DD) systems with digital modulation formats such as non-return-to-zero (NRZ) and 4-level pulse amplitude modulation (PAM-4) are promising candidates.
- 5G A-IFoF implementations which are spectrally efficient transport schemes and can support extremely high capacities.

![Figure 1. A WSS-based hybrid optical transport architecture.](image)

**3. Analog Fronthaul Based on the Development of a Real-Time A-IFoF Transceiver**

As discussed in the previous sections, in order to surpass the bandwidth bottleneck of 5G fronthaul networks, two alternative approaches have emerged. The first one considers the evolution of the current D-RoF fronthaul through moving the functionality and processing stages to the RUs or to intermediate DUs resulting in new protocols, such as the enhanced CPRI (eCPRI). The second approach involves the migration to analog fronthauling solutions and goes far beyond the propagation of digitized on-off keying (OOK) streams, leaving room for transmission enhancements by the physical layer modifications that are driven by the adoption of emerging technologies and innovative layouts. [26]

While the evolution of eCPRI interfaces is driven by industry cooperation that is aimed at defining publicly available specifications [27] mainly from the market consensus [28], A-RoF interfaces have been revisited in the past years by academic and research groups that are targeting bandwidth-efficient fronthaul interfaces. Beyond these lab-scale experiments
and demonstrations, in the last years the RoF systems that are suitable for access network applications have been also moved towards the standardization phase [29]. The key for A-RoF systems to further penetrate into the application and market landscape is the use of deployment-oriented A-RoF baseband processors that are based on state-of-the-art processor platforms and their interfacing with optoelectronics.

Through the past years, multiple A-IFoF fronthaul implementation ideas have been presented in this direction [26,30,31]. In all of these implementations, the efficiency of the scheme in densified deployments, stemming from the removal of digital-to-analog conversion (DAC) and analog-to-digital conversion (ADC) units from the RUs, the advanced bandwidth availability and the possibility for the convergence of multiple optical and radio technologies have been highlighted and demonstrated through proof-of-concept experiments. Indicatively, an A-RoF fronthaul implementation, which is based on the development of a real-time A-IFoF signal processor, has been recently reported in [26] employing an Intel Arria 10 SoC development board that provides Cyclic Prefix-OFDM (CP-OFDM) signals for external baseband (BB)-to-intermediate frequency (IF) up-conversion through an analog mixing unit that is operating in the range of 2.25 GHz to 5.5 GHz. In general, the coexistence of both analog and legacy optical transceivers in the same core infrastructure remains a challenging step for the migration to hybrid transport implementations [32,33]. For this purpose, real-time reconfigurable FPGAs have been investigated as Ethernet-compatible baseband processor platforms for the creation and processing of IF-upconverted signals and their integration into legacy infrastructures for the delivery of real-world services [34].

In the next paragraph, the implementation of an A-IFoF transceiver comprising a state-of-the-art Radio Frequency System-on-Chip (RFSoC) board for the baseband processing functionalities and low-cost IM/DD optoelectronic components is described. The key part of the transceiver implementation was the FPGA-based real-time network adaptor (Figure 2) that served both as an Ethernet bridge and as a DSP engine. The full stack of DSP functions was implemented in order to realize efficient fiber/Over-the-Air (OTA) transport through OFDM waveforms. A network adapter was implemented in order to realize the conversion of the Ethernet packets into complex native radio waveforms (and vice versa) via a single integrated, high power and efficient RFSoC platform. This platform (a Xilinx Zynq UltraScale+ RFSoC device on a ZCU111 development board, manufactured by Xilinx (San Jose, CA, USA) [30]) consisted of a 10G/25G Ethernet core, an FPGA board and DACs/ADCs and it served as a bidirectional Ethernet to IF-upconverted OFDM bridge. The developed platform implemented the Ethernet en/de-capsulation of the data, the baseband processing in both the transmitter (Tx) and receiver (Rx) sides and the interfacing with the optoelectronic units transferring analog radio waveforms. The details of each implementation block are briefly discussed below:

- **Ethernet en/de-capsulation**: RFSoC has increased capabilities in terms of its Gigabit Ethernet connectivity, as its Gigabit transceivers (GTY) can support up to 25 G Ethernet with the MAC and physical coding sublayer (PCS) that are implemented on the FPGA fabric. The Ethernet core performed data link layer functionalities in order to map the incoming Ethernet traffic to the DSP engine, as well as to recover the Ethernet frames from the demodulated waveforms. These functionalities include basic error handling, flow control for access to the physical layer, frame encapsulation and virtual local area network (VLAN) tagging.

- **Baseband processing**: The signal processing functions of the implemented A-IFoF transceiver were executed within the FPGA fabric of the RFSoC platform. The multiple lane processing of up to 4 independent data streams was applied for low-latency implementation. Two independent and identical transmitter/receiver side DSP block chains were developed within the RFSoC for the establishment of full-duplex connectivity. At the transmitter side, the incoming bit-stream was initially mapped to quadrature phase shift keying (QPSK) symbols, while the OFDM signals were generated using a fixed 256-tap inverse frequency Fourier transform (iFFT) algorithm. The FPGA clock was
highly linear optoelectronic units were used in order to realize an IM/DD communication strategy for the optical segment. In more detail, the use of an electro-absorption modulated laser (EML)-based analog IFoF transmitter was selected as a cost effective, integrated solution that has been extensively proposed for the emerging densified 5G network topologies [35]. Commercial off-the-shelf photoreceivers were used in order to detect the analog optical signals, thereby providing the radio waveforms to the mixer stages of the mmWave boards. As such, the specific power consumption details of each stage of the transceiver are presented in Table 1. Apparently, the conversion of the digital streams to analog signals and vice versa is the most power-consuming process.

The evaluation of the presented A-IFoF transceiver design was initially performed through the investigation of latency and power-consumption measurements (Table 1). The execution time for the accomplishment of the transmitter-side processing functions for each stream was measured to be 5 usec and the execution time for the receiver-side processing was found to be 9 usec. Given that the wireless signal propagation delay is negligible, compared to the fiber transmission delay (5 usec/km for standard single mode fiber (SSMF)), the fiber transmission length was the main contributing factor to the total delay budget of the experiments. As a result, even for ultra-reliable and low-latency communication (URLLC) applications with up to 100 usec of latency requirements for one way transmission delay [36], optical propagation distances of up to 18 km can be supported by our
presented solution. Furthermore, the power consumption of the technology solutions that are involved in A-IFoF-based transport implementations is a key feature. As such, the specific power consumption details of each stage of the transceiver are presented in Table 1 in which it is apparent that the conversion of the digital streams to analog signals and vice versa was the most power consuming process of the RFSoC, whilst the RF amplifications that were connected to the electro–optic components also contributed to a fair share of the power consumption.

Table 1. Power Consumption per Unit.

| Unit                     | Power Consumption (Watt) |
|--------------------------|--------------------------|
| RFSoC                    | 2.3                      |
| CPUs (used for signal performance monitoring) | 2.7                      |
| RFSoC clocks             | 1.2                      |
| DAC/ADC units            | 3.3                      |
| Optical modulation       | 1.5                      |
| Photoreceiver            | 2.07 (Driver) + 0.2 (EML)|

4. Custom A-IFoF Transceiver Preliminary Evaluation and Integration to Deployed MNO’s Infrastructure

Figure 3 shows that the experimental setup used an initial evaluation of a FiWi link, involving the Tx side of the presented transceiver, the RFSoC board serving as signal generator and the EML unit for optical modulation. These measurements and their off-line post-processing have also been the baseline for the definition of the real-time receiver side DSP development. To explore the reconfigurability potential of the platform, in this set of measurements the FPGA clock was real-time adjusted at 256 MHz or 500 MHz, corresponding to the transmission of 204 MHz or 394 MHz of useful bandwidth after zero-padding (52 out of 256 sub-carriers). The above band sizes were selected having in mind the latest 3GPP new radio (NR) specifications [37]. Furthermore, the modulation format of the sub-carriers was real-time adjusted to QPSK or 16-quadrature amplitude modulation (QAM16). Employing the digital up-conversion stage of the DAC board, a complex OFDM-based radio waveform at an intermediate frequency (IF) of 750 MHz was generated.

The complex radio was then fed to a frequency translation stage in order to further upconvert the IF to 3.5 GHz through an analog active mixer. The additional mixing stage enabled the modification of the IF value by adding one more degree of flexibility to the setup. The output of the active mixer was then connected to the RF port of a bias tee that was responsible for driving the electro-absorption modulator (EAM) segment of the EML. The driving voltage for the EAM section of the chip was set at 560 mVpp, whereas the reverse bias voltage of “−” 0.63 V was used to ensure linear operation. The laser segment of the EML was injected with a 110 mA current while it operated at 23.6 °C, providing + 2 dBm of optical power at the emission wavelength of 1560.42 nm. The optical output

Figure 3. FiWi transmission experimental setup that was used in the initial performance evaluation of the implemented A-IFoF transceiver.
was then transmitted over a fiber spool of SSMF. The IFoF signal of $-3.5 \text{ dBm}$ was detected by an off-the-shelf 14 GHz linear photoreceiver after its propagation over a 25 km SSMF spool. The photoreceiver output was connected to the IF-to-mmWave upconverter radio board that was operating at 60-GHz and a V-band directional transmitter-side antenna module (Tx-antenna). An identical receiver side antenna module (Rx antenna) that was located at a 3 m horizontal distance was used to receive the mmWave radio waveforms. Both of the commercial V-band radio [38,39] components operated at 60 GHz and allowed for OTA transmission, while the standard pyramidal gain horn antennas featured 23 dBi gain and $10^\circ$ beamwidth. At the receiver side, an off-line DSP was applied to the signal, including the demodulation of the received OFDM symbols, as well as a ZF equalization algorithm. For the channel estimation, 21 pilot sub-carriers that were multiplexed with the data subcarriers were also transmitted.

Figure 4 depicts the EVM performance of the transmitted OFDM-based IFoF signals after the 7 km and 25 km fiber link as well a set of constellation diagrams that were obtained after the post-processing chain. Taking into account that the EVM measured at the electrical Tx output was 3% for the QPSK-OFDM format and 3.9% for the QAM16-OFDM signals, the short reach optical part of the setup, including the EML, the 7 km SSMF and the 14 GHz photoreceiver, degraded the 204 MHz signal’s performance by 3.8% (for the QPSK-OFDM) and 3.7% (for the QAM16-OFDM) and the 398 MHz signal’s EVM by 4.3% (for the QPSK-OFDM) and 4.5% (for the QAM16-OFDM), indicating the absence of strong limiting effects related to the active electro–optic module’s response or to the fiber transmission. By extending the fiber spool link from a 7 km to 25 km fiber link, the obtained EVM penalty was slightly increased by less than 2.5%. This added EVM penalty mainly originated from the lower received optical power that was linked with the fiber loss, since the dispersion-induced power fading can be neglected for this low IF carrier frequency [34].

![EVM diagrams](image_url)

**Figure 4.** (a) EVM values for 204 MHz Bandwidth (BW) after 7 km and 25 km fiber transmission, (b) Constellation diagrams for 204 MHz BW after 7 km and 25 km fiber transmission, (c) Constellation diagrams for 398 MHz BW after 7 km and 25 km fiber transmission and (d) EVM values for 398 MHz BW after 7 km and 25 km fiber transmission.

The second part of the present experimental study focused on the performance evaluation of a DL scenario by exploiting the deployed fiber–wireless fronthaul topology. Figure 5 illustrates an EVM bar diagram of the QPSK-OFDM and QAM16-OFDM modulated radio for both the 204 MHz and 398 MHz bands after 25 km of fiber transmission and OTA transmission over a 3 m horizontal distance using V-band radio equipment. The introduction of the active V-band radio part and the link caused an increase in the EVM performance of our link by less than 1.1% for the 204 MHz band, whilst the EVM performance was degraded by less than 2.5% for the wider version of radio bands at the 398 MHz band. The above EVM penalties are mainly associated with the IF/mmWave radio boards that included power amplifiers (PAs) and complex frequency translation stages. It should be also mentioned...
that the higher order QAM OFDM waveforms that were occupying wider bandwidths suffered from severe distortion that was reflected into their higher EVM values, while the presence of nonlinear distortion was also evident in all of the 16-QAM constellation diagrams. Nevertheless, the transmission in all of the cases was successful according to the 3GPP specifications [33].

Figure 5. (a) EVM values for 204 MHz BW after 25 km fiber–V-band wireless transmission, (b) EVM values for 398 MHz BW after 25 km fiber–V-band wireless transmission and (c) Constellation diagrams for both cases.

The next step of the presented work was to extend the measurements that are described above by also employing the receiver side of the developed A-IFoF transceiver. As a further step, by integrating the real-time transceiver over an existing mobile infrastructure the acquired measurements go beyond the EVM-based physical performance evaluation of the deployed setup by demonstrating the delivery of real-world services. The employed experimental setup is illustrated in Figure 6. The existing mobile infrastructure of Greece’s largest mobile network operator (COSMOTE) was exploited, which (among other features) includes an evolved packet core (EPC) and a small cell. Between these two network units, the FPGA-based converged A-IFoF–mmWave setup was interposed. For the generation of the downlink/uplink (DL/UL) complex OFDM signals, two pairs of DACs and ADCs were employed for their digital up- and down-conversion at 1.5 GHz IF. RF baluns were also used for the conversion of the DACs/ADCs’ differential inputs/outputs to single-ended, resulting in the generation of 350 mVpp RF signals at the outputs of the RFSo, C. A digital amplification stage at the ADC units offered the flexibility of receiving voltage swings varying between 150 mVpp and 1 Vpp without affecting the reception’s performance.

Moreover, the presented experimental setup was customized so as to emulate three different optical–wireless network layouts. The FiWi and its symmetrical wireless–fiber (WiFi) layouts apply to a bidirectional wired–wireless scenario, while the extended fiber–wireless–fiber (FiWiFi) layout served as a wireless bridge interconnecting the terminals of two spatially separated fiber transport segments [40–42]. It should be noted that, due to the lack of laboratory equipment, the alternative layouts were implemented in one direction, while in the other direction the IF signals were propagated over a passive RF cable. Regarding the WiFi layout, an inverted but symmetrical link of the FiWi layout was implemented, as depicted in Figure 6b. In addition, as it is shown Figure 6c, the FiWi layout was extended with an extra EML and a photoreceiver in order to setup the FiWiFi layout and evaluate its performance. It should be also mentioned that the voltage input levels of all of the electro–optic and active RF components were carefully selected in order to ensure their operation in the linear regime.
Figure 6. Experimental setup of (a) FiWi, (b) Wireless-Fiber (WiFi) and (c) FiWiFi downlink segments of the FPGA-enabled EPC-to-small cell interconnection.

Figure 7 shows the EVM results of the received IF signal after its converged FiWi, WiFi and FiWiFi transmission and the corresponding constellation diagrams after real-time processing. The initial signal that was generated by the RFSoC exhibited an EVM of 2.7% (Figure 7a), while the use of the optical and RF modules through the FiWi setup introduced an EVM increase of 4.6%. As it was originally expected, the FiWi (Figure 7b) and WiFi (Figure 7c) transmission performances were similar, with an EVM offset of 0.2%. The identical EVM measurements in both links are a strong indication that the active RF/optoelectronic units of the FiWi and WiFi testbeds were operating at their linear region. The extension of the FiWi link with an additional optoelectronic conversion stage was responsible for an increase in the EVM value of 2.3% (Figure 7d) compared to the FiWi case. Nevertheless, in all of the cases the transmission was well below the 3GPP threshold of 17.5% EVM for the successful demodulation of the QPSK modulation [33], indicating the robustness of the proposed A-IFoF–V-band–IFoF transport solution and thus its scale-up capabilities.

Figure 7. EVM measurements and constellation diagrams after (a) btb (b) FiWi, (c) WiFi and (d) FiWiFi real-time transmission, (e) iPerf measurements of the FiWi segment, (f) photo of the implemented testbed and screenshot of 4K video streaming.
Aside from the performance metrics in the physical transport layer, the end-to-end EPC-to-small cell bidirectional connectivity over the presented layouts was presented, using real-world services. Mobile user equipment (MUE) was employed in order to perform Iperf measurements using Transmission Control Protocol (TCP) traffic exhibiting 100 Mbps stable connectivity (Figure 7e). Finally, 4K online video streaming (Figure 7f), uninterrupted live IP-video teleconferences and web browsing were successfully demonstrated over the presented A-IFoF–mmWave network configurations.

5. Experimental Demonstration of the Proposed Hybrid Transport Implementation

Figure 8 illustrates the experimental layout of the implemented hybrid analog–digital optical network topology. The targeted architecture aims to integrate different transport technologies in a shared optical network segment, facilitating the transition from existing PtP links towards 5G connectivity. In detail, as it was explained in Section 2, the proposed approach relies on the coexistence of legacy CPRI connectivity (LTE/4G), broadband binary streams for D-RoF 5G deployments and B5G A-IFoF implementations in order to support extremely high capacities, such as hot-spot areas. The integration of the A-IFoF transport segment implementation that was discussed in the previous two Sections was a significant step for the demonstration of heterogeneous protocols’ coexistence delivering real-world services. Network flexibility was provided using a WSS-based optical node which could handle optical wavelengths that were implementing different transport protocols. This SDN-compatible, dynamically controlled optical switching node allowed for wavelength routing, provided dynamicity to the network and facilitated the protocol-agnostic coexistence of heterogenous streams.

![Figure 8. The 4λ–optical transport experimental layout.](image)

In our proposed WDM-enabled deployment for the implementation of an optical switching node, an arrayed waveguide grating (AWG) followed by an erbium-doped fiber amplifier (EDFA) and a commercial 1 × 4 WSS (NISTICA FFLB-C04L000-4UC) were utilized in order to multiplex and dynamically route four different optical streams. The WSS node was based on the digital light processing (DLP) technology of Texas Instruments [43], which is applied to commercial WSSs by optical component vendor NISTICA (Bridgewater, NJ, USA). The dynamic operation of this optical switching node was achieved by controlling the WSS, being the only active block of the node, through a custom MATLAB 2018a script that was developed for the interface between the SDN agent and the WSS. Its main elements were a “listener” and a “controller”, as shown in the block diagram of Figure 9a. This script could recognize any changes to a common text file (.txt) where the SDN agent wrote the network commands. In this way, the WSS was configured to route the wavelengths to the proper destination output according to the commands in this file. For the purpose of this experiment, the .txt file was changed manually as the configuration script was running.

The optical streams at $\lambda_1$ and $\lambda_2$ that were carrying A-IFoF and optical binary signals, respectively, were used for the physical layer performance evaluation, while the optical
streams at λ3 and λ4 were used for the demonstration of true mobile services. Regarding the RoF transceivers’ implementation, a signal generator (arbitrary waveform generator) was used for the generation of complex up-converted waveforms (A-IFoF) and of the NRZ signals (D-RoF) supporting both sub-carrier multiplexing (SCM) A-IFoF transmission at a center intermediate frequency (IF) of 1.6 GHz and an up to 10 GHz binary optical stream, respectively. The IF up-converted stream was fed to an externally modulated laser (EML) emitting at λ1. After propagation over SMF, the analog stream was detected via a 10 GHz avalanche photodiode (APD), transmitted over a wireless PTP link that was operating at 60 GHz and captured by a real-time oscilloscope (RTO). For the post-processing of the IF waveforms, vector signal analysis (VSA) software was used. The binary stream carrying the D-RoF traffic was modulated via a Mach–Zehnder modulator (MZM) at λ2. After the SMF transmission, the binary stream was detected by a 14 GHz photoreceiver and fed to the RTO. Offline processing involving a 21-tap feed-forward equalizer (FFE) was performed. For the demonstration of the services, the existing mobile infrastructure was exploited. This infrastructure included, among other features, an EPC and a small cell. These two network units were interconnected along the node via 1 Gbps SFP transceivers emitting λ3. Finally, the MNO’s equipment was also used for the delivery of services through A-IFoF waveforms enrolled at λ4 transmitted over a converged FiWi link. In this case, the implemented FPGA-based A-IFoF transceiver reported in [44] served as a bridge for the transmission of the 1 Gbps SFP traffic, modulated by a 10 GHz EML that was emitting at λ4.

**Figure 9.** (a) The SDN interface script for the WSS control, (b) Constellation diagrams corresponding to switching between port 2 and port 3 of WSS, (c) Performance evaluation of λ1 after single and WDM transmission, (d) Evaluation of successful concurrent λ4 transmission.

The WSS-based optical node, described above, exhibited total insertion losses of 11 dB (4.5 dB coming from the AWG and 6.5 dB from the 1 × 4 WSS), for this reason an EDFA was used in order to mitigate the optical loss. Figure 9 comprises the experimental results regarding the performance of the abovementioned different optical node routing RoF transport lanes. Figure 9b shows the constellations and corresponding EVM measurements after the switching of λ1 (SCM A-IFoF stream) between two output ports of the optical node. The EVM difference of 0.8% that was observed in the optical domain only (without the radio boards) can be attributed to the use of the different photoreceivers in the two links. Figure 9c illustrates two different transmission scenarios of a λ1 optical stream, carrying single-band QPSK signals. In the first case, only λ1 is propagated through the optical node, while in the second one, four optical streams are propagated through the node. In the WDM transmission, small EVM differentiations of up to 1.1% were observed, associated with the gain competition on the used EDFA due to the different power levels of the incoming signals.

Figure 9d presents the successful evaluation of the concurrent transmission of four optical streams through the node. The wavelength λ1 was modulated with 3-band QPSK signals of 500 MHz, corresponding to 1.5 GHz analog aggregated radio traffic, and exhibited values well-bellow the 3GPP threshold of 17.5% EVM for the successful demodulation...
of the QPSK modulation after the IFoF–V-band transmission per Argyris et al. [40]. The wavelength $\lambda_2$ was carrying 10 GHz on–off keying (OOK) signals that were emulating 10G D-RoF traffic and the measured Q-factor of 16.8 dB indicated error-free transmission (Bit-error-rate < $10^{-9}$) [37]. The CPRI traffic that was transmitted over $\lambda_3$ was validated with the use of a MUE performing Iperf measurements, exhibiting up to 180 Mbps of stable connectivity. Moreover, 4K online video streaming, uninterrupted live IP-video teleconferences and web browsing were successfully demonstrated over $\lambda_4$ where the A-IFoF–mmWave link was integrated by using the FPGA based A-IFoF platform in [44].

6. Conclusions

To summarize, a hybrid analog–digital optical transport topology that is supported by a dynamic, reconfigurable WSS-based optical switching node has been presented. The targeted architecture aims to integrate different transport technologies in a shared optical network segment, contributing to the transition from the existing PtP fiber-based mobile transport networks to dynamically reconfigurable PtMP architectures with the multiplexing of multiple BBUs and radio hardware, towards B5G connectivity. Targeting beyond the lab-scale demonstration of the proposed node, we demonstrated a multi-technology environment, the co-integration of an A-IFoF Ethernet-compatible transceiver, providing converged FiWi connectivity along with both digital and analog transport lanes over the common flexible, hybrid optical transport layer.

Throughout this work, the implementation path and the performance evaluation of an FPGA-based analog transceiver that is based on a state-of-the-art Xilinx RFSoC platform is extensively described, proving the potential for the successful transmission of reconfigurable bandwidths and modulation formats over fiber and converged FiWi transport links. Thereinafter, we demonstrate the experimental evidence of the dynamic optical routing of both legacy CPRI, 1.5 GBaud A-IfoF–mmWave and 10 Gbps binary optical waveforms, showing acceptable EVM values for the complex radio waveforms and error-free operation of the binary optical streams. Besides these high-capacity transport experiments, 4K video streaming and IP-calls over both the analog and digital lanes were successfully demonstrated, showing the potential of our presented node to dynamically handle high-throughput links and services.

The reported results denote the strong potential of the proposed hybrid optical topology to support future B5G network reconfigurable transport deployments with bandwidth steering capabilities. The demonstrated transport architecture opens the door to the flexible interconnection of centralized BBU pools and multiple RUs distributed in the field over both standard digital and post-eCPRI analog implementations, depending on the service demand.

Author Contributions: Conceptualization, G.G., G.L. (George Lentaris) and D.A.; methodology, all.; software, K.K., I.S. and E.A.P.; validation, all; formal analysis, all; investigation, K.K., P.T., K.T., I.S. and E.A.P.; resources all; data curation, K.K. and P.T.; writing—original draft preparation, K.K., P.T. and I.S.; writing—review and editing, all; visualization, K.K., P.T., K.T. and I.S.; supervision D.R., D.S. and H.A.; project administration, D.A. and H.A.; funding acquisition, H.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Commission H2020 5GPPP Project 5GPHOS, under the grant agreement 761989 and 5G-COMPLETE, under the grant agreement 871900.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.
Acknowledgments: The 60 GHz antenna boards were granted by the WinPhos of Aristotle University of Thessaloniki.

Conflicts of Interest: The authors declare no conflict of interest.

References
1. Saad, W.; Bennis, M.; Chen, M. A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems. IEEE Netw. 2020, 34, 134–142. [CrossRef]
2. Ericsson. A Technical Overview of Time-Critical Communication with 5G NR. Available online: https://www.ericsson.com/en/blog/2022/2/time-critical-communication--5g-nr (accessed on 1 December 2021).
3. Browning, C.; Cheng, Q.; Abrams, N.C.; Ruffini, M.; Dai, L.Y.; Barry, L.P.; Bergman, K. A Silicon Photonic Switching Platform for Flexible Converged Centralized-Radio Access Networking. J. Light. Technol. 2020, 38, 5386–5392. [CrossRef]
4. Alimi, I.A.; Patel, R.K.; Muga, N.J.; Pinto, A.N.; Teixeira, A.L.; Monteiro, P.P. Towards Enhanced Mobile Broadband Communications: A Tutorial on Enabling Technologies, Design Considerations, and Prospects of 5G and beyond Fixed Wireless Access Networks. Appl. Sci. 2021, 11, 10427. [CrossRef]
5. Argyris, N.; Giannoulis, G.; Kanta, K.; Iliadis, N.; Vagionas, C.; Papaioannou, S.; Kalfas, G.; Apostolopoulos, D.; Caillaud, C.; Debergues, H.; et al. A 5G mm-wave Fiber-Wireless IFoF Analog Mobile Fronthaul Link With up to 24-Gb/s Multiband Wireless Capacity. J. Light. Technol. 2019, 37, 2883–2891. [CrossRef]
6. Li, H.; Breyne, L.; Van Kerrebrouck, J.; Verplaetse, M.; Wu, C.-Y.; Demeester, P.; Torfs, G. A 21-GS/s Single-Bit Second-Order Delta-Sigma Modulator for FPGAs. IEEE Trans. Circuits Syst. II Express Briefs 2019, 66, 482–486. [CrossRef]
7. Zou, J.; Magee, A.; Eiselt, M.; Straw, A.; Edwards, T.; Wright, P.; Lord, A. Demonstration of X-Haul Architecture for 5G over Converged SDN Fiber Network. In Proceedings of the 2018 Optical Fiber Communications Conference and Exposition (OFC), San Diego, CA, USA, 11–15 March 2018; pp. 1–3.
8. Agarwal, V.; Sharma, C.; Shetty, R.; Jangam, A.; Asati, R. A Journey Towards a Converged 5G Architecture & Beyond. In Proceedings of the IEEE 4th 5G World Forum (SGWF), Montreal, QC, Canada, 13–15 October 2021; pp. 18–23.
9. Yoo, S.; Chen, Y.-W.; Su, S.-J.; Alfageme, I.; Vagionas, C.; Papaioannou, S.; Kalfas, G.; Apostolopoulos, D.; Caillaud, C.; Debergues, H.; et al. A 5G mm-wave Fiber-Wireless IFoF Analog Mobile Fronthaul Link With up to 24-Gb/s Multiband Wireless Capacity. J. Light. Technol. 2019, 37, 2883–2891. [CrossRef]
10. Li, H.; Breyne, L.; Van Kerrebrouck, J.; Verplaetse, M.; Wu, C.-Y.; Demeester, P.; Torfs, G. A 21-GS/s Single-Bit Second-Order Delta-Sigma Modulator for FPGAs. IEEE Trans. Circuits Syst. II Express Briefs 2019, 66, 482–486. [CrossRef]
11. Zou, J.; Magee, A.; Eiselt, M.; Straw, A.; Edwards, T.; Wright, P.; Lord, A. Demonstration of X-Haul Architecture for 5G over Converged SDN Fiber Network. In Proceedings of the 2018 Optical Fiber Communications Conference and Exposition (OFC), San Diego, CA, USA, 11–15 March 2018; pp. 1–3.
12. Giannoulis, G.; Tokas, K.; Pouloupolou, G.; Kanakis, G.; Tourmas, P.; Kanta, K.; Apostolopoulos, D.; Avramopoulos, H. Integrated Photonic Filters in Support of Converged 5G Mobile Fronthaul & Midhaul Transport Layers. Fiber Integr. Opt. 2019, 38, 333–348. [CrossRef]
13. Koenig, S.; Antes, J.; Lopez-Diaz, D.; Schmogrow, R.; Zwick, T.; Koos, C.; Freude, W.; Leuthold, J.; Kallfass, I. 20 Gbit/s Wireless Bridge at 220 GHz Connecting Two Fiber-Optic Links. J. Opt. Commun. Netw. 2013, 5, 54–61. [CrossRef]
14. Maximidis, R.; Vagionas, C.; Ruggeri, E.; Kalfas, G.; Leiba, Y.; Miliou, A.; Pleros, N. A Centralized and Reconfigurable 4x2.5Gb/s Fiber-Wireless mmWave Fronthaul for Network Sharing Applications. In Proceedings of the ECOC 2021, Bordeaux, France, 13–16 September 2021.
15. Zhang, J.; Ji, Y.; Yu, H.; Huang, X.; Li, H. Experimental demonstration of fronthaul flexibility for enhanced CoMP service in 5G radio and optical access networks. Opt. Express 2017, 25, 21247–21258. [CrossRef] [PubMed]
16. Zou, J.; Eiselt, M.; Alfageme, I.; Agusti, J.; Teres, C.; Ciria, P.; Veisllari, R.; Fontaine, M.; Elbers, J.-P. Recent Trials of G.metro-Based Passive WDM Fronthaul in 5G Testbeds. In Proceedings of the 2019 IEEE International Conference on Communications Workshops (ICC Workshops), Shanghai, China, 20–24 May 2019; pp. 1–6.
17. Bogale, T.E.; Le, L.B. Massive MIMO and mmWave for 5G Wireless HetNet: Potential Benefits and Challenges. IEEE Veh. Technol. Mag. 2016, 11, 64–75. [CrossRef]
18. Next Generation Mobile Networks Alliance. 5G White Paper; NGMN: Frankfurt, Germany, 2015.
19. Li, R. Network 2030: Market Drivers and Prospects. In Proceedings of the ITU Workshop on Network 2030, New York, NY, USA, 2 October 2018.
20. Lim, C.; Tian, Y.; Ranaweera, C.; Nirmalathas, T.A.; Wong, E.; Lee, K.-L. Evolution of Radio-Over-Fiber Technology. J. Light. Technol. 2019, 37, 1647–1656. [CrossRef]
21. Kappaport, T.S.; Sun, S.; Mayzus, R.; Zhao, H.; Azar, Y.; Wang, K.; Wong, G.; Schulz, J.K.; Samimi, M.; Gutierrez, F. Millimeter Wave Mobile Communications for 5G Cellular: It Will Work! IEEE Access 2013, 1, 335–349. [CrossRef]
22. Sung, M.; Kim, J.; Cho, S.; Chung, H.S.; Lee, J.K.; Lee, J.H. Experimental Demonstration of Bandwidth-Efficient Indoor Dis-tributed Antenna System based on IFoF Technology supporting 4G LTE-A and 5G Mobile Services. In Proceedings of the 2018 Optical Fiber Communications Conference and Exposition (OFC), San Diego, CA, USA, 11–15 March 2018.
23. Kuwano, S.; Terada, J.; Yoshimoto, N. Operator perspective on next-generation optical access for future radio access. In Proceedings of the 2014 IEEE International Conference on Communications Workshops (ICC), Sydney, NSW, Australia, 10–14 June 2014.
24. Alimi, I.A.; Teixeira, A.L.; Monteiro, P.P. Toward an Efficient C-RAN Optical Fronthaul for the Future Networks: A Tutorial on Technologies, Requirements, Challenges, and Solutions. IEEE Commun. Surv. Tutor. 2018, 20, 708–769. [CrossRef] [PubMed]
24. 5G C-RAN Architecture: A Comparison of Multiple Optical Fronthaul Networks. In Proceedings of the 2017 International Conference on Optical Network Design and Modeling (ONDM), Budapest, Hungary, 15–18 May 2017.

25. 5G Infrastructure Public Private Partnership. Space Division Multiplexing 5G Fronthaul with Analog and Digital Radio-over-Fiber and Optical Beamforming—The blueSPACE Concept; Eindhoven University of Technology: Eindhoven, The Netherlands, 2018. [CrossRef]

26. Available online: http://www.cpri.info/downloads/ECPR1_v_2.0_2019_05_10c.pdf (accessed on 22 December 2021).

27. Available online: http://www.cpri.info/pages.html (accessed on 1 December 2021).

28. Available online: https://www.itu.int/rec/T-REC-G.9803-201811-I (accessed on 1 December 2021).

29. Marti, A.V.; Vokik, N.; Hofer, M.; Milovanovic, D.; Zemen, T.; Schrenk, S. Hybrid Analogue/Digitized Radio-over-Fibre Downlink Through Orthogonal Optical mm-Wave and 10 Gb/s Baseband Transport. In Proceedings of the 2021 European Conference on Optical Communication (ECOC), Bordeaux, France, 13–16 September 2021.

30. Tsakyridis, A.; Ruggeri, E.; Kalfas, G.; Oldenbeuving, R.M.; van Dijk, P.W.L.; Roeloffzen, C.; Leiba, Y.; Miliou, A.; Pleros, N.; Vagionas, C. A Flexible and Reconfigurable Si3N4 ROADM-enabled 5G mmWave IFoF Fiber Wireless Fronthaul with 60 GHz beamsteering capabilities. In Proceedings of the 2020 European Conference on Optical Communications (ECOC), Brussels, Belgium, 6–10 December 2020; pp. 1–4. [CrossRef]

31. Kanta, K.; Pagano, A.; Ruggeri, E.; Agus, M.; Stratakos, I.; Mercinelli, R.; Vagionas, C.; Toumapi, P.; Kalfas, G.; Giannoulis, G.; et al. Analog fiber-wireless downlink transmission of IFoF/mmWave over in-field deployed legacy PON infrastructure for 5G fronthauling. IEE/OSA J. Opt. Commun. Netw. 2020, 12, D57–D65. [CrossRef]

32. Rommel, S.; Cimoli, B.; Grivas, E.; Dodane, D.; Morales, A.; Pikasis, E.; Bourderionnet, J.; Feugnet, G.; Carvalho, J.B.; Katsikis, M.; et al. Real-Time Demonstration of ARoF Fronthaul for High-Bandwidth mm-Wave 5G NR Signal Transmission over Multi-Core Fiber. In Proceedings of the 2020 European Conference on Networks and Communications (EuCNC), Dubrovnik, Croatia, 15–18 June 2020; pp. 205–208. [CrossRef]

33. Li, L.; Zhang, X.; Kong, D.; Jia, S.; Hu, W.; Hu, H. Low-Cost and High-Spectral-Efficient Co-Transmission Integrating 28-Gbaud PAM-4/NRZ and 5G-mmW ARo, F. In Proceedings of the 2020 European Conference on Optical Communications (ECOC), Brussels, Belgium, 6–10 December 2020; pp. 1–4. [CrossRef]

34. Zynq UltraScale+ RFSoC, Overview. Available online: https://www.xilinx.com/support/documentation/data_sheets/ds8891-zynq-usp-rfsoo-overview.pdf. (accessed on 25 May 2021).

35. Kim, B.G.; Bae, S.H.; Kim, H.; Chung, Y.C. RoF-Based Mobile Fronthaul Networks Implemented by Using DML and EML for 5G Wireless Communication Systems. J. Light. Technol. 2018, 36, 2874–2881. [CrossRef]

36. Available online: https://www.fujitsu.com/us/images/gig5/FNC-Fujitsu-C-RAN-Mobile-Architecture-Migration-White-Paper.pdf (accessed on 1 December 2021).

37. 3GPP Specification TS 38.201, NR; Physical Layer; General Description. April 2017. Available online: https://www.etsi.org/deliver/etsi_ts/138200_138299/138201/15.00.00_60/ts_138201v150000p.pdf (accessed on 25 May 2021).

38. Available online: https://www.gotmic.se/documents/gTSC0020B_Rev%20A01-17.pdf (accessed on 1 December 2021).

39. Available online: https://www.gotmic.se/documents/gRSC0016B_Rev%20A01-16.pdf (accessed on 1 December 2021).

40. Argyris, N.; Kanta, K.; Iliaidis, N.; Giannoulis, G.; Apostolopoulos, D.; Avramopoulos, H.; Papaioannou, S.; Vagionas, C.; Kalfas, G.; Pleros, N. DSP enabled Fiber-Wireless IFoF/mmWave link for 5G Analog Mobile Fronthaul. In Proceedings of the IEEE 5G World Forum, Silicon Valley, CA, USA, 9–11 July 2018.

41. Bekkali, A.; Kobayashi, T.; Nishimura, K.; Shibagaki, N.; Kashima, K.; Sato, Y. Performance evaluation of real-time 10GbE data connectivity over a converged IF-over-Fiber links and millimeter-wave wireless bridge. In Proceedings of the 2017 IEEE International Conference on Communications (ICC), Paris, France, 21–25 May 2017; pp. 1–6. [CrossRef]

42. Sung, M.; Kim, J.; Kim, E.S.; Cho, S.H.; Won, Y.J.; Lim, B.C.; Pyun, S.Y.; Lee, J.K.; Lee, J.H. Demonstration of 5G Trial Service in 28 GHz Millimeter Wave using IFoF-Based Analog Distributed Antenna System. In Proceedings of the 2019 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 3–7 March 2019; pp. 1–3.

43. Available online: http://www.ti.com/lit/ds/symlink/dlp-technology-dlp-technology-home.page (accessed on 1 December 2021).

44. Toumapi, P.; Kanta, K.; Tokas, K.; Stratakos, I.; Papatheofanous, E.A.; Giannoulis, G.; Mesogiti, I.; Theodoropoulou, E.; Lyberopoulou, G.; Lentaris, G.; et al. Demonstration of FPGA-based A-IFoF/mmWave transceiver integration in mobile infrastructure for beyond 5G transport. In Proceedings of the 2021 European Conference on Optical Communication (ECOC), Bordeaux, France, 13–16 September 2021.