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Reconfigurable Radio Access Unit for DWDM to W-Band Wireless Conversion

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***Abstract*—In this letter a reconfigurable Remote Access Unit (RAU) is proposed and demonstrated, interfacing dense wavelength division multiplexed (DWDM) optical and W-band wireless links. The RAU is composed of a tunable local oscillator, a narrow optical filter and a control unit, making it reconfigurable via software. The RAU allows selection of a DWDM channel and tuning of the radio carrier frequency. Real-time transmission results at 2.5 Gbit/s and performance measurements with offline data processing at 4 and 5 Gbit/s are presented. Error free real-time transmission was achieved after 15 km of standard single mode fiber and 50 m of wireless transmission with carriers between 75 and 95 GHz.**

***Index Terms*—Radio-over-fiber, millimeter-wave communications, W-band wireless, real-time systems.**

I. INTRODUCTION

GROWING demand for high speed wireless data transmission increases year to year mostly due to the emerging end user demand for wireless services like 4K/Ultra High Definition TV or mobile gaming [1]. The new 5G mobile standard will meet those requirements partially by the use of higher radio frequencies from the millimeter wave (mm-wave) range [2], [3]. Operation at these frequencies– from 30 GHz to 300 GHz – allows the use of wider transmission channels and clearly opens a possibility for significantly higher bit rates. Furthermore, regulations for the use of mm-waves allow lightly licensed or unlicensed link establishment. Nevertheless, signal generation in the mm-wave frequency range with traditional oscillators is complex.

To overcome this problem the use of optical heterodyne signal upconversion was proposed [4] and in recent years has attracted interest of many researchers [5]–[8] and even joint projects were established in this field. Those projects aim to provide feasible solutions, integrating present and future optical networks with wireless communications by utilizing photonic techniques. The Integrated Photonic Broadband Radio Access Units for Next Generation Optical Access Networks (IPHOBAC-NG) project is one thereof and aims to provide seamlessly integrable photonic solutions for wireless communications and to adapt them into currently existing wavelength division multiplexed passive optical networks (WDM-PONs) and even ultra dense wavelength division multiplexed PONs. The project targets to provide a complementary broadband access with speeds between 1–10 Gbit/s and a mobile backhaul with the speed of 3 Gbit/s. To fulfill these requirements the IPHOBAC-NG project assumes the development of a new photonic RAU which will support reconfiguration of the optical channel allocation, which will not have an impact on the digital signal processing in the optical network unit (ONU) and optical network terminal (ONT), and will be energy efficient, fully integrated and compact. The proposed IPHOBAC-NG heterogeneous network architecture is presented in Fig. 1.

In this letter a reconfigurable Remote Access Unit (RAU) is proposed and demonstrated, interfacing DWDM optical and W-band wireless links to enable the IPHOBAC-NG network architecture. The proposed RAU utilizes optical heterodyne signal upconversion [9] for mm-wave wireless signal generation. The proposed RAU is composed of a reconfigurable optical filter for DWDM channel selection, a reconfigurable optical reference signal source, a photodiode and a control unit; section II provides a full description. Section III describes measurement setup and procedure. In section IV bit error rate measurements after transmission over 15 km of fiber and a wireless distance of 50 m are shown for 2.5 Gbit/s real-time transmission and 4 and 5 Gbit/s transmission with offline data processing.

II. REMOTE ACCESS UNIT DESIGN

The reconfigurable RAU proposed in this letter and presented in Fig. 1 assumes a 100 GHz spaced, C-band DWDM input signal which is fed into a tunable, voltage-controlled, optical fiber Fabry-Perot filter, selecting the desired channel. The filter employed has 2.5 dB insertion losses, a 3 dB bandwidth of 15 GHz and a 20 dB bandwidth of 125 GHz, allowing operation in 100 GHz spaced DWDM systems. The filter is controlled through a digital analog converter (DAC), providing an adjustable output voltage range between −18 V and 18 V with 16 bit resolution, ensuring finesse to select any DWDM channel and easily reaching the required 16 V range for filter tuning across the whole C-band.

The selected channel from the DWDM signal is fed into a 3 dB coupler where is combined with the reference signal from a local oscillator (LO, a tunable laser with 100 kHz linewidth and fine frequency tuning). The polarization of the LO is controlled with a manual polarization controller, to align signal

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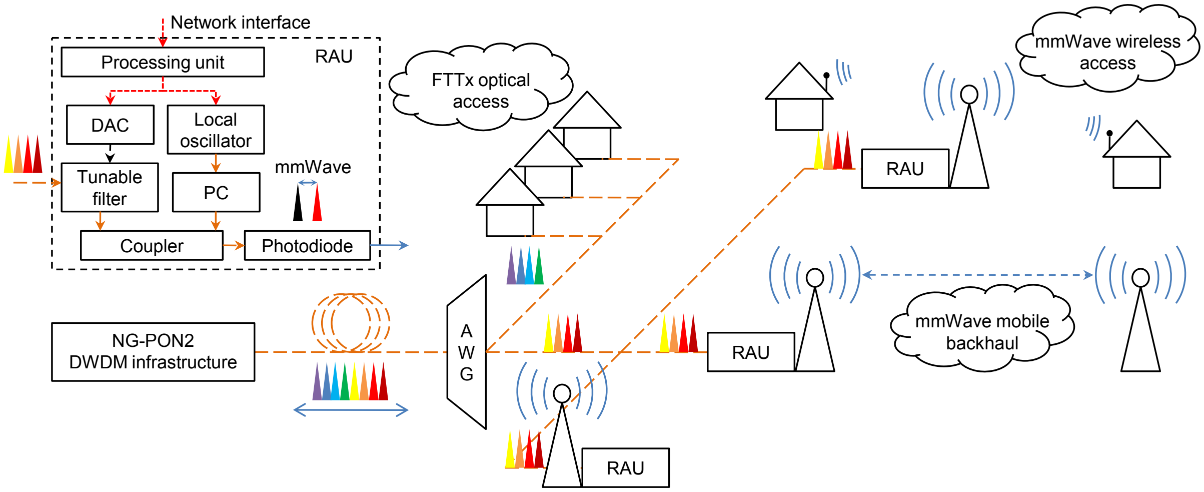

Fig. 1. IPHOBAC-NG architecture and block diagram of the proposed RAU, converting a DWDM optical signal to a W-band wireless signal.

and LO polarization and thus maximize beating efficiency on the photodiode. The addition of automatic LO polarization control – similar to eg. [10] – would alleviate need for manual intervention and allow a fully remote controlled RAU. The LO wavelength and DAC output are controlled by the processing unit, in the present case a low-cost Raspberry Pi 2 which can control a number of devices. Moreover, this single-board controller can be loaded with software-defined networking (SDN) extensions, effectively softwarizing the RAU.

The coupled data and reference signal, spaced according to the desired radio frequency, are sent to a photodiode (Finisar XPDV4120R) with 90 GHz 3 dB bandwidth and a responsivity of 0.5 A/W. As a result of the heterodyning process at the photodiode, a radio signal with a carrier frequency in the W-band range is generated. The total RAU optical insertion losses are 5.5 dB 2.5 dB from the optical filter and 3 dB from the coupler.

III. TRANSMISSION PERFORMANCE MEASUREMENTS

A. Experimental Setup

Fig. 2 depicts a block diagram of the experimental setup. Eight 100 GHz spaced lasers were multiplexed in two 4×1 couplers with distinction for even and odd channels. Next, the two streams of four wavelengths each were fed into two Mach-Zehnder modulators (MZM), preceded by two polarization controllers (PC). Both MZMwere biased at the center of their linear region and driven with two 2.5 Gbit/s (4 and 5 Gbit/s for offline data processing) non-return-to-zero (NRZ) pseudo random bit sequences (PRBS) with a length of $2^{11}-1$ bits from a pulse pattern generator. The sequence modulating the odd channels was negated and shifted with a delay line to impose signal decorrelation. The signals from MZMs were combined in a 3 dB coupler and transmitted through a combination of 10 km standard single mode fiber (SSMF) and 5 km of bend insensitive fiber (ITU-T G.657.B3) (BIF). This combination secures compatibility with deployment scenarios where BIF fiber is required to avoid large bending losses, while having little impact on the performance of the hybrid optical wireless system [11].

After the fiber, the DWDM signal was amplified with an erbium doped fiber amplifier (EDFA) to provide sufficient power for radio frequency (RF) signal generation and transmission. The EDFA was placed at the RAU rather than before fiber transmission, due to a limited output power of the available EDFA and thus insufficient power per channel if placed before fiber transmission. The use of an EDFA with an exemplary output power of 22 dBm would allow EDFA placement in the central office (OLT) and yields a maximum fiber distance in the considered system configuration exceeding 20 km (assuming 13 dBm per channel after the EDFA, 0.3 dB/km fiber attenuation, 5.5 dBm insertion losses of the RAU and a required power of 1 dBm on the photodiode). The use of any EDFA might be avoided through the use of a semiconductor optical amplifier after the optical filter in the RAU.

After the EDFA the amplified signal is fed to the RAU. For each of the measured channels, polarization of the LO signal was adjusted to provide the maximum beating on the photodiode. The unused output of the coupler was used for signal monitoring with an optical spectrum analyzer (OSA). The output RF signal was transmitted over a distance of 50 m using a pair of parabolic W-band antennas with 48 dBi gain each.

After 50 m of wireless transmission, the output of the receiver antenna was amplified and downconverted with a W-band Schottky diode envelope detector (ED) with a 3 dB bandwidth of 3 GHz. For the 2.5 Gbit/s real-time measurement two bias tees (BT) were cascaded, the first removing unwanted DC components from the envelope detector and the second providing the required 3.3 V DC for the clock and data recovery module (CDR). The output of the CDR was connected to a bit error rate tester (BERT) allowing direct bit error rate (BER) measurements. The receiver configuration for 4 Gbit/s and 5 Gbit/s transmission is analog to that described in [8].

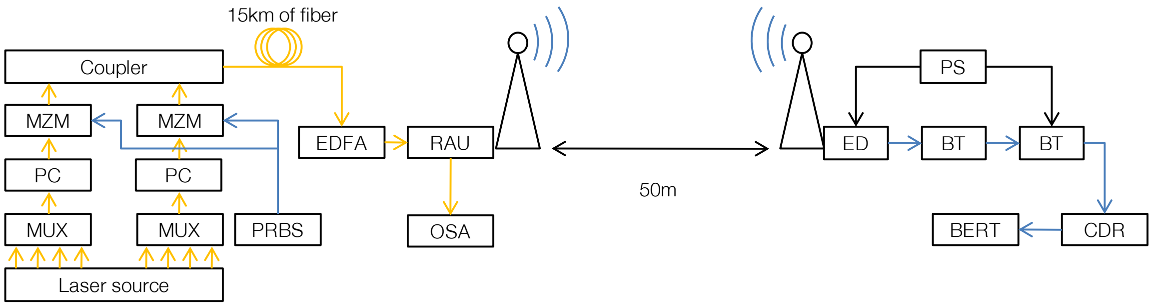

Fig. 2. Experimental setup for hybrid photonic 2.5 Gbit/s real time wireless transmission.

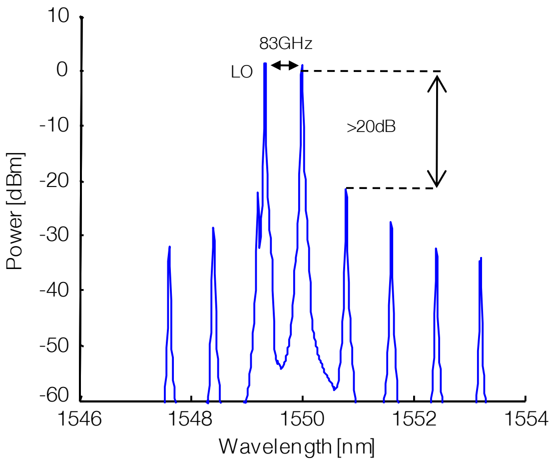

Fig. 3. Optical signal spectrum inside the RAU (after the coupler).

B. Measurement Procedure

The 2.5 Gbit/s real time and 4 Gbit/s with offline processing experiments were conducted for RF carrier frequencies between 75 GHz and 95 GHz with 2 GHz steps. Those measurements were performed for 1st, 5th and 8th DWDM channel. The 95 GHz frequency upper bound was due to the operational bandwidth limit of the photodiode. The 5 Gbit/s experiment was performed for all DWDM channels at a frequency of 83 GHz. The decision to use W-band frequencies was made mainly due to lower attenuation in comparison to the 60 GHz V-band which is also considered for 5G networks.

The measurements conditions were set through the control unit of the RAU, to which channel number and mm-wave frequency target were indicated. The control unit, through a look-up table, automatically set up the filter and LO. The LO was manually co-polarized with the signal and its power set level to the data channel to provide maximum generated RF signal power [7], [12]; the actual power was 1 dBm each. Fig. 3 presents the optical spectrum for the 5th DWDM channel inside the RAU after the filter and with the LO set 83 GHz apart from the data channel. It can be clearly observed that adjacent DWDM channels are suppressed by over 20 dB. For the real-time 2.5 Gbit/s transmission 5×10^{10} bits were evaluated per measurement point. For the 4 Gbit/s and 5 Gbit/s measurements the number of analyzed buts was >20 Mbit.

IV. RESULTS AND DISCUSSION

Fig. 4 presents results for the 2.5 Gbit/s real-time measurement. Independent of the selected DWDM channel, similar BER characteristics were obtained. In the frequency range from 75 GHz to 87 GHz transmission with a BER below the limit of 3.8×10^{-3} for a commercial forward error correction (FEC) with an overhead of 7 % is possible for all tested channels. For carrier frequencies located close to 80 GHz transmission considered as error free (BER $< 10^{-9}$) can be achieved. It is worth to mention that this frequency range was designated for high-density fixed wireless services by the US Federal Communication Commission (FCC) and the RAU proposed in this letter can be easily utilized for this application.

For carriers above 87 GHz an increase in the BER is visible, caused partially by the limited bandwidth of the photodiode and thus a lower conversion efficiency and second by interference from adjacent channels. Although adjacent channels are suppressed by more than 20 dB, their remainders may beat with the selected channel, causing an RF component at 100 GHz, i.e. within W-band and thus within the transmission bandwidth of the antennas and the bandwidth of the receiver. Further impact may be taken from a loss of LO power due to beating with the closest adjacent channel. These are especially significant for the higher carrier frequencies and further explain the small advantage in BER observed for the outer channels where only one adjacent channel exists.

Fig. 5 shows the results obtained for the 4 and 5 Gbit/s transmission with offline data processing. At 4 Gbit/s transmission below FEC limit was achieved for frequencies up to 85 GHz. Above this frequency strong impact of the effects described above occur, especially for 5th channel where the difference in BER at 87 GHz between this channel and the 1st is two orders of magnitude and compared to 8th exceeds three orders of magnitude. Consequently the 5th channel shows the worst performance among all channels. This relationship was further confirmed by the measurement at 5 Gbit/s and 83 GHz where the 5th channel also showed worst performance, close to the FEC limit. These results demonstrate that the middle channels are most affected by unwanted mixing products and loss of LO power even though the adjacent channels are attenuated more than 20 dB. Never the less transmission of a 5 Gbit/s signal was successful for all channels on a 83 GHz carrier.

It should be noted that the achieved maximum wireless distance of 50 m is limited only by the available RF power

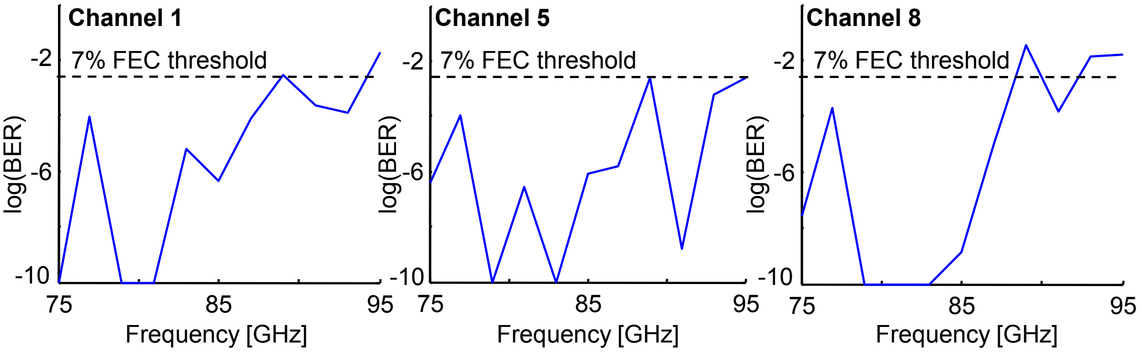

Fig. 4. BER measurement results obtained for 2.5 Gbit/s real time data transmission at frequencies ranging from 75 to 95GHz: a) 1^{st} b) 5^{th} and c) 8^{th}. DWDM channel

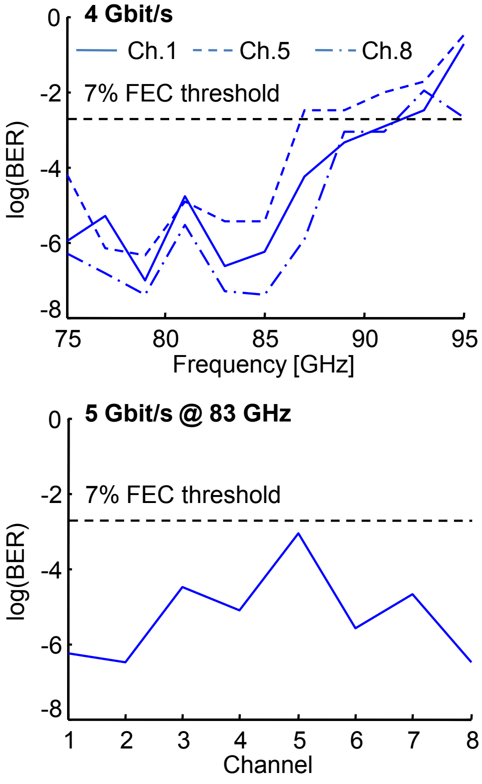

Fig. 5. Results of 4 and 5 Gbit/s tests with offline data processing

and significantly longer distance should be achievable as demonstrated in [8].

V. CONCLUSIONS

In this letter, a RAU utilizing optical heterodyne signal upconversion for generation and transmission of radio signals in millimeter-waves range was proposed and experimentally validated. The proposed RAU is widely reconfigurable allowing direct selection of the desired DWDM channel and gapless tuning of the local oscillator signal, allowing free selection of the radio carrier frequency in the W-band. Furthermore, the proposed RAU meets the requirements of the IPHOBAC-NG project, effectively and smoothly interfacing the optical and the wireless media. By allowing easy integration with existing PONs and by allowing extension of the control unit to support SDN it thus enables heterogeneous network architectures as envisioned in IPHOBAC-NG.

The performed measurements demonstrate error free (BER$< 10^{-9}$) real-time transmission with a bitrate of 2.5 Gbit/s after 15 km of fiber and 50 m of wireless links. Transmission at data rates up to 5 Gbit/s is achieved with offline processing and a BER below the FEC limit. An increase in wireless distance analog to [8] by increasing the RF power is possible, and therefore the wireless distance demonstrate in these experiments is not limited by any fundamental impairment.

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