# Bidirectional Millimeter-Wave Radio-Over-Fiber System Based on Photodiode Mixing and Optical Heterodyning

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# BIDIRECTIONAL MILLIMETER WAVE RADIO-OVER-FIBER SYSTEM BASED ON PHOTODIODE MIXING AND OPTICAL HETERODYNING

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**Abstract - We demonstrate a bidirectional millimeterwave (mmW) radio-over-fiber system based on the use of a p-i-n photodiode (PD) used in non-linear regime. Since frequency down-conversion and photodetection are carried out by a single photodiode, base station (BS) architecture is simplified. Down-link transmission employs optical heterodyning technique for mmW generation and remote local oscillator (LO) delivery to BSs. Up-link scheme uses the electrical port of the PD as an input for optoelectronic mixing with the remotely delivered LO. Up-link and down-link have been successfully demonstrated for 397 Mbps and 794 Mbps binary phase shift keying complying with 60 GHz ECMA 387 standard. Error vector magnitude measurements and theoretical analysis are discussed as regards PD bias conditions. It is shown that PD can be used in this bidirectional system without any switching of the PD bias.**

**Key words:** radio-over-fiber, millimeter wave, bidirectional transmission, photodiode mixing, optical heterodyning, ECMA 387.

## I. INTRODUCTION

Radio-over-fiber (RoF) systems operating at millimeter-wave (mmW) frequencies are widely discussed in literature for the provision of future gigabit per second wireless access networks with wider service coverage, and possible integration with future passive optical networks (PON) infrastructures [1, 2]. In order to simplify the design of the base stations (BS), optical domain has been used to offer signal processing functions such as optical mmW generation for the down-link. Recently optical heterodyning systems have been shown great interest to centralize optical mmW frequency generation for the down-link, providing reduction of cost by sharing a single optical modulator to realize mmW generation for many BSs [3] or by using dual baseband/mmW radio modulations for future converged wireless/wireline PON networks infrastructures [4]. Since centralization of signal processing, such as frequency down-frequency, is not possible for the up-link scheme, it makes it too expensive the use of one mmW bandwidth electrical to optical (E/O) transceiver per BS. In [5], a broadband electronic mixer is used for up-link RF auto-heterodyning detection in the BS but it cannot be used for all modulation formats used in the future 60 GHz standards such as ECMA 387. Especially developed devices as mmW bandwidth heterojunction phototransistor (HPT) with photodetection and mixing capabilities have been especially developed for demonstration of bidirectional mmW over fiber system at data rate 20 Mbps [6]. More recently, 70 GHz bandwidth reflective electro absorption modulator (REAM) have been used for 3 Gbps bidirectional mmW over fiber links [7], but it needs different bias voltages to be used either as an optical receiver or an optical modulator, which supposes remote control of the REAM and fast enough voltage switching time. Even if research work in the last decade has been mostly concentrated on the down-link mmW RoF systems, it is obvious that the cost of a bidirectional system will be dramatically increased by the cost of broadband electronics in BSs for the up-link transmission. Though, one key issue for bidirectional mmW RoF system is to achieve efficient and cost-effective optoelectronic frequency up/down conversions in the BSs.

In this paper, a novel bidirectional mmW RoF architecture is demonstrated based on the use of a commercial off the shelf (COTS) p-i-n photodiode. This photodiode (PD) is used in non-linear regime to perform both photodetection for the mmW RoF down-link and frequency down-conversion for the mmW RoF up-link, without the need of changing PD bias voltage. In the up-link scheme, the so-called PD electrical output is used as an input for the mmW radio signal to realize optoelectronic mixing with remotely delivered LO from the down-link. The down-link scheme uses typical optical heterodyning scheme for mmW generation [4] and the impact of the non-linear PD on down-link performances is investigated. mmW RoF bidirectional system is demonstrated using modulation formats and data rates which are compliant with 60 GHz ECMA 387 standard [8].

The organization of the paper is as follows: Section II briefly introduces the general architecture of the proposed bidirectional mmW RoF system. In section III, investigations on the up-link scheme are presented, leading to optimized PD biasing conditions. Sections IV deals with the influence of the non-linear PD on the optical heterodyning down-link performances.

## II. Bidirectional mmW RoF System Set-Up

The proposed bidirectional RoF system is presented in Fig. 1. In the central station (CS), a single mode distributed feedback (DFB) laser diode (LD) is used to generate a continuous wave (CW) optical signal at wavelength $\lambda_0$=1550.7 nm. To generate two spectral lines with a frequency interval of about 50 GHz, we use a Mach Zehnder Modulator (MZM #1) biased at minimum of transmission and driven by a CW radiofrequency signal at frequency $f_1$ =26.9 GHz. MZM#1 optical output signal is then amplified using an erbium doped fiber amplifier (EDFA). To select the two mmW spaced optical spectral lines, the amplified optical signal is sent into a four-channel wavelength demultiplexer (DEMUX) with a channel spacing ($BW_{Demux}$) of 25 GHz. At WDM demultiplexer channel 2 output, optical field is modulated by using a second MZM (MZM#2 on Fig. 1). MZM#2 is driven in linear regime with a BPSK signal at $f_2$=4.52 GHz for the down-link operating mode and not modulated for the up-link operating mode, for remote local oscillator (LO) delivery to the BS. MZM#2 optical output is combined to the WDM demultiplexer channel 4 output using a 3 dB optical coupler. A particular attention is paid to adjust the optical delay between the 2 optical paths from WDM demultiplexer to avoid phase to intensity noise conversion [9]. Polarization controllers (PC) are used to combine both optical fields with equal polarizations. After optical coupling, signal is fed into a singlemode fiber. In the BS, a 70 GHz bandwidth p-i-n PD biased in non-linear regime is used either for photodetection process (down-link) or for mmW frequency downconversion process (up-link).

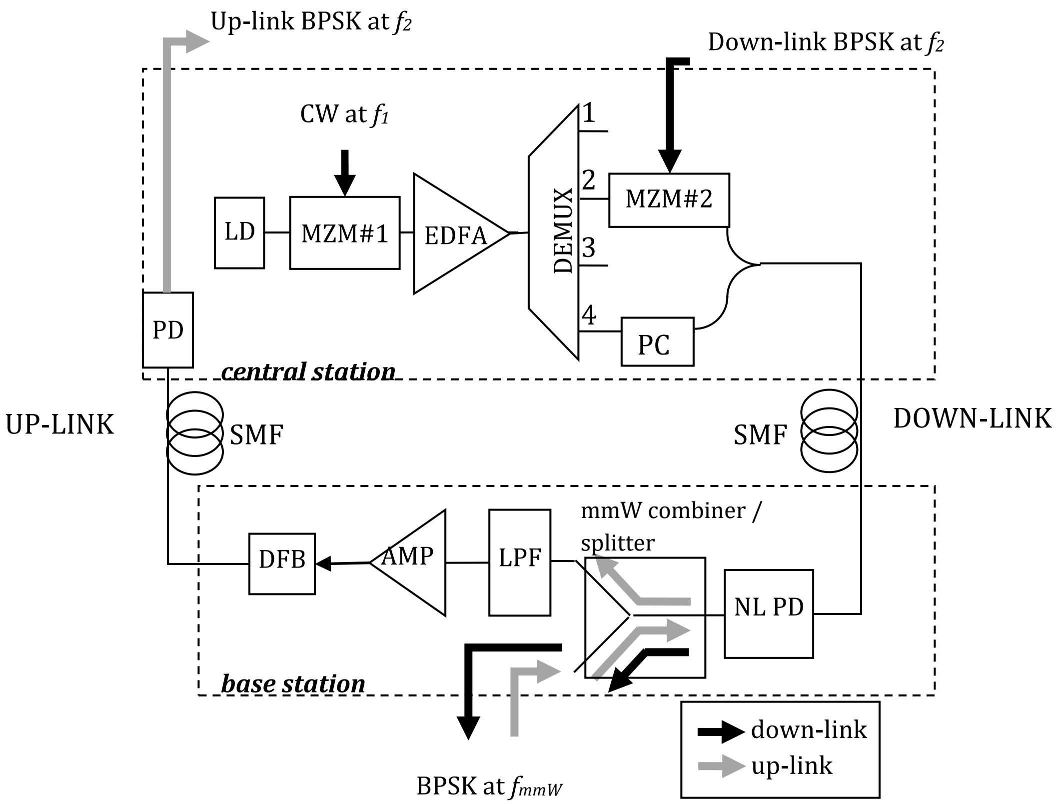


*Fig. 1 Bidirectional WDM-RoF system architecture (NL-PD: non-linear PD, AMP: RF amplifier. LPF: low-pass filter).*

## III. Up-link Based on Photodiode Mixing

### *A. Up-link Set-Up*

For the up-link operating mode, PD detects a remotely delivered LO signal at $2f_1 = 53.8$ GHz from MZM#1 since no BPSK is applied on MZM#2 (Fig. 1). As shown on Fig. 2, a mmW BPSK signal at frequency $f_{mmW}$=58.32 GHz and bit rate $D_b$ = 397 Mbps or $D_b$ = 794 Mbps, which complies with the first and second data rates of the 60 GHz ECMA standard [8], is sent to the electrical port of the PD through the mmW combiner. The PD is used as an optoelectronic mixer to down-convert the frequency of the incoming mmW signal to the intermediate frequency $f_2 = f_{mmW} - 2f_1$=4.52 GHz. The unwanted intermodulation products are filtered out using a low-pass filter (LPF). The down-converted radio signal is amplified with a 10 GHz bandwidth amplifier (AMP) with gain $G_{amp}$=45 dB and finally transmitted back to the CS throw an intensity modulation direct detection (IMDD) optical system composed of a DFB laser, a SMF fiber and a 10 GHz bandwidth PD. Up-link signal is analyzed with spectrum analyzer (SA) and digital storage oscilloscope (DSO) at AMP output, demodulation is performed with vector signal analysis software.

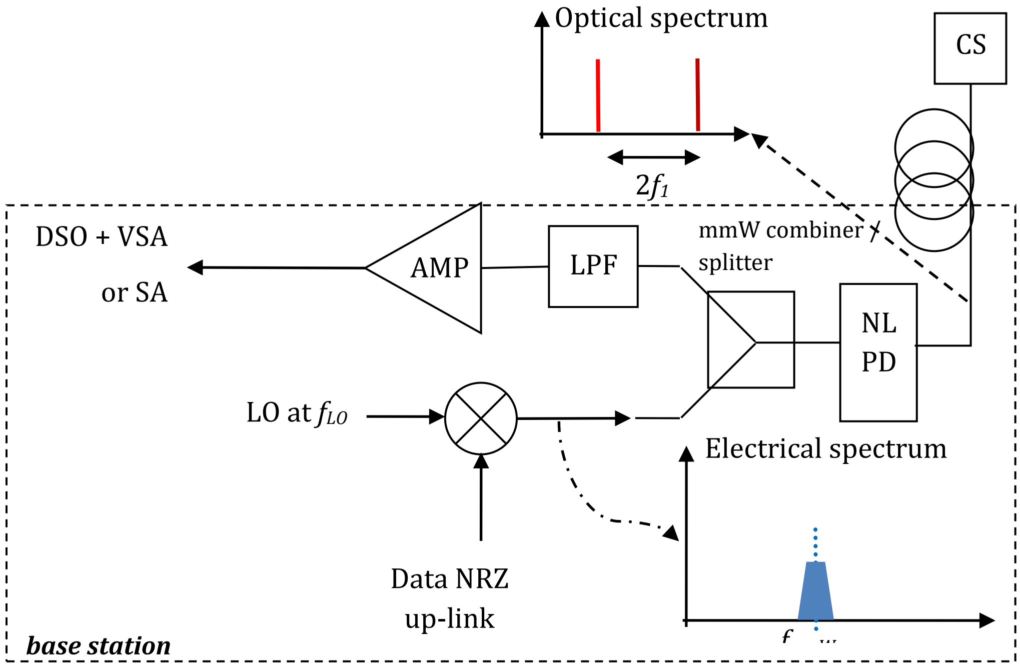


*Fig. 2 Experimental set-up for the up-link (NL PD: non-linear photodiode. AMP: RF amplifier. LPF: low-pass filter. LO: local oscillator. NRZ: non-return to zero)*

### *B. Photodiode Biasing For Optimal Mixing*

The PD is biased in non-linear regime. The mmW signal at frequency $f_{mmW} = 58.32$ GHz which is electrically fed into the PD produces oscillations of the PD voltage, which results in oscillations of the PD responsivity. As a consequence, the photodetected remote delivered LO signal at $2f_1 = 53.8$ GHz will mix with the mmW signal to generate the down-converted signal at frequency $f_2 = f_{mmW} - 2f_1$. In order to obtain an efficient opto-electronic mixing process, it is necessary to set the PD bias voltage value to maximize the PD non-linearity parameter ($A$) [10] defined as:

$$A = \eta_{PD} \frac{d\eta_{PD}}{dV_{PD}} \qquad (1)$$

where $\eta_{PD}$ is the photodiode responsivity, $V_{PD}$ is the PD bias voltage.

We have already investigated PD non-linearity parameter in [10]. Measurement of the PD non-linearity parameter has been realized at 60 GHz and has shown a maximum for a reverse bias voltage $V_{PD}$ of 0.3 V.

### *C. Up-link experimental results and discussion*

Fig. 3 shows mixing power and signal EVM at AMP output (Fig. 2), IMDD up-link being transparent for SNR analysis. As expected from the *A* parameter analysis, optimal mixing power ($P_{mix}$) is obtained for a PD bias voltage of 0.3 V. EVM as low as 13.1 % for $D_b$ = 397 Mbps and 23.5% for data rate $D_b$ = 794 Mbps (not reported on Fig. 3) are obtained which comply with the EVM limits for the ECMA 387 standard (33.4 % and 23.7% for data rates $D_b$ = 397 Mbps and $D_b$ = 794 Mbps respectively) [8].

Dominant noises at photodetection have been identified to be amplified spontaneous emission (ASE) signal beat noise and additive noise from DSO, which variances in current ($\sigma^2_{ASE/Signal}$ and $\sigma^2_{DSO}$ respectively) are expressed as :

$$\sigma^2_{ASE/Sign} = 4\eta^2_{PD} N_{ASE} P_{PD} BW_{Demux} \qquad (2)$$

$$\sigma^2_{DSO} = \frac{4kT_0\, BW}{R_0} NF_{DSO} \qquad (3)$$

where $N_{ASE}$ is the ASE power spectral density, $P_{PD}$ is the optical power at the PD input, *k* is the Boltzmann constant, $T_0$ is the ambient temperature, $R_0$ is the DSO input resistor, *BW* is the BPSK signal bandwidth, $NF_{DSO}$ is the DSO noise figure. As it can be seen from (2) and (3), when PD bias decreases, $\sigma^2_{ASE/Signal}$ drops to the DSO noise floor $\sigma^2_{DSO}$ because of the decrease of photodiode responsivity, whereas mixing power reaches a maximum for $V_{PD}$=-0.3 V, which leads to an optimal EVM for the mixing signal at $V_{PD}$=0.15 V. EVM has been evaluated from SNR calculation derived from output mixing power and noise contributions (2) (3) and reported on Fig. 3. Calculated EVM shows good agreement with measured EVM. EVM analysis shows that PD bias voltage for which minimum EVM is reached does not correspond to the one for which mixing power is maximum, due to the PD responsitivy dependent noise contribution.

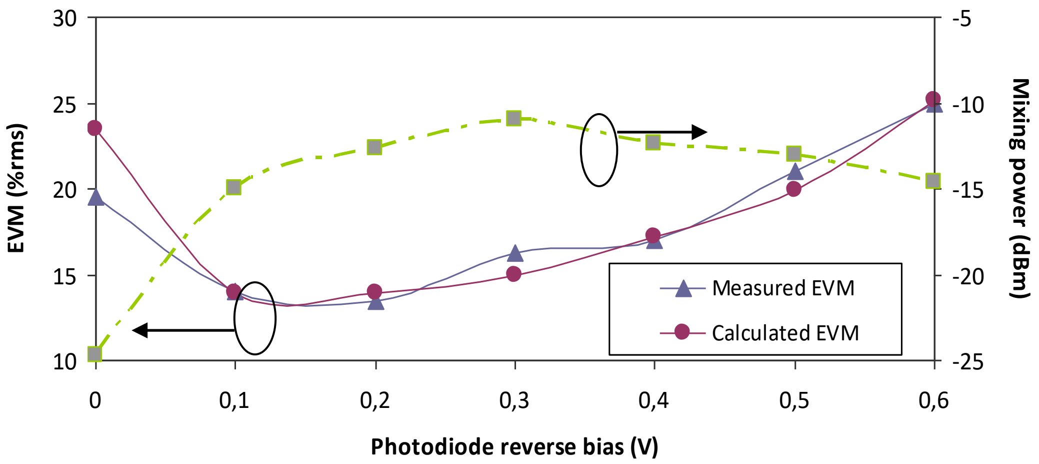


*Fig. 3 Up-link experimental and theoretical results for the mixing power and EVM after frequency frequency donwconversion as a function of the PD bias voltage for a BPSK data rate of 397 Mbps.*

Insertion loss of the wideband combiner ($IL_{comb}$) is evaluated at 7 dB. The mmW input power ($P_{mmW\_up\text{-}link}$) is set at -8 dBm. PD mixing conversion loss $CL_{PD}$ is defined as:

$$CL_{PD} = P_{mix} - G_{amp} + IL_{comb} - P_{mmWup-link} \qquad (4)$$

$CL_{PD}$ is evaluated at -39 dB, which corresponds to typical values found in literature [11] when PD is used as an optoelectronic mixer with 2 input modulated optical signals. It shows that the new PD operating condition proposed in this work, which uses the traditional electrical PD output as a mmW input for the up-link, does not introduce severe additional penalty on the mixing process. The drawback of large conversion loss is partly compensated by the fact that a unique device is used for 2 functions in the bidirectional system: mixing and photodetection.

## IV. Down-Link Based On Optical Heterodyning

We have already investigated in [4] a mmW RoF down-link based on optical heterodyning. In this section, we focus on the impact of the PD bias voltage on the down-link performances.

*A- Down-Link Set-Up*

In the BS, mmW BPSK is generated at frequency $f_{mmW} = 2f_1 + f_2$=58.32 GHz by the beating of the optical spectral lines on the PD (Fig. 4). Two main other spectral lines at frequencies $f_{lower} = 2f_1 - f_2$ = 49.28 *GHz* and $2f_1$ = 53.8 GHz are also photodetected. As seen on Fig. 4, PD output signal is coupled to the mmW combiner of which second output port should be connected to a mmW band-pass filter to suppress undesired spectral lines and sent to the mmW antenna for radio emission. In our set-up (Fig. 4), mmW combiner output is connected to either a 70 GHz SA for power analysis or a mmW electrical mixer to down-convert the mmW BSP signal in the DSO bandwidth of 6 GHz. Waveguide connector of the electronic mixer acts as a 60 GHz -75 GHz band-pass filter, filtering out undesired spectral lines.

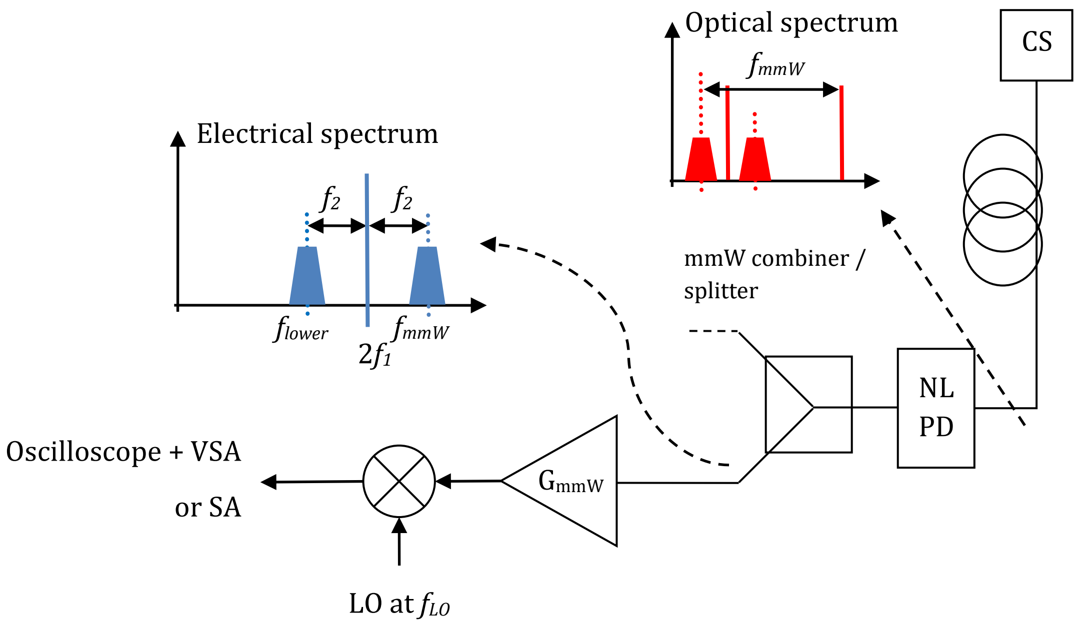

*Fig. 4 Experimental set-up for the down-link*

*B- Experimental Results For The Down-Link*

Experimental results obtained for down-link output mmW power ($P_{mmW}$) and EVM are reported on Fig. 5, as a function of the PD bias voltage $V_{PD}$. For $V_{PD}$ higher than 1 V, $P_{mmW}$ stays independent of $V_{PD}$ because the PD works linearly. As seen on Fig. 5, for $V_{PD}$ from 1 V to 0 V, $P_{mmW}$ decreases due to the decrease of the PD responsivity, as discussed in section III. $P_{mmW}$ can be expressed as:

$$P_{mmW} = \eta_{PD}^2 m^2 IL_{comb} P_{PD}^2 \qquad (5)$$

where $m$ is the intensity modulation index.

Referring to (2), (3) and (5), we can infer that PD output SNR remains constant as regards $V_{PD}$ when $\sigma^2_{Sign\ ASE}$ is dominant over $\sigma^2_{DSO}$ (for $V_{PD}$>0.15 V) and decreases when $\sigma^2_{DSO}$ is the dominant noise (for $V_{PD}$<0.15 V). EVM being related to the inverse of SNR, this analysis is compliant with the measured EVM results reported on Fig. 5. For PD reverse bias voltage of 0.15V, there is no penalty on the down-link in terms of SNR (or EVM), compared to the use of the PD in linear regime. Nevertheless, there is a penalty on the generated mmW mixing power of about 4 dB compared to the measured mmW mixing power when the PD is used in linear regime, which could be compensated by increasing the gain of an additional mmW broadband amplifier used before radio emission, in order not to penalize the BS radio coverage.

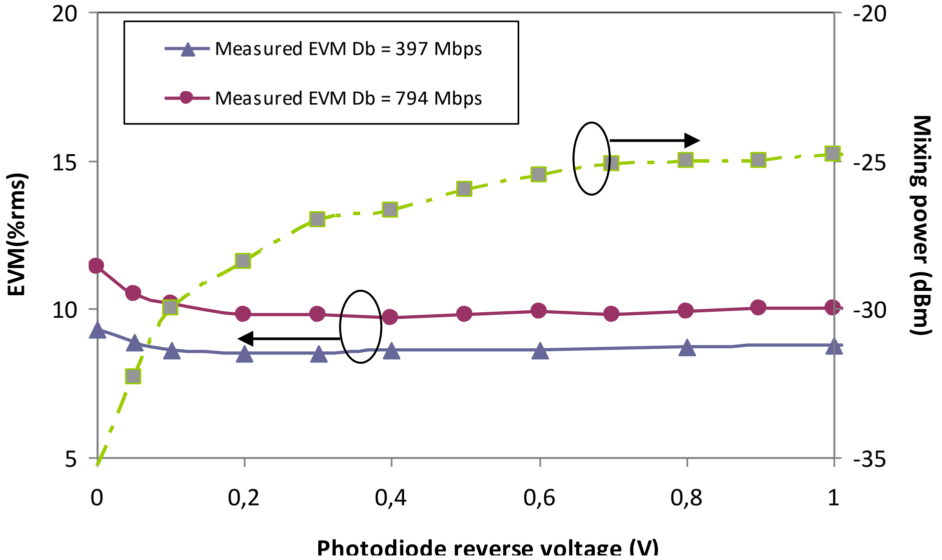


*Fig. 5 Down-link experimental results for the mixing power and EVM for the generated mmW BPSK at data rates 397 Mbps and 794 Mbps.*

## V. CONCLUSION

A new bidirectional mmW BPSK RoF system using a non-linear PD and remote LO delivery is demonstrated. The down-link system, based on optical heterodyning, allows for high data rate mmW generation and remote LO delivery to the BSs. For the up-link, optoelectronic mixing technique, based on the use of a non-linear PD which is fed with mmW BPSK by its RF output connector, is presented and experimentally demonstrated. Optimal PD bias conditions have been discussed regarding mixing power and noise contributions to optimize SNR. Despite large mixing conversion loss, EVM remains in the limit of ECMA 387 standard for data rate up to 794 Mbps. For the down-link system, no penalty on SNR has been observed for the generated mmW BPSK, but a decrease of mmW power of 4 dB has been measured compared to the use of the PD in linear regime. This approach uses COTS photodiode and provides the possibility to eliminate frequency mixers and oscillators in BSs, it is expected to reduce the complexity and cost of bidirectional mmW RoF base stations.

## VI. ACKNOWLEDGEMENT

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