Radio-over-Fiber Dual-Parallel Mach–Zehnder modulator system for photonic generation of Millimeter-Wave signals through two stages

Fabio B. de Sousa¹,² · Fiterlinge M. de Sousa¹,² · Igor R. S. Miranda¹,² · Waldomiro Paschoal Jr.³,⁴ · Marcos B. C. Costa¹,²,⁵

Received: 20 May 2020 / Accepted: 11 April 2021 / Published online: 5 May 2021
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Abstract

In this work, we presented a radio-over-fiber (ROF) access network through two modulation stages for the generation of multiple millimeter wave (mm-wave) signals with frequencies of 20, 40, 60 and 80 GHz for the transmission rate of 10 Gbps as a function of the variation of link distance and signal power. The specific purpose of the paper was to design and to investigate a RoF system based on the variation of mm-wave frequencies in order to implement a simple and effective system. In stage 1, there are two modulators in parallel (MZMa and MZMb) called dual-parallel Mach–Zehnder modulator (DP-MZM) and in stage 2 there is only one modulator (MZMd), connected to three pulse generators: Non-Return-to-Zero (NRZ), Return-to-Zero (RZ) and Gaussian, which were selected individually to each simulation in optisystem software. A single-mode fiber (SMF) and optical filter Gaussian (GOF) and an erbium-doped fiber amplifier (EDFA) were also used to send signals to base stations (BSs). The numerical analyzes of the results of the eye diagrams showed excellent bit error rate (BER) and quality factor (Q-factor) values, which proved the good performance of the proposed RoF- DP-MZM system, for the three encoding formats used, which was able to generate 3-tupling mm-wave for multiple wireless accesses.

Keyword Radio-over-Fiber · Dual-Parallel · Mach–Zehnder Modulator · NRZ · RZ · Gaussian

1 Introduction

Radio-on-fiber (RoF) technology has been increasingly used to meet the current and future demands of access networks, as it is able to provide low transmission loss, increased bandwidth, immunity to radio frequency (RF) interference, high flexibility and increased coverage, thus being essential to meet the needs of various wireless multimedia services, such
as: high-definition television (HDTV), digital multimedia broadcasting (DMB) and three-
dimensional TV (3DTV) (Singh and Raghuvanshi 2015; Xu et al. 2014; Wang et al. 2016).
Therefore, the RoF type communication system consists of a microwave photonic (MWP)
technique, in which the optical signal of a laser is directly or externally modulated in a cen-
tral station (CS) and is then transmitted through an optical fiber to a photodiode, which pro-
duces millimeter waves (mm-Wave) that are sent to a radio with antennas in a base station
(BS), with the aim of allowing access to multiple devices on the wireless network (Sousa
et al. 2020; Idowu et al. 2017), through the use of different access technologies, such as:
3G, 4G, 5G, WiFi (IEEE 802.11), Bluetooth (IEEE 802.15.1), ZigBee (IEEE 802.15.4),
UWB (IEEE 802.15.3), WiMAX (IEEE 802.16) simultaneously on a single antenna (Das
and Zahir 2014; Sharma and Rana 2017; Chen et al. 2017).

Conventional systems designed for RoF technology consists of several disadvantages,
such as: limited number of users, undesirable frequencies in the signals (sidebands),
non-linearities and poor system quality (Sharma and Rana 2017; Patel and Dalal 2017).
However, when compared to other telecommunications systems, RoF offers the following
advantages: lower loss of attenuation, better coverage, increased capacity, resistance to RF
interference, engineering reduction, lower energy consumption, lower execution cost and
project maintenance (Das and Zahir 2014).

Worldwide interoperability for microwave access (WiMAX) technology provides a
more useful solution in resolving the telecommunications bottleneck, but according to
(Chen et al. 2017) the 5th generation (5G) mobile communications network is the most
anticipated, for offering data transmission and reception capacity 1000 times greater
than the current cellular phone system, in addition to having a cost-effective deployment
and a high level of flexibility that can be exploited by design strategies that activate and
move baseband functions on demand according to need (Patel and Dalal 2017; Khorsandi
et al 2019), these and other factors have motivated the scientific community to carry out
research in this area.

Several approaches to RoF systems for photonic generation of mm-wave have been
reported in the literature over the past 20 years. In this sense, Zhu et al. (2013) proposed
and demonstrated the RoF system with frequency 12-tupling optical mm-wave genera-
tion using an integrated nested MZM. They showed that with the proper adjustment of the
direct current polarization voltages of two sub-MZMs, in which they obtained excellent
performance results with BER values of 10–10 and a power penalty of 0.67 dB for the sig-
nal transmitted for more than 60Km.

Zhu et al. (2015) proposed and demonstrated a new scheme for the generation of
120 GHz mm-wave through a local RF oscillator (LO) with an MZM. With the proper
adjustment of the dc bias of the modulator, they achieved frequencies of 12-tupling with
an optical sideband suppression ratio (OSSR) greater than 37 dB without the use of a filter.
They found that both the extinction rate and the phase difference between the two arms of
the optical coupler have an influence on the performance of the generated mm-wave.

According to Zhu et al. (2016), a dual-parallel polarization modulation (DPPolM) was
proposed for the generation of 24 GHz frequency sextupled microwave signal without the
use of a filter. The signal performance was also analyzed in terms of the OSSR and the
spurious suppression ratio (RFSSR), through adequate adjustments of the polarization
directions, power and phase differences of the modulated optical signals. The results were
satisfactory, with an OSSR greater than 31 dB and an RFSSR greater than 25 dB for a
4 GHz microwave signal. Later, in another paper they showed that frequency octupling,
sextupling, or quadrupling microwave signal can also be obtained experimentally, through
the appropriate adjustments of the polarization state, the modulation index of the serial modulators and the phase of the RF driving signal (Zhu et al. 2016).

In Muthu and Raja (2016) is shown a new low-cost approach to 16-tupling frequency generation was demonstrated through a 60 GHz bidirectional RoF system using two parallel cascading MZMs. This system simultaneously supported two base stations with bidirectional data transmission between BS and CS through wavelength reuse, so the connection distance can be extended up to 60 km with a power penalty of 0.5 dB and BER of 10−9 for both the upstream signal and the downstream signal.

Gao et al. (2016) experimentally proposed and demonstrated a photonic system using polarization-division multiplexing Mach–Zehnder modulator (PDM-MZM), which simultaneously performed frequency downconversion, multichannel phase shifting, and in-phase (I) and quadrature (Q) demodulation for wideband microwave signals without changing any configuration. They stated that, this system can be easily extended to multichannel applications with independent phase change in each channel and continuously adjusted in the range of 360 degrees. Thus, in the scheme proposed by them, the 40 GHz vector signals with various modulation formats were successfully demodulated, thus they stated that this system could potentially be used in other applications, including beam forming, phase detection, phase noise, and Doppler frequency shift Measurement.

Zhu et al. (2017a, b) presented states that with a double polarization modulator in a RoF communication system without a filter, it is possible to generate frequency sextupled microwave signal and achieve suppression of optical sidebands. Thus, by properly adjusting the power ratio of the orthogonal polarization directions, it is possible to cancel two first order sidebands and achieve the pure frequency sextupled signal with an OSSR greater than 38 dB and RFSSR greater than 32 dB.

Zhou et al. (2018) proposed an ROF system based on the four-wave mixing (FWM) technique, for transmission rate of 2.5Gbps and with RFs of 20, 40 and 60 GHz, capable of providing frequency multiplication, through the use of a dual-parallel Mach–Zehnder modulator (DP-MZM) in CS and a semiconductor optical Amplifier (SOA) after an SMF with a length of up to 40 km. The RoF system presented by them was able to conduct and support multiple mm-wave wireless accesses with excellent performance results.

Alipoor et al. (2018) studied the nonlinear effects of FWM in a 16-channel dense wavelength division multiplexing radio over fiber (16—DWDM—RoF) system with direct and external optical double side band (ODSB) moduation. The results of the simulations of this project showed that the external modulation obtained the best performance than the direct modulation in the parameters such as optical signal-to-noise ratio (OSNR), Q-Factor and bit error rate (BER) both in the variation of input power, spacing between channels, bit rate and length of the SMF. Thus, for a RoF system with external ODSB modulation with input power of 10 dBm, channel spacing of 100 GHz, bit rate of 10Gbps and link of 20 km, they obtained Q-factor of about 20 and BER less than 10−6, but for the RoF system with direct modulation the Q-factor was 3.5 and the BER was less than 10−4.

In this paper, we propose the simulation of a RoF DP-MZM system based on nonlinear and dispersive effects through the external modulation technique. Our RoF system was built according to the techniques proposed in (Chen et al. 2011; Li et al. 2015; Gao et al. 2016; Alipoor et al. 2018; Sousa et al. 2018) where it was able to considerably reduce nonlinear and dispersive effects on the link with a distance of up to 80 km and signal power of up to 15 dBm. The article structure was organized as follows: the theoretical analysis of the modulation technique, the operating principle and the proposed ROF system setup are presented in Sect. 2, the simulations and results analysis are presented in Sect. 3. Finally, the conclusion is presented in Sect. 4.
2 Mechanism of the proposed system

2.1 Simulation setup

Mach–Zehnder modulators (MZM) are opto-electric (OE) converters, which through special techniques may be able to compensate for linearization or dispersion individually or simultaneously. The phase and amplitude relationship between the optical carrier and the new sidebands generated can be tuned according to the phase and amplitude control techniques of the optical carrier, this is, using an integrated polarization-division multiplexing Mach–Zehnder modulator, the radio frequency (RF) signals can be frequency downconverted to multichannel intermediate frequency (IF) signals and the phase of each IF signal can be independently and arbitrarily tuned (Gao et al. 2016; Kumar et al. 2016).

Figure 1 shows the conceptual diagram of a DP-MZM, with two sub-MZMs that act on each arm of the main modulator (MZMₐ). In its operating principle, the MZMₐ is driven by the RF \( V_E(t) \) signal and the dc-bias polarization \( V_{\text{bias-a}} \) and the MZMₐ is driven by the dc-bias polarization \( V_{\text{bias-b}} \) and finally a dc-bias polarization \( V_{\text{bias-c}} \) controls the phase relationship of the two sub-MZMs, after DP-MZM. Therefore, with this cascade modulators scheme it is possible to achieve the generation of mm-wave of several orders at the signal output, after the DP-MZM. In the simulations, we investigated a simple scheme for the generation of mm-wave, which operates without an electric phase shifter and with an optical filter.

The used simulation configuration for the verification of the proposed system is shown in Fig. 2. An optical carrier given by a continuous wave (CW) laser source \( E_{\text{in}}(t) = E_0 \exp \left\{ j[\omega_c t + \phi(t)] \right\} \) was divided equally into the two modulators in parallel (MZMₐ and MZMₐₐ) that produced fields such as (Tao et al. 2020):

\[
E_a = \sqrt{\gamma} \sum_{n=-\infty}^{\infty} (-1)^n J_2(n \beta) \exp \left\{ j[\omega_c t + 2n\omega_c] \right\} + \sqrt{\gamma} (1 - 2\gamma) \sum_{n=-\infty}^{\infty} (-1)^n J_{2n-1}(n \beta) \exp \left\{ j[\omega_c t + (2n - 1)\omega_c] \right\} + j \frac{\pi}{2}
\]

and

\[
E_b = \left[ \sqrt{1 - \gamma} \cos \left( \frac{\pi V_{\text{bias-b}}}{2V_e} \right) \right] \exp \left( j\omega_c t \right) + \sqrt{1 - \gamma} \cdot (2\gamma - 1) \sin \left( \frac{\pi V_{\text{bias-b}}}{2V_e} \right) \exp \left( j\omega_c t + \frac{\pi}{2} \right)
\]

Fig. 1 Conceptual diagram of a Dual Parallel Mach–Zehnder Modulator (DP-MZM)
MZMc is DC biased at $V_{bias-c}$ to introduce a phase difference into the output electrical fields of the MZMa and the MZMb. The output of the MZMc is given by Eq. 3, disregarding the side band terms (Tao et al. 2020):

$$E_{out} = E_a + E_b \approx \left[ \gamma J_0(\beta) + (1 - \gamma) \cos \left( \pi \frac{V_{bias-c}}{2V_c} \right) \exp \left( j\pi \frac{V_{bias-c}}{V_c} \right) \right] \cdot \exp \left( jo \omega_c t + \frac{\pi \omega_c}{2} \right) + \left[ (1 - \gamma)(2\gamma - 1) \sin \left( \pi \frac{V_{bias-c}}{2V_c} \right) \cdot \exp \left( j\pi \frac{V_{bias-c}}{V_c} \right) \right] \cdot \exp \left[ j(\omega_c t + \frac{\pi \omega_c}{2}) \right] - (1 - 2\gamma)\gamma J_1(\beta) \cdot \{ \exp \left[ j(\omega_c t + j\frac{\pi \omega_c}{2}) \right] - \gamma J_2(\beta) \cdot \exp \left[ j(\omega_c + 2\omega_m) t + j\frac{\pi \omega_c}{2} \right] \} + [j(\omega_c - 2\omega_m) t + j\frac{\pi \omega_c}{2}] + \gamma J_3(\beta) \cdot \{ \exp \left[ j(\omega_c + 3\omega_m) t + j\frac{\pi \omega_c}{2} \right] \} + [j(\omega_c - 3\omega_m) t + j\frac{\pi \omega_c}{2}] + \gamma J_4(\beta) \cdot \{ \exp \left[ j(\omega_c + 4\omega_m) t + j\frac{\pi \omega_c}{2} \right] \} + \exp \left[ j(\omega_c - 4\omega_m) t \right] \}$$

where $E_0$ is the input field, $\omega_c = 2\pi f_c$ is the angular frequency of the optical carrier, $\phi(t)$ is the phase fluctuation of the optical field, $\beta = \pi V_m/2V_c$ is the modulation index (MI), $V_m = V_{RF} \cos(\omega_m t)$, $\omega_m$ are the amplitude and the angular frequency of the RF driving.
signal, $V_s$ is the half-switch voltage, $g$ is the power splitting ratio of the DP-MZM, $J_n(\cdot)$ is the nth-order Bessel function of the first kind.

Figure 2 presents stage 1 of the proposed RoF- DP-MZM system. This system is composed of two sub-Mach–Zehnder Modulators (sub-MZMs) external and they act on each arm of the main modulator, which is called of dual-parallel Mach–Zehnder modulator (DP-MZM). Both sub-MZMs are biased in their maximum transmission point (MATP). The sub-MZMs are triggered by the RF signal sent by the sine generator with frequencies from 20 to 80 GHz. A continuous wave (CW) laser was used as an optical carrier with frequency for the wavelength of 1552.5 nm and power from −15 dBm to 15 dBm at the DP-MZM input. According to this scheme was possible to achieve the generation of 3-tupling mm-wave at the signal output, which are side bands of ± 3rd order symmetrically spaced in the frequency domain, below and above the optical carrier.

The output signal of the DP-MZM was coupled by a WDM interleaver Demux and was later sent to stage 2, which is a Mach–Zehnder interferometer (MZI) with another Mach–zehnder modulator (MZM_d) in its upper arm. The WDM interleaver Demux had the function of dividing the stage 1 signal for each of the MZI arms. In the upper arm of the MZI, the baseband data with three encoding formats (NRZ, RZ or Gaussian) was added to the signal for the transmission rate of 10Gbps, which were later modulated by the MZM_c, and then, the optical mm-wave signal and the optical carrier were coupled at the output of the pump coupler co-propagating and sent to a SMF of up to 80 km in length.

The signal composed of the sidebands and the carrier after being transmitted by several kilometers of SMF was amplified by an erbium doped fiber amplified (EDFA) and later a gaussian optical filter (GOF), it was used to reduce the amplified spontaneous emission (ASE) noise emitted by EDFA and, also, to remove the sidebands of the signal and allow the propagation of the optical carrier only.

Then, the optical carrier signal was distributed through a power splitter for each of the BSs. As shown in Fig. 2, the BSs are composed of a positive intrinsic negative (PIN) photodetector that was responsible for converting the optical signal into an electrical signal and a low pass Bessel filter that was used to remove noise in the electrical signal. The performance analysis of the RoF DP-MZM system was performed according of the eye diagram which provides BER and Q-factor values through the use of BER analyzer at the signal output in each of the BSs.

### 3 Numerical simulation results and discussion

In this work, the MATLAB and OptiSystem softwares were used to simulate and to analyze the performance of the RoF-DP-MZM scheme with three coding signals: Non-Return-to-Zero (NRZ), Return-to-Zero (RZ) and Gaussian, which are shown through the graphs of pulse formats and eye diagrams in Figs. 3, 4, respectively. In the simulations, the three types of coding were used alternately according to the simulation parameters tabulated in Table 2 (appendix). The analysis of the system performance of the system for the transmission rate of 10Gbps was performed through the results collected from the optical spectrum and the eye diagram as a function of the variation of the following parameters: mm-wave frequencies from 20 to 80 GHz, input power from −15 dBm to 15 dBm and the fiber length from 0 to 80 km.
The performance analysis of digital transmission systems through the eye diagram has been considered a simple and powerful technique (Agrawal 2012), which is also convenient for the study of the effects of intersymbol interference (ISI) and losses in signal quality due to dispersion and non-linearities. Thus, through the study of the eye diagram it is possible to visualize distortions in the shape of the received signal and extract various useful information, such as: height of eye opening, timing jitter, noise level, bit error rate (BER) and quality factor (Q-Factor). The results of these parameters have been widely used for the analysis of fiber optic communication systems in several related studies (Singh and Raghuranshi 2015; Xu et al. 2014; Sousa et al. 2018; de Sousa et al. 2020), but the proposed RoF system analysis was performed only through the Q-factor and BER.

Figure 5a shows the optical spectrum graph of the CW laser output (optical carrier) with a central frequency of 1552.5 nm and an input power of 0 dBm. In Figs. 5b and c, the graphs of the spectra of the signal output after the DP-MZM are shown for the mm-wave frequencies of 20 and 80 GHz, respectively. We highlight that the data were collected for the variation of mm-wave frequencies of 20, 40, 60 and 80 GHz, but for reasons of organization of this paper, we prefer to present initially the optical spectra only for the cases with mm-wave frequencies of 20 and 80 GHz, which are sufficient to show the effects that occur in the signal depending on the variation of the mm-wave frequency.

In the spectra of Figs. 5b and c can be observed the presence of symmetrical side bands downstream (1552, 1552.2, 1552.3, 1552.7, 1552.8 and 1553 nm) with the optical carrier (1552.5 nm). These symmetrical side bands are harmonic up to ±3rd order, with wavelengths and powers that are presented neatly in Table 1, where it is possible to observe an increase in the spacing between the side bands and the optical carrier, when the frequency of mm-wave was increased of 20 to 80 GHz.

After the signal transmission through the WDM interleaver Demux, part of the side bands was suppressed, leaving only the optical carrier and the side bands, which were later sent to the SMF. As shown by the results of the optical signal spectrum after WDM interleaver Demux in Fig. 6a, a power value of −22.9 dBm was obtained for the optical carrier and for the sidebands of -3rd order (1552 nm) and +3rd order (1553 nm), powers equal to −63 dBm and −67.3 dBm, respectively.

Figure 6b shows the optical spectrum amplified by EDFA, which performed a process of amplification and gain of optical signal power. In this optical spectrum there is still the presence of the side bands together with the optical carrier and ASE noise. Subsequently, the side bands were suppressed by GOF as shown by the optical spectrum of the signal in Fig. 6c. As was observed in the numerical simulations, the suppression of the side bands of ±3rd order occurred regardless of the SMF length and the mm-wave frequency, in the three pulse formats proposed. Therefore, the signal arrived at the base stations (BS1, BS2 and BS3) without the presence of side bands and with power of approximately -17 dBm, as shown in Fig. 6d.

3.1 Fiber length effects

The performance analysis of the communication link for the transmission rate of 10Gbps and input power of 0 dBm, was carried out through the eye diagrams of the downstream data of 20, 40, 60 and 80 GHz, after the SMF with 0 km (B-T-B), 20 km, 40, 60 and 80 km, for the power of the 0 dBm CW laser with RZ, NRZ and Gaussian encoding, which are shown in Fig. 7a, b c and d, respectively. Through the results obtained, it was possible to observe that due to the increase of the non-linear effects, dispersion and attenuation in the...
Table 1  Wavelengths and Powers of Downstream Sidebands

| Nº | RF Frequencies |
|----|----------------|
|    | 20 GHz | 40 GHz | 60 GHz | 80 GHz |
|    | Wavelength (nm) | Power (dBm) | Wavelength (nm) | Power (dBm) | Wavelength (nm) | Power (dBm) | Wavelength (nm) | Power (dBm) |
| −3 | 1552 | −46.5 | 1551.6 | −46.4 | 1551 | −46.5 | 1550.6 | −46.7 |
| −2 | 1552.2 | −28.9 | 1551.8 | −29 | 1551.5 | −28.9 | 1551.2 | −28.9 |
| −1 | 1552.3 | −15.2 | 1552.2 | −15.5 | 1552 | −15.6 | 1551.9 | −15.2 |
| 0  | 1552.5 | −7.9 | 1552.5 | 7.5 | 1552.5 | −8 | 1552.5 | −7.9 |
| 1  | 1552.7 | −15.2 | 1552.8 | −15.5 | 1553 | −15.6 | 1553.1 | −15.2 |
| 2  | 1552.8 | −28.9 | 1553.2 | −29 | 1553.5 | −28.9 | 1553.8 | −28.9 |
| 3  | 1553 | −46.5 | 1553.4 | −46.4 | 1554 | −46.5 | 1554.4 | −46.7 |
signal transmission, the performance of the proposed RoF system was reduced, because the quality factor decreased and consequently, the bit error rate increased as the length of the SMF increased. Therefore, for all cases, the best performance occurred for the 20 km fiber and the worst performance was found for the 80 km fiber, this can also be seen through the eye diagrams in Figs. 8, 9 and 10.

In the obtained results was possible to note that in most cases the RoF DP-MZM scheme with NRZ encoding obtained better tolerance to dispersion, to nonlinear effects and to the noise manifested with the increase in SMF length, consequently the best transmission performance results were obtained, that is, higher quality factor values and lower bit error rate values, when compared to the RoF- DP-MZM schemes with RZ and Gaussian encoding, according to the Q-Factor graphs versus transmission distance for the signal received in the BSs, shown in Fig. 7a, b, c and d.

In the eye diagrams of Figs. 8, 9 and 10, the red color graph represents the BER value as a function of the SMF length for each encoding format used, both for 80 GHz downstream data. Thus, for the RoF- DP-MZM system with NRZ encoding format the Q-Factor values obtained for 20, 60 and 80 km were: 15.5957, 12.7422 and 7.42646, respectively. Similarly,

![Fig. 3](image-url) (a) NRZ pulse, (b) RZ pulse and (c) Gaussian Pulse

![Fig. 4](image-url) Eye diagram of the received signal for 20 GHz mm-wave and for pulse formats NRZ (a), RZ (b) and Gaussian (c)
the BER values obtained for 20, 60 and 80 km were: $3.83014 \times 10^{-55}$, $1.72215 \times 10^{-37}$ and $5.52838 \times 10^{-14}$, respectively (Fig. 8). For the RoF DP-MZM system with RZ encoding format, the Q-Factor values obtained for 20, 60 and 80 km were: 12.9256, 3.46564 and 2.63623, respectively. Similarly, the BER values obtained for 20, 60 and 80 km were: $1.3792 \times 10^{-38}$, 0.000264215 and 0.00364023, respectively (Fig. 9). And for the RoF- DP-MZM system with Gaussian encoding format the Q-Factor values obtained for 20, 60 and 80 km were: 11.2757, 9.39981 and 5.56815, respectively. Similarly, the BER values obtained for 20, 60 and 80 km were: $8.47293 \times 10^{-30}$, $2.7279 \times 10^{-21}$, $1.28668 \times 10^{-8}$, respectively (Fig. 10).

Thus, the eye diagrams of Figs. 8, 9 and 10 show that for the three encoding formats used in the proposed RoF- DP-MZM system, that there was also a reduction in the height and amplitude of the eye diagram as the length of the SMF increased, mainly for the RoF system with 80 km SMF, where it was possible to clearly observe that the eye diagrams are stressed, mainly for the RoF- DP-MZM system with RZ encoding format. In this sense, the RoF- DP-MZM system with RZ encoding format had a greater performance reduction from 60 to 80 km of SMF, as shown by the eye diagrams of Figs. 9b and c, when compared with the RoF- DP-MZM systems with NRZ coding in Figs. 8b and c and with Gaussian coding, presented in Figs. 10b and c.

### 3.2 Input power effects

Figure 11 shows the log BER versus Input Power graphs, where the signal power was varied from −15 dBm to 15 dBm for the mm-wave frequencies varied from 20 to 80 GHz.
and also for each of the baseband signals with Non-Return-to-Zero (NRZ), Return-to-Zero (RZ) and Gaussian encodings. In the simulations it was noticed that with the increase of the input signal power the non-linear and dispersive effects increased resulting in undesirable distortions in the signal, which reduced the quality factor and increased the bit error rate, therefore, consequently the proposed RoF schemes had reduced performance for the three types of encoding signals used.

The Log BER behavior with Input Power (Fig. 11) is due to in any fiber optic communication system the Q-factor value should be as high as possible up to a certain threshold for an optimal power value of the transmitted signal. In this sense, for low power levels the performance of the system is limited by undesirable noises, while for high power levels the system performance is reduced by non-linear effects. Another fact is that during the process of data transmission in SMF, various nonlinear and dispersive effects can induce power variations, which also affect system performance according to transmission time (Agrawal 2012).

According to the graphs of log BER versus the input power signal, which are shown in Figs. 11a, b, c and d, it was possible to observe that in most cases, again the RoF scheme with NRZ encoding obtained better tolerance to dispersion, non-linear effects and noises, which were manifested with the increase in signal power. Thus, the best results of signal transmission performance were obtained, that is, higher values of the quality factor and lower bit error rate values were obtained, when compared to RoF schemes with RZ and Gaussian encoding. This can also be seen through the eye diagrams shown in Figs. 12, 13 and 14, in which the red color graphs represent the Q-factors values as a function of the variation of the input signal power of −15 dBm, 0 dBm and 15 dBm for each encoding format used, both for 80 GHz downstream data.

Thus, for the RoF system with NRZ encoding format, the Q-Factor values obtained for −15 dBm, 0 dBm and 15 dBm were: 4.5286, 16.0638 and 15.9194, respectively. Similarly, the values obtained from BER were: $2.96085 \times 10^{-6}$, $2.24129 \times 10^{-58}$, $2.27664 \times 10^{-57}$ (Fig. 12). For the RoF system with RZ encoding format, the Q-Factor values obtained for −15 dBm, 0 dBm and 15 dBm were: 2.02644, 12.7328 and 13.531, respectively. Similarly, the values obtained from the BER were: 0.0213597, 1.64137 $\times 10^{-37}$, 4.24391 $\times 10^{-42}$ (Fig. 13). And for the RoF system with Gaussian encoding format, the values obtained from the Q-Factor for the input power −15 dBm, 0 dBm and 15 dBm were: 3.46999, 11.5584 and 11.3665, respectively. Similarly, the values obtained from BER were: 0.000260192, 3.26753 $\times 10^{-31}$, 2.9895 $\times 10^{-30}$ (Fig. 14).

Therefore, the eye diagrams of Figs. 12, 13 and 14 show that for the three encoding formats used in the proposed RoF system, there was an increase in the Q-factor and a reduction in the BER up to a certain threshold as the input signal power increased. However, from the power limit of each of the proposed RoF systems, there was a reduction in the height and amplitude of the eye diagram as the input power of the signal was increased up to 15 dBm, this can be seen clearly in the eye diagrams in the Figs. 12(c), 13(c) and 14(c). It is also noteworthy that for RoF systems with input power of −15 dBm, the eye diagrams are considerably stressed, this was due to the limitation of the systems to the noises that manifested during the signal transmission process, which resulted in low performance for the three types of encoding used for 80 GHz downstream data, however this effect also occurred with the other mm-Wave frequencies used as shown in the graphs of Fig. 11.
Conclusion

The proposed RoF DP-MZM system was numerically demonstrated, which was able to satisfactorily generate ±3rd order mm-wave for the purpose of providing multiple multiband wireless accesses in the various BSs, at a transmission rate of 10Gbit/s and RF frequencies of 20 GHz, 40 GHz, 60 GHz and 80 GHz. The system performance was investigated through signal power and SMF length. The results showed the Q-factor value and the eye diagram were excellent for the three coding formats used, especially the NRZ, which obtained better performance values both for the variation of the SMF length and in the variation of the signal power. Therefore, the proposed RoF system can be considered of simple structure and suitable for the implementation of modern wireless communication systems in the presence of non-linear and dispersive effects.
Fig. 7  Q-Factor versus transmission distance for Downstream data of 20 GHz (a), 40 GHz (b), 60 GHz (c) and 80 GHz (d) for baseband signals with NRZ, RZ and Gaussian encoding.

Fig. 8  Eye diagram for the proposed RoF system with (a) 20 km and (b) 60 km and (c) 80 km, both for 80 GHz downstream data of NRZ encoding.
Fig. 9 Eye diagram for the proposed RoF system with (a) 20 km, (b) 60 km and (c) 80 km, both for RZ encoding 80 GHz downstream data

Fig. 10 Eye diagram for the proposed RoF system with (a) 20 km, (b) 60 km and (c) 80 km, both for 80 GHz downstream gaussian encoding data
Fig. 11 Log BER versus Input Power for Downstream data of 20 GHz (a), 40 GHz (b), 60 GHz (c) and 80 GHz (d) for baseband signals with NRZ, RZ and Gaussian encoding.

Fig. 12 Eye diagrams for, (a) −15 dBm input power, (b) 0 dBm input power and (c) 15 dBm input power for the Non-Return-to-Zero (NRZ) encoding signals.
Table 2 shows the used components parameters in the simulation of the proposed RoF-DP-MZM system, which they were indispensable for the construction of this optical network project.

**Appendix**

Table 2 shows the used components parameters in the simulation of the proposed RoF-DP-MZM system, which they were indispensable for the construction of this optical network project.
Table 2  Used simulation parameters in the proposed RoF system

| Transmitter parameters                                   | Value                           |
|----------------------------------------------------------|---------------------------------|
| Sine generator frequency                                 | 20 GHz to 80 GHz                |
| Sine generator phase                                     | 90 deg                          |
| CW laser power                                           | −15 dBm to 15 dBm               |
| CW laser frequency                                       | 1552.5 nm                       |
| CW laser line width                                      | 10 MHz                          |
| MZM extinction ratio                                     | 20 dB                           |
| MZM symmetrical factor                                   | −1                              |
| Power combiner Number of input ports                     | 2                               |
| Power combiner Loss                                      | 0 dB                            |

**Mach–Zehnder Interferometer parameters**

| Parameter                                             | Value                           |
|-------------------------------------------------------|---------------------------------|
| WDM interleaver demux frequency                        | 1552.5 nm                       |
| WDM interleaver demux frequency spacing                | 10 GHz                          |
| WDM interleaver demux bandwidth                        | 0.06 nm                         |
| WDM interleaver demux insertion loss                   | 1 dB                            |
| MZM extinction ratio                                   | 20 dB                           |
| MZM symmetrical factor                                 | −1                              |
| Pump coupler co-propagating signal attenuation         | 3 dB                            |
| Pump coupler co-propagating pump attenuation           | 0 dB                            |

**Stage 2 parameters**

| Parameter                                             | Value                           |
|-------------------------------------------------------|---------------------------------|
| Pseudo-random bit sequence generator Bit rate          | 10e9Bits/s                      |
| Pseudo-random bit sequence generator operation mode    | Order                           |
| Pseudo-random bit sequence generator operation order   | log(Sequence length)/log(2)     |
| Pseudo-random bit sequence generator number of leading zeros | (Time window * 3 / 100) * Bit rate |
| Pseudo-random bit sequence generator number of trailing zeros | (Time window * 3 / 100) * Bit rate |
| NRZ and RZ pulse generators rectangle shape            | Exponential                     |
| NRZ and RZ pulse generators amplitude                  | 1 a.u                           |
| NRZ and RZ pulse generators bias                       | 0 a.u                           |
| NRZ and RZ pulse generators                             | 0 bit                           |
| NRZ and RZ pulse generators rise time                  | 0.05 bit                        |
| NRZ and RZ pulse generators fall time                  | 0.05                            |
| Gaussian pulse generators amplitude                    | 1 a.u                           |
| Gaussian pulse generators bias                         | 0 a.u                           |
| Gaussian pulse generators width                        | 0.5 bit                         |
| Gaussian pulse generators position                     | 0 bit                           |
| Gaussian pulse generators order                        | 1                               |

**Link parameters**

| Parameter                                             | Value                           |
|-------------------------------------------------------|---------------------------------|
| SMF attenuation                                       | 0.17 dB/km                      |
| SMF dispersion                                         | 17.8 ps/nm/km                   |
| SMF dispersion slope                                   | 0.08 ps/nm²/km                  |
| SMF effective area                                     | 80 m²/km                        |
| Length                                                | 0 to 80 km                      |
| EDFA gain                                              | 12 dB                           |
| EDFA noise figure                                      | 4 dB                            |
| GOF frequency                                          | 1552.5 nm                       |
Acknowledgements  This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001. The authors gratefully acknowledge financial support from PROPESP/UFPA. The author W.Paschoal Jr. gratefully acknowledge supporting from FACIN/UFPA, FACFIS/UFPA, PPGF/UFPA, ICEN/UFPA, PROEG/UFPA, NanoJovem/PROEX/UFPA, PIBID/CAPES, and the Brazilian agencies FINEP, CAPES and MAI/MCTIC/CNPq.

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Authors and Affiliations

Fabio B. de Sousa\textsuperscript{1,2} · Fiterlinge M. de Sousa\textsuperscript{1,2} · Igor R. S. Miranda\textsuperscript{1,2} · Waldomiro Paschoal Jr.\textsuperscript{3,4} · Marcos B. C. Costa\textsuperscript{1,2,5}

\textsuperscript{1} Programa de Pós-Graduação Em Engenharia Elétrica, Universidade Federal do Pará, Rua Augusto Corrêa, 01, Guamá, Belém 66.075-110, Pará, Brasil

\url{https://dgp.cnpq.br/dgp/espelho_grupo/8017792785061258}

\textsuperscript{2} Programa de Pós-Graduação em Física, Universidade Federal do Pará, Rua Augusto Corrêa, 01, Guamá, Belém 66.075-110, Pará, Brasil

\url{https://dgp.cnpq.br/dgp/espelho_grupo/2896588912634757}

\textsuperscript{3} Universidade Federal do Pará, Faculdade de Engenharia de Materiais, Rodovia BR-316, km 7, Levilândia 66.000-000, Pará, Brasil