Modulation and Equalization Techniques for mmWave ARoF

Citation for published version (APA):

Document license:
TAVERNE

DOI:
10.1007/978-3-030-74648-3_8

Document status and date:
Published: 06/11/2021

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 25. Sep. 2023
Chapter 8
Modulation and Equalization Techniques for mmWave ARoF


Abstract Fifth generation (5G) is the emerging mobile communications platform that aims to meet the market requirements in terms of enhanced broadband connectivity based on harnessing small cell and mmWave technology. These two in synergy will provide high capacity gain not only through the hyperdense deployment of small cell but also through accessing large swathes of untapped spectrum at mmWave frequencies. The envisaged architecture entails an integrated optical wireless network architecture, where optical technology will complement radio in order to handle the new demands on capacity over the backhaul and fronthaul network, leading to the notion of analog radio over fiber (ARoF). The goal of this chapter is to provide novel approaches to optimize the performances of mmWave ARoF systems that includes developing enabling technology from a digital to signal processing (DSP) and device perspective.

8.1 Introduction

The fifth generation (5G) of mobile networks is the new solution to cater for emerging market requirements that aims to deliver in terms of flexibility, cost, power
consumption, latency, bit rate, reliability, and coverage. A centralized radio access network (C-RAN) is defined for 5G that can deliver enhanced received signal quality through centralized processing, with the potential to deliver reduced service latency, and greater network flexibility to the mobile operators.

This had led to a new disruptive 5G architecture that entails an integrated optical wireless network architecture, where optical technology will complement radio in order to handle the new demands on capacity over the backhaul and fronthaul network, leading to the notion of analog radio over fiber (ARoF). ARoF implies attractive benefits such as wide area coverage, high spectral efficiency, simple receivers, reduced power consumption, and low latency. Nevertheless, the combination of these technologies implies new challenges, such as high free-space path loss (FSPL), chromatic dispersion, phase noise, and combined mmWave radio and optical channel impairments, that will affect radio detection performance.

This chapter aims to study and analyze techniques to reduce the degradation introduced by the mmWave ARoF channel by revisiting the signal processing in the radio-optical transceiver link. The right modulation format selection is key to achieve higher performance in any communication system. The analysis of modulation formats in optical and wireless channels has been well studied independently. However, modulation formats have not been analyzed comprehensively in mmWave ARoF scenarios, where optical and wireless channels are joined. In this context, Sect. 8.2 compares experimentally the main radio modulation candidate formats in a mmWave ARoF setup and provides new insights into the best modulation options that suggests that legacy OFDM modulation might not tick all the boxes as it once did. Moreover, in such as a converged system, the analog radio signal will be subject to chromatic dispersion in the standard single-mode fiber (SSMF), spurring the need for equalization to compensate dispersion in the fiber. Section 8.3 studies channel equalization at the radio receiver based on a simulated mmWave ARoF scenario and provides new insights in performance. Optical amplifiers and modulators are crucial devices in mmWave ARoF systems. The REAM (reflective electroabsorption modulator)-SOA (semiconductor optical amplifier) integrated into a single chip is investigated as an alternative to the directly modulated lasers (DMLs) in the optical link, where EAM-based transmitters have the potential to provide better transmission performances because of the absence of adiabatic chirp. On the one hand, the SOA is sought to increase signal propagation distances to envisage the 5G coverage requirements. At the same time, the transceiver module of a 5G fronthaul must be able to operate at any wavelength of the WDM (wavelength-division multiplexing) system by being either wavelength-tunable or wavelength-independent (colorless). In this context, Sect. 8.4 investigates the device and optical link performance in terms of key parameters such as extinction ratio, insertion losses, and gain. In particular, an experimental digital transmission is demonstrated by utilizing this device, achieving a bit rate of 50 Gb/s. Finally, Sect. 8.5 provides the chapter conclusions.
8.2 Feasibility Study on New Modulation Formats for mmWave ARoF

The right modulation format selection is key to achieve higher performance in any communication system. The analysis of modulation formats in optical and wireless channels has been well studied independently. However, modulation formats have not been analyzed thoroughly in mmWave ARoF scenarios, where optical and wireless channels are joined.

Since mmWave ARoF combine wireless and optical channels, the selection of the modulation format becomes more crucial [1]. Orthogonal frequency-division multiplexing (OFDM) is the selected modulation format by 3rd Generation Partnership Project (3GPP) in the first 5G standard. However, it is not clear that OFDM is the best choice for mmWave ARoF systems. Therefore, in this section, a comprehensive comparison and analysis of the main modulation formats for 5G is realized in a mmWave ARoF system.

This section is structured as follows: first, a 5G architecture based on mmWave cells over an ARoF layer is explained in Sect. 8.2.1; next, the examined modulation formats are described in Sect. 8.2.2, highlighting its advantages and disadvantages; finally, the experimental setup and results of the modulation format comparisons are shown in Sect. 8.2.3.

8.2.1 ARoF Architecture for 5G Fronthauling

5G aims to support many types of services with different requirements and needs. These services are classified by 5G into three scenarios [2]: enhanced mobile broadband (eMBB), where the main goal is to achieve high bit rate; ultra-reliable low-latency communications (URLC), where latency and reliability are the main requirements; and massive machine-type communications (mMTC) supporting a huge quantity of connected devices. Video streaming is the most common user case for eMBB, while autonomous driving and smart cities are clear examples of URLC and mMTC scenarios, respectively.

Network slicing is one of the most suitable strategies to manage and adapt the resources of the network according to the service requirements. Network slicing is based on software-defined networking (SDN) and network function virtualization (NFV), allowing to slice the physical network into several logical networks and, then, provide resources for a distinct application scenario [3].

As mentioned before, exploiting the mmWave domain is necessary to achieve the 5G requirements in terms of bit rate. However, the use of mmWave frequencies implies high free-space path loss (FSPL), and, thus, the cell radius is reduced into ranges of 10–200 m [1]. Hence, mmWave cells lead to a huge increase in the number of cells in contrast to the sub-6 GHz cells, to cover the same surface. Moreover, 5G
Fig. 8.1 ARoF fronthauling architecture employing mmWave cells for different applications

scenario exhibits a heterogeneous network where the mmWave microcells and the sub-6 GHz macrocells coexist and cooperate together.

The complexity of the remote unit (RU) is much less in ARoF system than in the current common public radio interface (CPRI) [4]. Therefore, an ARoF solution is a suited technology to give support to the enormous quantity of mmWave cells. Furthermore, C-RAN is a preferred option in terms of flexibility, latency, and energy consumption since most of the processes can be performed from a central office (CO) [5].

Therefore, due to the inherent benefits of the individual components, mmWave cells over C-RAN ARoF transport layer in synergy play a pivotal role in the 5G architecture. However, with several challenges still to solve, the ARoF will continue to be at the forefront of 5G research as we head toward the beyond 5G era.

Figure 8.1 shows the scheme of a C-RAN ARoF architecture with mmWave cells for the 5G fronthauling. In this system, most of the processes are arranged in CO. First, the electrical signals are generated in multiple streams. Then, the radiofrequency (RF) carrier is aggregated to each signal. Next, the resulted signals are converted to the optical domain. These three processes are managed and monotonized by a SDN/NFV control plane in order to perform the network slicing. Last, the multiple optical signals are multiplexed into an optical fiber ring. This multiplexing process can be arranged by different technologies: wavelength-division multiplexing (WDM), spatial-division multiplexing (SDM), or mode-division multiplexing (MDM). For instance, using WDM technology, each mmWave cell is located in a single wavelength.

The optical fiber ring achieves the different mmWave cells through demultiplexing access points. After the demultiplexing process, the optical signal reaches the RU of its corresponded mmWave cell. In the RU, the optical signal is converted to the electrical domain with the desired mmWave carrier frequency. Then, the mmWave wireless link is established between the RU and receiver point.
There are depicted several examples of mmWave cell use-cases in Fig. 8.1. The first use-case consists of a typical mobile cell where the end users correspond to mobile phones. The mobile phones can request resources for many types of services such as video streaming, augmented reality, video calls, etc. Another example of a mmWave cell user is the fronthauling along a highway. In this example, the mmWave cell supports a certain number of microcells that are distributed along the highway. Applications, such as autonomous driving, can be achieved through this deployment. The last example is based on a point-to-point communication. In this case, the RU is connected to several buildings in a city. In this context, smart houses with Internet of things (IoT) solutions can be supported in this communication system. Moreover, sub-6 GHz cells can also be supported through the C-RAN ARoF solutions. In this way, the 5G heterogeneous network can be managed by a single technology. Thus, the remote processes can be simplified, and the cell cooperation management can be optimized.

8.2.2 Proposed Modulation Formats Under Test

Modulation formats study is essential to enhance the performance of any communication system. Each communication system requires determined specification for the employed modulation format. For example, the wireless communication requires high robustness to frequency-selective channels due to the multipath effect in this type of communications. Since mmWave ARoF combines the optical and wireless channels, the design requirements for the modulation formats are more extensive and complex. The mmWave ARoF requirements for modulation formats can be expressed in terms of key performance indicators (KPIs). The main KPIs for modulation formats in a mmWave ARoF system are the following [6]:

- **Peak-to-average power ratio (PAPR)**: this parameter is obtained by dividing the maximum peak by the power average of the signal. High PAPR leads to important degradations of the signal in devices such as digital-to-analog converters (DAC), MZM, and RF amplifiers. Since all these devices are involved in a mmWave ARoF system, low PAPR is a relevant KPI for this type of systems. Moreover, there are multiple techniques that take a step toward reducing the PAPR by DSP. However, any PAPR reduction technique implies at least one of the following: power increase, bandwidth expansion, or bit error rate (BER) degradation.

- **Robustness to phase noise**: phase noise represents a random fluctuation in the phase of the waveform. This impairment is produced in the mmWave tone generation to upconverting or downconverting the information signal. In ARoF systems, this generation can be performed in the optical or electrical part. The phase noise level depends on the employed technique to generate the mmWave tone. The phase noise represents one of the major limiting factors in ARoF systems [7]. For this reason, high robustness to phase noise is a crucial KPI to reach high performances in ARoF systems.
• **Robustness to multipath channels:** as the signal of the transmitter antenna follows different paths in a wireless environment, the receiver antenna receives copies of the transmitted signal with delays and attenuations corresponding to each of these multipaths. This multipath effect produces a degradation in the received signal. In this context, high robustness to multipath channels is an important KPI for any wireless link. However, since the secondary paths are more attenuated in high carrier frequencies due to reflections and refraction processes, the mmWave channel displays less multipath effect than in lower-frequency bands. Therefore, robustness to multipath channels is not a determinative KPI for mmWave ARoF systems.

• **Spectral efficiency:** this parameter is related to the achieved throughput of the used bandwidth. When the bandwidth of the system is fixed, the spectral efficiency determines the maximum bit rate that can be reached. As most of the communication channels are limited in spectrum, high spectral efficiency is a relevant KPI to be considered. This KPI is more critical in the mmWave wireless channel in contrast to its optical counterpart since optical spectrum is much wider than mmWave spectrum. Furthermore, since the frequency spectrum was commercialized, high spectral efficiency implies lower costs.

• **Complexity:** a commercial communication system requires a real-time DSP process. Field-programmable gate array (FPGA) is a suitable solution to achieve real-time DSP in prototypes with reduced manufacturing time process. However, FPGA devices are limited in process blocks. Thus, low complexity is a KPI that allows to integrate modulation formats in FPGA systems. In addition, low complexity KPI reduces latency and cost because the DSP is simplified.

Modulation formats can be classified into two big groups: single-carrier (SC) waveforms and multi-carrier (MC) waveforms. The “under-test” MC waveforms are the following: OFDM, universal-filtered multi-carrier (UFMC), and generalized frequency-division multiplexing (GFDM). On the other hand, single-carrier frequency-division multiplexing (SC-FDM) and multiband carrierless amplitude phase modulation (multi-CAP) are the examined SC waveforms. However, SC-FDM and multi-CAP are not pure SC waveforms. Therefore, these modulation formats present hybrid SC and MC waveform properties.

SC waveforms present lower PAPR level than MC waveforms. Moreover, SC waveforms are more robust in terms of phase noise. However, SC waveforms are less tolerant to multipath channels, and MC waveforms can imply higher spectral efficiency due to its low out-of-band (OOB) emissions. Hence, the characteristics of a modulation format can be briefly resumed depending on the waveform group that it belongs.

Table 8.1 shows a qualitative comparison of the under-test modulation formats according to the KPIs previously explained. As it can be observed, it does not rationalize to assess the best modulation format since each one of these presents advantages and disadvantages. For example, GFDM is a good choice in terms of spectral efficiency and robustness to multipath channels. However, GFDM presents high PAPR and complexity. On the other hand, multi-CAP performs better than
Table 8.1 Comparison of the evaluated modulation formats in terms of mmWave ARoF KPIs

<table>
<thead>
<tr>
<th></th>
<th>OFDM</th>
<th>SC-FDM</th>
<th>UFMC</th>
<th>GFDM</th>
<th>Multi-CAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAPR</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Robust. to phase noise</td>
<td>Medium</td>
<td>Medium/high</td>
<td>Medium</td>
<td>Medium/high</td>
<td>Medium/high</td>
</tr>
<tr>
<td>Spectral efficiency</td>
<td>High</td>
<td>High</td>
<td>Very high</td>
<td>Medium/high</td>
<td>Medium/high</td>
</tr>
<tr>
<td>Robust. to multi. chan.</td>
<td>High</td>
<td>Medium/high</td>
<td>High</td>
<td>High</td>
<td>Medium/high</td>
</tr>
<tr>
<td>Complexity</td>
<td>Medium</td>
<td>Medium/high</td>
<td>Medium/high</td>
<td>High</td>
<td>Medium/low</td>
</tr>
</tbody>
</table>

GFDM in terms of complexity and PAPR. However, the spectral efficiency and robustness to multipath channels of multi-CAP is lower than in the GFDM case.

As mmWave ARoF channel is very complex to analyze, it is very difficult to determine the most relevant KPI. Therefore, a qualitative comparison of the mmWave ARoF KPIs is not sufficient to decide the best modulation format choice for this type of system. For this reason, a comparison of the examined modulation formats in an experimental mmWave ARoF system is realized, which is elaborated in the next subsection.

8.2.3 Practical Experiment

Since it is very complex to select the best modulation format in mmWave ARoF systems through a qualitative comparison, an experimental comparison is needed to determine the best modulation format candidate. In this subsection, this experimental comparison is presented and explained as two parts: in the first part, the experimental mmWave ARoF setup is explained thoroughly, while the second part provides the analysis and interpretation of the results.

8.2.3.1 ARoF Testbed Description

Figure 8.2 shows all the components used in the experimental comparison. In this experimental comparison, a scenario of Fig. 8.1 is simulated.

Figure 8.2a represents the mmWave ARoF scheme. First, an external cavity laser (ECL) generates an optical carrier at 1550 nm. Then, this optical signal is modulated by an MZM, biased in the null point, and driven by a sinusoid of 12.5 GHz. This sinusoid is produced by a vector signal generator (VSG). At the MZM output, two optical tones with a separation of 25 GHz are generated. These two optical tones correspond to the second harmonic of the MZM. The optical spectrum of these two tones can be observed in Fig. 8.2b. In this graph, it can be noticed that the undesired central tone is not totally removed. In addition, as the MZM is sensitive to optical polarization, a polarization controller (PC) is set in the input of this device. Therefore, the optical output power of the MZM can be optimized by tuning this
PC. After the MZM, the two optical tones are boosted with an erbium-doped fiber amplifier (EDFA) because the MZM introduces high attenuation.

The signal of the under-test modulation formats is produced electrically by an arbitrary waveform generator (AWVG) with a sampling rate of 12 GSa/s. In the AWVG, the DSP process of the transmitter is realized. This process is performed offline. Each evaluated modulation format has its specific baseband transmitter scheme. The spectrum of the OFDM baseband signal is represented in Fig. 8.2c as a reference. The bandwidth of this baseband spectrum is 245.76 MHz. After the baseband process of each modulation format, an intermediate-frequency (IF) process is realized. This IF process is common to all the evaluated modulation formats, and its block diagram is represented in Fig. 8.2d. In this diagram, the first block corresponds to the specific process of a determined modulation format in the baseband domain. Then, a preamble is included in the baseband signal for synchronization at the receiver. Next, the real and imaginary parts are separated and upconverted independently. The real and imaginary parts are filtered by a pulse shaping. Subsequently, the real and imaginary parts are multiplied by a sine and cosine of 1 GHz, respectively. Finally, the signals of both branches are combined. In this way, the signal of each modulation format is upconverted to an IF of 1 GHz. The spectrum of this IF signal is shown by Fig. 8.2e. The two optical tones are modulated by a second MZM and driven by the IF signal. As in the previous MZM, the second MZM needs a PC to maximize its output power. The two modulated tones are transmitted through a standard single-mode fiber (SSMF) of 10 Km. All the processes behind the SSMF are realized in the CO of Fig. 8.1. The SSMF corresponds to the optical fiber ring of Fig. 8.1.
The output of the SSMF is boosted by a second EDFA. A photodiode (PD) is employed to convert the optical tones into the electrical domain. In the PD, the two tones beat generating an RF signal at 25 GHz corresponding to the separation of both tones. Then, the electrical signal is boosted by a 30 dB medium power amplifier (MPA), and the boosted signal is transmitted over a wireless mmWave link through two 18.5 dBi horn antennas. The RU of Fig. 8.1 are compounded by the PD, MPA, and transmitter horn antenna in this experiment. Figure 8.2f shows a photo of the experimental wireless link at 25 GHz. The distance of this wireless link is 9 m.

In the second horn antenna, the received signal is amplified by a 40 dB low-noise amplifier (LNA). Then, the amplified signal is multiplied with a sinusoid of 23 GHz by a RF mixer. Thereby, the electrical signal is downconverted to a second IF at 2 GHz. Finally, the downconverted IF signal is sampled by a digital phosphor oscilloscope (DPO) with a sampling rate of 12.5 GSa/s.

An offline DSP process is realized with the sampled IF signal. The block diagram of this DSP process is depicted in Fig. 8.2g. First, the IF signal is downconverted to the first IF (1 GHz) by a Costas loop process. The Costas loop process enables phase tracking in this downconversion. Then, the resulted signal is downsampled and filtered by a band-pass filter (BPF). After the BPF process, the real and imaginary parts are obtained by multiplying the filtered signal with a sine and cosine of 1 GHz, respectively. Hence, a complex baseband signal is achieved. Next, the baseband signal is filtered by a low-pass filter (LPF) and synchronized by using the preamble inserted in the transmitter. Finally, the specific baseband receiver process of each modulation format is performed.

According to the configuration parameters employed in each under-test modulation format, the OFDM configuration is based on the first 5G standard [2]. The employed OFDM parameters for this experimental comparison are the following: subcarrier spacing of 60 kHz, cyclic prefix (CP) of 1.2 μs, 4096 total subcarriers, 3168 active subcarriers, 928 null subcarriers to reduce the OOB emissions, and 1 pilot tone inserted on every 12th active subcarrier. In respect of the parameters of the remaining modulation formats, the used UFMC configuration employs 128 sub-bands; GFDM uses 3 sub-symbols; and multi-CAP uses 9 sub-bands. The rest of the parameters are adapted to the OFDM configuration described previously.

In order to have a fair comparison, all the evaluated modulation formats employ the same bandwidth (245.76 MHz) and modulation order. The employed modulations are quadrature phase-shift keying (QPSK) and 16-quadrature amplitude modulation (16-QAM). Thereby, the spectral efficiency is the same for all the modulation formats. By using QPSK modulation, the throughput is 325 Mbps, and by using 16-QAM, 650 Mbps. Therefore, the spectral efficiencies for QPSK and 16-QAM cases are 1.32 bit/s/Hz and 2.64 bit/s/Hz, respectively.

8.2.3.2 Analysis and Interpretation

This subsection presents a thorough analysis and interpretation of the experimental results obtained in the setup explained in the previous subsection. The results are
shown in Fig. 8.3. These graphs represent the BER results as a function of the optical power received in the PD. As mentioned before, QSK and 16-QAM modulations are used to compare the under-test modulation formats, Fig. 8.3a–b, respectively. Furthermore, the 7% overhead forward error correction (OH FEC) is represented by the red dotted line. In addition, the constellation of the received symbols of all the modulation formats in the maximum power points is also illustrated in both graphs.
Observing the maximum power point (−3 dBm) in the graph of Fig. 8.3a, it can be noticed that the performances of the modulation formats in terms of BER follow this order: SC-FDM, multi-CAP, OFDM, UFMC, and GFDM; this also corresponds to the PAPR level exhibited by each modulation, being SC-FDM the modulation format with minimum PAPR and GFDM the modulation format with maximum PAPR (see Table 8.1). Therefore, a low PAPR of the transmitted signal is an important KPI to achieve better performance in the proposed experimental mmWave ARoF setup.

On the other hand, examining the maximum optical power point (2 dBm) in the graph of Fig. 8.3b, the best modulation formats in terms of BER follow this order: multi-CAP, SC-FDM, OFDM, UFMC, and GFDM. In the 16-QAM case, multi-CAP outperforms SC-FDM despite presenting higher PAPR. Multi-CAP presents 2.5 dB of optical power gain respecting the SC-FDM solution for the 7% OH FEC threshold. The reason for this being that the employed channel equalizer is different in the multi-CAP case in contrast to the remaining modulation formats. Multi-CAP uses decision feedback equalizer (DFE) with the least mean square (LMS) algorithm in the time domain, while the remaining modulation formats use least-squares (LS) equalizer in the frequency domain. Multi-CAP utilizes a different equalization process because each sub-band is independent as an SC waveform, and thus the LS equalizer is not suitable for compensating the channel on an SC waveform. Multi-CAP performs much better than the rest in the 16-QAM comparison because its equalizer amplifies less the noise in contrast to the LS equalizer. Thereby, the equalizer strategy is also crucial in mmWave ARoF scenarios to obtain the best yield.

The conclusions that can be raised through the analysis and interpretations of the presented experimental results are the following: low PAPR and optimum equalizer selection are keys to achieving high performances in this type of system. Moreover, the results show that the standardized OFDM is not clearly the best modulation format candidate for mmWave ARoF systems and other modulation formats, such as SC-FDM and multi-CAP, should be considered.

According to the future lines, this work can be followed by varying the mmWave wireless channel conditions: longer distance of the link, outdoor experiment, non-line-of-sight (NLOS) propagation, etc. Moreover, several optical schemes to generate mmWave tones can be compared: external modulation, two free-running lasers, phase-locked lasers, etc. One of the key challenges of this work consists of increasing the bit rate by using higher modulation orders such as 64-QAM and 256-QAM. To achieve this, both DSP and hardware systems must be optimized. Another key challenge is related to the adaptation of the bit rate according to the channel conditions in real time. This adaptable bit rate system can be realized by utilizing machine learning.
8.3 Channel Equalization for OFDM-Based mmWave ARoF Systems

8.3.1 Introduction

In OFDM (orthogonal frequency-division multiplexing) systems, channel estimation, and channel equalization play a key role in overcoming distortions caused by phenomena like fading, delay spread, and multipath effect. Channel equalization is needed in optical fiber communication systems due to the effect of chromatic dispersion (CD) in the optical link making it very difficult to decode the received OFDM symbols as the bit symbols get broadened and distorted.

Currently, the Common Public Radio Interface (CPRI) is mainly utilized in the fronthaul links between central units (CUs) and distributed units (DUs), which is a digital transmission scheme of quantized waveforms of baseband signals, called “digital radio over fiber (DRoF).” However, CPRI requires extreme high transmission capacity compared to the original user throughput due to the digitization process. Considering the approaching 5G system, in which the peak throughput will be around 20 Gb/s, it is obvious that CPRI is not scalable [8]. To improve the bandwidth utilization efficiency, analog radio over fiber (ARoF) has been used instead of digital radio over fiber (DRoF).

8.3.1.1 Noise and Distortion Effects on OFDMmmWave RoF Systems

When OFDM signal is carried by mmWave RoF systems, its performance is affected by various physical layer impairments such as noise, dispersion, and nonlinear distortion. The nonlinear distortion effect is a critical problem that affects the performance of OFDM signal causing the loss of orthogonality among the different subcarriers and resulting in performance degradation.

The dispersion leads to pulse broadening due to the different spectral components of the signal having different group delays. The chromatic dispersion of a fiber mode is given by

$$ D = \frac{d}{d\lambda} \left[ \frac{1}{c} \frac{d\beta}{dk} \right] $$  \hspace{1cm} (8.1)

where $c$ is the speed of light in vacuum. The bracketed quantity in (8.1) is the group-delay time per unit length. The chromatic dispersion (CD) is the change in group-delay time per unit fiber length per unit wavelength interval and is typically expressed in units of ps/nm·Km. For conventional telecommunications fiber operating near 1550 nm, this dispersion is typically +16 ps/nm·Km [9].

For bit rates up to 2.5 Gbit/s, problems related to dispersion can be solved using narrowband transmitters. For high bit rate systems ($\geq 10$ Gb/s) as in the case of orthogonal frequency-division multiplexing (OFDM), the dispersion
limits the transmission distance. This raises the need for some sort of dispersion compensation. Also, for high bit rate systems ($\geq 10$ Gb/s), the dispersion slope becomes an important factor since strength due to CD is reduced by the square of the bit rate [10].

### 8.3.1.2 Equalization Requirements for Converged mmWave and RoF System

Cloud-based radio access networks (C-RANs) provide a cost-effective, energy-efficient, and high spectral-efficient solution for future access network. A backhaul network connecting a growing number of small base stations and supporting a C-RAN network is extremely important. Such a backhaul network should have high energy efficiency, flexibility, low transmission delay, low cost, and high capacity. The most obvious solution to realize such a backhaul network would involve the use of a converged mmWave network. At the mmWave bands, 60 GHz has 7–9 GHz of license-free bandwidth worldwide, while the 70–90 GHz spectrum (71–76, 81–86, and 92–95 GHz) has 13 GHz of licensed bandwidth available [11]. The convergence of mmWave with optical fiber networks provides high capacity, flexibility, wide area coverage, cost-effectiveness, and energy efficiency for multiple-gigabit signal delivery in high-speed mobile and broadband wireless access networks [12]. However, such a converged system would suffer from the chromatic dispersion in the standard single-mode fiber (SSMF). So, there is a need of equalization to compensate dispersion in the fiber as it deteriorates the output signal.

### 8.3.2 Enabling Technologies

#### 8.3.2.1 MmWave ARoF Systems

RoF jointly takes advantage of the huge bandwidth offered by the optical fibers with the mobility and flexibility provided by wireless systems [13, 14]. The scarcity of the spectrum in the lower region of the microwave frequency band, where many mobile and wireless communication services operate, has led to the interest in mmWave communication systems. MmWave RoF technology plays a key role in the next-generation optical wireless networks, having great potential to deliver multi-gigabit wireless services through centralized control unit and simplified remote base stations with low loss and bandwidth abundant fiber-optic connectivity. RoF systems operating at 60 GHz have gained much attention due to the large unlicensed bandwidth availability.

The mmWaves are the electromagnetic waves with wavelength ranging from 1 to 10 mm. Therefore, mmWave band ranges from 30 to 300 GHz. Different mmWave frequency bands have been proposed for high capacity wireless systems employing
RoF: in the 24–30 GHz band and 75–110 GHz band [15], at 120 GHz, at 250 GHz, and more recently at 220 GHz. However, the frequency band that has attracted major importance in recent research activities is around 60 GHz, mainly due to two reasons: 1) reduction of the cell size due to high atmospheric attenuation [16] leads to frequency reuse, expanding the wireless system capacity [17] the spectrum license at 60 GHz is free and such a high frequency can provide huge bandwidth.

8.3.2.2 OFDM Techniques for RoF Passive Optical Networks

PONs use multicarrier modulation like OFDM, which provides an opportunity for increased bandwidth at affordable cost. OFDM provides better spectrum utilization and high transmission by harnessing M-ary modulation on its subcarriers, such as phase-shift keying (PSK) or quadrature amplitude modulation (QAM). In the OFDM-PON, a passive optical splitter is used to connect two or more optical network units (ONUs) [18].

In [19], the authors design a WDM RoF PON based on OFDM and optical heterodyne, which can achieve 40 Gbit/s per wavelength channel and wired/wireless access synchronously.

In [20], the authors experimentally demonstrated a WDM-PON system to provide the triple-play services using centralized light wave sources with symmetric data at 10 Gbit/s per channel for both downstream and upstream data.

8.3.2.3 Generation of mmWave Signal

A CW laser and an external modulator such as Mach-Zehnder modulator (MZM) or electroabsorption modulator (EAM) are used to modulate the intensity of light. In this scheme, an electrical signal from “FuncSinEl” is input into a Mach-Zehnder modulator (MZM). At the output of the “FuncSinEl” module in VPI, the signal consists of many sidebands as shown in Fig. 8.4, with frequency separation between two successive components equal to the frequency of the input electrical signal. In our simulation setup, a signal with a frequency separation of four times the input electrical signal frequency is selected (Fig. 8.4). The input electrical signal frequency is 15 GHz.

The generated optical signal is then passed through an arrayed waveguide grating (Filter_AWVG) module, and frequency spacing between adjacent channels is adjusted. Subsequently, a “bus selector” module is used to select the appropriate sidebands where two sidebands are selected as shown in Fig. 8.5 separated at 60 GHz.

Next a “WDM_MUX” module is used to merge the two sidebands to a single sideband. An optical band-pass filter (OBPF) is used to reduce the amplified spontaneous emission noise. With this scheme, a flexible-frequency mmWave signal could be generated, presenting a simple and flexible method for mmWave signal
8.3.2.4 Channel Equalization and LMS Approach

In OFDM systems, channel equalization plays a key role in overcoming distortions caused by phenomena like fading, delay spread, and multipath effect. The basic operation of channel equalization is to inverse the transmission channel impairments.
such as frequency-dependent phase and amplitude distortion. Adaptive equalization is a technique that automatically adapts to the time-varying properties of the communication channel. The least mean square (LMS) algorithm is one such popular technique that can be used for adaptive channel equalization. The criterion used in this algorithm is to minimize the mean square error (MSE) between the desired output and the actual output [21]. The approach used here in this work is to provide the distorted signal and ideal signal extracted from the setup built in VPI software and import these to LMS equalizer implemented in MATLAB. First, both signals are normalized in the equalizer, and the equalizer taps are then found by an iterative method that is used to find the equalized signal. After equalization of the received distorted symbols, error vector magnitude (EVM) of the equalized constellation is calculated. Figure 8.7 shows the calculation of the EVM metric.
8.3.3 Simulation Model and Performance Evaluation

8.3.3.1 Direct Detection Converged OFDM RoF mmWave System: 60GHz

To design a complete system consisting of a converged OFDM RoF and mmWave, first we design an OFDM transmitter in a commercially available simulation software VPI transmission maker. The blocks used inside the OFDM transmitter module in VPI (Tx_EL_OFDM_vtmg1) are shown in Fig. 8.8. This module generates electrical signals corresponding to the real and imaginary parts of an OFDM signal.

The pseudorandom binary sequence (PRBS) block is used to generate data, at a rate determined by the modulation level and the bit rate. The raw digital binary bits are distributed into data streams, and each stream is then encoded according to the settings in the “subcarrier Modulation” parameters group of the coder block. The number of bits encoded in each symbol is given by the parameter “Bits Per Symbol QAM.” Individual modulation formats can also be specified for different subcarriers. The OFDM coding stage is then followed by pulse shaping. In this stage, the rectangular input pulses are pulse-shaped by a filter with a raised cosine characteristic. After the pulse shaping stage is the RF upconversion stage, in which the in-phase channel data modulates a cosine wave carrier, while the quadrature channel data modulates the sine wave carrier via an RF phase shifter, using a sine wave generator and mixers. Finally, an OFDM signal is upconverted to the chosen RF frequency, with multilevel in-phase and quadrature phase M-QAM coded symbols. Subsequently, a 60GHz mmWave signal is generated as described in the previous section. The generated converged mmWave and OFDM signal is then sent to a standard single-mode fiber (SSMF). The signal is then detected on a single photodiode and then sent to OFDM receiver to recover the subcarriers. The blocks used inside the OFDM receiver module in VPI are shown in Fig. 8.9.
OFDM receiver module decodes an electrical QAM-OFDM signal by reversing the process of the transmitter. The demodulation process begins with the electrical signal first being downconverted to baseband. Following this, pulse shaping is applied, and the signal is decoded in the decoder module. After decoding the signal, constellation viewer is used to view the constellation. A complete simulated setup is shown by Fig. 8.10.

8.3.3.2 Performance Evaluation

The system described in Sect. 8.3 is simulated in a commercially available design suite “VPI transmission maker,” and the data is extracted from the simulation and processed offline in MATLAB with the proposed algorithm identified in Sect. 8.3.2 (“Channel Equalization and LMS Approach”).

Offline processing resulted in constellation diagrams and error vector magnitude (EVM) measurements, as shown by Figs. 8.11 and 8.12, where 4-QAM and 16-QAM are the modulation formats used in each OFDM subcarrier. The performance
of the algorithm is tested in the form of maximum transmission distance achieved in the presence of fiber dispersion and other nonlinearities. It can be seen that for the 4-QAM case, as a modulation format in each subcarrier, a maximum transmission distance of 30 Km has been achieved with an error vector magnitude (EVM) of 16.47% after equalization and in the case of 16-QAM as a modulation format, a maximum transmission distance of 15 Km has been achieved with an error vector magnitude of 12.05% after equalization. Both EVM values are below the suggested threshold of 3GPP for the corresponding modulation formats. In particular, Figs. 8.11 and 8.12 present the constellation diagrams obtained before and after equalization in a converged mmWave radio over fiber setup as described by Sect. 8.3; EVM vs fiber length for 16-QAM is shown by Fig. 8.13.
8.3.4 The Key Challenges Ahead

The main contributions presented in this work spur several new research lines for future investigation on coherent OFDM mmWave systems. These include comprehensive analysis on the range of different parameters involved in the system such as the number of channels used in the OFDM framework; modulation formats (e.g., 64-QAM, 128-QAM, 256-QAM) on different OFDM subcarriers and equalization approaches, among others, are currently missing; and the direct detection analysis of the converged OFDM RoF mmWave at 60 GHz investigated in Sect. 8.3.3 can be further extended to a coherent setup with a similar analysis for equalization.

The importance of this future work would be to ensure better equalization with coherent detection and long reach in single-mode fiber.

8.4 Reflective Electroabsorption Modulator for 50 Gb/s Colorless Transmission

8.4.1 Optical Components for 5G Fronthauling

The fronthaul is an optical link between the digital unit (DU) or the baseband unit (BBU), depending on the modulation scheme, and the remote radio head (RRH). Some of the key requirements of a 5G fronthaul are ultralow latency, high reliability, large number of connected users, and high data rate [22]. The number
of connected users can be increased via network densification. To minimize the 
end-to-end (E2E) delay, wavelength-division multiplexing passive optical network 
(WDM-PON) is a promising solution. The actual WDM-PON implementation can 
follow a logical point-to-point (PtP) or a point-to-multipoint topology. The latter 
introduces additional delay though as multiple end users share a single wavelength 
channel. The International Telecommunication Union (ITU) in its next-generation 
PON2 (NG-PON2) standard recommends implementing a time-and-wavelength-
division multiplexing (TWDM) scheme to share up to eight WDM channels [23]. 
As a result, the standard is commonly referred to as TWDM-PON.

On the other hand, the high-speed requirement of a 5G fronthaul network 
can be satisfied in a cost-effective manner by employing transmitters that are 
based on electroabsorption modulators (EAMs). Compared to directly modulated 
lasers (DMLs), EAM-based transmitters provide better transmission performances 
because of the absence of adiabatic chirp which is not the case in DMLs. In TWDM-
PON, the transceiver components are also required to be wavelength-tunable on 
both the optical line terminal (OLT) and the optical network unit (ONU). Although 
IEEE’s 50 Gb/s Ethernet PON (50G-EPON) standard recommends using fixed-
waveband sources, it is based on multiplexing only two 25 Gb/s wavelength 
channels [24]. In any case, it is necessary to increase the number of WDM 
channels for a large-scale deployment of 5G networks satisfying the transport 
lacacy requirement. At the same time, the transceiver module of a 5G fronthaul 
must be able to operate at any wavelength of the WDM system by being either 
waveband-tunable or wavelength-independent (colorless).

However, by the nature of tunable devices, they require tight wavelength control. 
If such devices are used in a burst mode transmission, which causes frequency 
drift due to thermal variation between burst on and off states [25], complex 
control circuitry will be required to stabilize the emission wavelength. Colorless 
transmitters, on the other hand, do not require wavelength tunability and thus can be 
utilized to realize low-cost 5G fronthaul transmitters. For example, a reflective EAM 
multiplexically integrated with a semiconductor optical amplifier (SOA) can be used 
as a standalone colorless transmitter at the ONU or as an array at the OLT. The 
main drawback of such a configuration is the need for an external optical source. 
But a single multi-wavelength fixed source such as a comb laser can be used to 
support multiple sites. Figure 8.14a shows a schematic diagram of an uplink WDM-
PON transmission network topology using reflective EAM-SOAs (REAM-SOAs) as 
ONU transmitters. In this section, we present a complete characterization of REAM-
SOAs that can operate up to 50 Gb/s with simple digital modulation formats such 
as non-return-to-zero (NRZ) without equalization. Although the results presented 
here are for digital signals, the components can also be effectively applied to analog 
transmissions.
Reflective EAM-SOAs were widely studied until 2015, the year NG-PON2 was standardized by ITU, mainly for using the devices as colorless transmitters. As a result, for compatibility reasons, most device demonstrations available in the literature are in the C-band, operating at 10 Gb/s for a minimum transmission distance of 20 km [26, 27]. Figure 8.14b summarizes state of the art of REAM-SOAs in terms of data rate and transmission distance.

For C-band transmissions, there is always a tradeoff between data rate and the transmission distance because of high chromatic dispersion in optical fibers. A few C-band devices were demonstrated at higher bit rates than 10 Gb/s. For example, [28] demonstrated a REAM-SOA based on AlGaInAs/InP technology that can operate up to 40 Gb/s NRZ, but the transmission distance was limited to 2 km. When operated at 10 Gb/s NRZ, the same device is capable of transmitting up to 20 km. Similarly, [29] demonstrated a 25 Gb/s REAM-SOA transmitting up to 20 km, but the experiment involved offline digital signal processing (DSP), which is not generally desirable for access network components as it increases the transceiver cost. We demonstrated a dispersion-limited 16 km C-band transmission at 25 Gb/s NRZ without equalization using an InGaAsP-based REAM-SOA [30].

For the O-band wavelengths, on the other hand, chromatic dispersion is very low, and it is possible to achieve long-distance transmission at very high bit rates. However, without external amplification, the transmission distance will be limited by fiber attenuation which is higher in the O-band than the C-band. We recently demonstrated a 50 Gb/s NRZ transmission using a 100 μm O-band EAM in REAM-SOA configuration [31].
8.4.3 Device Design and Technologies Applied

Figure 8.15a shows schematic diagram of a reflective EAM-SOA. Our photonic integrated circuit (PIC) comprises an EAM, an SOA, and a spot-size converter (SSC). To realize a reflective device configuration, the back facet is treated with a high-reflection (HR) coating, and the front facet is treated with an anti-reflection (ARF) coating. The devices are based on InGaAsP multiple quantum well (MQW) structures on an n-doped InP substrate, and they are realized with industrially compatible technologies. More specifically, the waveguide structures are defined by using a semi-insulating buried heterostructure (SI-BH) technology whose schematic diagram is shown in Fig. 8.15b. The semi-insulating behavior is achieved by hydrogen ion (H\(^+\)) implantation applied to the undoped InP cladding surrounding both sides of the waveguide region. Compared to other technologies used for waveguide definition, SI-BH technology provides efficient thermal dissipation, more circular (symmetric) optical mode, and improved modulator bandwidth [32].

On the other hand, the epitaxial growth process involves independent optimization of the EAM, the SOA, and the SSC sections and combining them by using a butt-joint integration technology (a multi-step growth process) which is schematically illustrated in Fig. 8.16. The design layout of a REAM-SOA with integrated SSC is also shown in the figure. One important aspect of this approach is the flexibility to separately design and engineer the bandgaps of the various active and passive components integrated into a single chip (e.g., laser, modulator, amplifier, waveguide, etc.). Detailed information about the components and operating principles of a REAM-SOA can be found in [30] and [31].

To study the effect of EAM length on both modulation bandwidth and achievable extinction ratios, we fabricated and characterized devices with different EAM lengths. In particular, we studied reflective devices with 150-μm- and 80-μm-long EAMs in the C-band and a 100-μm-long EAM in the O-band. The C-band devices are presented for comparison, especially to demonstrate the effect of chromatic dispersion on the transmission distance.
8.4.4 Device Performance Evaluation

8.4.4.1 Spot-Size Converter

The SSC is a tapered waveguide with a $7^\circ$ tilt. The taper increases the size of the optical mode and thus improves fiber coupling efficiency. The tilt, on the other hand, is intended to minimize optical feedback to the gain (SOA) section. A linear taper running from 1.3 $\mu$m (for O-band devices or 1.5 $\mu$m for the C-band) to 0.7 $\mu$m is integrated with the REAM-SOAs. To avoid an abrupt change of curvature in the optical path, the tapered waveguide starts with a straight section and slowly bends toward its end until the final tangential angle becomes $7^\circ$.

Figure 8.17a–b shows contour plots of simulated optical mode profiles at the taper input and output, respectively. As expected, the mode size increases at the output of the taper. For example, for the C-band devices that integrate a taper running from 1.5 $\mu$m to 0.7 $\mu$m, the simulated optical mode has a horizontal width of 2.2 $\mu$m and a vertical width of 2 $\mu$m. Similarly, the O-band taper having a narrower input waveguide has a mode diameter of 1.4 $\mu$m $\times$ 1.2 $\mu$m. After fabrication, we estimated the size of the optical beam at the output of each taper by using far-field measurement data and taking the beam diameter at $1/e^2$ point as shown in Fig. 8.17c.

Table 8.2 summarizes the estimated mode diameters of the tapers and a lensed fiber used in our experiments. The difference between simulated and measured mode diameters is attributed to fabrication tolerances. In the next subsection, we will see contributions of input/output coupling efficiencies to the total insertion loss.
Table 8.2 Simulated and measured mode diameters of a 0.7 μm taper and a lensed fiber

<table>
<thead>
<tr>
<th>Component</th>
<th>Simulated mode diameter (μm)</th>
<th>Measured mode diameter (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal</td>
<td>Vertical</td>
</tr>
<tr>
<td>C-band taper (1.5 μm–0.7 μm)</td>
<td>2.2</td>
<td>2</td>
</tr>
<tr>
<td>O-band taper (1.3 μm–0.7 μm)</td>
<td>1.4</td>
<td>1.2</td>
</tr>
<tr>
<td>Lensed fiber</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

8.4.4.2 Insertion Losses and SOA Gain

The dominant insertion loss contributions in a REAM-SOA (or its opposite RSOA-EAM) come from input/output facet coupling losses and intrinsic (material) absorption losses of the EAM and the SSC sections. By using a lensed fiber having a mode diameter of 3 μm to couple light to and from the chip, we estimated a total insertion loss of 12 dB for our reflective devices (EAM biased at 0 V). The input/output coupling efficiency contributes a 2 dB loss in each direction (4 dB total), and the two-way EAM and taper absorption losses are 6 dB and 2 dB, respectively.

Insertion loss generally limits the system power budget which is a key parameter in WDM-PON systems. However, the presence of an SOA on chip with the EAM allows to fully compensate insertion losses and thus improve the system power budget. For wavelengths close to the peak of the SOA gain, we even obtain a net gain in the optical power. Figure 8.18 shows the fiber-to-fiber gain spectrum of a 300-μm-long O-band SOA in a reflective device configuration.

The results are obtained after all component-related losses are compensated by the SOA (only external losses are calibrated). The SOA gain peak is designed to be close to the zero-dispersion region. At 1310 nm, for example, the net device gain is >8.5 dB for an SOA current of 60 mA. The PIC also shows a net gain of >5 dB over a 25 nm range (1300 nm–1325 nm), which is another important device characteristic for colorless operation.
8.4.4.3 EAM Absorption and Extinction Ratio

The absorption strength of an EAM depends on both its cavity length and thickness of the active region (expressed in terms of optical confinement factor, $\Gamma$). In a reflective EAM-SOA configuration, the EAM absorbs the input light twice—before and after reflection. As a result, for a given EAM length and vertical structure, a higher extinction ratio can be obtained from a reflective EAM compared to its single-pass counterpart. The modulator’s length also affects its bandwidth, but in a negative way. Hence, the EAM’s length can be shortened when it is used in a REAM-SOA configuration to obtain high modulation bandwidth while providing acceptable extinction ratios.

The physical process that enables electroabsorption is a change in the absorption coefficient of the EAM (red shift) due to an externally applied electric field [33]. In a quasi-two-dimensional system such as MQWs, this process is known as quantum-confined Stark effect (QCSE). Since electroabsorption is directly related to the bandgap energy of the active region, the EAM’s absorption increases with the increasing photon energy (decreasing wavelength). As a result, higher extinction ratio is obtained at shorter wavelengths.

Figure 8.19 shows static extinction ratio of the 100-µm-long EAM in a REAM-SOA configuration for different input wavelengths (1300 nm and 1320 nm). At 1300 nm, the device exhibits a very high extinction ratio of 16.5 dB between 0 V and $-3$ V. However, a stronger absorption at a shorter wavelength also means a reduced modulated output power. Hence, there is a tradeoff between extinction ratio and output power. The extinction ratios obtained from our devices are high enough even at longer wavelengths. For example, the extinction ratios at 1310 nm and 1320 nm are 12.5 dB and 10 dB, respectively. Since the SOA has no effect on the static performance of the EAM, there is no difference in static extinction ratios between REAM-SOA and RSOA-EAM configurations as shown in Fig. 8.19b. However, the position of the EAM along the optical path has a strong effect on its dynamic performance (bandwidth) as discussed in the following subsection.
8.4.4.4 Small-Signal Frequency Response

To estimate the modulation bandwidths of the EAMs in our PICs, we measured their frequency responses ($S_{21}$ parameters) by applying a small modulation signal, typically $<$300 mV peak-to-peak voltage ($V_{PP}$). The electro-optic (E/O) bandwidth of an EAM is inversely proportional to its length because its bandwidth becomes RC-limited—parasitic capacitance increases with increasing EAM length. Similarly, bandwidth decreases as thickness of the active region increases because it takes a longer time to sweep out photogenerated charge carriers from the active region [33]. Although the RC limit is the dominant limiting factor to bandwidth, thickness of the active region must also be kept at minimum in order to reduce the required EAM bias voltage (reduce its power consumption). In a reflective device configuration, the effective EAM length is doubled. As a result, a reduction in the E/O bandwidth is generally expected compared to a single-pass configuration.

Figure 8.20 shows measured frequency responses of different EAM lengths. The 3 dB cutoff bandwidth of the 100 $\mu$m O-band EAM in REAM-SOA configuration is $\sim$34 GHz as shown in Fig. 8.20a ($\lambda = 1310$ nm). To demonstrate the effect of EAM length on its bandwidth, the frequency responses of a 150 $\mu$m and an 80 $\mu$m C-band EAMs are shown in Fig. 8.20b. The E/O bandwidth of the 150 $\mu$m EAM in REAM-SOA configuration is $\sim$23.5 GHz, whereas that of the 80 $\mu$m EAM is still flat at 26.5 GHz (setup limit; estimated value is $>40$ GHz).

On the other hand, an EAM’s bandwidth is significantly reduced, regardless of its length, when it is used in an RSOA-EAM configuration. This reduction is primarily due to the round-trip delay inside the SOA section. For example, the 3 dB bandwidth of the 100 $\mu$m O-band EAM in a RSOA-EAM is only 12 GHz (see dashed line in Fig. 8.20a). Therefore, for next-generation high-speed applications (e.g., $\geq$50 Gb/s NRZ), the REAM-SOA configuration with a reasonably short EAM is preferable.
8.4.5 System Demonstration

8.4.5.1 Colorless Transmission at 25 Gb/s NRZ

One important aspect of a reflective device configuration is the prospect of using the devices as colorless transmitters over a wide range of operating spectrum. As such, a single transmitter module can cover the entire width of a given WDM system without any additional tuning complexities. When mass produced, such devices can be used to realize low-cost transceivers, which is particularly important for large-scale 5G fronthaul deployment.

To demonstrate the colorless capabilities of our components at very high bit rates, we performed a preliminary test at 25 Gb/s NRZ, simply because it can be done with a standard bit error rate (BER) test setup.

For our experiments, the 25 Gb/s NRZ digital signal is generated by a signal quality analyzer with a bit pattern of $2^{31} - 1$ pseudorandom binary sequence (PRBS31). Then it is mixed with a DC biasing voltage via a Bias-T and applied to the EAM section to modulate the optical carrier. We obtained clearly open eye diagrams in both back-to-back (BtB) and 10 km configurations. At 1310 nm, the BtB dynamic extinction ratio (DER) obtained from the 100 $\mu$m O-band EAM in REAM-SOA configuration is ~10.2 dB when it is biased at $-1.3$ V with a 2.6 Vpp voltage swing. Similarly, the DERs at 1300 nm and 1320 nm are 13.5 dB and 8.1 dB, respectively. As expected, for the longer 150 $\mu$m C-band EAM, the DER is higher than that of the 100 $\mu$m EAM. For example, at 1530 nm, the DER is ~14.5 dB at 2.2 Vpp. The DER at 1545 nm is ~11.5 dB ($-1.3$ V$_B$/2.6 V$_{pp}$). All results are obtained at 25 $^\circ$C.

Figure 8.21a shows BER performances of the 100 $\mu$m O-band EAM in REAM-SOA configuration at 1300 nm and 1320 nm ($\Delta \lambda = 20$ nm) when modulated with a 25 Gb/s NRZ signal.

Since chromatic dispersion is very low in this region, there is no dispersion penalty after 10 km transmission over a standard single-mode fiber (SSMF)—the
BtB and the 10 km BER curves overlap for each wavelength. Here, the transmission distance is rather limited by external losses (fiber attenuation, switches, filter, etc.). External amplification is not used during the experiment so as to demonstrate a passive optical network. The slight difference in the BER curves between 1300 nm and 1320 nm is attributed to the lower extinction ratio obtained at a higher detuning as shown earlier in Fig. 8.19 (>5 dB difference in extinction ratio). As a result, a slightly higher input power (<0.5 dB penalty) is required at longer wavelengths to obtain the same BER as the one obtained at shorter wavelengths.

On the contrary, chromatic dispersion in optical fibers is very high for the C-band wavelengths, and its effect on the transmission distance is clearly visible in the BER curves shown in Fig. 8.21b. For a 10 km transmission at 25 Gb/s NRZ, the dispersion penalty is ~3 dB between 1530 nm and 1545 nm (Δλ = 15 nm) for a BER of 10^{-3}. Therefore, to obtain the same BER as the one obtained at 1530 nm, we need 3 dB more input power at 1545 nm. Since the DERs at both wavelengths are very high (>11 dB), the penalty observed here is primarily caused by chromatic dispersion.

Nevertheless, such wide spectral ranges (Δλ ≥ 15 nm) may not be required in practice for the devices to operate in colorless modes. For example, the spectral window defined for TWDM-PON is only ~2.5 nm wide, which is far lower than the range our C-band devices are tested. That means our components can be easily optimized to support the entire TWDM-PON spectral window without any significant performance degradation. The O-band devices, on the other hand, can support a 20-nm-wide WDM system with only a 0.5 dB tolerance requirement. Therefore, we can conclude that our reflective devices can support colorless operation at 25 Gb/s NRZ in their respective frequency bands.
8.4.5.2 50 Gb/s Digital Transmission

The downlink transmission capacities of both TWDM-PON and 50G-EPON standards are based on multiplexing four (up to eight) or two wavelength channels, respectively [23, 24]. The latter reduced the number of wavelength channels from four to two to minimize cost associated with channel multiplexing. However, as technology matures, satisfying the required data rate with a single device will have the advantage of either saving cost or doubling the total bit rate for the same multiplexing cost. Similar to the 50G-EPON, ITU-T also selected 50G PON technology with NRZ modulation format as the focus for its next-generation high-speed PON (HSP) standard [34]. Thus, it is imperative to realize high-speed transmitters that can operate beyond the nominal 50 Gb/s line rates. High-speed EAMs operating up to 64 Gb/s NRZ are already demonstrated in a single-pass (transmitter) configuration.

To demonstrate the high-speed capabilities of our reflective devices, we modulated the 100 μm O-band EAM in REAM-SOA configuration with a 50 Gb/s NRZ signal. Figure 8.22 shows a schematic diagram of the experimental setup used to generate and transmit the 50G signal. The setup is customized to capture the 50 Gb/s eye diagrams only (without BER data). Further details about the device’s dynamic characteristics including its 50G PAM-4 performance can be found in [31].

Two 25 Gb/s NRZ PRBS31 signals are generated by a signal quality analyzer and injected into a 2:1 selector module from III-V Lab. A delay line is connected to one arm of the input to interleave the two signals in time and generate a 50 Gb/s NRZ signal. Both the selector (transmitter side) and the oscilloscope (receiver side) are provided with a common clock source for synchronization by splitting the clock output of the signal quality analyzer. The 50G electrical signal is then amplified by a...
linear driver to obtain a peak-to-peak voltage swing of 2.4 V (eye amplitude). Figure 8.23a shows eye diagram of the 50 Gb/s NRZ electrical signal generated in this way.

The REAM-SOA chip is mounted on a high-frequency (HF) carrier with a ground-signal-ground (GSG) electrical connection provided to access the EAM. An external tunable laser (TL) is used to generate a continuous wave light. Since our components are sensitive to the polarization state of the input light, we used a polarization controller (PC) in order to inject transverse electric (TE)-polarized light into the chip. An optical circulator is inserted for bidirectional transmission over a single fiber. Finally, the RF signal and the EAM biasing voltage (−1.1 V) are combined inside a Bias-T and applied to the EAM. A DC current of 40 mA is applied to the SOA section to amplify the optical signal. At the receiver side, a tunable optical filter (OTF) of 2 nm bandwidth is inserted to suppress the amplified spontaneous emission (ASE) noise generated by the SOA. A wideband photoreceiver (PD) converts the optical signal to electrical signal, and its output is connected to a sampling oscilloscope to capture the eye diagrams.

Figure 8.23b–c shows the 50 Gb/s NRZ BtB eye diagrams obtained from the REAM-SOA at 1300 nm and 1320 nm, respectively. At 1300 nm, we obtained a clearly open eye diagram with a high DER of ~10 dB. The DER at 1320 nm is ~6.6 dB, which is slightly lower than expected. The maximum peak-to-peak voltage swing is limited to 2.4 V (setup limited). As a result, a fixed VPP is used over the 20 nm range. Hence, the relatively lower DER observed at 1320 nm is attributed to the lower VPP used during the 50G modulation. Dynamic performance of the EAM is not significantly degraded at 50 Gb/s compared with the one at 25 Gb/s NRZ. For example, at 1310 nm, the 50 Gb/s NRZ DER (which is ~9 dB) is only 1.2 dB lower than the DER at 25 Gb/s. Based on these observations, we also expect no significant degradation in BER performance at 50 Gb/s for the same 10 km transmission.

At this point, it is worth to mention that we recently demonstrated a 10 Gb/s multi-channel analog radio over fiber (ARoF) transmission using an RSOA-EAM satisfying 3GPP’s requirement for 16-QAM signals [35]. Therefore, our devices can find application in several next-generation high-speed optical networks such as HSPs, data centers, and 5G fronthauling (analog and digital). Finally, further improvements in the future can be achieved by employing on-chip impedance matching techniques. Moreover, one can also focus on designing devices for uncooled operations, low polarization dependence, low bias voltage, and integrating array of REAM-SOAs to realize low-cost WDM transmitters.
8.5 Conclusion

In this chapter, a comprehensive study on mmWave ARoF systems is presented that focuses on the modulation and equalization approaches for enhancing the integrated fiber-radio link performance. In this context, the relevance of using mmWave ARoF technologies is highlighted for 5G and beyond is addressed in Sect. 8.1. However, mmWave ARoF still presents several challenges (such as nonlinearities, phase noise, or high-power losses) to be resolved. In particular, the choice of modulation format is pivotal toward ensuring spectral efficiency and reliability in the communication link. Therefore, Sect. 8.2 conducted a study on the link level modulation formats that are able to take a step toward attaining the stringent 5G KPI targets, where it was concluded that legacy OFDM was clearly not the modulation format of choice. Alternative schemes, such as SC-FDM and multi-CAP, should be considered.

Signal degradation introduced by optical fiber dispersion in mmWave ARoF systems is shown in Sect. 8.3. Moreover, the enabling technologies for mmWave ARoF are also explained. A mmWave ARoF simulation is performed over different fiber lengths. In these simulations, the LMS equalization is used to reduce the nonlinearity effects of the fiber and thus achieve reduced lower EVM values.

Optical amplifiers and modulators are crucial devices in mmWave ARoF systems. The characterization of a REAM-SOA integrated into a single chip is realized in Sect. 8.4. In this characterization, key parameters (such as extinction ratio, insertion losses, and gain) of this device are thoroughly investigated. Furthermore, an experimental digital transmission is demonstrated by utilizing this device, achieving bit rate of 50 Gb/s.

Therefore, this chapter serves to highlight the viability of mmWave ARoF links for 5G and beyond by analyzing techniques and methods to achieve high performance. Regarding the future lines of this work, Sect. 8.2 can be extended by changing the conditions of the experimental setup: different distances of the wireless link, NLOS propagation, or wireless channel with greater multipath effect. For Sect. 8.3, varying the parameters involved in the simulations is a straightforward way to continue with this part. Achieving high modulation orders such as 64-QAM and 256-QAM is one of the most relevant key challenges in both Sects. 8.2 and 8.3. Finally, for Sect. 8.4, future work can be achieved by employing on-chip impedance matching techniques.

Acknowledgment This research was funded by the European Commission through H2020 ITN 5G STEP FWD (grant agreement 722429) project.

References


