Millimeter-Wave Frequency Radio over Fiber Systems: A Survey

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***Abstract*—In recent years considerable attention has been devoted to the merging of radio frequency and optical fiber technologies aiming to the distribution of millimeter-wave (mm-wave) signals. This effort has given birth to the field of Radio over Fiber (RoF) technologies and systems. This sort of systems have a great potential to support secure, cost-effective, and high-capacity vehicular/mobile/wireless access for the future provisioning of broadband, interactive, and multimedia wireless services.**

In this paper we present a comprehensive review of mm-wave frequency RoF systems. In our integral approach, we identified the most important figures of merit of an RoF system, which is divided into three main subsystems: Central Station (CS), Optical Distribution Network (ODN) and Base Station (BS). In each subsystem, the most promising technologies are classified: downlink transmission techniques at the CS, ODN architectures, and optical configurations of the BS. The impact of technology choice on the overall system performance is discussed, and the figures of merit are studied and used to assess the subsystem's performance. Finally, we suggest technological opportunities and future developments that should be attracting the attention of researchers and developers.

***Index Terms*—Radio over fiber, millimeter wave frequency, broadband wireless, hybrid fiber-wireless networks**

I. Introduction

DURING the past two decades, the personal communications industry has faced an impressive growth in the number of subscribers worldwide and in the demand of high speed data transmission. Additionally, large coverage, high mobility and on-line connectivity have become ubiquitous requirements for the wireless communications networks. The objective of mobile broadband wireless access, that aims to provide the above mentioned aspects, has been addressed by the IEEE standard [1], [2] and by the ITU evolving standard International Mobile Telecommunication-Advanced (IMT-Advanced) [3]. The need for efficient systems, which could support high bit rates envisioned for the future wireless networks, are encouraged to exploit the advantages of both, optical fibers and millimeter-wave (mm-wave) frequencies [4]. While optical fiber technologies provide much higher bandwidth and support long transmission links, the use of mm-wave frequencies offers large bandwidths in the wireless domain and also overcomes the problem of spectral congestion at lower frequency ranges. Such systems that use an Optical Distribution Network (ODN) for delivering mm-wave radio signals from a Central Station (CS) to many remote Base Stations (BSs) have long been recognized to allow the increase of user capacity, bandwidth, and mobility [5]–[7].

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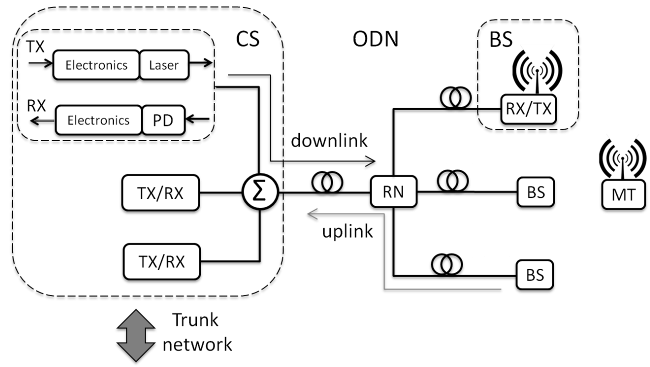

Fig. 1. General RoF system architecture, where Central Station (CS), Optical Distribution Network (ODN), and Base Stations (BS) are presented.

A typical Radio over Fiber (RoF) system is shown in Fig. **1**. There is a CS that contains data resources, optical transmitters (TX) and receivers (RX) with lasers and photodetectors (PDs), respectively. The CS has interconnections with the Trunk Network, with the Internet, and switching capabilities. In the downlink direction, the CS up-converts the electrical signal to optical domain and uses the ODN to communicate with the BSs, in some cases using Remote Nodes (RNs) where the optical signal is amplified in the case of active network, and splitted or demultiplexed towards the corresponding BS that converts it back to electrical domain and radiates it to the Mobile Terminal (MT) end-user in the mm-wave bands [8]. In the uplink direction, the BS receives the mm-wave signal from the MT, and depending on the configuration of the BS, this signal can be down-converted before modulating an electro-optical device to transmit the uplink information via the ODN back to the CS.

RoF communication systems have in principle, several advantages over conventional coaxial cable or wireless systems:

- Low attenuation by the use of optical fibers.
- Simplicity and cost-effectiveness since it centralizes resources at the CS where they can be shared; and remote simple BSs consisting only of an optical-to-electrical converter, Radio Frequency (RF) amplifiers and antennas.
- Low cost expandability as they are virtually modulation format agnostic.
- High capacity because higher frequencies can be transported through RoF systems allowing data rates to accommodate future service demands.
- Flexibility because it allows independent infrastructure providers and multi-service operation, the same RoF network can be used to distribute traffic from many operators and services.

- Dynamic resource allocation, since functions such as switching, modulation and others are performed at the CS, being able to allocate capacity dynamically.

Commercial products for wireless access are available for wireless networks operating in frequency bands from 2.4 to 5.8 GHz [9], and they are still unable to supply data rates comparable to wired standards such as gigabit Ethernet and High-Definition Multimedia Interface (HDMI). Thus, when fully developed, high-speed indoor/outdoor wireless access communication systems will operate at higher frequency bands in order to reach higher data rates (over 2 Gbps) [10]. RoF systems operating at mm-waves are the subject of extensive research and development activities, as presented in an extensive review of RoF engineering patents in [11]. The mm-waves, or Extremely High Frequencies (EHF), term denotes the electromagnetic waves with wavelength in the range from 1 to 10 mm. Therefore, mm-wave band ranges from 30 to 300 GHz, even if some authors extend this band down to 20 GHz based on the similarities in the wireless propagation characteristics [12].

Different mm-wave bands have been proposed for high-capacity wireless systems employing RoF: in the 24 to 30 GHz band (600 Mbps) [13], 75 to 110 GHz band (40 Gbps) [14], at 120 GHz (10 Gbps) [15], at 250 GHz (8 Gbps) [16], and more recently at 220 GHz (20 Gbps) [17]. However, the frequency band that has attracted major interest is around 60 GHz, mainly because of two reasons: 1) this frequency coincides with the oxygen absorption peak, which results in high atmospheric attenuation exceeding 15 dB/Km [18]. High attenuation allows reduction in the cell size and frequency reuse distance in cellular systems, increasing the wireless system capacity [19]. 2) in North America there is 7 GHz of unlicensed spectrum in around 60 GHz that overlaps with unlicensed spectra in Europe, Japan, and Australia, which opens the opportunity for worldwide standardization and commercial products [20], [21]. RoF at 60 GHz has been demonstrated in [22], [23] to support transmission of data throughputs up to 27.04 and 32 Gbps, respectively.

The major drawbacks of an RoF system are that, as the RF frequency increases, so does the requirement for high-speed optical components, more sophisticated mm-wave generation techniques, and a larger number of BSs with broad bandwidth PDs to cover a service area. In addition, effects of chromatic dispersion across the ODN become a problem even over relatively short fiber spans for conventional double sideband modulation; therefore, advanced modulation and transmission schemes must be employed. These requirements have led to the development of optical components operating in the mm-wave band [22], [24], [25], techniques for efficient generation and transmission of mm-wave radio signals over the optical fiber [26]–[28]. Moreover, multiple system architectures have been proposed where functions such as signal routing, processing, handover, and frequency allocation are carried out at the CS, for BS simplification [29].

In this paper we present an overview of RoF downlink techniques, ODN architectures, and BS configurations for wireless communications at mm-wave frequencies with special attention to the figures of merit and the basic enabling technologies for the downlink/uplink transmission in the land network. The paper is organized as follows: Section II presents a summary of RoF figures of merit needed to assess the system's performance, section III presents the most important CS downlink transmission techniques, section IV reviews ODN architectures and recent developments in this field, section V focuses on the BS configurations. Finally, in section VI, research opportunities and future developments are presented. To the authors' knowledge, this is the first work in which an updated, complete, and detailed overview of a mm-wave frequency RoF system is presented.

II. Figures of Merit in RoF systems

The overall performance assessment of an RoF system must take into account the figures of merit of the different subsystems; namely the CS, the ODN, and the BS. In this section we present what we consider the most important figures of merit of a mm-wave frequency RoF system, which need to be considered for an integral system design to satisfy the network requirements.

A. Cost and Simplicity

The design and implementation of an efficient and cost effective telecommunication network that will seamlessly migrate toward future services, is always a primary objective for developers. Several network cost models to derive the improvement point, and establish the directions and the design principle for the network operation efficiency have been proposed [30], [31].

For an RoF system, the general guideline includes the selection of the appropiate technologies for each subsystem with the goal of reducing capital and operational expenses of the network [32]. At the CS high frequency electro-optical modulators and electronics have to be avoided due to their high cost [33] and power consumption [34]. In the same way, complex implementations of downlink transmission techniques are also averted because they result in higher manufacturing and maintenance costs. As for the ODN, the cost is mainly determined by the fiber installation more than by the optical components. Thus, integrating optical segments into hybrid solutions (fiber sharing) for the next generation of ODNs is a key factor as it enables cost reductions. However, it is important to minimize fiber length while keeping in mind that topologies with the minimum fiber often offer poor availability performance [35]. Regarding the BS, it is critical to keep it as simple as possible because an elevated number of them are required in the RoF system, meaning a BS with the lowest possible number of components. Simplicity of the BSs, drives the reduction of costs associated with site acquisition, site leasing, and energy consumption. It is desirable for the BS to work without any expensive climate control facilities at the remote site [36].

Also, as demonstrated in current cellular wireless networks, the increasing demand for new services will lead RoF systems to support different traffic characteristics. For this reason, an appropriate pricing scheme needs to be selected to allow service providers to assure the continuous quality of service provisioning and at the same time to be economically survivable [37].

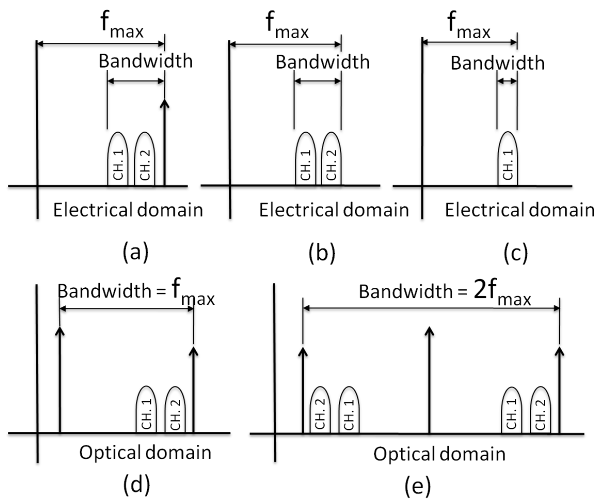

Fig. 2. mm-wave frequency and bandwidth at electrical domain: (a) Two modulated channels and mm-wave carrier, (b) Two modulated channels, (c) One modulated channel. Optical Domain: (d) Optical Single Side Band (OSSB), e) Optical Double Side Band (ODSB)

B. mm-Wave Frequency and Bandwidth

This figure of merit is related to the capacity of the RoF system to generate a mm-wave signal at the desired frequency with the required bandwidth. In this context, mm-wave signal should be understood as the sum of all spectral components that will be wirelessly radiated or received by the BS within the desired band. Depending on the system architecture, the mm-wave signal may include an mm-wave carrier and one or multiple data channels. As shown in Fig. **2**(a-c), two different bandwidths should be contemplated: electrical and optical. Thus, in the electrical domain the bandwidth of the mm-wave signal is defined as the difference between the maximum and minimum frequency components, which should not be confused with the channel bandwidth [38]. In the optical domain, the bandwidth depends on the maximum mm-wave frequency in the electrical domain, f_{max}, and whether Optical Single Side Band (OSSB) Fig. **2**(d), or Optical Double Side Band (ODSB) Fig. **2**(e) modulation scheme, is used [8]. Each subsystem of an RoF system has to be designed to fulfill mm-wave frequency operation and bandwidth requirements. With high-speed uni-travelling-carrier photodiodes (UTC-PDs) which can provide 3 dB bandwidths up to 300 GHz [39], and relatively mature ODN components [40], the downlink transmission technique is typically the main factor limiting the maximum frequency.

C. RF Output Power and Signal Power

RF output power accounts for the total power available at the output of the PD at the BS [39] (Fig. **1**), which may comprise a single or double modulation sideband and a mm-wave carrier. In RoF systems this carrier can assist the MT to down-convert the mm-wave signal back to baseband, avoiding high-frequency Local Oscillators (LOs) [41]: in self-homodyne MTs, the mm-wave carrier is used as the reference oscillator and, in envelope detector MTs, it is used to advent over-modulation. It is important to note that, in the case of RoF systems where mm-wave carrier is transmitted, the power of the modulation sideband transporting the information, denoted as signal power, is a fraction of the total power and must be specified [38]. The signal power is computed as the power over a reference bandwidth that covers most of the modulation signal. The ratio of the carrier power to the signal power can be understood as the energy efficiency of the transmitted signal, in the same way as modulation index is a metric for amplitude modulation signals. The required value of this ratio depends on the wireless channel attenuation and MT design: in self-homodyne detection where a high power reference oscillator is required, higher ratio is permissible, on the contrary when an envelope detector is used at the MT, high power ratio requires high RF power in order for the signal power to be above the sensitivity of the MT. Even if both, the maximum RF output and signal power, depend on the whole RoF architecture, the main limiting factor differs depending on whether the ODN is passive or active. In the case of a passive ODN, the maximum RF output power is limited by the optical power at the input of the PD, which further depends on the optical output power at the CS and the losses in the ODN. In contrast, in active ODN networks, the main limitation frequently arises from the maximum output power of the PD [38]. A common criterion to assess it at a particular frequency is the 1 dB compression point, that is, the power at which the transfer characteristic drops by 1 dB with respect to the ideal linear transfer function [42]. It is worthwhile noting that the power relation between the carrier and the signal is determined at the CS and remains almost unaltered through the ODN and the BS.

D. Spectral-Purity and Frequency Accuracy of mm-wave Carrier

Both spectral-purity and frequency accuracy are figures of merit of the mm-wave carrier quality and are related to the phase stability: the former accounts for short-term phase fluctuations while the latter is related to the long-term stability [43]. For spectral purity or linewidth, single side band phase noise measurement is the best indicator of performance. Phase noise is typically expressed in units of dBc/Hz, representing the noise power relative to the carrier contained in a 1 Hz bandwidth centered at a certain offset from the carrier. According to [44], the following maximum values for the single sideband phase noise are desirable for a mm-wave frequency mobile broadband system: -68 dBc/Hz at 10 kHz, -84 dBc/Hz at 100 kHz, and -100 dBc/Hz at 1 MHz. Besides, the frequency accuracy of the generated mm-wave is the degree of conformity to a specified frequency value, it can be expressed as a frequency range or in fractional units (i.e. ppb - parts per billion). In an RoF system, the mm-wave is generated as a result of the beating of optical tones at the BS in the photodetection process. Thus, the phase noise of the generated signal depends on the correlation degree of the beating tones [38]. Precise temperature control of the optical source is required at the CS in order to achieve the frequency accuracy of the mm-wave generated at the BS, and also to maintain the optical signal within its corresponding optical channel in the ODN. High spectral-purity and frequency accuracy are specially required when an independent oscillator is at the

MT, since poor spectral-purity and frequency accuracy result in higher phase noise and attenuation in the down-converted signal, respectively. In addition, regardless of MT scheme, higher mm-wave frequency accuracy allows reduction of the guard band between channels and, therefore, higher spectral efficiency is obtained.

E. Transmission Integrity

The transmission integrity can be evaluated using Bit Error Rate (BER) or Error Vector Magnitude (EVM) metrics. The BER is defined as the fractional number of errors in a transmitted sequence, and the EVM is the average of the magnitude difference between the reference and the received constellation at a specific point in the system, it is more significant in complex modulation formats. Generally, these metrics are plotted against the received power in order to be able to calculate the system's performance and the sensitivity for a given BER/EVM threshold [45]. Several authors measure the transmission integrity of an RoF system at the MT, considering the wireless transmission effects and the MT architecture [14]–[17], [23], [41], while others, are concentrated only on the effects of the RoF land network by measuring signal integrity at the output of the PD at the BS [13], [26], [46], [47].

Therefore, transmission integrity analysis can be separated into two stages, which correspond to the two different physical channels that the signal traverses to get MT from CS and vice versa: optical and wireless.

1) Optical Channel: In the optical domain, link performance degradation is caused by non-linearities, noise, and undesired phase modulation or chirp. The main sources of noise in the optical path of the RoF link are PD shot and thermal noise, the Amplified Spontaneous Emission (ASE) of the optical amplifiers, and the Relative Intensity Noise (RIN) of the light source [48]. In addition, the beating of the different optical components at the PD results in a phase-to-amplitude conversion and therefore frequency chirp and fiber-induced dispersion further increase the output noise power [28]. Non-linear effects include clipping distortion and third order intermodulation distortion caused mainly by the non-linear modulation.

As a general rule, non-linearities limit the maximum power generated, transported, or received, while noise establishes the minimum power boundary for a given BER or EVM. Non-linear effects in the RoF transmission at the CS are caused by the non-linear behavior of the laser if direct modulation is used or by the External Modulator (EM) non-linearities, in case of external modulation. In addition, direct modulation introduces higher RIN and stronger frequency modulation than external modulation.

In the ODN, non-linear effects arise from the fiber [49], and in active ODN from optical amplifier gain compression [50], [51]. Fiber chromatic dispersion is a serious problem even over relatively short spans for conventional double sideband modulation. Its effect produces different phase shifts of the signal sidebands, and when these sidebands are mixed with the optical carrier in the PD at BS, the output signal is reduced depending on the mm-wave frequency and the fiber link length. In the worst case scenario, for fiber dispersion-induced signal cancellation effect, the detected signal amplitude can go down to zero level [28].

Regarding noise, the dominating noise sources in the active ODN are the optical amplifiers, for passive ODN the effect of in-band crosstalk on system's performance when both downlink and uplink signals are transmitted through the same fiber need to be considered [52]. Also, when two or more optical signals carrying mm-wave modulation operate with very close spaced wavelengths, beating between the optical signals and Four-Wave Mixing (FWM) terms can occur, increasing the noise at the PD. This type of noise is called Optical Beat Interference (OBI), which degrades the Signal-to-Noise Ratio (SNR) at the output of the PD, limiting the network capacity [28].

In the BS, the gain compression of the received downlink signal at elevated frequencies [39] is an important source of non-linearities. There are two principal causes of noise at the BS, the PD for the received downlink signal, and in the uplink transmission depending on whether direct modulation or external modulation is used [53].

2) Wireless Channel: In the wireless domain, the RF Power Amplifier (PA) stage used is a key element to establish the link budget and the power requirements for acceptable SNR levels. However, the maximum amplifier gain is constrained by the maximum transmitter noise and spurious emissions requirements of the wireless system specification (considering the maximum power density of 18 μW/m^2 allowed by the FCC [54]). Also, BS and MT stability requirements limit the power levels, since high gain for both uplink and downlink directions may lead to oscillation [55].

The signal power at the input of an mm-wave receiver at MT and BS, is determined by the wireless link power which accounts for the transmitted power, the wireless channel path loss, and the transmitter and receiver antenna gains [54]. Therefore, it becomes crucial to understand the propagation characteristics of the particular scenario where the RoF system is going to be deployed: line-of-sight indoor, non-line-of-sight indoor, point-to-point outdoor, point-to-multipoint outdoor. The mm-wave TX/RX system should be designed accordingly, which may require highly directional, omnidirectional, or adaptive antennas capable to implement algorithms to overcome shadowing and multipath [56], [57]. Progress in the areas of on-chip antennas, mm-wave PAs, Low Noise Amplifiers (LNAs), Voltage-Controlled Oscillators (VCOs), mixers, Analog-to-Digital Converters (ADCs), and mm-wave channel characterization will result in improvements on the RoF mm-wave wireless link [54].

In conclusion, the transmission integrity of an RoF system (either measuring BER or EVM) may be present as a function of an equivalent SNR which accounts for all impairments both in the optical and mm-wave wireless domains. In this way, non-linearities and fiber dispersion suppose an addition power penalty to the SNR that only considers the noise.

F. Scalability

Scalability is defined as the capability of the RoF system to increase coverage, capacity, and services within the network to meet usage demand without a significant cost increase.

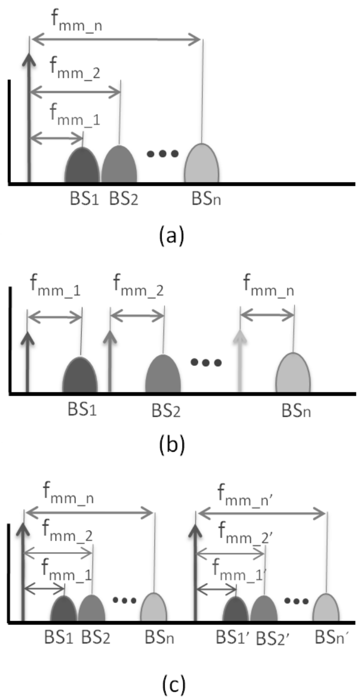

Fig. 3. Frequency multiplexing techniques (optical spectrum): (a) subcarrier multiplexing (SCM), (b) wavelength division multiplexing (WDM), (c) combined SCM and WDM

Aiming at minimizing the cost, a large number of low cost BSs should be fed with highly equipped CS and minimal amount of optical components in the ODN [58]. Therefore, different BSs are fed with the same fiber where different signals are multiplexed. In this way, the design of the CS, the ODN, and the BS impact significantly on the overall system scalability. Downlink transmission techniques using multi-wavelength light sources exhibit better capabilities to escalate than others using single wavelength [59], [60]. The multiplexing scheme plays an important role in the network scalability, Fig. **3** shows the spectrum of the most popular frequency multiplexing schemes for downlink transmission:

- Subcarrier Multiplexing (SCM): Multiplexing is done in the electrical domain; in this way, signals for different BSs are carried into a single optical wavelength using frequency division multiplexing as depicted in Fig. **3**(a). The expense of the downlink transmission is shared among the different BSs at the cost of higher non-linearities and lower signal power delivered to each BS [47].
- Wavelength Division Multiplexing (WDM): in contrast to SCM, different signals are transported in different wavelengths as presented in Fig. **3**(b). This is generally achieved by using a dedicated laser for each wavelength [61]; nevertheless, it is possible to use a single source to generate signals at different wavelengths [62].
- Combined SCM and WDM: Different wavelengths are modulated by subcarrier signals, each for a different BS as shown in Fig. **3**(c). [63].

With respect to the uplink, Time Division Multiplexing (TDM) has to be added, as well as its combinations [64]. The uplink multiplexing technique impacts primarily on the BS design. WDM is almost compulsory but within each wavelength SCM or TDM can be implemented. The former requires tunable oscillators, at relatively low frequencies, the latter precise time synchronization of the BSs. For the ODN, other aspects as amplification [65], switching capabilities [66], and reconfigurable nodes [67] are key parameters that need to be considered when assessing the network scalability.

There are several factors limiting the mm-wave RoF system scalability in terms of coverage and capacity. We present some of the main concerns and the key enabling technologies available to overcome these limitations.

1) Network Coverage: For transmission of mm-wave signals over optical fiber links, is very important to consider advanced modulation and transmission schemes to overcome the chromatic dispersion effects [26]–[28]. The power budget is of high importance especially when more complex optical network topologies with combined multiplexing schemes are deployed.

In the optical link, an exhaustive analysis of launch power (limited by non-linearities) and power penalty across the ODN is mandatory to achieve the appropriate levels at the optical receiver on each BS. Optical amplifiers and pre-distortion circuits are key elements to overcome this limitation.

In the wireless link, all channels must share the composite power, therefore the larger the number of channels, the lower the power per channel, which in general will lead to reduced network coverage [55]. This performance reduction can be mitigated to a limited extent by increasing the gain of the BS PA. However, as mentioned earlier, the maximum amplifier gain is constrained by maximum transmitter noise and BS stability requirements.

2) Network Capacity: The RoF network will require a high number of multiplexed channels, with wider channel bandwidth, and modulation formats with higher spectrum efficiency. SCM within WDM is the preferred multiplexing option for network capacity scalability, because it minimizes the need for extra optical fibers and optical wavelengths [48], [55]. Orthogonal Frequency Division Multiplexing (OFDM) is a broadband multi-carrier modulation method that provides higher spectral efficiency and robustness in the optical and wireless channels [68].

As mentioned previously, wider channel bandwidths are being envisaged to increase network capacity. However, channel noise scales directly with bandwidth, which means that a higher signal power is needed to maintain SNR above the receiver sensitivity [55].

In the optical link, a high number of optical channels carrying mm-wave modulation will lead to an increase of OBI. Fortunately, several techniques to reduce OBI effects have been proposed, which can be divided into two main categories: 1) Spectral broadening, utilizing the characteristic that OBI noise is inversely proportional to optical bandwidth [69], and 2) Wavelength separation, by implementing optical frequency controls [28], [70].

For the wireless link, a key technique called Multiple-Input-Multiple-Output (MIMO), which increases the number of radio channels transported by the RoF links by spatial multiplexing, has been exploited and considered as a key technology to improve network traffic capacity [71]–[73]. The use of multiple antennas at both the transmitter and receiver side could improve not only the network capacity but also the system reliability through spatial diversity. However, MIMO channel capacity depends on the statistical properties and antenna element correlations of the channel. Therefore, understanding the mm-wave propagation characteristics, and frequency-dependant channel models, is very important to improve accuracy of capacity and coverage predictions [74].

G. Power Consumption

Considerable effort has been dedicated to the development of "green" energy-saving communication networks. Thus, the power consumption of a network has become an important figure of merit, which can be expressed by the power consumption per user versus the average access rate (Watts/Mbps). Another useful measure of the energy efficiency of a network is the energy consumed per bit of data transferred (Joules per bit) [75]. An approach for modeling the power consumption of an access network infrastructure is based on the network segmentation. For a range of access rates, the energy consumption of each part of the network is calculated using manufacturers data on equipment energy consumption for a range of typical types of hardware. This approach provides a platform to predict the growth in power consumption as the number of users and access rate per user increase [76]–[78].

In an RoF system, the power efficiency in the CS should account for both electrical and optoelectronic components. Regarding the first, early implementations were based on III-V semiconductor compound materials due to their better noise and power efficiency, at the cost of higher price and lower digital integration. In recent years, silicon-made Complementary Metal-Oxide-Semiconductor (CMOS) devices have been reported with progressive lower consumption. However, the electronics at mm-wave band are still quite power hungry [21], [79]. In order to enable any future power reduction, significant innovation in materials and CMOS structure will be required [80]. With less contribution, a majority of the power consumption of optoelectronic components is in the transmission lasers and amplifier's pump lasers of an active ODN, and in the electronic components that perform the control and management functions at the RNs.

Power consumption of the mm-wave BSs is of special importance because of the large number of them required to cover a service area. In commercial mobile wireless networks, BS accounts for up to 70% of the total power consumption [81]. Therefore, it is found that BS design has the most opportunities for saving energy.

The power consumption model for mm-wave RoF BS must consider the transmission schemes for uplink and downlink, the mm-wave frequency to be radiated, and the expected cell coverage or transmitting power. The transmission scheme and the operational mm-wave frequency will determine the BS configuration and its required components. For RoF networks operating at lower frequencies (3G cellular systems), several transmission schemes have been proposed, Baseband-over-Fiber (BoF), IF-over-Fiber (IFoF), RF-over-Fiber (RFoF), Digitized IF-over-Fiber (DIFoF), and Digitized RF-over-Fiber (DRFoF) [82]. And it has been demonstrated that, although analog RFoF and IFoF schemes require less components, the energy efficiency is limited by the poor electrical PA efficiency which increases the overall power consumption compared to the digitized schemes [82]. However, for mm-wave RoF systems, the feasibility of digitized schemes must be carefully analyzed, considering that the maximum carrier frequency processed with the scheme is strictly limited by the performance of electrical ADCs [83]. Even though ADCs have reached sampling speeds as high as 40 Gs/s, possibly allowing direct sampling of mm-wave frequencies, they have required very high power [84]. Thus, amplifier efficiency becomes an essential factor for mm-wave BS energy-saving. The efficiency of mm-wave PAs is degraded by parasitic elements in active and passive components, and it can be improved by proper design of transmission line elements [85].

On the other hand, the BS power consumption varies depending on the transmitting power and traffic load. The higher the traffic or transmitting power, the higher the power consumed by the BS. Therefore, some work on how to implement "green" BS has already been done focused on optimizing energy saving methods. Among the proposed approaches, we can find BSs with power consumption adapted to the traffic load [86] and BSs equipped with regenerative energy sources [87].

H. Reliability and Availability

Network reliability indicates the quality of the network to transport traffic, and it is defined as the probability that there exists one functional path between a given pair of entities [88]. Availability is the level of operational performance that is met during a measured period of time; it is usually expressed as the percentage of time when the system is operational [35]. For an RoF system we can distinguish two different types of reliability and availability: 1) That related to discrete components in the CS and BS and, 2) that related to the ODN. The difference mainly stems from the Mean Time to Repair (MTTR) and Failure Rate (FR). If a fiber is cut at the ODN, the MTTR is typically long. And, if no protection scheme is implemented, several BSs can be down for a considerable period of time. In contrast, devices at the CS and BS are easier to access and the MTTR is much shorter, however the FR is higher for active components, where redundancy schemes must be considered [35]. Conventionally, in WDM metropolitan networks for fix Internet access, dual rings have been employed for protection against fiber failure [89]. However, the use of two optical paths increases the fiber installation cost and adds extra components that inherently have more potential failure points [90]. Thus, single fiber bidirectional self-healing protection schemes by using Optical Add Drop Multiplexer (OADM) has emerged to improve network availability and reliability at a lower cost [91], [92].

III. Downlink Transmission Techniques at the Central Station

The most challenging stage in the downlink transmission is the generation at the CS of the optical signal that, after detecting by a square-law PD in a remote BS, results in the

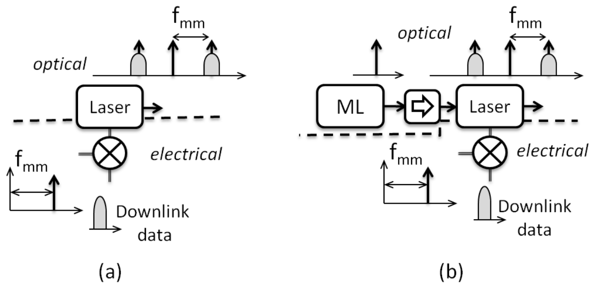

Fig. 4. (a) directly modulated laser (b) directly modulated laser with OIL

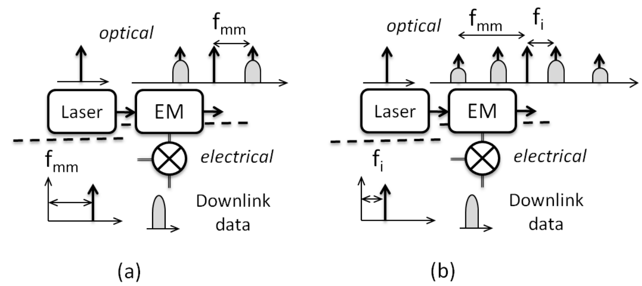

Fig. 5. Externally modulated CW laser: (a) Without OFM (*fmm*), (b) With OFM (*fi*).

desired mm-wave signal. An increasing number of techniques have been proposed in the last years to perform this task based on different approaches, some of which have been covered by previous reviews [25]–[27], [93]–[95].

In the present section we list the techniques that to our criterion are the best candidates for future RoF systems. First of all, we distinguish two processes: 1) mm-wave carrier generation and 2) downlink data modulation, which can be performed simultaneously or in different stages. Different techniques are classified according to the mm-wave generation scheme and then, the different ways in which downlink data is modulated are presented.

A. Directly Modulated Laser

1) Directly modulated laser: A laser is directly modulated with the downlink signal at the desired mm-wave frequency as shown in Fig. **4**(a). The transmitter configuration is extremely simple and cost effective but its performance is severely limited by the laser modulation impairments. On the one hand, the frequency chirp, the significant non-linearities, and high RIN cause poor frequency stability and transmission integrity [96]. On the other hand, the maximum modulation frequency is generally limited by the laser resonance peak [97]. Even if lasers with resonance frequencies above 20 GHz have been fabricated (30 GHz [98], 37 GHz [99], and 40 GHz in [100]), the maximum frequency reported in a RoF system is limited to 25 GHz [101]–[103]. It is important to note that the low available bandwidth and high non-linearities make this technique unsuitable for generation of multiple channels using SCM or to increment transmission capacity, what leads to poor scalability performance. In terms of the energy consumption, although a priori it is low because a single component is used; the low capacity makes the consumption per bit ratio (Joules per bit) quite high.

2) Directly modulated laser with OIL: Strong Optical Injection Locking (OIL) in which a laser is subject to relatively high power external light coming from a Master Laser (ML) as shown in Fig. **4**(b), has demonstrated to enhance the modulation characteristics of the injected laser: enhanced resonance frequency [104], reduced chirp [105], lower RIN [106], and non-linearities reduction [107]. These improvements allowed the generation of a 60 GHz signal carrying 3 Gbps downlink data as reported in [108], [109]. In comparison to non-injected directly modulated laser, system cost and power consumption increase because of the higher number of components. However, these increases can be relatively low if the ML is used to inject multiple lasers. OIL techniques using a multi-wavelength ML to inject multiple optical transmitters in a Dense WDM (DWDM) scheme have been demonstrated for transmissions up to 2.5 Gbps in Passive Optical Networks (PON) [110], [111]. The high bandwidth available in this technique permits simultaneous generation of multiple SCM channels, which improves the scalability. Regarding frequency stability, it is better than that obtained in the absence of injection locking but it is still poor due to the residual chirp of the injected laser.

B. Externally Modulated Laser

In order to overcome the impairments of the direct modulation, external modulation is the straightforward solution. The simplest implementation consists of a Continuous Wave (CW) laser followed by an EM that modulates the laser light with an intermediate frequency (IF - *fi*) or an mm-wave tone (*fmm*), Fig. **5**. The EM used in this technique can be an intensity modulator (a Mach-Zhender Modulator (MZM) or an Electro Absorption Modulator (EAM)), or a Phase Modulator (PM), whose output is optically filtered [26]. Since the CW-laser is not directly modulated, the main impairments in the transmission of the signal derive from the EM. Non-linearities in the transmission characteristic result in the generation of higher order harmonics that depending on the architecture can be undesired or required to implement Optical Frequency Multiplication (OFM) [112]. The power of these harmonics is controlled by the bias voltage and the modulation index.

The reason to convert to optical frequencies without OFM, is merely to allow the transmission over the fiber link as shown in Fig. **5**(a), meaning that the desired mm-wave frequency is electronically generated at the CS to up-convert the downlink signal [113], [114]. In contrast, if OFM is performed at the electro-optical conversion, the downlink signal has to be electronically up-converted not to the desired mm-wave frequency but to a sub-harmonic of it (*fi*), then two sidebands separated at the desired *fmm* are selected, this technique reduces the complexity of the electronics at the CS [26], [112], [115] as shown in Fig. **5**(b).

1) Externally modulated laser without OFM: The major impairment of this technique is the EM bandwidth limitation and the complexity of the associated electronics. Remote generation of mm-wave signals using broad bandwidth modulators and mm-wave frequency LO has been reported using EAM [113], [114], MZM [116], and PM [117]. This

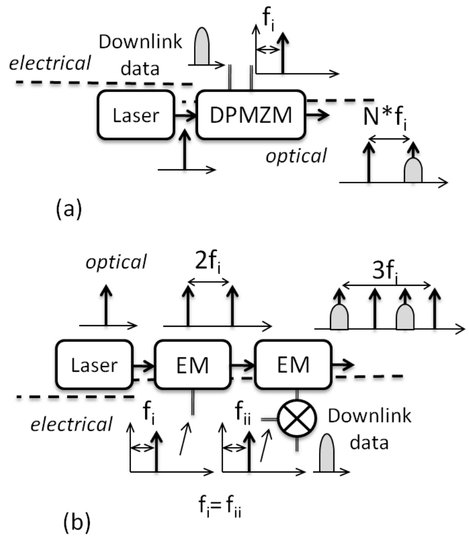

Fig. 6. Externally modulated laser: (a) DPMZM for OSSB modulation, (b) multiple EMs for high order OFM.

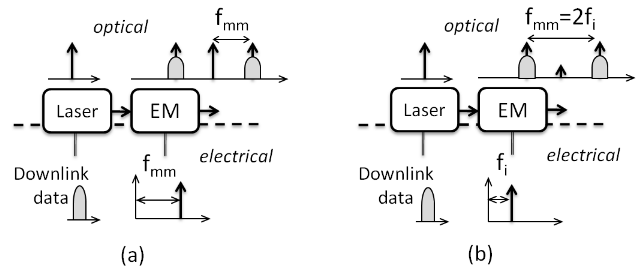

Fig. 7. Directly modulated laser with downlink data and external modulation for mm-wave carrier generation: a) Without OFM (fmm), (b) With OFM (fi).

technique is shown in Fig. **5**(a). In conventional external intensity modulation systems, the laser output is modulated to generate the optical carrier and ODSB. Under this scheme, the chromatic dispersion over the ODN causes each spectral component to experience different phase shift, which produces power degradation in the detected RF signal at the BS [118]. Dispersion effects can be reduced by the transmission of an OSSB signal. Therefore, several techniques to generate OSSB signals have been reported: an optical filter is used to suppress the undesired optical sideband [119], [120], while in [121], [122] one dual-electrode MZM is used to produce an OSSB signal.

2) Externally modulated laser with OFM: Since the cost of the EM and the electrical oscillator increases as the mm-wave frequency does, OFM has been proposed to generate mm-wave signals at frequencies above the EM bandwidth using IF sub-harmonic electrical signals *fi* as shown in Fig. **5**(b). There are two main approaches for OFM:

The first is to take advantage of the generation of higher order harmonics. The CW-laser is externally modulated with *fi* that is a sub-harmonic of the desired mm-wave frequency *fmm*. With proper bias and modulation index, higher order harmonics are excited and multiple sidebands separated by *fi* are generated at the output of the EM. Then, two sidebands whose separation matches *fmm* are selected by using optical filters [115]. The maximum order of the OFM is then limited by the harmonic generation efficiency and depends on the selected EM [123], [124].

The second alternative is to implement OFM by suppressing the carrier in an ODSB-Suppressed Carrier (ODSB-SC) [125]. In this way, the beating between the two sidebands results in an mm-wave signal at double frequency of the LO *fi* [126]. Carrier can be suppressed by either using a notch filter [127] or an optical interleaver [128] at the output of a PM; or using a MZM and biasing it at null-transmission point [129]. However, ODSB is more sensitive to fiber dispersion than OSSB [118]. A possible approach to simultaneously generate OSSB and take advantage of OFM is reported in [47], [130], [131] using a Dual-Parallel MZM (DPMZM) [132] as shown in Fig. **6**(a), where *N* is the OFM order.

In addition, multiple MZMs can be used to increment the order of the OFM. In [133], ODSB-SC modulation is achieved by using a MZM followed by OSSB modulation in a DPMZM as shown in Fig. **6**(b). Also in [46], OSSB modulation scheme with frequency sextupling is implemented by using two DPMZM, where two IF frequencies (*fi* and *fii*), are required for each EM.

There is a broad variety of ways in which downlink information can be modulated:

- The EM is used to simultaneously modulate data and to generate the mm-wave carrier as in [134] where an unbalanced electrode MZM is used to generate OSSB signal at 18 GHz, or in [113] where an EAM is modulated with 59.064 GHz signal with a data rate of 155.52 Mbps as shown in Fig. **5**(a).
- Simultaneous modulation of downlink data and generation of the ODSB in a single MZM is reported in [23], [135], as shown in Fig. **5**(b).
- The laser is directly modulated with downlink data and then the mm-wave carrier is generated without OFM (*fmm*) [136] as shown in Fig. **7**(a), or using OFM (*fi*) in a MZM [137] with ODSB-SC as shown in Fig. **7**(b), or in a PM with ODSB [138].
- Frequency doubling has been reported using ODSB-SC with a MZM in [126], [139] as shown in Fig. **8**(a), and ODSB with a PM [128], [140] as shown in Fig. **8**(b), using, in both techniques, a second MZM to modulate the optical signal with downlink information.
- The external modulation of filtered optical sideband of an ODSB-SC modulation scheme is another alternative to introduce downlink data. In this scheme the selected sideband is filtered using an Arrayed Waveguide Grating (AWG) and externally modulated with downlink data and coupled together using an Optical Coupler (OC) with the non-modulated sideband which is separated at the desired mm-wave frequency. In [47], a DPMZM is used for the generation of multiple optical sidebands (ODSB-SC), which are demultiplexed by an AWG (λ_1 and λ_2), and a single-drive MZM is used to intensity modulate one of the optical sidebands (λ_1) as shown in Fig. **9**(a). In [141] a Reflective Semiconductor Optical Amplifier (RSOA) is used to modulate data into an optical sideband

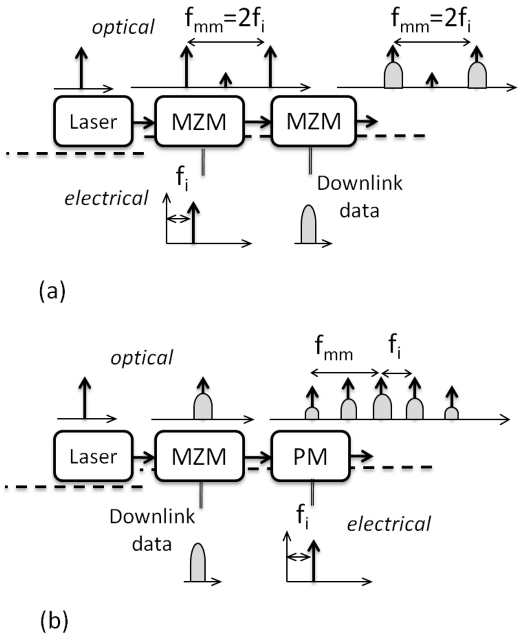

Fig. 8. External modulation using cascaded EMs for frequency doubling: a) MZM for mm-wave generation and second MZM for downlink data modulation, (b) MZM for downlink data modulation and PM for mm-wave generation.

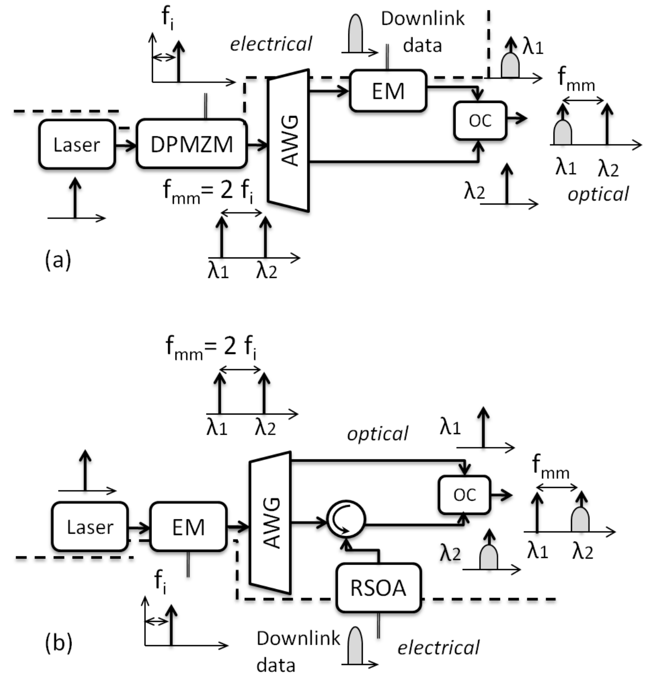

Fig. 9. External modulation of filtered optical sideband of an ODSB-SC modulation scheme: a) Using an EM for downlink data modulation, (b) using an RSOA for downlink data modulation.

(λ_2) coming from an ODSB-SC source as shown in Fig. **9**(b).

C. Multimode Light Sources

Multimode light sources, such as Fabry-Perot Lasers (FPL), Mode Locked Lasers (MLL), dual-mode lasers, or Super-continuum Sources (SCS) have gained attention as a low cost alternative to expensive broad bandwidth EMs and high number of independent lasers. Multimode light sources can be used in two different ways: as a multicarrier generator and as a way to generate the different beating tones for mm-wave frequency generation. For the latter, many variants have been reported in the literature but the mechanism behind them is the same, two optical modes are used to beat them at the BS's PD and generate the desired mm-wave signal, therefore, in most cases, the multimode source is designed to present modes separated by the desired carrier frequency. A further classification divides the multimode light sources in: 1) two-mode sources, comprising dual mode lasers, and 2) sources with higher number of modes that encompass MLL, FPL, and SCS.

1) Dual-mode laser: The two-mode source technique is presented in [142], a single chip dual-mode multisection long-cavity Distributed Feedback (DFB) semiconductor laser is used for the generation of mm-wave signals between 40-60 GHz (controlling the bias current). The phase noise was -77 dBc/Hz at 10 kHz offset. Recently, lower phase noise -94.6 dBc/Hz at 10 kHz offset for mm-wave generation of 42 GHz was demonstrated in [143] by using an integrated dual-mode laser. The two optical modes produced at the output of the device have a frequency separation equal to the desired mm-wave signal (λ_1 and λ_2) as shown in Fig. **10**(a). Data transmission is achieved by modulating both modes with an EM as reported in [144], for transmission of 155 Mbps and an mm-wave signal generation of 40 GHz.

2) Mode locked lasers (MLL): Regarding MLLs, they have extensively been used to generate mm-wave carriers. In [145] a passive MLL is used to generate 39.9 GHz tone, in [146] an active MLL is employed for the generation of an mm-wave frequency of 37.1 GHz, while in [147] generation of mm-wave signal at 163.66 GHz has been achieved by active mode-locking of a Distributed Bragg Reflector (DBR) integrated with an EAM. For RoF systems, MLLs have been used for data transmission, the MLL mode separation equals the desired mm-wave frequency, thus its output can be externally modulated with an EM for downlink signal transmission as is shown in Fig. **10**(b). Using this approach, in [22] a passive MLL is externally modulated with 5 Gbps downlink data signal using an EAM, and in [148] an active MLL is externally modulated with 3 Gbps data signal using a MZM. External modulation can be avoided by directly modulating the MLL. Nevertheless, direct modulation is not as straightforward as external modulation since it interferes with the mode locking process. Direct modulation of MLL can be found in [149] where a 54.8 GHz MLL is modulated with 3.03 Gbps or in [150] where a wireless hybrid 40 GHz MLL (whose pulsation frequency is synchronized to an external mm-wave tone) is modulated with a maximum data rate of 56 Mbps.

3) Supercontinuum source (SCS): A SCS followed by an AWG has been used to generate 12.5 GHz spaced optical carriers from 1512 to 1580 nm [151], and 50 GHz spaced optical carriers on the ITU grid over a seamless spectral range from 1425 to 1675 nm [152]. In [62], the SCS output is launched to an AWG with 25 GHz channel spacing (*fc*).

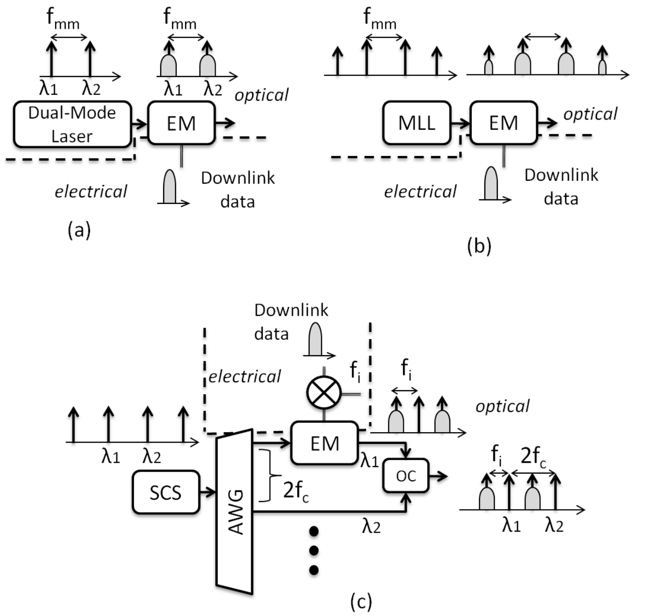

Fig. 10. Multimode light sources: (a) Dual-mode laser, (b) passive or active MLL with downlink external modulation, (c) SCS with external modulation.

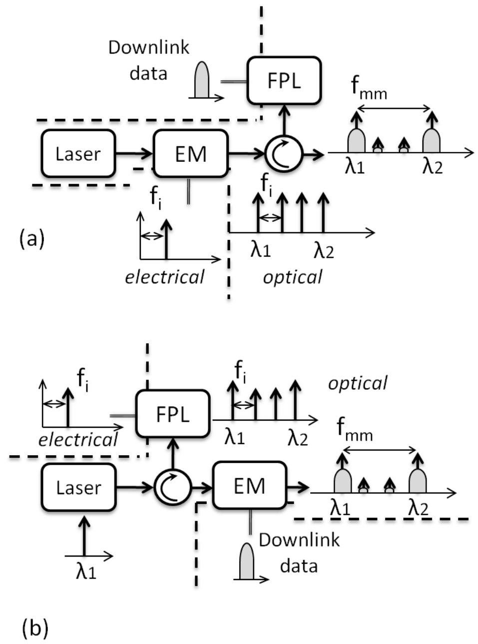

Fig. 11. Multimode light sources: (a) two-mode locked FPL with downlink direct modulation, (b) and sideband injection locked FPL with downlink external modulation.

Two SCS modes with 50 GHz (*2fc*) spacing (λ_1 and λ_2) are used for the mm-wave signal generation. One of the extracted SCS modes λ_1 is externally modulated with a MZM by an IF signal (*fi*= 10 GHz) carrying 156 Mbps data (the SCS mode is modulated in ODSB and ODSB-SC formats, respectively). The 60 GHz mm-wave signal (*2fc* + *fi*), can be generated after combining the non-modulated signal λ_2 and the remaining ODSB modulated mode λ_2 by an OC as shown in Fig. **10**(c). Further characterization of this scheme is performed in [153]. A significant advantage of this technique is that different modes are segregated at the output of the AWG, and only one of the two modes to be beat at the BS PD is modulated. The generation of the mm-wave takes advantage of the stability among the SCS modes. Therefore, no mm-wave band components are required at the CS. Since only two SCS modes are used for the photodetection at the BS, the degradation of the system's performance due to the chromatic fiber dispersion effect does not become serious, as confirmed in [154]. Phase noises of 50 and 60 GHz beat signals were -96.1 and -88 dBc/Hz at 10 kHz apart from the carrier, respectively.

4) Fabry-Perot lasers (FPL): In the case of FPL, different approaches have been reported to generate mm-wave signals: Carrier generation using two-mode injection-locked FPL [155], [156], directly modulated FPL and externally injected by a CW laser for sideband injection and synchronization [157], and a FPL injecting another FPL to operate as a multiwavelength source [158].

- In [155] and [156], a CW DFB laser output is modulated by a PM and MZM, respectively. The modulator is driven by the reference signal *fi* and it is connected with the FPL through a three-port optical circulator as is shown in Fig. **11**(a). The mode spacing of the FPL is 60 GHz, which coincides with the desired mm-wave frequency. When the pair of sidebands from the modulator (λ_1 and λ_2) are nearly the same as the central frequency of any two modes of the FPL, the modes are simultaneously locked, and the optical signal for mm-wave generation is ready. Using this scheme, in [159], downlink fiber transmission of three 156 Mbps signals on the 60 GHz band was demonstrated, the downlink data is introduced by directly modulating the FPL.
- More recently, in [157] a directly modulated and injected FPL was used to generate 40.2 GHz mm-wave signal carrying 2.5 Gbps downlink data. In this case, the FPL is driven by an IF signal (*fi*= 13.4 GHz), and thus there are harmonic sidebands spaced exactly at *fi* generated around each longitudinal mode of the FPL. A master CW laser source is externally injected through an optical circulator, and its wavelength λ_1 is aligned to enhance the upper third harmonic of one particular FPL longitudinal mode of λ_2 to achive the frequency-tripling desired mm-wave frequency as shown in Fig. **11**(b). The generated optical signal is then externally modulated with downlink information by a MZM.
- In [158], two FPLs having the same mode spacing are used. As shown in Fig. **12**(a), all the modes of the master FPL are modulated by an IF signal (*fi* = 15 GHz) using a MZM biased to generate an ODSB signal. This output signal is injected into the slave FPL, and by adjusting the operating temperature of the FPLs, OSSB carriers are generated at the output of the slave FPL. This output is spectrally divided to channels by an AWG, and the optical signal of each channel is injected to a gain saturated RSOA to reduce Mode Partition Noise (MPN) and modulate optical carriers with 1.25 Gbps downlink data. This scheme is very interesting, and requires further investigation on the generation of mm-wave frequencies,

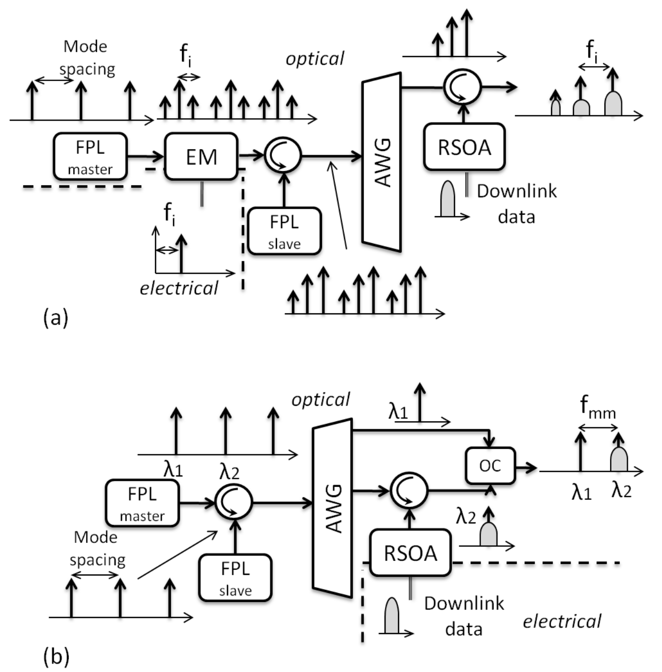

Fig. 12. Multimode light sources: (a) Master FPL locking a slave FPL at intermediate frequency *fi* with downlink external modulation using an RSOA, (b) master FPL locking a slave FPL at its mode spacing for mm-wave generation with downlink external modulation using an RSOA.

since only a pair of FPLs is necessary to generate several WDM channels to feed a high number of BSs. As shown in Fig. **12**(b), two FPLs with the same mode spacing which matches the mm-wave frequency are used to operate as a multimode light source for RoF. An AWG demultiplex two modes λ_1 and λ_2, an RSOA modulates λ_2, and an OC is used to combine λ_1 and λ_2 for downlink transmission.

D. Heterodyning Two Lasers

Multimode sources are not the only way to generate two optical tones whose beating results in mm-waves. Two lasers with emission frequencies separated by the desired frequency can be mixed to generate mm-wave signals [160]–[162]. These lasers can be phase-correlated or not, depending on the technique implemented as explained next.

1) Uncorrelated lasers: For this technique, two independent lasers with wavelengths λ_1 and λ_2 which separation equals the desired mm-wave frequency are combined using an OC. This technique has been proposed to transmit information modulating one of the laser directly [160], [161] as shown in Fig. **13**(a), or externally [41], [163] as shown in Fig. **13**(b). This scheme altough simple is suitable to generate high mm-wave frequencies with a high frequency tuning capability, however, the frequency generation flexibility is achieved at the cost of mm-wave frequency inaccuracy due to the temperature driven laser emission frequency drift and the high phase noise in the resulting mm-wave signal, which depends on the linewidths of the beating lasers [164]. Some control strategies have been proposed to address the frequency inaccuracy [160], [165], [166], while phase noise of the resulted frequency requires narrow-linewidth lasers such as external-cavity lasers [167] or fiber grating lasers [161]. In [160] the mm-wave carrier is generated by heterodyning the uncorrelated optical signals of two semiconductor lasers and, using an automatic frequency control loop to stabilize the laser's frequency difference, 140 Mbps in the band of 62-63 GHz are transmitted by directly modulating one of the lasers. On the other hand, in [161] two fiber grating lasers with linewidths below 50 kHz are beat to generate an mm-wave tone of 39.2 GHz with 100 kHz linewidth, the modulation performance was evaluated by applying 2.6 Gbps to the electrical input of one fiber grating laser. Using external modulation, in [41] two uncorrelated DFB sources (with linewidths of the order of few MHzs) demonstrated good performance to generate an mm-wave of 33 GHz carrying 7.5 Gbps by externally modulating one of the lasers with a MZM.

2) Correlated lasers: In optical sideband injection locking (OSBIL), a DFB master laser (ML) is directly modulated by a tone at *fi*, generating multiple modulation sidebands separated by *fi*. The output of the ML is split using an OC and injected to two slave lasers (SLs) which are locked to modulation sidebands (λ_1 and λ_2) separated by *fmm*. The combined signals of both SLs are coupled with a second OC as shown in Fig. **13**(c). With this technique both, frequency inaccuracy and phase noise issues are sorted out. The mm-wave signals generated through OSBIL present much spectrally purer RF carrier than with independent lasers due to the phase correlation imposed by the ML to the SLs. Frequency locking of the SLs to specific modulation sidebands guarantees mm-wave frequency stability [168]. Using OSBIL, transmission of 155 Mbps downlink signal at 64 GHz has been reported in [169], high spectral purity was achieved by obtaining a phase noise of $\leq$-90 dBc/Hz at 100 kHz offset.

The main advantage of using two optical tones separated by the mm-wave frequency is the reduction of high frequency components at the CS, and therefore, the maximum *fmm* is limited by the PD bandwidth at the BS. In OSBIL, the maximum bandwidth of the downlink signal is determined by the locking range of the modulated SL, since a high bandwidth signal causes the SL to run out of synchronization. OSBIL takes advantage of the modulation characteristics enhancement of OIL and of the phase correlation of SLs synchronized to different modulation sidebands. In contrast, the main drawbacks of this technique are the complexity and the high number of optical components compared to directly modulated laser or simple external modulation, which is compensated by the frequency flexibility that OSBIL offers.

E. Comparison of Downlink Transmission Techniques

Table **I** summarizes the advantages and disadvantages of the downlink transmission techniques in terms of the proposed figures of merit. It suggests that simple techniques operating with directly or externally modulated lasers show practical advantages as a result of the low cost and configuration simplicity. However, the mm-wave frequency is limited by the laser and EM bandwidth, respectively. On the other hand, two main groups of techniques can be easily identified, those which require mm-wave electronics to generate the downlink signals and those which do not. The latter make use

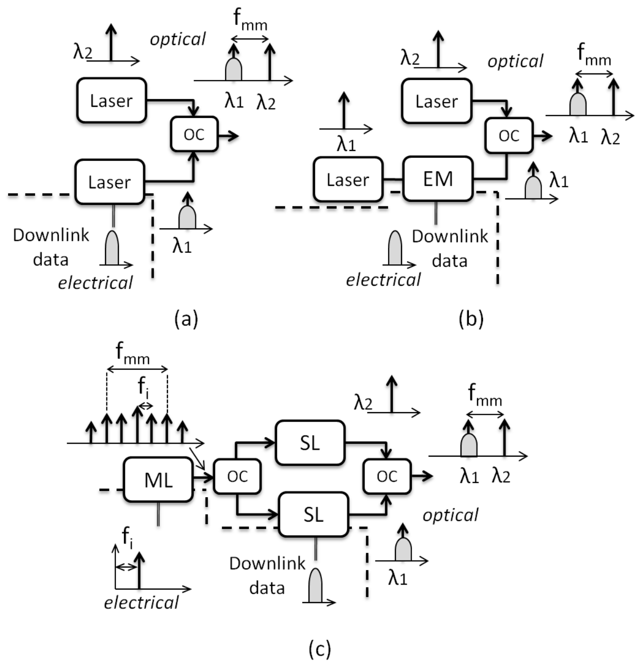

Fig. 13. Heterodyning two lasers: (a) uncorrelated lasers for mm-wave generation and direct modulation on one laser for downlink transmission, (b) uncorrelated lasers for mm-wave generation and external modulation on one laser for downlink transmission, (c) optical sideband injection locking and direct modulation in one SL

of photonic mm-wave generation which is a very attractive scheme with a capability to generate high mm-wave frequency signals with reduced power consumption, provide network configurability, and scalability in the optical domain. This implies that these techniques will be the desirable candidates for full-duplex multi-channel RoF networks.

IV. Optical Distribution Network Architectures

Current connectivity between BSs and BS controllers (which manage and control several BSs) in cellular systems relies mostly on three types of links: copper (coaxial), microwave radio, and optical fiber links. In the US, for example, coaxial links constitutes approximately 90% of the network implementations followed by microwave links (about 6%) and optical fibers (about 4%) [170]. However, the required distribution network capacity is still increasing due to the increment of subscribers and the availability of high-speed data services. To cope with such constraints, the trend is to continue the deployment of optical fiber links in dense urban and suburban locations, which are considered high traffic areas. These fiber deployments, benefit the design and planning of the future mm-wave RoF ODN. Since RoF services can coexist with existing hybrid optical-wireless solutions, and outperform the network in terms of total capacity, bandwidth allocation flexibility, and number of users [171].

The RoF ODN elements directly depend on the selected schemes at the CS and BS to downlink/uplink the RoF signals. Thus, in this section, we present the key enabling technologies that support the ODN architectures for different network scenarios.

A. Optical Fiber Type

In recent years a variety of optical fiber designs have being investigated for RoF systems, among those the most important are: Single Mode Fiber (SMF), Multi Mode Fiber (MMF), and Polymer Optical Fibers (POF). The optical fiber selection for the RoF systems depends on the network characteristics and the available resources. SMF is a fiber type that has been previously validated for indoor [172] and outdoor (long-distance) applications [173]–[175], to transport with quality mm-wave signals, however when SMF is deployed, its installation cost becomes an important issue. Thus, a number of research groups have proposed innovative approaches to design RoF systems using low-cost fibers.

The advantage for indoor applications is that, currently, many large offices and public buildings have already a network of optical fiber installed, which in most cases is MMF for carrying the Ethernet data. There are several commercial examples of transmission of broadband wireless IEEE 802.11b/g signals over MMF for in-building solutions, these systems provide a wideband Distributed Antenna System (DAS) approach to deliver effective wireless coverage for large buildings [102], however they operate at low-frequencies ($\leq$10 GHz). For mm-wave frequencies, experimentally, the OFM technique at the CS has shown its capabilities to generate mm-wave carriers with high spectral purity, and to overcome the multimode fibers modal dispersion [176]. A point to point optical link using external modulation of a laser at 1310 nm was demonstrated for radio signal transmission up to 30 GHz over a long MMF link employing the OFM method [177], in this experiment the theoretical modal bandwidth limitation of MMF was overcomed and the modulation frequency was limited by the PD bandwidth rather than by the MMF bandwidth. Furthermore, in [178] a full duplex point to multi-point RoF system over MMF to feed several BSs by a common MMF demonstrated the transmission of downlink channels carrying 120 Mbps at 24 GHz over a 4.4 Km long MMF fiber ring.

POFs have also been proposed as a low-cost alternative for short reach in-building networks [179]. The POF combines the advantages of optical fibers with ease of installation equivalent to that of copper wires. In [140], a 60 GHz RoF system that delivers 500 Mbps signal over 100 meters graded-index POF was experimentally demonstrated. Due to the multimode dispersion of POF and modal mismatch between SMF and POF, an additional 30 dB insertion loss is induced on the fiber link, which is compensated by an optical amplifier (ODN uses POF, however BS and CS equipment connections are with SMF). The effects of the fiber modal dispersion are overcomed by employing a dispersion-tolerant modulation format such as OFDM. Tolerance is further enhanced by keeping guard intervals among the subcarriers.

B. Network Topology

The network topology of RoF systems should provide high reliability, excellent flexibility, and network scalability. A complete analysis of network topologies for RoF systems is presented in [35]. Several topologies options as shown in Fig.**14** such as star (a), ring (b), multilevel rings (c), multilevel stars (d), hybrid multilevel star-rings (e), and ring-stars (f) are

TABLE I
COMPARISON OF DOWNLINK TRANSMISSION TECHNIQUES AT THE CS.

Techniques		Ref.	Advantages	Disadvantages
Directly modulated Laser	Direct Modulation	[96-103]	Low cost and simplicity.	mm-wave frequency limited < 30GHz. Poor transmission integrity due to the non-linearities, noise, and frequency chirp.
	Direct Modulation with OIL	[104-111]	Enhanced Modulation laser bandwidth (> 80GHz). Commercially available components. Improved transmission integrity by reduction of laser non-linearities and chirp.	Mm-wave frequency electronics required . High power consumption due to extra laser required and setup insertion losses.
Externally modulated Laser	External Modulation without OFM	[113,114] [116-122]	Mature technology. Broad bandwidth modulators allow mm-wave frequency operation. Flexibility on modulation schemes (OSSB/ODSB).	mm-wave frequency electronics required . High cost for high frequency operation.
	External Modulation with OFM	[47,23,115] [123-141]	High frequency signals are generated with lower frequency electronics and EM. Flexible configurations provide high downlink transmission scalability.	mm-wave frequency and bandwidth limited by EM harmonic generation efficiency (Low OFM order). Optical filters required to eliminate undesired harmonics.
Multimode light sources	Dual-mode laser	[142-143]	mm-wave frequency electronics and broad bandwidth lasers are not required reducing cost and power consumption. Possibility to tune mm-wave frequency.	Spectral purity and frequency accuracy limited by laser bias current and temperature controls. Single WDM channel generation. Low scalability due its customized design.
	Mode Locked Lasers (MLL)	[22] [145-150]	It is possible not to use mm-wave frequency electronics. Possibility to generate multiple WDM channels.	Spectral purity and frequency accuracy limited by MLL design. Optical filters required for ODSB.
	Supercontinuum Source (SCS)	[62] [151-154]	mm-wave frequency electronics and broad bandwidth EM are not required. High scalability, one SCS can be used to generate multiple WDM channels.	Expensive and bulky but it is shared among many WDM channels. Because of the AWG: mm-wave frequency configurability is achieved with external oscillators.
	Fabry-Perot Lasers (FPL)	[155-158]	mm-wave frequency electronics and broad bandwidth lasers are not required. High scalability, it can be used as a multicarrier to generate several WDM channels.	Mode selection depends on the FPL free spectral range. Long cavity FPL are required.
Heterodyning two Lasers	Uncorrelated Lasers	[41] [160-167]	High mm-wave frequencies are achievable avoiding high frequency electronics and broad bandwidth optical devices. High scalability since reference laser can be used for different channels.	Spectral purity and frequency accuracy limited by laser linewidth and temperature controls. Low phase noise requires narrow linewidth lasers.
	Correlated Lasers	[168-169]	High mm-wave frequencies are achievable avoiding high frequency electronics and broad bandwidth optical devices. High spectral purity, frequency accuracy and flexibility.	Complex and expensive setup and controls. External oscillator required for the ML.

compared in terms of link distance, reliability and availability of the network. This research demonstrates that a multilevel-ring topology provides the best performance for large RoF networks where thousands of BSs are connected to the CS. The second best option is the ring-stars topology, which presents better scalability because it allows a relative easiness for the network's growth when a new BS is required at a certain location. The star topology presents the worst reliability and the longest fiber link distance, any failure of one of the optical paths would disable a BS. In the star topology the BS does not have a capability to route signals to other directions unless a protection scheme is implemented. The ring topology shows the shorter fiber link distance with good reliability and availability performance. The better performance of ring topologies is due to the fact that the BS is assumed to have a capability to use other optical paths to transmit and receive signals if a failure occurs. This protection scheme does not require extra fiber installation but extra optical components in the BS [180].

A star topology for an RoF system is presented in [181]. An important feature of this architecture is the form of WDM technology employed. The CS connects each BS using a MUX/DEMUX, each BS is connected directly to the CS by independent optical paths, and a dedicated wavelength pair for frequency full-duplex operation is assigned. However, in order to reduce the number of light sources, the MUX/DEMUX can be replaced by a passive optical splitter, downlink signals for different BSs can be transported in the same wavelength using SCM, in that case, the uplink could operate using TDM as the standardized PON concepts. The combination of SCM with WDM maximizes the infrastructure transparency, increasing network scalability as it was demonstrated using a hybrid multilevel starts (tree-star) topology presented in [182]. On the other hand, in ring architecture operating with a WDM scheme each BS is provided with an OADM to select the corresponding channel. In order to reduce the number of wavelengths required by the network, a combined SCM and WDM scheme can also be used. Under this approach, each ring is assigned with a unique optical signal, and the OADM is replaced with a passive OC to power-split the WDM downlink optical signal containing SCM signals assigned to different BSs within the ring [63], [183].

C. Optical Interfaces

In the ODN, optical components between the CS and the BSs should be chosen to work properly at the designated

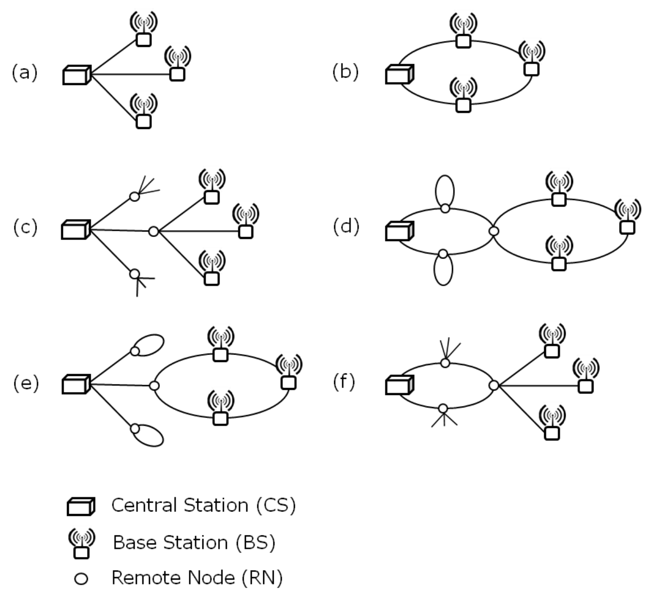

Fig. 14. ODN Topologies: (a) Star, (b) ring, (c) multilevel stars, (d) multilevel rings, (e) hybrid multilevel star-rings, and (f) hybrid multilevel ring-stars

operating optical frequency and with the adequate bandwidth. This is especially important in the case of optical filters and optical wavelength multiplexers to downlink/uplink signals in the network. Depending on the downlink transmission technique, and the BS configuration, additional optical filtering is required to avoid interference and maintain the transmission integrity of the system. Optical filters are critical in achieving tight signal bandwidths and center wavelength detuning with high spectral efficiency. Technologies that have been used to implement tunable optical band pass filters with these characteristics include Fiber Bragg Grating (FBG) [184], thin-film filters [185], and optical Micro Electro-Mechanical Systems (MEMS) devices [186]. In [187] a study of optical filtering techniques is presented for DWDM channel allocation of broadband mm-wave RoF signals in ODSB format. Experimental results revealed that the dispersion effect of FBG add/drop filters is a critical parameter for the network's design [187]. In order to reduce dispersion effects introduced by the filter, a novel scheme adopting the OSSB filtering technique was proposed taking advantage of a square and narrow-band response of a FBG filter. For MMF networks, a full-duplex MMF-WDM ring for the distribution of broadband wireless services was successfully demonstrated in [178]. It used wavelength selecting multimode OADM modules based on narrowband MMF Bragg gratings.

A custom-designed optical ODN component to provide network flexibility had been proposed in [67], it consisted of a special optical interface capable of dropping and adding DWDM interleaved channels at a BS. Experimental results confirm the viability of the interface in ring/bus network architectures.

D. Optical Amplification Technology

Optical amplifiers compensate for propagation losses in long distance links and branching losses in the access network. In other words, amplification allows distributing an optical signal from the CS over larger distances towards the BSs and increases the number of BSs that can share a signal resource when a power-splitting scheme is used. These capabilities are essential for network flexibility and scalability, and they have a high impact on determining the transmission integrity. In [50] a comparison study between Distributed Raman Amplifiers (DRA) and Erbium Doped Fiber Amplifiers (EDFAs) amplification technologies in WDM RoF networks is performed. In the experimental setup, amplifiers are used for boosting power in the downlink and for pre-amplification in the uplink for an RoF system at 1550 nm using OSSB scheme. Results revealed limitations on both, pre-EDFA and boost-EDFA, amplification schemes. For boost-EDFA, gain saturation limits the launched optical power per channel. While in pre-EDFA, Optical Signal to Noise Ratio (OSNR) is the dominant limiting effect due to the small amplifier input signal. In contrast, DRA exhibited a better performance by suppressing the gain saturation effect in the uplink and improving noise performance in the downlink, compared with its EDFA counterpart. Additionally, DRA has a simpler design as amplification is achieved by taking advantage of the fiber in the ODN and no doped fiber is required. Despite the advantages of DRA, its implementation requires exhaustive analysis to model all Raman interactions since not only the launched pumps contributes to amplification, but also power exchange can result between some adjacent channels carrying information, causing cross-talk and leading to signal degradation [188].

More recently, in [51] a power penalty analysis was performed for a WDM RoF system using direct and external modulation with either EDFA or Semiconductor Optical Amplifier (SOA). Four different system setups were proposed using different combinations of laser modulation (external or direct) and amplification technologies (EDFA or SOA). Optical simulations were used to demonstrate a small power penalty of 2 dB between the direct and the external modulation with an EDFA. But a large power penalty of 27 dB was reported depending upon the choice of the optical amplifier EDFA or SOA. Better performance was found when using SOA as the optical amplifier in the RoF network. When employing SOA, it should be considered that its gain saturation can increase the signal distortion, which becomes more critical as the modulated signal bandwidth and the number of WDM channels increase [189], in contrast to an EDFA which has recombination lifetimes of the order of milliseconds leading to negligible signal distortion for multichannel schemes [190].

E. Channel Spacing - Optical Spectra Usage

A strong multiplexation candidate to support all BSs in the ODN of an RoF system is WDM. As presented in Section II, for downlink transmission techniques, at least two optical tones are required per BS, whose spectral spacing matches the desired mm-wave frequency. Thus, frequency spectral efficiency becomes an issue because the bandwidth of the mm-wave signal is much narrower than the mm-wave carrier causing that the optical spectrum cannot be fully utilized. Although there are reports of DWDM with optical channel spacing up to 50 GHz [191], Optical-Frequency-Interleaving

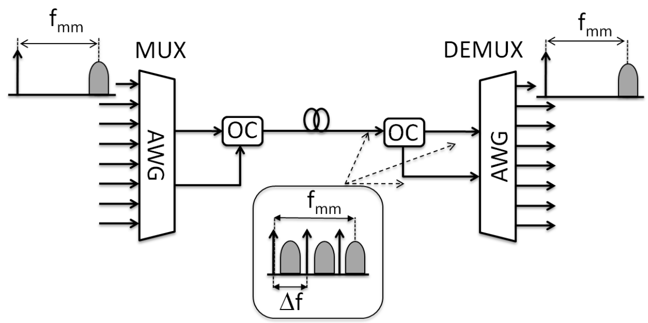

Fig. 15. Interleaving technique using 2xN AWG and an OC.

(OFI) technique is preferable to increase spectral efficiency with optical channel spacing ≤25 GHz to support a higher number of BSs operating at mm-wave frequencies ≥50 GHz in an RoF system [192].

In [193], a MUX/DEMUX frequency-interleaved DWDM RoF signals using FBG optical filters for 36 GHz-band was demonstrated. Three WDM channels, with OSSB modulation, spaced 24 GHz where interleaved with their side bands. A capacity analysis, assuming 30 nm bandwidth of an EDFA, revealed that the technique is capable of increasing the maximum number of channels that can be accommodated by almost 75%.

By using EMs in 60 GHz-band RoF systems, the smallest channel spacing achieved is 200 GHz for ODSB [123] modulation format and 100 GHz for OSSB [113]. By using OFI, the optical spectral efficiency can be improved four times for the case of 25-GHz spacing as reported in [192]. The original concept of the OFI setup used a high-finesse Fabry Perot etalon and an optical circulator connected to an AWG with two inputs and *N* outputs for demultiplexing and the same array, inverting AWG and circulator direction, can be used for multiplexing. OFI technique was demonstrated for 25 GHz separated two ODSB channels modulated by a 60 GHz mm-wave. However, this scheme presented some difficulties to control the desired frequency of the FP filter at the remote access node without monitoring and feedback.

Improvements on OFI techniques for DWDM RoF systems using AWG have been reported in [194]. They used a narrow channel spacing AWG to simplify the configuration by removing the high-finesse FP filter required in [192]. The DEMUX consists of an OC and a *2xN* AWG, which has 2 input ports and *N* output ports. The configuration of the MUX is applicable to that of the DEMUX if the direction of the signal transmission is reversed as shown in Fig. **15**. The two input ports at the DEMUX are separated by the frequency interval of the desired mm-wave RoF signal f_{mm}, and the *N* output ports are separated equally by the DWDM channel Δf. Experiments demonstrated the device performance for its use in a realistic commercial implementation [40].

F. Protection Scheme

Conventionally, in WDM metropolitan networks, dual rings for 1+1/1:1 schemes have been employed for protection against fiber failure [89], [90], [195]. Under 1+1, a copy of the data signal is transmitted simultaneously on a working and on a protection link. The receiver selects the copy with better signal quality. In contrast 1:1 sends a copy of the data signal on a working link only, while the protection link is reserved to cases when the working link fails. The protection link in 1:1 can either be reserved for restoration purposes or can be used to carry other channels. Thus, unlike 1:1 protection scheme, 1+1 does not allow protection link to carry any other channels. Both schemes induce to add extra optical components, however in 1+1 the expenses of installing extra fiber increase the overall ODN cost.

For WDM systems, a single-fiber self-healing ring network configuration using bidirectional OADM has recently emerged to reduce the required amount of fiber by half and duplicate the network's capacity [92], [180]. This can be achieved by the use of optical switches to change transmission and reception directions after a fiber failure, thus the same optical link is used for network restoration.

Recently, a cost-saving bidirectional OADM for a single-fiber self-healing access ring network for metro core WDM systems was proposed and demonstrated in [196]. However, the proposal requires a total of 16 optical components per remote station to operate, which is still very complex for RoF networks where thousands of BSs are needed. Furthermore, a full multilevel WDM hybrid star-rings topology is presented in [197] to support high capacity RoF systems using a single-fiber self-healing scheme; all sub-rings are connected by star topology using a centralized AWG MUX/DEMUX at a RN. In [53] a self-healing WDM multi-rings architecture was demonstrated, sub-rings are connected by several dynamic bidirectional OADM located in RNs, each BS in the sub-ring uses an optical-electrical-optical transceiver structure to connect downlink from the CS to cascade with other BSs within the same sub-ring.

On the other hand, for power splitting PON systems, a self-protected network in a ring-architecture using a single-fiber-path has been demonstrated in [198]. The physical layer of each Optical Network Unit (ONU) is constructed by a 2x2 OCs and two line termination or double transceivers that in case of failure, can route optical signals to one or other direction in the ring. The architecture can be applied in an RoF system by using the ONU technology described within the BSs.

G. Comparison of ODN Architectures

Table **II** summarizes the advantages and disadvantages of the ODN architectures in terms of the proposed figures of merit. Three main factors are identified for the appropriate selection of these technologies: 1) Environment scenario: if the network operates in an indoor or outdoor environment, meaning short and long link distances, respectively. 2) Design: if the network is passive or active (in terms of amplification and configurability). 3) Capacity: operating mm-wave frequency, bandwidth, and number of users supported per BS. Thus, ODN architectures adaptable to the network operator needs will be the key technologies of mm-wave frequency RoF deployments.

TABLE II
COMPARISON OF ODN TECHNOLOGIES.

Technologies		Ref.	Advantages	Disadvantages
Fiber type	SMF	[172-175]	High bandwidth limited by chromatic dispersion and the number of channels is limited by non-linearities. Capable to transmit high quality signals over short and long distances (indoor and outdoor).	High cost of installation. Long time to repair in outdoor environments.
	MMF	[102] [176-178]	Available on existing buildings and offices to carry Ethernet data.	Bandwidth and transmission integrity limited by modal dispersion.
	POF	[140,179]	Low cost and simple installation.	Bandwidth and transmission integrity limited by modal dispersion and attenuation. Available only for indoor applications. Short distance links.
Topology	Star	[35,181, 182]	High available bandwidth (one fiber per link). Simple, a central optical component for distribution.	Expensive, long fiber length in the network. Poor availability only one path connecting CS to BS.
	Ring	[35, 180,183]	Cost-effective, short fiber length in the network. High availability two optical paths available in the ring.	An add/drop optical component required for each BS. Unfair signal integrity delivered per BS when WDM/SCM scheme used due insertion loss across the network.
	Ring-star	[35]	High scalability, easy network expansion.	RN required for each star.
	Multi-rings	[35,63]	High scalability, easy network expansion. High availability in main ring and sub-rings.	RN required for each sub-ring and add/drop optical component per each BS.
Amplification	EDFA	[50-51, 190]	Simple implementation.	Transmission integrity limited by noise and non linearities for high number of wavelengths.
	Raman	[50, 188]	High bandwidth. S,C,L and U band (130 nm). Low noise.	Reliability limited by laser pumps.
	SOA	[51, 189]	Low-cost component.	Transmission integrity limited by noise and non linearities in multi-wavelength amplification.
Channel spacing	WDM	[113,123]	Low-cost optical components required. Robust to fiber non-linearities because of the broad channel spacing.	Low spectrum efficiency. Bandwidth limited by channel spacing.
	DWDM	[191-194]	High spectrum efficiency. Interleaving techniques allowing channel spacing up to 12.5 GHz.	High cost optical components due to lower specification tolerances. Transmission integrity more sensitive to fiber non-linearities due narrow channel spacing.
Protection scheme	Protection 1+1	[89,90, 195]	Simple implementation. High availability, protection path always available.	High cost , duplication in the fiber link and switching components.
	Single fiber self healing	[53,92, 180] [196-198]	Low cost, no additional fiber installation required.	Lower transmission integrity performance on restoration mode.

V. BS CONFIGURATIONS

The main function of the BS in an RoF system is to transport the mm-wave signals to and from the user terminals (MTs) within a coverage area. Since the BSs are connected to the CS over optical fiber, it is imperative to provide the BS with an electric-to-optic converter in the transmission path, and an optic-to-electric converter in the receiver path. The key for making an mm-wave RoF system practical for commercial implementation is the deployment of a low-cost and "green" BS by installing functionally simple and compact equipment with minimal optical and electronics inventory and with the lowest possible energy consumption. Several BS configurations using advanced technologies have been proposed in order to achieve this goal. BS uplink configurations can be divided into two main categories: 1) BS with a laser installed and 2) Laser-free BS. When a laser is installed at the BS, it can be directly modulated with uplink data or an external modulation scheme can be selected by adding an EM. When the CS is providing an optical signal for uplink transmission, the BS does not need a light source installed. Under this scheme, the optical signal from the CS can arrive as a non-modulated optical tone or a modulated signal to the BS, the latter requires an erasing process to reuse it and modulate it with uplink data before it can be re-transmitted back to the CS.

In many cases, the wireless uplink signal received from the MT at the BS is first down-converted to baseband or low-frequency IF subcarrier. In this case, an electrical Down-Conversion Circuit (DCC) is required; it can be composed by an envelope detector or an electrical LO, enabling in this way a low-cost electric-to-optic converter for direct transmission of the uplink channels. However, the LO at the BS increases its complexity, therefore several schemes of remote LO delivery have been proposed [199], [200]. On the other hand, if the DCC is not implemented at the BS, then the mm-wave signal from the MT modulates directly the BS transmitter, and the down-conversion process of uplink data is performed at the CS. This configuration requires that the optical component assigned for uplink transmission, operates at mm-wave frequencies, which increases their cost and complexity [201]. The decision for choosing to down-covert or not the mm-wave signal from the MT at the BS depends on the overall network characteristics and requirements.

In this section, we will refer to the downlink signal as a signal composed by two wavelengths: λ_1 carrying downlink data plus λ_2 as the reference tone for mm-wave generation. λ_3

is referred as an extra non-modulated signal transmitted from the CS to the BS for uplink purposes. This nomenclature is used from Fig. **16** to Fig. **19**.

A. BS Using a Laser for the Uplink

1) Base station using directly modulated laser: In a conventional BS configuration, as is shown in Fig. **16**(a), the downlink signal coming from the CS is demultiplexed and received in an mm-wave bandwidth PD at the BS when using WDM technology. On its side, the uplink optical signal is generated by directly modulating a laser, the WDM component multiplex the signal towards the CS. The laser installed at the BS can be a Vertical-Cavity Surface-Emitting Laser (VCSEL) [202] or a DFB laser [203], and it can be modulated by baseband or intermediate down-converted signals depending upon the scheme selected. For mm-wave frequencies higher than 30 GHz, direct modulation can be a difficult and expensive choice because the modulation bandwidth of the laser [98]–[100], thus, the implementation of a down-conversion process from mm-wave frequencies to baseband or IF signals is necessary (DCC). Then, this BS configuration requires two independent optical components (laser and PD), and it needs a DCC for the mm-wave signals from MT. For low frequencies, simple and cost effective transceiver architecture including laser and PD had been proposed in [204], the same approach can be utilized for mm-wave frequencies to make this type of configuration more efficient.

A clear disadvantage of having a laser installed at the BS is its fixed operation wavelength, which reduces network flexibility. In order to overcome this limitation a FPL installed in the BS is proposed as depicted in Fig. **16**(b). For this configuration, a non-modulated optical tone λ_3 along with the downlink signal is transmitted from the CS to the BS. A three port optical circulator at the input of the BS directs signals to a tunable FBG filter, which is used to reflect portion of the non-modulated tone to the FPL while it allows downlink signal to be detected by the PD. One of the longitudinal modes in the FPL is selectively injection locked by λ_3 and a single-mode lasing to the appropriate uplink channel is realized [205]. The remotely injection-locked FPL is directly modulated for uplink transmission.

Another approach of the BS using directly modulated laser, is the photonic active integrated-antenna concept, which consists on the integration of photonic devices as lasers [150], [206] and PDs [22] with antennas including resonating matching circuits. These optoelectronic integrated circuits can lead to superior performance that exceeds the limits of conventional modular components.

2) BS using externally modulated laser: For an external modulation scheme, MZM, PM, or an EAM is required at the BS in combination with a laser. This configuration is not typical, because of the cost added by the EM; even when the DCC for the mm-wave signal coming from the MT can be avoided with the use of a broad bandwidth EM, the cost of the EM is still a drawback because it increases with the operating frequency. In this configuration, a WDM component at the input of the BS is used to demultiplex downlink signal to the BS mm-wave bandwidth PD and multiplex the uplink optical signal from the EM output back to the CS as presented in Fig. **16**(c). Presently, several approaches integrating the laser and the EM in a single component are proposed. The EAM monolithically integrated with a DFB is the most practical device, because of the high coupling efficiency achievable in the integrated structure. This leads to a high output power of the modulated signal, which gives it an advantage over other modulators such as MZM, and contributes to reduce the system size and cost [207]. Wavelength reconfiguration features can be available by using a hybrid integrated module consisting of a wavelength tunable laser and a semiconductor MZM [208], although commercial components performing this operation are available in the market, a high number of BSs will represent a significant network cost increase.

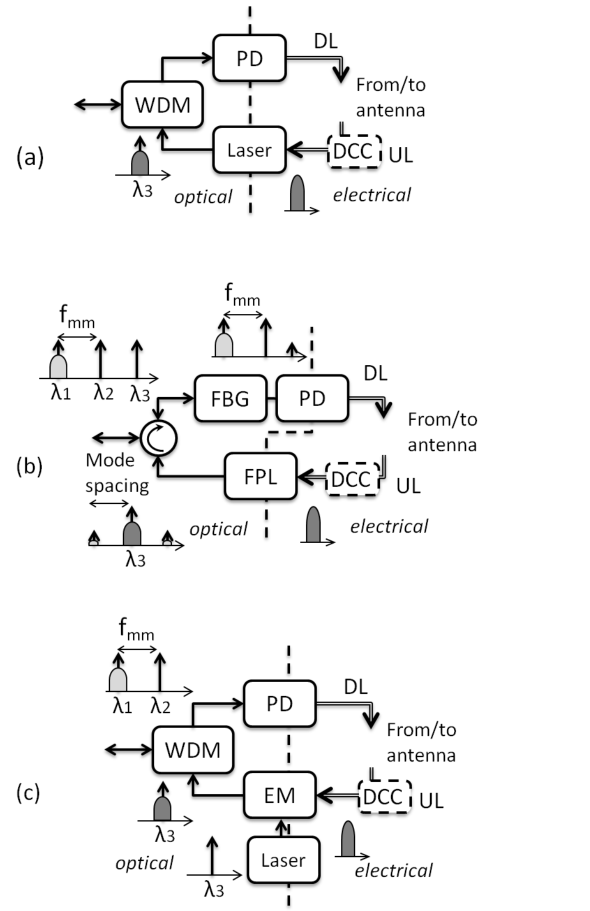

Fig. 16. BSs with laser. (a) Fix wavelength laser at the BS, (b) Tunable FPL at the BS, (c) Externally modulated laser (UL: uplink, DL: downlink, DCC: Down-Conversion Circuit).

B. Laser-Free BS for Uplink

So far, considerable effort has been done to simplify the BS design combining the use of external modulation and custom-designed optical components, such as looped-back AWG, multiport circulators, and FBG, to achieve functionalities such as OADM and optical carrier reuse [209]. The major advantage of removing the laser from the BS is that the wavelength assignment and resource monitoring can be done in a centralized way at the CS. Several laser-free BS schemes have been proposed, in this subsection we present the most promising configurations.

1) EM at the BS for uplink: A configuration used to avoid a laser in the BS consists of an EM that modulates an optical signal transmitted from the CS. This configuration can be supported by multi-wavelength light source with an AWG at the CS and it can be implemented at the BS using two different configurations.

- Optical signals from CS are filtered out and transmitted to the BS, one is the downlink signal and the second one is a non-modulated optical tone to be used for the uplink transmission. At the BS, a WDM component separates downlink signal to the BS mm-wave bandwidth PD and the non-modulated signal λ_3 to EM input as presented in Fig. **17**(a). λ_3 is externally modulated with uplink data and transmitted back to the CS. An OC can also be used instead of the WDM component as reported in [113], [173].
- At the BS, a three port optical circulator directs the downlink signal to a FBG filter, the downlink signal is filtered to the BS mm-wave bandwidth PD, while portion of the reference tone λ_2 is reflected back to the optical circulator which directs it to EM input [209]. The EM modulates λ_2 with uplink data and transmits it back to the CS as shown in Fig. **17**(b). The advantage of this configuration is that the non-modulated tone of the downlink signal is reused for uplink transmission and no extra tone is required.

In both configurations presented above, the EM can be either a MZM modulator with down-converted uplink data (requiring the DCC) [103], [173], or an EAM modulated with the uplink mm-wave signal coming from MT [58], [113].

2) RSOA at the BS for uplink: The architectures incorporating RSOAs located at the BS for the uplink transmission allow dynamic network reconfiguration through the wavelength reassignment to different BSs [55], [60], [210]. The RSOA replaces WDM light source at the BS, its multi-functionalities, such as colorless operation, re-modulation, amplification and envelope detection, make the BSs implementation more compact, less complex and cost effective, improving the utilization of wavelength resources in the RoF network with centralized light sources. RSOA can be used in two different ways: 1) reusing the downlink signal or 2) using an extra non-modulated optical tone generated at the CS as shown in Fig. **18**(a-b) and (c), respectively. When an RSOA is used at the BS, the mm-wave signal from the MT needs to be down-converted to meet the electrical bandwidth limits of the RSOA. Three BS configurations using RSOA are presented:

- When reusing the modulated λ_1 downlink signal, an OC is installed in the BS to split the incoming optical signal. One optical path carries a portion of the downlink signal (e.g. -3dB) to BS mm-wave bandwidth PD, while a second path distributes the rest of the power of the downlink signal to the RSOA, which erases the downlink information, and modulates the signal with uplink data and reflects it back to the CS as presented in Fig. **18**(a). Thus, only one wavelength is carrying bidirectional data between the CS and BS. The RSOA acts as both, an optical saturator and a modulator [60], [211].

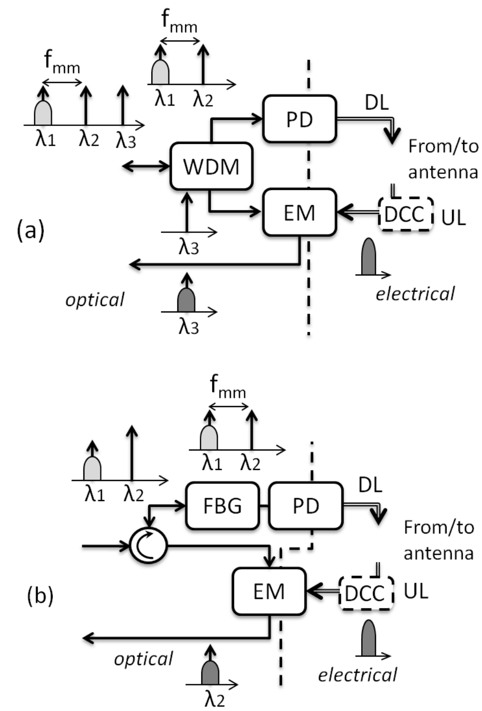

Fig. 17. BS with EM. (a) External modulation of an non-modulated tone transmitted from CS for uplink, (b) Reuse of downlink signal reference tone for uplink transmission, (UL: uplink, DL: downlink, DCC: Down-Conversion Circuit).

- On the other hand, when reusing the non-modulated reference tone λ_2 from downlink signal, a three port optical circulator is used at the input of the BS to direct downlink signal to a FBG filter, the downlink signal is filtered to the BS mm-wave bandwidth PD, while portion of the reference tone λ_2 is reflected back to the optical circulator which directs it to RSOA input [209]. The RSOA modulates λ_2 with uplink data and transmits it back to the CS as shown in Fig. **18**(b). Note that in this configuration RSOA is acting as modulator only.
- A third configuration using RSOA is when it operates with an extra non-modulated optical tone from the CS (λ_3), under this configuration, a WDM component demultiplex downlink signal to the BS PD and λ_3 to RSOA as shown in Fig. **18**(c) [181].

RSOAs will play an important role in future optical communication links and have been continuously investigated through simulations [211], and experiments [212] aiming to find the best internal RSOA parameters such as the length and optical confinement factor to increase bandwidth and linearity.

3) EAT at the BS: A single optical component approach at the BS is the Electro Absorption Transceiver (EAT) depicted in Fig. **19**(a) [183]. This scheme utilizes the EAT that works simultaneously as an mm-wave bandwidth PD for downlink data and as an optical modulator for the uplink at different wavelengths. Since the cost of the BS is the most significant in an RoF system, EAT should be cheap, reliable, small and lightweight with low power consumption. The transceiver receives two optical signals from the CS, downlink which is absorbed, and a non-modulated signal λ_3 from CS, that is

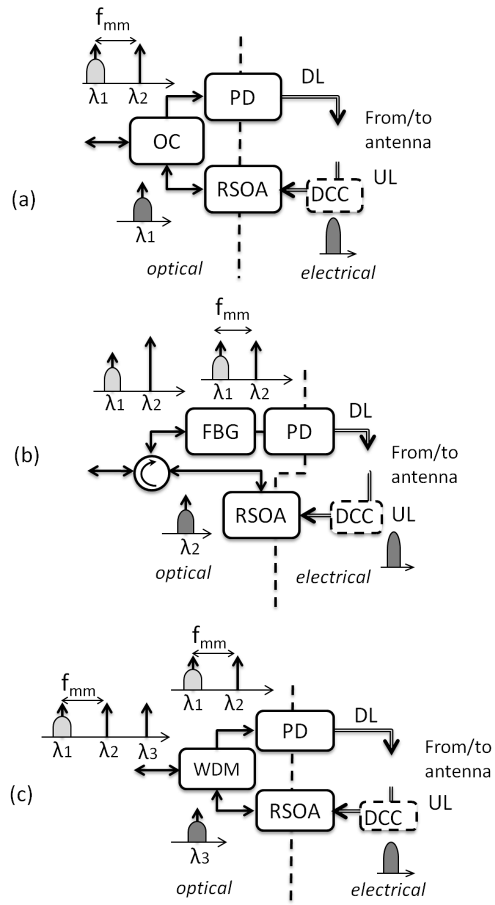

Fig. 18. Laser-free BS. (a) RSOA reusing downlink optical signal at the BS for uplink, (b) RSOA using a non-modulated optical tone from CS for uplink, (c) Reuse of downlink signal reference tone for uplink transmission (UL: uplink, DL: downlink, DCC: Down-Conversion Circuit).

modulated at the BS with uplink data. The essential characteristic of this device is that it not only acts as a modulator but also as a PD [32], [183], [201]. The EAT has an optical input to collect both, downlink modulated and remote non-modulated signals. In [213], the EAT is proposed as a single component at the BS, not requiring amplifiers or power supplies to be used effectively for picocells. Later on, in [183] a dual-lightwave approach is used in conjunction with an EAT to simultaneously achieve optimum modulation and detection performance. A 60 GHz EAT module was developed in [32], [201]. The EAT module has individual RF input and output ports, each one of them with impedance-matching circuits that enhance detection and modulation efficiencies at 60 GHz, avoiding the requirement of frequency down-conversion at the BS for uplink mm-wave signals from MT.

4) REAM at the BS: The Reflective-EAM (REAM) consists of an EAM with a reflection layer. The device has a low power requirement and a low insertion loss, little sensitivity to optical polarization and inherent integration capability with other components. Full duplex capability is achieved by the use of two REAMs as demonstrated in [214], [215], one REAM is configured to operate as a PD for detection of the downlink signal, while the second one is biased to function as

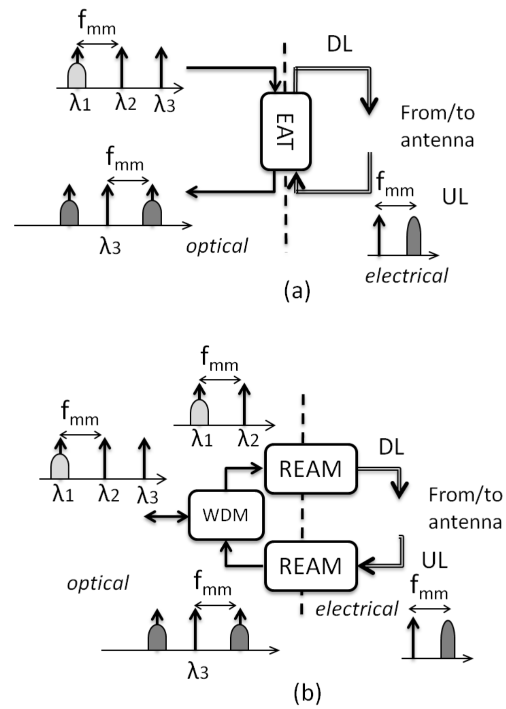

Fig. 19. Laser-free BS. (a) Electro Absorption Transceiver (EAT) at the BS and (b) Reflective Electro Absorption Modulator (REAM) (UL: uplink, DL: downlink).

an EM, modulating and reflecting a light remotely delivered throughout the network from the CS to the BS. The REAM employed in [214] has 11 GHz RF modulation bandwidth over its working bias range, and therefore, a DCC has to be used before modulating the uplink REAM.

A 60 GHz REAM was designed in [216], and used for a bidirectional optical signal distribution system with 3 Gbps in [217]. For this configuration, the BS requires a WDM component to demultiplex the downlink signal to REAM configured as mm-wave bandwidth PD, and the non-modulated optical tone λ_3 from the CS to an REAM operating in reflective modulator mode as shown in Fig. **19**(b). In this case, the uplink signal from MT directly modulates the REAM avoiding the use of a DCC at the BS.

C. Comparison of BS Configurations

Table **III** summarizes the advantages and disadvantages of the BS configurations in terms of the proposed figures of merit. It is foreseen that a high number of BS are required for an RoF network operating at mm-wave frequencies, therefore the laser-free BS configurations have a clear advantage over the others configurations in terms of scalability and power consumption. Another key feature of the BS configuration is the avoidance of mm-wave electrical circuits. Thus, BS configurations capable of performing optical-electrical-optical conversions for downlink reception and uplink transmission using a single integrated photonic transceiver are considered as key enabling components to support mm-wave wireless networks.

TABLE III
COMPARISON OF BS CONFIGURATIONS.

BS Technology		Ref.	Advantages	Disadvantages
Laser at BS	Directly modulated laser	[98-100] [202-204]	Simple implementation. No need for remote tone generation.	Electrical DCC required for uplink transmission. Low network scalability and configurability since a fix wavelength is assigned per BS. Precise temperature and bias control is required for accurate emission frequency .
	Remotely configurable FPL	[205]	Relatively high scalability and configurability, the same BS can setup to emit at different wavelengths. OIL provides enhanced modulation laser bandwidth and improved transmission integrity by reduction of laser non-linearities and chirp.	Electrical DCC required for uplink transmission. Remote tone has to be generated and distributed, unless part of the downlink signal is used.
	EM	[207-208]	Monolithically integration of EM and laser. Capability to avoid a DCC at the BS if broad bandwidth EM is used.	High cost optical components. EM or DCC is required. High power consumption due to EM insertion losses. Low network scalability and configurability since a fix wavelength is assigned per BS.
Laser-Free BS	RSOA	[55,60] [209-212]	High scalability and configurability. BS is wavelength agnostic and it has capability to reuse the downlink optical signal for uplink transmission.	Uplink transmission integrity limited by RSOA efficiency. Electrical DCC required for uplink transmission.
	EM	[58,103,113 ,173,]	Low power consumption at BS for uplink transmission. High bandwidth.	High cost optical component (EM) per each BS or a DCC. Uplink transmission integrity limited by EM insertion losses.
	EAT	[32,183,201 ,213]	High scalability and configurability. BS is wavelength agnostic. Single component.	High cost optical component (EAT) per each BS. RF output power and signal power of downlink received signal limited by EAT efficiency.
	R-EAM	[214-217]	High scalability and configurability. BS is wavelength agnostic. It has capability to avoid a DCC at the BS if broad bandwidth EAM is used.	High cost, two EAM required for full duplex operation. RF output power and signal power of downlink received signal limited by EAM efficiency.

VI. RESEARCH OPPORTUNITIES

Considering this review, there are still a tremendous number of opportunities available to provide flexible technologies that adequately assist the overall network requirements and the high-priority figures of merit of each subsystem. In this section we review existing challenges and present our vision of research directions.

- Dynamically-reconfigurable RoF systems require the adequate implementation of reconfigurable multi-wavelength light source at the CS, the design of cost effective RNs at the ODN for seamless network control, and efficient techniques for remotely configurable BSs.
- RoF system sustainability mandates every effort to reduce the total power consumption. Therefore, the energy efficiency analysis of the different downlink transmission techniques is a relevant challenge. This requirement will drive the characterization of link budgeting, including an exhaustive study of power consumption of the different BS configurations.
- High-throughput mm-wave wireless communications has been demonstrated in RoF experimental systems. However, for commercial deployment, the study of different modulation and transmission schemes is mandatory to reduce implementation costs.
- An available and reliable RoF network necessitates the implementation of a simple (with the minimum potential failure points) self-healing architecture with monitoring capabilities.
- The design of an mm-wave RoF access network is a very knowledge-rich domain, due to the particularities and complexity of each network subsystem and their interconnection, as well as the emerging nature of the art. Therefore, it is imperative to develop an integral design methodology. It must adequately assist the overall network requirements and the high-priority figures of merit.

Table **IV** presents what we consider the most important technical opportunities classified by figure of merit and subsystem, also the opportunities from the overall network point of view.

VII. CONCLUSIONS

We have studied several available technologies to support key functionalities at the CS, ODN, and the BS of an RoF land network. Much progress has been clearly made on the development and experimental demonstration of network

TABLE IV
SUMMARY OF RESEARCH OPPORTUNITIES FOR RoF SYSTEMS

	Figures of Merit	CS	ODN	BS	RoF System
Research Opportunities	Cost and Simplicity	Cost effective mm-wave generation technique. - Multiple light sources	Simple architecture. Manageable and easy to maintain.	Single component, with photonic and electronic subsystems using cost-effective materials.	Practical cost models. -Overall cost optimization methodology.
	mm-wave Frequency and Bandwidth	Integration of photonic components for mm-wave generation. -Monolithic integration of multiple CW lasers.	Further characterization of optical interfaces with mm-wave bandwidth. - Study of the frequency band limitation due to cascading different optical components.	Broadband single component with photonic and electronic subsystems.	Analysis of the overall system bandwidth, and study of the spectral purity degradation in the RoF network with different CS, ODN, and BS configurations.
	Spectral-Purity and Frequency Accuracy	Low phase noise downlink techniques using remote LO delivery. - Development of narrow linewidth lasers. - Frequency difference stabilization. - Generation techniques with correlated tones.	Enhanced optical interfaces to exploit optical interleaving techniques. - Reduction of non-linearities due to fiber and amplifiers.	Efficient configuration for non-linearities reduction.	
	Transmission Integrity	Robust modulation and channel coding schemes.	Characterization of optical amplification technologies for multi-channel RoF systems. - Analysis of the non-linearities in the ODN.	Low-noise configuration.	Quality of service control mechanisms. - Analysis of transmission integrity degradation. - RF and optical power management to optimize transmission integrity.
	RF Output power and signal power	Downlink techniques with strong signal strength remote delivery.		High efficiency mm-wave photodiodes.	
	Scalability	Downlink technique with tunable multi-wavelength light source.	Easily configurable RN technology.	Flexible and remotely configurable.	Scalable multiplexation schemes and modulation formats. - Effects of the scalability format on the system transmission integrity.
	Power Consumption	Energy efficiency analysis of the different downlink transmission techniques.	Optimization of optical amplification technologies.	Study of power consumption of the different BS configurations.	Power efficiency assessment methodology.
	Reliability and Availability	Field deployable downlink technique with the minimum potential failure points.	Simple self-healing architecture with monitoring capabilities.	Single component with restoration features.	A robust reliable RoF architecture. - Analysis of cost and transmission integrity of the different protection schemes.

subsystems to meet the quality requirements. Furthermore, there are commercial applications of RoF access networks operating at low frequencies ($\leq$10 GHz), and important efforts in the standardization to support research and development for the migration to mm-wave frequencies are in progress.

However, there are still challenges for specific mm-wave RoF implementations. It is a must to achieve a capable, simple, practical and cost-effective system design to ultimately lead the success for suppliers on this market. To this date, this is still an ongoing research and development process, with strong competition from other transmission media technologies which are still more attractive for broadband deployments. Nevertheless, the forecast for the use of RoF to support higher data demands is promising for the forthcoming years.

It is expected that with this exhaustive review, many researchers and developers will be encouraged to investigate even further and develop newer technologies for the use of RoF for broadband wireless communications, expanding this knowledge in the advent of newer services and applications likely to be deployed in the near future.

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