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Review

A Review on MIMO Wireless Signals over Fibre for Next Generation Fibre Wireless (FiWi) Broadband Networks

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Received: 2 October 2020; Accepted: 24 November 2020; Published: 28 November 2020

Abstract: Next-generation access/mobile networks have set high standards in terms of providing wireless services at high data rates in order to keep up with the vast demands for other mobility and multiple services. Wireless-optical broadband access network (WOBAN) technology, also known as fibre-wireless (FiWi), has uncovered incredible opportunities for the future of next-generation networks because it gets the best of both domains: huge bandwidth provided by the optical fibre and high ubiquity of the wireless domain. The objective of FiWi networks is to integrate the high data rate and long reach provided by optical networks and the ubiquity and mobility of wireless networks, with the target to decrease their expense and complexity. Multiple-input–multiple-output (MIMO) is an inevitable technique for most of the new mobile/wireless networks that are driven by the huge data rates required by today's users. Consequently, to construct any FiWi system for next-generation (NG) access/broadband networks, an MIMO technique has to be considered. This article presents a comprehensive, contemporary review of the latest subsystems, architectures and integrated technologies of MIMO wireless signals backhauling using optical fibre or fibre access networks, such as passive optical networks (PONs). An overview for FiWi, PONs and MIMO wireless systems is provided. In addition, advanced techniques of accommodating the MIMO wireless signals over optical fibre are explained and compared. Different types of wireless MIMO signals over fibre, such as 5G, WiFi and related transport technologies, are reviewed. Moreover, future research trends are also discussed.

Keywords: fibre wireless access network; multiple-input multiple-output; passive optical network

1. Introduction

With the increasing number of smartphones and their broadband demanded applications [1], there is a huge need for high bandwidth broadband infrastructure. Moreover, the rapidly growing demands on bandwidth and end users' new data rates consuming applications such as YouTube, Netflix, peer-to-peer downloading and cloud computing, call for the combination of the fibre and wireless domains in a unified infrastructure. FiWi networks merge wireless networks with optical networks. The wireless networks have the availability, flexibility and coverage, while optical networks support transmission speeds and overcome distance limitations [2]. FiWi systems have started to draw in broad research enthusiasm as they offer great potential for tackling the issues of high-speed Internet access "over the last mile". Specifically, FiWi systems with a passive optical network (PON) as the optical system have been seriously concentrated in the previous years as a PON can give high transmission bit rates for today's bandwidth killing applications [2].

One of the best schemes to deliver the wireless signals over optical fibre is radio-over-fibre (RoF) [3]. The RoF technique has shown a promising solution for the future of mobile and access networks because of its seamless integration of the large capacity provided by the optical fibre and the flexibility, mobility and freedom of radio systems [4] and, as such, RoF has become an appealing answer for the high data rate demands and overall cost reduction of wireless systems [5].

MIMO is a foreseeable technique for most of the new mobile/wireless networks that are driven by the huge data rate required by today's users [6]. The MIMO technique is intended to enhance transmission distance, data rate and reliability compared to the performance offered by a single-input single-output (SISO) system [7,8]. Consequently, in order to build any FiWi system to provide wireless connectivity for next generation (NG) broadband networks, the MIMO technique has to be considered [9].

In this paper, we present a comprehensive, contemporary review of the latest subsystems, architectures and integrated technologies of MIMO wireless signals backhauling using optical fibre or fibre access networks, such as passive optical networks (PONs). Sections 2–4 introduce PONs, FiWi and MIMO wireless systems, respectively, with the basic technologies and concepts enabling these systems and networks. Section 5 addresses more specific topics in wireless MIMO signals over fibre techniques. Section 6 focuses on more specific technologies for the transport of different types of wireless MIMO signals over fibre. Integrated technologies and backhauling of MIMO wireless signals over PONs are reviewed in Section 7, Section 8, suggests future work and, finally, the conclusion is presented in Section 9.

2. Introduction to PONs

Different types of multiplexing techniques are used when many users share a point-to-multipoint PON-based topology. There are four types of PONs, which can be classified based on the used multiplexing technique: time division multiplexing (TDM), optical code division multiplexing (OCDM), wavelength division multiplexing (WDM), and orthogonal frequency division multiplexing (OFDM). Of these various approaches, two of them are highly recommended to see broad future use, which are TDM-PON and WDM-PON techniques [10,11]. Moreover, Pure WDM-PON, OCDM-PON, or OFDM-PON techniques are not as standardised and studied as TDM-PON today [12]. In addition, other WDM schemes (based on OFDM or OCDM) do not offer advantages over the WDM/TDM hybrid PON [13]. Here, a brief overview is provided for these two types of multiplexing techniques (TDM and WDM) and then the hybrid techniques between them, because they are related to this paper.

2.1. TDM-PON

TDM-PON is a widely used PON technique and is beginning to see huge implementations in different places over the world. In TDM-PON, Optical Line Terminal (OLT) assigns time slots to Optical Network Unit (ONUs) according to their bandwidth demands, which allows centralised resource allocation. Each ONU utilises the full Upstream (US) bandwidth of optical networks within its period of the allocated time slot. The Downstream (DS) uses a broadcast and select scheme; that is, the DS data and video are broadcast to each user with media access control (MAC) addresses, and the user selects the data packet-based MAC addresses [14]. Figure 1 shows the operation of a TDM process. To attach the multiple ONUs to a single feeder fibre, a passive optical power splitter/combiner PS/C is used at the Remote Node (RN). Since the TDM-PON can service N = 32 or more subscribers, the overall allocated bandwidth to separate ONU is typically a small percent of the total data rate. In addition, current TDM-PON tree topology compromises its protection and restoration [15].

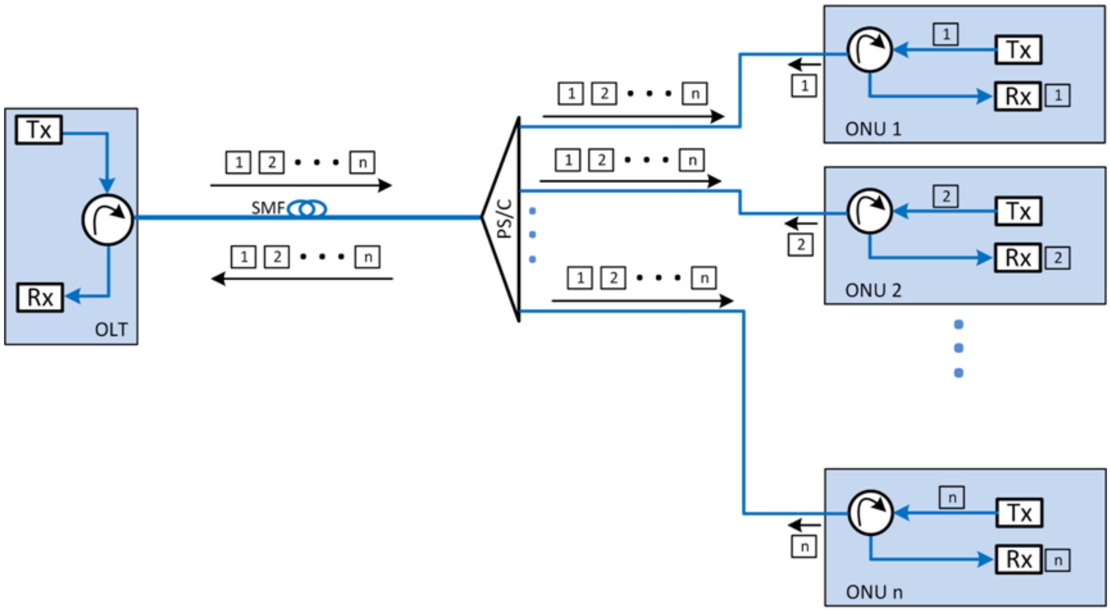

Figure 1. Operation of a time-division multiplexing process in time division multiplexing (TDM)-passive optical network (PON).

2.2. WDM-PON

WDM-PON allows a virtual optical point-to-point transmission by assigning two wavelengths (for DS and US) to each ONU. The difference in the Optical Distribution Network (ODN) between WDM-PON and TDM-PON is changing the PS/C in a TDM-PON with an arrayed waveguide grating (AWG) or WDM multiplexer/demultiplexer (Mux/DeMux), as shown in Figure 2. WDM-PON has many advantages, such as scalability, very low optical power loss and protocol transparency [16,17]. In addition, it provides high data rate, long reach and excellent privacy since each user receives its own wavelength. However, it has high components costs compared to TDM-PON. Moreover, each user requires a dedicated transmitter and receiver in the OLT.

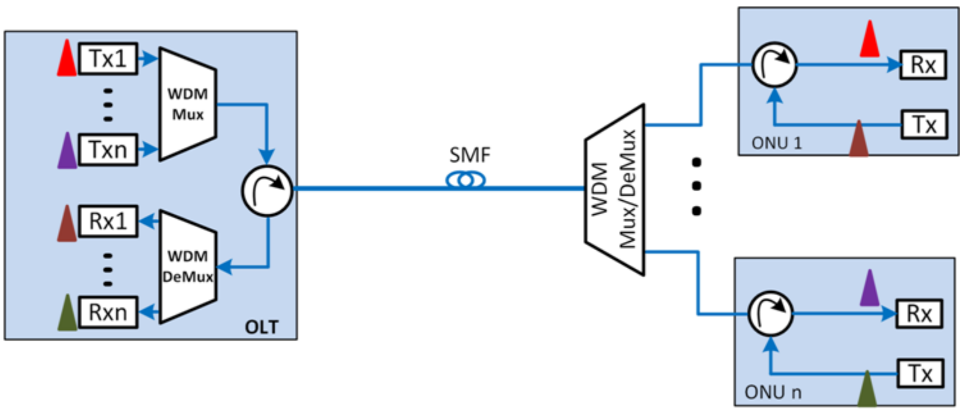

Figure 2. Network architecture of wavelength division multiplexing (WDM)-PON.

2.3. Hybrid WDM/TDM-PON

Lately, many solutions have been proposed and even developed to cope with the disadvantages of WDM-PONs and TDM-PONs by using hybridisation methods. The hybrid WDM/TDM-PON aims to obtain the better of the two options [18]. Embedding TDM-PONs within different wavelengths of a WDM-PON leads to a high density network that is able to offer connectivity to a large number of subscribers. Figure 3a shows an example for this hybrid technique (considering four wavelengths for each direction).

Since changing the ODN of the currently deployed TDM-PON is very costly, a solution which keeps the current ODN unchanged is highly desirable. Therefore, enabling the use of WDM should be realised using the same infrastructure [13]. Stacked TDM-PON, which is also called also broadcast-and-select WDM-PON, time and wavelength-division multiplexed PON (TWDM-PON) or multi-wavelength TDM-PON, is a most promising infrastructure for NG-PON. Figure 3b depicts the architecture of stacked TDM-PON, which is proposed as a solution for reusing the currently deployed (TDM-PON) ODNs. In the broadcast-and-select WDM-PON architecture, the wavelength filtering is not implemented as a typical WDM-PON on the RN. Instead, the filtering stage is moved to the ONUs where each ONU chooses its wavelength by a tunable optical filter. In the proposed solutions for this function are a liquid crystal tunable filter, angle-tuned FP filter and thermally tuned Fabry–Perot (FP), and filter injection-tuned silicon ring [19,20]. Moreover, the ONUs needs either a fixed-wavelength laser, a laser-array, or a tunable laser [12]. For NG-PON, TWDM-PON (stacked TDM-PON) is selected by the Full-Service Access Network (FSAN) group as the main solution [21].

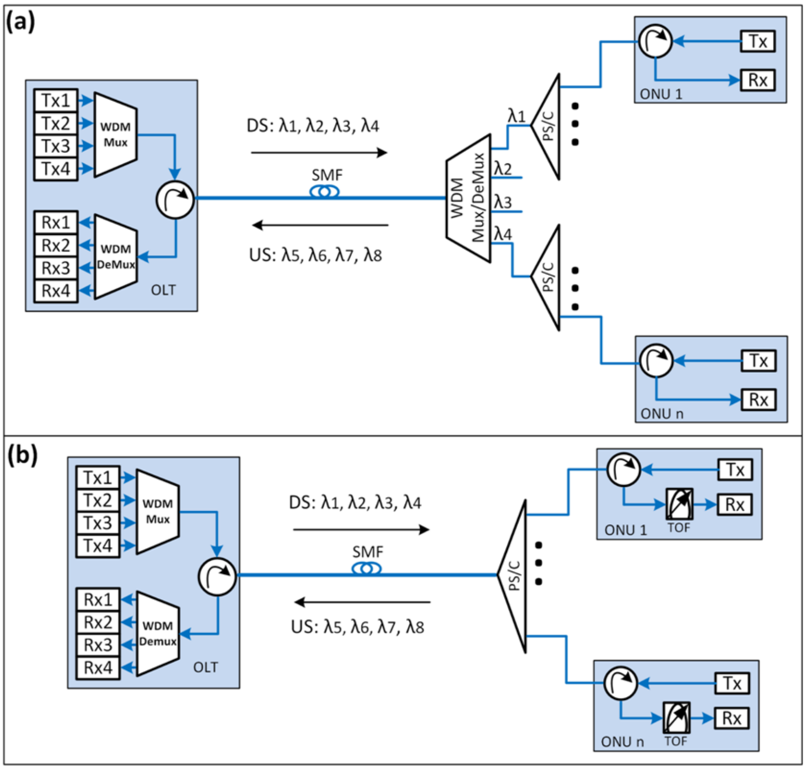

Figure 3. (**a**) Hybrid TDM/WDM-PON architecture and (**b**) stacked TDM-PON (TWDM-PON) architecture.

3. Introduction to FiWi Systems

NG networks need huge data rates to deliver in a quadruple-play manner (broadband Internet access, television, telephone and wireless) for the increasing high data rate demands of video, gaming and, smartphones [22]. Thus, mobility and high data rates are essential requirements for NG access networks for satisfying the bandwidth greedy applications of today's smartphones and other devices. RoF technology is considered to be one of the greatest reliable candidates for the future of broadband access networks, since it takes the best of the two worlds by integrating the huge bandwidth provided by the optical fibre and the high mobility of wireless communication [4].

Basically, two main transmission schemes are used to transport the wireless signals in the hybrid wireless optical systems: baseband over fibre (BBoF), and RoF schemes [23].

3.1. BBoF

The BBoF technique is implemented to deliver RF wireless signals as a baseband signal over fibre. After the baseband signal is transmitted over fibre, at the access point (AP) the baseband signal is modulated and decoded to the desired wireless signal, as depicted in Figure 4. In this technique, the sent DS signal is upconverted by direct modulation using an optical modulator and then propagated as a baseband signal over optical fibre. The AP receives the transmitted signal and performs direct detection using photodiode (PD), a low pass filter (LPF), and decoder. Therefore, the output of the PD is then modulated using the RF modem at the required carrier frequency f_{RF}. In the other direction (upstream), the received wireless signal from the AP is converted to BB signal and sent back to the Central Office (CO). This technique has many advantages, such as chromatic dispersion effects reduction, and using well-known methods for signal processing at the AP. Further, there is no need for high bandwidth photodiode detectors at the AP [24,25]. However, this technique can be considered a complicated scheme compared to the RoF technique where no BB to radio signal conversion is required at the AP [25].

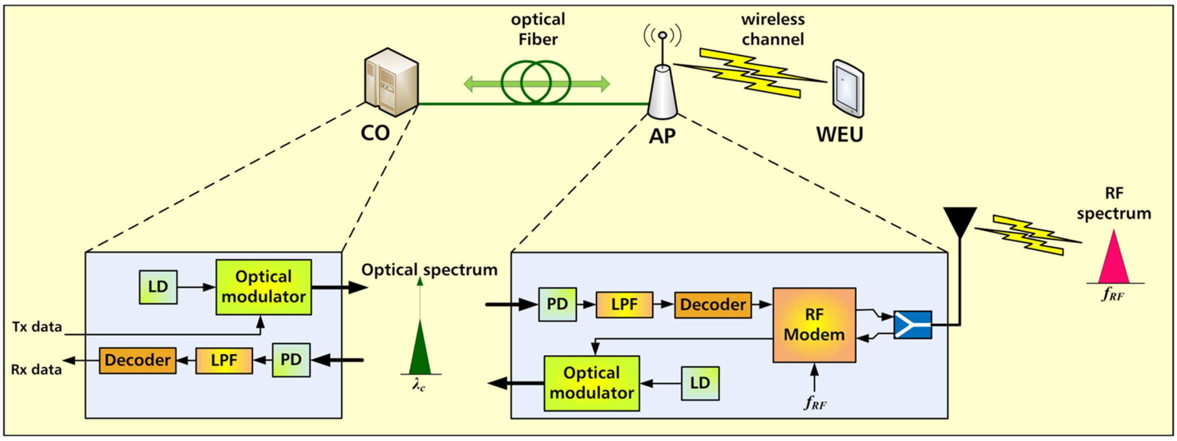

Figure 4. Baseband over fibre (BBoF) transmission scheme.

3.2. RoF

RoF technology distributes RF signals from a central location (CO) to remote antenna units (RAUs)/APs through an optical fibre link. Since the RF wireless signal is formatted into its last shape at the CO, this removes all the RF signal processing functions to a centralised shared location. In such way, the cost of the RAUs is greatly reduced, since the signal after the optical to electrical conversion is directly fed into the antenna, and other signal processing functions, for example, carrier modulation, frequency up-conversion and multiplexing are achieved in the CO. This cost reduction in the RAU has a great impact on the total cost, because the RAU is installed at each subscriber's premises [26].

In this technique, the data meant to be transmitted are first modulated using the RF modem at the required RF carrier frequency f_{RF}. Then the data that are mixed with the RF carrier frequency are upconverted using an optical modulator, which is driven by a laser diode (LD) at an optical carrier frequency (λc). An optical double sideband (ODSB) signal is generated at the CO, as shown in Figure 5. Just a single high-speed PD, trailed by a bandpass filter (BPF), is sufficient to regenerate the wireless signal directly. Then, amplification is performed on the wireless signal and then send to the wireless end user (WEU) through the wireless medium. The RF signal optical modulation is not necessary to be an ODSB. Currently, there are three dissimilar modulation schemes existing for generation and distribution of RF signals over a fibre link using an external modulator: ODSB, optical single sideband with carrier (OSSB+C), and optical carrier suppression (OCS) technique [25–29].

The main two types of RoF transmission are: analogue digital RoF (DRoF) and digital RoF (DRoF) [30]. The major disadvantage of using ARoF is it gets nonlinear effects such as distortion caused by an optical transmitter. On the other hand, when it comes to nonlinearity, DRoF transmission is very robust [31]. Since the distortion requirements in the mobile standards are tougher than the wireless standards, DRoF is the preferred choice. DRoF formats are used extensively in 5G, such as the common public radio interface (CPRI) [32]. In a DRoF system, the radio frequency signal is converted to a digital signal using an analogue-to-digital converter. The generated digital signal is modulated with the required optical wavelength using a direct modulation done by an optical modulator such as the Mach–Zehnder modulator (MZM) [33].

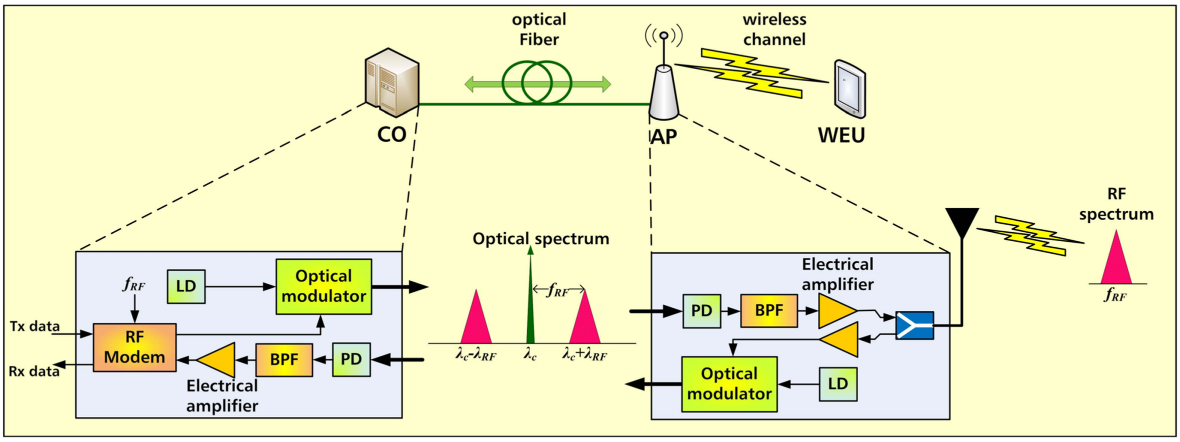

Figure 5. RoF transmission scheme.

4. Introduction to MIMO Wireless Systems

MIMO technology has been exploited and considered as the finest way to solve the bottleneck of traffic capacity in future wireless networks [34]. Moreover, MIMO constitutes a breakthrough in the design of wireless communication systems, and is already at the core of many existing and emerging wireless standards [35]. MIMO transmission is very significant in 4G and future 5G/6G networks, as it raises the capacity for end users [36].

The MIMO system enhances the traditional SISO system by many factors, such as improved transmission range, reliability and delivery of higher data rate [7]. Figure 6 shows the MIMO wireless communication system and how this system works. The MIMO technique takes advantage of a multipath wireless channel to enhance data rate, range and reduce the interference [37]. Therefore, the MIMO system can use multiple MTx transmit antennas at the transmitter side to propagate multiple parallel wireless signals along the wireless channel to multiple MRx receive antennas at the receiver side. The MIMO system usually is distinguished by an $MT_x \times MR_x$ MIMO system, such as the 2×2 MIMO system in Figure 6. There are two types of multiple antenna techniques: spatial multiplexing technique and diversity technique [38].

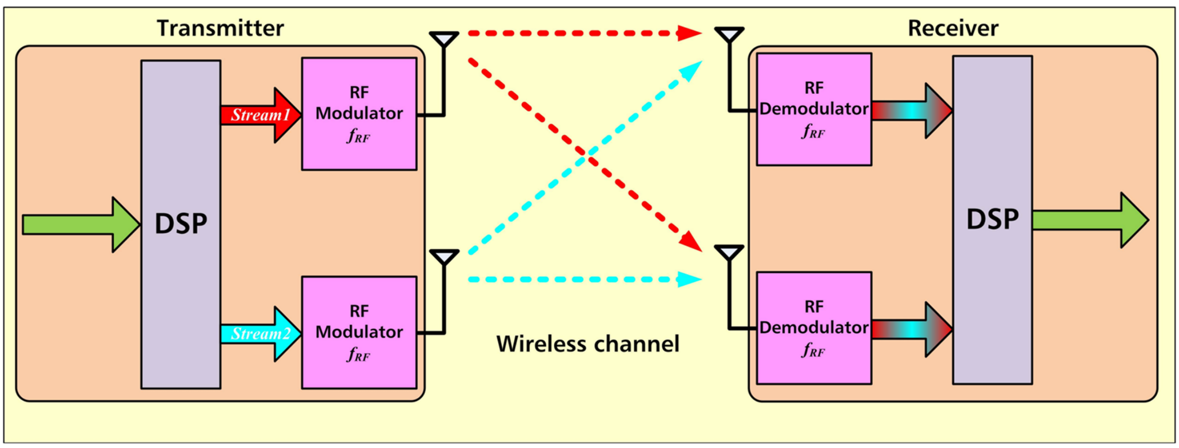

Figure 6. Multiple-input–multiple-output (MIMO) wireless system.

5. Wireless MIMO Signals over Fibre Techniques

This section addresses the challenges of manipulating different MIMO wireless signals with the same carrier frequency to fit in the same optical wavelength. The main problem in sending MIMO signals that have similar carrier frequency over a single optical wavelength directly is that they overlap in the frequency domain. There are several solutions that are proposed to solve this problem, which are discussed and compared in this section. On the other hand, in the case of sending the MIMO wireless signals in different wavelengths, there is the challenge of how to make good utilisation of the unlimited wavelength capacity and not waste it on a single MIMO stream. This challenge is also addressed by many researchers, which are discussed here. In addition, the techniques of sending MIMO signals as BBoF and its advantages and disadvantages are also presented in this section. In the next section (Section 6), the focus will be on sending different types of MIMO wireless signals over fibre.

Figure 7 shows the concept of sending MIMO signals over fibre. Depending on the configuration type, we can define the user interface with the MIMO transmission unit as AP/RAU or ONU. If the transmitted MIMO wireless signals are sent as BBoF, we can call the MIMO transmission unit an ONU. When the transmitted MIMO wireless signals are sent as RoF we can call the MIMO transmission unit RAU or AP.

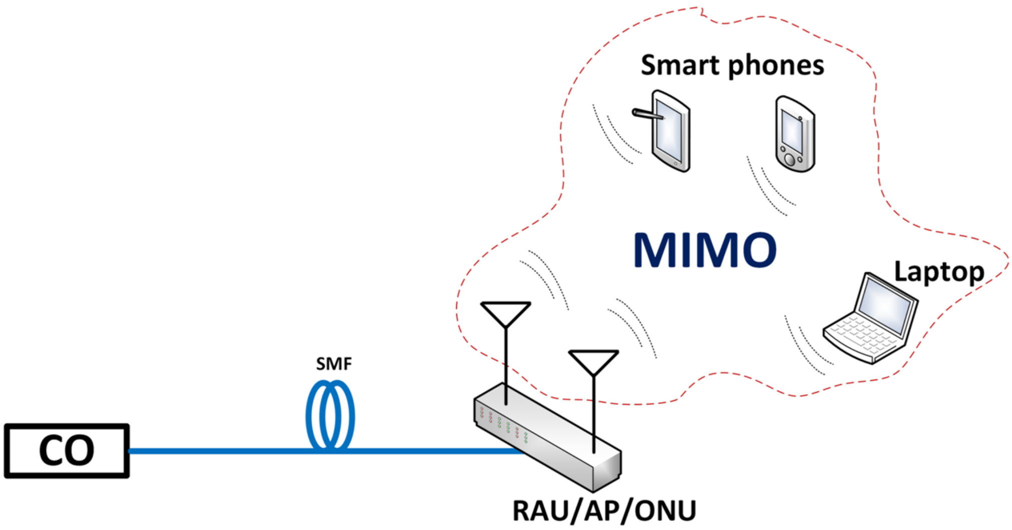

Figure 7. Wireless MIMO signals over a simple fibre system.

Sending the MIMO wireless signals as BBoF is a very simple scheme for transmitting MIMO signals over fibre, as proposed in [39]. However, it is not cost-effective, since the ONU has to be associated with a wireless modem to transfer the baseband signal to its final MIMO wireless format before the wireless transmission. Therefore, it is more appealing and less expensive to deploy RoF for the transmission of MIMO wireless signals over fibre [40–45]. Moreover, analogue signal transmission leads to simpler RAUs and the analogue signals generally obtain less bandwidth than their baseband equivalents [43]. Moreover, all the advantages of the RoF scheme will be gained, such as simple configuration and no frequency up-conversion is needed at the RAU.

In the case of sending the MIMO wireless signals (spatial multiplexed) over fibre as RoF signals, the main problem in sending MIMO signals that have similar carrier frequency over a single optical wavelength directly is that they overlap in the frequency domain. There are several solutions that are proposed to solve this problem, such as using WDM [42,46]. However, it adds more cost, since, for each MIMO wireless signal, an optical source and photodetector is mandatory.

In [42], a 4 $\times$ 4 MIMO-RoF system is proposed for NG wireless-communication systems. To handle the MIMO signals over a single optical fibre, nine-channel coarse wavelength-division-multiplexed (CWDM) optical channels are utilised: one for link delay measurement and signal transmission control, four for downlink, and the others for uplink. This means that each MIMO stream needs a separate wavelength widely separated from the adjacent wavelength since CWDM is used. This will limit the number of users, especially if the system is used in a PON environment. The same drawback (cost) is associated with subcarrier multiplexing (SCM), in addition to its low data rate [47]. Transmission of multiple wireless MIMO signals over an optical fibre is proposed and explained using an electrical single sideband frequency-translation (ESSB-FT) technique [48]. In this approach, local oscillators at the transmitting and receiving ends are required, which is a drawback. In [49], transmission of two wireless MIMO signals with similar carrier frequency over fibre using an optical single sideband frequency-translation (OSSB-FT) technique has been proposed and demonstrated. The major disadvantage of this approach is using one wavelength for each sent MIMO stream. This consumes the optical spectrum domain, which limits the total number of users. For example, in the case of 4×4 MIMO, each RAU will need four wavelengths. In [40,50], polarisation division multiplexing (PDM) is implemented to carry each MIMO stream at a different polarisation of similar wavelength taking advantage of the wavelength's two polarisations, as shown in Figure 8a. However, this method limits the number of MIMO streams per wavelength to only two. Among these methods, the most used and proven to be successful are: PDM [6,40,50–60], using comb techniques to generate multiple wavelengths [49,61–64] and also hybrid method between them as shown in Figure 8c [6]. It takes benefit from the optical frequency comb techniques and high bandwidth optical modulators (up to 100 GHz) as shown in Figure 8b [64–67], and multiple widely separated wavelengths can be produced from one continuous-wave (CW) laser. Figure 8 illustrates these three methods of transmission of wireless MIMO signals over fibre.

Sending MIMO signals with different frequencies (MIMO diversity technique) over fibre as RoF is easy since there is no overlap in the frequency domain. However, sending MIMO signals with the same frequency (MIMO spatial technique) over fibre as RoF is not straightforward. The problem with sending MIMO signals that have similar frequency over a single optical wavelength directly is that they overlap in the frequency domain. A diversity technique can be implemented with a stable antenna transmission technique, such as space diversity [68,69] as explained earlier. Also, the diversity technique can be implemented optically by using optical delay before the wireless transmission. For example, in [62], one of the optical signals was delayed using an additional 6 km single-mode fibre to be de-correlated with the other. In [70], the two techniques have been extensively compared for MIMO-RoF systems and it was found that, in a wireless or optical channel, the technique of spatial multiplexing is less reliable in terms of BER, which means doubling the data rate using spatial multiplexed MIMO-RoF signals will come with a cost of increasing the BER and high reception power will also be required to perform, compared with the diversity technique [70]. In can be considered that, in future implementation, a hybrid technique will be used to realise the advantages of the two techniques in the same MIMO-RoF system. In such case, the reception of the signal and separation will be a challenge in the digital signal processing (DSP) domain since it has been degraded during the optical and wireless transmission.

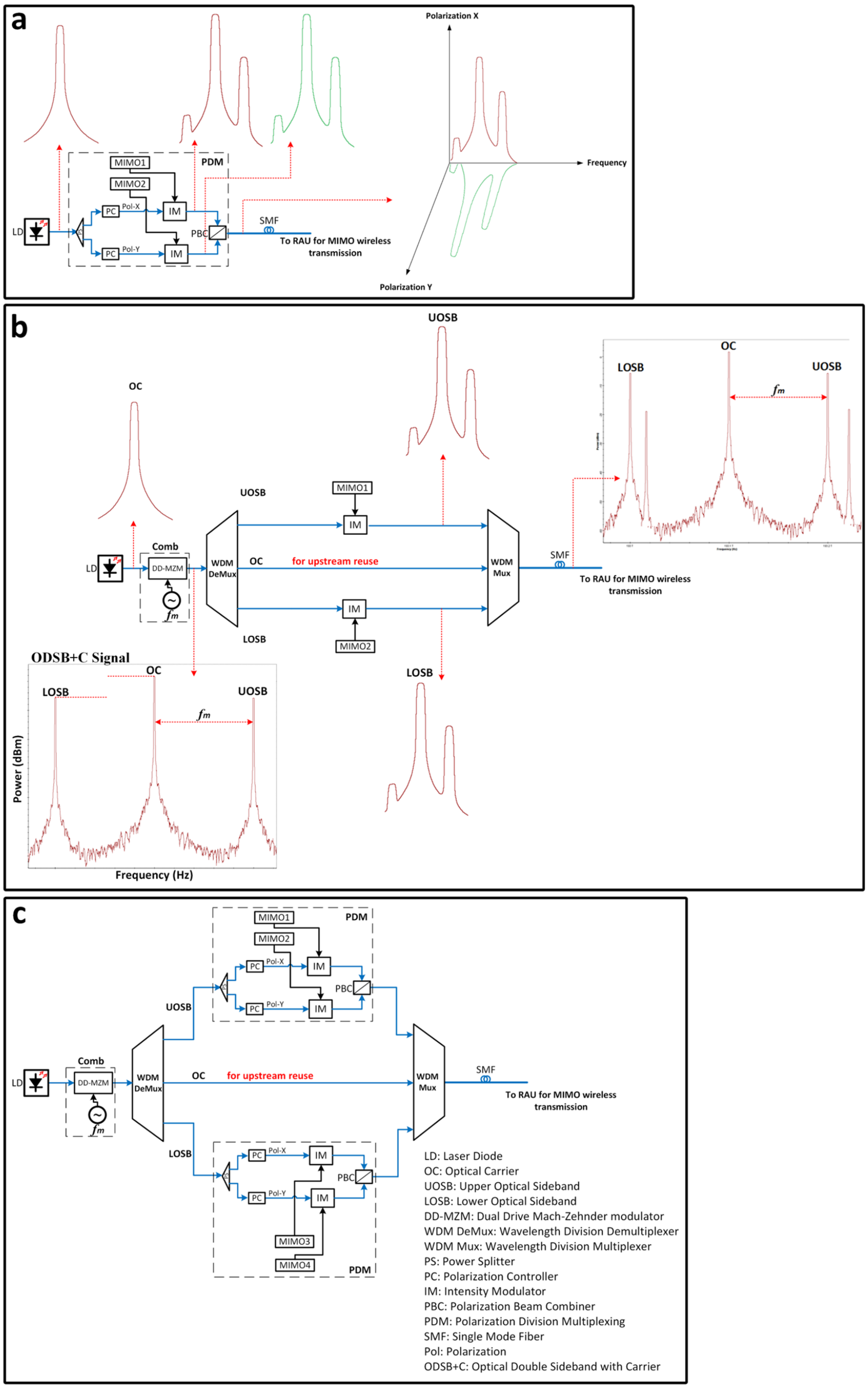

Figure 8. Three wireless MIMO signals over fibre transmission techniques: (**a**) PDM, (**b**) comb, (**c**) hybrid.

Table 1 summarises some of the previously proposed approaches to handle wireless MIMO signals over fibre and their disadvantages and advantages.

Table 1. Wireless MIMO signals over fibre schemes.

Ref	Approach	Explanation	Disadvantages	Advantages
[34,50]	Polarisation-division-multiplexing (PDM)	Carrying each MIMO stream at different polarisation of the same wavelength, taking advantage of the wavelength two polarisations (x and y).	It is applicable just for 2 × 2 MIMO streams. The studies do not consider complete PON, just PtP communication system.	One wavelength for two MIMO streams. High data rate.
[39]	Formatting the MIMO streams at the RAU	MIMO streams are sent as baseband RZ-DPSK signals over optical fibre then at the RAU converted into binary form and then upconverted (BBoF), so that it can be adopted as an input to the transmitter of the MIMO-OFDM system.	Complex RAU due to the MIMO traffic formation process.	Very high data rate. Long distance transmission.
[71]	Time Domain Multiplexed MIMO	Each MIMO RF signal is multiplexed by optical TDM into one wavelength channel.	Using pure WDM-PON at the backhaul, which is costly for this particular application.	Low cost RAU.
[42,46]	WDM	Each MIMO stream is carried at different wavelength channel.	It is not cost-effective, since for each MIMO signal an opticalsource and photodetector are required.	Very high data rate. Long distance transmission.
[47]	Optical Subcarrier-Multiplexing (SCM)	Using SCM to multiplex different MIMO streams.	Using local oscillators at the transmitting and receiving sides. Low data rate.	Low cost. Applicable for more than two MIMO streams.
[48]	ESSB-FT	Using an electrical single-sideband frequency-translation (ESSB-FT) the technique to shift the frequency of each MIMO stream at the transmitter side to a different frequency and to shift them again at the receiver side to the same frequency.	Using local oscillators at the transmitting and receiving sides. Low data rate.	Low cost. Applicable for more than two MIMO streams.
[49]	OSSB-FT	OSSB-FT technique is used to generate multi-wavelength from a single laser diode, then the MIMO streams carried at these wavelengths.	Dedicating a wavelength for each MIMO stream.	Low cost. Applicable for more than two MIMO streams. High data rate.

6. Different Types of MIMO Wireless Signals over Fibre

The previous section presents the insertion techniques of MIMO signals inside the optical fibre regardless of the wireless signal type. This section focuses on different types of MIMO wireless signals over fibre. Since each wireless signal type has its own characteristics, each type will exhibit different behaviour when it is sent over fibre.

6.1. WiFi MIMO Signals over Fibre

WiFi based on IEEE 802.11 standards has grown widely over the most recent 15 years for local area networks (WLANs). The ubiquity of 802.11-based WLAN is because of ease of installation, speed and low cost [23]. All the new WiFi standards support the use of the MIMO technique, for example, the latest WiFi standard (IEEE 802.11ax) supports the use of up to eight MIMO streams.

In [45,63,72], comb techniques are used to generate separated wavelengths instead of requiring several optical sources (such as the one shown in Figure 8b to carry the WiFi MIMO signals). For example, in [45], multiple wavelengths are produced using a microring resonator (MRR) system. Then, each wavelength is used to carry IEEE802.11n MIMO signal. RF power degradation because of the fibre dispersion can be overcome by implementation of the OSSB modulation technique. In this scheme, the transmission of MIMO RF signals is feasible for up to a 50 km single Mode Fibre (SMF) path length and a wireless distance of 15 m.

In [48], the ESSB-FT technique is used to shift the frequency of each IEEE802.11n MIMO signal at the transmitter side to a different frequency and to shift them again at the receiver side to the same frequency before the wireless transmission. In such way, the MIMO signals can be combined electrically and modulated directly into the optical fibre, as presented in Figure 9b. The principle of this method is also shown in Figure 9a.

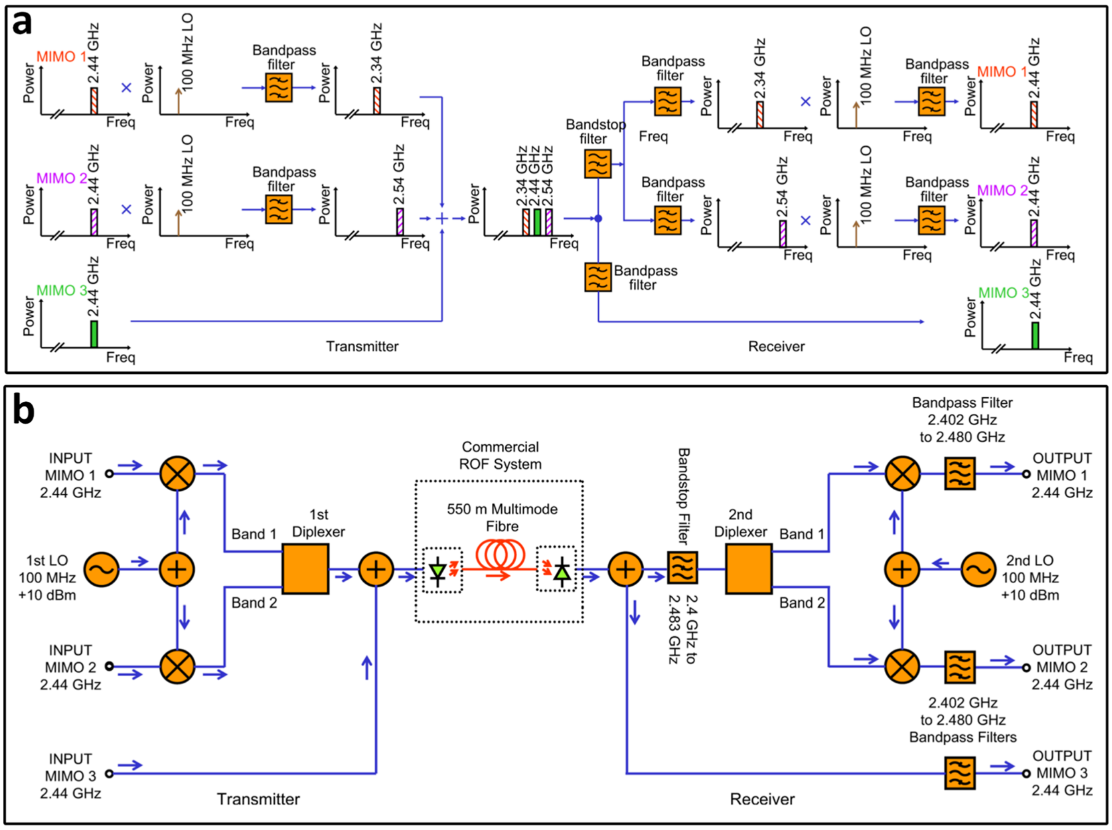

Figure 9. (**a**) Principle of the electrical single sideband frequency-translation (ESSB-FT) technique proposed in [48] (**b**) experimental setup in [48].

The use of 3 × 3 MIMO wireless signals (IEEE 802.11 n/ac) over a single MMF is proposed in [73]. The three main advantages of the proposed system are: using commercial IEEE 802.11 n/ac APs, using MMF instead of SMF (with comparable performance), and it may encounter tight MMF bending conditions. However, each MIMO signal will need a dictated laser diode (LD) and photodiode (PD). Table 2 summarises some of the previously proposed approaches to handle WiFi MIMO signals over fibre.

6.2. UWB MIMO Signals over Fibre

Ultrawide band (UWB) technology has grown quickly in the previous decade due to its remarkable advantages, for example, transmitting high data rates at low power consumption [74].

Experimental representation of transmitting OFDM signals following ECMA-368 UWB standard in RoF system is reported [75] as shown in Figure 10 Combining PDM and OFDM modulation allows maximising the optical transmission capacity. Successful MIMO-RoF transmission of multiuser OFDM-UWB over 25 km SMF reach is demonstrated. However, due to the fact that the transmitted UWB covers a wide range of frequencies (occupying large bandwidth), frequency selectivity causes inter-symbol interference [76]. Further research will be needed to overcome this issue in the UWB MIMO signals over fibre transmission. Table 3 summarises some of the previously proposed approaches to handle UWB MIMO signals over fibre.

Table 2. WiFi MIMO signals over fibre schemes.

Ref	Capacity	Distance	WiFi Standard/ MIMO Stream Order	Infrastructure Cost	Link Performance
[45]	300 Mb/s	50-km SMF 15 m wireless	IEEE802.11n 2×2	Relatively high. Due to the use of two PDs ant the base station. Also, two MZM is required for only two MIMO streams.	For a BER threshold of 3.8×10^{-3}, the power the penalty is 5.2 dB for 50 km SMF transmission.
[63]	240 Mb/s	20-km SMF 100 m wireless	IEEE802.11n 2×2	Low. One wavelength/ LD for two MIMO streams.	Achieved BER 10^{-5}.
[72]	7.68 Gb/s (optical back-end, aggregated capacity for multiple users) 240 Mb/s for the outdoor wireless front-end.	20-km SMF 100 m wireless	IEEE802.11n 2×2	Low. One wavelength/ LD for two MIMO streams.	Achieved BER 10^{-5}.
[48]	240 Mb/s	550-m MMF (Wireless transmission is not available, the paper focuses on the optical backhaulperformance.)	IEEE802.11n 3×3	Very low. One wavelength/LD and one PD for three MIMO streams.	The maximum crosstalk level between the different MIMO channels was 67 dB.
[73]	1 Gb/s	1 km MMF (Wireless transmission is not available, the paper focuses on the optical backhaul performance.)	IEEE802.11n/ac 3×3	High. Three LDs and three PDs for three MIMO streams.	With all fibre bending radii tested, within each 5 min measurement time, the fibre the channel is found to be good enough to provide throughput greater than twice the average SISO value for more than 87.66% of the time (the main the concern of the paper is to study the effect of MMF bending when MIMO streams are sent).

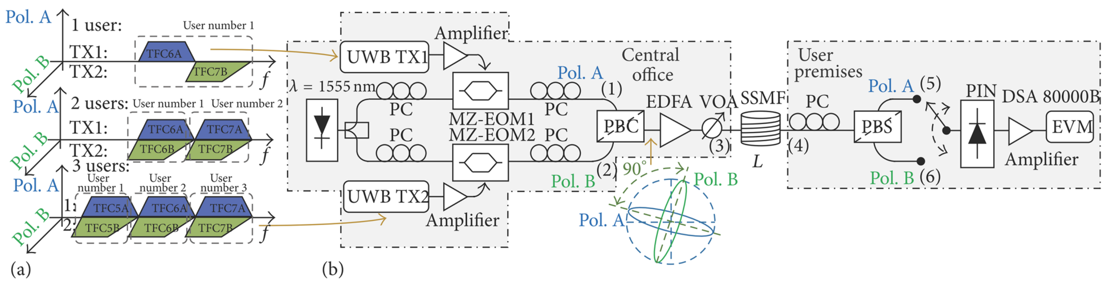

Figure 10. (**a**) Ultrawide band (UWB) multiuser configurations using two polarisations, (**b**) experimental setup for MIMO-UWB transmission with PDM [75].

Table 3. UWB MIMO signals over fibre schemes.

Ref	Capacity	Distance	UWB Standard/ MIMO Stream Order	Infrastructure Cost	Link Performance
[75]	1.2 Gb/s	25-km SMF (Wireless transmission is not available, the paper focuses on the optical backhaul performance.)	UWB ECMA-268 3×3	Low. One LD/PD for three MIMO streams.	The results indicate that the SCM-UWB multiuser signal transmitted on both polarisations achieve successful communication (EVM under −14.5 dB) over a distance up to 25 km.
[63]	128 Gb/s	80-km SMF 0.6 m wireless	No specific standard is used. 2×2	Low. One LD/PD for two MIMO streams.	After 80-km SMF transmission and 0.6-m wirelessdelivery the Achieved BER is 3.8×10^{-3}

6.3. LTE MIMO Signals over Fibre

Long-term evolution (LTE) standards need to rethink mobile radio access networks with packet switching to address the demands for high data rate and low delay [77].

Successful long-reach optical transmission of LTE-Advanced (LTE-A) signals using 2 × 2 MIMO spatial diversity is experimentally demonstrated in [51]. The LTE-A MIMO signals are combined optically using PDM technique. Transmission of five LTE-A transmits over 25 km, three LTE-A carriers over 75 km and an LTE-A carrier over 100 km of standard single mode fibre to deliver pervasive MIMO wireless service to many users is demonstrated, as shown in Figure 11. For long-reach transmission (longer than 35 km), EDFA is needed, as shown in Figure 11.

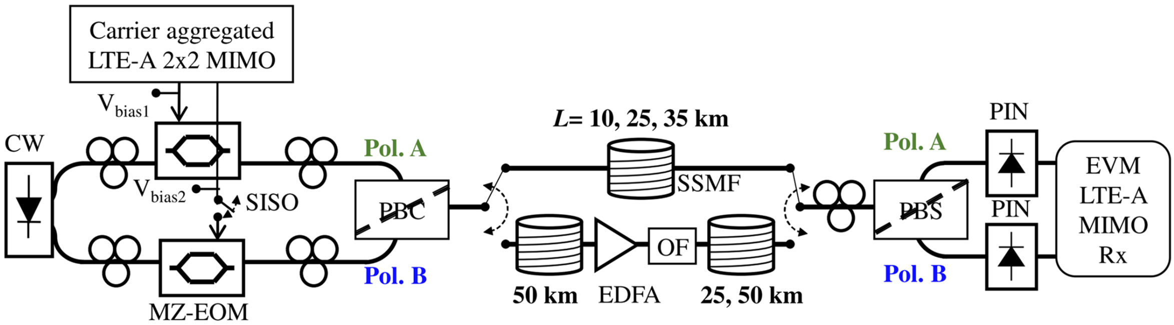

Figure 11. Experimental setup for MIMO LTE-A PDM RoF transmission in optical networks [51].

Another LTE-A system is proposed in [78], which can support up to 4 × 4 MIMO LTE-A spatially multiplexed signals on Multicore Fibre (MCF). However, four Mach–Zehnder (MZ) electro-optical modulators are needed in the transmission side and four optical detectors are needed in the reception side, which will increase the overall cost of the proposed system. The main advantage is the system's ability to provide more MIMO signals in similar or dissimilar frequency bands employing the proposed radio-over-multicore fibre, which makes the system a good candidate for massive MIMO implementations. A demonstration of 2 × 2 MIMO LTE signals transmission of fibre is presented in [79]. It is suitable for short distance and indoor transmission, since multi-mode fibre (MMF) is used. The main advantage of this system is the combination of the LTE signal with IEEE 802.11g signal, which makes the system a good option for supporting multiple services in indoor environments. Table 4 summarises some of the previously proposed approaches to handle LTE MIMO signals over fibre.

Table 4. Long-term evolution (LTE) MIMO signals over fibre schemes.

Ref	Distance	LTE Standard/ MIMO Stream Order	Infrastructure Cost	Link Performance
[51]	100-km SMF (Wireless transmission is not available, the paper focuses on the optical backhaul performance.)	LTE-A 2 × 2	Relatively low. One wavelength/LD for two MIMO streams. However, two PDs are required.	The experimental results demonstrate successful 2 × 2 MIMO Pol-Mux RoF transmission over 100 km employing QPSK mapping.
[79]	550-m MMF (Wireless transmission is not available, the paper focuses on the optical backhaul performance.)	LTE 2 × 2	Very low. One wavelength/LD and one PD for two LTE MIMO streams and one WiFi signal.	In the wide-band signal transmission experiment, it is verified that the system can achieve a good EVM. The average EVM (5.1% for 20 MHz LTE and 1.2% for IEEE802.11 g) is well within the requirements set by the standards.
[78]	150 MCF (Wireless transmission is not available, the paper focuses on the optical backhaul performance.)	LTE-A 4 × 4	High. Each MIMO stream required dedicated MZM, LD and PD.	The four-antenna LTE-A system implementing 4 × 4 MIMO spatial multiplexing over MCF is received within the LTE-A EVM recommendation. The proposed system enablesproviding almost four times the bitrate of a single-antenna system overthe same bandwidth with 5 dB extra powermargin between the optical paths.

6.4. MMW MIMO Signals over Fibre

Millimetre-wave (MMW) frequencies have many advantages and applications, such as outdoor point-to-point backhauling or high speed indoor wireless demanding applications, such as 4K streaming [80].

In [34,54,58], the MMW MIMO signals are multiplexed using PDM technique. In [34], a 48 Gb/s PDM-QPSK RoF system over 2 × 2 MIMO wireless transmission is demonstrated. The baseband PDM-QPSK signal is up-converted to 40 GHz mm-wave and broadcasted through the 2 × 2 MIMO wireless system. The transmission distance is 400 km fibre link and 1m wireless link and the PDM method is deployed to combine the two MIMO signals. Every single polarisation component and a heterodyne carrier frequency optical source with 0.32 nm wavelength spacing are joined and detected at the PD for up-conversion to 40 GHz MMW. However, performing the up-conversion in the RAU optically will add additional cost, since an optical source will be required in the RAU for this purpose.

The centralised photonic precoding technique for MMW multicell MIMO wireless communications is proposed [81]. Through applying the multicell MIMO and later exploiting the spatial multiplexing gain over MMW, the system capacity is improved compared with the conventional SISO system. By using this technique, the diversity gain is increased using multicell MIMO to deliver desired transmitter antenna spacing, as shown in Figure 12. However, in the CO, each MIMO stream requires an LD at different wavelengths. Also, EDFAs are required for each MIMO-RoF signal amplification.

RoF downlink design for spatial modulation and multi-set space-time shift-keying (MS-STSK) with optical up-conversion to an MMW carrier frequency is proposed in [82]. The proposed system leverages the advantages of MS-STSK, optical up-conversion and beamforming. No electronic oscillators, mixers, phase shifters or ADC-and-DAC are needed and a bit rate of 10 Gbps and 10 km is achieved. Table 5 summarises some of the previously proposed approaches to handle MMW MIMO signals over fibre.

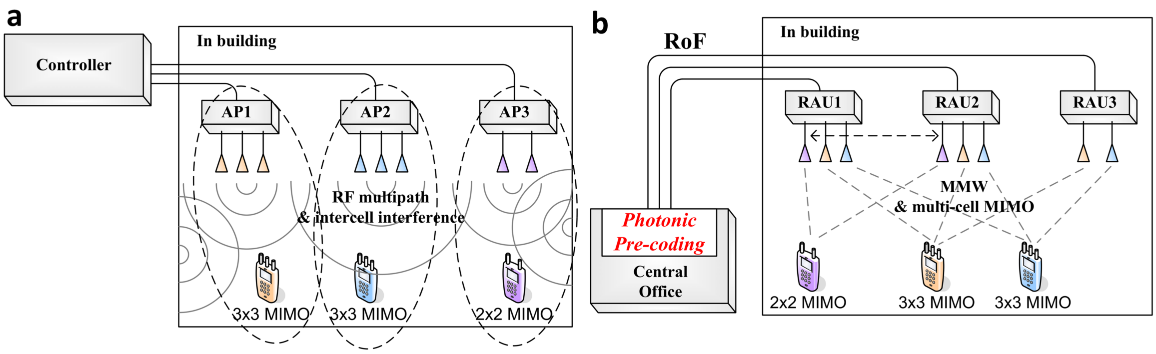

Figure 12. (**a**) Conventional intra-cell MIMO in low-frequency RF communications taking advantage of multipath (**b**) multicell MIMO in MMW communications using centralised photonic precoding based on the RoF system [81].

Table 5. Millimetre-wave (MMW) MIMO signals over fibre schemes.

Ref	Capacity	Distance	MMW Standard/ MIMO Stream Order	Infrastructure Cost	Link Performance
[34]	48 Gb/s	400-km SMF 100 cm wireless	No specific standard is used 2×2	Relativity low. One LD and two PDs for two MIMO streams. Also, considering the high data rate and the long reach, the system can be considered as cost effective system.	The BER performance after over 400-km fibre link and 100-cm wireless link clearly demonstrates the feasibility of the proposed PDM-QPSK RoF system over 2×2 MIMO wireless link.
[81]	2 Gb/s	20-m fibre 0.61 m wireless	No specific standard is used 2×2	High. Each MIMO stream required dedicated MZM, LD and PD.	A two cell MIMO downlink transmission using the proposed method is demonstrated experimentally and its capacity is doubled without obvious penalty compared with SISO transmissions.
[58]	324 Gb/s	25-km SMF 80 cm wireless	No specific standard is used 2×2	Relatively low. One wavelength/LD for two MIMO streams. However, two PDs are required.	The BER is below the 7% forward error correction (FEC) threshold of 3.8×10^{-3}

6.5. Terahertz MIMO Signals over Fibre

The forecasted demand for wireless data rates has been driving the research progress of terahertz (THz) technologies at an accelerating pace from both the device and the system level. Researchers have recently been seeking the use of THz waves in which the frequency is over 100 GHz for ultrahigh-speed wireless links [83,84].

In [85], hybrid THz photonic-wireless transmission based on a THz orthogonal polarisation dual-antenna scheme that features high data rate MIMO streams is proposed. The drawback of the proposed system is its low MIMO order, which is 2×1. The high data rate is achieved due to the use of optical PDM besides a high-order modulation of 64-QAM. Moreover, combining the 64-QAM with OFDM gave the system a high spectral efficiency of 4.445 bit/s/Hz.

A 2×2 MIMO wireless transmission system at THz-band is proposed in [86]. The proposed system takes advantage of PDM as in [85], but it realises a 2×2 MIMO wireless transmission. In this system, a 6×20-Gb/s six-channel PDM-QPSK THz-wave signal can be delivered over a 10-km SMF link and 142-cm wireless 2×2 MIMO link.

6.6. Optical MIMO Signals over Fibre

Instead of using RF-MIMO signals, optical-MIMO signals can be used for the wireless transmission, such as free-space optics (FSO) and infrared (IR) light. Optical wireless communication (OWC) systems depend on optical radiations to transmit information with wavelengths ranging from infrared to ultraviolet [87].

FSO has many advantages and among these are the lower costs related with the system, no RF license is required and the ability to exploit the massive potential bandwidth of OWC [88,89]. Using the MIMO technique in these types of systems has revealed great potential to improve the system performance [90,91].

An effective indoor optical wireless system is proposed in [90] using space-time block (STB) MIMO coding techniques coherently to provide gigabit level of indoor broadband communication. A straightforward extension of the SISO is proposed to provide a 2×2 optical IR MIMO system. It is discovered that coherent IR optical systems take benefit of the diversity gain offered by STB MIMO coding methods.

FSO systems gain the advantages of MIMO technique by the use of multibeam. In the FSO multibeam system, the same signal is sent from different LDs all using the same wavelength, as shown in Figure 13. In [92], the evaluation of the conventional 1-beam FSO system and 4-beam FSO (Figure 13) system are compared under heavy rain events from the point of view of BER versus link distance L, and SNR. Figure 14 illustrates the relationship among BER and reached distance when the BER is 10^{-9}, when multiple transceivers are used. Clearly, the various FSO transceivers framework gives a major improvement in reached distance and data rate [93].

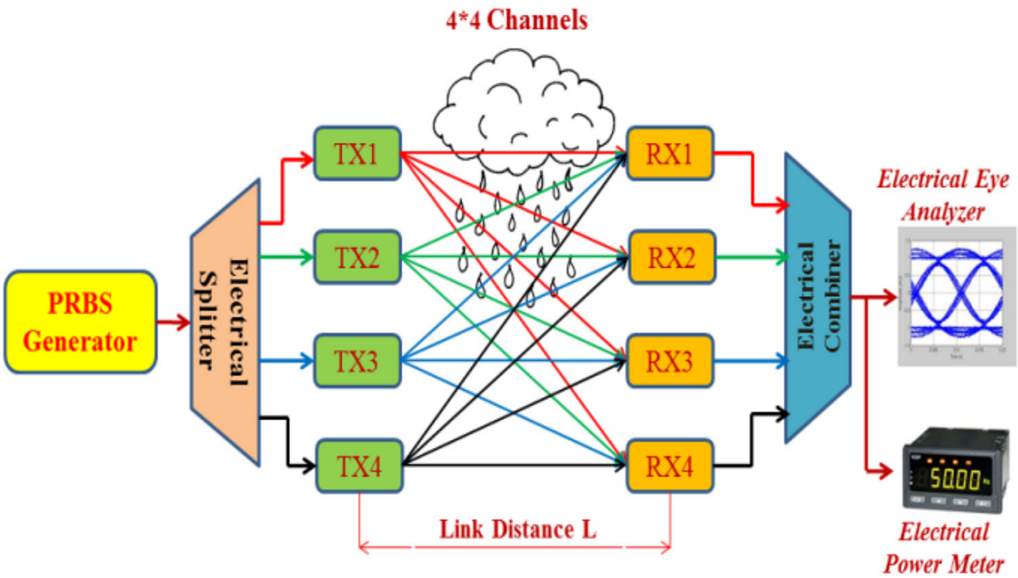

Figure 13. Block diagram for four beam free-space optics (FSO) system [88].

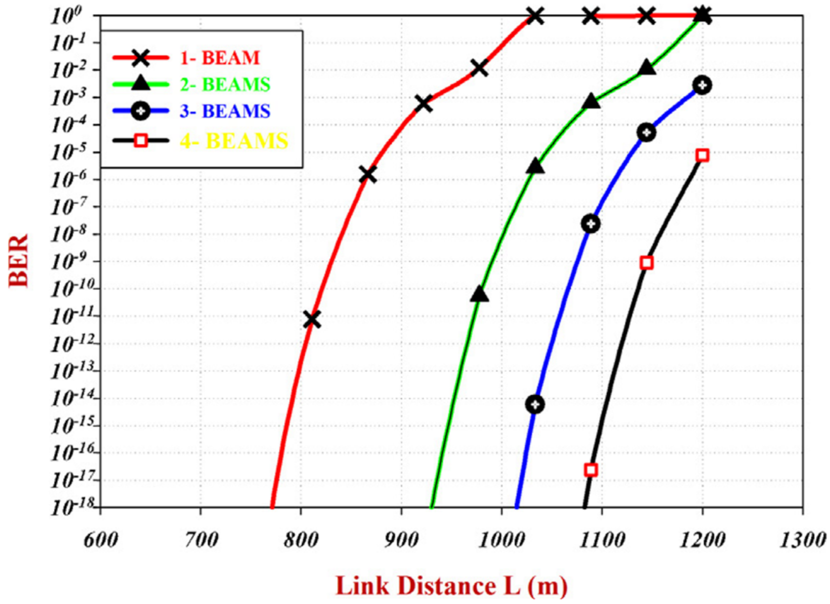

Figure 14. Bit error rate (BER) versus L for one-beam, two-beam, three-beam, and four-beam FSO system [92].

6.7. 5G MIMO Signals over Fibre

It is observed that 5G network technology would enable 20 Gb/s peak rate per cell and 1000 times data traffic compared to the existing 4G LTE [94]. 5G systems can support MIMO technology, enhancing the spectral efficiency and satisfying the high data rate requirements for today's mobile devices [67]. Moreover, the RoF is the qualifying technology for the future 5G cellular networks [95,96], which can be used in combination with the MIMO technology.

A unique 5G architecture for the backhaul of 5G MIMO signals over an optical network that is based on UDWDM is proposed in [67]. A big number of OLTs is unified through a ring architecture permitting them to communicate, exchange information and deliver access to ultra-dense mm-wave networks, as shown in Figure 15. One of the main advantages of this system is the use of a comb generator to generate multiple wavelengths from a single laser source. However, multiple LDs and PDs are still needed in the ONU. In addition, the wireless transmission in only over 2.2 m. The extreme bit rate is equal to 4.8 Gbit/s over a bandwidth of 1.96 GHz.

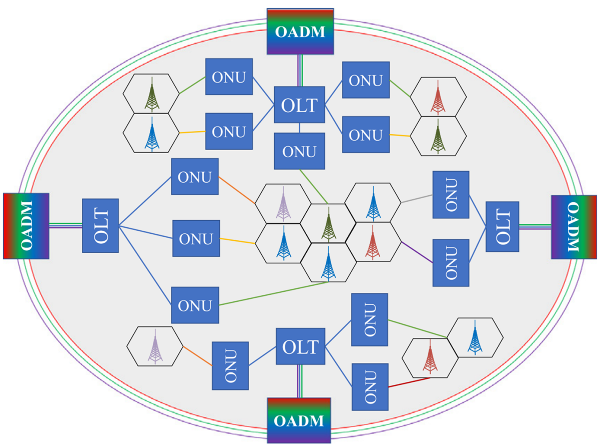

Figure 15. The ring infrastructure of the UDWDM PON based on the approach of 5G over PON presented in [67].

An analogue indoor dispersed antenna system (DAS) for 5G mobile communications, which supports 4 × 4 MIMO, is demonstrated in [94]. The maximum bit rate is identical to 5.3 Gbit/s. CWDM is utilised in order to multiplex the different 5G MIMO signals, which means each MIMO stream needs a separate wavelength widely separated from the adjacent wavelength. This will limit the number of users especially if the system is used in a PON environment as in [42,97].

In [96], a high capacity MIMO-enabled all-optical analogue-millimetre-wave-over fibre (A-MMWoF) fronthaul architecture is demonstrated for 5G. WDM is for transporting MMW MIMO signals in the optical domain.

6.8. DRoF MIMO Signals over Fibre

Both ARoF and DRoF solutions have been studied to provide the last-mile wireless coverage [98]. ARoF based systems also suffer from chromatic dispersion, nonlinearity, and losses in the optical sources, detectors, links, and other passive or active components [99]. On the other hand, DRoF system can completely remove these effects on the analogue carrier for long-distance transmission by conveying digital bits, which present the radio frequency (RF) carriers over optical fibre with an error-free transmission till bit error rate (BER) is intolerable. However, for short distances, the traditional ARoF will be more practical, since no digital to analogue is required and the fibre dispersion effect is not high. In [100], both ARoF and DRoF are compared as fronthaul for 5G 8 × 8 MIMO signals. The ARoF reduces the cost of the infrastructure. However, it is not as future proof as to the DRoF system. The study concludes that there is a trade-off between Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) for a given deployment. For example, if there is no plan for future expenditure or other types of traffic to be introduced to the network in the future, then ARoF is the right choice in this case.

7. MIMO Wireless Signals over PON

For wireless broadband transmission, MIMO is an indispensable technique for all the new wireless standards and systems that require a high data rate. On the other hand, PONs are well established as high broadband speed access networks. The integration of the MIMO technique with the existing PONs is highly desirable to get the better of the two worlds. In this section, integrated technologies and backhauling of MIMO wireless signals over different types of PONs are reviewed.

7.1. MIMO Wireless Signals over TWDM-PON

In [6], a bidirectional RoF-PON capable of manging MIMO streams at slight cost, high spectral efficiency and backward compatibility with currently installed PON is proposed. The major advantage of this work is the compatibility with currently deployed PON. Reusing the existing deployed ODNs is extremely beneficial and cost-effective for providing the original high data rate wireless demands, as shown in Figure 16. Moreover, most of the existing PON are based on TDM-PON ODN and FSAN has designated TWDM-PON (TDM-PON ODN with WDM operation) as a primary solution for NG-PON.

This architecture is a bidirectional asymmetric RoF-PON with whole 40/10Gb/s DS/US transmission for 32 RAUs at a distance of 20 km. Figure 17 illustrates the RoF-PON architecture that is able to handle multiple MIMO streams. The OLT has eight LDs and, using the comb technique (Figure 8b, twenty-four wavelengths are produced from these. Sixteen of them (upper and lower sidebands) are used to transmit the DS traffic and the other eight wavelengths are used to transmit the US traffic. Each two MIMO wireless signals in the DS transmission are optically merged using PDM, as shown in Figure 17.

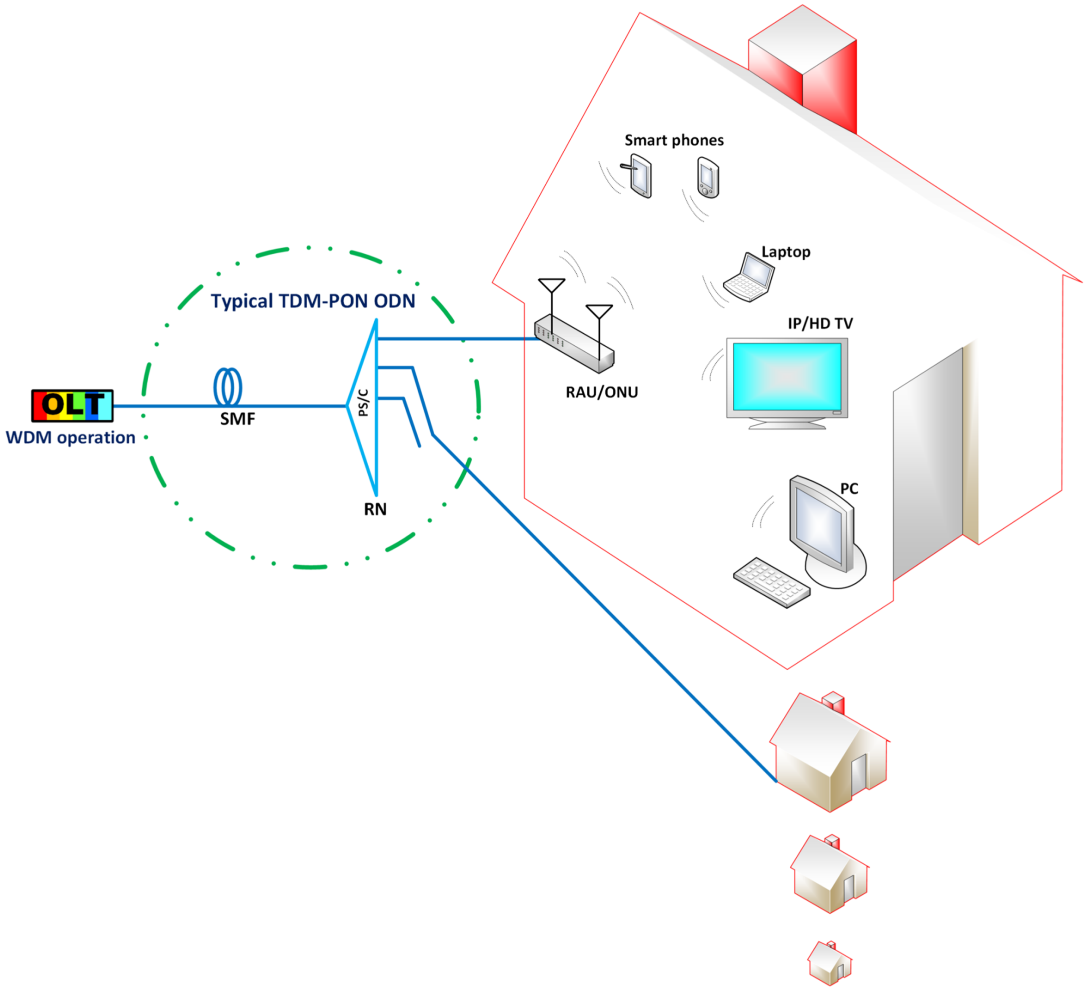

Figure 16. Generic architecture of compatible MIMO RoF-PON.

Figure 18 illustrates the constellation diagrams of the US wavelengths, which are still clearly separated even after a transmission of 20 km SMF. Hence, there is still a possibility for improvement in this system since NG-PON requires a reach higher than 40 km [101]. Also, the number of ONUs/RAUs is required to be 64 RAUs or above [102].

In [103], Massive MIMO over TWDM-PON is proposed with a support for beamforming. Three heuristic algorithms were proposed to optimise the fronthaul bandwidth and radio resource utilisation. This study’s concern is on resources utilisation, such as antennas, optical wavelength and radio frequency. It is found that the optimisation is heavily dependent on the number of antennas in an ONU.

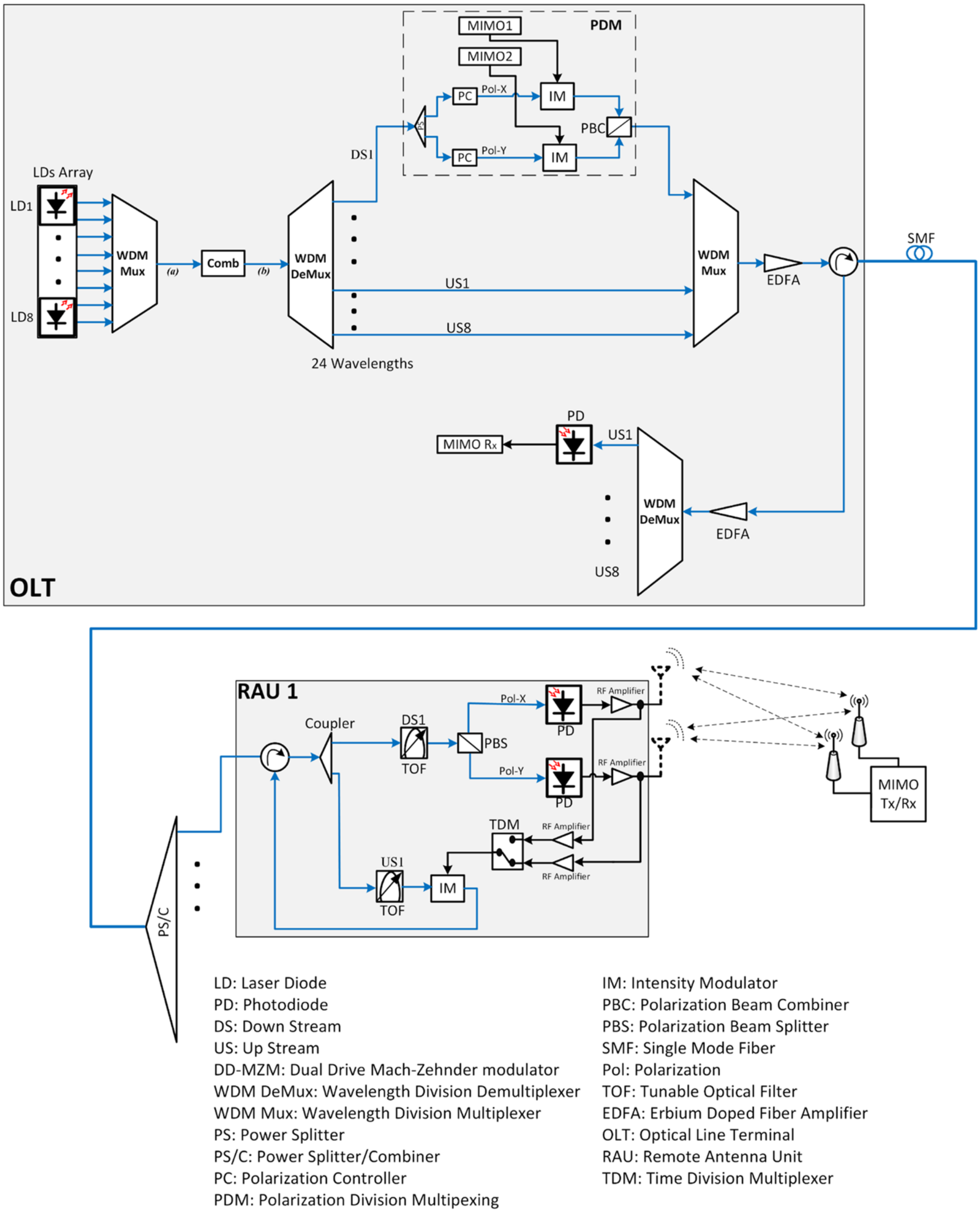

Figure 17. Detail block diagram of the proposed MIMO ROF-PON design [6].

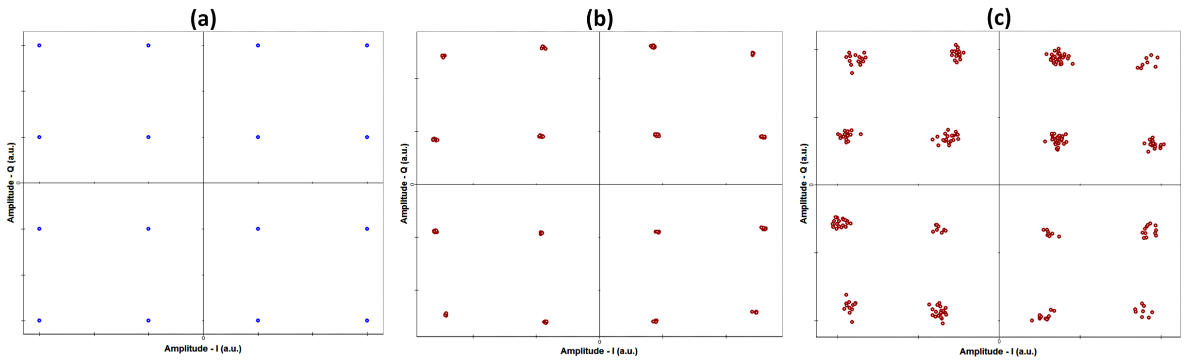

Figure 18. Constellation diagrams of one of the US wavelengths for (**a**) transmitted signal, (**b**) BtB, and (**c**) 20 km [6].

7.2. MIMO Wireless Signals over WDM-PON

In [40], a novel technique is proposed to carry two MIMO streams along with one BB wired signal in a single wavelength. This system can upgrade the conventional WDM-PON to support MIMO wireless transmission besides the extant wired signal, as shown in Figure 19.

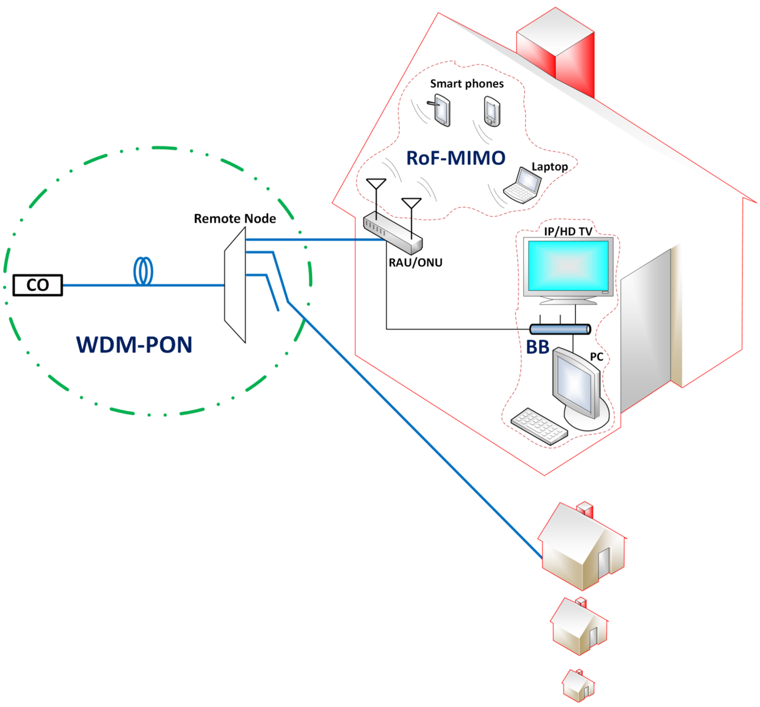

Figure 19. Generic architecture of the BB and MIMO-RoF WDM-PON.

First, the BB wired signal is modulated at a low extinction ratio (ER). Then, the same optical signal is reused to modulate two wireless MIMO streams, which are multiplexed optically using PDM.

Figure 20 illustrates the schematic diagram of the proposed system with the relevant spectra where the signal transmitter in the CO and a receiver in the ONU (or RAU) are organised, which can be implemented using a WDM-PON architecture. Figure 21 shows the constellations of one of the MIMO signals in the three cases (BtB, 20 km and 60 km) when the signal is transmitted and received. Even after a transmission of 60 km, the system is still maintaining a good performance as well as the BB signal, which also has a wide-open eye diagram, as shown in Figure 22. Hence, the overall system performance is extremely dependent on the BB signal's ER. Integration between the MIMO signals and the BB signal without BB signal's ER dependency is more preferable.

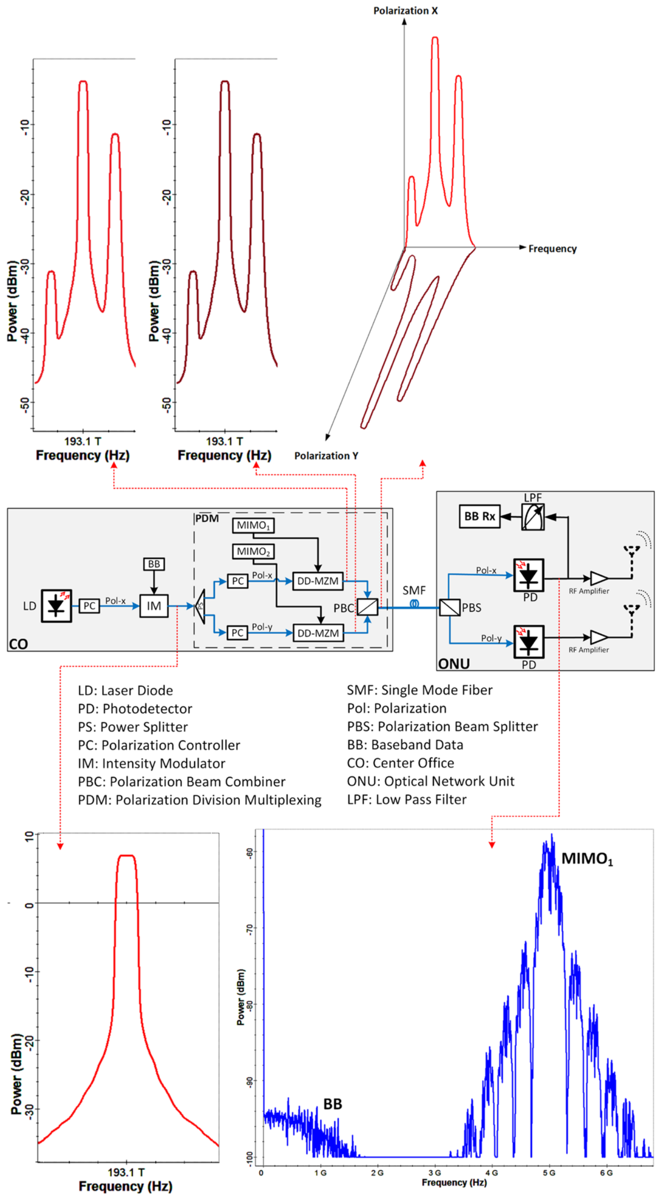

Figure 20. Schematic diagram of the proposed system with the corresponding spectra [40].

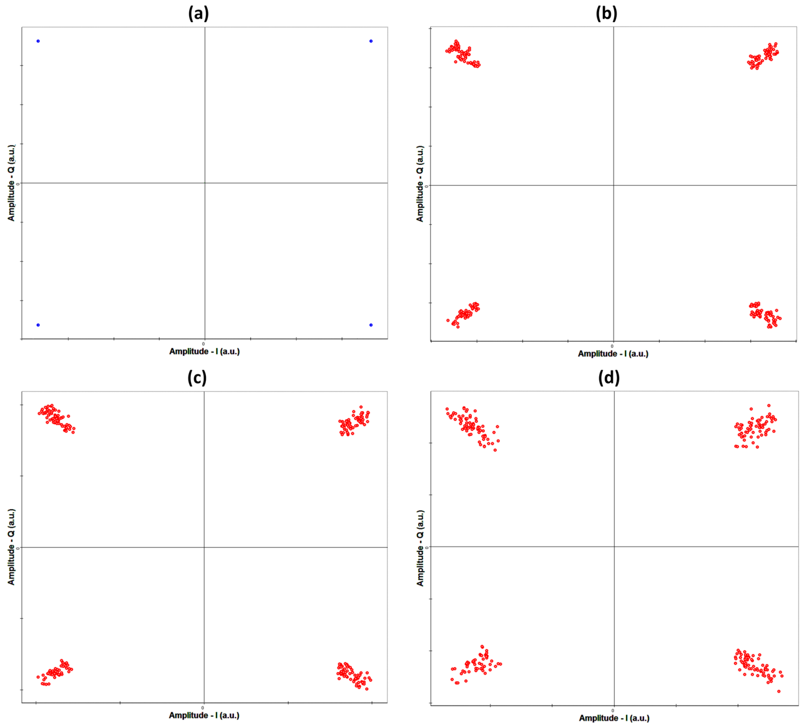

Figure 21. Constellation diagrams of $MIMO_1$ for (**a**) transmitted signal, (**b**) BtB, (**c**) 20 km, and (**d**) 60 km [40].

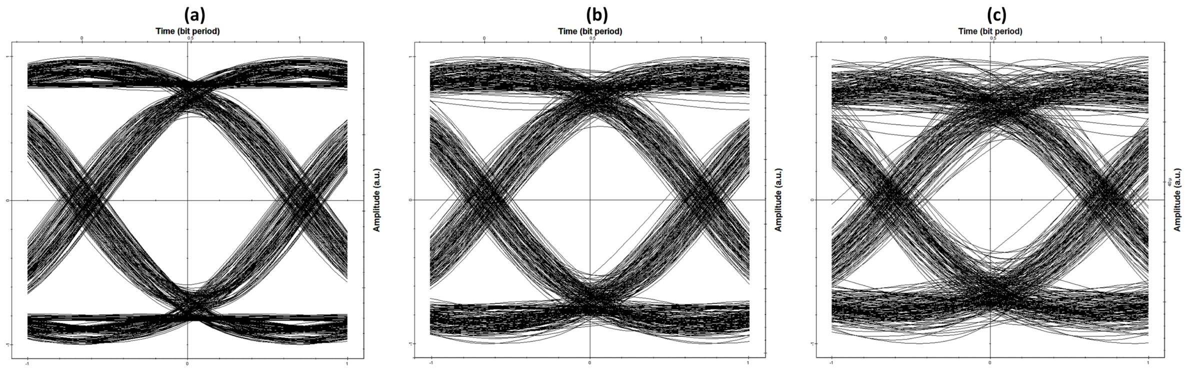

Figure 22. Eye diagrams of the BB signal for (**a**) BtB, (**b**) 20 km, and (**c**) 60 km [40].

7.3. MIMO Wireless Signals over Hybrid TDM-WDM PON

A spectral efficient hybrid wireless optical broadband access network (WOBAN) is demonstrated and proposed based on the transmission of wireless MIMO OFDM signals (WiFi type) over hybrid TDM–WDM PON, as shown in Figure 23. WOBAN consists of an OLT, which sends the traffic to different wireless APs using bidirectional SMF. The tasks of assigning the different wavelengths and time frames to the APs are performed in the OLT. Each LD at the OLT generates three wavelengths using the comb technique (Figure 8a). The first and the second are used to carry X_1 and X_2 signals and the third is reused in the AP for the upstream, as shown in Figure 23.

The constellation diagrams of the received and transmitted signals for one of the APs are shown in Figure 24. It is clear that, after the WiFi wireless transmission and 20 km SMF transmission, a clear scatter-plot is achieved.

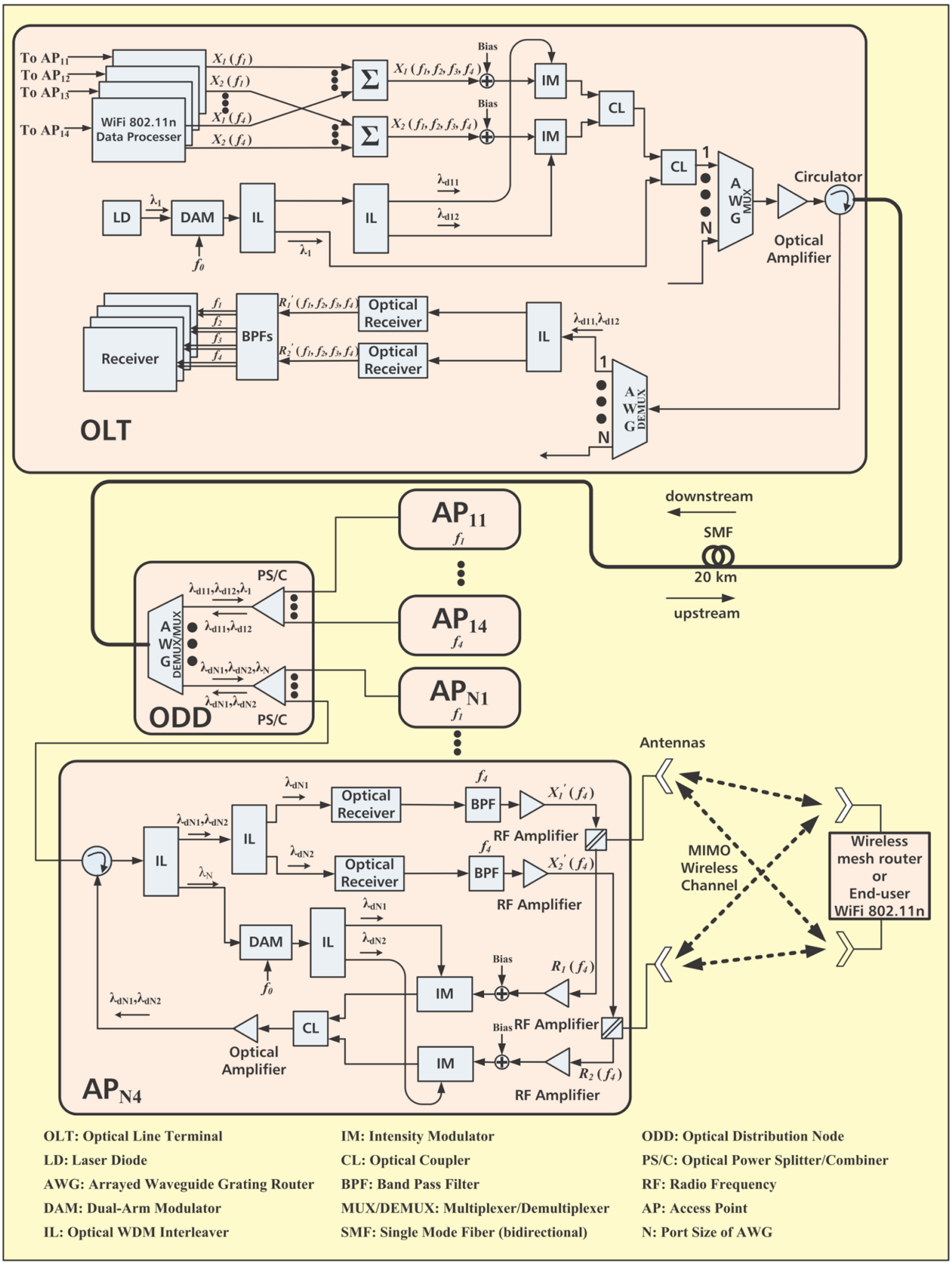

Figure 23. Detail block diagram of the proposed wireless optical broadband access network (WOBAN) [72].

This system can be improved by introducing high-density modulation or a higher order QAM modulation, such as 256-QAM as proposed in the new WiFi standards. Another possible way to improve is to introduce massive MIMO and study the trade-off between increasing the modulation order and increasing the MIMO streams.

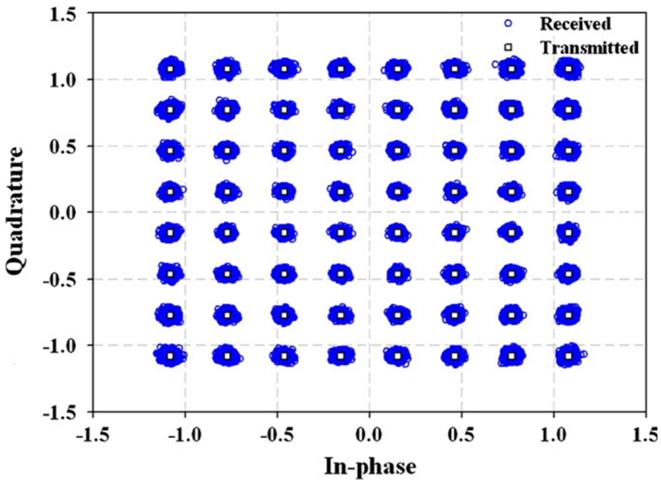

Figure 24. The constellation diagram of the transmitted and received power signal from the data processor of the AP11 at OLT to the wireless end-user [72].

8. Future Research Trends

The research directions given below are likely to be important for future FiWi MIMO access networks:

- Most of the proposed MIMO-RoF systems are considering low order MIMO streams. Since Massive MIMO (high order MIMO streams) is a key point in the future of broadband wireless transmission and 5G networks [80,104], it has to be considered in the upcoming research of MIMO-RoF systems.
- In 5G technology, besides using Massive MIMO, the "mobile communication systems need to support the digital baseband modulation techniques with large constellation size in order to provide higher data transmission rates. However, realising the attractive benefits of the massive MIMO and higher order QAM modulation in practice faces some challenges in wireless transmission, and one of which is the uplink multiuser signal detection due to the increased multiuser interference and the shrunk spacing among the modulation constellation points" [105]. The optimised solution has not been studied for Massive MIMO signals and high-order modulation over fibre. In spite of the importance of this topic and that it is a bottleneck for cost-effective next-generation wireless coverage, it is not studied for wireless MIMO signals over fibre transmission.
- Even though OFDM-PON is a very promising technology for NG-PON [106,107], so far there are no proposed integrations for MIMO-RoF wireless transmission over OFDM-PON.
- Low-cost solutions for integrated transport of diverse MIMO wireless technologies, for example, multiband OFDM-UWB and WiFi IEEE 802.11ax, are particularly important for infrastructure consolidation through long-reach PONs [77].
- Also, from an economical point of view, it is very desirable for operators to upgrade current PONs to deliver wireless services by the least changes in the deployed infrastructure [12,108]. Therefore, reusing the existing ODNs is highly valuable and cost-effective for providing the new high data rates demands. More research studies are needed for seamless integration and compatibility of underlying MIMO wireless transmission over deployed ODNs (as proposed in [6]). Moreover, backhauling of 5G/6G signals has not yet been studied enough as RoF signals over PONs.
- 5G and beyond will implement small cells; therefore, it is highly desirable to lower the cost of the RAU/AP, since multiple RAUs/APs will be used in a relatively small area.

9. Conclusions

In this paper, we focused on hybrid optical–wireless networks, mainly MIMO wireless signals over optical fibre. We discussed numerous promising solutions for MIMO-RoF and hybrid MIMO FiWi networks. The transport schemes of MIMO wireless signal over fibre were also reviewed and compared. Both basic and advanced transport techniques have been discussed. Integration and backhauling of MIMO wireless signals over PONs are also presented. Using the MIMO technique with FSO/OWC systems for wireless transmission was also reviewed. The MIMO technique can improve future performance of FiWi bandwidth-demanding networks.

Author Contributions: Conceptualisation, M.A.E., and A.S.; methodology, M.A.E, A.S., and A.A.; formal analysis, M.A.E, A.S., and K.R.; software, validation, writing—original draft preparation, M.A.E., and A.S.; writing—review and editing, M.A.E., A.S., A.A., and K.R.; supervision, project administration, and funding acquisition, M.A.E., and K.R. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would like to express their gratitude to the Ministry of Education and the deanship of scientific research—Najran University—Kingdom of Saudi Arabia, for their financial and technical support under code number NU/ESCI/17/084.

Conflicts of Interest: The authors declare no conflict of interest.

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