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Towards a Converged Optical-Wireless Fronthaul/Backhaul Solution for 5G Networks and Beyond

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1.1 Introduction

Recently, there has been a high increase in cellular wireless traffic. The traffic surge can be attributed to the exceptional proliferation of smart mobile devices as well as perpetual deployment of bandwidth intensive applications and services. To attend to the network demands, radio access networks (RANs) have been revolutionized from one generation of network to the other. The fifth generation (5G) wireless networks are envisaged to be the viable solutions for meeting the increasing network demands by offering ultra-reliable low-latency communications (URLLC). There are different aspects of the system that need consideration in order to make future wireless communications feasible. One such is the link spectrum efficiency (SE) in which the bandwidth of point-to-point radio frequency (RF) transmissions have been exploited through the implementation of multiple-input and multiple-output (MIMO) techniques, high-level modulation formats, and advanced channel coding schemes such as Turbo and low-density parity-check (LDPC) codes. Nevertheless, the system SE can be further improved by employing schemes such as cognitive radio in order to dynamically exploit the underutilized or "white space" spectrum [Liu et al. - 2014; Alimi et al. - 2017c, b, 2018a, 2017d].

Furthermore, coordinated multipoint (CoMP) transmission can be employed for adjacent cell coordination so that they can jointly transmit signals to cell-edge users. The implementation can considerably improve the system SE by alleviating inter-cell interference and enhancing the data rate of the edge users. In addition, apart from the limited, heavily regulated, and congested RF in the lower-frequency spectrum, there are vast and unexploited spectra at higher RF bands such as the millimeter-wave (mm-wave) band [Liu et al. - 2014; Chang et al. - 2013]. Apart from the fact that the bands are capable of supporting multi-gigabit wireless transmission, the use of

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complicated and time-consuming modulation and coding techniques are not necessary [Chang et al. - 2013]. Moreover, small-cell concepts have also been considered for improving the system performance, mainly in terms of capacity. The concept is based on reducing the cell size in order to reuse limited spectral resources among cells. Nonetheless, apart from inter-cell interference management, which is really challenging in small-cell implementation, capital expenditure (CAPEX) and operating expenses (OPEX) are also demanding [Liu et al. - 2014; Chang et al. - 2013].

The chapter is organized as follows. Section 1.2 discusses the cellular network interface and solution. In Section 1.3, we present a comprehensive discussion on the 5G enabling technologies. We introduce the concept of fiber-wireless network convergence in Section 1.4. In Section 1.5, we present a broad explanation of the radio-over-fiber transmission scheme. Optical transport network multiplexing schemes are detailed in Section 1.6. Wireless based transport networks are considered in Section 1.7. Experimental channel measurement and characterization are presented in Section 1.8. The obtained simulation and experimental results as well as comprehensive discussions are presented in Section 1.9 and concluding remarks are given in Section 1.10.

1.2 Cellular Network Interface and Solution

This chapter primarily focuses on centralized/cloud RAN (C-RAN) architectures due to their salient advantages such as cost-effectiveness, efficient centralized processing, better service provisioning, support for dynamic resource allocation and mobile traffic load balancing. So, in this section, we consider C-RAN interfaces such as mobile backhaul (MBH) and mobile fronthaul (MFH). Moreover, more attention is paid to the MFH interface because of the stringent requirements that it presents to current and future networks. To achieve this, we discuss the associated radio interface that can be employed for the in-phase and quadrature (IQ) data transmission between central units (CUs) and distributed units (DUs).

1.2.1 MBH/MFH Architecture

This subsection presents the concepts of MBH and MFH network connectivity segments for a C-RAN.

1.2.1.1 Mobile Backhaul (MBH)

In a C-RAN, the core network is generally connected to the base stations (BSs) through the MBH. The connection can be typically realized by means of an IP/ethernet based network. Consider the long term evolution (LTE) network for instance: the evolved node Bs (eNBs) are connected to one another via X2 interfaces. Moreover, S1 interfaces connect the eNBs to the evolved packet core (EPC). Furthermore, the eNBs are connected to the mobility management entity (MME) and serving gateway (S-GW) through the S1-MME and S1-U interfaces, respectively. It is worth mentioning that the S1 is a logical interface that has the ability to maintain many-to-many relations among MMEs/S-GWs and eNBs. In general, the MBH is the transmission medium for the user data as well as control and management data between the EPC and eNB. In addition, it is the transmission medium for handover and coordination signals between the eNBs [Alimi et al. - 2018a].

1.2.1.2 Mobile Fronthaul (MFH)

The MFH-based network is related to a centralized architecture in which the baseband processing functions are centralized so that not only remote antenna unit (RAU) operation can be simplified but also an enhanced cooperation can be realized among the BSs. In general, the fiber-optic-based MFH can be grouped into analog MFH and digital MFH.

Signal transmission between the network elements such as baseband units (BBUs) and remote radio heads (RRHs) is mainly based on digital radio over fiber (D-RoF) technology. This is in an effort to ensure waveform transparency as well as cost-effectiveness. Furthermore, the connection between the BBUs and RRHs are mainly based on the common public radio interface (CPRI). However, with URLLC, enhanced mobile broadband (eMBB), and massive machine-type communications (mMTCs) that are envisaged by the 5G RANs, there is a considerable need for a diverse spectrum and carrier aggregation (CA) of radio carriers to enhance the system capacity, throughputs, and efficiency. In addition, mm-wave and massive MIMO (M-MIMO) antenna are promising technologies that will be integrated into both standalone and non-standalone versions of 5G new radio for a significant network capacity improvement. However, implementation of these technologies give rise to enormous capacity requirements in the MFH network.

The exigent bandwidth required by the MFH network, as discussed in subsection 1.3.2, is really difficult to be addressed by the CPRI-based fronthaul solution. Therefore, alternative solutions are required for an effective and viable MFH. One such solution is analog radio-over-fiber (A-RoF) transmission technology [Alimi et al. - 2018a]. The associated advantages of A-RoF implementation are discussed in Section 1.5. In the following subsections, we discuss the ideas of MBH/MFH transport network integration.

1.2.2 Integrated MBH/MFH Transport Network

As stated earlier, due to the high-cost of a limited radio spectrum and the growing demand for mobile broadband capacity, radio features require disruptive infrastructural change and redesign. So, for effective network redesign, consolidated BS schemes such as C-RAN can be adopted. Moreover, adoption of C-RAN systems aids in the implementation of schemes such as CoMP and CA, which can be of great help in radio coverage expansion and optimization. Furthermore, since C-RAN is based on decoupling the BBUs and remote radio units (RRUs), the link between them is no longer a mere one-to-one connection because of the increase in distance as well as consequential transmission latency that may significantly impact radio performance [Eri - 2018a]. The subsequent network link is known as a fronthaul transport network. The fronthaul networks are mainly based on CPRI for the baseband samples distribution. It is remarkable that, besides the Open Base Station Architecture Initiative (OBSAI), enhanced CPRI (eCPRI) can as well be used for connecting eCPRI radio equipment and eCPRI radio equipment control [Parties - 2017]. The major function of the fronthaul is to ensure that the BBUs connect seamlessly to the RRUs without impacting radio performance. To achieve this, certain stringent radio requirements have to be met in cost-efficient ways. Moreover, in the LTE C-RAN architectures, a backhaul transport network signifies the internet protocol (IP) network from the centralized BBUs to the EPC [Eri - 2018a].

It is envisaged that the 5G transport networks will employ heterogeneous data plane technologies for supporting both fronthaul and backhaul traffic. So, there have been different innovative integrated fronthaul/backhaul transport networks such as 5G-Crosshaul [Dei et al. - 2016; Xhaul et al. - 2018; Anyhaul Nok - 2017]. The transport networks are majorly software-controlled for flexible and efficient management of the fluctuating nature of the new generation network capacity demand. A way of achieving this is by employing a common frame format and forwarding abstraction for information exchange in the network [Dei et al. - 2016].

1.3 5G Enabling Technologies

The International Mobile Telecommunication 2020 (IMT-2020) envisioned 5G application scenarios/use cases towards unprecedented mobile broadband communications considering high data rate, ultra-low latency as well as ubiquitous access are URLLC, eMBB, and mMTC. There are a number of enabling technologies that can be employed for effective realization of the 5G concepts in order to support the use cases. In general, there will be tremendous need for ultra-dense deployment of small cell and M-MIMO with the integration of high-data-rate MFH networks based on mm-wave frequencies. Apart from being license-free or light licensed, mm-wave enables higher frequency reuse. Also, C-RAN architecture can also be employed for better radio resource management and coordination so as to mitigate inter-cell interference. So, in this section, fundamental concepts and technologies such as ultra-densification, mm-wave small cells, M-MIMO, advanced radio coordination, C-RAN and RAN virtualization, as well as optical-wireless convergence are presented.

1.3.1 Ultra-Densification

In 5G and B5G networks, there will be huge demand for ultra-dense deployment of small cells. The major concept of ultra-densification is to enhance the RAN capacity by means of dense deployment of low-power and low-cost small cells for both indoor and outdoor scenarios. This can be achieved by overlaying small cells on the conventional macro cells that are primarily deployed for coverage purposes. Consequently, the transport networks are facing huge increase in the number of connected network elements. The growing connections not only increase the transport network complexity concerning cost but also regarding power consumption. Therefore, there is a need for further efforts to achieve more energy-efficient and cost-effective transport solutions for the 5G and B5G networks [Fiorani et al. - 2015].

1.3.2 C-RAN and RAN Virtualization

Conceptually, C-RAN is based on separation of conventional cell sites digital BBUs from the mostly analog RAUs/RRHs. Moreover, for centralized signal processing and management, the BBUs are redeployed to the "cloud" (BBU pool). This decoupling simplifies the usually complicated conventional cell sites, consequently enabling the implementation of power-efficient and cost-effective RRHs. This also helps in reducing the environmental effects and CAPEX for deploying a massive small-cell system by helping in reducing the footprint and cooling/power requirements at the cell sites. Furthermore, with centralized processing, network management can be simplified considerably. Also, advanced and efficient coordination among cells can be achieved to enhance the system performance and reduce the OPEX [Liu et al. - 2014].

There are different measures that can be employed in achieving the cloud-RAN objectives. BBU centralization or BBU hoteling can be implemented. In this scheme, several independent BBUs running on specialized hardware (HW) are co-located at the central office (CO). Moreover, BBU pooling is another scheme that can be employed. In this scheme, dedicated HW resources are shared between the co-located BBUs. In addition, a "cloud" RAN platform can also be employed. In this scheme, BBU functions are supported and running on commercial off-the-shelf HW that is located in the cloud. It should be noted that BBU pooling and cloud RAN platforms are associated with the existing development in network function virtualization (NFV). The NFV idea is based on sharing of resources by isolation and abstraction of network functionalities. Centralization of baseband processing functions is highly essential for HW resources sharing and virtualization. This helps HW resources to run on general purpose processors (GPPs) in the RAN virtualization schemes. There are various advantages to C-RAN and RAN virtualization. A notable one is the reduction of CAPEX and OPEX through HW sharing that can enable the use of low-cost GPPs. Moreover, it supports centralization of baseband processing, control and management functions. This facilitates CoMP by ensuring tighter and dynamic coordination between cells [Liu et al. - 2014].

Furthermore, it should be noted that, within the 5G and B5G context, ultra-dense deployment of RRHs is envisaged. This results in a deployment challenge considering the availability and cost of fiber-optic for the MFH/MBH networks. It is noteworthy that stringent requirements are also imposed on the fronthaul links concerning jitter, latency, and bandwidth for transporting multiple duplex radio transmissions. This is even more challenging with the application of CoMP since the number of RRHs that can access the same BBU pool at the same time will be limited.

D-RoF based CPRI is the most extensive means of conveying digital baseband oversampled I/Q streams in the C-RAN fronthaul. Nevertheless, optical links based on CPRI require huge throughput and capacity of the backhaul/fronthaul networks [Kuwano et al. - 2014; Chang et al. - 2013]. In addition, due to the separation of the media access control (MAC) and PHY layer functionalities at the BBU and RRH, jitter and latency become considerable issues in the digital-sampling-based C-RAN MFH links [Liu et al. - 2014; Chang et al. - 2013]. Meanwhile, the requirements for transmitting multiple streams, multi-RRH joint processing, high number of radio channels, and channel monitoring and estimation demand a high bit-rate in the order of Tbit s^{-1} [Monteiro and Gameiro - 2016, 2014].

Practically, multiple antennas as well as multiple radio access technologies (RATs) are usually supported by the mobile network operators (MNOs) MFH network. Consequently, it is desirable to aggregate the bit-rates into multiple tens of Gbps with several RRHs that are connected to a common BBU pool by the CPRIs. Moreover, the achievable data rate is contingent on features like the carrier bandwidth, the RAT being employed, as well as the number of employed multiple antennas. Considering these, the CPRI bandwidth for multi-sector and multi-antenna configurations can be defined as [Alimi et al. - 2018a]

$$B_{\mathrm{CPRI}} = N_{\mathrm{s}} M f_{\mathrm{s}} \upsilon N C_w C, \tag{1.1}$$

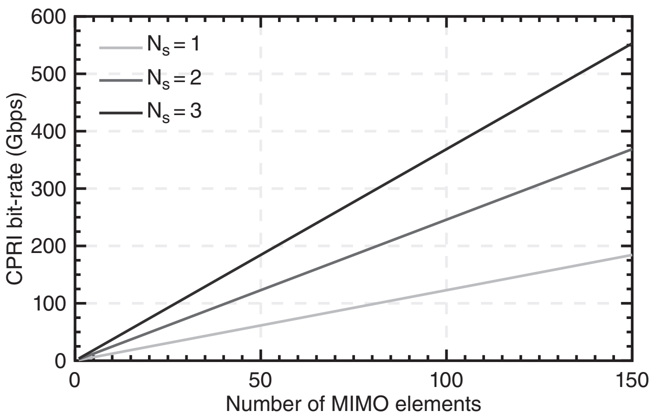


Figure 1.1 CPRI data rate for multi-sector and multi-antenna configurations.

where N_s represents the number of sectors per RRH, M signifies the number of antennas per sector, f_s is the sampling rate (frequency) that is employed for digitization (sample/s/carrier), N denotes the sampling bit-width (bits/sample) for I/Q samples, the number $\upsilon = 2$ is a multiplication factor to account for the (IQ) data, C_w denotes the factor of CPRI control word, and C is a coding factor (either 10/8 for 8B/10B code or 66/64 for 64B/66B code).

Figure 1.1 illustrates the required bandwidth of a CPRI for multi-sector and multi-antenna configurations. It can be inferred that the required bandwidth increases with an increase in the number of sectors N_s and/or the number antennas M per sector. For instance, when $N_s = 3$, the required bandwidth for 4×4 antenna configurations is 14.75 Gbps, this eventually increases to 29.49 Gbps with 8×8 antenna configurations.

In 5G and B5G networks, the required bandwidths are expected to be even more challenging. For instance, with CA of five 20 MHz LTE, a mobile signal with 8×8 MIMO antennas and $N_s = 3$, about 147.5 Gbps fronthaul data rate will be required by the CPRI. Consequently, to attain the high-bandwidth requirement of the current and future mobile fronthaul technologies, installation of new optical fibers or a substantial amount of high-speed optical ON–OFF-keying transceivers will be needed to support high data rate MFH implementation [Liu et al. - 2016]. Consequently, employment of advanced measures is essential to realize bandwidth-efficient MFH that is capable of addressing the bandwidth and flexibility limitations [Liu et al. - 2014]. Furthermore, the 5G RANs are envisaged to have as a feature, 100 MHz channels with M-MIMO; this brings about enormous capacity demand in the MFH. Therefore, the CPRI-based oversampled approach might be challenging considering effective scalability. Subsequently, this can result in the implementation of the conventional analog A-RoF transmission technology, as discussed in Section 1.5.

1.3.3 Advanced Radio Coordination

It is envisaged that future networks will adopt different innovative radio coordination schemes like enhanced inter-cell interference coordination (eICIC) as well as CoMP in order to improve the system performance. The schemes can be implemented for adjacent cell coordination. This will ensure that the signal is jointly and effectively transmitted to the cell-edge users. The implementation can considerably improve the radio network spectral efficiency specifically by alleviating inter-cell interference and enhancing the data rate of the cell-edge users [Fiorani et al. - 2015; Alimi et al. - 2018a]. In addition, there are a number of coordination levels, such as moderate, tight, and very tight, that present distinct limitations on the transport network. For instance, a moderate coordination technique like eICIC introduces no precise requirement regarding transport performance. However, tight coordination schemes present stringent latency constraints (i.e. between 1 and 10 ms), although very strict capacity constraints (i.e. < 20 Mbps) are not presented. Furthermore, unlike the moderate and tight coordination schemes, a very tight coordination scheme poses very challenging constraints regarding both capacity (i.e. several Gbps using CPRI) and latency (< 0.5 ms) [Fiorani et al. - 2015].

1.3.4 Millimeter-Wave Small Cells

It has been observed that the lower-frequency bands of RF are limited, heavily regulated and highly congested. Consequently, the recent research trend for 5G wireless communication is towards the employment of higher-frequency bands that are under utilized or unexploited. The higher-frequency band that is under consideration is the mm-wave band (30–300 GHz). The interest in this band is as a result of its sufficient spectral resource and ability to offer 1000× throughput demanded by the 5G networks. It is remarkable that there are vast unexploited spectra in the 70–80 GHz E-band in which the 60 GHz band, with 7 GHz license-free bandwidth that is more appropriate for the 5G mobile communications, is the major band of interest [Liu et al. - 2014; Kalfas et al. - 2016; Stephen and Zhang - 2017; Zhang et al. - 2016; Alimi et al. - 2018a].

The band has been attracting significant attention due to its support for compact and high-dimensional transmission and reception antenna array equipment [Kalfas et al. - 2016; Stephen and Zhang - 2017; Alimi et al. - 2018a]. In addition, the band has been taken into consideration because of the issued 60 GHz standards like WiHD (WirelessHD Consortium), 802.11ad (Wireless Gigabit Alliance), and 802.15.3c (IEEE 802.15.3 Task Group 3c) for multi-gigabit (high rate) wireless communication systems [Alimi et al. - 2018a]. Furthermore, like wired-based optical fiber solutions, implementation of mm-wave in RAN systems for MFH/MBH has been considered. This is due to certain offered benefits such as easy of deployment. Unlike wire-based solutions, the benefit makes it promising for the envisaged ultra-dense small-cell RRHs to be deployed in 5G networks. However, implementation of mm-wave for mobile cellular communications possesses a number of challenges. The requirements for line-of-sight (LOS) communication as well as high-speed but low-cost MFH/MBH links for supporting several small-cell RRHs is really challenging. In addition, inter-cell interference and mobility management deserve further consideration. Similarly, due to the characteristic as well as high propagation losses, mm-wave communications offer a shorter network range, although this is advantageous for the 5G small-cell C-RAN implementations [Liu et al. - 2014; Chang et al. - 2013; Kalfas et al. - 2016; Stephen and Zhang - 2017; Zhang et al. - 2016; Alimi et al. - 2018a]. This is due to the fact that implementation of small-cell C-RAN architecture ensures effective exploitation of the mm-wave bandwidth as well as minimization of the associated inter-cell interference and mobility management cost [Chang et al. - 2013].

1.3.5 Massive MIMO

The conventional MIMO concepts have been employed in standards such as 802.11ac (Wi-Fi), 802.11n (Wi-FI), WiMAX, HSPA+, and LTE. M-MIMO, an enhancement of conventional MIMO, is expected to play an important role in 5G and B5G networks by being one of the key enablers. As 5G and B5G networks are envisaged as supporting a huge amount of traffic, devices, applications and services, the capability of a large antenna array-based M-MIMO for spatially multiplexing multiple autonomous terminals concurrently at the physical layer enables it to be a promising and effective technology for attending to the envisioned next generation network requirements. In general, M-MIMO is a wireless technology that employs multiple transmitters (Txs) and receivers (Rxs) with a minimum of a 16×16 array for more data transfer. M-MIMO technology presents viable features that are really promising for 4G network evolution toward 5G and B5G [Eri - 2018b].

M-MIMO normally exploits the terminals' prolific as well as unique propagation signatures by using smart processing at the corresponding array in order to realize a superior performance. Consequently, it is able to present an outstanding throughput and better spectral efficiency desired by MNOs and subscribers by employing the same time-frequency resource for multiple terminals spatial multiplexing [Eri - 2018b]. Moreover, M-MIMO offers improved energy efficiency through array gain exploitation that enables a reduction in the radiated power. Thus, large antennas aid in more precise spatial energy focus in the miniature elements so as to achieve substantial throughput improvements as well as enhanced energy efficiency. These features enable M-MIMO base stations to offer better performance and at the same time help in reducing wireless network interference and eventually enhancing the end-user experience. However, for a transport network, M-MIMO present an enormous transmission capacity that might be really challenging for the CPRI-based fronthaul networks, as discussed in Section 1.3.2 [Fiorani et al. - 2015].

1.3.6 New Multicarrier Modulations for 5G

In an effort to meet the 5G requirements, innovative modulation and multiple access schemes have been investigated. It should be noted that the existing wireless networks have been leveraging on orthogonal frequency division multiplexing (OFDM) based transmission schemes due to their effectiveness and simplicity. However, OFDM modulation exhibits some drawbacks when employed in a system. A notable one is due to the reduction in power and spectral efficiency that is a result of cyclic prefix redundancy. Also, narrow band interference and low tolerance to frequency offset/synchronization errors are other implementation disadvantages. These limitations might be really challenging in an un-coordinated multi-user environment. These drawbacks necessitate innovative modulation formats for the 5G and B5G networks. A number of modulation formats that are based on precoding, pulse shaping and filtering have been presented in an attempt to reduce the out-of-band (OOB) power radiation or OFDM side-lobe leakage. However, a simple method for reducing the OOB leakage is filtering. Consequently, multi-carrier schemes such filter bank multi-carrier, generalized frequency division multiplexing, and universal filtered multi-carrier schemes have been presented. Furthermore, each waveform exhibits a tradeoff depending on the implementation scenario [Cai et al. - 2018; Maliatsos et al. - 2016].

1.4 Fiber-Wireless Network Convergence

With the inception of C-RAN, the network architecture is classified as a centralized unit (BBU pool), transport network, and remote unit (RU), which is typically the RRHs. As aforementioned, there have been different evolutions in RAN systems in order to cope with continuous growth in the network traffic. Subsequently, it is imperative for the transport network to also evolve accordingly. The MFH transport network is an essential segment of the 5G C-RAN due to the stringent requirement imposed on it [Liu et al. - 2014].

The transport networks are typically implemented with T1 lines, microwave point-to-point links, and optical fiber links. However, with the need for high-capacity transport network development in accordance with evolving RAN systems, optical fiber solutions are promising and attractive transport links with inherent huge and scalable capacity for 5G and B5G fronthaul and midhaul architecture implementations [Liu et al. - 2014]. As a result of the high data rate required by MFH, network centralization demands a huge number of fiber cores that are not only scarce but also expensive. Moreover, transport technologies like an optical transport network and wavelength-division multiplexing (WDM) can be employed to provide protection and conserve fiber consumption; however, the deployment costs for additional transport equipment presents economic concerns [Chih-Lin et al. - 2015]. Therefore, for fixed-mobile convergence, there has been active research effort on an effective means of leveraging different passive optical network (PON) architectures like 10 gigabit-class PONs and the next generation PON stage 2 (NG-PON2) defined by IEEE, Full Service Access Network (FSAN) and International Telecommunication Union, Telecommunication Standardization Sector (ITU-T) for fixed access and backhaul networks [Liu et al. - 2014].

Furthermore, for microwave-photonics technologies, optical fiber links can offer ultra-high-speed internet access for fiber to the x applications and backhaul networks while high-speed wireless access provisioning can be achieved by employing small cell based on C-RAN architectures as well as mm-wave MFH/MBH. It is remarkable that network convergence can be realized both for indoor and outdoor conditions. For instance, apart from indoor local area network visible light communication with the capability to offer energy-efficient lighting and high-speed, short-range wireless communication concurrently [Gupta and Chockalingam - 2018], WiFi systems and mm-wave small cells that are based on high-rate in-building optical fiber networks can be employed in the indoor scenario for enhancing the link throughput. Furthermore, outdoor networks can be achieved by employing optical fiber systems for mobile MFH/MBH of macro-cell and C-RAN systems [Liu et al. - 2014].

In general, the transport network should be made of high-capacity switches as well as heterogeneous transmission links such as high-capacity wired (e.g. copper, optical fiber) and wireless (e.g. mm-wave, optical wireless communication) links for connecting different network elements like the RRHs and BBUs. Also, they should have provisions for different cell types such as macro and small cells to be supported by the 5G and B5G networks. Furthermore, another important reason for heterogeneous transmission links is to achieve reliable communications. For instance, since outdoor small cells are normally mounted on lampposts instead of rooftops, it might be challenging to have a reliable connection. This is as a result of several obstacles in the rural–urban settings that can block the LOS between the transmitting and receiving network entities. Consequently, this shows the need for non-LOS technologies that can serve as alternative/complementary solutions [Oliva et al. - 2015].

1.5 Radio-Over-Fiber Transmission Scheme

The inception of C-RAN has brought about major architectural and functionality changes to cellular systems. A notable instance is in the BBU centralization that facilitates simplification of the RRH design in a power-efficient and cost-effective way [Monteiro et al. - 2015; Maier and Rimal - 2015]. This assists in dense deployment of the RRHs as close as possible to the network subscribers in order to enhance the enjoyed quality of experience.

In the C-RAN based architecture, the baseband signal processing and MAC layer functions have been moved to the CO BBU [Liu et al. - 2014; Chang et al. - 2013]. Additionally, with employment of smart antenna systems, the C-RAN architecture has the capability of increasing the system capacity considerably with low-energy consumption [Zakrzewska et al. - 2014].

1.5.1 Digital Radio-Over-Fiber (D-RoF) Transmission

As discussed in Section 1.2.1.2, signal transmission between the BBU pool and RRHs in the C-RAN is primarily based on D-RoF technology. This is normally achieved by a serial constant bit rate interface, CPRI, due to its efficient mapping methods. The PHY layer of the CPRI is generally optical fiber and is small form pluggable connectivity based. Moreover, the baseband processing centralization in the C-RAN architecture exploits the processing power multiplexing gain and helps in achieving a better energy-efficient cooling. These benefits comparatively enable the C-RAN architecture to be a more energy efficient system. Furthermore, it remarkable that the C-RAN architecture initiates innovative low-latency and high-speed transmission connectivity fronthaul links between the RRHs and the BBUs. However, as discussed in Section 1.3.2, stringent requirements are imposed on the fronthaul links due to D-RoF technology based CPRI being employed. Moreover, another digitized wireless transport technology is digitized intermediate frequency over fiber. The limitations of digitized wireless transport technologies demand effective MBH/MFH networks. Furthermore, efficient transport links can be realized by exploiting analog wireless transport technologies such as A-RoF and intermediate IFoF. It is remarkable that each technology has its benefits and drawbacks, depending on the application [Urban et al. - 2016; Alimi et al. - 2018a].

1.5.2 Analog Radio-Over-Fiber (A-RoF) Transmission

Additionally, the RAN system architecture can further be simplified by employing the A-RoF (RoF) transmission technologies. The A-RoF implementation helps in shifting expensive analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) to the BBU pool [Urban et al. - 2016; Alimi et al. - 2018a]. This results into another technology that is known as a cloud-RoF (C-RoF) access system. It is remarkable that, compared to the C-RAN architecture, the C-RoF access system simplifies the RU functionality by moving not only the ADC/DAC but also the RF frontend functions to the BBU pool. Subsequently, RF antennas with O/E and E/O converters are the major components that are left at the RU [Urban et al. - 2016; Liu et al. - 2014; Chang et al. - 2013].

Moreover, the C-RoF access scheme offers a number of advantages that makes it attractive for signal transmission. Due to the fact that the RF frontend has been moved to the BBU pool, then the generated RF signals at the BBU are transmitted to RUs over optical fiber fronthaul. With this, extensive RF ranges (i.e. ∼1–100 GHz) can be transmitted through the shared C-RoF infrastructure. In addition, compared to the typical digital-baseband-transmission method that usually allows one band or service at a time, the RoF schemes support multi-service, multi-band and multi-operator coexistence in a shared infrastructure. The protocol-agnostic and infrastructure-sharing attributes of the RoF scheme assist in reducing the associated cost of small-cell deployment. With an IFoF system, multiple wireless signals can be assigned with multi-IFs and then multiplexed in the frequency domain in order to support MIMO services [Cho et al. - 2014]. Also, compatibility issues between the existing services and the future ones can be addressed by the RoF scheme [Urban et al. - 2016; Liu et al. - 2014; Chang et al. - 2013].

1.6 Optical MBH/MFH Transport Network Multiplexing Schemes

MBH/MFH transport network provisioning is largely based on optical fiber solutions. These can be achieved with single mode fiber (SMF) and/or multi-core fiber (MCF) [Alimi et al. - 2018a]. In the subsequent subsections, we expatiate on schemes such as WDM and spatial-division multiplexing (SDM) that can be employed for performance enhancement of MBH/MFH transport networks. Also, we put emphasis on SDM due to its salient features that can help in attending to the capacity crunch in the network.

1.6.1 Wavelength-Division Multiplexing (WDM) Based Schemes

Furthermore, for MFH network flexibility, optical wavelength division multiplexing PON (WDM-PON), coarse-WDM (CWDM) PON, as well as dense-WDM (DWDM) PON schemes can be implemented [Alimi et al. - 2018a]. In [Alimi et al. - 2018a], we presented a comprehensive discussion on the use cases of the PON schemes. The schemes' implementations will further enhance the C-RoF system performance by enabling the coexistence of multiple MNOs in a shared infrastructure in which different WDM wavelengths are employed. Likewise, different wireless services on lower- and higher-RF bands can be easily propagated concurrently in the RoF MFH/MBH of each MNO. Also, multiple sub-bands as well as multiple MIMO data streams can coexist in the RoF link for each wireless service without incurring detrimental interference, which may hinder high-rate services. Similarly, with centralized management, multiple services, multiple operators, as well as multiple wireless schemes can coexist in a shared small-cell infrastructure while still maintaining autonomous configurability. Consequently, the centralized scheme not only facilitates swift implementation of innovative radio technologies such as mm-wave radio and CoMP but also aids in more effective network management techniques. Also, with the implementation of schemes such as software-defined networking and NFV, it can offer further CAPEX and OPEX reductions [Liu et al. - 2014; Chang et al. - 2013].

It should be noted that there are certain associated design challenges for the C-RoF networks. The design of optoelectronics (i.e. O/E and E/O) interfaces at both RUs and BBU sides differ considerably from the typical digital baseband-over-fiber system. For instance, C-RoF application demands high linearity for generating, detecting, and transmitting optical signals in the network. Moreover, it is noteworthy that severe performance impairments may result from the RoF system nonlinearity-induced interference. This is even more intricate when multi-band multi-carrier RoF signals are under consideration [Liu et al. - 2014; Chang et al. - 2013].

1.6.2 Spatial-Division Multiplexing (SDM) Based Schemes

We are now in an era in which traffic growth, dominated by high-definition video streaming, multimedia file sharing, and other information technologies, is increasing faster than system capacity [Cisco - 2017]. By 2020 it is estimated that 30 billion devices will be connected to a 5G-enabled Internet of Things [Cisco - 2017]. This combination of broadband services and large scale of network-connected end devices will shortly lead to a capacity crunch, making the increment capacity of optical communication networks mandatory. Such high-demand for capacity is shared by core, metro, and access networks, as well as by optical networks directly supporting 5G infrastructure, i.e. optical fronthaul and backhaul.

In addition, SDM is a new approach to avoid capacity crunch. SDM has been evolving worldwide as key technology capable of breaking the limitation of conventional single-core single-mode optical fiber based communications systems, where the transmission capacity is considered limited to at most about 0.1 petabits s^{-1} [Qian et al. - 2011] due to the limitation on the launched input power or interference between signals [Mizuno et al. - 2016].

1.6.2.1 State-of-the-Art of SDM in 5G Infrastructure

Due to its natural potential to increment the capacity of optical communications, SDM is being proposed in the context of short-reach application networks, e.g. data-center connectivity or 5G infrastructure transport. Notice that, besides its potential role to avoid a future capacity crunch, the SDM concept can also be used for providing key solutions to such issues as achieving effective infrastructure operation/management and lower power consumption [Nakajima et al. - 2016]. In [Llorente et al. - 2015], a next generation RAN was proposed, employing MCFs in optical wireless fronthaul and mode-division multiplexing in the backhaul to overcome the capacity limitation of single-mode fibre systems. Such proposed optical fronthaul was based on RoF transmission on MCF. The combination of RoF and MCF permits cost- and energy-efficient support of MIMO wireless present in actual 4G cellular systems, which is a key requirement for next generation 5G radio technology. Recently, MIMO SDM on MCF was experimentally proposed and evaluated in multi-antenna LTE-advanced systems [Morant and Llorente - 2018].

MCF was also proposed as a compact medium to implement fiber-distributed signal processing, which may provide both radio access signal distribution (including MIMO antenna connectivity) and RF signal processing [García and Gasulla - 2016]. Applications of such a solution may cover a variety of application scenarios that will be especially demanded in 5G and B5G communications [Gasulla et al. - 2017].

1.6.2.2 Spatial Division Multiplexing Enabling Tools

The SDM techniques can be concretized by mode-multiplexing, using for instance few-mode fibers (FMF), or by different optical paths in different fiber optical cores, i.e. using MCFs [Richardson et al. - 2013]. Actually, MCFs can also be designed in order to support multiple modes in each fiber core [Mizuno et al. - 2016]. MCFs can be roughly grouped in coupled-core MCFs and in uncoupled MCFs. In the first case, the spacing between the cores, i.e. the pitch, is smaller than the one used in uncoupled MCFs, which results in a higher spatial density of cores. In this case, all the spatial channels are strongly coupled and the spatial channel can be described as a super-mode, or spatial superchannel, for a given wavelength. On the other hand, in uncoupled MCFs, each core is used as an individual waveguide and one can neglect any kind of interaction between the different cores supported by the MCF. This approach has received the most attention among all of the SDM technologies due to the possibility of avoiding MIMO processing [Fernandes et al. - 2017b]. In general, the overall bit rate of an SDM system is increased in proportion to the number of spatial modes/cores, with diverse SDM transmission systems being explored, demonstrating its potential by setting milestones in transmission capacity and capacity-distance product per fiber [Mizuno et al. - 2016]. For instance, a 2.15 petabit s^{-1} transmission over 31 km of a homogeneous 22-core single-mode multi-core fiber using 399×25 GHz spaced, 6.468 terabits s^{-1} spatial-super-channels comprising 24.5 GBaud PDM-64QAM modulation in each core was obtained in [Puttnam et al. - 2015]. Recently, the record-long WDM/SDM transmission experiments over FMFs with transmission reach exceeding 2500 km for a 12-core 3-mode MC-FMF and 6300 km for a single-core FMF have been demonstrated [Shibahara et al. - 2018]. Moreover, 159 terabit s^{-1} data transmission over 1045 km distance using a three-mode optical fiber was reached in [Rademacher et al. - 2018]. Such a high-capacity value was reached as mode multiplexing was used in combination with 16-QAM (quadrature-amplitude modulation), which is a practical high-density multi-level modulation optical signal, for all 348 wavelengths. It is worth mentioning that the FMF used in that experiment had a standard 125 μm outer diameter, which represents a key advantage as it can be cabled using existing equipment.

Figure 1.2 shows a schematic of an SDM transmission system that is based on optical coherent detection and advanced digital signal processing (DSP). On the Tx side, dual-polarization IQ modulators (DP-IQM) are driven by four signals generating a set of DP-quadrature amplitude modulation (DP-QAM) signals that, after optical space multiplexing, are propagated through the SDM transmission link. After optical SDM de-multiplexing, each tributary is detected in a digital optical coherent receiver (coherent Rx), comprised of an optical front end, analog-to-digital stage and advanced DSP subsystems.

Analogously to the case of single-mode fiber based systems, the real implementation of fiber-optic SDM systems requires assistance at both optical and digital domains. Such supporting tools can be employed as key optical subsystems, e.g.

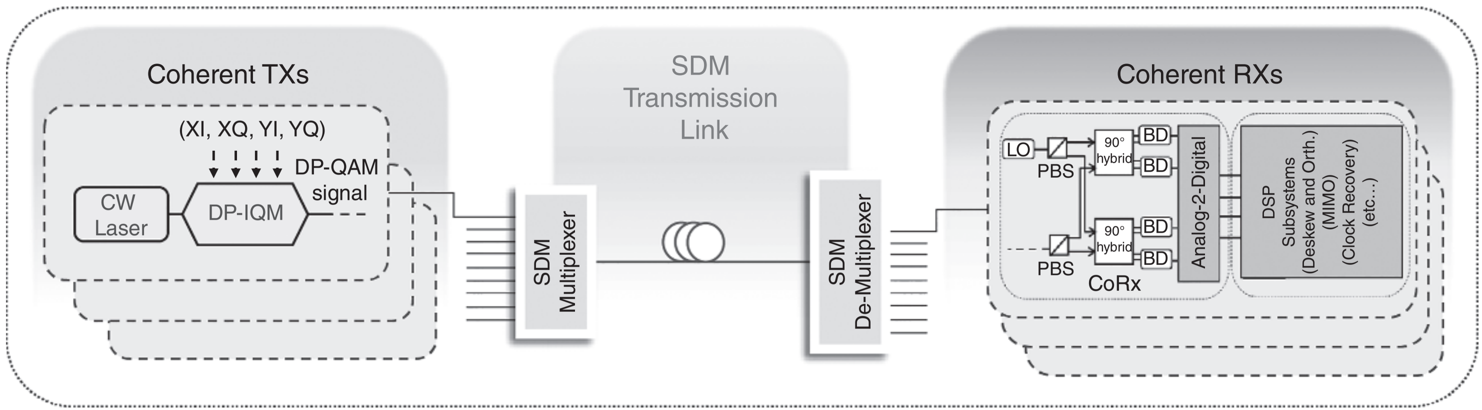
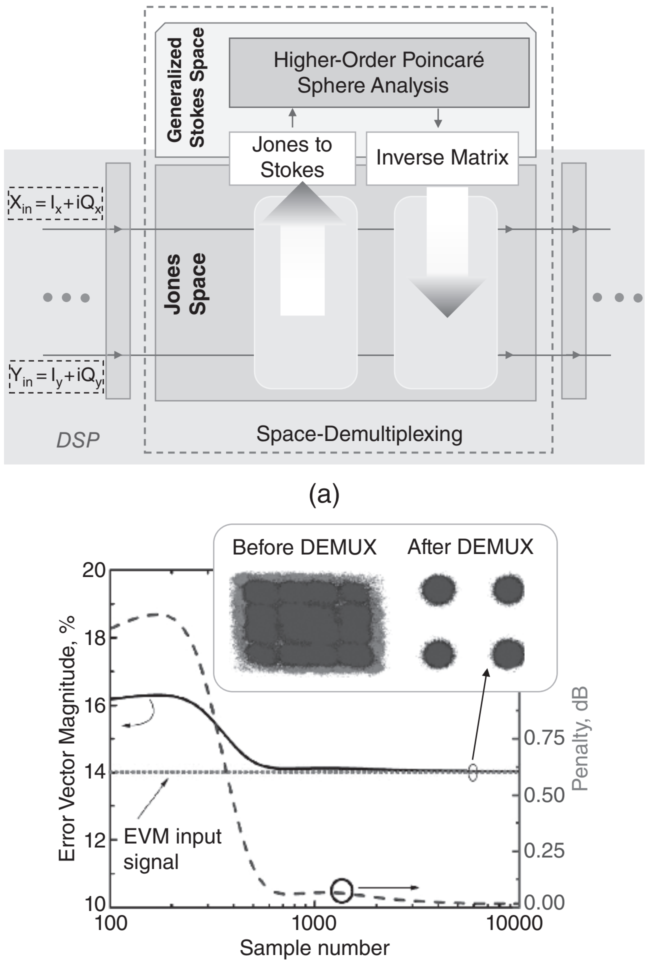


Figure 1.2 Schematic of an SDM transmission system.

optical switchers/couplers or amplifiers, or as compensation/mitigation techniques to deal with the impairments suffered during the signal propagation. As shown in [Fernandes et al. - 2015], an optical signal propagating in a particular core can be switched to any other core or distributed over all the cores exploring the acousto-optic effect. It was also shown that by tuning the acoustic wave amplitude, one can adjust the amount of optical power transferred between the cores [Fernandes et al. - 2015]. The light transfer/switching can also be attained inline by using long-period gratings inscribed in heterogeneous multi-core fibers [Rocha et al. - 2016]. The two previously mentioned techniques have the advantage of being inline techniques, thus avoiding coupling/decoupling processes and respective insertion losses. Regarding optical amplification and also employing an inline approach, a 6-mode and 580-wavelength multiplexed transmission with an dual C+L-band cladding-pumped few-mode erbium doped fiber amplifier (EDFA) was reported in [Wakayama et al. - 2018]. Such systems allow a total capacity of 266.1 terabit s^{-1} over a 90.4 km transmission line at a spectral efficiency of 36.7 bit s^{-1} Hz^{-1}. In real scenarios, mechanical perturbations are expected to cause mode coupling variations on time scales as short as tens of microseconds, requiring fast adaptive digital MIMO techniques with tolerable computational complexity [Arik et al. - 2014]. In that way, SDMs must use different signal processing approaches than wireless and SMF systems to ensure near optimum DSP with tolerable complexity.

Analogously to the case of single-mode fiber based systems, SDM techniques can also benefit from the combination of coherent detection and advanced DSP techniques [Fernandes et al. - 2017a]. A particular example is the adaptive MIMO equalization to compensate for modal crosstalk and modal dispersion. Such techniques can be implemented both in time and frequency domains, with different tradeoffs between performance and computational complexity. The least mean squares and recursive least squares frequency-domain equalization algorithms have been deeply analyzed in [Arik et al. - 2014]. Recently, a new approach based on Stokes space analysis has also been proposed for signal equalization both in classical single mode fiber systems [Muga and Pinto - 2015] and in SDM systems. Again, this approach can also be implemented both in time [Fernandes et al. - 2017a] and frequency [Caballero et al. - 2016] domains. The space-demultiplexing algorithm based on higher-order Poincaré spheres, presents important advantages when compared with its counterparts, e.g. modulation format agnostic, free of training sequences and robust to the local oscillator phase fluctuations and frequency offsets [Fernandes et al. - 2017a]. Figure 1.3(a) illustrates a block diagram of a higher-order Poincaré sphere based digital space-demultiplexing subsystem in a coherent transceiver with polarization, phase, and space diversity. Moreover, Figure 1.3(b) shows an error vector magnitude (left y-axis) and remaining penalty (right y-axis) as a function of the number of samples for the space-demultiplexed signal. Also, the left- and right-hand side insets show the quadrature phase shift keying (QPSK) constellations for one tributary before and after demultiplexing, respectively. Results show a fast convergence speed as the technique reaches negligible penalty values for a number of samples smaller than one thousand.



(a)

(b)

Figure 1.3 Block diagram of (a) a higher-order Poincaré sphere system, (b) an error vector magnitude (left *y*-axis) and remaining penalty (right *y*-axis) with insets that show the quadrature phase shift keying (QPSK) constellations.

1.7 Wireless based MFH/MBH

As aforementioned, C-RAN MFH can be achieved by a number of solutions, nevertheless, the low-latency and high-capacity requirements of the fronthaul render optical fiber-based solutions attractive. Furthermore, it is noteworthy that the flexibility and cost-effectiveness advantages of the C-RAN may be hindered by the implementation of optical fiber-based solutions for ultra-dense RRH deployment. In general, fiber deployment is time consuming and cost-intensive in an ultra-dense network, especially when trenching is required. In addition, wireless-based MFH solutions are highly attractive ways of exchanging information between the CUs and the DUs. The interest can be ascribed to the associated higher flexibility, lower cost, and ease of deployment compared with the fixed wired fronthaul solutions. Therefore, scalable and flexible solutions such as mm-wave (discussed in Section 1.3.4) and free-space optical (FSO) communication systems are means of realizing efficient and realistic wireless MFHs.

1.7.1 FSO Communication Systems

The FSO system is an optical wireless alternative technology of fiber-based fronthaul networks. In contrast to the RoF scheme discussed in Section 1.5, implementation of the FSO system does not depend on optical cables. Thus, without a fiber medium, FSO can be used for RF signals transmission via the free space between the transmit and receive apertures. Moreover, being an optical wireless technology, its deployment is not contingent on trenching. This feature is highly beneficial regarding cost and time compared with the usual optical fiber technology.

Furthermore, the fact that FSO can be employed in areas where physical connections by optical fiber cables are unrealistic is one of its major benefits. Also, as a result of the inherent FSO advantages like high-bit rates, full duplex transmission, ease of deployment, protocol transparency, and high transmission security, it has been acknowledged as an effective broadband access scheme that is capable of attending to the bandwidth requirements using MFH and MBH networks [Alimi et al. - 2017a, 2016, 2017e].

Figure 1.4 illustrates an FSO system as well as different typical components that are needed at both sides of the link. However, seamless connection FSO system does not demand signal conversion from optical to electrical and vice versa before transmission or reception via the free space. Therefore, optical-electrical as well as electrical-optical converters are not needed. Thus, this facilitates a data rate and protocol transparent FSO link. In addition, the system can be used along with other cutting-edge optical schemes like an EDFA and WDM in order to improve the system capacity considerably [Alimi et al. - 2018a; Kazaura et al. - 2010, 2009; Dat et al. - 2010].

In addition, the notion of transmitting radio signals over FSO (RoFSO) leverages the high-transmission capacity of optical systems and ease of deployment of wireless technologies. Consequently, DWDM RoFSO systems are capable of supporting multiple wireless signals concurrently. Nevertheless, FSO systems are considerably vulnerable to factors such as local weather conditions and atmospheric turbulence effects. It should be noted that, atmospheric turbulence is caused by the air refractive index variations through the transmission path [Alimi et al. - 2017a, 2016, 2017e,f; Sousa et al. - 2018; Alimi et al. - 2018b].

There are a number of statistical models for defining FSO intensity fluctuation in the literature for different turbulence regimes. For instance, log-normal (LN) distribution has been widely used due to the experimental measurement fits. Other models that have been extensively used are gamma–gamma ($\Gamma\Gamma$), negative exponential, K and I–K distributions [Alimi et al. - 2017c,b]. This work focuses on the LN and $\Gamma\Gamma$ distribution models.

1.7.1.1 Log-Normal Distribution (LN)

The LN model is just appropriate for weak turbulence situations with a link range of about 100 m. Consequently, the weak turbulence intensity fluctuation probability

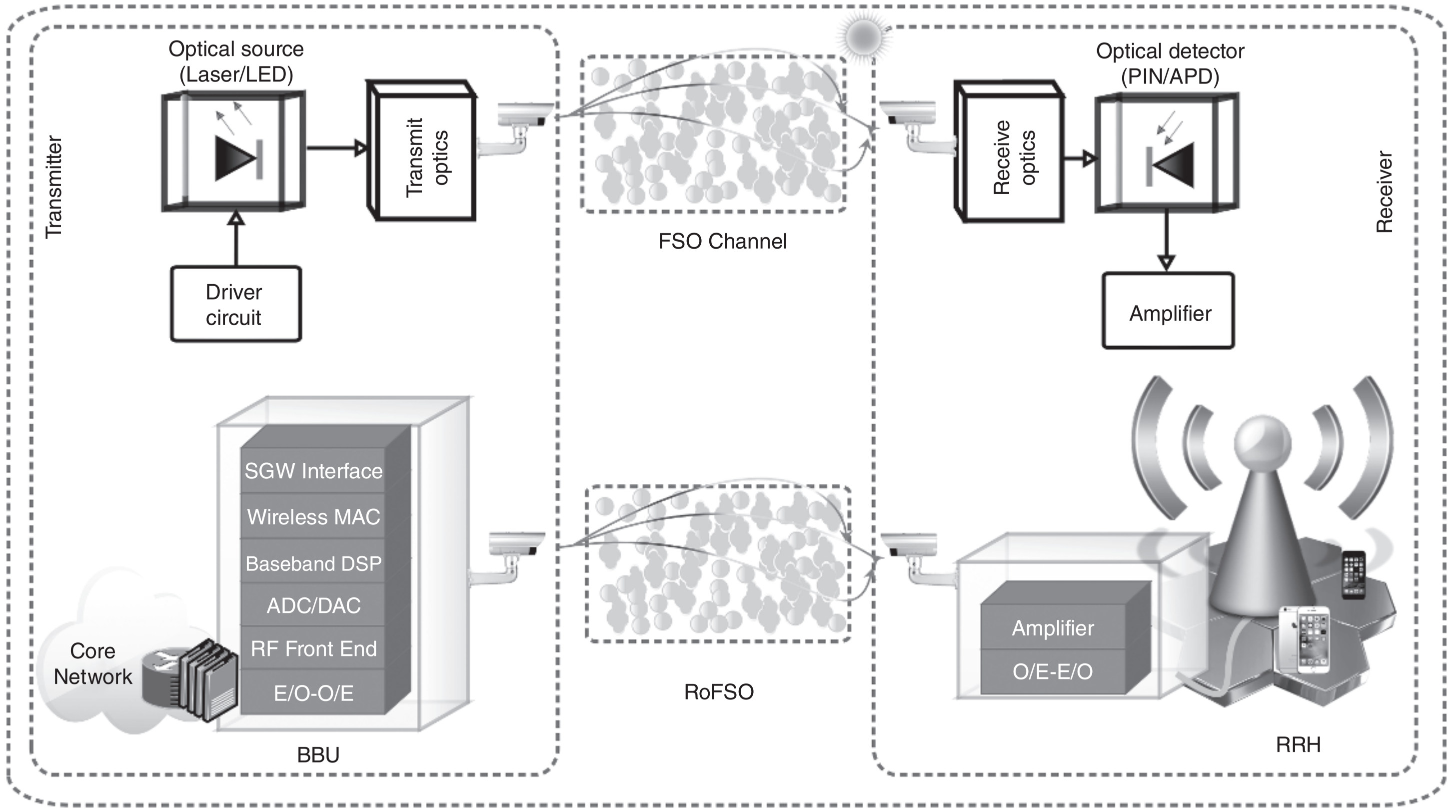


Figure 1.4 Block diagram of an RoFSO system.

density function (pdf) for the LN distribution is defined as [Alimi et al. - 2016, 2017c,b]

$$f_{h_a}(h_a) = \frac{1}{2h_a\sqrt{2\pi\sigma_x^2}} \exp\left(-\frac{(\ln(h_a) + 2\sigma_x)^2}{8\sigma_x^2}\right), \tag{1.2}$$

where h_a denotes atmospheric turbulence-induced fading, $\sigma_x^2 = \sigma_l^2/4$ denotes the log-amplitude variance defined for plane waves and spherical waves, respectively, as [Alimi et al. - 2016, 2017c,b]

$$\sigma_x^2|_{\text{plane}} = 0.307C_n^2k^{7/6}L^{11/6}, \tag{1.3a}$$

$$\sigma_x^2|_{\text{spherical}} = 0.124C_n^2k^{7/6}L^{11/6}, \tag{1.3b}$$

$$\sigma_l^2|_{\text{plane}} = 1.23C_n^2k^{7/6}L^{11/6}, \tag{1.3c}$$

$$\sigma_l^2|_{\text{spherical}} = 0.50C_n^2k^{7/6}L^{11/6}, \tag{1.3d}$$

where σ_l^2 represents the log-irradiance variance, $k = 2\pi/\lambda$ denotes the optical wave number, L represents the distance, and C_n^2 signifies the altitude-dependent index of refraction structure parameter.

1.7.1.2 Gamma-Gamma (ΓΓ) Distribution

The ΓΓ distribution is typically used in modeling the scintillation effects in the strong turbulence regimes where the LN distribution characterization is not valid. Furthermore, the ΓΓ model is also suitable for modeling and characterizing the fading gains from the weak to strong turbulence regimes. The pdf of h_a for the ΓΓ distribution can be expressed as [Alimi et al. - 2017c,b]

$$f_{h_a}(h_a) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)}(h_a)^{\frac{(\alpha+\beta)}{2}-1}\mathrm{K}_{\alpha-\beta}(2\sqrt{\alpha\beta h_a}), \tag{1.4}$$

where $\Gamma(\cdot)$ denotes the gamma function, $K_v(\cdot)$ represents the modified Bessel function of the second kind of order v, and α and β represent the effective number of large-scale and small-scale eddies of the scattering process, respectively. The parameters α and β are expressed respectively for the plane wave as [Alimi et al. - 2016, 2017c,b]

$$\alpha = \left[\exp\left(\frac{0.49\sigma_{\mathrm{R}}^2}{(1 + 1.11\sigma_{\mathrm{R}}^{12/5})^{7/6}}\right) - 1\right]^{-1}, \tag{1.5a}$$

$$\beta = \left[\exp\left(\frac{0.51\sigma_{\mathrm{R}}^2}{(1 + 0.69\sigma_{\mathrm{R}}^{12/5})^{5/6}}\right) - 1\right]^{-1}, \tag{1.5b}$$

also for the spherical wave, they can be defined as [Alimi et al. - 2017c,b]

$$\alpha = \left[\exp\left(\frac{0.49\sigma_R^2}{(1 + 0.18d^2 + 0.56\sigma_R^{12/5})^{7/6}}\right) - 1\right]^{-1}, \tag{1.6a}$$

$$\beta = \left[\exp\left(\frac{0.51\sigma_R^2(1 + 0.69\sigma_R^{12/5})^{-5/6}}{(1 + 0.9d^2 + 0.62d^2\sigma_R^{12/5})^{5/6}}\right) - 1\right]^{-1}, \tag{1.6b}$$

where $d \triangleq (kD^2/4L)^{1/2}$, D denotes the diameter of the receiver aperture, σ_R^2 represents the Rytov variance that is a metric for the strength of turbulence fluctuations. The σ_R^2 is expressed for the plane and spherical waves, respectively, as [Alimi et al. - 2017c,b]

$$\sigma_R^2|_{\text{plane}} = 1.23 \quad C_n^2\ k^{7/6}\ L^{11/6}, \tag{1.7a}$$

$$\sigma_R^2|_{\text{spherical}} = 0.492 \quad C_n^2\ k^{7/6}\ L^{11/6}. \tag{1.7b}$$

In addition, the normalized variance of the irradiance that is also known as the scintillation index (σ_N^2) can be defined with respect to σ_x^2 as well as eddies of the scattering process (α and β), respectively, as [Alimi et al. - 2017c,b]

$$\sigma_N^2 \triangleq \frac{\langle h_a^2\rangle - \langle h_a\rangle^2}{\langle h_a\rangle^2} \tag{1.8a}$$

$$= \frac{\langle h_a^2\rangle}{\langle h_a\rangle^2} - 1 \tag{1.8b}$$

$$= \exp(4\sigma_x^2) - 1 \tag{1.8c}$$

$$= 1/\alpha + 1/\beta + 1/(\alpha\beta). \tag{1.8d}$$

As aforementioned, an atmospheric turbulence-induced fading and local weather conditions bring about the received optical intensity fluctuation. Therefore, the resulting impairments hinder the optical wireless scheme from being a reliable technology like a typical optical fiber solution. This does not only limit RoFSO system performance but also hinders FSO from being an effective standalone MFH solution. Several PHY layer schemes like maximum likelihood sequence detection, diversity schemes and adaptive optics are normally used for mitigating turbulence-induced fading [Alimi et al. - 2018a]. In the following subsection, we present advanced technologies that can be employed to improve FSO-based MFH system performance.

1.7.2 Hybrid RF/FSO Technology

RF/FSO systems have been presented in an effort to make FSO a better technology. The RF/FSO system is a hybrid scheme that exploits and integrates high-transmission capacity exhibited by optical schemes as well as ease of deployment of wireless systems while addressing the associated weaknesses of both technologies. This enables a reliable and concurrent transmission of heterogeneous wireless services (multiple analog and digital signals). Likewise, the idea is also to integrate the RF solution's scalability and cost-effectiveness with the FSO solution's low-latency and high-data rate. Consequently, the hybrid scheme helps in realizing the low-latency and high-throughput requirements of the future networks in a cost-effective way. In a hybrid RF/FSO system, based on the application and deployment scenario, there are two parallel links between the Tx and Rx that have the ability for data transmission. Nevertheless, either of the links can be used to transmit data based on the electromagnetic interference levels and weather conditions.

1.7.3 Relay-Assisted FSO Transmission

The spatial diversity technique is one of the effective means of mitigating turbulence-induced fading. This entails deployment of multiple transmit/receive apertures with the intention of exploiting and establishing additional spatial degrees of freedom. The technique has been extensively employed for mitigating fading because of the inherent redundancy. However, multiple aperture deployment presents challenges not only in terms of an increase in the system complexity but also regarding cost. Moreover, stringent requirements like adequate aperture spacing have to be met to prevent spatial correlation.

In RF communication, dual-hop relaying has been widely used not only to simplify spatial diversity implementation but also to enhance the quality of the received signal and extend the coverage area considerably. Furthermore, the benefits of MIMO schemes can be achieved by employing a relay-assisted transmission in which *virtual* multiple-aperture systems are logically created. A relay-assisted scheme utilizes both the FSO and RF features in order to provide an efficient system. In addition, it is a mixed RF/FSO dual-hop technology where the source-relay links are RF links whereas relay-destination links are FSO links.

It is remarkable that the mixed RF/FSO dual-hop relay system is comparatively different from the hybrid RF/FSO approach since parallel RF and FSO links exist between the source (Tx) and the destination (Rx). Moreover, the main function of the FSO link in the mixed RF/FSO dual-hop approach is to enable the RF users to connect with the backbone network so as to bridge the connectivity gab between the last-mile and the backbone networks. This scheme efficiently addresses the system last-mile transmission bottleneck by multiplexing and aggregating multiple RF users into a single shared high-speed FSO infrastructure with the intention of harnessing the intrinsic optical bandwidth. In addition, any kind of interference can be prevented due to the fact that FSO and RF operate on dissimilar frequency bands. Thus, this configuration provides improved performance compared with the conventional RF/RF transmission system. In Figure 1.5, we present an implementation scenario for some of the discussed schemes for a converged fiber-wireless access network.

1.8 Experimental Channel Measurement and Characterization

The performance of an FSO link is studied experimentally under a real atmospheric turbulence condition. We measure σ_N^2 from the channel samples acquired in an attempt to determine the extent of atmospheric turbulence as well as consequent effects on the FSO link performance. To achieve this, we use the setup shown in Figure 1.4. The setup comprises a point-to-point link that is based on intensity modulation/direct detection scheme. We generate a 10 Gb s^{-1} non-return-to-zero signal using a $2^{23} - 1$ pseudorandom binary sequence. Furthermore, the generated electrical signal is injected into a laser that operates at 1548.51 nm. The optical output signal is then launched from the laser to a 3 mm diameter collimator using a standard single-mode fiber (SSMF). In addition, the input optical power of the collimator is set to 0 dBm. Consequently, the collimated beam is conveyed through a 54 m length FSO channel. At the receiver, the converged optical signal focuses on the collimator that is SSMF coupled to the photodetector. The subsequent optical signal is converted to electrical signal by means of a 10 Gb s^{-1} photodiode. Then, C_n^2 is estimated as discussed earlier.

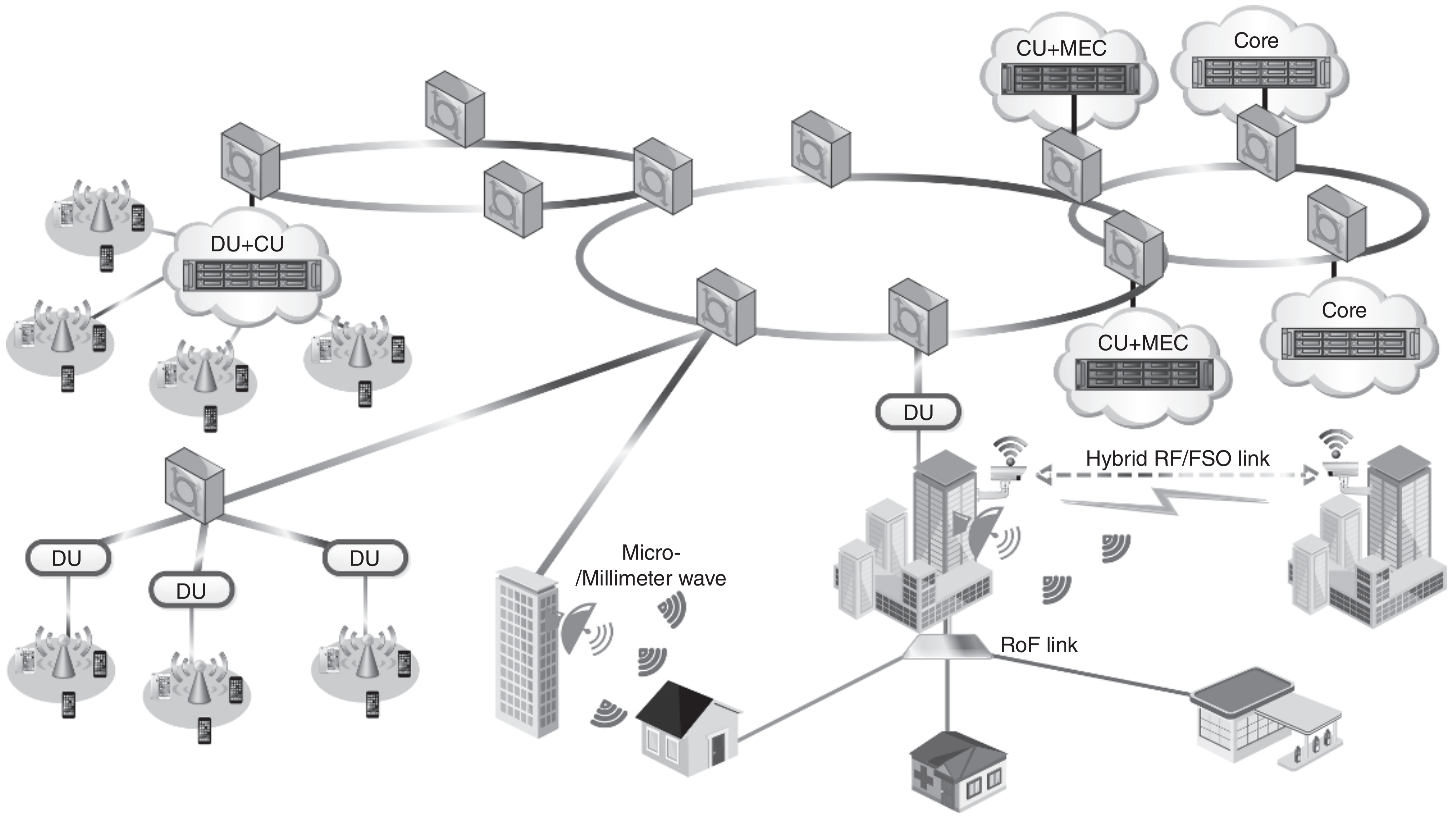


Figure 1.5 Converged fiber-wireless access networks scenario for 5G implementation.

1.9 Results and Discussions

Figure 1.6 presents both theoretical and experimental results of the weak turbulence condition for a link range of 54 m. Figure 1.6(a) shows the LN pdf for different values of log-irradiance variance using the logarithmic scale. It is evident that, as σ_l^2 increases, the distribution is further tilted. This behavior indicates the irradiance fluctuation magnitude of the system. Furthermore, the refractive-index structure parameter C_n^2 characterization is realized by fitting the nearest LN as well as the ΓΓ pdf curves to that of the received data. Figure 1.6(b) shows the resulting fittings of the measurement taken around 9:30 pm on 18 November 2015. The scintillation index σ_N^2 is evaluated and the obtained value is 0.0052. Under this condition, i.e. $\sigma_N^2 = 0.0052$, the LN as well as the ΓΓ

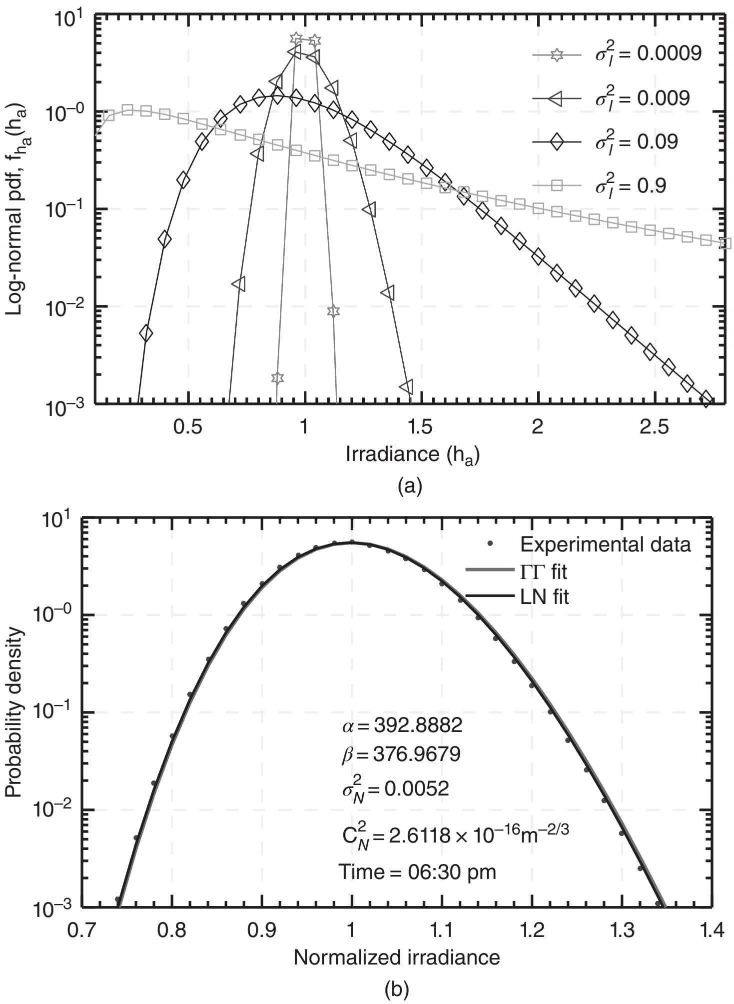


Figure 1.6 Irradiance for (a) log-normal pdf and (b) experimental log-normal and gamma-gamma fittings.

are perfectly fitted to the measured channel samples σ_N^2.This result indicates that both models are suitable for weak atmospheric fading characterization.

1.10 Conclusion

In this chapter, we have presented a number of fundamental features and techniques that can facilitate effective deployment of a 5G wireless network. Being one of the main supporting architectures for the 5G and B5G networks, we have focused on the small-cell C-RAN and the related RAN virtualization. We have also emphasized the need for high-capacity and low-latency architecture as well as energy- and cost-efficient mobile fronthaul links. Furthermore, implementation of mm-wave and optics-based schemes that support multi-service, multi-band and multi-operator coexistence in a shared network infrastructure have been comprehensively discussed. Moreover, the main requirements of the MFH/MBH networks for supporting 5G and B5G networks have been presented considering optical and wireless access network convergence. In addition, we have presented not only analytical expressions but also numerical and experimental results to demonstrate the effects of atmospheric turbulence-induced fading that can hinder the number of RRHs that can access the same BBU pool at the same time. We also discuss research challenges and open-ended issues on means of achieving the requirements of 5G network in terms of jitter, capacity, and latency in an economical manner.

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