Chapter 5

Integration of Hybrid Passive Optical Networks (PON) with Radio over Fiber (RoF)

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Additional information is available at the end of the chapter

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Abstract

A cost effective, robust, and high capacity access network necessitated to meet the mounting customer demands for bandwidth-desirous services. A remarkable evolution of access networks is observed both in wired and wireless, predominantly driven by ever-changing bandwidth requirements. A wireless connection releases the end user from the restrictions of a physical link to a network that results in mobility, flexibleness, and ease of use. Whereas, optical networks offer immense amount of bandwidth that appease the most bandwidth voracious customers compared to bandwidth limited wireless networks. The integration of wired and wireless domains in the access landscape that presents a technical analysis of optical architectures suitable to support radio over fiber (RoF) is the objective of this chapter. Investigate the main trends that drive the merger of fiber and wireless technologies in access networks. Moreover, study the primary terms and the particular transmission features of integrated fiber-radio links to form a well-defined classification of hybrid systems and techniques. This work also recognizes the major problems for realization of RoF systems and examines the limitation, advantages, and diversity of integrated RoF-PON technology.

Keywords: radio over fiber, passive optical network (PON), hybrid PON, next generation PON (NG-PON-2), millimeter wave, IEEE 802.11ad

1. Introduction

In the upcoming telecom networks, end users need mobility, high speed, and large capacity. Luckily, we know the solution, wireless provides the mobility and optical fiber provides the speed and capacity. Traditionally, the radio signals were typically employed for voice and low rate data communication systems, while optical signals applied for high bandwidth metro and long haul wired communication systems. The existing network technologies (i.e. twisted pair, coaxial cable, optical fiber, and wireless links) allow variable range of mobility and bandwidth to end users [1]. The current technologies have very diverse techniques of signal generation, transmission, and reception. Moreover, their installation, working, and maintenance are also different in design, structure, and implementation.

The cost of access, metro, and core network is greatly impacted by Internet traffic growth [2]. It is expected that Internet traffic will continue its exponential growth trend in the future due to the large scale spreading of smart phones, tablets, and laptops. Moreover, mobile and fixed broadband access connections (LTE, WLAN, and FTTx) will have extensive growth in coming years all over the world. These developments will permit end users to relish social networking, cloud computing, online shopping, and multimedia applications. The terabits per second in back bone networks with gigabits per seconds in access network is shaping new life in telecommunication industry [3]. Furthermore, 3D, HDTV, and UHDTV cable television transmission is accessing home users. It would lead to give a motivation for the development of many services that face band width limitations in present networks. High speed transmission gives impetus to develop competitive signal processing platforms and equally high speed switching devices [4].

However, it is the great challenge for all the network technologies to meet the requirements of the increasing demand of broadband and mobile communications. The present network technologies either wireless or wired just fulfill a partial demand due to inherent limitations. Therefore, realizing the growing requirements and limitations of the network technologies, there appears a need of integration to overcome the limitations of one technology with aid of some other technology [5]. The enormous opportunities arisen to design and develop future high data rate networks by combining the advantages of wireless and fiber technologies. A high throughput networks anticipated after the coexistence of both radio frequency electronics and fiber optics to develop RoF systems. The term RoF is used for modulating a light beam by radio frequency signal and propagating through an optical fiber link to finally transmit radio signal in free space.

The RoF system can adequately resolve the generation, propagation, and synchronization issues of broadband signal. RoF is a perfect technology for the integration of wireless and wired networks that it aggregates the best features of both communication technologies. Hence, RoF provides the best optimum solution to end users by allowing them to maintain their mobility along with the needed bandwidth for both current and future communication/entertainment applications. The RoF networks also deliver greater geographical coverage and tractability as compared to use either wired or wireless technology. Furthermore, extremely high spectral efficiency can be attained by optical generation of radio frequencies that is the most important parameter for long haul networks. RoF also provides frequency synchronization to solve the performance constraints of wireless interconnect systems. Finally, RoF system offers numerous advantages in different levels of communication systems.

After a brief introduction of our topic in section 1, a comprehensive overview about integration of RoF is presented in second section. In third section, the candidate optical technologies to realize radio over fiber are discussed. The complete network architecture concentrated

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on pragmatic execution strategies of radio over fiber systems, along with millimeter wave applications and standardization (IEEE 802.15.3c, ECMA-387, Wireless gigabit alliance, IEEE 802.11ad) are presented. Finally, this chapter concluded with future dimensions.

2. Integration of RoF with PON

The RoF technology is the propagation of wireless signal through low loss optical fibers to achieve long reach, which is not possible by direct transmission of radio signals. This coexistence of wireless/optics systems paved the way for many promising solution for broadband networks. It also facilitates the network and service providers to offer mobility, bandwidth, and multi ways of connectivity to customer by integrating wireless and wire line solutions [6]. The broadband modulation techniques are being implemented to enable baseband and RF technologies to coexist together in the same access network. The high bandwidth capabilities of the optical fiber can effectively be utilized by taking advantage of advances in both wired and wireless telecommunication systems. A mix of services and technologies such as PON, cellular mobile, and fixed wireless base stations are integrated and served by a single fiber infrastructure as illustrated in **Figure 1**. This integrated optical infrastructure involved independent modulation of baseband and RF signals and then multiplexed together in the access domain. This hybrid radio-optic system is considered as a very attractive solution to offer low-cost multi gigabit wireless services. The integration of both technologies over the same

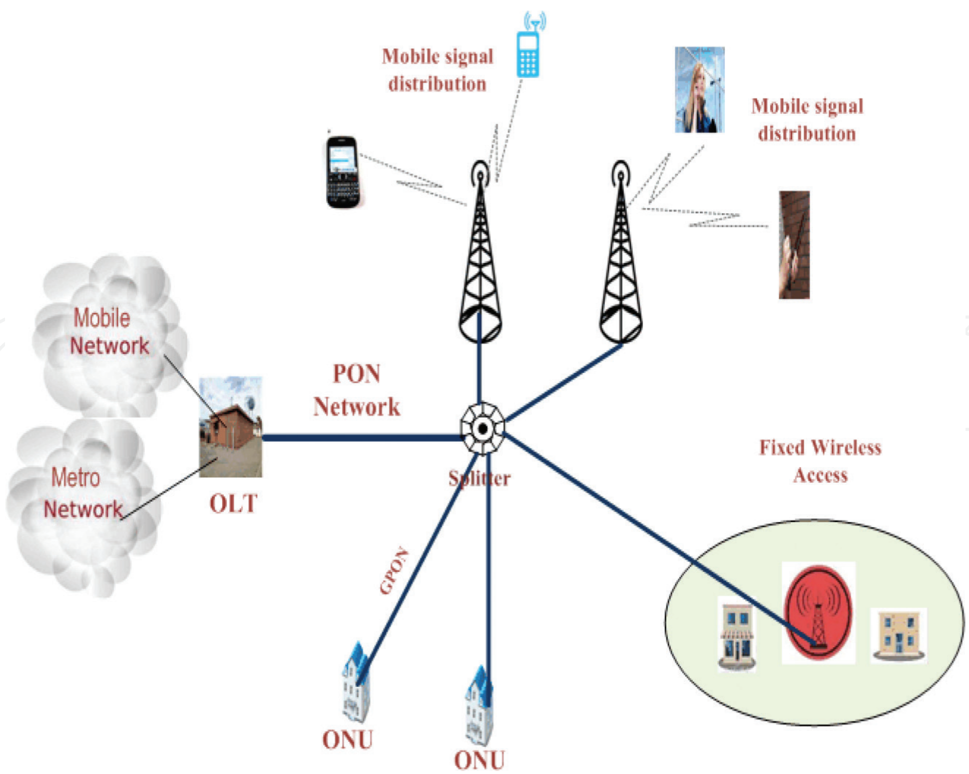

Figure 1. Integrated RoF and PON system.

optical infrastructure is evaluated on the basis of existing standards of fiber access and radio networks. The integrated multiplexing techniques either wavelength division multiplexing-time division multiplexing (WDM-TDM) or WDM-subcarrier multiplexing (SCM) are two preferable choices for serving higher user density RoF antenna sites on optical infrastructure.

After specifying the preferable network architecture for integrated systems, the possibility of analog or digital transmission modes is analyzed to carry radio signals. The mapping of radio signals on hybrid PON network is assessed by evaluating their bandwidth capacity requirements. The first generation of the primary standards defined for time division multiplexing (TDM) PON such as gigabit PON (GPON) and Ethernet PON (EPON) are insufficient to fulfil the bandwidth requirement for digital protocols designed for multi-gigabit systems. In such situations, the sequential upgradation to high data rate PONs from next generation XG-PON/10G EPON to NG-PON2 and beyond are recommended.

For implementation of mm-wave RoF networks in pico or femto-cell environment, multipoint to multipoint (MP2MP) architectures are preferred for home networks. In MP2MP architectural design, NxN nodes are used for distributed antenna units. The laser of each antenna unit through the logical mesh network of the nodes is connected to the every photodiodes of this network to provide connectively to every other wireless device in this network. Therefore, all the wireless devices are visible to each other in the same network. Optical MP2MP is preferred topology for small scale mm-wave enable home network.

The ROF system like any fiber-based system has problem of inter symbol interference (ISI) due to fiber dispersion. The dispersion penalty is mainly introduced by optical filters and cascading multiplexing stages in integrated RoF-PON networks. The converged radio-optical signals will face degradation due to dispersion in hybrid network. So, the RoF networks will be designed with simple network architectures to bring the flexibility, reliability and resilience against all transmission impairments.

3. Candidate fiber platforms to implement RoF

In late 1980s, optical fiber systems were introduced in long haul communications to provide high capacity and long distance communication. This development has started a new era of information and telecommunication systems. The available high capacity in back bone network has guided to increase the capacity and data rates in access networks. The legacy copper and radio networks were unable to support very high data rates in last mile networks. Optical fiber-based access networks were introduced to offer high data rates in the access networks. However, the economical and flexible solutions still needed to make it available for everyone. On the other hand, the tele-density in the world is raised to many folds after the unveiling of cellular networks, but they are limited to voice and low data rate communications.

A new access work is required to fulfill the requirement of data devouring applications. To meet this goal, multi-gigabit radio systems were designed in the form of wireless fidelity (WiFi), worldwide interoperability for microwave access (WiMAX), and long term evolution (LTE) systems. Although, these systems can support very high data rates in access network but

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only when appended with optical fiber systems from central office to base stations. After the introduction of Qualcomm, QCA6320 (60 GHz MAC/BB) + QCA6310 (60 GHz RF transceiver and commercial products (i.e. TP-link AD7200 (Talon), NETGEAR R9000-100EUS Nighthawk X10 AD7200, ASUS RT-AD7200) which are utilizing 60 GHz mm-wave band and offering data rates around 7 Gb/s. To meet such high data demands, optical access network with very high capacity and affordable prices are intended to be designed. Moreover, TV overlay is required with PON to provide ultra-high definition (UHD) TV service with no latency and with all the existing and future auxiliary services of IPTV with minimum cost involved at ONU [7].

It is projected that the rapid development of optical technologies particularly for passive optical networks will continue to ensure cost-competitiveness with current access technologies. For wire-line access networks, point-to-multipoint passive optical network is the leading technology being deployed in many countries in contrary to other available options of network topologies. It is commonly acknowledged that fiber to the home (FTTH) and time-wavelength multiple access (TWMA) PON is the most optimum solution for present and near future that will be able to support the upcoming interactive multimedia services. Other multiple access techniques as wavelength division multiple access (WDMA), optical code division multiple access (OCDMA), or orthogonal frequency division multiple access (OFDMA) still did not find wide scale acceptance for optical access network by network operators due to huge cost involved per customer to implement these techniques. Currently, many advanced hierarchical designs of passive optical networks (PON) are being deployed to implement FTTH. The first generations of PONs (broadband PON, gigabit PON, and Ethernet PON) that were standardized by IEEE and ITU already installed in many countries [8]. Among the numerous approaches proposed for FTTH, hybrid (TDM-WDM) PON technology straightforwardly offers a new dimension for this upgrade. To reduce the cost of ONU, colorless ONU configurations have been suggested to reuse the optical downstream carrier for upstream modulation. However, to reduce the influence of the downstream modulation on the upstream data, different approaches especially the adoption of different modulation formats for downstream and upstream transmissions are recommended. The devices such as chirp managed laser (CML), injection locked Fabry-Parot laser diodes (FP-LDs), semiconductor optical amplifier (SOA), and reflective semiconductor optical amplifier have laid the foundation for colorless ONU in hybrid PON. The extraordinary features of the hybrid passive optical networks and 60 GHz mm-wave RoF technique are motivating the research toward the convergence of both technologies that is the single most important point of this chapter.

Many technologies are recommended for high-bandwidth passive optical networks to deliver required data rates for current and future services. They are 40 Gbit/s time division multiplexing (TDM) PON, wavelength division multiplexing (WDM) PON, orthogonal frequency division multiplexing (OFDM) PON, coherent ultra-dense WDM-PON (UDWDM PON), and time-wavelength division (TWDM) PON [9]. The full service access network (FSAN) group under International telecommunication union (ITU-T) has adopted the TWDM-PON for its next generation PON-2 standardization. A hybrid TWDM-PON system that stacks four 10G-PONs onto a single fiber to deliver 40 Gbit/s integrated capacity in downstream. The ITU-T and FSAN has adopted smooth path for multi gigabit PON (GPON) evolution, based on incremental and targeted at the ultimate goal of migration to NG-PON2, cost effectively making full reuse of deployed fiber infrastructure [9]. The early installation work has already started on next generation of PON (TWDM-PON) in many countries. The path being adopted by network operators is seamless migration to protect their legacy PON architecture investments [10]. The laying of appropriate fiber infrastructure is very important for network operators to cope the requirement of never-ending upgrades.

The hybrid time-wavelength multiplexing for TWDM is certainly less expensive than pure dense wavelength division multiplexing (DWDM) PON [11]. The wavelength leasing option is available besides offering additional bandwidth than legacy TDM-PON [12]. The different operators can utilize wavelength leasing by sending their traffic on different colors (wavelengths) over the same infrastructure. This feeding of different mesh networks feature will be very attractive for Wi-Fi networks operators. The TWDM PON is designed on distinctive characteristic of sequential upgrade that allows the usage of the legacy GPON point-to-multipoint network and involves changes only in optical devices at the optical line terminal (OLT) and optical network units (ONUs). Huawei has proposed a prototype network for TWDM PON employing intensity modulation and offline digital signal processing [13, 14]. The features of XG-PON1 and NG-PON-2 are compared without possible options for implementations of NG-PON2 [15, 16]. A comparison is made between the possible options for wavelength selection and transmitter/receiver design for implementation of NG-PON2 [17].

FSAN did not recommend particular frequency band for downstream band width selection and choice made open for network operators. A possible selection for downstream 4-wavelengths group selection from S-band, L-band, C-band, and O-band is analyzed in our previous study [17]. The optimal transmitter design is also examined between probable options of chirp managed laser diode and Lithium Niobate (LiNbo3) Mach Zehnder modulator along with the option of tunable transceiver or remotely fed colorless ONU [17].

The IUT-T and IEEE have already defined wavelength groups for downstream (S-band: 1480–1500, C-band: 1550–1560, L-band: 1575–1580) and upstream (O-band: 1260–1360) for implementation of GPON and XG-PON [14]. The S-band is primarily defined for GPON, L-band for XG-PON, and C-band for TV overlay. In our previous analysis, we found that the choice of group of four downstream wavelengths can easily be made without uprooting current wavelengths assigned for legacy PONs. Being restricted to currently specified bands for PON, their performances for downstream communication is compared as represented in **Figure 2**. The optimal options to design optical transmitter for data rates 10 Gbit/s or higher are chirp managed laser and conventional LiNbO3 MZ modulator. The modulators were considered as the first choice for access, metro and long-haul networks till very recent [18]. But, the excessive power consumption and bulky size of Mach Zehnder modulator left the market open to better alternatives. However, Mach Zehnder is still the most reliable mean to achieve very high data rates. The chirp managed lasers (CML) is appeared to address the concerns of cost, power consumption, and size of MZ modulators. CML provides intense optical output power on low driving voltage in standard single mode fibers with 50–100 GHz ITU grids spacing for DWDM wavelengths [19]. The remotely fed colorless ONUs and tunable receivers are the two most recent trends for designing of an optical receiver. A tunable receiver made up of a thin film Fabry-Perot tunable semiconductor filter, an avalanche photo diode (APD)

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and a trans-impedance amplifier (TIA). The current tunable receiver can easily be tuned to more than 16 nm covering part of the ITU-T bands [20]. Whereas, the tunable external cavity laser (T-ECL) can be tuned to more than 26 nm covering part of the ITU-T band to couple with tunable receiver [21]. The remotely fed colorless ONU is based on the remote seeding that relieves need of laser diode at optical network unit (ONU) end.

For designing an optical access network, the capital and operational costs are vitally important due to the fact of its low cost sharing characteristics. Easily manageable, simple to upgrade, customer friendly, highly reliable, and overall satisfactory performance are crucial parameters for achieving a well-designed optical access network. A detail description of network topology, standards, and hierarchy of optical access network with some latest and ongoing developments need to be examined. At present, most of the field deployed optical access networks based on the passive power splitter at the remote node to broadcast information to all optical network units [22].

It is really challenging to generate mm-wave frequencies by using electrical devices due to the limited frequency response. The more optimum solution is to generate millimeter waves by photonic means. Recently, many groups have proposed different techniques of photonic generation of mm-wave and RoF transmission systems. The photonic generation of mm-wave is mostly accomplished by direct laser modulation, external intensity modulation, and remote heterodyning.

The photonic generation methods of mm-wave are vastly investigated in literature. These methods include the technique using the external intensity modulator (ODSB, OSSB, and OCS), dual-mode laser, optical phase-locking loop (OPLL), optical injection phase-locked loop (OIPLL), four wave mixing (FWM), external phase modulation, stimulated Brillouin scattering (SBS), and harmonic generation by SOA and OFDM [23]. The most important and basic process in RoF systems is modulation technique, where the radio frequency signal applied to modulate the optical carrier. RoF modulation methods can be broadly categorized into direct and external modulation. In direct modulation, the mm-wave is directly applied to a semiconductor laser to generate an intensity modulated optical signal. It is the simplest and least expensive method and remained focus in early research. However, the relaxation

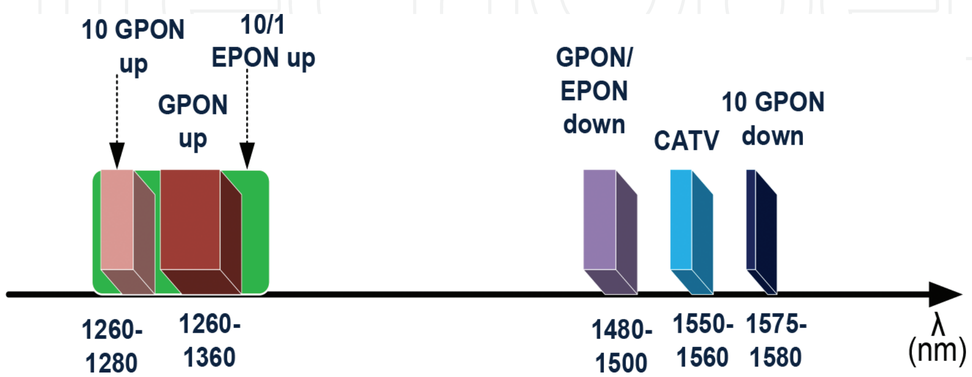

Figure 2. Wavelength allocation by ITU-T and IEEE for GPON/EPON.

oscillation limits achievable modulation bandwidth and results in high intensity noise. While on the contrary, devices such as intensity modulator, phase modulator, and interferometer can be used to modulate the phase of the optical carrier. External modulation is preferred than the direct modulation due to it is better resilience against chromatic dispersion at high speeds. Therefore, external modulation is mostly preferred for higher speeds or when the light cannot be directly modulated. Advance modulation techniques to achieve high data rates and higher mm-wave frequencies are also introduced based on OFDM and semiconductor optical amplifier (SOA). Multiband techniques are also described to achieve multiuser communications.

To fully utilize the potential of mm-wave RoF systems, its performance and reliability should be improved and considerably reduced the cost. This can be accomplished by large-scale photonic integrated circuits (PICs) [24]. PICs can enable integration of several components, such as lasers, couplers, modulators, and detectors on the same chip, reducing optical losses. But to develop PICs require very advanced design and processing techniques. Research is underway all around the world to develop them.

4. Radio over fiber systems

The wireless technology has survived as an essential telecommunication mean with time since its origination in the late 19th century. After the remarkable innovation of mobile or cellular phone, this technology has outnumbered the wired technologies in telecommunication field. Even now, there is more than 100% density of cell phones in the world. Telecommunication industry is at the epoch of a new revolution where high-speed digital signal processing (DSP) is being applied to replace most of the analog circuitry used to modulate and demodulate the radio and optical waves. After this excogitation, many new, lucrative, and adaptive solutions appeared that have not only improved the efficiency of wireless communication channels but also make possible coordinated multipoint (CoMP) transmission [25].

The RoF is used as backbone technology for wireless access networks and makes it possible to combine the RF signal processing utilities in one common area (central office). The optical fiber is used to distribute the RF signals to the remote antenna units for low signal loss (0.2 dB/km at 1550 nm wavelength) [26]. A fiber-fed distributed antenna network can be implemented for microcellular network. The remote antenna units are connected with central office through analog optical fiber links. All the de-multiplexing and signal processing is done at central office in this setup [27]. Therefore, each remote antenna site just contains an optical transmitter, an amplifier and the antenna unit, which significantly reduces the cost of the microcellular antenna sites. The spectral efficiency of radio network can be improved by distributed antenna system with the liberty of adaptive antenna selection and adaptively assigning the channels. The major advantage of RoF configuration is the reduction of the signal losses by employing the low loss optical fibers for signal propagation from central office to remote antenna units. Moreover, this scheme provides the system protection against electrical discharges and lightning strikes.

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In the generic radio over fiber architectures, the performance gains of optical fiber and radio technologies are combined to offer an alternate system for broadband wireless access as shown in **Figure 3**. In a typical RoF system, a large number of remote antenna base stations are connected with a central office (CO) through an optical feeder fiber network where all the switching and signal processing devices can be located for centralized control and monitoring. The wireless links for access networks in the last mile segment of the data transport are offering mobility, flexibility, and high capacity links to the end user. Moreover, in cellular based access networks a certain geographical area is covered by a number of base stations (BS) in the form of cluster of cells. In the next generation of cellular networks, the reach of the wireless link will be short to achieve a substantial increase in data rates. It will need higher RF carriers and advance modulation formats to attain high capacity links. To offer adequate coverage and support multi input multi output (MIMO) system, the number of antenna units per geographical area will be increased that will need rigorous control on large number of distributed nodes. The transport of aggregated data from/to a central office (Co) will need a high capacity backhaul optical fiber network for high density of antenna units [28].

In radio over fiber (RoF) systems, the radio signal modulation can be achieved by two alternate methods either to perform the baseband to RF up or down conversion at the remote BS. It will result digital transport of the information through the fiber backhaul or using optical fiber for the analog transport of wireless signals transparently [9]. On the basis of the applications,

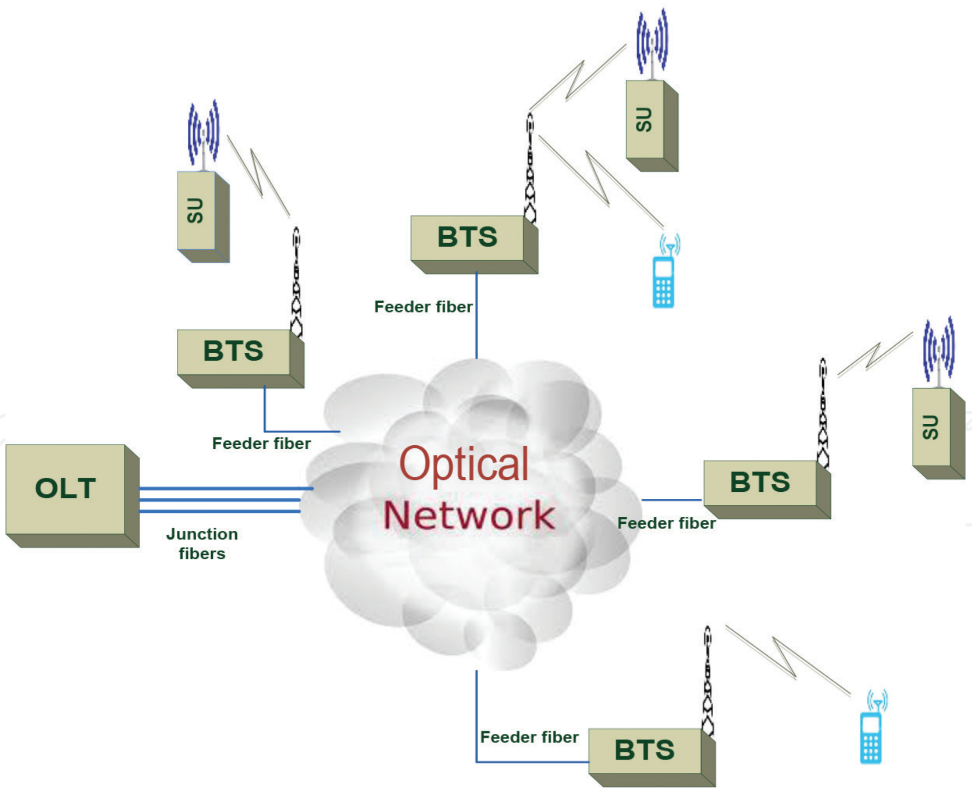

Figure 3. Radio over fiber system architecture. SU: Subsriber unit, BTS: Base transceiver station.

the fiber feeder network can be used as active or passive optical network. In general, passive feeder network is applied for the RoF systems and all the active devices are either located at the CO or at the BSs. However, if the RoF system is applied as a metro network, the feeder network will contain multiple active devices in this infrastructure.

The centralized network arrangement is the best optimum solution for RoF systems that allows securing the sensitive and delicate equipment at one location and shares them among a larger numbers of end users. Furthermore, the centralized control enables dynamic and reconfigurable channel assignment to base stations that improves the performance of network quite considerably [12]. The dynamic channel assignment techniques allow assigning multiple frequency channels to a particular cell of base station that is heavily loaded with users to avoid the blocking probability from insufficient frequency capacity [21]. The performance of the transport layer is very crucial for the performance of radio over fiber access network. RoF can also be employed to simplify the overall access network architecture and reduce operating costs in some situations. Intensity modulation with direct detection (IM-DD) is the simplest technology for the transport layer in RoF links [25]. To accomplish this, the analog radio signal is directly modulated by the optical intensity of a laser and an analog receiver performs direct detection.

By applying hybrid TWDM technology, the capacity of the RoF systems can be enhanced appreciably for optic feeder networks. In this way, a large number of RoF channels can be carried by each wavelength from the base stations to the central office and vice versa through a single fiber that also provides quantum increase in network capacity without the need for laying new fiber [17].

To develop and implement a simple, compact, low-cost, and light-weight remote antenna base station, the integration of optics and optoelectronic components will be essential. The base stations with such architectures can decrease per customer cost and speed up the deployment of the RoF systems. There are many system design are proposed by different research groups and institutions to achieve this goal as fiber-wireless (FiWi), wireless optical broadband access network (WOBAN), metro-access ring integrated network (MARIN), grid-based reconfigurable optical-wireless network (GROW-Net), fiber optic networks for distributed, extendible heterogeneous radio architectures and service provisioning (FUTON), and a converged copper-optical-radio OFDMA based access network with high capacity and flexibility (ACCORDANCE).

4.1. Pragmatic design approaches for applying RoF systems

The radio over fiber (RoF) is not merely a transport technique for wireless signals over optical fibers but it involves photonic generation of radio waves and integration of radio-optics technologies. To promote and enhance the quality of wireless broadband services, seamless networking capabilities for optical and wireless domains need to be further explored. The first barrier to overcome in this direction is the integration of medium access control (MAC) protocols for both segments. The seamless propagation can only be achieved by resolving the layer-1 issues such as propagation delay, noise, and interference on converged medium of fiber and radio. The sub-layers logical link control (LLC), and dynamic bandwidth allocation

(DBA) within data link layer are responsible for adaptively managing the diverse traffic types over common media through coordination with medium access control (MAC) strategy of error control [25].

In converged RoF systems for applying TDMA technique in upstream, a downstream authorization message sent to a specific ONU to assign bandwidth share. The ONUs communicates with the OLT to get permission to send their data by sending a report message of current buffer status. Whereas, in the wireless segment of this converged system, carrier sense multiple accesses with collision avoidance (CSMA/CA) under 802.11 protocol suites is adopted technique. The CSMA/CA works well for converged system due to the restricted coverage area for wireless due to propagation losses in atmosphere. The integration of radio and fiber technologies to achieve converged RoF system is not straightforward. Most of the studies on converged RoF systems perceive the optical domain just as reach extension of radio signals from main switching unit to base stations or remote antenna units (RAUs). In P2MP techniques for applying RoF, the MAC only works well if propagation delay of optical fibers was not considered. In 802.16e, the maximum allowable delay spread is 300 ns for multipath interference that impose an upper limit on remote antenna spacing and overlapping coverage so that tolerance for inter symbol interference (ISI) remained in limits [29]. To overcome MAC restrictions of RoF systems, a protocol translation strategy is proposed by some research groups to meet optical-wireless borderline. This technique is known as radio and fiber (R&F) that achieved some further integration in contrary to RoF. However, it is still noncomprehensive and caused extra overhead and complexity. Recently, a third technique is proposed to apply integrated technologies for sharing the common resources between the two parts of RoF systems.

The evolution of new mm-wave technology that is capable to offer multi-gigabit signal propagations over a radio frequency channel. The latest progress in 60 GHz radio over fiber systems has made it one of the promising solutions for the multi-gigabit mm-wave wireless access networks. The Federal communications commission (FCC) in United States allocated 7 GHz of continuous spectrum 57–64 GHz for license free operation [30]. The huge free bandwidth of 7 GHz has pulled the attentions of researchers around the world. It is considered as a solution to offer multi Gbit/s wireless access for communication systems with high security and anti-interference ability [31], especially due to congestion in the lower frequency bands.

The actualization of multi-Gbit/s wireless access network at 60 GHz band comes across number of technical challenges. It suffers high air-link loss and quite low power efficiency and device performance compared to lower frequency bands (i.e. path-loss at 60 GHz is about 30 dB higher than at 2.4 GHz). The 60 GHz band undergoes 15–30 dB/km atmospheric absorption loss based on atmospheric conditions of the area [28]. The coverage area is less than 10 m for a cell at 60 GHz that needs large number of antenna units along with high-capacity feeder network to provide wireless coverage [9]. The 60 GHz signal propagation in atmosphere is estimated by Friis transmission equation. It is not possible to realize ubiquitous wireless service coverage as WiMAX and LTE with 60 GHz band [10]. Therefore, 60 GHz band can only be implemented in cost effective and practical mode as non-line-of-sight (NLOS) transmission at indoor environment. This requires inexpensive and flexible base station management at brown areas [31].

On the other hand, the mm-wave (especially 60 GHz band) radio technology can easily approach multi-gigabit capacity. It is readily apparent that multi Gbit/s data rates can be achieved by emerging high capacity mm-wave radio links with high bandwidth and small coverage distance [32]. The key consequence of this fact is that the small pico or microcells with multiple access points are required to cover a particular area (home or office) with mm-wave system. Therefore, the radio home networks will be like a multi cellular network. In this context, an integration is required to achieve the potential offered by mm-wave with the optical infrastructure to link the different remote antennas to provide a inexpensive and adjustable solution. The coordinated research efforts are required for the development and improvement of millimeter pico-cellular personal access networks at low cost in the presence of many performance constraints.

Telecom regulatory authorities have announced this band license free world wide to attract researchers, telecom operators and telecom vendors to develop systems for this band. Many groups are formed to standardize the unlicensed mm-wave band to utilize its potential as a RF carrier band for wireless access networks. The IEEE 802.15.3c-2009 was published on September 11, 2009 to attain this goal. However, the first economical and pragmatic systems for this band were marketed conforming to the IEEE 802.11ad.

4.2. Millimeter wave applications

Many indoor applications at 60 GHz band are proposed [33].

1. Uncompressed high definition (HD) video display to a remote screen wirelessly with wired equivalent "I" quality experience.
2. The gigabytes wireless file transfer.
3. Wireless personal area network that permits wireless connection with multiple peripherals like monitor, keyboard, and mouse etc. It will save the frequent need of plug and unplugs.
4. Wireless gigabit Ethernet connection that allows multi-gigabit bi-directional Ethernet traffic. This feature is very attractive for smart phones, tablets and personal digital assistants (PDAs).

Radio over Fiber (RoF) technology has attracted great interest in the last decade to offer optical transmission of radio signals to simplified base station (BS) [15].

4.3. Standardization of millimeter wave band

The great interest in 60 GHz wireless transmission has motivated the formation of many International mm-wave standardization groups and industry alliances in last few years. Unlicensed mm-waveband has been considered a possible RF carrier band for future wireless access networks. To attain this goal, the IEEE 802.15.3c task group was constituted to formulate an alternate physical layer to support mm-wave communications for the present

IEEE 802.15.3 WPAN standard [34]. In August 2006, ECMATC-48 began an effort to standardize data link and physical layer for mm-wave unlicensed band for multimedia and data applications [33]. A wireless high definition (HD) consortium was formed in October 2006, with a focus to develop a number of superior quality uncompressed multimedia applications using 60 GHz technology. In May 2009, the wireless gigabit alliance (WiGig) was created to develop a set of common specification for mm-wave band to develop a global system for interoperability of products for a diverse nature of applications. IEEE has published first mm-wave standard 802.15.3c on September 11, 2009 [18]. The IEEE 802.15.3c and IEEE 802.15.3a were proposed for wideband personal area networks. In IEEE 802.15.3c, four channel OFDM mm-waves are proposed to employ free spectrum of 57–64 GHz to achieve the data rate up to 7.3 Gbit/s [19].

4.3.1. IEEE 802.15.3c

The IEEE 802.15.3c group was formed under the supervision of the Japanese research center national institute of information and communications technology (NICT) to design a WPAN standard capable of being used at 60 GHz [14]. It is the first IEEE standard designed for multi-Gigabit/s wireless transmission to operate in the mm-wave band. This standard was published in 2009 [35]. In this standard, three physical layers are defined to meet different market segments,

Single carrier (SC) mode is based on single carrier modulations and bit rate is ranging from 25.8 Mbit/s to 5.2 Gbit/s with recommended modulation techniques are pi/2 binary phase shift keying (BPSK), Gaussian minimum shift keying (GMSK), quadrature phase shift keying (QPSK), quadrature amplitude modulation (8-QAM), 16-QAM, on off keying (OOK) and digital radio broadcast (DRB). The high speed interface (HSI) mode is based on OFDM modulations where bit rates are defined from 32.1 Mbit/s to 5.7 Gbit/s and approved modulation techniques are QPSK, 16-QAM and 64-QAM. Audio/Visual (AV) mode is based on OFDM modulations and wireless high definition (HD) specifications with physical layer throughput ranging from 952 Mbit/s to 3.807 Gbit/s and modulation formats are BPSK, QPSK, and 16-QAM.

4.3.2. ECMA-387

This Standard specifies a physical layer (PHY), distributed medium access control (MAC) sub layer, and high definition multimedia interface (HDMI) protocol adaptation layer for mm-wave networks. The ECMA-387 was adopted by ISO in June 2009. The most important feature of this standard was the channel widening by associating adjacent channels that makes it possible to support the data rates up to 25 Gbit/s.

4.3.3. Wireless gigabit alliance

The wireless gigabit alliance (WiGig or WGA) was formed in May, 2009.The purpose of this formation to brings together major telecommunication players like Intel, Wilocity, Broadcom, Atheros, and many others to work together to develop common standards for mm-wave products [34]. The first WiGig specification (Vl.O) is published in December, 2009. While, the second version introduced in 2011. The WiGig specifications are drafted to allow devices to communicate at multi-gigabit speeds without wires. The standard has recommended wireless transmission of high data rate for video and audio applications to enhance the performance of WLAN devices.

4.3.4. IEEE 802.11ad

Recently, IEEE has put in a new wireless standard 802.11ad that promises very high speed for short distance communication. The commercial products based on this standard provide 7-Gbit/s data rate over 60 GHz mm-waves. 802.11ad allows devices to exchange data over four 2.16 GHz wide channels to support data rates up to 7 Gbit/s. The IEEE standard for mm-wave was initially created in January, 2009. It was designed and developed to work at 60 GHz as a new generation of Wi-Fi systems for the IEEE 802.11 family [21]. The IEEE 802.11ad enabled chips are being installed in millions of devices. 802.11ad supports all native 802.11a/b/g/n/ac standards and enables devices to seamlessly switch between 2.4, 5, and 60 GHz bands [29]. One of the major advancements comes from the single carrier is low power consumption. It can enable advance power management and long battery life of device. For 60 GHz band, the data rate around 7 Gbit/s that makes it more attractive than the common Wi-Fi standards at 2.4 and 5 GHz. The IEEE 802.1lad standard maintains the Wi-Fi user experience at the same time with backward compatibility to the previous 802.11 systems.

This new 60 GHz Wi-Fi standard provides support to internet protocol (IP), high definition multimedia interface (HDMI), display port(a digital display interface developed by the video electronics standards association), universal serial bus (USB) and peripheral component interconnect express (PCie). Therefore, it is multi-protocol used to communicate with various peripherals including IP, audio-visual (AV), and input–output (I/0) data ports. In 802.11ad, single carrier (SC) modulation is formulated to support multi gigabit/s data rates for line of sight (LOS) short distance communication but maintaining low power consumption and low system complexity. Whereas, OFDM is adapted for high data rates for non-line of sight (NLOS) transmission but only for a maximum distance of 10 m.

5. Conclusion

The ever increasing customer demands for high capacity broadband services has ensued the development of fiber based access networks. A comprehensive overview about radio systems capable to provide multi gigabit data rate with special focus on 60 GHz millimeter wave is provided. The 60 GHz mm-wave allocated spectrum, its applications and standardization, and system approaches are also highlighted. Most of the present studies are concentrating the point-to-point fiber-wireless transmission using hetero optical suppressed carrier mm-wave systems, whereas multi-user applications such as pico or femto-cells still need exhaustive research efforts. The simulation and experimental systems need to be designed to further reduce the cost of devices conforming to optical access process introduced in the IEEE 802.11ad standard.

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