

APT REPORT

ON

DESCRIPTION OF RADIO OVER FIBER TECHNOLOGIES
FOR SEAMLESS ACCESS COMMUNICATION SYSTEMS

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# Introduction

It is well known that radio over fiber (RoF) technologies have been utilized to provide radio signals through optical fiber cables to such radio equipment as radio access units. It is also recognized that RoF technologies can provide compact radio access units which have no digital signal processing functions. A number of applications utilizing RoF technologies have been discussed to specify technical requirements for the wired and wireless seamless access communication systems. Those technical requirements have been published to provide guidance to implement RoF technologies in wired and wireless seamless access systems for APT member countries. This Report summarizes those applications and provides APT members a broad understanding of the essence of RoF technologies.

# Scope

This Report addresses the architectures, features, technical characteristics and applications of RoF technologies for seamless access communication systems. This Report also provides some guidance to implement RoF technologies in the millimeter-wave access communication systems.

# References

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[ITU-T G.989.1]: Recommendation ITU-T G.989.1, 40-Gigabit-capable passive optical networks (NG-PON2): General requirements.

[ITU-T J.185]: Recommendation ITU-T J.185 (2012), Transmission equipment for transferring multi-channel television signals over optical access networks by frequency modulation conversion.

[ITU-T J.186]: Recommendation ITU-T J.186 (2008), Transmission equipment for multi-channel television signals over optical access networks by sub-carrier multiplexing (SCM).

[ITU-R F.1332]: Recommendation ITU-R F.1332, Radio-frequency signal transport through optical fibers.

[ITU-R F.2106]: Report ITU-R F.2106, Fixed service applications using free-space optical links.

# Abbreviations and acronyms

This Report uses the following abbreviations and acronyms:

3GPP Third Generation Partnership Program

BBU Baseband unit

BPSK Binary phase-shift-keying

CATV Cable television

CD Chromatic dispersion

C-RAN Cloud-radio access network

DSP Digital signal processing

EMC Electromagnetic compatibility

EMI Electromagnetic interference

ENG Electronic news gathering

EVM Error vector magnitude

FM Frequency modulation

FOD Foreign object debris

FSOL Free-space optical link

FTTH Fiber to the home

IM3 Third-order intermodulation distortion

MBH Mobile backhaul

MFH Mobile fronthaul

MSF Modulation maintaining format

NF Noise figure

ODN Optical distribution network

OOK On-off-shift-keying

PON Passive optical network

QAM Quadrature-amplitude-modulation

QPSK Quadrature-phase-shift-keying

RAN Radio access network

RF Radio frequency

RIN Relative intensity noise

RoF Radio over Fiber

RoFSOL Radio on free-space optical link

RoRoF Radio on radio-over-fiber

RRH remote radio head

SEFA Signal extraction with frequency arrangement

SFDR Spurious free dynamic range

SSB Single sideband

WDM Wavelength division multiplexing

# Architecture of seamless access communication systems

**5.1 System overview**

The principle of seamless access between wired and wireless links is to maintain a modulation symbol format consistently, which means that a modulation symbol format should be seamlessly transmitted over all physical transmission paths such as optical cables and airs, where we call it “modulation-symbol-format (MSF) maintaining transmission”. Figure 1 shows the fundamental configuration for MSF maintaining transmission, which consists of a pair of MSF-maintaining media conversion processors and a physical transmission path/medium. The portion consisting of the pair of MSF-maintaining media conversion processors and the transmission path/medium corresponds to an MSF-maintaining link. In this case, the MSF-maintaining media conversion processor should basically have functions of both frequency conversion and physical interface from/to the physical transmission path/medium.



Figure 1 Modulation-symbol-format (MSF) maintaining transmission

**5.2 Radio over Fiber (RoF) link**

RoF refers to a fiber optic link where the optical signal is modulated at radio frequencies (RF) and transmitted via the optical fiber to the receiving end. At the receiving end, the RF signal is demodulated and transmitted to the corresponding wireless user.

Figure 2 shows a basic configuration of the RoF link consisting of E/O or O/E conversions and an optical fiber cable, which corresponds to MSF-maintaining media conversion processors and physical transmission path/medium introduced in section 5.1. The transmission loss of a standard single mode fiber is 0.2dB/km at a wavelength of 1550nm. The total link gain or loss of the RoF link is largely depends on the efficiency of E/O and O/E conversions. The characteristics of millimeter waves radiated from antennas depend on the performance of the components e.g. RF (Radio frequency) amplifiers and transmitting antenna. The received signals from the air are superimposed on the optical carrier and then transmitted to O/E converter through an optical fiber.

There are various techniques used to transmit data in RoF system such as the optical phase-locked loop (OPLL) (Langley et al., 1999), optical-injection phase-locked loop (OIPLL) (Johansson and Seeds, 2001), dual sideband (DSB) modulation (Laurêncio et al, 2010), using stimulated Brillouin scattering (SBS) (Shee et al., 2009; Shee et al., 2010; Mohamad et al., 2011) and the dual sideband optical carrier suppression (DSB-OCS) (Hsueh et al., 2009; Park et al., 2010; Seo et al., 2006).

Figure 3 shows the schematic illustration of subcarrier transmission principle of RoF link. The RF signals superimposed on an optical carrier are schematically shown at the upper-sideband of an optical carrier.



Figure 2 RoF link configuration for transmission of RF signals.



Figure 3 Subcarrier transmission of RoF link.

**5.3 Features of RoF link**

***Market setting***

Because one of carrier frequencies for the next generation of the mobile systems will be moved to microwaves to millimeter-waves, a variety of deployment architectures and scenarios such as ultra-dense network, multi radio access, mobile relay, cloud- radio access network (C-RAN), Coordinated Multi-Point (CoMP), indoor and outdoor hotpots and moving hotspot including backhaul have been proposed in ITU-R, other standard organizations and international forums. There will be many opportunities for the RoF link to be used as one of important seamless access communication links.

***Transparency***

As mentioned in section 5.1, the signals transmitted through RoF link can seamlessly transmit over all physical transmission paths such as airs, coaxial cables, waveguides, etc. The modulation scheme, carrier frequencies and channel arrangements of those signals are continuously maintained in each transmission media.

***Electromagnetic compatibility***

The optical carrier frequencies of the RoF link are much higher than the frequency range used in the electromagnetic compatibility (EMC). In addition to the characteristics, the RoF links do not interfere with the electromagnetic environments due to much smaller relative dielectric constant of the fiber cable than that of the coaxial cable. Because of the general characteristics of the fiber cable, the RoF link has the benefits of immunity to EMI (Electromagnetic interference).

***Broadband capability***

Since the current O/E and E/O conversion devices can operate in the frequency range from millimeter-wave to terahertz, the high-speed data transmission through fiber cables is feasible. The radio frequencies up to terahertz can also be generated by optical means at either transmitter or receiver. WDM technologies also utilizes enormous bandwidth of the optical fiber.

***Bias-free device implementation***

Considering the huge number of radio access points required for the next generation of the mobile systems, there is an urgent need to improve the energy efficiency of the mobile systems and to reduce the power consumption of the radio access points. The RoF link can provide a bias-free access point whose functions are only E/O and O/E conversions without RF amplifications. The RoF link can be a part of energy-efficient components for the green seamless communication networks.

***Beamforming***

The current wireless LAN standards specify the beamforming function of LAN devices as normative references. Optical multi beamforming networks have been intensively investigated to utilize advantages of optical devices such as a wide bandwidth, high immunity to EMI, low power consumption, small size and light weight. The additional benefit to integrate the RoF link with optical beamforming networks is that the link can be directly connected to the optical beamforming networks without any signal processing units. Although the characteristics of the RoF link is relatively sensitive to RF and optical components and drifts, the performance of the beamforming networks including that of the RoF link may be controlled by optical parameters.

***Applicability***

The RoF technologies were first applied to CATV system and satellite remote antenna system. Then the Rof links were used for providing the broadcast wave to poor reception areas of TVs as well as the radio signals to insensitive areas of the cellular phone systems. Additionally, there are many application areas of the RoF link to the cellular phone systems, such as the connection between remote antenna and indoor equipment in the base station, the distribute antenna system for insensitive areas in the building, the connection between antenna with amplifiers and indoor equipment with modulation/demodulation baseband units in the small-cell base station. With respect to broadcast applications, the RoF links are utilized to transmit the broadcast wave from the studio to the transmitting tower.

***Scalability***

There have been many applications of the RoF links to the cellular phone and broadcasting systems, as mentioned above. However, the cellular phone systems are moving to so-called 5G era and considerable research has been carried out by various organizations on feasibility study for the future cellular systems which utilizes spectrum above 6 GHz and requires very high throughput data links to cope with the growth of the data traffic. It is not difficult for the RoF link to carrier millimeter-wave signals to meet the requirement of 5G systems due to its broadband transmission capability. The RoF links also have possibility to support the ultra-dense network with small cells, moving cells and cloud-RAN whose functions are studied for the future 5G systems. In particular, a C-RAN architecture centralizes the baseband and higher layer processing units so that the processing resources can be managed and allocated dynamically on demand, while the remote antenna units including active antennas can be distributed through the RoF link. In addition to the cellular-type systems, the RoF link can be extended to the other applications such as sensing and imaging systems operating at millimeter-wave frequencies.

***Dynamic resource allocation***

The RoF systems can distribute more or less number of subcarriers depending on the traffic peak or off-peak time, respectively. The RoF systems can also distribute multi-operator and multi-service traffic which brings in huge economic savings by allocating optical wavelengths.

***Free-space connectivity***

Radio on free-space optical link (RoFSOL) is introduced to connect the RoF link via free-space optical link (FSOL). Because of this transmission link, the RoF link can be connected, for examples, between buildings, rivers, etc. where the fiber cable cannot be installed.

***Interoperability***

The RoF related standard has to support interoperability between E/O and O/E conversion devices. All relevant interfaces to facilitate interoperability shall be defined in the appropriate APT Recommendations to be developed by ASTAP.

***Susceptibility***

There many degradation factors of the RoF links such as multiple reflection by optical connectors, chromatic dispersion (CD) characteristics of the fiber cable, stimulated Raman scattering by the fiber nonlinearity, non-linearity characteristics of E/O conversion device and relative intensity noise (RIN) of laser sources. In addition to the optical device characteristics, the noise performance of RF receiver and nonlinearity of RF transmitter also affect the total characteristics of the RoF link. To overcome the above-mentioned shortcomings, the digital transmission techniques will be applied to the current RoF link structures as appropriate.

***Compatibility***

Since the certain wavelengths are already allocated to the legacy and newly standardized PON systems, the wavelengths for the RoF links should be carefully selected to co-exist with those PON systems including RF video taking into account the degradation factors mentioned above.

# System characteristics

This section provides key elements for designing the basic RoF link for seamless access communication systems.

**6.1 Link gain and noise figure**

Figure 4 shows a block diagram to evaluate the linearity of RoF link using an external optical modulator, an optical amplifier, an optical bandpass filter and a photodetector. The optical amplifier is used to compensate the optical losses caused by other components including fiber cable. The link gain is defined as the ratio of the input power of an external modulator and the output power of a photodiode. An 8dB of the link gain and noise figure was obtained at 60 GHz frequency, as an example. The link gain and noise figure (NF) of the RoF link are optimized by considering optimal apportionment of gain and NF of each optical and RF device. The low RIN and spectral line width of laser sources should be selected to minimize their effect to the RoF link performance as well. The CD of the fiber cable can be eliminated by use of single-sideband (SSB) optical modulator and heterodyne detection. Another possibility to suppress a CD is to use a zero-dispersion wavelength such as 1310 nm. In the practical use case of the fiber link, it is very difficult to avoid fiber connections to accomplish MSF maintaining transmission through the optical distribution network (ODN). The fiber connections generate multiple reflections and increase losses of the fiber cable due to the Fresnel reflection loss. The other element is the cross talk between the wavelengths caused by the stimulated Raman scattering. The degradation by these losses should be taken into account if the long distance transmission of the RoF link is demanded.



Figure 4 Single-side-band modulated signal transmission of RoF link.

**6.2 Spurious free dynamic range**

Spurious free dynamic range (SFDR) is an important evaluation parameters for RoF link linearities. A SFDR larger than 80dBHz2/3 at 60 GHz subcarrier frequencies was obtained by the commercially available devices. Since the SFDR depends on technical characteristics of RF and optical components as well as frequency ranges, it is important to select low noise RF and optical devices to avoid nonlinear distortion effect. Several techniques have been proposed to improve SFDR. One technique was published as ITU-T Recommendation J.185 which proposes to us frequency modulation (FM) conversion. In this FM conversion technique, subcarrier multiplexing signals are simultaneously converted into one single wideband FM signal. This FM signal is then transmitted through the RoF link by using the intensity optical modulation. The second is the signal extraction with frequency arrangement (SEFA) which can increase the optical modulation index to suppress the third-order intermodulation distortion (IM3) produced by E/O conversion. The third is the signal level compression (SLC) technique which improves the dynamic range for the RoF link. The higher gain value of the compressor could be adjusted if a signal of lower level is received at the antenna. The SLC technique improves the received C/N at the O/E conversion for the low-level signals received at the antennas. Since nonlinearity which limits SFDR is mainly influenced by the characteristics of the optical devices, these SFDR improvement techniques are performed in the optical domain.



Figure 5 SFDR of RoF link.

**6.3 Error vector magnitude**

The digital modulation scheme is dynamically evaluated by a parameter of error vector magnitude (EVM). The EVM is defined in the base station conformance testing technical specifications of the Third Generation Partnership Program (3GPP). The EVM is a measure of the difference between the reference waveform and the measured waveform. The difference between the two is the modulation error and it can be expressed as an EVM, Figure 6 shows the results of EVM of the RoF link shown in Figure 4. The π/2-BPSK EVMs of an RF back to back and an RoF link whose fiber transmission length is 180 m are 3.3% (-29.6dB) and 12.7% (-17.9dB), respectively. Since the EVM characterizes the modulation accuracy of the demodulated received signals, the degradation factors of the RoF link can be evaluated.



Figure 6 60-GHz π/2-BPSK signal transmission experiment.

**6.4 Link latency**

The link latency is defined as the time to send a packet of data to a receiver. The lower the latency of the RoF link, the better the application systems performance. The intrinsic latency of the RoF link is important factors to design the transmission fiber distance in the ODN and air propagation distance in the cellular zone. The intrinsic link latency of the RoF link caused by RF and optical components, as shown in Figure 4 is about 100 ns. The additional delay time by optical fiber cables is 5 ns/m.



Figure 5 Delay time of RoF link.

**6.4 Co-existance with other PON systems**

A lot of wavelengths have been allocated for several types of PON systems, as shown in Figure 6. The 40-Gigabit-capable passive optical networks have introduced a shared spectrum for the point-to-point WDM systems to co-exist with the incumbent PON systems. These wavelength arrangements to the PON systems should be taken into account if the certain wavelength for the RoF link is allocated either in the shared spectrum or other spectrum. The stimulated Raman scattering and other elements also should be considered for compatibility study between the RoF link and PON systems. The wavelength for the RoF link will be identified taking into account those requirements.



Figure 6 Wavelength arrangement for PON systems.

# Main applications of RoF technologies

This section specifies the main applications of RoF technologies for seamless access communication systems.

**7.1 Resilient access networks**

Optical fibers can provide high-speed transmission, while radio-wave communications can have agile deployment capability. Seamless integration of optical fiber based wired links and radio-wave based wireless connections would be useful for highly resilient communication systems.

Simple modulation formats, such as on-off-keying (OOK), binary phase-shift-keying (BPSK), are commonly used in conventional optical transmission systems, because lightwave device technologies were not precise enough to transfer signals in advanced modulation formats such as quadrature-phase-shift-keying (QPSK), quadrature-amplitude-modulation (QAM), etc., which are commonly used for wireless communication systems. Recently, a lot of effort was focused on development of digital coherent optical communication technologies based on high-performance digital signal processing (DSP) and on vector optical modulation/demodulation. On the other hand, the radio-wave signals are effectively generated and transferred by using RoF technologies. The ultra-high-speed wireless communication systems which utilize the millimeter-wave wide-bandwidth transmission capability are feasible by combining the digital coherent and RoF technologies.

The wired and wireless seamless transmission link for the resilient access networks consists of the optical link and the wireless link as a backup. However, bitrates would be lower than a few Gbps in the current wireless systems, while optical fiber communication systems can provide over 100 Gbps data transfer. Therefore, much higher bit-rate wireless transmission technologies are required to mitigate surge of traffic demands in particular cases such as disaster recovery. Millimeter-waves are more attractive for high-speed data transmission rather than microwaves , because wide frequency bands are available in high frequency range over 60GHz. RoF technologies with DSP can provides over 10Gb/s ultra-high-speed data transmission through millimeter-waves. In terms of atmospheric attenuation, the use of W-band (75–110 GHz) is better than 60GHz, because the attenuation within this band tends to be less than 1 dB/km. The RoF systems integrated with W-band wireless would be useful for high-speed data transmission in metropolitan and/or rural areas for particular purposes as well as for disaster recovery and are recommended to be seamless access communication network. The detailed specifications of resilient access networks are provided in APT Report (APT/ASTAP/REPT-11).

**7.2 Mobile fronthaul/mobile backhaul**

The Radio over Fiber (RoF) for radio signal delivery over optical fiber networks, and Radio on Radio over Fiber (RoRoF) for transportation of microwave signals on a millimeter-wave carrier over optical fiber networks are recommended to use the mobile fronthaul (MFH) and mobile backhaul (MBH) which provides the connection speed to each mobile terminal over 10 Gb/s. To realize such high-speed connection, a carrier frequency of the radio should be increased to millimeter-wave band. In addition, high throughput for enhancing user experiences requires to make cell-size/coverage by each radio base station small. A function of the base station should be separated to the combination of a baseband signal processing unit (BBU) and a radio access unit (RAU). Many RAUs are connected to the BBU through MFH whose transmission capacity should be high and latency The MBH for the connection between the BBU and the core/metro networks should have the capacity much larger than that for the MFH.

The RoF and RoRoF have a feature on seamless conversion between the optical (wireline) signal and a radio (wireless) signal. A part of the RoF technologies has been already utilized as an MFH link, and has been discussed the possibility for seamless integration to a fiber to the home (FTTH). On the other hand, the RoRoF has features as low latency of a media conversion and avoidance of the frequency interferences owing to the encapsulation of the incumbent services to the millimeter-wave carriers. The proof-of-concept and detailed specifications of RoF and RoRoF technologies are provided in APT Report [APT/ASTAP/REPT-25].

**7.3 RoF relay links for indoor networks**

Architectures and characteristics of Radio over Fiber (RoF) relay links for indoor communication systems to connect wireless devices which are wirelessly disconnected by obstacles such as concrete walls, floors, etc. are recommended to be seamless access communication network. RoF relay transmission links can transmit RF signals in the frequency range from microwaves to millimeter-waves due to broadband conversion characteristics of O/E and E/O devices. If RF signals cannot penetrate the walls between two indoor spaces, and optical fiber cables are already installed between two spaces, then the RF signals can be transmitted from one space to the other through an optical fiber cable. RoF relay transmission links cannot be only applied to indoor communication systems, but also to outdoor repeaters to provide subcarrier frequencies for the broadcasting and mobile systems. The detailed specifications of RoF relay link for indoor networks are provided in APT Report [APT/ASTAP/REPT-20].

**7.4 Integration of RoF with WDM-PON**

Radio over Fibre is a rather ideal technology for the integration of wireless and wired networks. The main reason being is that it combines the best attributes of two common communication methodologies. A wireless network connection frees the end-user from the constraints of a physical link to a network, which is a drawback of conventional fibre optic networks. Meanwhile optical networks have an almost limitless amount of bandwidth with which to satiate even the most bandwidth hungry customers where bandwidth for wireless networks can be a significant bottleneck. Thus, RoF networks offer customers the best of worlds by allowing them to maintain their mobility while also providing them with the bandwidth necessary for both current and future communication/entertainment applications.

Furthermore, RoF networks also provide for greater geographical flexibility as compared to using either one or the other methodologies. Such network topologies could be useful in places such as large buildings, subways and tunnels where large amounts of people are mobile thereby making physical connections impossible and standalone wireless systems being faced with the difficulty of bandwidth limitations and handover issues. With that reason, architecture of the hybrid RoF-WDM PON is recommended to be considered as application for seamless access communication network. The implementation of RoF-WDM PON architecture at residential area and the block diagram of integration radio over fiber WDM PON are provided in APT Report [APT/ASTAP/REPT-19]. Additional technical information is provided in Annex 1.

**7.5 Multiservice signal transmission system**

The multiservice transmission system which uses multiple microwave signals on a millimeter-wave carrier over optical fiber network is recommended for the distributed antenna systems. The system combines multiple wireless communication services such as wireless LAN and LTE into one infrastructure using millimeter-wave carriers that are distributed through optical fiber, with last mile and indoor connectivity are completely wireless. The proof-of-concept and detailed specifications of multi radio signal delivery over optical fiber and radio transmission links based on RoF technology is provided in APT Report [APT/ASTAP/REPT-26].

**7.6 Broadband railway communication systems**

RoF technologies for millimeter-wave radio signal delivery to the radio transceiver along the trackside over an optical fiber link for application of the broadband railway communication system (RCS) are provided in APT Report (APT/ASTAP/REPT-38).

**7.7 Other applications of seamless access systems**

**7.7.1 Remote antenna system for broadcasting**

A remote antenna system with RoF technologies has been deployed for radio shadowing areas such as skyscraper, underground, subway and tunnel using radio waves relaying technologies. The detailed explanation of remote antenna system is provided in APT Report [APT/ASTAP/REPT-03 Rev4].

**7.7.2 Electronic news gathering for broadcasting**

To maintain a line-of-sight link between electronic news gathering (ENG) transmitters and ENG receivers in the metropolitan area where may skyscrapers are built, RoF technology is introduced to connect ENG receivers which are installed on the highest tower and TV broadcasting control stations. The detailed explanation of electronic news gathering is provided in APT Report [APT/ASTAP/REPT-03 Rev4].

**7.7.3 Foreign object debris detection system**

Because the detection of the foreign object debris (FOD) on the airport surface is the most important safety issues for the airport management, the stable operation and high-resolution radar detection systems should be introduced at each airport. The detailed explanation of Foreign object debris detection system using RoF technologies is provided in APT Report [APT/ASTAP/REPT-03 Rev4].

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Annex 1

**Integration of Radio over Fiber with WDM PON for Seamless Access Network**

**A1.1 Introduction**

Figure A-1 and A-2 shows the block diagram of integration Radio over Fiber with WDM PON. From the both figures, it can be divided into 4 sections. First section is an Optical Line Terminal (OLT) which consists of a number of GPON cards and ROF Cards in several cabinets and X:1 WDM MUX. The GPON cards and ROF Cards which used to generate PON wavelength, (𝝺1,2GPON) and RoF wavelength, 𝝺RoF, (𝝺a, 𝝺b, 𝝺c and etc) respectively are linked together at the WDM MUX. This architecture ideally is suggested to implement at new development area which requires both PON system and RoF network. A multiples combination of wavelength then goes through the WDM MUX is transmitted to the second section called distribution network.

In this section, all fiber connectivity from WDM MUX is connected to Optical Distribution Frame (ODF) which is functioning as an intermediate interface between in-building fiber connection and external distribution fiber network connection. The ODF will manage the arrangement of a ring network connection for each coverage areas with the respective cabinets within the exchange building. For this architecture, the single-mode fiber (SMF) is proposed to use for the ring network fiber connection between ODF and Fiber Distribution Cabinet (FDC) which located about 5km away from the exchange building. The FDC contains WDM DEMUX used to separate the wavelength of the respective optical signals to respective Pedestal Distribution Points (PDP) or Remote Antenna Units (RAU). The total 20km distance and 10km from ODF-FDC-PDP-ONU and from ODF-FDC-RAU-CPE respectively are calculated based on accepted signal attenuation for PON system and accepted noise distortion for RoF network. In the PDP, there is a 1: Y splitter which used to distribute the optical power to each customer premise at same the wavelength (𝝺1,2GPON) while in the RAU, there is a 1:Z WDM DEMUX which used to separate the wave length to specific wavelength (𝝺a, 𝝺b, 𝝺c and etc) for each customer premise.



Figure A-1 Block diagram of integration radio over fiber WDM PON.



Figure A-2 Implementation of RoF-WDM PON architecture.

**A1.2 Radio-collaborating optical distribution network (ODN)**

A few approaches to solve a geographical problem for access network, it is desired that the ODN area should be extended with radio technologies as mentioned in the previous section. Figure A-3 shows some fundamental radio-collaborating ODNs, in which a part of ODN is replaced with a radio link. Figure A-3(a) represents the ODN, in which a dropping fiber is partially replaced with a radio link. Figure A-3(b) represents the ODN, which makes good use of the multi-casting nature of radio at a distribution point. Figure A-3(c) represents the ODN, in which a consolidating fiber is partially replaced with a radio link. The required bandwidth of radio link strongly depends on PON services. Since the bandwidth of PON services is much broader than that of conventional radio services, high-efficient radio transmission techniques, such as multi-level modulation, multi-input multi-output transmission, multi-band aggregation, and so on, may be also required even if a millimeter-wave-band radio is used.



(a)



(b)



(c)

Figure A-3 Radio-collaborating ODN: (a) in a dropping line, (b) at a distribution point, and (c) in a consolidating line.

Moreover, we can configure any combination of radio-collaborating ODNs shown in Figures A-3(a) to (c)

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