Chapter 2
Evolution and Trends of Broadband Access Technologies and Fiber-Wireless Systems

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Abstract This chapter provides the introduction to technical trends and market status of both broadband wireline and wireless access networks and also summarizes the technology evolution of fiber and wireless networks. The technical introduction on broadband wireline access networks includes xDSL, coaxial cable and hybrid fiber coax (HFC), and various passive optical network (PON) architectures. The current global deployments on broadband wireline access are also presented here. As for the study on the broadband wireless access technologies, this chapter addresses the technical evolution path for dominant Wi-Fi, WiMAX, and mobile communications systems. As wireless and wireline technologies converge and the dividing lines become less clear, the common denominator will be optical fiber. In this chapter, technology synergies and recent research activities are also described for the integrated fiber-wireless access networks.

2.1 Traffic Trend

Today, the broadband access paradigm has seen phenomenal growth to almost all corners of the globe and forms an indispensable part of the daily life of billions of people. In the future, it is envisioned that this paradigm will evolve toward full broadband capability with more connections, less delay, and much higher bandwidth to satisfy the end users' demand. Internet and leased line bandwidth demand continue to grow at more than 20 % per year driven by more and more video streaming and proliferation of cloud computing, big data, social media, and mobile data delivery. In terms of video data and traffic, an enhancement of high-definition video such as 8K Ultra High Definition (UHD) will be available around 2020, and the provisional estimate of the total video communication traffic in 2020 carried

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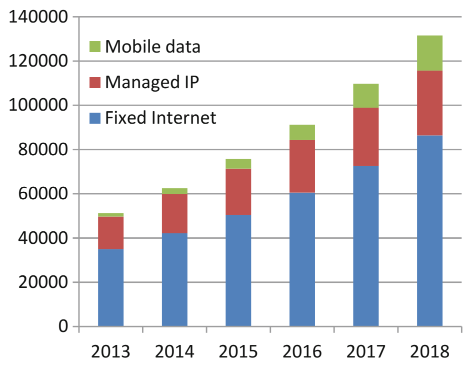

Fig. 2.1 Global IP traffic by type (petabytes per month). *Source* Cisco VNI 2014 (adopted from [3])

over mobile and fixed systems is more than 2600 times the traffic in 2010 [1]. As for the mobile data, global mobile broadband subscriptions grew by around 35 % annually and reached 2.3 billion in Q1 2014 and are predicted to reach 7.6 billion by 2019 [2]. The growth will also be accelerated by new types of communication services, such as proximity-aware services including device-to-device (D2D) communications, which enables direct links between the wireless devices using the same spectrum and interface, and machine-to-machine communications (M2M) where the objective is to attach a large number of low-rate, low-power devices to the cellular network. Figure 2.1 shows IP traffic growth during 2013–2018 predicted by Cisco Visual Networking Index (VNI) published in 2014. Annual global IP traffic will surpass the zettabyte (1000 exabytes) threshold in 2016. By 2018, global IP traffic will reach 1.6 zettabytes per year, or 131.6 exabytes per month. Global IP traffic has increased more than fivefold in the past 5 years and will increase threefold over the next 5 years. Overall, IP traffic will grow at a compound annual growth rate (CAGR) of 21 % from 2013 to 2018, in which mobile data will increase extremely fast with a 61 % CAGR.

Figure 2.2 shows the traffic growth prediction of global consumer Internet video, which is mainly over-the-top (OTT) services. The traffic of Internet video grows even faster with 27 % CAGR for fixed Internet and 70 % for mobile Internet. The rapid growing traffic reflects a great demand for broadband with more and more

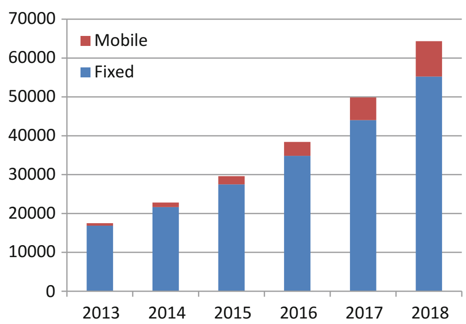

Fig. 2.2 Global consumer Internet video by network (petabytes per month). *Source* Cisco VNI 2014 (adopted from [3])

bandwidth. It can be predicted that the broadband access data rate will be threefold in 2018 compared to 2013, and 100 Mb/s per user will be required for high-value users. Currently, Google Fiber has provided 1 Gb/s symmetric data rate for some US cities, which is a breakthrough for broadband access services.

For the future user's demand trend, more and more customers are expecting to have the same quality of experience from Internet applications anytime, anywhere, and through any means of connectivity. This expectation is now being achieved by the significant technological evolution of both broadband wireline and wireless access networks. The goal is to make full use of the synergies of the two networks by narrowing the gap between wired and wireless environments.

2.2 Technologies of Broadband Access Networks

2.2.1 Broadband Wireline Access Networks

Broadband wireline access network provides promising and stable bandwidth to user premises. The medium to user premises can be coaxial cable, optical fiber, twisted pair, or hybrid of fiber and copper. Broadband services normally refer to "triple play," which is the service provisioning of broadband Internet access, television, and telephone over a single broadband connection.

In global broadband deployment, all types of wireline access networks exist simultaneously. Even in a single area, many types of wireline access networks might coexist under different conditions and for different users. PON allows user premises to connect to broadband networks via fiber with a superior bandwidth according to demand, as high as 1 Gb/s. The reach can also be up to 20 km. Consequently, PON is the most popular access network worldwide.

xDSL could take advantage of existing telephone line; hence, it is widely accepted in countries with rich copper line resources. The up-to-date xDSL technology such as VDSL and VDSL2/2+ is able to provide more than 50 Mb/s bandwidth within several hundred meters distance from user premises to the central office. Other wireline access networks based on copper include twisted pair and coaxial cable technologies, such as Ethernet, which can provide 100 Mb/s within a short range typically less than 100 m.

In some scenarios, PON and copper technologies are combined to achieve both low deployment cost and better performance. For instance, PON could connect the signal to the curb, and then, telephone line or twisted pair will carry the signal to user premises using xDSL or Ethernet.

In the following sections, these popular wireline access network technologies will be introduced in detail, including PON, xDSL, twisted pair, coaxial cable, and fiber–copper hybrid.

2.2.1.1 Passive Optical Network (PON)

In comparison with copper, fiber almost has infinite bandwidth. Recently, optical fiber is more and more applied in access networks instead of copper that dramatically decreases the OPEX and increases the performance of the network. The emergence of PON brings a feasible solution to the last mile for operators. PON technologies employ optical fiber as the transmission medium and all passive devices through the entire link and hence greatly reduce the maintenance cost.

The optical distribution network (ODN) is comprised of optical power splitters, fiber distribution boxes, etc. PON distributes or aggregates the signal to each optical network unit/optical network terminal (ONU/ONT) through power splitters. Figure 2.3 illustrates the basic architecture of PON technology. The key components and devices of a PON are an optical line terminal (OLT), which is normally located in the operators' central office, ONUs/ONTs at the user ends and an ODN. At the OLT, data and voice services are integrated and transmitted over 1490 nm wavelength in the downstream direction, while 1310 nm is assigned for the upstream direction. Video services occupy 1550 nm from the OLT to ONUs/ONTs. The OLT connects the PON and upper metro networks, and the ONU serves as the interface to the user. The ODN distributes the signal into multiple copies and transmits it to each ONU/ONT. The splitting ratio could be 2–64 with typical values of 8, 16, 32, and 64. In the real installation, the distance between OLT and ONU/ONT can be up to 20 km.

Different PON technologies could employ different rates, including 155 Mb/s, 622 Mb/s, 1.25 Gb/s, and 2.5 Gb/s. For instance, Ethernet PON (EPON) has a symmetric upstream and downstream data rate of 1.25 Gb/s, while Gigabit PON (GPON) has asymmetric downstream and upstream data rates of 2.5 and 1.25 Gb/s, respectively. Different PONs also apply different data encapsulations.

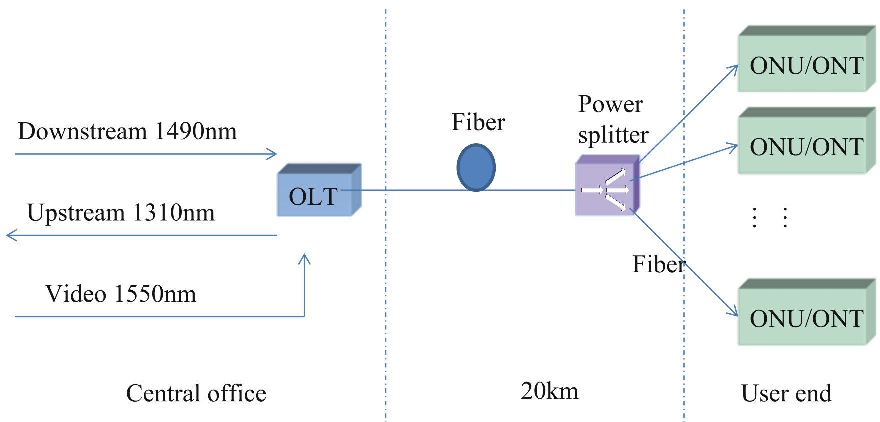

Fig. 2.3 Architecture of PON technology

The ONU/ONT is located at the user premises. Compared with OLT, ONU/ONT always encounters an unstable environment. The functions of ONU/ONT are to provide optical interfaces with the PON, introduce the signal into the user premises, and provide possible electrical interfaces such as Ethernet and video. The ONU divides the video, data, and voice information from the OLT and transmits the information to the corresponding local interfaces. Meanwhile, the ONU processes the signal from the user premises and transmits it via an upstream channel to the OLT.

The OLT has two basic functions, which are user services control and dynamic bandwidth allocation for the ONUs. Considering that there are up to 64 ONUs using the same wavelength, there must be some multiple access methods to avoid conflict among the ONUs. The easiest way is time-division multiple access (TDMA), which allows each user to transmit and receive information during assigned time slots. Both EPON and GPON employ TDMA for upstream communication; thus, they are categorized as TDM-PONs. An efficient mechanism to allocate bandwidth is dynamic bandwidth allocation (DBA). When a time slot is empty, it will be assigned to ONUs that require more bandwidth. DBA is implemented using certain algorithms in the OLT according to users' priority, quality of service (QoS), and bandwidth demand. For downstream information, the OLT broadcasts all data to every ONU. All ONUs receive the broadcasted information from the OLT, and each ONU accepts or discards data according to the identifier (ID) in the frame head. To ensure the safety and privacy of the information, all data must be encrypted.

Fiber-to-the-home (FTTH) is the access structure that employs PON technologies and fiber from OLT all the way to the user premise. FTTH has started to be massively deployed worldwide since 2008. Especially after 2010, FTTH is the major solution for access network infrastructure installations and upgrades. The OLT is located in the central office, while the power splitter is settled in the community or inside the building. The horizontal part of the fiber (red solid line) inside the building can employ butterfly cable, and the ONU is normally set in the box outside the user premise. FTTH is the ultimate form of access network, which can provide more than 100-Mb/s bandwidth for each user. The structure of FTTH is shown in Fig. 2.4.

Nowadays, there are two types of PON technologies deployed worldwide, EPON and GPON. EPON is widely deployed in East Asia including China, Japan, and South Korea, while GPON is more accepted in Europe and USA. GPON is more and more popular recently because it can provide larger bandwidth and receives strong support from the industry.

1. EPON

1G EPON was proposed and standardized by IEEE802.3ah EFM working group where the main purpose of EFM is to promote Ethernet in access networks. EPON standard was published in 2004, and it defined the physical and MAC layer. EPON is the modified version of IEEE802.3, which mostly reused the contents of

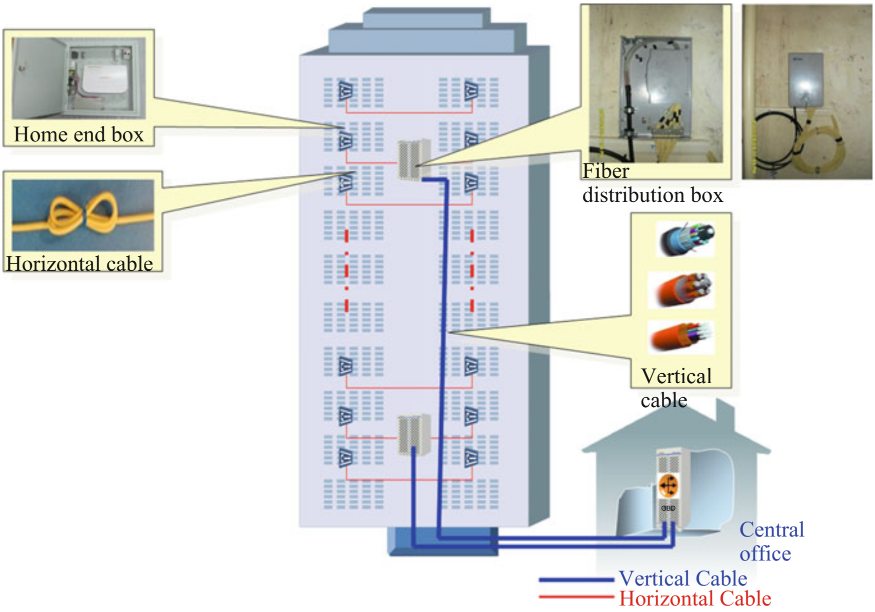

Fig. 2.4 Structure of FTTH

IEEE802.3. EPON standard also includes Operation and Maintenance (OAM) mechanism for convenient network maintenance [4].

The signal between OLT and ONU is based on the IEEE802.3 Ethernet frame, which employs 8B/10B line coding. The data rate is symmetrical 1 Gb/s, while the line rate is 1.25 Gb/s. EPON supports 1:64 splitting ratio and a maximum of 20 km reach. The key of EPON is the multi-point control protocol (MPCP) in the MAC control layer. MPCP controls and visits point to multi-point (P2MP) topology through message, state machine, and timer. EPON provides a dedicated OAM mechanism to implement link monitoring, as well as remote loop and service layer management with expansion [5].

EPON standard sacrifices some performance to reduce the technical complexity and implementation difficulty; hence, it has shortage on bandwidth and efficiency. To further increase the competence of EPON, IEEE established 802.3av working group to study 10G EPON. 10G EPON increases the bandwidth to 10 times that of EPON, but the bandwidth efficiency has not been improved. The target of 802.3av is to define 10 Gb/s symmetric and asymmetric (upstream 1.25 Gb/s downstream 10 Gb/s) access technology. To support two types of data rates, 802.3av redefined the physical layer of 10G EPON [6]. 10G EPON is technically mature now, and operators have recently started to commercialize it.

2. GPON

GPON is the standard based on ITU-T G.984.x. It was first proposed by Full Service Access Network (FSAN) in 2002. Before that, FSAN had already developed Broadband PON (BPON). FSAN designed new physical and TC layers based on the BPON architecture and came up with the GPON standard. GPON employs a single fiber for upstream and downstream with 1290–1330 and 1480–1500 nm, respectively. If there is existing Cable TV (CATV) service, it will be carried on 1550 nm. The PON interface can support Class B+ and C+ optical modules. The system structure and functions of OLT and ONU are similar to EPON with additional specialties as below [7]:

- Strong full service supporting capabilities. GPON is able to carry ATM frame and GPON Encapsulation Method (GEM) frame, as well as data, voice, video, PDH/SDH, and ATM.
- The data rate of GPON can reach 2.5 Gb/s and theoretically cover 60 km distance. The maximum reach difference can be 20 km.
- Flexible bandwidth allocation with QoS guarantee.
- Supports TDM services more efficiently. TDM can be mapped to GEM frame. TC frame of GPON is also 125 us, which can support TDM directly.
- More effective encapsulation. GEM of GPON provides a flexible encapsulation protocol, which can support fixed and unfixed framing. In this way, multiple services can be mapped generally without protocol transfer. The encapsulation efficiency can be up to 94 %.
- Stronger OAM capabilities. GPON provides three types of OAM channels: embedded OAM channel, physical-layer OAM (PLOAM), and ONT Management and Control interface (OMCI).
- Complex technology with higher cost than EPON. However, as more and more operators choose GPON to deploy FTTH, the cost of GPON dramatically decreases and is currently equal to EPON.

Along with EPON and GPON's massive deployment worldwide, next-generation PON technologies have also attracted significant attention. 10G EPON and 10G GPON are the upgrade of EPON and GPON, which are developed in IEEE and ITU-T, respectively. Both 10G EPON and 10G GPON can support 1:120 splitting ratio and are able to provide more than 100-Mb/s bandwidth to each user. Currently, the devices of 10G EPON and 10G GPON are generally mature, but there are still interoperability problems. There are few 10G EPON and 10G GPON real installations because of lack of bandwidth requirements.

Either 10G EPON or 10G GPON still belongs to TDM-PON. The upstream of TDM-PON works in burst mode. When the data rate exceeds 10 Gb/s, it is very difficult to manufacture laser sources working in burst mode. While seeking for solutions of next generation of 10G PON (NGPON2), another form of multiplexing method is introduced: wavelength division multiplexing (WDM). PON technologies employing WDM include time and wavelength division multiplexed PON (TWDM-PON) and WDM-PON. TWDM-PON is widely accepted as the major solution of NGPON2, which is a mixture of TDM-PON and WDM-PON. The wavelength channel number is 4–8, and 10G GPON is used inside each channel. There is a complex mechanism to allocate the wavelength of each user, and each user should be able to transfer among all channels. The standard series is G.989.x and G.989.1/2 (general requirements/physical layer), which have been consented, while G.989.3 (transmission convergence layer) is under development.

Different from TWDM-PON, WDM-PON employs pure wavelength multiplexing for both upstream and downstream. Each user occupies an individual wavelength, which can provide superior security and bandwidth. The data rate of each user can be 2.5 Gb/s or more. The structure is also simple, which does not require P2MP protocols but only Ethernet. The key technology of WDM-PON is colorless optical module at the user end. Fixed wavelength assignment is not acceptable in real installations. ONU has to be uniform to be installed in all users' premises. Therefore, the optical module has to be colorless. There are many ways to achieve colorless optics, such as self-seeded, tunable wavelength, and wavelength reuse. No matter the technology finally accepted, it has to be economically viable. WDM-PON has been proposed to carry wireless services such as CPRI signal between baseband unit (BBU) and remote radio unit (RRU) because of superior performance. The standardization of WDM-PON is being discussed in FSAN and ITU-T SG15.

2.2.1.2 xDSL Technology

DSL is the abbreviation of Digital Subscriber Line. There exist many DSL technologies such as Asymmetric DSL (ADSL), Rate Automatic adapt DSL (RADSL), High-speed DSL (HDSL), and Very-high-bit-rate DSL (VDSL). For simplicity, all of these DSL technologies are called xDSL. The general system architectures of the DSL technologies are similar, but with different data rate, reach, and implementation methods.

xDSL, especially ADSL and VDSL, is widely deployed worldwide because it takes advantage of the most popular medium-copper telephone line. Users could get the benefit from the telephone services to enjoy broadband services. Tremendous amount of investment is saved in this way. Even now when fiber is more and more accepted as the main access network medium, xDSL still plays a very important role in Europe and North America.

ADSL and VDSL are candidates for today's broadband access. ADSL initially existed in two versions before discrete multi-tone (DMT) was chosen for the first ITU-T ADSL standards, G.992.1 and G.992.2 (also called G.dmt and G.lite, respectively). Therefore, all modern installations of ADSL are based on the DMT modulation scheme. At the telephone exchange, ADSL generally terminates at a digital subscriber line access multiplexer (DSLAM) where a frequency splitter separates the voice band signal for the conventional phone network. Data carried by the ADSL are typically routed to the operator's data network and eventually reach the Internet. Actual ADSL speed may reduce depending on line quality; usually, the

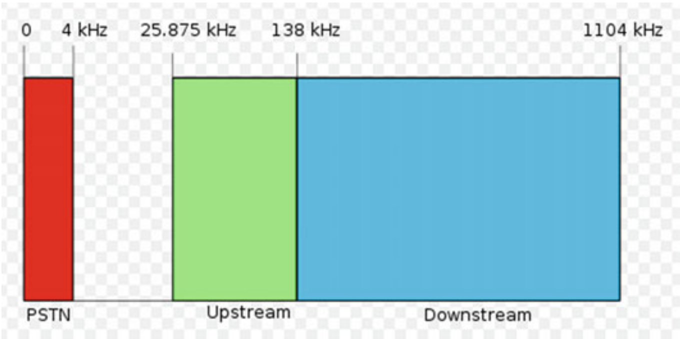

Fig. 2.5 Upstream and downstream band of ADSL

most significant factor in line quality is the distance from the DSLAM to the customer's equipment. ADSL only supports short distances, typically less than 4 km. If more reach is required, the data rate has to be sacrificed. For example, the data rate is normally around 4 Mb/s with the distance less than 2 km.

ADSL allows a single telephone connection to be used for both broadband services and voice calls at the same time through full duplex. Full duplex is usually achieved by either frequency-division duplex (FDD), echo-canceling duplex (ECD), or time-division duplex (TDD). FDD uses two frequency bands as upstream and downstream. The upstream band is used for communication from the end user to the DSLAM. The downstream band is used for communicating from the DSLAM to the end user. With commonly deployed ADSL, the band from 26.075 to 137.825 kHz is used for upstream, while 138–1104 kHz is used for downstream, as shown in Fig. 2.5. Under the usual DMT scheme, each of these is further divided into smaller frequency channels of 4.3125 kHz.

ADSL2 is also referred as ITU-T G.992.3. It optionally extends the capability of basic ADSL in data rates to 12 Mb/s downstream and up to 3.5 Mb/s upstream (with a mandatory capability of ADSL2 transceivers of 8 Mb/s downstream and 800 kb/s upstream). ADSL2 uses the same bandwidth as ADSL but achieves higher throughput via improved modulation techniques. ADSL2+ is derived from the ADSL2 standard and also referred to as G.992.5. It extends the frequency range from 1.1 to 2.2 MHz and the subcarrier number from 256 to 512. The minimum data rate supported by ADSL2+ is downstream 16 Mb/s and upstream 800 Kb/s. The maximum downstream data rate is up to 25 Mb/s. ADSL2+ is a breakthrough of ADSL technology not only regarding the bandwidth, but also the reach, as it extends it to 6 km. ADSL2+ is a smooth migration of ADSL; hence, currently it is widely deployed in the world [8].

VDSL is the next-generation xDSL technology providing data transmission faster than ADSL, which is up to 52 Mb/s downstream and 16 Mb/s upstream. VDSL uses the frequency band from 25 kHz to 12 MHz. VDSL is capable of supporting applications such as high-definition television and cloud computing. VDSL can be deployed over existing wiring used for analog telephone service and lower-speed ADSL connections, so it is widely accepted worldwide. VDSL is also referred to as ITU-T G.993.1. Similar to ADSL, VDSL also allows voice services and broadband to be connected at the same time through frequency-division duplex. The key technology of VDSL is DMT modulation and discrete wavelet multi-tone (DWMT). DWMT comes with better performance than DMT as it applies wavelet orthogonal transform. After wavelet transform, 99 % of the subcarriers' power concentrates on the main lobe; hence, the signal-to-noise ratio (SNR) dramatically increases.

Second-generation systems (VDSL2; ITU-T G.993.2 approved in February 2006) use frequencies of up to 30 MHz to provide data rates exceeding 100 Mbit/s simultaneously in both the upstream and downstream directions. The maximum available bit rate is achieved at a range of about 300 m; performance degrades as the distance increases. VDSL2 is the synthesizer of xDSL technology. The maximum distance of VDSL can reach up to 3 km with enhanced transmit power, echo suppression, and advanced frequency band, which is a tremendous increase compared to 1.5 km of VDSL.

VDSL2 is compatible with ADSL2+ because it defines DMT as the only modulation format and uses the same subcarrier frequency below 12 MHz. Above 12 MHz, VDSL2 applies flexible subcarrier frequency to achieve the ultimate rate of 200 Mb/s. The frequency band of VDSL2 is shown in Fig. 2.6. Therefore, VDSL2+ provides a smooth migration path from ADSL2+ to VDSL2 in order to protect the capital investment and reduce the risk of network upgrade.

Vectoring is a transmission method that employs the coordination of line signals to reduce crosstalk level and improve performance. It is based on the concept of noise cancelation, much like noise-canceling headphones. The ITU-T G.993.5 standard, "self-FEXT cancelation (vectoring) for use with VDSL2 transceivers" (2010), also known as G.vector, describes vectoring for VDSL2. The scope of Recommendation ITU-T G.993.5 is specifically limited to the self-FEXT (far-end crosstalk) cancelation in the downstream and upstream directions. The far-end cross talk (FEXT) generated by a group of near-end transceivers and interfering with the far-end transceivers of that same group is canceled. This cancelation takes place between VDSL2 transceivers, not necessarily of the same profile [9]. There are mature equipments of VDSL2 vectoring coming out at the moment; however, the real network deployment is still ahead.

Fig. 2.6 Upstream and downstream band of VDSL

In general, VDSL2 assembles all the advantages of different xDSL technologies. VDSL2 supports flexible and symmetric transmission rate. It has superior data rate within short reach and could cover longer distances than other xDSL technologies.

2.2.1.3 Twisted Pair Technology

Electrical cables are a popular wireline medium. Twisted pair is one of them in which two conductors of a single circuit are twisted together for the purposes of canceling out electromagnetic interference (EMI) from external sources, for instance, electromagnetic radiation from unshielded twisted pair (UTP) cables, and cross talk between neighboring pairs. Category 5 (cat 5) is a twisted pair cable for carrying signals, which is the most popular and widely deployed. This type of cable is used in structured cabling for computer networks such as Ethernet. The cable standard provides performance of up to 100 MHz and is suitable for 10BASE-T, 100BASE-TX (Fast Ethernet), and 1000BASE-T (Gigabit Ethernet). Cat 5 is also used to carry other signals such as telephone and video. Most cat 5 cables are unshielded, relying on the balanced line twisted pair design and differential signaling for noise rejection. To support Gigabit Ethernet, a higher performance version of cat 5, enhanced cat 5 or cat 5e has been developed. Cat 5e has new performance requirements to permit higher data rate operation [10, 11]. The cat 5e specification improves upon cat 5 by tightening some crosstalk specifications and introducing new crosstalk specifications that were not present in the original category 5 specification. The bandwidth of category 5 and 5e is the same, which is 100 MHz.

The broadband provided on twisted pair normally adopts Ethernet, which is called Ethernet over twisted pair. In 1980s, the potential of simple unshielded twisted pair by using cat 3 cable—the same simple cable used for telephone systems—has been shown. This led to the development of 10BASE-T and its successors 100BASE-TX and 1000BASE-T, supporting speeds of 10, 100, and 1000 Mbit/s, respectively. The higher-speed implementations support the lower-speed standards making it possible to mix different generations. All these standards support both full-duplex and half-duplex communication. Cat 5 is the standard cabling of newly built buildings in some countries. Therefore, to carry signals over existing cat 5 using Ethernet is an economic way to provide broadband services. Further, category 6 cable, referred to as cat 6, is also used in newly built houses nowadays that is backward compatible with the cat 5, 5e, and 3 cable standards. It provides performance of up to 250 MHz and is suitable for 10BASE-T, Fast Ethernet, Gigabit Ethernet, and 10-Gigabit Ethernet. Compared to cat 5 and cat 5e, cat 6 includes more strict specifications for crosstalk and system noise.

2.2.1.4 Coaxial Cable Technology

Coaxial cable is a type of cable that has an inner conductor surrounded by a tubular insulating layer, surrounded by a tubular conducting shield. Many coaxial cables also have an insulating outer sheath or jacket. Coaxial cable is used to carry radio frequency transmission normally for broadband or cable TV (CATV).

Short coaxial cables are commonly used to connect home video equipment and computer networks, in particular Ethernet. However, twisted pair has replaced them in most applications except in the growing consumer cable modem market for broadband Internet access. Long-distance coaxial cable was used in the twentieth century to connect radio networks, television networks, and long-distance telephone networks though this has largely been superseded by later methods such as optical fiber. Shorter coaxial cables still carry CATV signals to the majority of television receivers, and this is the main application carried on coaxial cables.

In CATV systems, multiple television channels are distributed to user residences through a coaxial cable, which comes from a trunk line originating at the cable company's local distribution facility, which is called headend. The trunk line could be either coaxial cable or optical fiber. Multiple channels are transmitted through the cable by frequency-division multiplexing. At the headend, each television channel is translated to a different frequency. Therefore, television signals do not interfere with each other. At the user's residence, either the user's television or set-top box provided by the cable company translates the desired channel back to its original baseband signal. There are also upstream signals to send data from the user to the headend, for advanced features such as requesting video on demand, cable Internet access, and cable telephone service. The downstream channels occupy a band of frequencies from 50 MHz to 1 GHz, while the upstream signals occupy frequencies of 5–42 MHz.

Coaxial cables are capable of bidirectional carriage of signals as well as the transmission of large amounts of data. Cable television signals use only a portion of the bandwidth available over coaxial lines. This leaves plenty of space available for other digital services such as cable Internet and cable telephone. Broadband Internet access is achieved over coaxial cable by using cable modems to convert the network data into a type of digital signal that can be transferred over coaxial cable. One problem with some cable systems is that the older amplifiers placed along the cable routes are unidirectional. Many cable systems have upgraded or are upgrading their equipments to allow for bidirectional signals, thus allowing for broadband connections with large bandwidth. The first Ethernet standard, known as 10BASE5 (ThickNet) in the family of IEEE 802.3, specified baseband operation over 50-ohm coaxial cable, which remained the principal medium until the late 1970s. Then, 10BASE2 (ThinNet) coaxial cable replaced it in deployments in the 1980s. However, both of them were replaced in the 1990s when thinner, cheaper twisted pair technology came to dominate the market. The use of coaxial cable for Ethernet is still supported as CATV operators strive to use existing 75-ohm coaxial cable installations to carry broadband data into the home. Novel technologies are applied in the ITU-T G.hn standard to achieve higher bandwidth, which can be comparable with fiber. The G.hn standard provides up to 1 Gb/s data rate over existing coaxial cable, power lines, and phone lines. It defines an Application Protocol Convergence (APC) layer for encapsulating standard Ethernet frames into G.hn MAC Service Data Units (MSDUs). There is also a great effort going on in IEEE 802.3 to apply EPON technology on coaxial cable which is called EPoC [12].

2.2.1.5 Hybrid Fiber–Copper Technology

Optical fiber has been more and more deployed because of its large bandwidth, easy maintenance, and low cost. For the last mile, it is not necessary to connect fiber to the user premise directly. If there is existing copper such as twisted pair, telephone line, or coaxial cable, it is more economical to carry the last mile service on these copper lines. Other than FTTH, fiber can be deployed midway, and then, existing copper can reach the end user.

Depending on the end point of the fiber, access networks can be divided into fiber-to-the-node (FTTN), fiber-to-the-curb (FTTC), fiber-to-the-building (FTTB), and fiber-to-the-home (FTTH). These are all called fiber-to-the-x (FTTx), which is a broadband network architecture using optical fiber to provide all or part of the access network used for last mile telecommunications. FTTN means that the fiber is terminated in a street cabinet, possibly miles away from the user premises, with the final connections being copper. FTTC is very similar to FTTN, but the street cabinet or pole is closer to the user premises, typically within the range (500 m) for high-bandwidth copper technologies such as xDSL or Ethernet. FTTB means fiber reaches the building, such as the basement in a multi-dwelling unit, with the final connection to the individual living space being made via alternative means, similar to FTTN and FTTC. These FTTx technologies employ the same architecture but with different fiber termination points; hence, the data rate provided ranges due to different copper lengths.

The fiber connecting the OLT central office and the main power splitters is called trunk fiber. The fiber from the main splitters to the fiber distribution box or multi-dwelling unit (MDU) inside the building is called feeder fiber. The last piece of fiber from the fiber distribution box or MDU to the ONU at the user premises is called drop fiber. The architecture of FTTx is shown in Fig. 2.7.

2.2.1.6 Global Roll-Out Strategies

Broadband has been proven to be closely related to economic growth worldwide. Lots of countries and operators have established their broadband strategies focusing on the broadband penetration and data rate increase. Therefore, fiber technologies, especially FTTH based on PON, have become the major choice, while some countries also upgrade xDSL technologies to VDSL2 or VDSL2+ which can provide as much bandwidth as FTTH and save on the previous investment. The followings are some examples [13].

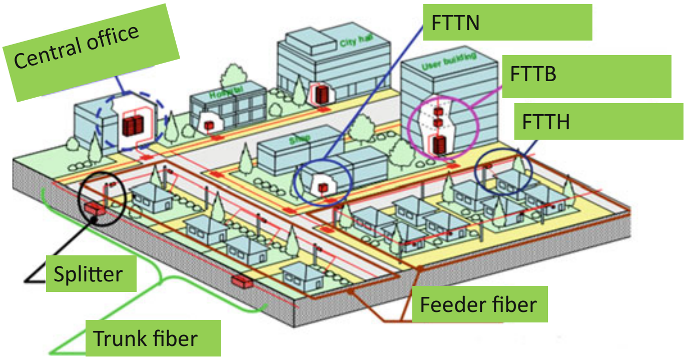

Fig. 2.7 Architecture of FTTx

Federal Communications Commission (FCC) published an investment of 7.2 billion US dollars to develop national broadband in 2009 [14]. The main purpose of FCC's plan is to promote the penetration of broadband in the whole nation, especially for the minorities to enjoy broadband services. On March 16, 2010, FCC unveiled "Connecting America: The National Broadband Plan" to Congress. The plan is seeking to ensure that the entire broadband ecosystem is healthy. Six national broadband goals are set for the next decade, including ensuring every American has access to a robust (typically 4 Mb/s) broadband and at least 100 million homes have affordable access to 100 Mb/s broadband. As for the operators, Verizon has started FTTH deployment in 2004 to support the FIOS services. Verizon has covered more than 30 million homes using FTTH with more than 8 million ONUs really connected. Because the FTTH investment is huge, Verizon has slowed down the FTTH deployment in 2010 and has started to focus on the increase in FTTH users. GPON is the primary technology employed. However, AT&T does not put much effort on FTTH, as it relies on current copper line to deploy VDSL2+, so as to protect its previous investment. Cable TV companies such as Comcast also provide large bandwidth broadband to users through coaxial technologies.

China also published "Broadband China" strategy in 2013 with a two-stage target [15]. By the end of 2015, it aimed at 50 % of fixed broadband penetration, 4 Mb/s bandwidth in rural areas, 20 Mb/s in urban areas, 100 Mb/s in big cities, mobile broadband penetration of 32.5 %, and the whole broadband coverage exceeding 95 %. Meanwhile, Broadband China also aims at a further target of 2020, which is 70 % of fixed broadband penetration, 12 Mb/s bandwidth in rural areas, 50 Mb/s in urban areas, 1 Gb/s in big cities, mobile broadband penetration of 85 %, and the whole broadband coverage exceeding 98 %. From the operators' prospective, China Telecom and China Unicom started FTTH as early as 2009. In metropolitan areas, 100 % 20 Mb/s capability has been achieved, and in some prosperous areas, 100 Mb/s service is provided to users. In the countryside, the data rate is normally above 4 Mb/s. Both EPON and GPON are used, while there is no

10GPON deployed for FTTH yet. China Mobile uses GPON and deploys FTTH in metropolitan areas.

Japan has established “i-Japan strategy 2015,” which had four aims: easy-to-use digital technologies, breaking down the barriers that hinder the use of digital technologies, ensuring security when using digital technologies, and creating a new Japan by diffusing digital technologies and IT throughout the country [16]. The strategy also included national coverage target of 100+ Mb/s for mobile broadband and 1 Gb/s for fixed broadband by 2015. NTT started massive FTTx construction using EPON as early as 2003; by the end of 2011, the FTTH users have reached 20 million. 10G EPON has been deployed since 2010 to increase the bandwidth toward the 1 Gb/s target.

In December 2010, the UK government presented its national broadband strategy aiming to provide the best superfast broadband network in Europe by 2015, which means 2 Mb/s coverage nationwide and 90 % 24 Mb/s coverage [17]. Nine hundred and seven million US dollars have been issued to support the rural broadband program. As of 2013, 2 Mb/s broadband was available for 97 % of all, while superfast broadband reached 82 %. British Telecom (BT) started FTTx construction in 2009, among which 75 % is FTTC and 25 % is FTTH. FTTC covered 40 % of all homes by the end of 2012, and it was anticipated that FTTC/H will cover more than 2/3 by the end of 2014. GPON is used for FTTC and FTTH, and VDSL2 is used to support the last mile while using FTTC.

France’s national broadband strategy was adopted in 2011, and it aims to ensure 30 Mb/s broadband coverage by 2020 [18]. Another target is to provide superfast broadband access (100 Mb/s) to 100 % of the population through FTTH deployment. French Telecom (FT) trialed FTTH in 2006 and started deployment in 2007. By the end of 2012, 4 million homes have been connected, and it was expected that this number would increase to 9 million by the end of 2015.

Germany adopted its national broadband plan in 2009 and revised it in 2013. The revised target was to provide broadband with 50 Mb/s to 100 % of the population by 2018 [19]. Deutsche Telecom (DT) mainly deployed FTTH in Germany, Croatia, and Slovakia. DT has more than 2 million homes currently connected. In other areas, DT also relies on FTTB+VDSL2+ to provide large bandwidth broadband.

2.2.1.7 Penetration of Different Broadband Technologies

The Organization for Economic Co-operation and Development (OECD) publishes broadband-related information of its members every year. As China is not an OECD member but owns the most broadband users in the world, China’s broadband information is also put together in some charts with OECD information for reference.

As an example, Fig. 2.8 lists the total fixed broadband subscriptions of OECD members and China mainland by the end of 2013. China is shown to be the biggest fixed broadband market and has the most fixed broadband users totaling 189 million.

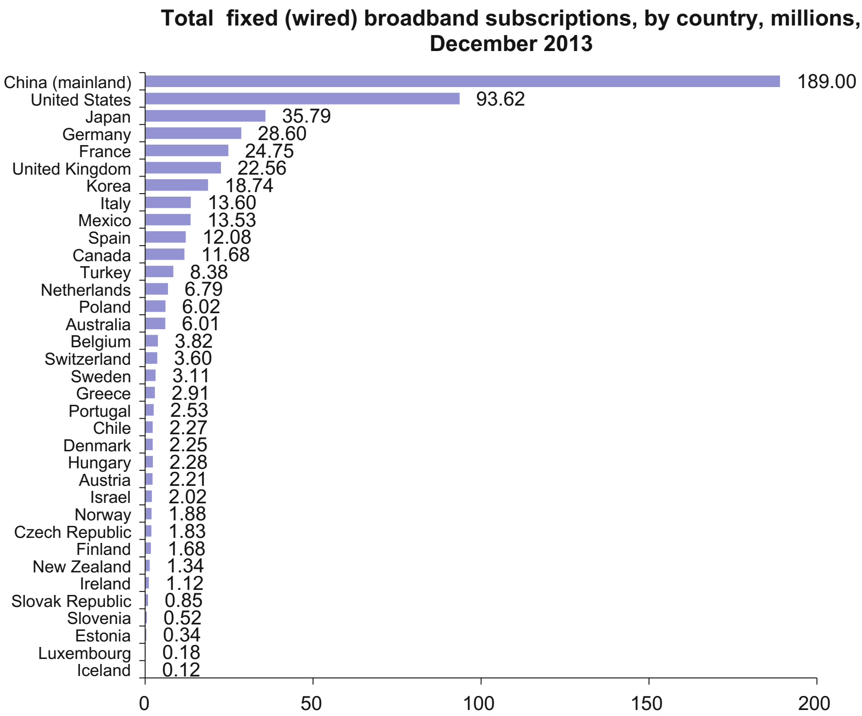

Fig. 2.8 Fixed broadband subscriptions (in millions) in total by the end of 2013 [20]

USA is ranked second with 94 million fixed broadband users, followed by Japan and Germany. Figure 2.9 lists the total wireless broadband subscriptions of OECD members and China mainland by the end of 2013. China still has the most wireless broadband users of 500 million, while USA, Japan, Korea, and the UK are ranked as No. 2–5.

OECD also indicates the broadband penetration of different countries by technology, as shown in Fig. 2.10. The penetration rate is greatly different from the total subscriptions. China has a very low fixed broadband penetration of 12.7 % because of it imbalanced development and large population, which is a contrast to its numerous broadband users. Meanwhile, it is noted that China has a relatively high portion of FTTH and LAN access, which is owed to its recent massive FTTH deployment. European countries such as Switzerland, The Netherlands, Denmark, and France have the best penetration of fixed broadband, with Switzerland having 45 % of fixed broadband penetration and ranked as No. 1. USA's penetration is in the middle, at 29.8 %. Considering the technologies, USA behaves much differently than China. The majority of fixed broadband technology is cable (coaxial technology), which reflects a different pattern from China. The second most-used technology is xDSL, while fiber/LAN has been used by only 2.4 % of the homes. Korea and Japan have the most penetration of fiber/LAN technology; hence, the

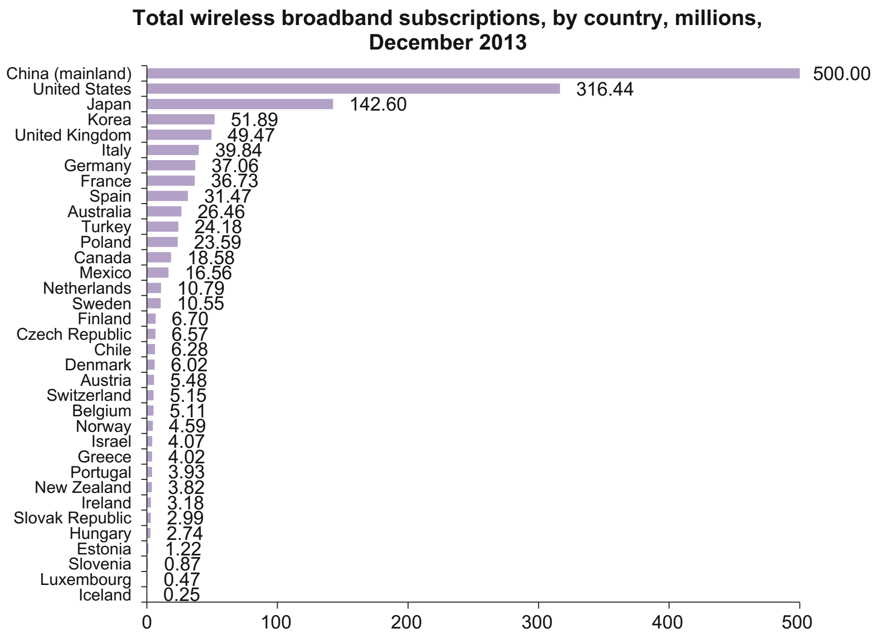

Fig. 2.9 Wireless broadband subscriptions (in millions) in total by the end of 2013 [20]

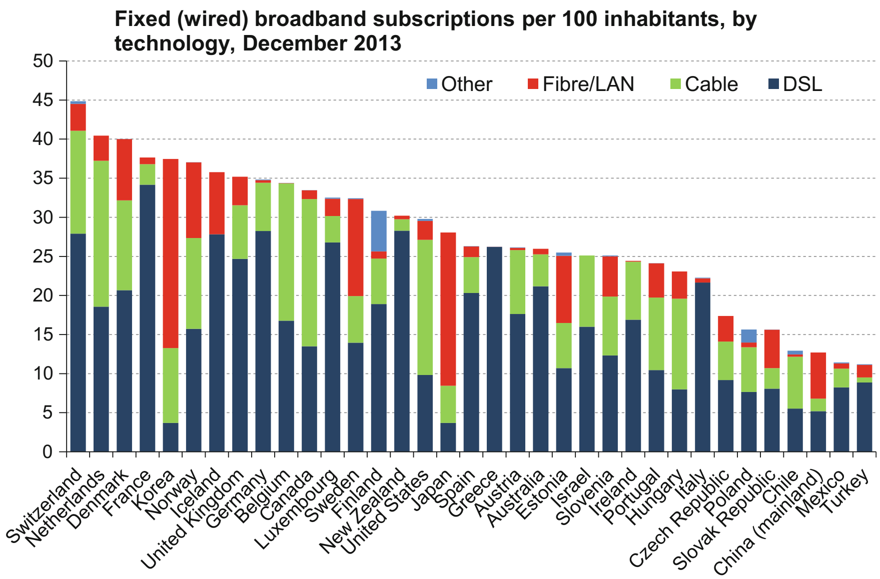

Fig. 2.10 Fixed (wired) broadband subscriptions per 100 inhabitants, by technology, by the end of 2013 [20]

largest bandwidth was provided to the users. Overall, xDSL is still the main technology used, especially in European countries.

2.2.2 *Broadband Wireless Access Networks*

In contrast to wired access networks, long-range wireless links can serve users over a widely distributed geographical area and can therefore be seen as a true alternative to the wired access options like fiber/PON networks. On the other hand, short-range wireless links only cover a small area such as a home or a building. Short-range wireless technologies therefore need to be augmented by wired backhaul access technologies in order to provide a complete solution for broadband access to the end user.

Many types of wireless access systems coexist and can be differentiated by spectrum, bandwidth, range, and applications. Wireless Personal Area Networks (WPANs, IEEE 802.15) allow the connectivity of personal devices within an area of about 30 feet. The current available technologies include Bluetooth, Infra Red (IR), Wireless USB, and Wireless HD, as cable replacement for peripherals. Fixed wireless access under the title “Wireless Metropolitan Area Networks” (WMANs, IEEE 802.16) become an alternative or backup to laying copper or fiber cabling. Although the 802.16-based standard has evolved to provide mobile access, due to the lack of actually developing an ecosystem with enough critical mass to justify the investment, this type of systems has not been able to gain any significant market share and will continue to see adoption in small-scale commercial and possibly military systems. As such, we will not delve into the details of this technology any further.

The two types of technologies that are most popular for providing broadband access today are the IEEE 802.11-based Wireless LAN (WLAN) standard, popularly known as Wi-Fi, and the current third, fourth, and future fifth generations of cellular technology.

2.2.2.1 Wi-Fi Technology Evolution and Market Status

Wi-Fi has been the most widely adopted wireless access in the world, both in terms of devices and in terms of infrastructure. Wi-Fi chipsets have been part of the standard network interfaces in laptops and smartphones for many years now. The major growth drivers for Wi-Fi evolution for the current market include the following points:

- Integration of Wi-Fi into more consumer products: smartphones, digital cameras, e-readers, media players, gaming consoles, Blu-ray players, HDTVs;
- Increasing adoption and use of WLAN in companies, small office/home office, hospitals, etc. Enterprise market growing faster than retail market;

- Use of Wi-Fi to offload data from cellular networks;
- New applications: health/fitness, medical, smart meters, home automation.

Wi-Fi has evolved through the years to accommodate demands for faster data rates and greater bandwidth to support more feature-rich content and applications. Figure 2.11 details the evolution of the IEEE 802.11 Wi-Fi standard, demonstrating how new frequency bands, radio channels, signaling techniques, and multiple antennas have been used to dramatically increase Wi-Fi data rates. Wi-Fi is standardized by the IEEE under their 802 umbrella of standards for local area networks (LANs). Strictly speaking, "Wi-Fi certified" is the trademark name given to products that are certified to be interoperable by the Wi-Fi Alliance, which is a trade association that started in 1999 and promotes Wi-Fi and performs the certifications. As shown in Fig. 2.11, the Wi-Fi was invented in 1991 by NCR Corporation/AT&T. The first 802.11 standard was adopted in 1997. The first set of enhancements to the 802.11 standard—the 802.11a and 802.11b amendments—were ratified in September 1999. The 802.11b provided higher speeds for operation in the 2.4 GHz band by adding two higher rates—5.5 and 11 Mbit/s—to the already existing rates of 1 and 2 Mbit/s. The next speed boost for Wi-Fi systems was provided by the introduction of OFDM to the physical layer. The 802.11a standard supports rates range from 6 to 54 Mbit/s at a bandwidth of 20 MHz. Although the 802.11a standard was ratified in 1999, along with the 802.11b standard, availability of products lagged behind that of 802.11b, mainly due to the higher complexity and cost of the early implementations of OFDM chipsets [21–24].

The 802.11g standard was ratified in 2003. This version of the standard takes the OFDM PHY as specified in 802.11a and adds support for backward compatibility with legacy 802.11b systems already operating in the 2.4 GHz band. The major

- 1991: Wi-Fi was invented by NCR Corporation/AT&T with speed of 1/2Mbps.
- 1999: the Wi-Fi Alliance was formed and the first standard was released.
- 2000: first commercial use of the term Wi-Fi.

Ratified year	1997	1999	1999	2003	2009	2013	Future
IEEE Standard	802.11	802.11a	802.11b	802.11g	802.11n	802.11ac	802.11ad
Frequency Band	2.4GHz	5GHz	2.4GHz	2.4GHz	2.4GHz, 5GHz (Concurrent or selectable)	5GHz	60GHz
Max Data Rate	2Mbps	54Mbps	11Mbps	54Mbps	600Mbps	1.3Gbps	7Gbps
Technology	SISO	SISO	SISO	SISO	MIMO	MU-MIMO	MU-MIMO

Fig. 2.11 Evolution of Wi-Fi technologies

enhancement introduced by 802.11n was the inclusion of MIMO with support for up to four spatially multiplexed streams. In addition, the bandwidth supported was doubled to 40 MHz. Over this bandwidth, with four spatial streams, 802.11n boasts a top speed of 600 Mbit/s. The highest order QAM modulation stays the same (64-QAM) as 802.11a. 802.11n has been specified for operation in both the 2.4 GHz band and the 5 GHz band.

The latest version of the WLAN standard, 802.11ac [25–27], was ratified in December 2013. The 802.11ac specification mandates operation in the 5 GHz band, where there is relatively less interference and more channels are available compared to the 2.4 GHz band. 802.11ac achieves a maximum throughput of 6.93 Gbps in 160 MHz bandwidth mode in the 5 GHz band, using eight spatial streams and 256QAM modulation. 802.11ac has also specified multi-user MIMO (MU-MIMO), which allows simultaneous transmission of MIMO streams to multiple client devices. For the initial systems which are likely to be 80 MHz, the peak speed per spatial stream is 433 Mbit/s. In addition, 802.11ac has defined a single closed-loop method for transmit beamforming, which is expected to be an optional feature of the Wi-Fi Alliance certification plan. 802.11ac has also introduced dynamic bandwidth management to optimize the use of available bandwidth. These new features of 802.11ac deliver the next leap in performance, which also includes simultaneous streaming of multiple HD video streams.

IEEE Working Group and the Wireless Gigabit Alliance (WiGig) jointly proposed IEEE 802.11ad, which is targeting short-range communication with up to 7 Gb/s speed that uses approximate 2 GHz spectrum in 60 GHz. With the huge number of existing client devices, backward compatibility with current standards using the same frequency range is vital. The goal is for all IEEE 802.11 standards to be backward compatible and for 802.11ac and 802.11ad to be compatible at the medium access control (MAC) or data-link layer. They should differ only in physical-layer (PHY) characteristics. Devices could then have three radios: 2.4 GHz for general use, 5 GHz for more robust and higher-speed applications, and 60 GHz for ultra-high-speed operation within a room—as well as support session switching among them.

IEEE 802.11ax is the successor to 802.11ac and will increase the efficiency of Wi-Fi networks. This project has the goal of providing 4× the throughput of 802.11ac used in dense deployment scenarios. 2019 is the target date for a ratified 802.11ax standard. Currently, it is in very early stage. Another newly designed protocol is IEEE 802.11ah. It utilizes sub 1 GHz license-exempt bands to provide extended range Wi-Fi networks and benefits from lower energy consumption, allowing the creation of large groups of stations or sensors that cooperate to share the signal, supporting the concept of the Internet of Things (IoT). The standard is expected to be finalized and arrive in 2016, with chips and systems based on 802.11ah already hitting the market.

From the market perspective, over 2.4 billion chipsets were expected to ship during 2014, dual-band 802.11n/802.11ac will comprise the vast majority of chipsets shipped among all the protocols as shown in Fig. 2.12 (ABI Research).

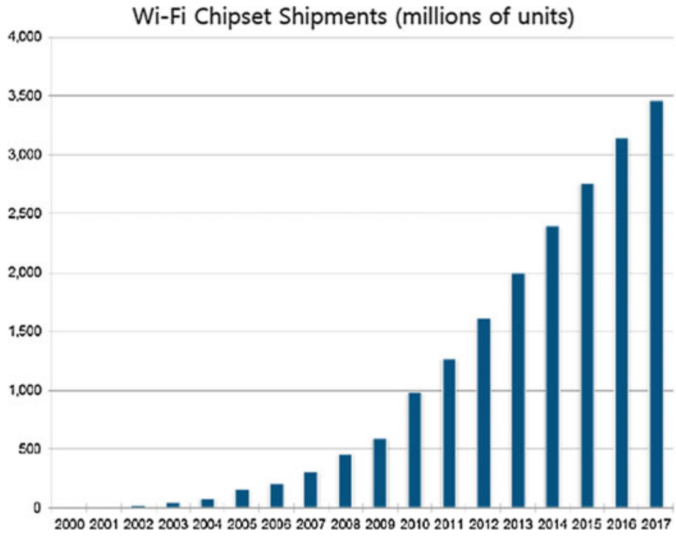

Fig. 2.12 Wi-Fi market prediction

Nearly 18 billion more chips will ship cumulatively from 2015 to 2019 with a strong ramp of tri-band 802.11n/802.11ac/802.11ad during that period [24–27].

2.2.2.2 Mobile Network Technology Evolution and Market Status

Mobile networks provide connectivity over a wide geographical area and support handover mobility and cell roaming. Compared to Wi-Fi systems, mobile systems are more complex, as they are designed to support high-grade voice services, with seamless mobility, over a much greater area. Of the 6.8 billion mobile subscriptions in the world today (compared to the global population of 7 billion) [28], 2.1 billion are mobile broadband, which is three times the number of fixed broadband accounts [28].

Wireless communications have evolved from the so-called second-generation (2G) systems of the early 1990s, which first introduced digital cellular technology, through the deployment of third-generation (3G) systems with their higher-speed data networks, and the fourth-generation technology utilized today, to the much-anticipated fifth-generation technology being developed today. This evolution is illustrated in Fig. 2.13, which shows that fewer standards are being proposed for the newer generations compared to previous generations. For example, only two 4G candidates are being actively utilized today: 3GPP LTE-Advanced and IEEE 802.16 m, which is the evolution of the WiMAX standard known as Mobile WiMAX™.

The 2G systems, which are still in wide use today, are based on a technology called GSM (Global System for Mobile), which was developed only for voice

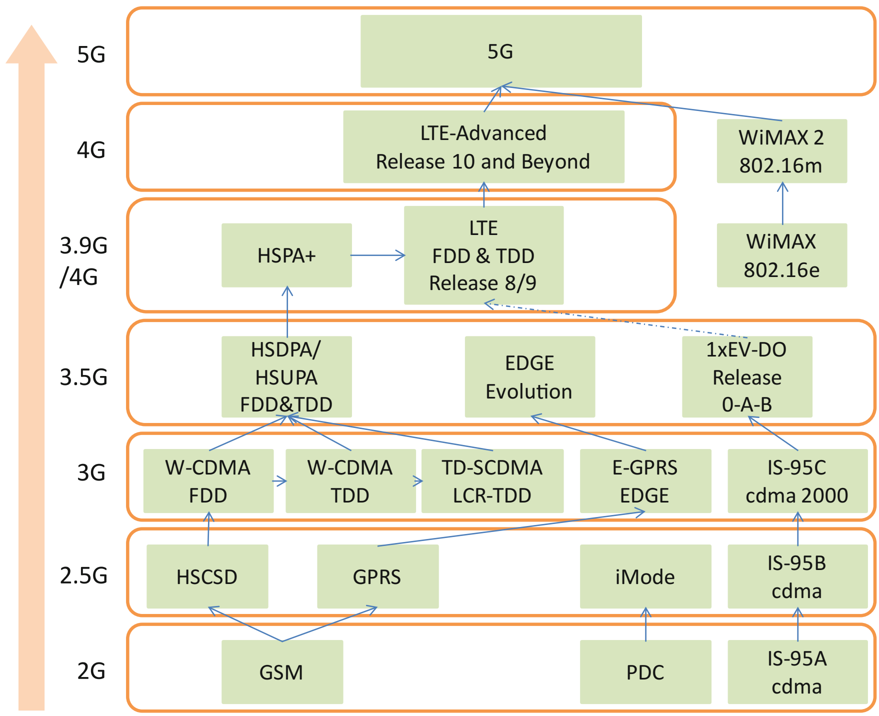

Fig. 2.13 Mobile network evolution

services. It was enhanced to support data services, first by the introduction of the GSM Packet Radio System (GPRS), and next by the addition of Enhanced Data Rates for GSM Evolution (EDGE). However, these systems were designed to depend fundamentally on the GSM air interface structure, and they were, therefore, limited in their ability to deliver true broadband speeds. The second alternative development of a new system designed to support both data and voice from the outset resulted in the third generation of cellular systems, which were based on an entirely different air interface technology. The Universal Mobile Telecommunication System (UMTS) was developed as the 3G cellular standard. UMTS is the umbrella term used for 3G systems that are based on the wideband-CDMA (WCDMA) air interface and a core network that has evolved from the GSM-based core network for circuit-switched and packet-switched services. The standardization of 3G UMTS systems was carried out under the auspices of the Third Generation Partnership Project (3GPP). This is a standards development organization (SDO) in which the partners and participation are drawn from regional standards organizations including ATIS (North America), ETSI (Europe), ARIB (Japan), TTA (Korea), TTC (Japan), and CCSA (China). Another system based on a relatively narrowband CDMA air interface, called CDMA2000, represents a parallel technology evolution of the IS-95 standard. It was developed by a sister organization of the 3GPP called 3GPP2 [29].

There have been a number of different releases of UMTS, and the addition of High-Speed Downlink Packet Access (HSDPA) in Release 5 ushered in the informally named 3.5G. The subsequent addition of the Enhanced Dedicated Channel (E-DCH), better known as High-Speed Uplink Packet Access (HSUPA), completed 3.5G. The combination of HSDPA and HSUPA is now referred to as High-Speed Packet Access (HSPA). In the meantime, 3GPP2 developed another access technology, CDMA2000, which is conceptually very similar to WCDMA. In terms of worldwide subscribers, in early 2012, the number of CDMA2000-based 3G users represented about a fifth of the all 3G users, who were predominantly users of UMTS/HSPA. The subscribers were mainly in Asia/Pacific (Japan and Korea) and North America (subscribers of Verizon Wireless and Sprint in the USA). One of the fundamental differences between CDMA2000 and UMTS is in how it evolved to support high-speed data. The original CDMA2000 specification, called 1 RTT for 1 carrier Radio Transmission Technology, was published in 1999. A new uplink and downlink structure was developed to support high-speed data, but was designed only to carry packet-switched services. This evolution was originally called 1 eV-DO for Data Only. Later, eV-DO was modified to represent Data Optimized. However, the key difference between UMTS and CDMA2000 evolutions was that separate carriers were needed for voice and data services in CDMA2000, whereas the same carrier could support simultaneous voice and data on UMTS.

The Long-Term Evolution project was initiated in 2004. The motivation for LTE included the desire for a reduction in the cost per bit, the addition of lower cost services with better user experience, the flexible use of new and existing frequency bands, a simplified and lower cost network with open interfaces, and a reduction in terminal complexity with an allowance for reasonable power consumption. LTE arrived with the publication of the Release 8 specifications in 2008. LTE-Advanced is often abbreviated LTE-A, and the term LTE-A is now commonly used to describe Release 10 and Release 11. Small cells provide a cost-effective way for service providers to add focused capacity or coverage where needed within the nominal footprint of a macro-cell, via the use of low-power nodes. The LTE air interface is robust enough to allow the operation of such low-power small cells directly in the interference environment of a high-power macro-cell. However, in some environments, such as dense urban deployments, the footprint of the small cells may be too small for cost-effective offload of macro-cell users. As a result, the range of the small cell may need to be expanded to where the macro-cell signal may be several times stronger than that of the small cell. In order to operate the network in such a severe interference environment, a time-domain partitioning of subframes between the macro-cell and small cell, called eICIC, was introduced in the specification of Release 10.

In order to be able to keep deriving new terms to describe the technology as it evolves, the term LTE-B is now being used to describe Release 12 and beyond. The major feature added to Release 11 is the ability of multiple eNodeBs to coordinate their transmission and reception to provide improved performance using a class of techniques called Coordinated Multi-Point, abbreviated as "CoMP." This uses signals from multiple sources in a coordinated fashion to improve the quality of the desired signal, which can be either through the combining of useful signals in a constructive manner, or by the suppression of interfering signals in a synchronized manner. This processing usually results in the most improvement at the cell edge where interference is of most concern, because it is in this region that coordination between different eNodeBs can provide the most benefit. Like small cells, the benefit comes at the price of increased backhaul cost, because high-speed and low latency backhaul links are needed to share the information needed for coordination.

The wireless industry is quickly expanding LTE coverage in countries and cities across the world with several hundred networks in more than 100 countries. LTE-advanced, which is an evolution of LTE and a "true 4G" mobile broadband, is under development with many LTE-Advanced commercial deployments in several countries. 3GPP Release 12 (Rel-12) is the latest standard version of 3GPP to provide mobile operators with new enhancements in the three broad categories: LTE small cell and heterogeneous networks; LTE multi-antennas (e.g., MIMO and beam forming); LTE procedures for supporting diverse traffic types (further work on HSPA+ was also included).

For the current market situation, it is believed that as 3G coexists with 2G systems in integrated networks, LTE systems will coexist with 3G and 2G systems. Multi-mode devices will function across LTE/3G or even LTE/3G/2G, depending on market circumstances. However, the decline of global 2G GSM connections began in 2013, and the trending growth of 3G and 4G mobile broadband HSPA and LTE technologies continues unabated. Of the estimated 6.8 billion total wireless subscriptions as of the end of 2013, there were 1.6 billion HSPA and LTE mobile broadband subscriptions. This number is expected to grow to 5.6 billion in another 5 years. As shown in Fig. 2.14, while GSM represents 66 % of the global market in 2013, this will decline to 22 % worldwide GSM market share in 5 years. HSPA will more than double and LTE will grow eightfold.

Most industry experts saw WiMAX as a competing technology to LTE because both were designed to provide truly high-speed broadband access in a mobile

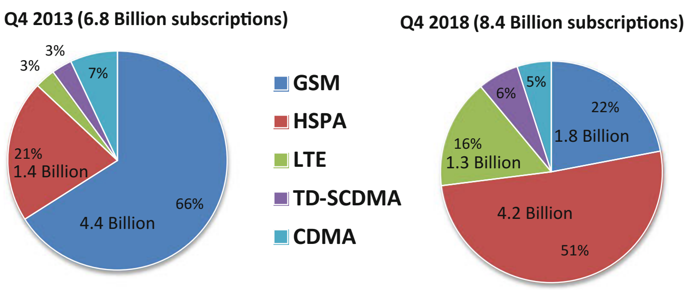

Fig. 2.14 Global mobile technology shares 4Q 2013—Forecast 4Q 2018

setting, using a fourth-generation air interface based on OFDM. As such, WiMAX had a head start of at least a year before the Release 8 LTE specifications were ready. However, major industry players, such as Qualcomm and Ericsson, did not back the technology, and the leading operators in the USA, AT&T and Verizon, decided to deploy LTE. Only one US operator, Sprint, deployed WiMAX on a large scale, with a smattering of smaller deployments around the world.

In the future, it is believed that two significant trends will emerge: (1) Everything will be connected by wireless to enable monitoring and collection of information and control of devices. Examples of these services include remote monitoring and real-time control of a wide variety of devices, which support M2M services and the Internet of things (IoT), such as connected cars, connected homes, moving robots, and sensors; (2) wireless services will become more extensive and enhanced through richer content being delivered in real-time and with safety. Examples of such emerging services include high-resolution video streaming (4K), media-rich social networks, and augmented reality. It is also believed that besides the huge growth of total mobile traffic growth, there will be more traffic dynamics in the traffic volume depending on the time, location, application, and type of device.

Despite the advances made in the design and standard evolution of 4G mobile networks, new market trends are imposing unprecedentedly challenging requirements, which are driving the wireless industry toward next-generation mobile technologies, namely a fifth-generation system (5G). It is currently being researched and developed for deployment plans in 2020 or later with even further enhanced capabilities.

The race to search for innovative solutions to enable the 5G era has begun worldwide. In early 2013, the European Commission announced that it would invest €50 million in 2013 for 5G research in multiple projects such as METIS, quickly followed by the formation of the Chinese Government-led IMT-2020 Promotion Group in February 2013, the initiation of the Korean Government-led 5G Forum in May 2013, and the formation of 2020 and Beyond Ad hoc within ARIB (Association of Radio Industries and Businesses), Japan, in October 2013. Recently, the European Commission also announced that it would invest €700 million to 5G research through Horizon 2020 program. Much of the 5G activity in the Americas has been taking place in various universities. These research activities are often joint activities with private industry, funded through government grants, or a combination of the two, such as Berkeley Wireless Research Center (BWRC), NSF Grant for Evaluation of 60 GHz Band Communications, and Polytechnic Institute of New York University (NYU-Poly) Program. From the standardization perspective, 3GPP is currently working on additional 4G enhancements in 3GPP Releases 12 and 13. The ITU has recently initiated activities on defining requirements for International Mobile Telecommunications (IMT)-2020, similar to how ITU has previously defined requirements for IMT-2000 and IMT-Advanced. Eventually, this could lead to what is commonly referred to as “5G.” While the standardization of 5G specifications is still several years away, many share the vision of targeting 2020 for the initial commercialization of 5G cellular with drastically enhanced user experience.

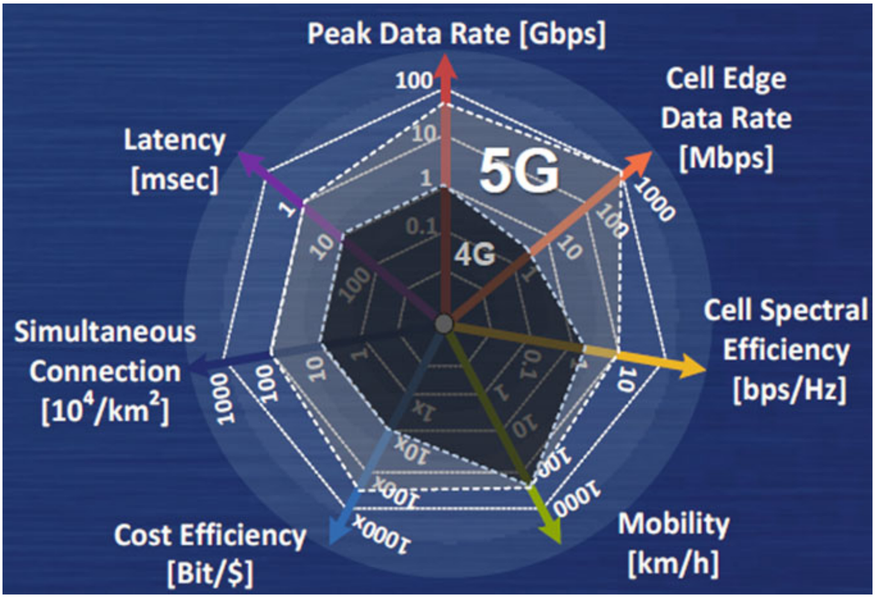

Fig. 2.15 Key requirements of 5G

The high-level key requirements of 5G are summarized in Fig. 2.15. 5G has to be able to manage traffic volume of many orders of magnitude larger than today's networks. It has to provide higher data rates for both peak data rate and user-experienced throughput everywhere. 5G has to allow massive number of devices to be connected simultaneously to the network in order to support all-time connected cloud services and more low-rate and low-power machine type devices for IoT. Reduced latency of less than 1 ms over the RAN is another necessity for future cloud and new services. 5G has also to reduce network cost and be energy-efficient and resilient to natural disasters. Enhanced mobility and spectral efficiency become important for meeting the challenges of future traffic trends.

Several possible technology areas may play a role in meeting these requirements: such as massive MIMO/adaptive beam forming and enhanced MIMO for interference cancelation, flexible full-duplex via the joint operation of FDD&TDD and/or unlicensed spectrum bands (60 GHz), non-orthogonal multiple access (NOMA) with the utilization of power domain, and other advanced modulation and coding technologies. These are all radio access technologies (RAT) from the wireless transmission perspective. Regarding the wireless networking level, centralized radio access network (C-RAN) is gaining great interest because of its potential to bring reduced costs, improved performance, and fixed/mobile convergence. Software-defined networking (SDN) and network function virtualization (NFV) will reshape the entire mobile ecosystem for best utilization of the whole wireless systems [30–33].

2.3 Fiber-Wireless Convergence and Technology Evolution

Today's wired networks, based on PON access technologies as discussed in previous sections, have the capability of providing huge bandwidth to end users using optical fiber, but they are not flexible enough to allow convenient roaming connections. On the other hand, wireless-based access solutions offer portability and flexibility to users, but they do not possess abundant bandwidth at lower microwave frequencies or have the difficulties to transmit longer distance at the millimeter-wave frequencies because of high attenuation in the air. To make full use of the huge bandwidth offered by optical fiber and flexibility features presented via the wireless, future broadband access networks will be bimodal, capitalizing on the respective strengths of both optical and wireless technologies and smartly merging them in order to realize future-proof Fiber-Wireless (FiWi) networks that strengthen our information society while avoiding its digital divide [34].

In the following section, some of major fields on the technologies of fiber-wireless convergence are identified and described including both commercial applications and research activities.

2.3.1 Fiber-Based Distributed Antenna Systems (DASs)

DASs using radio-over-fiber (RoF) links, the dominant market for RoF technology today, have been demonstrated and deployed to achieve broadband wireless access and improve wireless coverage in buildings with the features of low attenuation, large capacity, small-size remote antenna units (RAUs), and centralized management. As shown in Fig. 2.16, a DAS can be designed for use indoors or outdoors and can be used to provide wireless coverage to hotels, subways, airports, hospitals, businesses, roadway tunnels, etc. The wireless services typically provided by a DAS include cellular, Wi-Fi, WiMAX, police, fire, and emergency services. In a RoF-DAS, multiple RAUs are fiber-connected to a center unit where base station facilities are placed. In the downlink, the RAUs receive the optical signals carrying the RF signals from the center unit and convert them into electrical signals and then radiate them into air without any signal processing. A reverse process happens in the uplink. In this field, whether RoF based or not, there are a number of players currently offering DAS system for telecom carriers or enterprises. While Corning Mobileaccess, TE Connectivity, and Commscope dominate the marketplace, ABI Research has identified Axell Wireless, Solid Technologies, Optiway, Alvarion, Zinwave, and Powerwave as the foundation of the next phase of market development. Worldwide DAS Market Size was about \$1.9 Billion in 2012 (Telecomlead). While awareness of small cells is increasing, most DAS vendors do not really see small cells as a threat today. The two technologies, however, are more likely to complement each other rather than compete [35, 36].

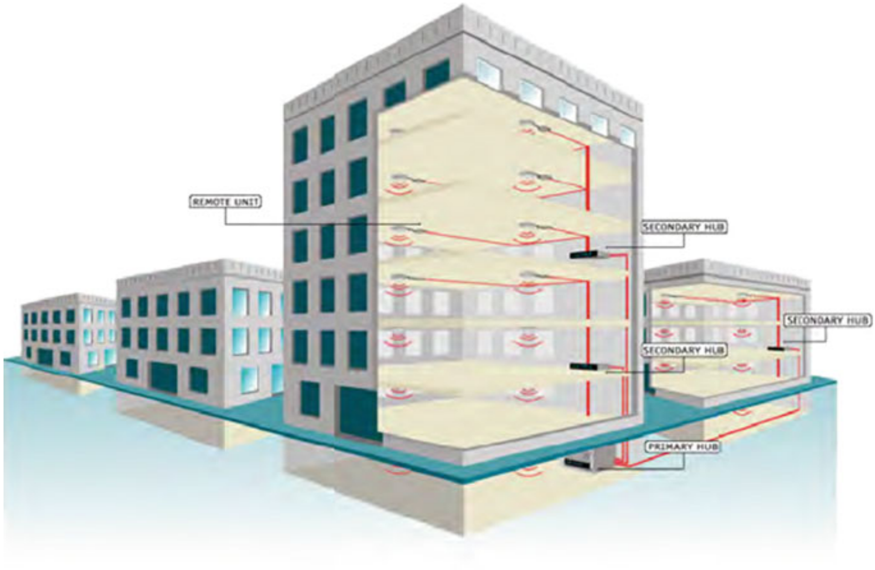

Fig. 2.16 Fiber-based DAS systems for indoor/outdoor wireless coverage

2.3.2 Ultra-High-Speed Fiber-Wireless Transmission

With the advent of popular bandwidth-hungry applications such as high-definition (HD) video and high-speed Internet, future wireless systems need to offer data speeds exceeding 1 Gbps. Because of limited frequency spectra at low frequencies, coupled with congestion caused by the large number of consumer products sharing the frequency spectra, it will be necessary to utilize higher carrier frequencies in the future, including mm-waves, to achieve much faster wireless communication at multi-gigabit-per-second speeds. The wireless link speed depends on the frequency and the bandwidth of the wireless carrier. Thus, a high carrier frequency with a large bandwidth is suitable for the realization of a high capacity wireless link. Some wireless link experiments with data rates greater than 10 Gb/s have been performed at a frequency greater than 60 GHz. Multi-Gb/s wireless transmission systems can be constructed by the use of millimeter-wave bands such as V (50–75 GHz), E (60–90 GHz), or W (75–110 GHz) bands, where wide radio frequency resources are available for telecommunications. Unlicensed 60-GHz millimeter wave is very suitable for in-room transmissions due to reduced interference with other systems using the same frequency band. Antenna array and beam-forming technologies are essential avoid blockage due to environment change. In terms of atmospheric attenuation, the use of W-band transmission appears to be suitable, as the attenuation within this band tends to be less than 1 dB/km. However, due to limitation of electric signal processing performance, it is rather difficult to modulate or

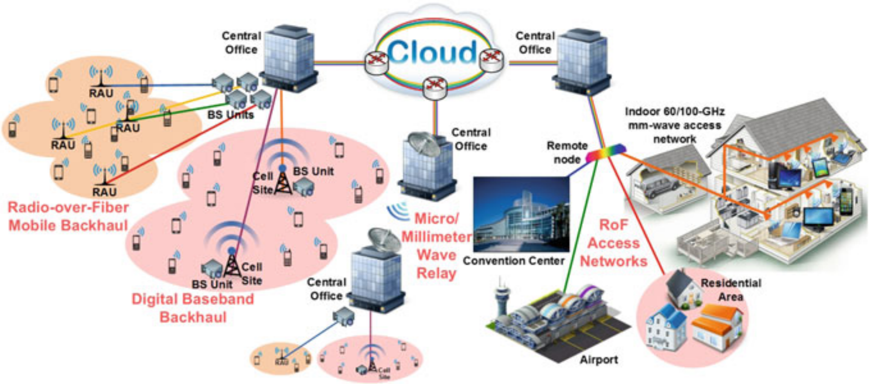

Fig. 2.17 Illustration of convergence of fiber-wireless networks

demodulate wideband millimeter-wave signals by using electric devices designed for narrowband radio systems [37–39].

The generation of wireless signals, based on the RoF technology, is expected to be suitable for high-frequency wireless transmissions as well as in applications involving an optical/wireless seamless network. Generally, the RoF signal is a combination of a RoF local oscillator (LO) carrier component and an optically modulated baseband component. It is easy to convert the optical RoF signal to a wireless signal with a frequency up-conversion technique, which is the so-called direct optical up-conversion technique that utilizes high-speed photodetectors. It is possible that the photodetector, whose frequency is less than the separation frequency between the RoF-LO component and the baseband component, can detect only the baseband components, as in the case as the conventional optical communication scheme. Therefore, the generated RoF signal would be available for the dual services of both optical baseband and wireless communications. The conceptual system block is shown in Fig. 2.17. Recently, large capacity up to 100 Gb/s millimeter-wave wireless links have been demonstrated by the use of RoF technology aided by advanced modulation formats (QPSK/16QAM/64QAM) and MIMO antenna array. Visible light communication (VLC) allows using indoor light-emitting diodes (LEDs) light sources for short-range wireless data transmission and illumination. However, the wireless transmission distance is limited due to inherent characteristics of the light source [40].

2.3.3 Fiber-Wireless for Backhaul and the Fronthaul of HetNet

In the past, the relatively low data-rate requirements of backhaul and the relatively large cell sites keep fiber deployment low in wireless backhaul. As the demand for

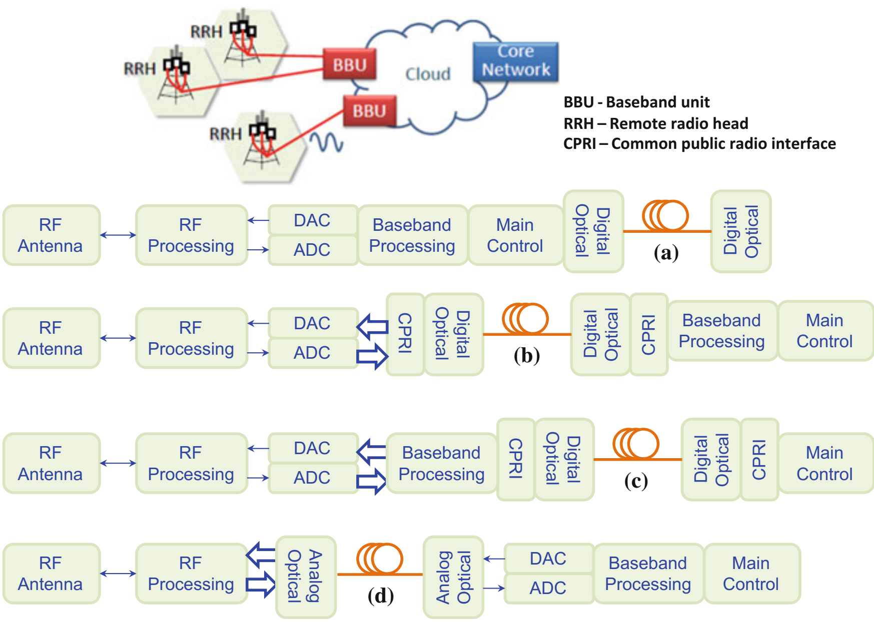

Fig. 2.18 Potential solution for fronthaul and backhaul implementation by RoF technology

capacity in metropolitan areas has grown, macro cells have reached their limits in terms of the number of locations and/or penetration capability in indoor or densely populated locations. For example, the required total traffic capacity per 1 RU would be approximately 58.9 Gb/s to support LTE-A services employing signal bandwidth of 20 MHz, 2 carrier/antenna, 3 sectors, and 8 × 8 MIMO antennas (data rate = Number of antenna per sector (MIMO) * number of carriers/antenna * number of sectors * sampling rate (30.72Msamples/s/carrier for 20 MHz Channel Bandwidth) * sample width (16 bit/sample) * 2 (I and Q) * 1.25 (overhead)) [41]. Compared with traditional backhaul, fronthaul refers to the interface between the cellular base station's processing elements (namely, the baseband unit or BBU) and the attached radio units, which is shown in Fig. 2.18.

Small cells, low-powered radio access nodes that have a range of 10 m to 1 or 2 km, are one major innovation that is being currently deployed in larger volumes for capacity enhancements in hotspots in metropolitan areas. A more recent trend has seen mobile operators reconsidering decentralization of the radio-processing resources. This follows global trends of centralization of infrastructure to create a cloud-RAN or C-RAN. To this end, the BS architecture has changed from coax and fiber backhaul to centralize the BBUs and increasing the range of the distribution to RRHs using optical technologies. These techniques create a new paradigm of fronthaul to identify the connection between a baseband unit (BBU) or DU and a remote radio head (RRH) or remote radio unit (RRU) as opposed to backhaul which is from the BBU back into the core network. The pooling of BBUs provides opportunities to implement dynamic capacity reconfigurability and a reduction in operational expenditure from centralization and consolidation of equipment. It has also been argued that this type of functionality is key in supporting advanced co-processing functions such as Heterogeneous Networks (HetNet) and CoMP, which are hotly tipped to be fundamental features of next-generation wireless networks. It is being predicted that small cells and carrier Wi-Fi deployments will generate nearly $350 billion of revenue from mobile data services by the end of the decade. Figure 2.18 shows a number of potential implementations that use optical fiber to support the deployment of RANs. Besides the conventional digital connection (a), Digital RoF using the CPRI interface standard with all baseband functions is centralized (b), Digital RoF where the higher layer functions are centralized while radio and lower layer baseband functions remain at the RRH (split eNodeB) (c), analog RoF is also potential solution due to the system simplification, centralized control, and multi-service provisioning. Another potential benefit can be obtained by taking advantage of optical control in CoMP functions [42–44] as shown in Fig. 2.19.

Recently, some research groups have tried to use intermediate frequency over fiber (IFoF) technology as a mobile fronthauling technique to reduce the CAPEX and OPEX. In the IFoF system, it is possible to allocate multi-wireless signals with a particular bandwidth on any IF and then modulate it with a single optical carrier. For MIMO services, multi-wireless signals are assigned with multi-IFs and also multiplexed in the frequency domain [41]. In the meantime, another direction is targeting the convergence of conventional PON access and dedicated wavelengths for mobile traffic fronthaul and backhaul on a single fiber infrastructure. WDM-related access technology (TWDM/WDM-PON) is an attractive candidate for flexibly upgrading the total bandwidth of a mobile network and multiplexing

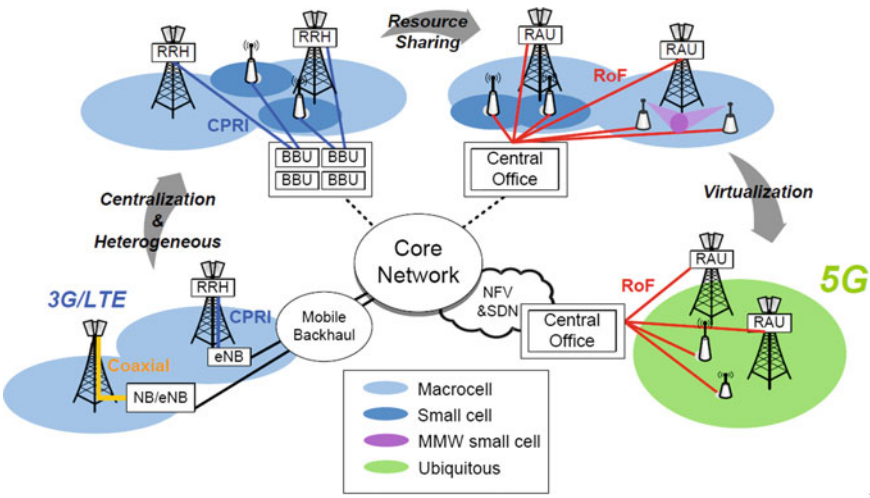

Fig. 2.19 Evolution of CoMP technology

different services on the same optical fiber distribution network. Fiber-wireless convergence will further optimize the use of the most costly part of fixed and mobile networks and drastically decrease cost and energy consumption, thus improving the return on investment of access and aggregation infrastructures: It will also allow central office consolidation of fixed networks to be performed in strong synergy with the development of mobile access infrastructures.

2.4 Conclusions

A variety of disruptive technologies are emerging to broaden the data and control plane functionalities of both broadband wireline and wireless access networks to meet the ever-increasing bandwidth requirements. In the meantime, the fiber-wireless convergence continues to evolve from the conventional DAS fiber feeding system and ultra-high optical-based wireless transmission to the architecture innovation in the implementation of fronthaul and backhaul system in mobile networks. Converged fiber-wireless access networks hold great promise to become the most promising solution of broadband access by capitalizing on synergies of two separate systems and are now well recognized for providing realizable service for both fixed and mobile users. It is believed that fiber-wireless system will play more important role in future evolved broadband access networks.

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