Wi-Fi Could Be Much More

Weiping Sun, Okhwan Lee, Yeonchul Shin, Seongwon Kim, Changmok Yang, Hyoil Kim, and Sunghyun Choi

ABSTRACT

Wi-Fi has become an essential wireless technology in our daily lives, although the original intention of its introduction was to replace Ethernet cable. In this article, we outline the most remarkable features introduced during its ongoing technological evolution in terms of three major directions: throughput enhancement, long-range extension, and greater ease of use. By stitching these advanced features together, we also envision a promising future that Wi-Fi technology will bring us in terms of spectrum heterogeneity, seamless service provisioning, and possible relations with cellular networks.

INTRODUCTION

Wi-Fi, the preferred term for IEEE 802.11 wireless local area networks (WLANs), has become an everyday tool for broadband Internet access in our daily lives.

Gradually, its position as the dominant carrier of wireless data traffic is being firmly cemented. According to the statistics in South Korea, the United States, Canada, Japan, Germany, and the United Kingdom, Wi-Fi contributed to about 73 percent of total wireless traffic on Android smartphones in April 2013, increased from 67 percent in August 2012 [1]. Such proliferation could be ascribed mainly to the support of the wide range of user devices (smartphones, tablet PCs, etc.), exploding network coverage, ongoing technological evolution, and the long-standing development of global standards.

This article offers a picture of paradigm shifts triggered by the development of Wi-Fi technologies currently underway. The picture, at its core, captures the idea that Wi-Fi, which was originally developed as an Ethernet cable replacement, has become an essential wireless technology in our daily lives, and will continue evolving to keep pace with spectrum availability and technological development.

The IEEE 802.11 Working Group (WG) released the first IEEE 802.11 standard, defining medium access control (MAC) and Physical (PHY) layers, in 1997, and has since adopted IEEE 802.11a, b, g, and n versions [2], with operations all restricted to the 2.4 GHz and 5 GHz unlicensed frequency bands. In its early stage, throughput enhancement was at the top of the list of the challenges faced by Wi-Fi. Starting with data rates up to 2 Mb/s (defined by the first standard), a number of significant advances have been made to enhance throughput.

The first step on the path to high-throughput WLAN was the introduction of orthogonal frequency-division multiplexing (OFDM) PHY, a popular technique that increases capacity by dividing a radio signal into multiple sub-signals which are transmitted simultaneously at different sub-carriers, first adopted by IEEE 802.11a in 1999. Although the maximum available data rates up to 54 Mb/s exposed Wi-Fi to more data-craving applications, the technology was far from a satisfactory solution until the advent of IEEE 802.11n in 2009.

The data rates defined in IEEE 802.11n are up to 600 Mb/s — more than 10 times 802.11a's 54 Mb/s. IEEE 802.11n was the first Wi-Fi standard with a speed comparable to that of wired networks (e.g., Ethernet). The key drivers of such significant improvements were the adoption of many cutting-edge technologies of the time, such as multiple-input multiple-output (MIMO), channel bonding, and frame aggregation, through which the efficiencies of spatial, spectral, and temporal resource utilizations were substantially enhanced. The triumph of IEEE 802.11n has resulted in unprecedented prosperity of Wi-Fi on both the technical and commercial fronts. "With 802.11n, there was a significant jump in minimizing the number of applications you had to keep a wired infrastructure for," said Dorothy Stanley, head of Standards Strategy at Aruba Networks.

In order to achieve prolonged growth, innovation, and vitality, Wi-Fi is expected to become more versatile and agile in dealing with its growing and diversified use in various scenarios such as indoor and outdoor, throughput and coverage, and personal and professional. Therefore, the IEEE 802.11 WG and Wi-Fi Alliance (WFA) continue to define and develop a number of advanced technologies that can be broadly classified into three broad categories: throughput enhancements, long-range extensions, and greater ease of use (Fig. 1).

Throughput Enhancements — From the beginning, high throughput has been a paramount concern for 802.11 WLAN. Several forces are still driving the trend of faster Wi-Fi technologies: the demand to extend its usability to more applications that otherwise required

Weiping Sun, Okhwan. Lee, Yeonchul Shin, Seongwon Kim, Changmok Yang, and Sunghyun Choi are with Seoul National University.

Hyoil Kim is with Ulsan National Institute of Science and Technology.

 0163-6804/14/$25.00 © 2014 IEEE

wired infrastructure, and the need for more powerful wireless access technologies to support high-quality data-intensive applications, such as high-definition (HD) video streaming.

Long-Range Extensions — The current operating frequency bands, the 2.4 GHz and 5 GHz bands, have set limits on the transmission range of IEEE 802.11; hence, Wi-Fi has always been treated with indifference for outdoor environments. To make Wi-Fi more favorable to enlarged coverage, the Wi-Fi spectrum is being extended to other frequency bands.

Greater Ease of Use — As Wi-Fi functionality improves, its configuration and manipulation become more burdensome for users. The technology should be built on the premise of convenience.

In this article, we outline the most telling features in light of these three main directions that in which Wi-Fi technologies are advancing.

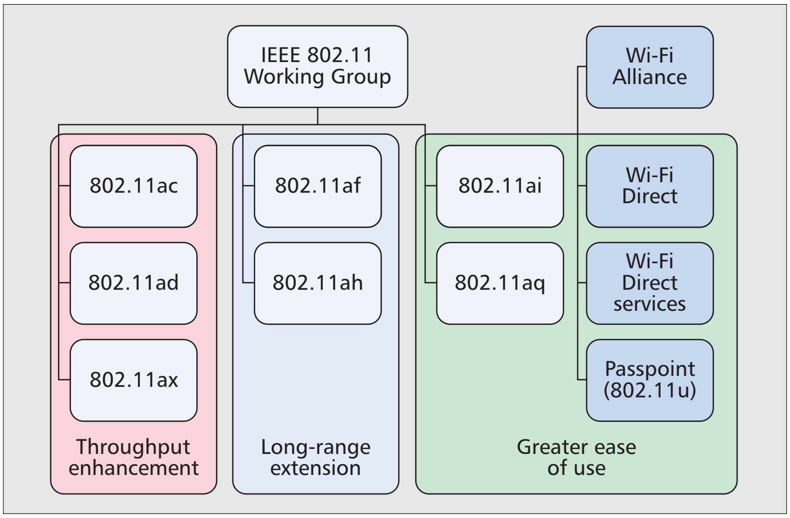

Figure 1. The evolution directions of Wi-Fi technologies.

Throughput Enhancements

Two recently approved IEEE 802.11 amendments, IEEE 802.11ac [3] and IEEE 802.11ad [4], have been designed to follow the trend of faster Wi-Fi; the goal of both amendments is to provide theoretical maximum throughputs beyond 1 Gb/s [5]. "This level of performance has been a longtime goal of Wi-Fi proponents," stated Todd Antes, vice president of Product Management at Qualcomm Inc.

IEEE 802.11ac Very High Throughput

IEEE 802.11ac, a 5 GHz-only successor to 802.11n (Fig. 2a), improves the maximum throughput primarily by the following approaches: larger channel bandwidths of 80 and 160 MHz, multi-user MIMO (MU-MIMO), and higher-order modulation, that is, 256-quadrature amplitude modulation (QAM).

Wider Bandwidth Channels — The widening of channel bandwidth, called channel bonding, was first adopted in 802.11n, where the maximum channel bandwidth of 40 MHz is yielded by bonding two adjacent 20 MHz channels. When combining two channels, the theoretical data rate more than doubles since the guard band between the two bonded channels is removed.

IEEE 802.11ac takes further steps to support 80 MHz and optionally 160 MHz channels by bonding adjacent channels. Moreover, to increase the probability of composing a 160 MHz channel, 802.11ac also allows the generation of a 160 MHz channel by combining two physically non-adjacent 80 MHz channels, called 80+80 MHz.

Multi-User MIMO — Higher data rates can also be achieved with the multiple-antenna system known as MIMO. In the case of single-user MIMO (SU-MIMO), which is supported in 802.11n, the transmitted data is divided into multiple independent spatial streams and transmitted simultaneously via multiple antennas to a single receiver. MU-MIMO advances SU-MIMO by enabling an access point (AP) to transmit multiple spatial streams via multiple antennas to multiple receivers simultaneously.

MU-MIMO improves performance by serving multiple Wi-Fi clients in parallel rather than serially, as was the case in 802.11n, where the highest rate, 600 Mb/s, is available only when both AP and client are equipped with four antennas such that there are four spatial streams available to MIMO transmission. The number of antennas embedded in the client (e.g., smartphone or tablet PC), however, is usually limited to one or two due to the space limits of the device, although an AP with three to four antennas has become commonplace, resulting in the bottleneck of maximum data rate available in practice. MU-MIMO alleviates such inefficiency by enabling simultaneous reception at multiple clients so that the number of spatial streams is governed by the total number of antennas embedded in the clients, not per-client. IEEE 802.11ac supports downlink MU-MIMO only, with up to four receivers and up to eight spatial streams, thus doubling the number of supported spatial streams in 802.11n.

Higher-Order Modulation — The highest-order modulation in 802.11 WLAN has been 64-QAM ever since the adoption of 802.11a. IEEE 802.11ac newly adopts 256-QAM, thus enabling encoding four times as dense as the 64-QAM used by 802.11n.

In the 160 MHz mode (with 468 data subcarriers per OFDM symbol), a data rate of 866.7 Mb/s can be achieved with a single spatial stream using 256-QAM (i.e., 8 bits/sub-carrier/OFDM symbol), 5/6-rate coding, and a short guard interval: 8 (bits) × 468 (data sub-carriers) × (5/6) (code rate) × 277.8 (ksym/s). With the maximum number of spatial streams (eight), data rates up to 6.9 Gb/s are possible.

IEEE 802.11ad Very High Throughput

60 GHz Wi-Fi — IEEE 802.11ad, also known by its nickname "WiGig," defines the operation of WLAN over the unlicensed 60 GHz frequency

IEEE 802.11ad defines a fast session transfer between 802.11 PHY layers and the sustenance of the quality of experience (QoE) of existing 802.11 users. Therefore, a tri-band operation over the 2.4 GHz, 5 GHz, and 60 GHz bands with backward compatibility to the legacy 802.11 WLAN is newly defined.

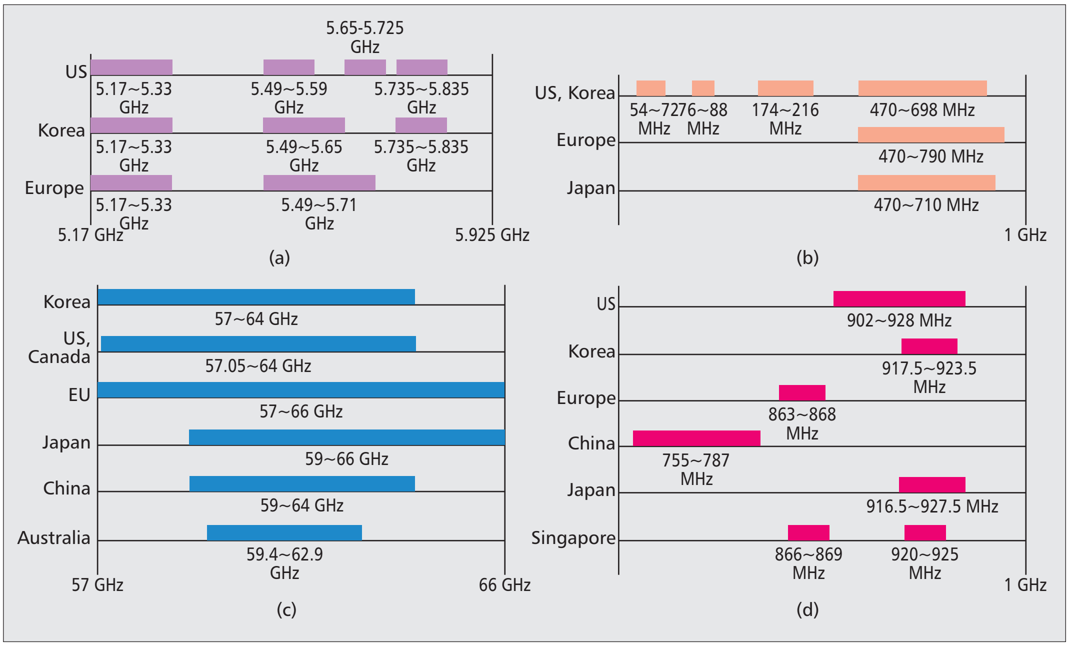

Figure 2. Frequency bands used by coming Wi-Fi technologies depending on regions: a) frequency bands of 802.11n/ac at 5 GHz; b) frequency bands of 802.11af at TVWS; c) frequency bands of 802.11ad at 60 GHz; d) frequency bands of 802.11ah below 1 GHz.

band, that is, the millimeter-wave (mmWave) band (Fig. 2c). Compared to 2.4 GHz and 5 GHz bands, communication over 60 GHz bands suffers from severe propagation loss and signal attenuation, thus resulting in a short communication range. On the other hand, it has an advantage of much broader available bandwidth. Moreover, thanks to the short wavelength in such a high-frequency band, a very large number of antennas can be deployed in a small area to form a high-directional beam, which concentrates the transmitted power to a particular direction and compensates for the signal attenuation. In this regard, 802.11ad is expected to be used for high-definition (HD) video transmission, high-rate data synchronization, and so on, while adaptive beamforming and multi-antenna configuration are becoming the core issues.

IEEE 802.11ad defines a fast session transfer between 802.11 PHY layers and the sustenance of the quality of experience (QoE) of existing 802.11 users. Therefore, a tri-band operation over the 2.4 GHz, 5 GHz, and 60 GHz bands with backward compatibility to the legacy 802.11 WLAN is newly defined.

PHY Feature — IEEE 802.11ad defines both single-carrier (SC) PHY supporting data rates up to 4620 Mb/s (with π/2-16QAM, 3/4-rate coding, and data symbol rate of 1540 Msym/s) and OFDM PHY supporting data rates up to 6756.75 Mb/s (with 64-QAM, 13/16-rate coding, 336 data sub-carriers, and OFDM symbol rate of 4125 ksym/s), both using 2.16-GHz-wide channels. The SC PHY is suitable for low-power mobile devices by virtue of its low power consumption. Besides, OFDM PHY can be adaptively used according to the link distance and the existence of obstacles for its longer communication range and greater resilience to delay spreads.

MAC Feature — The 802.11ad MAC, on the other hand, defines time-division multiple access (TDMA) above the existing contention-based carrier sense multiple access with collision avoidance (CSMA/CA) to support quality of service (QoS). It also supports high directivity with modifications on control frame operation such as beacon frames and clear-to-send (CTS) frames for direction-aware network allocation vector (NAV) allocation.

To be specific, a personal basic service set (PBSS) is defined in the 802.11ad MAC for peer-to-peer (P2P) communications. PBSS allows only a station chosen as a PBSS central point (PCP) to transmit beacon frames, possibly in different directions. Additional beamforming training and announcement after the beacon transmission allow directional MAC, thus enabling QoS guarantee and efficient power management.

IEEE 802.11ax High-Efficiency WLAN

Over the years, efforts on throughput enhancements (e.g., 802.11n/ac/ad) have been primarily focused on theoretical peak throughput in a single BSS environment. The tremendous progress made in this direction has brought us to a point where the emphasis has shifted to "real-world" performance.

Along with the growing population of Wi-Fi users, increasingly more APs are deployed in crowded areas to cater to both capacity and coverage demands. However, the goal is not likely to be achieved in reality simply by deploying more APs densely within a limited area; the resulting environments tend to be overlapping basic service sets (OBSSs), in which inter-BSS interference and collisions are likely to become more severe.

IEEE 802.11 TGax was recently established to address the challenges. IEEE 802.11ax, at its very early stage of standardization, aims to improve the efficiency of spectrum utilization by enhancing the area throughput (measured in bits per second per square meter) and average per-user throughput in both indoor and outdoor highly-dense deployment scenarios by advancing both PHY and MAC layers. It is the first time per-user throughput in multiple BSS environments are being considered, thus reflecting real-world performance more closely. Currently, TGax is considering state-of-the-art technologies including uplink MU-MIMO, orthogonal frequency-division multiple access (OFDMA), OBSS interference handling, and full duplex radio as 802.11ax key features.

LONG-RANGE EXTENSIONS

Along with the great advances that 802.11ac and 802.11ad will bring in terms of speed, the 802.11 WG triggered two new standard extensions, IEEE 802.11af [6] and IEEE 802.11ah [7], for the purpose of long-range extensions at frequency bands below 1 GHz.

IEEE 802.11AF TV WHITE SPACE

TV white space (TVWS) is the temporarily vacant spectrum resources in very high frequency (VHF) and ultra high frequency (UHF) bands originally licensed to TV broadcasters and wireless microphones, which can be opportunistically utilized by unlicensed devices as long as no harmful interference is imposed on the licensed users. TVWS resides in 470–790 MHz in Europe and the United Kingdom, and non-continuous 54–698 MHz in Korea and the United States, as shown in Fig. 2b.

IEEE 802.11af defines WLAN operations at TVWS to deliver so-called Super Wi-Fi. Thanks to the favorable propagation characteristics of such low-frequency bands compared to 2.4 GHz and 5 GHz, including reduced path loss and better wall-penetrating ability, a Super Wi-Fi signal can travel longer distances than a typical Wi-Fi signal. Therefore, over-the-air broadband access can be implemented at lower cost by deploying 802.11af APs much less densely.

IEEE 802.11af mandates an operation under strict regulatory constraints, based on location-aware devices and online databases called geolocation databases (GDBs). A GDB stores location-specific information of available spectrum and usage schedule, and geolocation-capable 802.11af APs access the GDB via the Internet to obtain the necessary conditions to operate only where (geographically and spectrally) and when they do not interfere with nearby licensed devices in the TVWS.

802.11af is supposed to fulfill several requirements in terms of operating frequency spectra such as narrow channel bandwidth (6–8 MHz depending on the regions) and non-contiguous available channels due to the time-varying TVWS usage by TV users. Accordingly, it employs most advanced features of 802.11ac such as MU-MIMO by designing its PHY based on 40 MHz 802.11ac PHY, and supports both contiguous and non-contiguous channel bonding of up to four channels. For protection of TV users operating in adjacent channels, it also introduces additional guard bands, achieving 55 dB adjacent channel leakage ratio (ACLR).

IEEE 802.11AH BELOW 1 GHZ

Although 802.11af aims to provide a long-range Wi-Fi, the regulatory restrictions on the availability of spectral and temporal resources inherently limit its applicability in many locations, especially in urban areas, where many TV broadcast stations almost fully utilize TV bands already. Due to the intrinsic drawbacks of 802.11af and the increasing demand for ubiquitous wireless access, IEEE 802.11ah was initiated to specify the operation at unlicensed bands below 1 GHz (e.g., 917.5–923.5 MHz in Korea and 902–928 MHz in the United States), as shown in Fig. 2d.

IEEE 802.11ah is expected to provide a much improved transmission range compared to conventional Wi-Fi thanks to the superior propagation characteristics. Due to the long-range but limited bandwidth, 802.11ah is considered highly suitable for large-scale low-rate sensor networks (e.g., smart grid), where the number of involved devices in a given network could be much larger than that of conventional 802.11 Wi-Fi. On the other hand, target devices in the sensor networks are likely to be battery-powered; hence, the power saving features become critical to the performance of 802.11ah. Another challenge encountered by 802.11ah is the scarcity of available spectra, so increasing spectral efficiency is one of the main concerns in its protocol design.

In order to cope with such expected requirements, 802.11ah has introduced a number of enhancements in terms of power saving, the number of supported stations per AP (i.e., up to 8191 stations compared with 2007 stations of the legacy standard), medium access schemes (e.g., a new medium access scheme called restricted access window, RAW, has been proposed to mitigate collisions among a large number of stations by dividing time resource into several intervals, each of which is designated to a certain group of stations for channel access), and greater compactness of various frame formats [8]. Moreover, 802.11ah has designed a new PHY layer based on a 10 times down-clocked operation of 802.11ac PHY (making 802.11ah 10 times slower than 802.11ac), thus able to inherit 802.11ac PHY's advanced features.

Figure 3 illustrates the supported data rates and transmission ranges of the above-presented 802.11 standards. Table 1 also presents an overall performance comparison among them.

GREATER EASE OF USE

IEEE 802.11ai [9] and IEEE 802.11aq [10] aim to enhance user friendliness by reducing the initial link setup delay and providing pre-association service discovery, respectively. WFA also defines a number of new standards and certification programs, including Wi-Fi Direct [11], for direct communication among Wi-Fi devices without the aid of an AP, and Passpoint [12], for automatically joining a Wi-Fi subscriber service at hotspot areas.

Along with the great advances that 802.11ac and 802.11ad will bring in terms of speed, 802.11 WG triggered two new standard extensions, IEEE 802.11af [6] and IEEE 802.11ah [7], for the purpose of long-range extensions at frequency bands below 1 GHz.

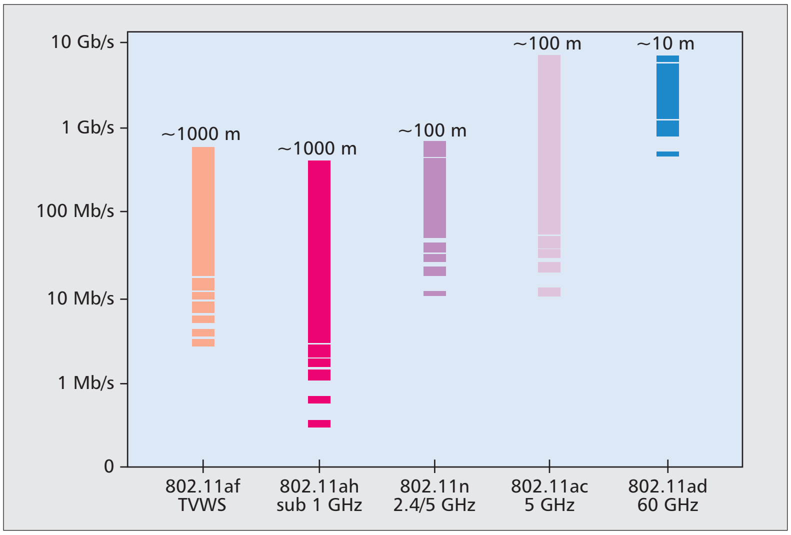

Figure 3. Supported data rates and transmission ranges of various 802.11 standards.

IEEE 802.11ai Fast Initial Link Setup

Typically, in order to use Wi-Fi service, a user should wait for a device to go through several steps before obtaining broadband Wi-Fi connectivity. The initial link setup — a technical term that specifies the procedures required for a first-time user to establish a secure Wi-Fi link with the most favorable AP — is, however, far from simple. The procedure basically consists of five steps: AP discovery, network discovery, authentication, association, and higher-layer configurations such as IP address configuration.

The challenges 802.11ai aims to address come from an environment where a large number of APs are densely deployed, and a massive amount of new users flock to the site. When these users simultaneously initiate link setup, the amount of traffic thus generated is likely to overwhelm the network capacity, and consequently, the time to wait for a connection setup exceeds the threshold users can tolerate. Therefore, there is a strong need for a more efficient and well scalable mechanism.

Accordingly, 802.11ai fast initial link setup (FILS) focuses on reducing the duration of the time spent in each step in order to complete the initial link setup within 100 ms. For example, the AP discovery time can be reduced by obtaining the information of the neighboring APs from another AP. Further optimization has also been made in both active and passive scanning. In active scanning, a station's probe request can be delayed or aborted by overhearing another station's probe request, and an AP's probe response can be broadcast instead of unicast so that all the nearby stations can acquire the AP information. The FILS Discovery (FD) frame, which conveys a part of the information of a beacon frame while being transmitted more frequently, is also designed to boost passive scanning performance.

IEEE 802.11aq Pre-Association Discovery

Wi-Fi is evolving into a more versatile technology that provides more than just Internet access. However, as service provisioning becomes more diverse, AP (or network) selection becomes more burdensome, still left to users' demand. This creates an opportunity for IEEE 802.11aq to help Wi-Fi users with the selection of the "right" AP by making more considerate information available to them before association.

For the delivery of service discovery information at the pre-association stage, technical modifications above the PHY layer are currently considered by TGaq. There are several existing higher-layer service discovery/description approaches, for example, Universal Plug and Play (UPnP), Bonjour, and Access Network Query Protocol (ANQP), as well as the mechanisms to deliver information at the pre-association stage, such as the IEEE 802.11u Generic Advertisement Service (GAS) framework; hence, TGaq will develop an approach by leveraging such existing schemes.

Wi-Fi Direct

"People tend to think of Wi-Fi as wireless Internet, but that's only one use of Wi-Fi," said Greg Ennis, WFA's technical director. Another step of Wi-Fi's evolution is to move into the P2P personal area networking realm, which until now has been the province of Bluetooth. This effort corresponds to the work being done in Wi-Fi Direct, the certification name of the Wi-Fi P2P specification defined by WFA to enable direct connections among devices without the help of an AP [11].

In order to inherit the advantageous features of traditional Wi-Fi (e.g., power saving for stations), Wi-Fi Direct mimics the infrastructure-based WLAN architecture. That is, Wi-Fi Direct devices form a group called a P2P group, where a group member, called the group owner (GO), works like an AP in the infrastructure-based WLAN. From the users' perspective, these devices provide P2P communication in the sense that the GO's identity is not revealed to the users while the GO is dynamically selected during the group formation stage.

To construct a P2P group, two devices should find each other first via the find phase operation, which is done by conducting active scanning at three "social" channels at 2.4 GHz (i.e., channels 1, 6, and 11). Then several subsequent steps, such as GO negotiation, Wi-Fi protected setup (WPS) provisioning, and IP address configuration, are taken. By completing all these steps, a device becomes a GO and serves other P2P clients via a secure wireless link.

Besides the power saving feature inherited from 802.11 WLAN, which is dedicated for stations, Wi-Fi Direct defines two novel power saving mechanisms for the GO, opportunistic power saving and notice of absence (NoA), since the GO is also likely to be a normal battery-powered portable device. Opportunistic power saving offers the GO a series of intermittent power saving opportunities by exploiting the time when every associated P2P client is in the doze state. NoA, by contrast, defines more active power saving operations that allow the GO to be absent for a scheduled duration by reporting its absence to the associated P2P clients in advance.

By utilizing Wi-Fi Direct, a mirroring service named Miracast has been standardized by WFA, and it allows multimedia contents, such as audio

	802.11ac	802.11ad	802.11af	802.11ah	802.11ax (expected)
Freq. spectrum	5 GHz	60 GHz	54–790 MHz	<1 GHz	2.4 & 5 GHz
Nominal range	~100 m	~10 m	~1 km	~1 km	~100 m
Channel bandwidths	20/40/80/160/ 80+80 MHz	2.16 GHz	6/7/8/12/14/16/ 24/28/32/ 6+6/7+7/8+8/ 12+12/14+14/16+16 MHz	1/2/4/8/16 MHz	—
Max data rate	6.933 Gb/s	6.756 Gb/s	568.9 Mb/s	346.7 Mb/s	—
Max mandatory rate	292.5 Mb/s	2.08 Gb/s	26.7 Mb/s	6.5 Mb/s	—
Key features	Downlink MU-MIMO, channel bonding, higher-order modulation	Beamforming	GDB-based channel access	Deep power saving, increased number of supported stations per AP, short frames, efficient medium access schemes	Uplink MU-MIMO full duplex, OFDMA, OBSS handling

Table 1. Comparison among upcoming Wi-Fi technologies.

and video, to be shared across devices seamlessly via Wi-Fi Direct connection. That is, it enables users to mirror the screen of a portable device (e.g., smartphone) onto a large screen TV or monitor in order to enjoy the entertainment more comfortably.

Even so, the lack of upper-layer applications has been one of the major handicaps that impede the debut of Wi-Fi Direct as a mainstream P2P technology. Correspondingly, a framework called Wi-Fi Direct services (WFDS) is under development to provide third-party developers a normalized platform interface so that the extensibility and interoperability of the resulting applications can be obtained easily, ultimately encouraging Wi-Fi Direct to become more essential in the future.

Passpoint

A new certification program called Passpoint has also been developed by WFA as an industry-wide solution to streamline the network access in hotspot areas [12]. Based on IEEE 802.11u [2] and WFA Hotspot 2.0 specifications, it eliminates the need for users to search and choose a network, to request the connection to the AP, and, in many cases, to re-enter their authentication credentials each time they initiate a Wi-Fi connection. Passpoint automates the entire process by enabling a seamless connection between hotspot networks and mobile devices while delivering a secure wireless link.

Envisioning the Future of Wi-Fi

In this section, we attempt to envision the future direction of Wi-Fi evolution by taking into account the aforementioned trend in Wi-Fi development.

More Versatile Wi-Fi Exploiting Spectrum Heterogeneity

Traditionally, the use of higher frequency bands has been a driving force for providing higher-speed Wi-Fi, mainly due to the availability of broader bandwidth. Nevertheless, the inferior propagation characteristics of such higher frequency bands have resulted in less competence in network coverage. The trade-off between capacity and coverage is well demonstrated in Fig. 4, which exhibits the maximum supported data rates according to the communication range regarding various Wi-Fi standards operating in 2.4 GHz, 5 GHz, and TVWS.

Diversification of Wi-Fi spectrum could introduce a more versatile Wi-Fi by adaptively integrating heterogeneous Wi-Fi standards according to the user context and network conditions [13]. For instance, an AP that jointly supports 2.4 GHz, 5 GHz, and TVWS may also be able to achieve the network performance corresponding to the upper envelope of the combined plots in Fig. 4 with multi-band multi-standard Wi-Fi users.

All-Wi-Fi Seamless Service Provisioning

Technological evolution and diversified frequency spectra have made Wi-Fi powerful and agile enough to be suitable for various environments, not solely restricted to indoor use. Combining the advantages of enhanced throughput, enlarged coverage, and easier use, we can envision ubiquitous broadband wireless access provided by a "Wi-Fi ecosystem," in which various Wi-Fi technologies take complementary roles for seamless service provisioning, as illustrated in Fig. 5.

For better understanding of the Wi-Fi ecosystem, here is a scenario that might happen in the near future:

Bob, a salesman, is watching TV at home in the morning. The HD contents are being transferred from a set-top box to the TV via 802.11ad, which replaces the traditional complex cable connections, giving the layout of the TV a higher degree of "freedom." At the same time, his tablet PC is connected to an 802.11ac AP, through which

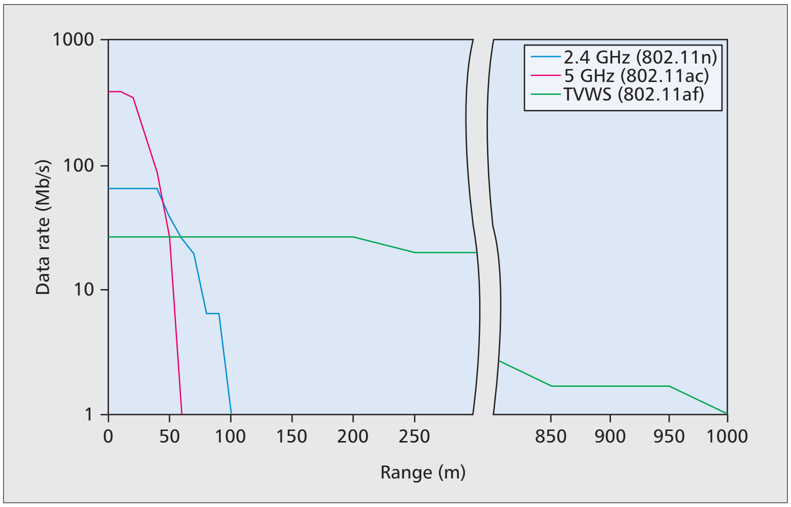

Figure 4. Trade-off between capacity and coverage among 2.4 GHz, 5 GHz, and TVWS Wi-Fi.

he enjoys smooth, flawless, and real-time video chat with his colleague, discussing today's meeting agenda. On his way to the subway, his phone tells him that there is an email to which he immediately responds using an outdoor Wi-Fi wirelessly backboned by 802.11af. At the subway station, his phone promptly discovers and associates with the "best" AP with the help of 802.11ai's FILS and 802.11aq's pre-association service discovery. During the commute, he watches video clips streamed from remote cloud servers via 802.11ax, which operates at high speed even in the highly dense environment with hundreds of other commuters, thanks to its high-efficiency design.

Although several technical challenges to make the scenario happen remain, Wi-Fi technology is evolving fast, filling the gap between reality and imagination.

Relationship with Cellular

Long-Term-Evolution (LTE), one of the most prominent cellular deployments across the world, is currently operating in the licensed spectrum (e.g., from 700 MHz to 2.6 GHz) to provide services in a more controlled manner than Wi-Fi operating in the unlicensed spectrum, by virtue of the exclusive spectrum occupancy. Recently, however, with the pressing need for additional spectral resources incurred by ever-increasing mobile traffic demand, the idea of deploying an LTE system in unlicensed bands (particularly the 5 GHz unlicensed band mostly used by Wi-Fi today) is on the horizon.

On the other hand, Wi-Fi, which thus far has been used by operators as a secondary carrier in indoor environments for the purpose of cellular traffic offloading, attempts to extend its territory to outdoor environments by increasing spectrum heterogeneity via the development of both 802.11af and 802.11ah.

As we have witnessed, the gap in spectrum usage policy, environments, and performance between these two major wireless systems, Wi-Fi and cellular, is narrowing along with the technological evolution [14]. Although we cannot yet anticipate what will happen to these two compelling options for mobile users, the possible anticipated outcomes include coexisting in a common system and becoming more tightly integrated, one of them being eliminated in a fierce competition, or a completely new wireless mobile system emerging, replacing both. Hence, it will be quite interesting to watch these innovative technologies unfold before us in the future.

Concluding Remarks

While Wi-Fi has become a dominant carrier of wireless data traffic, it continues evolving to keep pace with spectrum availability and technological development. In this article, we outline the most telling features of the Wi-Fi technologies being developed by the IEEE 802.11 WG and WFA in terms of their advantages of enhanced throughput, enlarged coverage, and easier use.

Several paradigm shifts that will probably occur in the near future have also been envisioned. First, diversification of Wi-Fi spectrum can improve Wi-Fi's versatility so that both coverage and capacity can be achieved by adaptively exploiting its augmented heterogeneity. Second, an all-Wi-Fi ecosystem is likely to be constructed by combining all the superior features of Wi-Fi technologies, in which seamless service provisioning can be provided with good service quality. Last but not least, Wi-Fi's relationship with the cellular network has so far been complementary, which might undergo revolutionary changes along with the ongoing evolution of Wi-Fi.

References

[1] M. Roberts, "Understanding Today's Smartphone User: An Updated and Expanded Analysis of Data-Usage Patterns in Six or the World's Most Advanced 4G LTE Markets," White Paper, June 2013.

[2] IEEE 802.11-2012, Part 11, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," Mar. 2012.

[3] IEEE 802.11ac, Part 11, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Enhancements for Very High Throughput for Operation in Bands Below 6 GHz," Dec. 2013.

[4] IEEE 802.11ad, Part 11, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Enhancements for Very High Throughput in the 60 GHz Band," Dec. 2012.

[5] L. Verma, M. Fakharzadeh, and S. Choi, "Wi-Fi on Steroids: 802.11 AC and 802.11 AD," *IEEE Wireless Commun*., vol. 20, no. 6, 2013, pp. 30–35.

[6] IEEE 802.11af, Part 11, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Television White Spaces (TVWS) Operation," Dec. 2013.

[7] IEEE P802.11ah/D1.2, Part 11, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Sub 1 GHz License Exempt Operation," Feb. 2014.

[8] W. Sun, M. Choi, and S. Choi, "IEEE 802.11 ah: A Long Range 802.11 WLAN at Sub 1 GHz," *J. ICT Standardization*, vol. 1, no. 1, 2013, pp. 83–108.

[9] IEEE P802.11ai/D1.3, Part 11, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Fast Initial Link Setup," Feb. 2014.

[10] Y. Yang and D. Gal, "Proposed Specification Framework for TGaq," IEEE 802.11-13/0300r1, Mar. 2013.

[11] Wi-Fi Peer-to-Peer (P2P) Tech. Spec., v. 1.1, Wi-Fi Alliance, P2P Tech. Group, Oct. 2010.

[12] "Wi-Fi Certified Passpoint," http://www.wi-fi.org/discover-wi-fi/wi-fi-certified-passpoint.

[13] H. Kim, K. Shin, and C. Joo, "Downlink Capacity of Super Wi-Fi Coexisting with Conventional Wi-Fi," *Proc. IEEE GLOBECOM*, 2013.

[14] Huawei, "LTE Small Cell vs. Wi-Fi User Experience," White Paper, 2013.

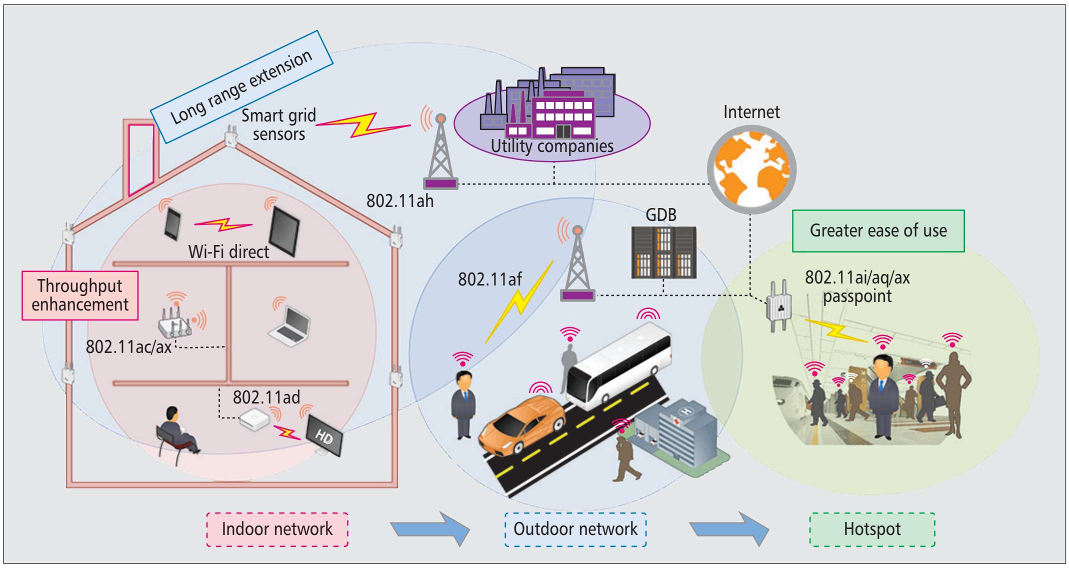

Figure 5. New paradigm of all-Wi-Fi heterogeneous access.

Combining the advantages of enhanced throughput, enlarged coverage, and easier use, we can envision ubiquitous broadband wireless access provided by a "Wi-Fi ecosystem," in which various Wi-Fi technologies take complementary roles for seamless service provisioning.

Biographies

WEIPING SUN [S'12] received a B.E. degree in network engineering from Dalian University of Technology, China, in 2010. He is currently working toward a Ph.D. degree in the Department of Electrical and Computer Engineering, Seoul National University, Korea. His current research interests focus on protocol design and performance evaluation of Wi-Fi networks.

OKHWAN LEE [S'09] received a B.S. from the School of Electronics Engineering at Seoul National University in 2006. He is currently pursuing a Ph.D. degree in the Department of Electrical Engineering and Computer Science, Seoul National University. His current research interests are in the area of wireless/mobile networks with emphasis on IEEE 802.11-based wireless mesh networking and the design of enhanced MAC/PHY protocols.

YEONCHUL SHIN [S'12] received his B.S. degree from the Department of Electrical Engineering of Seoul National University in 2010. He is currently working toward a Ph.D. degree in the Department of Electrical Engineering and Computer Science, Seoul National University. His current research interests include video multicast, QoS support, power management, algorithmic design, and performance evaluation for wireless networks, in particular, IEEE 802.11 WLANs.

SEONGWON KIM [S'12] is a Ph.D. student at the Department of Electrical and Computer Engineering, Seoul National University. He received his B.S. degree in electrical engineering from Pohang University of Science and Technology in 2011, and his M.S. degree from Seoul National University in 2013. His current research interests include IEEE 802.11 WLAN, enterprise networks, and next-generation mobile networks.

CHANGMOK YANG [S'14] received his B.S. degree in the Department of Electrical Engineering at Seoul National University in 2013. He is currently working toward a Ph.D. degree in the Department of Electrical Engineering and Computer Science, Seoul National University. His current research interests include protocol design and performance evaluation for wireless network, in particular, IEEE 802.11 WLANs.

HYOIL KIM [M'10] is an assistant professor at the School of ECE, UNIST, Korea, since 2011. Before joining UNIST, he was a postdoctoral researcher at the IBM T. J.Watson Research Center, 2010-2011. He received his B.S. degree in electrical engineering from Seoul National University in 1999, and M.S. and Ph.D. degrees in electrical engineering: systems from the University of Michigan in 2005 and 2010. His research interests include cognitive radios, mobile cloud computing, and next-generation WLAN. He served as a TPC member of IEEE GLOBECOM (2011-2014), ICUFN (2012-2015), and IEEE INFOCOM 2014, and as a publicity co-chair of ACM WiNTECH 2013.

SUNGHYUN CHOI [S'96, M'00, SM'05, F'14] is a professor in the Department of Electrical and Computer Engineering, Seoul National University. Before joining the university in 2002, he was with Philips Research USA. He received his B.S. (summa cum laude) and M.S. degrees from the Korea Advanced Institute of Science and Technology, and received a Ph.D. from the University of Michigan. He has co-authored over 180 papers and holds about 120 patents. He is serving as an Editor of *IEEE Wireless Communications*. He was named an IEEE Fellow in 2014 for his contribution to the development of WLAN protocols.