Wi-Fi Could Be Much More

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Abstract—Wi-Fi has become an essential wireless technology in our daily lives, although the original intention of its introduction was to replace the Ethernet cable. In this article, we outline the most remarkable features introduced during its on-going technological evolution in terms of three major directions, i.e., 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 the spectrum heterogeneity, seamless service provisioning, and possible relations with cellular networks.

I. INTRODUCTION

Wi-Fi, the trademark of 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 US, Canada, Japan, Germany, and the UK, Wi-Fi has contributed to about 73% of total wireless traffic on Android smartphone in April 2013, increase from 67% in August 2012 [1]. Such proliferation could be ascribed mainly to the support of the wide range of user devices (e.g., smartphone, tablet PC, etc.), exploding network coverage, on-going technological evolution, and the long-standing development of global standards.

This article offers a picture of paradigm shifts triggered by the development of the Wi-Fi technologies that are 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.

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], whose operations are all restricted at 2.4 GHz and 5 GHz unlicensed frequency bands. At its early stage, throughput enhancement was at the top of the list of the challenges that Wi-Fi faced. Starting with the data rates up to 2 Mbps (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 that are transmitted simultaneously at different sub-carriers, which was first adopted by IEEE 802.11a in 1999. Although the maximum available data rates up to 54 Mbps 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 Mbps—more than ten times of 802.11a’s 54 Mbps. IEEE 802.11n was the first Wi-Fi standard whose speed is comparable to that of wired networks (e.g., Ethernet). The key drivers of such significant improvements are 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 enhanced substantially. The triumph of the IEEE 802.11n has resulted in an unprecedented prosperity of Wi-Fi on both 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, personal and professional. Therefore, IEEE 802.11 WG and Wi-Fi Alliance (WFA) continue to define and develop a number of advanced technologies which can be largely 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 for extending its usability to more applications that otherwise required wired infrastructure, and the need of more powerful wireless access technologies for supporting high-quality data-intensive applications, e.g., High-Definition (HD) video streaming.

Long-range extensions: The current operating frequency bands, i.e., 2.4 GHz and 5 GHz bands, have set limits on the transmission range of the IEEE 802.11, and hence, Wi-Fi has always been treated with indifference in 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 the Wi-Fi functionality improves, its configuration and manipulation become more burdensome
The technology should be built on the premise of convenience. In this article, we will outline the most telling features in light of these three main directions that the Wi-Fi technologies are advancing in.

II. THROUGHPUT ENHANCEMENTS

Two recently approved IEEE 802.11 amendments named 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 Gbps [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.

A. IEEE 802.11ac Very High Throughput (VHT)

IEEE 802.11ac, a 5 GHz-only successor to 802.11n (Fig. 2(a)), 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, i.e., 256-Quadrature Amplitude Modulation (QAM).

1) Wider Bandwidth Channels: The widening of channel bandwidth, namely 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 to generate a 160 MHz channel by combining two physically non-adjacent 80 MHz channels, called 80+80 MHz.

2) Multi-User MIMO (MU-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 the performance by serving multiple Wi-Fi clients in parallel rather than serially, as was the case in 802.11n, where the highest rate, 600 Mbps, 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, and tablet PC), however, is usually limited to one or two due to the space limit of the device, although the AP with three to four antennas has become a commonplace, that resulted 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.

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

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

B. IEEE 802.11ad Very High Throughput (VHT)

1) 60 GHz Wi-Fi: IEEE 802.11ad, also known as its trademark “WiGig,” defines the operation of WLAN over the unlicensed 60 GHz frequency band, i.e., mmWave band (Fig. 2(c)). 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 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 HD video transmission, high rate data synchronization, etc., 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 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
the backward compatibility to the legacy 802.11 WLAN is newly defined.

2) PHY Feature: IEEE 802.11ad defines both Single Carrier (SC) PHY supporting the data rates up to 4,620 Mbps (with \( \pi/2 \)-16QAM, 3/4-rate coding, and data symbol rate of 1540 Msym/s) and OFDM PHY supporting the data rates up to 6,756.75 Mbps (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 more resilience to delay spreads.

3) 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, 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 PBSS Central Point (PCP) to transmit beacon frames possibly in different directions. Additional beamforming training and announcement after the beacon transmission allow directional medium access control, thus enabling QoS guarantee and efficient power management.

C. IEEE 802.11ax High Efficiency WLAN (HEW)

Over the years, the 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 is shifted to the “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.

An IEEE 802.11 Task Group called TGax has been recently established to take up the challenges. IEEE 802.11ax at its very early stage of standardization aims at improving the efficiency of spectrum utilization by enhancing the area throughput (measured in bps/m²) 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 to consider per-user throughput in multiple BSS environments, thus reflecting the 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.

III. LONG RANGE EXTENSIONS

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

A. IEEE 802.11af TV White Space (TVWS)

TV White Space (TVWS) is the temporarily vacant spectrum resources in Very High Frequency (VHF) and Ultra High Frequency (UHF) bands that are originally licensed to the 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 UK, and non-continuous 54–698 MHz in Korea and the US, as shown in Fig. 2(b).

IEEE 802.11af defines the WLAN operations at TVWS to deliver the so-called “Super Wi-Fi.” Thanks to the favorable propagation characteristics of such low frequency bands compared to 2.4 GHz and 5 GHz bands, including reduced path-loss and better wall-penetrating ability, the Super Wi-Fi signal can travel longer distances than the 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 the strict regulatory constraints, based on location-aware devices and online databases called Geolocation Database (GDB). The GDB stores location-specific information of available spectrum and usage schedule, and the 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 would 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 usages by TV users. Accordingly, it employs most advanced features of 802.11ac like 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).

B. IEEE 802.11ah Sub 1 GHz

Although 802.11af aims at providing 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 has been initiated to specify the operation at sub 1 GHz unlicensed bands (e.g., 917.5–923.5 MHz in Korea and 902–928 MHz in the US), as shown in Fig. 2(d).

IEEE 802.11ah is expected to provide a much improved transmission range compared with the 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, and hence, the power saving features become very critical to the performance of 802.11ah. Another challenge encountered by 802.11ah is the scarcity of the available spectra, for which increasing the spectral efficiency has been 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 8,191 stations compared with 2,007 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 ten times down-clocked operation of 802.11ac PHY (making 802.11ah ten times slower than 802.11ac), thus being able to inherit 802.11ac PHY’s advanced features.

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

IV. 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...
TABLE I
COMPARISON AMONG UPCOMING WI-FI TECHNOLOGIES.

<table>
<thead>
<tr>
<th></th>
<th>802.11ac</th>
<th>802.11ad</th>
<th>802.11af</th>
<th>802.11ah</th>
<th>802.11ax (expected)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Freq. spectrum</strong></td>
<td>5 GHz</td>
<td>60 GHz</td>
<td>54–790 MHz</td>
<td>&lt;1 GHz</td>
<td>2.4 &amp; 5 GHz</td>
</tr>
<tr>
<td><strong>Nominal range</strong></td>
<td>~100 m</td>
<td>~10 m</td>
<td>~1 km</td>
<td>~1 km</td>
<td>~100 m</td>
</tr>
<tr>
<td><strong>Channel bandwidths</strong></td>
<td>20/40/80/160/80+80 MHz</td>
<td>2.16 GHz</td>
<td>6/7/8/12/14/16/24/28/32/6+6/7+7/8+8/12+12/14/16/16 MHz</td>
<td>1/2/4/8/16 MHz</td>
<td>-</td>
</tr>
<tr>
<td><strong>Max data rate</strong></td>
<td>6.933 Gbps</td>
<td>6.756 Gbps</td>
<td>568.9 Mbps</td>
<td>346.7 Mbps</td>
<td>-</td>
</tr>
<tr>
<td><strong>Max mandatory rate</strong></td>
<td>292.5 Mbps</td>
<td>2.08 Gbps</td>
<td>26.7 Mbps</td>
<td>6.5 Mbps</td>
<td>-</td>
</tr>
<tr>
<td><strong>Key features</strong></td>
<td>Downlink MU-MIMO</td>
<td>Channel bonding</td>
<td>Beamforming</td>
<td>GDB-based channel access</td>
<td>Deep power saving Increased number of supported stations per AP Short frames Efficient medium access schemes</td>
</tr>
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</table>

service at hotspot areas.

A. IEEE 802.11ai Fast Initial Link Setup (FILS)

Typically, in order to use Wi-Fi service, a user should wait for a device to go through several steps before obtaining a broadband Wi-Fi connectivity. The initial link setup—a technical term that specifies the procedures required for the 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 that 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 that the users can tolerate. Therefore, there has been 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 targeting 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 been also 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 AP’s probe response can be broadcasted instead of unicast so that all the nearby stations can acquire the AP information. The FILS Discovery (FD) frame, which conveys a part of information of beacon frame while being transmitted more frequently, is also designed to boost the passive scanning performance.

B. IEEE 802.11aq Pre-Association Discovery (PAD)

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 which is still left to the users in 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 pre-association stage, technical modifications above the PHY layer are currently considered by the Task Group aq (TGaq). There are several existing higher layer service discovery/description approaches, e.g., Universal Plug and Play (UPnP), Bonjour, and Access Network Query Protocol (ANQP), as well as the mechanisms to deliver information at pre-association stage, e.g., IEEE 802.11u Generic Advertisement Service (GAS) framework, and hence, TGaq will develop an approach by leveraging such existing schemes.

C. 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, the WFA Technical Director. Another step of Wi-Fi’s evolution is to move into the P2P personal area networking realm that has until now 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 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 P2P group, where a group member, called 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, namely 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 notifying 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 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 so as 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 easily obtained, ultimately encouraging Wi-Fi Direct to become more essential in the future.

D. 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]. Being based on IEEE 802.11u [2] and WFA Hotspot 2.0 specifications, it eliminates the needs 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.

V. 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.

A. 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, due mainly 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.

B. 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 uses. 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 higher degree of “freedom.” At the same time, his tablet PC is connected to an 802.11ac AP, through which 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
Fig. 5. New paradigm of all Wi-Fi heterogeneous access.

an outdoor Wi-Fi wirelessly backboned by 802.11af. At the subway station, his phone promptly discovers and associates with the “best” AP by the help of 802.11ai’s fast initial link setup and 802.11aq’s pre-association based service discovery. During the commute, he watches video clips being 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 there still remain several technical challenges to make the scenario happen, the Wi-Fi technology is evolving fast, while filling the gap between reality and imagination.

C. 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, an idea of deploying LTE system in unlicensed bands (particularly 5 GHz unlicensed band mostly used by Wi-Fi today) is on the horizon.

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

As we have witnessed, the gap in the spectrum usage policy, environments, and the performance between these two major wireless systems, i.e., 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 that they will co-exist in a common system and become more tightly integrated, or one of them will be eliminated in a fierce competition, or a completely new wireless mobile system will emerge by replacing both. Hence, it will be quite interesting to watch these innovative technologies unfold before us in the future.

VI. 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 outlined the most telling features of the Wi-Fi technologies being developed by IEEE 802.11 WG and WFA in terms of their advantages of enhanced throughput, enlarged coverage, and easier use.

Several paradigm shifts that probably occur in the near future have been also 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 the least, Wi-Fi’s relationship with the cellular network has been so far complementary to each other, which might undergo revolutionary changes along with the ongoing evolution of Wi-Fi.
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