Survey and Performance Evaluation of the Upcoming Next Generation WLANs Standard - IEEE 802.11ax

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Abstract
With the ever-increasing demand for wireless traffic and quality of services (QoS), wireless local area networks (WLANs) have developed into one of the most dominant wireless networks that fully influence human life. As the most widely used WLANs standard, IEEE 802.11 will release the upcoming next generation WLANs standard amendment: IEEE 802.11ax. Thus, this article briefly surveys the key technologies of IEEE 802.11ax. Furthermore, performance requirements of IEEE 802.11ax are evaluated via a proposed systems and link-level integrated simulation platform (SLISP). Simulations results confirm that IEEE 802.11ax significantly improves the user experience in high-density deployment, while successfully achieves the average per user throughput requirement in project authorization request (PAR) of IEEE 802.11ax by four times compared to the legacy IEEE 802.11. To the best of our knowledge, this article is the first work to thoroughly and deeply evaluate the compliance of the performance requirements of IEEE 802.11ax.

Keywords Wireless local area networks · WiFi · IEEE 802.11ax · Multi-user MAC · Spatial reuse · Simulation platform · Performance evaluation

1 Introduction
The fast development of mobile Internet and the increasingly flourishing wireless network services, demands for wireless traffic and quality of service (QoS) have dramatically increased in recent years [1]. Wireless local area networks (WLANs), together with the cellular networks, have emerged as the primary traffic bearing wireless networks due to their high speed, flexible deployment, and low cost. According to Cisco report, the wireless traffic in the world would sharply increase with a 47% Compound Annual Growth Rate (CAGR) from 2016 to 2021. Moreover, WLANs carried data traffic from 42% in 2015 to 49% in 2021 [2]. Therefore, to respond to the rapid growth of traffic demands, researchers, enterprises, and standardization organizations are devoting to study on the key technologies and promote the standardization of the next generation WLANs. In recent years, IEEE 802.11 [3] is expected to release the next generation WLAN standard amendment: IEEE 802.11ax [4].

In IEEE 802.11ax, the maximum transmission rate as well as the access efficiency of WLANs has been significantly improved. However, the current WLANs standard still faces challenges to meet the high-dense deployment scenarios of the future wireless network. Therefore, in 2013, after the release of IEEE 802.11ac, IEEE 802.11 immediately launched an early study of the next generation WLANs standard amendment IEEE 802.11ax, whose predecessor is named by the high efficiency WLAN (HEW). It is worth emphasizing that, in contrast to previous versions of IEEE 802.11 standard amendments that mainly faced to the improvements of the peak transmission rate, IEEE 802.11ax pays more attentions to the network performance and user experience of the high-dense deployment scenarios, such as improvements of single user average throughput and area throughput [5]. Therefore, IEEE
802.11ax significantly enhances MAC layer technologies by introducing multi-user MAC (MU-MAC), spatial reuse (SR), and target wakeup time (TWT), which improves the access efficiency and the user experiences in high-dense deployment scenarios. On the other hand, IEEE 802.11ax also achieves a maximum transmission rate up to 9.6 Gbps by introducing 1024-QAM, orthogonal frequency division multiple access (OFDMA), uplink (UL) multi-user multiple input multiple output (MU-MIMO), enhanced channel bonding (CB), etc. Currently, the Draft 3.0 of IEEE 802.11ax is released. Considering that IEEE 802.11ax has introduced many new features of MAC layer technologies as well as PHY, we expect that it will become a new milestone in the evolution of the IEEE 802.11 standard. This is why, during recent years, both industrial and academia focus strongly on the standardization process and key technologies of IEEE 802.11ax [6–10]. Therefore, it is quite important to survey the key technologies of IEEE 802.11ax.

More importantly, on one hand, the Project Authorization Request (PAR) of IEEE 802.11ax, one of the most important documents of the standardization process, declares that IEEE 802.11ax needs to achieve four times at least of the average throughput improvement per STA in specific high-dense deployment scenarios. But, whether this objective has been achieved by IEEE 802.11ax needs to be answered. One the other hand, a series of new features are introduced in IEEE 802.11ax, the performance gain brought by these features, especially the PHY enhancements, MU-MAC, and SR, also need to be evaluated. Unfortunately, we notice that few existing studies answer the question or show comprehensive and objective performance results of IEEE 802.11ax evaluated by the designed specifically network simulation platform. This article overviews the key technologies of the next generation WLAN: IEEE 802.11ax and evaluating the performance through an integrated simulation platform.

We highlight the contributions as follows:

- Due to space limitation, this paper briefly overviews the key technologies for IEEE 802.11ax, including PHY enhancements, MU-MAC enhancements, SR technologies, and other technical enhancements.
- As we know, this is the first work to thoroughly and deeply evaluate the performance towards the performance requirements of IEEE 802.11ax. Based on the simulation results presented in this article, researchers may obtain a more profound insights of the MAC layer performance of IEEE 802.11ax. We believe that such an understanding is useful for future standardizations. It has been highlighted that the simulation platform named system & link level integrated simulation platform (SLISP) used in this article is the first integrated simulation platform in the world by integrating link level simulation and system level simulation for IEEE 802.11ax, which meets the requirements of the standard document [11–13]. Therefore, the performance results given in this article are objective and convincing.

The remainder of this article is organized as follows: Section 2 presents a general overview of the key technologies, including key technologies and the standardization process. The proposed integrated simulation platform is introduced in Section 3. Performance evaluation at single Basic Service Set (BSS) scenario and multiple BSSs scenario are shown in Sections 4 and 5, respectively. Section 6 concludes this article.

2 Brief survey of IEEE 802.11ax

2.1 Key technologies for 802.11ax

In response to the high-dense deployment scenarios and the objective and technical requirements, IEEE 802.11ax proposes a series of key technologies.

1) PHY enhancements

IEEE 802.11ax adopts some new modulation and coding technologies. Firstly, by introducing 1024-QAM, the maximum transmission rate could be further improved. Theoretically, IEEE 802.11ax can obtain the peak transmission rate as 9.6 Gbps. Secondly, dual carrier modulation (DCM) enhances the robustness of transmissions in both outdoor scenarios and UL transmission. Finally, low-density parity check (LDPC), as well as binary convolutional encoding (BCC) are chosen as a mandatory coding technique in IEEE 802.11ax.

A new subcarrier division mechanism is adopted for IEEE 802.11ax, which is more fine-grained compared to traditional IEEE 802.11. In IEEE 802.11ax, the 20 MHz band is divided into 256 subcarriers spacing, which is four times that of the legacy IEEE 802.11. This new subcarrier division mechanism leads to more precise and efficient scheduling of OFDMA resources, and further improved spectrum efficiency.

IEEE 802.11ax enhances the multiple access technology based on OFDMA and MU-MIMO to guarantee the MU parallel transmission in both frequency domain and spatial domain. This provides a solid foundation for improving the efficiency of WLANs.

The enhanced CB in IEEE 802.11ax enables APs and/or STAs to transmit frames on non-continuous channels, which improves channel utilization and fully uses the larger bandwidth. To support these new PHY technologies, PPDU is also enhanced accordingly.
2) **MU-MAC enhancements**

The most important enhancement for the MAC layer of IEEE 802.11ax is the enhancement of MU-MAC. MU-MAC is a type of high efficiency multiple access technologies, which enables multiple users to obey certain access rules to transmit UL data concurrently (known as UL MU-MAC), or to transmit downlink (DL) data concurrently (known as DL MU-MAC) through given network access resources (i.e., space domain, time domain, and frequency domain resources). MU-MAC covers OFDMA based and MU-MIMO based multiple access processes introduced by IEEE 802.11ax. Thus, in the absence of confusion, this article uses the term MU-MAC to refer to all the multiple user access proposed.

Firstly, UL MU-MAC is firstly introduced for WLAN by IEEE 802.11ax. Specifically, two detailed technologies are introduced, i.e., including UL OFDMA and UL MU-MIMO. Secondly, for DL MU-MAC, IEEE 802.11ac only supports DL MU-MIMO, but IEEE 802.11ax introduces DL OFDMA to further enhance DL parallel access.

Moreover, IEEE 802.11ax proposes a cascaded MU MAC, allowing the DL MU transmission and the UL MU transmission to occur alternately in a TXOP time duration, which further improves the MAC efficiency.

In summary, MU-MAC achieves more efficient spectrum efficiency, and makes the MAC layer overhead much lower.

3) **SR technology**

SR has been suggested to be an optional technology to enhance spectrum reuse capability and interference management ability in high-dense OBSS scenarios. By introducing the BSS color mechanism, a node can easily distinguish whether the received frame originated from the intra-BSS or inter-BSS, where intra-BSS represents the node’s own BSS and inter-BSS indicates other BSS. BSS color is the technical premise for the following three mechanisms of SR.

IEEE 802.11ax enhances the virtual carrier sensing mechanism by requiring the node to maintain two NAVs counters: intra-BSS NAV counter and basic NAV counter. Not only is two NAVs based virtual carrier sensing mechanism compatible with MU-MAC, but it also avoids the TXOP-ending chaos problem in high-dense deployment scenarios since all the existing NAVs would be ended by any CF-End frame.

OBSS_PD based SR mechanism introduced in IEEE 802.11ax allows one node to use a higher clear channel assessment (CCA) threshold for physical carrier sensing if the received frame originated from inter-BSS, which improves the probability of concurrent transmission.

Moreover, IEEE 802.11ax also introduces the spatial reuse parameter (SRP) mechanism, which allows STAs to perform spatial reuse in shorter time granularity, i.e., intra-PPDU granularity. Similarly as OBSS_PD, SRP also enhances the probability of concurrent transmission.

4) **Other MAC layer enhancements**

Another important breakthrough of IEEE 802.11ax is the service reservation mechanism. Specifically, based on the AP’s global vision as well as its powerful control and management capabilities, IEEE 802.11ax adopts TWT, thus enhancing the scheduling ability and QoS guarantee of WLANs by allocating different service times for different STAs. The TWT mechanism achieves service reservation in the time dimension, reduces the collision, and enhances the QoS guarantee of WLANs. It is worth noting that the original purpose of introducing TWT mechanism is to enhance power-saving. But, from the angle of technical generality, TWT mechanism introduces service reservation. Therefore, in this article, we will comprehensively describe service reservation based on TWT mechanism.

Moreover, to increase power efficiency, IEEE 802.11ax introduces a TWT based power save mechanism and intra-PPDU based power save mechanism. These mechanisms are better adapted to the MU-MAC introduced in IEEE 802.11ax, and improve the power efficiency for many scenarios.

2.2 Standardization process

To simplify understanding the standardization process of the IEEE 802.11, this subsection uses the standardization process of the IEEE 802.11ax as an example. After the release of IEEE 802.11ac in March 2013, IEEE 802.11 immediately sets up a study group (SG) named as HEW [14]. Via full discussion, a series of features have been confirmed as the main technologies for the next generation WLANs. Then, HEW completed two important documents: PAR [5] and criteria for standards development (CSD) [15]. PAR, as one of the most important documents in the standardization process, specifies the objectives and technical requirements, while CSD specifies the technical criteria standardization process.

In March 2014, HEW was replaced by the IEEE 802.11 task group (TGax), and Mr. Osama Aboul-Magd (one of the authors of this article) from HUAWEI was elected as chairman [16]. In the development process of TGax, for the first time, MU and SR were regarded as the most important research directions. To form the final IEEE 802.11ax amendment, TGax decided to form specification framework document (SFD) [17] first. In general, SFD is used to
stipulate the outline of the standard amendment and clarifies some technologies the draft should contain.

At the beginning of 2016, the development of SFD ended, and the first draft of IEEE 802.11ax was released in March 2016. In October 2018, IEEE 802.11ax released Draft 3.0 [4]. In addition, the final version of IEEE 802.11ax will be released in 2019. Figure 1 shows the timeline of the IEEE 802.11ax standardization process.

3 Simulation platform: SLISP

3.1 Requirements for the IEEE 802.11ax simulation platform

To more objectively verify the performance of key technologies in IEEE 802.11ax to effectively promote the standardization process, the TGax working group presents requirements for the simulation platform in the Evaluation Methodology document [12]. The advantage of simply using a system level or link level simulation platform is to simplify the design and expedite the simulation. Of course, this advantage is not obvious in the fast growth of computing. But, its shortcomings are more obvious: it is different from a real-world scenario, which is the advantage of an integrated simulation platform. Because the authenticity and objectivity of performance verification are more important targets, the document pointed out that it is necessary to build an integrated simulation platform for IEEE 802.11ax. Therefore, the authors build the SLISP simulation platform.

3.2 SLISP architecture

The system structure of SLISP is illustrated in Fig. 2, and the integration of link and system level simulation is implemented. SLISP mainly includes the system level simulation unit, link level simulation unit, and integrated entity unit, each of which is discussed briefly below.

The system level simulation unit mainly contains the application layer and IEEE 802.11ax MAC layer function, focusing on nodes and their behavior in the network. The application layer is mainly responsible for the generation and destruction of service data, which consists of the traffic generator module and sink module. IEEE 802.11ax MAC is primarily responsible for the proposed MAC layer technologies of IEEE 802.11ax, including a queuing management module, access module, and control carrier sensing control module. The transmission phase includes a frame control module, resource scheduling module, and transmission control module.

The link level simulation unit includes the IEEE 802.11ax PHY and channel model, which focuses on the communication link. The IEEE 802.11ax PHY is mainly responsible for the PHY-related functions, composed of resource unit (RU) and channel management module, power monitor module, and packet error ratio (PER) calculate module. RU and channel management are largely responsible for the management of RUs and channels; the power monitor module is mainly responsible for energy calculation and statistics; and the PER calculate module is mainly used for the node to calculate the PER of the received data frame according to the channel matrix obtained from the channel model, a process also called physical layer abstraction. The channel model needs to generate the H matrix of the channel according to the spatial correlation coefficient of the transmitting antenna and the receiving antenna and other parameters for the IEEE 802.11ax PHY layer.

The integrated entity unit is responsible for the integration of system and link level simulation, consisting of two
modules: link level discretization and a unified system and link level interface. The link level discretization module is responsible for incorporating link level simulation behavior into the discrete event simulation mechanism, which is an event-driven simulation mechanism. Specific to the network simulation, it considers all network behavior as events, and the simulation system only changes when a new event occurs. Thus, the simulation time is not uniform but instead triggered by events. Traditional link level simulation usually adopts a process-oriented or continuous time-oriented simulation mechanism, which is not consistent with the discrete event simulation mechanism. The biggest challenge in integrated simulation is to use the discrete event simulation mechanism in both link and system level simulation. As shown in Fig. 2, the link level discretization module is responsible for inserting the behavior of the IEEE 802.11ax PHY layer and the channel model as events into the discrete-event list. Therefore, both the system level (i.e., application layer and IEEE 802.11ax MAC layer) and link level simulation (i.e., PHY and channel model) will be incorporated into the discrete simulation event mechanism, which achieves the integrated design principle.

The unified system and link level interface is responsible for the implementation of a unified interface for the link and system levels, and the main interface is a MAC layer and PHY layer data transmission interface. Specifically, the IEEE 802.11ax MAC needs to send the encapsulated data frames to PHY when triggered by the transmission event; in turn, the PHY needs to send received data frames to the IEEE 802.11ax MAC layer when triggered by the
transmission complete event. In addition, some state settings and query interfaces also need to be implemented, such as the PHY carrier sensing state query, signal to interference and noise ratio (SINR) query, and etc.

### 3.3 Satisfaction of SLISP to the requirements

The design of the integrated simulation platform is restrained and suggested by IEEE 802.11ax [12, 18]. As shown in Table 1, ✓ represents SLISP support this feature, and * represents that this feature is not required by IEEE 802.11ax evaluation methodology documents [12] but is implemented by SLISP additionally. The integrated simulation platform (SLISP) designed and built by the authors not only meets all basic requirements specified in the document but those of its enhanced feathers, which are key to core technologies in IEEE 802.11ax (marked with an asterisk in Table 1), such as MU control frame, MU operation, SR, 1024-QAM, and so on.

### 4 Performance evaluation for single BSS

#### 4.1 Simulation scenarios and settings

In order to make the verification results more convincing, single BSS scenarios in the simulations follow the TGax Simulation Scenarios document presented by the TGax workgroup [18].

The indoor single BSS scenario of IEEE 802.11ax is shown in Fig. 3a. Each square represents a room with an area of $4m \times 2m$. The AP is in the center each area. Each AP serves 16 rooms symmetrically. There is an aisle between the middle and the four sides, and the distance between the rooms is 1m. There are four STAs randomly distributed in each room for 64 total STAs in the BSS. The detailed simulation parameter configuration of the indoor single BSS scenario is shown in Table 2.

The outdoor single BSS scenario of IEEE 802.11ax is shown in Fig. 3b. Each BSS has a hexagonal shape, and the AP is in the center. The radius of the inner circle of the cell is 65m, and each cell contains 50-100 STAs. The detailed simulation parameter configuration of the outdoor single BSS scenario is shown in Table 2. In this simulation, we compare the performance of three schemes as shown in Table 3.

#### 4.2 Simulation results

(1) **Performance analysis of indoor single BSS**

Figure 4 shows that the network performance of different schemes varied with the service rate in the indoor single BSS scenario, corresponding to the simulation results of bandwidth of 20MHz, 80MHz, and 160MHz, respectively. Take UL simulation results as an example (DL simulation results are similar): the saturation throughput of IEEE 802.11ax with OFDMA reaches 131%, 206%, and 273% performance gain in 20MHz, 80MHz and 160MHz, respectively, compared to IEEE 802.11ac. Obviously, the performance gain of IEEE 802.11ax increases with the the increase of bandwidth. This is because when the bandwidth increases, the MAC efficiency of IEEE 802.11ax and the stable MAC

| Table 1 The satisfaction of SLISP to IEEE 802.11ax simulation platform |
|---------------------------|---------------------------|
| **Basic features**        | **Feature**               | **SLISP** |
| Architecture              | Discrete event-driven based | ✓         |
| Scenario                  | High-dense indoor         | ✓         |
|                           | High-dense outdoor        | ✓         |
| MAC                       | CCA                       | ✓         |
|                           | Control frame (RTS/CTS/ACK/block ACK) | ✓         |
|                           | EDCA                      | ✓         |
|                           | Aggregation (A-MPDU in 11ac) | ✓         |
|                           | Link adaption             | ✓         |
|                           | Transmission mode (SU-OL, Beamforming, ...) selection | ✓         |
|                           | Power save mechanism      | ✓         |
| PHY                       | Beamforming vector        | ✓         |
|                           | MMSE                      | ✓         |
|                           | Effective SINR mapping and PER prediction | ✓         |
|                           | Energy detection          | ✓         |
| **Enhancement features**  | **Feature**               | **SLISP** |
|                           | Multiple channels         |           |
|                           | MU control frame (TF, MBA, OFDMA BA) | *         |
|                           | Management frame          | ✓         |
|                           | UL MU operation           | ✓         |
|                           | DL MU operation           | ✓         |
|                           | OBSS_PD mechanism         |           |
|                           | Two NAVs                  | *         |
|                           | MU-MIMO                   | ✓         |
|                           | RU allocation             | *         |
|                           | 1024-QAM                  | *         |
efficiency of IEEE 802.11ax with OFDMA will be decreased. In IEEE 802.11ax with OFDMA, the overhead of channel access and data transmission is shared with multiple STAs. Thus, the MAC efficiency of IEEE 802.11ax with OFDMA could maintain a relatively high level when the bandwidth is wide. Moreover, in the >20MHz scenarios, additional gains can be obtained from 1024-QAM.

The performance of combing OFDMA and MU-MIMO scheme is theoretically about two times that of IEEE 802.11ax with OFDMA scheme. Each time, the former supports twice the number of STAs for both the access and transmission. In IEEE 802.11ax, MU-MIMO could only be used if the number of subcarriers is no less than 106 tone, so some RUs (such as 26-tone) could not use MU-MIMO. In addition, when the number of STAs increases, the overhead of corresponding scheduling signaling and the cost of BA frames will increase accordingly. The actual simulation results show that the gain is approximately 1.8 times. In particular, the throughput of combining OFDMA and MU-MIMO reaches 5.67Gbps at 160MHz, and the UL throughput of IEEE 802.11ac

Table 2 Parameter configuration of single BSS scenario

| Parameters          | Description                                      |
|---------------------|--------------------------------------------------|
| Service type        | CBR (constant bit rate)                          |
| Per-STA service rate| 1M~13Mbps (20MHz), 4M~52Mbps (80MHz), 8M~104Mbps (160MHz) |
| STAs’ position      | Randomly distributed in each room                |
| MCS index           | 0~11; MCS 10 and MCS 11 are only employed when RU is wider than or equal to 242-tone |
| AP transmit power   | 18dBm                                           |
| STA transmit power  | 18dBm                                           |
| AP antenna height   | 1.5m                                            |
| STA antenna height  | 1.5m                                            |
| Frequency           | 5.57G                                           |
| CCA threshold       | -82dBm                                          |
| SIFS                | 16μs                                            |
| DIFS                | 34μs                                            |
| CWmin               | 15                                              |
| CWmax               | 1023                                            |
| TXOP duration       | 3.008ms                                         |
| Number of AP antennas| 8                                                |
| Number of STA antennas| 4                                           |

Table 3 Comparison of 3 schemes for single BSS

|                        | 802.11ac | 802.11ax with OFDMA | 802.11ax with OFDMA and MU-MIMO |
|------------------------|----------|---------------------|-------------------------------|
| EDCA-based channel access | ✓        | ✓                   | ✓                             |
| TXOP                   | ✓        | ✓                   | ✓                             |
| Aggregation and segmentation | ✓        | ✓                   | ✓                             |
| OFDMA                  | ✗        | ✓                   | ✓                             |
| UL MU-MIMO             | ✗        | ✗                   | ✓                             |
| Multi-channel          | ✓        | ✓                   | ✓                             |
is 1.2Gbps. The throughput of IEEE 802.11ax with OFDMA and MU-MIMO achieves 4.7 times as much as IEEE 802.11ac. As the numbers of STAs in the three schemes are the same in the simulations, the per-STA average throughput also reached 4.7 times. In summary, IEEE 802.11ax can meet the requirements of 4 times throughput gain in PAR compared to legacy IEEE 802.11.

Notably, network throughput in DL transmission is always greater than that of UL transmission. For DL transmission in IEEE 802.11ac, only the AP needs to contend for channel resources, whereas for UL transmission in IEEE 802.11ac, multiple STAs contend for channel access. Therefore, signaling overhead for channel access and data transmission in DL is less than in UL in IEEE 802.11ac. For IEEE 802.11ax, both the UL transmission and the DL data transmission are triggered by AP, and the overhead for both are the same. However, UL transmission in IEEE 802.11ax brings additional trigger frame (TF) based MU transmission and SIFS interval overhead, so the DL overhead is slightly lower.

(2) Performance analysis of outdoor single BSS

Figure 5 shows that the network performance of different schemes varies with the service rate in the outdoor single BSS scenario, corresponding to the simulation results of bandwidth of 20MHz, 80MHz, and 160MHz, respectively. Compared to the indoor scenarios, the performance fluctuation in outdoor scenarios is larger because the distance between the AP and STAs is uneven in the outdoor scenarios, and channel fading has a great influence on MCS selection. We average the simulation results of the outdoor single BSS scenarios by multiple simulations. In the indoor single BSS scenarios, AP and all STAs are very close, so the influence of channel fading is limited to the simulation results and the highest MCS is usually selected.

Consider the UL simulation results for example (DL simulation results are similar): the saturation throughput of IEEE 802.11ax with OFDMA achieves 145%, 221%, and 292% performance gain compared to IEEE 802.11ac in 20MHz, 80MHz, and 160MHz respectively. With an increase in bandwidth, the performance gain of IEEE 802.11ax with OFDMA also increases due to the stable MAC efficiency of IEEE 802.11ax with OFDMA.

One concern is that in the outdoor single BSS scenario, the performance of IEEE 802.11ax combing both OFDMA and MU-MIMO is roughly the same as that of IEEE 802.11ax with OFDMA, and throughput only increased slightly. Because of the poor quality of the wireless channel in the outdoor scenarios, STAs using MU-MIMO have to
use the lower MCS in the data transmission procedure, so the throughput of IEEE 802.11ax with OFDMA and MU-MIMO is not significantly increased. In addition, single user (SU) MIMO is used in IEEE 802.11ax with OFDMA, where throughput is improved by the antenna diversity gain because the AP has eight antennas while STAs have four. In summary, these findings indicate that data transmission with MU-MIMO is not suitable for outdoor scenarios or poor channel conditions.

Another interesting phenomenon is that, unlike in the indoor scenario, the UL saturation throughput of all the three schemes in the outdoor scenario is greater than the DL saturation throughput. For IEEE 802.11ac, the AP needs to send RTS successively, and the chance for STAs to receive an RTS is nearly equal. However, when UL STAs send RTS frames, the AP is more likely to receive the RTS sent by the STAs closer to it, and the channel quality of STAs near the AP is usually better than those far away from the AP. Thus, the UL throughput is larger than the DL throughput in IEEE 802.11ac. Let’s than consider the scenario of IEEE 802.11ax, because the transmission power of the AP and STAs is the same, the AP needs to allocate power in more than one RU in the DL transmission while the STAs use the maximum transmit power for UL transmission. Thus, overall transmit power of UL transmission increases, and STAs have more opportunity to select a higher-order MCS.

5 Performance evaluation for high-dense deployed multiple BSS

5.1 Simulation scenarios and settings

To make the verification results more convincing, the scenario setting of multiple BSS still follows the TGax Simulation Scenarios document put forth by the TGax workgroup [18].

The indoor multiple BSS scenario is shown in Fig. 6a. The whole network topology is composed of 32 indoor single BSS scenarios depicted as $4 \times 8$ matrices. The detailed network parameters of the indoor multiple BSS scenarios in our simulations are shown in Table 4.

The outdoor multiple BSS scenario is shown in Fig. 6b. The whole network topology is divided into three layers of BSS, and each BSS follows the rules of the outdoor single BSS scenario described previously. The distance between each adjacent AP is 130m. The detailed simulation parameter configuration of the outdoor multiple BSS scenario is shown in Table 4.

In this simulation, we compare the performance of three schemes as shown in Table 5.
Fig. 6 Multiple BSS scenarios in the simulations

(a) Indoor Scenario

(b) Outdoor scenario
Table 4 The parameter configuration of multiple BSS scenario

| Parameters          | Description                                                                 |
|---------------------|-----------------------------------------------------------------------------|
| Service type        | CBR                                                                          |
| Per-STA service rate| 0.05Mbps∼3Mbps                                                               |
| Bandwidth           | 20MHz                                                                       |
| STAs’ position      | Randomly distributed in each room                                           |
| MCS index           | 0∼11; MCS 10 and MCS 11 are only employed when RU is wider than or equal to 242-tone |
| AP transmit power   | 18dBm                                                                       |
| STA transmit power  | 18dBm                                                                       |
| AP antenna height   | 1.5m                                                                        |
| STA antenna height  | 1.5m                                                                        |
| Frequency           | 5.57G                                                                       |
| CCA threshold       | OBSS-PD level: -62dBm Traditional CCA level: -82dBm                        |
| CCA threshold       | -82dBm                                                                     |
| SIFS                | 16μs                                                                       |
| DIFS                | 34μs                                                                       |
| CWmin               | 15                                                                          |
| CWmax               | 1023                                                                        |
| TXOP duration       | 3.008ms                                                                    |
| Number of AP antennas| 2                                                                              |
| Number of STA antennas| 2                                                                              |

Table 5 The comparison of three schemes for multiple BSS simulations

|                          | IEEE 802.11ac | IEEE 802.11ax without SR | IEEE 802.11ax with SR |
|--------------------------|---------------|--------------------------|------------------------|
| EDCA-based channel access| ✓             | ✓                        | ✓                      |
| TXOP                     | ✓             | ✓                        | ✓                      |
| Aggregation and segmentation| ✓             | ✓                        | ✓                      |
| OFDMA                    | ×             | ✓                        | ✓                      |
| Spatial reuse            | ×             | ×                        | ✓                      |

5.2 Simulation results

(1) Performance analysis of indoor multiple BSS

- Throughput performance

Figure 7 shows the network performance of the DL transmissions in the high-dense indoor scenarios. The throughput of IEEE 802.11ax without SR is significantly larger than that of IEEE 802.11ac. Specifically, the 11ax with SR achieves 52.7% performance gain compared with IEEE 802.11ax without SR. Thus, it is clear that the SR technology introduced by IEEE 802.11ax can significantly improve the network throughput.

The performance of IEEE 802.11ac is slightly higher than that of IEEE 802.11ax without SR when the service rate is extremely low. The reason for this phenomenon is that the number of STAs for MU transmission is less than three (i.e., the RU number in the simulations is three) when the service rate is low, resulting in wasted resources. This problem can be addressed via a more optimized scheduling algorithm.

Table 5 The comparison of three schemes for multiple BSS simulations

Fig. 7 Performance of DL transmission in indoor scenarios with multiple BSS

Fig. 8 Performance of UL transmission in indoor scenarios with multiple BSS
• The influence of BSS position on throughput

In multiple BSS scenarios, a valuable and interesting notion is whether the performance between different BSS varies, which is important for network planning, especially for enterprise and campus networks. Figure 9 shows the throughput of 32 BSS adopting IEEE 802.11ax with SR. There are 64 STAs equipped with two antennas in each BSS, and the traffic rate of each STA is 3Mbps. If the BSS is closer to the corner of the network, it will probably achieve higher average BSS throughput; otherwise, if the BSS is closer to the middle of the network, it will probably achieve lower average BSS throughput. In other words, interference in the corner was slight, whereas the interference in the middle position is relatively large.

• The distribution of per-STA throughput

We perform a statistical analysis of per-STA throughput using the cumulative distribution function (CDF) curve in Fig. 10. There are 64 STAs equipped with two antennas in each BSS, and the traffic rate of each STA is 3 Mbps. First, we observe that per-STA throughput of IEEE 802.11ax with SR is larger than that of the scheme without SR and significantly larger than that of IEEE 802.11ac, consistent with previous simulation results. Next, we observe that IEEE 802.11ax improves the throughput of 5% of STAs, which meets the requirements of PAR. Finally, we also observe that the throughput of some STAs in the IEEE 802.11ac scheme is very large, suggesting that enhanced distributed channel access (EDCA) based channel access does not guarantee STA fairness. In contrast to IEEE 802.11ax, although there are differences in throughput among STAs and multiple BSS, fairness can be guaranteed to some extent in IEEE 802.11ax. We believe that the fairness of IEEE 802.11ax among STAs and multiple BSS can be further improved provided that more reasonable scheduling algorithms are designed.

(2) Performance analysis of multiple BSS in outdoor scenarios

Figures 11 and 12 show the respective performance of DL and UL throughput of multiple BSS in outdoor scenarios. There is a negligible difference between the performance of IEEE 802.11ax with SR and IEEE
802.11ax without SR; hence, adopting SR in outdoor scenarios does not bring performance gain. The distance between two adjacent BSS is too large, and the data frames received in adjacent BSS usually experience severe attenuation, leading to small inter-cell interference and difficulty in receiving data frames. Thus, it is challenging to use the OBSS_PD mechanism in outdoor scenarios. In addition, IEEE 802.11ax can still bring performance gain in outdoor scenarios, as the UL and DL throughput of IEEE 802.11ax increases to 127% and 117% compared to IEEE 802.11ac.

### 6 Conclusions

This article overviews the key technologies of IEEE 802.11ax. More importantly, the performance of IEEE 802.11ax are comprehensively evaluated via SLISP simulation platform. We highlight that SLISP is built by the authors and integrated both link-level and system-level simulation. Table 6 summarizes and compares some important simulation results; we set the performance of the IEEE 802.11ac to 100% in this table. The results indicate that IEEE 802.11ax satisfies the overall goal of significantly improving the user experience in high dense deployment scenarios, and achieves the single user throughput requirements of PAR, i.e., single user throughput needs to increase to four times compared to legacy IEEE 802.11. As far as we know, with regard to the performance requirements of IEEE 802.11ax, this article is the first to comprehensively and deeply evaluate the system performance of IEEE 802.11ax.

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### Table 6 Summary of performance evaluation results

| Single BSS scenario | Indoor (UL) | 20MHz saturation throughput | 80MHz saturation throughput | 160MHz saturation throughput | Outdoor (UL) | 20MHz saturation throughput | 80MHz saturation throughput | 160MHz saturation throughput | IEEE 802.11ac | IEEE 802.11ax with OFDMA | IEEE 802.11ax with OFDMA and MU-MIMO |
|---------------------|-------------|-----------------------------|----------------------------|-----------------------------|-------------|-----------------------------|-----------------------------|-----------------------------|--------------|--------------------------|-------------------------------------|
|                     | Indoor (UL) | 100%                        | 100%                       | 100%                        | Outdoor (UL)| 100%                        | 100%                       | 100%                        | 100%          | 130%                     | 171%                                               |
|                     | DL          | 100%                        | 140%                       | 206%                        | DL          | 100%                        | 127%                       | 127%                        | 100%          | 117%                     | 117%                                               |
|                     | UL          | 100%                        | 130%                       | 171%                        |             |                             |                             |                             |              |                          |                                                    |
|                     | DL          | 100%                        | 140%                       | 206%                        |             |                             |                             |                             |              |                          |                                                    |
References

1. Ericsson (2016) Ericsson mobility report: on the pulse of the networked society. Technical Report EAB-16:018498, Ericsson, Stockholm, Sweden
2. Cisco (2017) Cisco visual networking index: global mobile data traffic forecast update, 2016–2021 white paper. Technical Report Cisco white paper, Cisco, Jialefuniya, America
3. Afaqui MS, Garcia-Villegas E, Lopez-Aguilera E (2017) Ieee 802.11ax: Challenges and requirements for future high efficiency wifi. IEEE Wirel Commun 24(3):130–137
4. (2018) Wireless lan medium access control (mac) and physical layer (phy) specifications amendment 6: Enhancements for high efficiency wlan. IEEE Draft 802.11ax/D3.0,
5. IEEE (2014) 802.11 hew sg proposed par. doc. IEEE 802.11-14/0165r1, IEEE
6. Deng DJ, Chen KC, Cheng RS (2014) Ieee 802.11ax: Next generation wireless local area networks. In: 10th International Conference on Heterogeneous Networking for Quality, Reliability, Security and Robustness, pp 77–82
7. Li B, Qu Q, Yan Z, Yang M (2015) Survey on ofdma based mac protocols for the next generation wlan. In: 2015 IEEE Wireless Communications and Networking Conference Workshops (WCNCW), pp 131–135
8. Lin W, Li B, Yang M, Qu Q, Yan Z, Zuo X, Yang B (2016) Integrated link-system level simulation platform for the next generation wlan - iee 802.11ax. In: 2016 IEEE Global Communications Conference (GLOBECOM), pp 1–7
9. Sun W, Lee O, Shin Y, Kim S, Yang C, Kim H, Choi S (2014) Wi-fi could be much more. IEEE Commun Mag 52(11):22–29
10. Deng DJ, Lien SY, Lee J, Chen KC (2016) On quality-of-service provisioning in ieee 802.11ax wlans. IEEE Access 4:6086–6104
11. IEEE (2015) Tgax simulation scenarios. doc. IEEE 802.11-14/0980r16, IEEE
12. (2016) IEEE. 11ax evaluation methodology. doc. IEEE 802.11-14/0571r12, IEEE
13. IEEE (2014) Ieee 802.11ax channel model document. doc IEEE 802.11-14/0882r4
14. (2014) Status of ieee 802.11 hew study group high efficiency wlan (hew)
15. IEEE (2014) Ieee 802.11 hew sg proposed csd. doc IEEE 802.11-14/0169r1
16. (2017) Status of project ieee 802.11ax high efficiency (he) wireless lan task group
17. IEEE (2016) Specification framework for tgax. doc IEEE 802.11-15/0132R15 IEEE
18. IEEE (2015) Tgaxsimulation scenarios. doc IEEE 802.11-14/0980r16

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