世界无线局域网应用发展联盟
WLAN Application Alliance

WLAN Advanced User Experience Technologies Whitepaper

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（In no particular order）

Preface

About This White Paper

As the latest commercial WLAN technology, 802.11be provides a series of new features such as multiple links and multi-resource units. The increasingly mature intelligent technologies will bring opportunities to fully unleash the potential of air interfaces. At the same time, innovative scenarios and service applications such as cloud interaction, live streaming, and immersive reality are rapidly penetrating into all aspects of human production and life. Different from traditional WLAN services, frequent real-time human-machine interactions in the new service scenarios pose higher technical requirements on WLAN service bearing and experience assurance.

Providing technical capabilities that meet user experience requirements is key to the continuous prosperity of the WLAN ecosystem in the future. Therefore, to upgrade user experience, the current WLAN technologies are analyzed and reviewed based on new service scenarios to identify key challenges, propose solutions, and refine specific technologies and standards. This is a key measure to drive industry collaboration and achieve a positive ecosystem cycle.

This white paper discusses feasible measures, suggestions on standards, and action plans to enhance user experience based on the trend of WLAN development and AI-enabled inter-device collaboration. On this basis, the entire WLAN industry needs to work together to develop solutions to WLAN experience enhancement and support current and future service scenarios, to promote the continuous prosperity of the entire industry.

Contents

Chapter 1

Background and Motivation of WLAN Advanced Experience

1.1 Technical Requirements for Experience Assurance of New Services

WLAN has evolved through seven generations from 802.11a in 2000 to 802.11be today, with an average generation interval of about four years. Innovative technologies of each generation bring convenience to people's life and improve their work efficiency, and promote the rapid development of the WLAN industry. In the AI era, ICT-related innovative scenarios and services grow exponentially, and require stringent WLAN experience assurance. In this context, providing technical capabilities that meet user experience requirements is key to the continuous prosperity of the WLAN ecosystem in the future. This chapter mainly describes and analyzes new services such as cloud interaction, live streaming, and immersive reality applications and their technical requirements on networks, to tap into network requirements for service experience assurance.

Cloud interaction applications and experience requirements

With the development of digital twins, high-precision physical engines, and high-performance virtualization technologies, cloud gaming and cloud office desktops have gradually become cost-effective choices for homes and small- and medium-sized enterprises. For example, the recently popular game Black Myth: Wukong, with its refined image display and vivid physical experience, places players in the Journey to the West story world, and significantly drives up requirements for the performance of computer hardware. However, due to the high hardware costs (including GPU costs), many players choose to use cloud computers to enjoy the game. While the computer purchase cost is reduced, users have higher expectations for stable network latency and throughput.

Cloud desktop and gaming applications require that user instructions or game operations be sent to the cloud in real time, and images rendered on the cloud be transmitted to the users in real time. This process not only depends on the ultra-fast HD coding technology for shallow compression, but also requires low-latency and high-reliability network transmission. According to research, at a 4K display bit rate of 60 fps, the required transmission rate reaches about 300 Mbit/s, the desired WLAN latency is 10 ms, and the packet loss rate is required to be less than 0.1% [1, 2].

FIG.1 Diversified new services and application scenarios

Live streaming and experience requirements

In recent years, the live streaming services have gradually changed from single-anchor streaming to multi-anchor interactive streaming. New forms and new patterns, such as interacting with the audiences through microphones and virtual concerts, are emerging one after another. These new service forms make live streaming more interactive, and promote the continuous prosperity of the live streaming industry. From the technical perspective, the preceding service evolution changes live streaming from video and audio broadcast by a single anchor to multi-person real-time interaction at different locations. This development trend of the live streaming service poses stricter requirements on multi-party synchronization and end-to-end latency control. According to the evaluation, the end-to-end latency requirements corresponding to excellent, medium, and poor live streaming experience are 22 ms, 28 ms, and 55 ms [3], respectively. This means that the WLAN latency needs to be kept at 20 ms or lower to ensure premium experience.

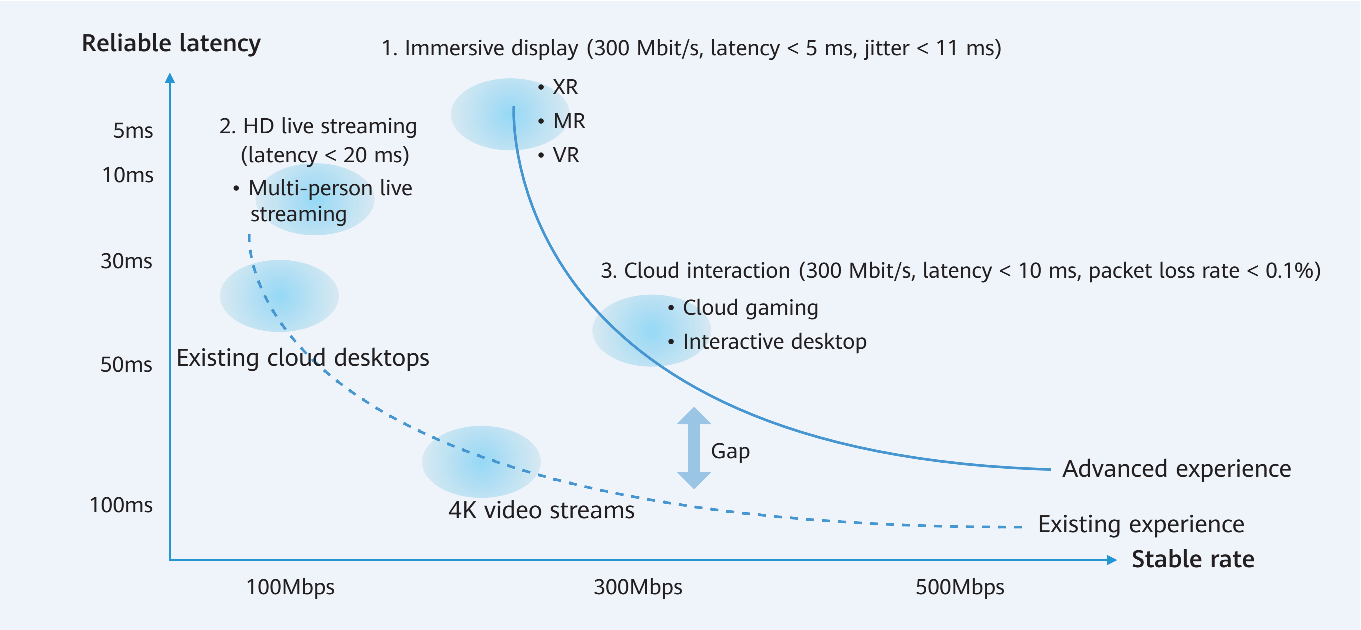
Immersive reality applications and experience requirements

Vision is the most direct way for humans to obtain massive information. Therefore, the visual service experience of a network has a direct impact on user's satisfaction on the network performance. Pioneering products such as head-mounted display in the AR/VR field also pose higher requirements on network experience. Apple Vision Pro is a representative product in this trend. Its binocular video reaches 4K or higher resolution and has a GPU whose rendering capability is equivalent to that of GTX 1660 for local visual rendering. Based on its information processing specifications, the required transmission rate is estimated at about 300 Mbit/s for a 4K 3D video stream at 90 fps. At the same time, the ideal latency and jitter must be less than 5 ms and 11 ms [4, 5] respectively, to achieve no dizziness.

1.2 Mapping Between Experience Requirements and Technical Requirements

For cloud gaming, in time-pressured adversarial games, if the data packets of key player operations are delayed or lost, win and lose may be even reversed. Frame freezing and erratic display also severely affect gaming experience. In cloud interaction applications, a data packet loss not only causes video resolution degradation or frame loss, but also annoys the users and affects the work and production efficiency. For VR visual services, the latency of data packets causes random lagging of visual images. Then, a serious misalignment occurs between the performed actions and the seen images, and consequently, the helmet wearers feel dizzy, severely affecting user experience. FIG. 2 compares the requirements of traditional and new services for reliable latency and stable rates. It can be seen that there are a large number of real-time human-machine interactions in various new application scenarios, and user intents or instructions need to be transmitted and responded in time through uplink channels. This is a key feature that the traditional services do not have. A reliable latency and stable rate are key to achieving ultimate experience in new services.

FIG. 2 Technical requirements for WLAN advanced experience



1.3 WLAN Network Capability Status and Improvement Objectives

Historically, the continuous upgrade of specifications of each device (each AP and STA) promotes WLAN evolution. From 802.11g to 802.11be, the channel bandwidth of each WLAN device increases from 20 MHz to 320 MHz, and the QAM order increases from 64 to 4096. After 802.11n starts to support multiple antennas, the standard MIMO specification increases from four streams to eight streams. While the channel bandwidth, number of MIMO streams, and modulation order increase continuously, OFDMA, MU-MIMO, and trigger-based mechanisms also make each device more flexible in terms of network access and scheduling. After 802.11ax optimizes the MAC efficiency-related mechanisms, 802.11be starts to support multiple links instead of a single link, improving the throughput and link robustness. However, this key technical innovation faces a series of challenges in compatibility, adaptation, and collaboration between APs and STAs in current market applications. It can be seen that the hardware upgrade of each WLAN device is difficult to bring experience gains. It is increasingly difficult to improve user experience only through the specifications upgrade.

However, new service scenarios and applications described in the preceding sections have clear technical requirements on the overall WLAN performance. Different from the traditional services, the new application scenarios have a large number of real-time human-machine interactions. Therefore, The technical idea of simply relying on data compression or early buffering to cope with the uncertainty caused by wireless channels will no longer work.

To cope with the preceding changes in service requirements, network-wide experience assurance has outweighed specifications of each device in WLAN evolution. In this context, this white paper defines the technical requirements for WLAN experience assurance in new service scenarios. Specifically, for different service requirements, WLAN air interface resources are guaranteed in terms of long-term stability and reasonable self-restraint for specific users or user groups in specific scenarios, to achieve a reliable throughput and latency. This definition serves as a basis for requirement analysis in WLAN evolution. The following sections will analyze the technical challenges and solutions for achieving network assurance objectives.

Chapter 2

Key Challenges and Overall Guideline

2.1 Technical Challenges

The wireless air interface is deeply coupled with the physical space and electromagnetic environment, resulting in highly uncertain transmission conditions. This is the root cause why it is difficult to guarantee high-quality human-machine interactions over wireless networks. More specifically, random changes in radio channels cause channel capacity fluctuations and changes in the best-matched transmission modes. Without sufficient instant feedback and a proper adaptive mechanism, the transmission rate of data packets in a selected mode may be higher than the channel capacity, causing data packet loss due to noise and interference, and further resulting in fluctuation and oscillation of throughput and latency of the entire communication link. As mentioned above, for the conventional video or data services, data compression and buffering solutions can basically shield the impact of random changes in an air interface channel on user experience without regard to fidelity and real-time performance. However, the preceding solutions are no longer effective for new services that require immersive and real-time interactions.

It should be further noted that, compared with a cellular network, the WLAN faces a more complex situation in air interface channels due to a distributed communication mechanism, compatibility and coexistence of multi-generation technologies, and access rules of unlicensed spectrums. For example, in WLAN unlicensed spectrums, a large quantity of non-coordinated APs usually contend for channels. Almost all APs face a risk that the channel has been occupied by another node and data of the APs cannot be transmitted. Therefore, urgent data packets usually need to wait for an unpredictable time before transmission.

The technical challenges faced by WLAN experience assurance need to be overcome through efficient collaboration among technologies, standards, and ecosystems.

2.2 Overall Guideline

Technical ideas:

Upgrade the WLAN communication gateway to WLAN communication AI agent.

Description:

According to the technical challenges described in section 2.1, the problem of poor WLAN communication experience can be further abstracted as a mathematical problem that multiple collaborative machine groups (APs and STAs) cannot fully perceive the external random environment and cannot perform large-scale parameter optimization and adaptive decision-making in a timely manner. More specifically, the conventional optimization methods used in a wireless communication system depend on long-time local statistics collection, with a long decision-making period and limited optimization approaches. Therefore, the conventional optimization methods cannot adapt to rapid changes in the traffic load and interference environment for unlicensed spectrums. Unlike traditional mechanisms, AI/ML can use information from more dimensions and prior knowledge for instant prediction and inference. Therefore, WLAN edge devices, such as APs and STAs, are upgraded from traditional communication NEs to WLAN communication AI agents to adapt to changing environments and support dynamic adjustment of various parameters, such as EDCA, MCS, GI, and CCA. This is a key approach to ensure WLAN advanced experience that requires long-term stability and reasonable self-restraint..

Further, the upgrade of the WLAN communication AI agents can achieve full perception and sharing of information at the environment, channel, and service layers, and enable coordinated scheduling (time-frequency-space multi-dimensional scheduling and cross-device association) between APs and STAs and between APs by means of AI. In this way, limited spectrums can be fully utilized, and channel randomness can be greatly reduced. Based on the preceding ideas, on the same WLAN network, information about the channels, load status, and services obtained by each device unit needs to be shared and merged on the entire network in a timely manner, so that the AI agents can make optimal collaborative decisions and execute instructions. Therefore, the WLAN industry requires a set of supplementary protocols that support information sharing and stricter authentication for compliance with specific existing protocols.

2.3 Design Principles

According to the preceding analysis, WLAN experience enhancement relies on the industry ecosystem to achieve premium experience at the minimum cost and ensure smooth technical evolution between generations. Therefore, its mechanism design and protocol formulation must comply with the following principles:

Based on 802.11be: According to the new features of the latest commercial WLAN, identify the function requirements for APs and STAs and the coordination requirements between APs, and between APs and STAs, and fully utilize new 802.11be features such as 4K-QAM, punctured transmission, multi-RU transmission, and multi-link operation.

Guided by 802.11bn: The 802.11bn standards are being designed for high-reliability networks, which mainly use the new physical layer of 802.11bn in combination with the MAC layer to increase the RvR, reduce the packet loss, and save energy. Its standards will be finished after 2027 and released in 2028. [6]. In terms of design ideas and specific solutions, it is extremely important to learn from the candidate technologies currently discussed in 802.11bn as much as possible.

AI-based intelligent decision-making: As a trend in the wireless technology field, AI can provide key enablement and optimization solutions for experience improvement. From the perspective of traditional technologies, services are diversified and the actual traffic characteristics are unpredictable, which poses great challenges to experience assurance. The WLAN protocol has undergone seven generations of evolution and supports various protocol tools. This means that there is a huge space for parameter optimization. Sufficient information needs to be provided for AI-based scheduling, roaming, energy conservation, and so on.

Chapter 3

Key Technologies and Suggestions for WLAN Experience Enhancement

As described in section 1.3, the assurance of advanced service experience needs to be implemented from two strategic directions: long-term stability and reasonable self-restraint. Essentially, WLAN access on shared channels involves multi-objective optimization, which considers not only the experience of local users, but also the common channel utilization efficiency and impact on the experience of other users. Traditional WLANs perform EDCA backoff to avoid CSMA collision events, which is a preliminary practice of the preceding design principles. Today's WLAN channel access has expanded from single-site time-domain behavior to multi-site frequency-domain and space-domain behavior. Trigger-based uplink access, multi-link, multi-RU, and spatial reuse (SR) all render more complex decision making. In today's intelligent network era, it is necessary to improve practices and make new attempts to improve service experience.

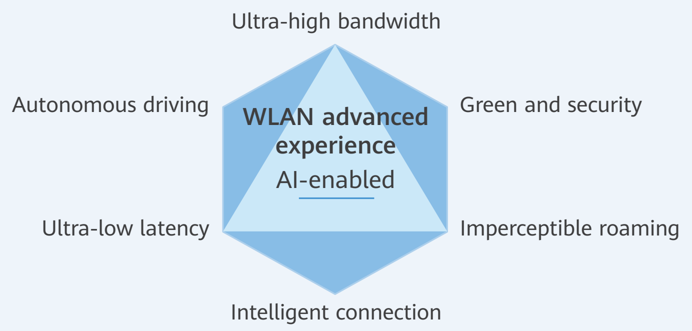
3.1 Definition and Interpretation of an Advanced Service Experience Hexagon

To better analyze technical problems and provide feasible technical suggestions, long-term stability and reasonable self-restraint must match with actual service experience in different dimensions, and the related approaches should be aligned. In the Home Service Experience Classification White Paper released by the Broadband Development Alliance, the service experience is analyzed from the following six dimensions: ultra-high bandwidth, ultra-low latency, imperceptible roaming, intelligent connection, green and security, and autonomous driving [7]. Based on these six dimensions, this white paper defines a WLAN advanced experience hexagon (see FIG. 3). The following describes the figure in detail.

The long-term stability policy aims to improve personal experience. Specifically, it ensures that users can obtain good service experience anytime and anywhere under network coverage, avoiding experience deterioration. On a wireless network, extensive coverage is the prerequisite for ensuring smooth experience. On this basis, we need to focus on roaming experience. Specifically, after multiple APs provide continuous coverage, smooth switchover between multiple APs can be achieved to ensure seamless roaming for the users based on predictable decisions and suggestions. On the other hand, for real-time interactive services, reliable bandwidth and latency need to be guaranteed. In the case of time-varying multipath, interference, and congestion, multiple generations of devices coexist on the same network, and a highly reliable bandwidth and latency become extremely challenging. Therefore, long-term stability is closely related to an ultra-high bandwidth, ultra-low latency, and imperceptible roaming. This means that for specific users (groups), the WLAN must meet requirements in the preceding three dimensions in real time based on the quantitative evaluation of specific service scenarios.

The reasonable self-restraint policy aims to strike a balance between concurrency and energy efficiency through network control and node contention. Excessive concurrency will cause severe mutual interference, resulting in rate degradation and packet loss. An excessive increase in transmit power will have similar results, and will also cause WLAN mobile devices to consume battery quickly. Intelligent connection and scheduling in networking are the key to improving energy efficiency. For example, the multi-link capability of 802.11be can be used to intelligently coordinate transmission on different channels through MLO on the 5 GHz high and low frequency band. This avoids concurrent contention on the 2.4 GHz high-interference frequency band and improves the energy efficiency. Further, MRUs can also bypass interfering sub-channels, to implement conflict-free transmission. In addition, full perception and understanding of the environment is the key for WLAN O&M to achieve "automation, self-optimization, and self-healing" in autonomous driving. Therefore, reasonable self-restraint matches the following three dimensions: "intelligent connection", "green and security", and "autonomous driving". From the perspective of the definition and working principles of AI agents, the two optimization directions of improving personal experience and enabling environmental friendliness are integrated. Timely and full comprehension of the external environment can help strike a balance between the multi-dimensional objectives. To ensure both personal experience and environment friendliness, an optimal balance needs to be achieved among people, machines, and environment. Intelligent connection is the link between long-term stability (experience improvement) and reasonable self-restraint (environmental friendliness). That is, on the premise of ensuring personal experience, intelligent connection implements network-wide online efficient O&M (autonomous driving), environment-adaptive energy saving, and security risk mitigation (green and security).

FIG. 3 Definition of a WLAN advanced experience hexagon

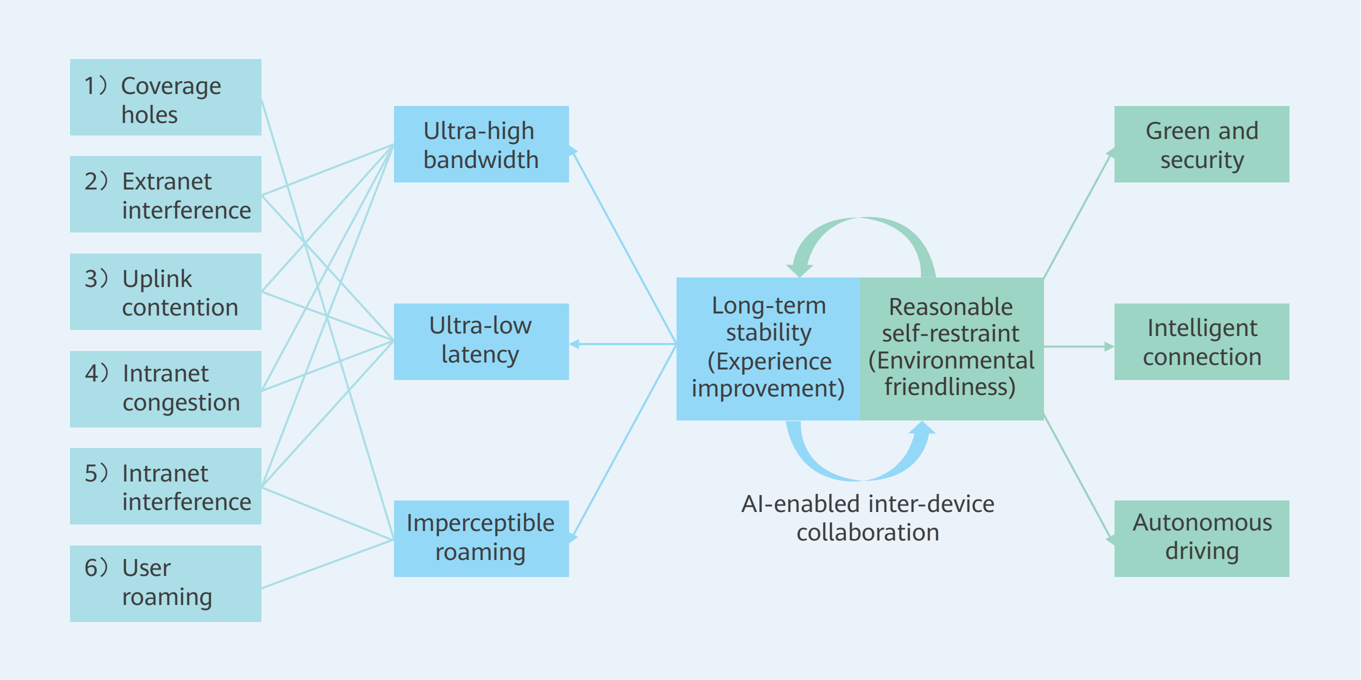


3.2 Root Causes and Feasible Solutions for Experience Issues

As described in section 2.1, the wireless air interface is deeply coupled with the physical space and electromagnetic environment, resulting in highly uncertain transmission conditions. This is the root cause why it is difficult to guarantee high-quality human-machine interactions over wireless networks. Based on the technical characteristics of WLAN networks, the preceding technical root cause involves the following six issues: (1) coverage holes; (2) external interference, (3) uplink contention; (4) intranet congestion; (5) intranet interference, and (6) user roaming. FIG. 4 shows the mapping relationship between the six issues and the experience hexagon defined above. In brief, all or some of the six technical issues together make it difficult to improve user experience from three dimensions and enable environmental friendliness from the other three dimensions.

The following sections will describe the six technical issues separately, and provide more specific technical measures and suggestions on standards based on AI-enabled inter-device collaboration mentioned in section 2.2.

FIG. 4 Mapping between WLAN advanced experience objectives and technical challenges



3.2.1 Problem 1: Coverage Holes

Description

Currently, poor signal quality and service freezing are mainly caused by insufficient coverage, specifically, insufficient downlink and uplink coverage. Compared with STAs, WLAN APs have more antennas and better power amplifiers. A downlink coverage area of the APs is usually greater than an uplink coverage area of the STAs. Therefore, the problem of insufficient uplink coverage is more obvious. Once uplink data sent by a user is lost, or the APs cannot receive acknowledgments or other responses from the STAs, queue transmission is suspended.

In terms of standard protocols, this problem has always attracted attention from WLAN standard makers and has been continuously mitigated in 802.11ax/be/bn generations by technical solutions such as the HE ER SU PPDU format, EHT DUP transmission mode, and ELR mode. The EHT DUP mode has low spectral efficiency and is only an optional mode in the 6 GHz frequency band. In terms of hardware design, increasing the transmit power of the APs or STAs is a simple method to expand the coverage. However, it is difficult to increase the power by much due to physical limits, and a higher power also causes severe interference and reduces spectrum resource utilization.

Suggested countermeasures

Multiple APs can be networked to implement indoor coverage in the target areas, shortening the distance between a STA and the associated AP. In this way, the link loss is reduced, improving the overall SINR in the target coverage areas. This lays a foundation for fully utilizing key 802.11be technologies, such as 4K-QAM and MLO, and improves spectrum resource utilization. Further, network and service status information is shared between the APs and STAs to a maximum extent, to support intelligent and dynamic networking and scheduling. In this way, conflicts caused by random channel access can be effectively alleviated, improving communication experience.

3.2.2 Problem 2: External Interference

Description

Because a basic WLAN communication mechanism shares spectrum resources and supports free contention, several WLAN devices usually coexist in actual service scenarios, inevitably causing mutual interference. The characteristics of the interference can be depicted in the following dimensions: the frequency domain, power domain, time domain, number of interference sources, and channel fluctuation. Common interference is usually caused by a random combination of these dimensions.

Frequency domain: mainly refers to a relative relationship between the frequency of interference signals and that of test signals on a spectrum, and generally results in WLAN interference and non-WLAN interference. The WLAN interference is classified into co-channel interference, overlapping-channel interference, and adjacent-channel interference.

Power domain: mainly refers to the energy strength (RSSI strength) of interference signals received by a receiver. Generally, the larger the interference energy, the greater the impact.

Time domain: mainly refers the proportion (the proportion of timeslots with interference ranges from 1% to 100%) of air interfaces occupied by interference signals in the time dimension and the duration of a single interference packet transmission. Generally, the larger the proportion of timeslots with interference, the greater the impact on performance.

Number of interference sources: mainly refers to a total quantity (0, 2, 20, or 128) of WLAN devices that coexist near a working AP. Generally, a larger quantity of devices results in greater impact on performance.

Channel fluctuation: refers to the fluctuation of signal transmission paths caused by dynamic changes of obstacles in the working environment. For example, a person passes between an AP and a STA. Generally, a larger and faster channel change results in a greater impact on performance.

Suggested countermeasures

Coordination between APs and STAs: As mentioned above, common interference in home scenarios usually comes from several dimensions. The interference characteristics cannot be accurately identified by a single AP. As a result, it is difficult to accurately and instantly obtain an optimal avoidance policy. In the case of device-pipe synergy between an AP and a STA, the STA feeds back locally identified interference characteristics, which help the AP identify the interference characteristics and mitigate the interference. In particular, a STA notifies the AP of the interference from a BSS, so that AI is enabled to perform scenario identification and inference and give specific execution instructions. For example, a channel with interference can be bypassed through multi-RU transmission, or the interference at the network edge is reduced by adjusting the working channel and transmit power in a multi-vendor scenario.

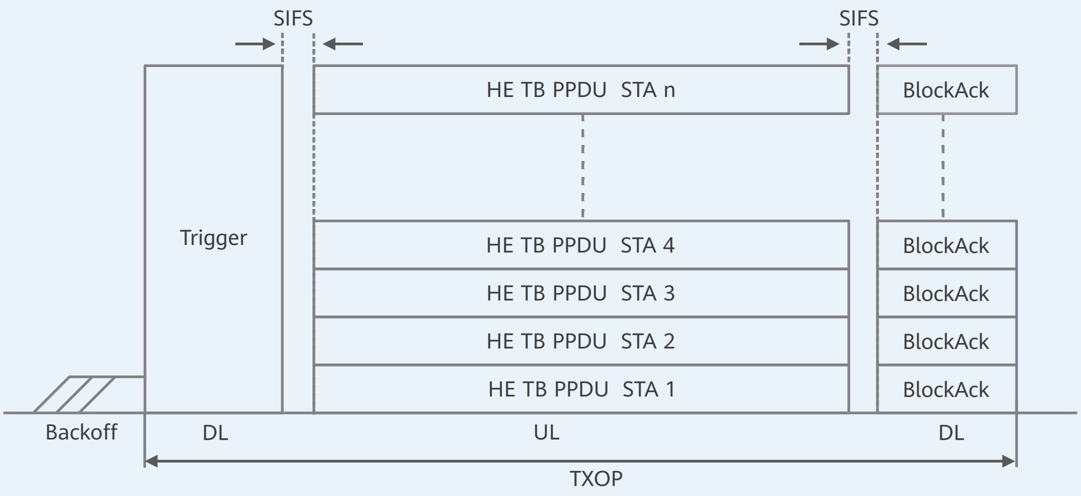
Proper utilization of multi-band resources: Based on the interference difference on multiple channels or frequency bands, channels with strong interference are avoided through the MLO technology of 802.11be. For example, 5 GHz high and low frequency bands are introduced to avoid 2.4 GHz interference. It should be noted that the device-pipe synergy solution between APs and STAs is the prerequisite for effective execution of this guideline.

3.2.3 Problem 3: Uplink Contention

Description

Multiple terminals on a WLAN randomly contend through the CSMA/CA mechanism for sending service data. This may bring the following impacts: (1) If uplink services with high real-time performance are delayed, service experience is affected. For example, operation delay and frame freezing occur in real-time gaming. (2) For TCP high-bandwidth services, the RTT latency fluctuates greatly, triggering TCP flow control on the server and affecting the overall TCP service performance.

FIG. 5 UL trigger mechanism introduced in 802.11ax



Source: IEEE 802.11ax Figure 10-14b

As shown in FIG. 5, the UL trigger mechanism introduced in IEEE 802.11ax enables the gateway to actively schedule STAs to send uplink data, effectively alleviating the foregoing problems caused by free uplink contention. However, the following challenges still exist:

- The UL trigger mechanism is not always available to APs. Specifically, a trigger frame sent by an AP has overheads. If the AP triggers a STA that has no data to be sent, network resources are wasted, reducing the efficiency of the entire network. With the BSR mechanism, a user can report the buffer information to the AP, so that the AP can use the UL trigger mechanism in a targeted manner. Unfortunately, the BSR is optional and not supported by all terminals.
- The MU-EDCA parameter mechanism used in combination with the UL trigger mechanism can manage uplinks of multiple users, and is optional in IEEE 802.11ax. Some terminals do not support the MU-EDCA parameter mechanism, limiting the use of the UL trigger mechanism.

Suggested countermeasures

The MU-EDCA parameter mechanism is introduced in IEEE 802.11ax to manage the uplinks of multiple users and the terminal buffer status reported by the BSR. The R-TWT mechanism is introduced in IEEE 802.11be to implement reasonable scheduling for uplink channel contention. In terms of uplink access, it is recommended that authentication be enhanced to improve the compliance with uplink collaboration protocols.

3.2.4 Problem 4: Intranet Congestion

Description

In a WLAN network, multiple users and services usually access the network at the same time. When multiple services coexist in the BSS, background services without rate limitation may occupy too much bandwidth, which affects the transmission of latency-sensitive services. If a STA can accurately notify the AP of network requirements for carrying services, the transmission resources can be properly allocated by using the AP scheduling algorithm based on the service requirements. When the link of an AP is overloaded and cannot meet user requirements, collaborative interaction between multiple links of APs, between multiple APs, and between the APs and STAs can be used to direct users to a different link of the APs or different APs for access, ensuring service continuity. In particular, AI is used to continuously learn the service characteristics and trends of STAs, improving the accuracy of accessing different radios by the STAs and improving the network experience of the two types of STAs.

Suggested countermeasures

The STAs report the service experience to the APs to ensure on-demand resource allocation using an intelligent scheduling algorithm. By adding a feedback step in the foregoing transmission process, AI can continually learn and optimize user experience in the case of service congestion.

3.2.5 Problem 5: Intranet Interference

Description

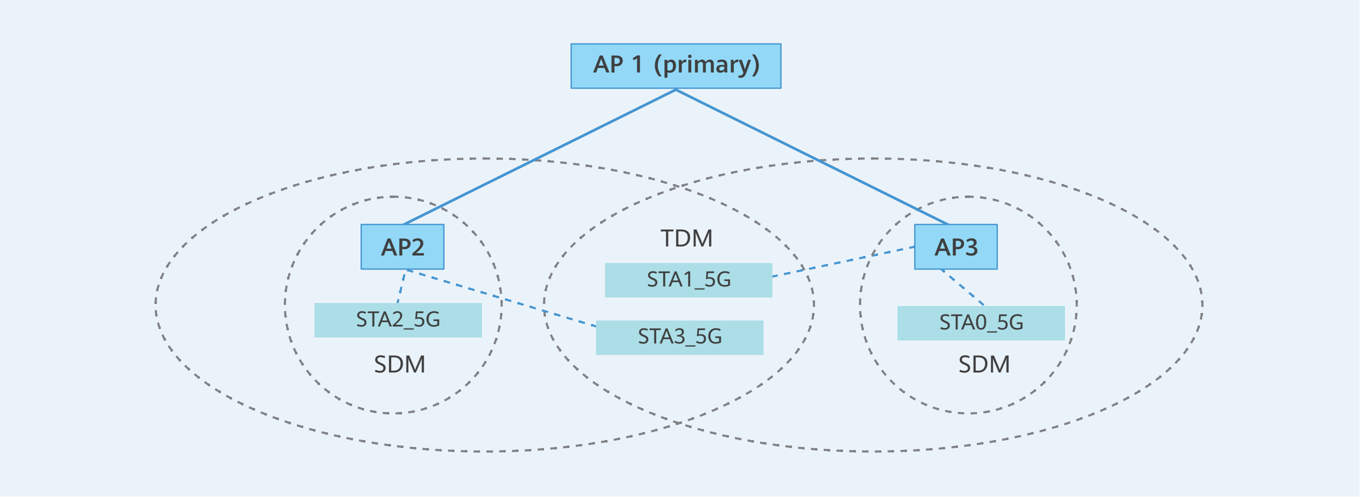
Intranet interference refers to concurrent interference between multiple BSSs in an ESS. On the premise of solving the coverage problem through networking, intranet interference becomes a technical problem that needs to be further solved. To meet the throughput and latency requirements of various new services described in chapter 1, it is necessary to use 80 MHz or higher spectrum resources for transmission. This makes intranet interference more prominent. For example, in a home scenario (see FIG. 6), concurrent high-throughput or interaction-intensive services in multiple rooms generate strong intranet interference, and further cause collisions. Especially for STAs located in the critical area between several hotspots, the throughput and latency severely deteriorate. Theoretically, allocation of more spectrum resources can effectively alleviate this problem. However, in reality, wireless spectrum resources are limited and regulated by different countries and regions. In addition, frequency bands supported by various STAs are not unified.

FIG. 6 Intranet interference in critical areas in typical home scenarios

Suggested countermeasures

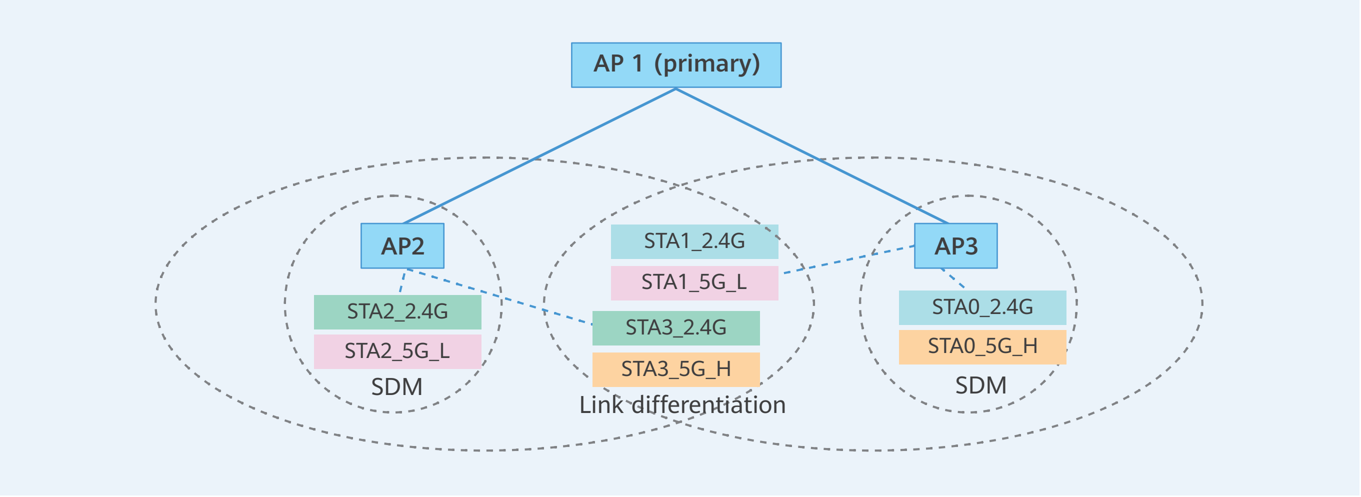
Coordinated spatial multiplexing (C-SR): The industry started research on throughput concurrency and service assurance in networking scenarios many years ago. From SR in 802.11ax to C-SR in the 802.11bn standard proposal, a controller collaborates with multiple hotspot APs of different transmit power to support parallel transmission at the same time over the same frequency. In this way, a higher throughput can be achieved and queuing latency can be reduced. However, because the SINR is relatively low in interference areas, time division multiplexing (TDM) (see FIG. 7) must be used. In addition, due to uplink contention of STAs, interferences and conflicts still occur at the air interfaces.

FIG. 7 SDM and TDM in intranet interference scenarios



MLO collaboration technology (C-MLO): 802.11be allows a controller to collaborate with APs in different rooms. By dynamically using different link channels, STAs in the critical area can transmit and receive data without interference. The 2.4 GHz spectrum resources total up to only 40 MHz, and have severe interference, failing to carry bandwidth-hungry services. Therefore, a combination of 5 GHz high and low frequency bands is used for different STAs in the critical area, as shown in FIG. 8. This helps to make full use of the advantages of the 802.11be multi-link technology, and is consistent with the solution to the extranet interference in section 3.2.2.

FIG. 8 SDM and multi-link differentiation in intranet interference scenarios



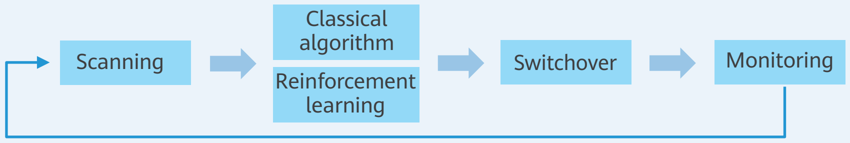
MRU collaboration technology (C-MRU): A controller dynamically allocates MRU resources to multiple APs. (1) When a STA requires high bandwidth (for example, multiple users watch HD videos at the same time), APs collaborate with each other to select appropriate channels for bundling and determine the puncturing policy based on the channel quality. For example, if there are multiple STAs that require high bandwidth in coverage areas of AP 1 and AP 2, the two APs analyze the channel conditions in their respective coverage areas and select continuous channels with less interference for bundling to form a larger-bandwidth MRU. In addition, channels are punctured based on a real-time interference to improve the coding rate and meet service requirements. (2) To reduce the interference, APs collaborate with each other to adjust MRU resource allocation. The APs continuously monitor the channel quality, such as movement or disappearance of an interference source and signal strength, and then optimize MRU resource allocation in real time based on the changes. If an interference source disappears, the MRU resource originally assigned to mitigate the interference is re-evaluated and may be released for better allocation, improving the spectral efficiency.

3.2.6 Problem 6: User Roaming

Description

When a STA moves to an area with weak AP signals, it may be disconnected from the AP, causing poor roaming experience. Network disconnection severely affects user experience in voice, video and other services. Users usually move to the network edge in roaming scenarios, and may experience weak signals and unsmooth switchover. 802.11be needs to determine not only the new AP to which a STA needs to be connected, but also links of the new AP to which the STA is connected. Theoretically, if the SINR of a STA deteriorates (when users go far away from the AP or due to interference) or the air interface resources that the STA can obtain are insufficient (other STAs or APs preempt air interface resources and cause severe channel contention), service requirements cannot be met. Therefore, a switchover needs to be performed (switching to a nearby AP or a new frequency band, or both).

FIG. 9 Roaming experience improvement solution combining classical and AI algorithms



State

Statistics on air interfaces and services, and KPI results after switchover

	Primary RSSI	AP1 Rssi	AP2 RSSI	Interference ratio	Packet loss rate	Throughput	RTT latency
STA1	-73	-55	-65	15%	5%	230M	80ms

Action

Switchover probability:

	Remain unchanged	Switch to AP 1	Switch to AP 2
STA1	0.05	0.8	0.15

Reward Modify actions to maximize KPIs (PER, throughput, and latency)

Suggested countermeasures

In this context, the following two measures are recommended:

1）With the MLO feature of 802.11be, an optimal link is automatically selected for transmission during movement, ensuring user experience during roaming.

2）As shown in FIG. 9, an AI-based enhanced learning algorithm is used to train the data by taking the KPIs (packet loss, throughput, and latency) during roaming as feedback, to obtain the optimal roaming frequency and switchover policy for each STA and each site.

The roaming feedback is especially important for forming a closed-loop mechanism. It can be used to comprehensively evaluate the signal strength, interference level, load level, and protocol capability between old and new APs. The connection to a target roaming object is accurately predicted based on the classic algorithm or deep learning algorithm, ensuring that the roaming decision meets the expected requirements.

3.3 Suggestions on Standard Protocols

In view of the preceding problems, the following suggestions are provided for device interaction protocols:

1）To solve the uplink contention problem, the uplink scheduling mechanism needs to be further improved, and authentication needs to be enhanced for compliance with the MU-EDCA and BSR mechanisms, so that the WLAN changes from disordered contention to orderly and controlled transmission and reception.

2）To solve the network congestion, the collaboration between the gateway and mobile phones and that between the WLAN and upper-layer services need to be strengthened, so that the gateway can allocate network resources more properly based on service experience requirements.

3）To suppress the intranet and extranet interference, co-authentication of various 802.11k measurement frames needs to be enhanced, including beacon request measurement and frame measurement. In addition, the measurement and report content are optimized to achieve more accurate and efficient interference measurement.

4）By using other network-end collaboration technologies, including network-end service quality collaboration and roaming collaboration [8,9], and by information sharing with the telecom network and timely feedback, service types can be identified and poor-QoE can be monitored, significantly improving WLAN user experience.

Chapter 4

Summary and Prospect

New services, such as cloud interactive operations, live streaming, and immersive reality applications, involve a large number of real-time human-machine interactions. User intents or instructions need to be transmitted through upstream channels and responded in a timely manner. Therefore, WLAN advanced experience technologies are required to provide more reliable service quality. To address the six key problems that affect user experience, AI is applied in a WLAN to achieve orderly and efficient uplink access, support high-bandwidth concurrent transmission, and effectively suppress the interference. It is a key measure to improve service experience and quality in a multi-service, multi-user, and multi-AP system.

The entire WLAN industry needs to cooperate to make full use of the flexible tools and scalability provided by existing protocols, define the optimal interface standards for applications, and take steps to build networks with WLAN advanced user experience, thereby promoting smooth upgrade and continuous prosperity of the WLAN industry.

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A Glossary

Acronym	Full name
AI/ML	Artificial Intelligence/ Machine Learning
AP	Access Point
AR/VR	Augmented Reality / Virtual Reality
BSS	Basic Service Set
CCA	Clear Channel Assessment
CSMA/CA	Carrier-Sense Multiple Access with Collision Avoidance
C-SR	Coordinated Spatial Reuse
C-MLO	Coordinated Multi-Link Operation
ELR	Extended Long Range
EHT DUP	Extremely High Throughput Duplicated
EDCA	Enhanced Distributed Channel Access
GPU	Graphic Processing Unit
GI	Guard Interval
HE ER SU PPDU	High-Efficient Extended Range Single User PPDU

ICT	Information and Communications Technology
MIMO	Multiple-Input and Multiple-Output
MU-MIMO	Multi-User Multiple-Input Multiple-Output
Multi-RU	Multiple Resource Unit
MCS	Modulation and Coding Scheme
MAC	Medium Access Control
MU-EDCA	Multi-User Enhanced Distributed Channel Access
MLO	Multi-Link Operation
OFDMA	Orthogonal Frequency-Division Multiple Access
PPDU	Physical layer convergence procedure Protocol Data Unit
QAM	Quadrature Amplitude Modulation
RU	Resource Unit
RvR	Rate verses Range
RSSI	Received Signal Strength Indication
STA	Station
SR	Spatial Reuse
SCS	Stream Classification Service
SINR	Signal to Interference plus Noise Ratio
UL Trigger	Up-Link Trigger
WLAN	Wireless Local Area Network

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