Abstract—With dramatically increased data traffic, the traditional low-frequency (LF) wireless local area networks (WLAN) are facing several difficulties, particularly limited available spectrum resources and low network efficiency. While the use of millimeter-wave (mmWave) could bring more spectrum, WLAN in high-frequency (HF) suffers poor reliability. In addition, the current distributed WLAN architecture and the coupled data and control planes lead to inefficient management and poor performance with increased network scale, which cannot meet the stringent requirements from diverse applications. In overcoming these difficulties, the control plane and data plane decoupled network architecture and sub-6GHz and mmWave dual-band cooperation are considered to be the critical solutions to improve the system performance in 5th-Generation (5G) and beyond networks. Therefore, to improve the throughput and reliability of the future WLAN, we propose a control plane and data plane decoupled WLAN architecture in this paper that supports both sub-6GHz and mmWave based on the existing control plane and data plane decoupled WLAN concept. Furthermore, new multi-beam transmission and sub-6GHz and mmWave dual-band cooperation mechanisms are developed to improve the throughput and reliability in our proposed WLAN architecture. Performance analysis and simulation show that with the multi-beam transmission and sub-6GHz and mmWave dual-band cooperation mechanisms in our proposed WLAN architecture, throughput and reliability are both significantly improved when compared with the traditional distributed WLAN architecture and operation mechanism.

Index Terms—WLAN, sub-6GHz, mmWave, control and data plane, multi-beam transmission.

I. INTRODUCTION

The evolution of wireless communications is a process of continuously pursuing higher data rate and higher reliability [1]. However, the traditional low-frequency (LF) band spectrum resources (e.g., sub-6GHz) are limited, since it is almost impossible to allocate new spectrum resources in the licensed band, and the unlicensed band (e.g., 2.4GHz and 5GHz) is also becoming more and more crowded, which restricts the future wireless communication systems to achieve higher data rate and higher reliability [1]–[4]. In recent years, millimeter-wave (mmWave) communication has become one of the most promising technologies for both the forthcoming 5th-Generation (5G) and the future generation wireless local area networks (WLANs, e.g., IEEE 802.11ad and 802.11ay) because of its huge available spectrum resources in the high-frequency (HF) mmWave band (i.e., 30GHz ~ 300GHz) [1], [5]. The U.S. Federal Communications Commission (FCC) recently opened up 3.85GHz licensed spectrum and 7GHz unlicensed spectrum in 28GHz, 37GHz, 39GHz and 64GHz ~ 71GHz for the future mmWave communication systems [6]. Meanwhile, the Ministry of Industry and Information Technology of China has approved 24.25GHz ~ 27.5GHz and 37GHz ~ 42.5GHz for the mmWave communication experimental frequency band of 5G in China [7]. These recent developments have laid an important foundation for the research of future ultra-high-speed wireless communication technologies, and will further accelerate the development of the future mmWave communication industries.

Although mmWave band can achieve ultra-high-speed transmission with large available spectrum resources, it faces severe path loss and penetration loss, which greatly limit the communication range [1]. In order to realize long-distance communications in mmWave band, beamforming enabled directional transmission is indispensable since it can significantly improve the mmWave link quality and transmission distance by concentrating the transmitting signal power and receiving region into a narrow beam [1], [5]. However, highly directional communications in mmWave band cannot provide ideal signal coverage with narrow beams. To alleviate this problem, intelligent beam management mechanisms [8]–[10], dense deployment strategies of mmWave base stations (BS) [10]–[14] and sub-6GHz and mmWave dual-band cooperation (also called “HF & LF cooperation” in this paper) technologies [15]–[17] have been studied.

Aiming at the problem of beam misalignment caused by user mobility in mmWave networks, we proposed some efficient and intelligent beam management mechanisms in [8] and [9], which can significantly improve the reliability of mmWave communications. However, some other problems still exist. For example, the dense deployment of mmWave BSs will cause serious interference [10], [13], then the additional...
increment of network capacity by means of densely deploying access points (APs) is limited [14]. Therefore, Zhao et al. in [14] proposed a combined design of density of APs and partially overlapped channel allocation to achieve capacity optimization. Then they derived that the optimal density of APs lies in the feasible region consisting of the lower bound and upper bound density. Gao et al. in [18] proposed a contention intensity-based distributed coordination (CIDC) scheme for safety message broadcast. It can achieve both a much lower collision probability and a smaller contention delay compared with the solution in 802.11p, since CIDC can select the initial back-off counter for each new packet based on the contention intensity, rather than randomly.

In addition, recent studies have shown that the centralized control network architecture can utilize global information gathering and network control capabilities to achieve global radio resource management and network optimization with the help of Access Controller (AC) [10], [13], [19], [20]. For example, Zhou et al. in [13] mentioned that the conventional uplink-downlink configuration change in the existing dynamic Time Division Duplexing (TDD) method of 5G ultra-dense networks (UDN) is prone to repeated congestion. Then, they developed a deep Long Short-Term Memory (LSTM) learning technique to achieve localized prediction of the traffic load at the UDN BSs, and thus the proposed algorithm can execute the appropriate action policy a priori to avoid/ameliorate the congestion in an intelligent fashion. Furthermore, in Long Term Evolution (LTE) and 5G-based cellular communication systems, the concept of heterogeneous network that is composed of an LF macrocell BS and multiple HF mmWave BSs has been widely adopted and studied by the academia and industry. Through the centralized control network architecture, all the mmWave BSs can be managed and controlled by the macrocell BS, thereby the optimal performance can be achieved through global radio resource allocation mechanisms [21]. However, in WLAN, the system performance will become relatively low when APs are densely deployed [14], [22]–[24], since all the APs will spontaneously occupy the channel in the distributed network architecture, and thus the interference becomes extremely severe. Therefore, to improve the performance of densely deployed WLANs, centralized control WLAN architecture is urgently needed [10], [25]–[27]. In [10], we proposed a centralized control architecture in dense mmWave WLAN, then the sum-rate can be significantly improved by running our proposed deep learning-based beam management and interference coordination algorithm at the central controller (i.e., AC). However, this network architecture just considered a scenario with one central control AP (e.g., Master AP) to control other Slave APs through directional mmWave beams, which cannot provide enough extensibility to achieve efficient network management. To improve the extensibility and flexibility of WLAN, the concept of software defined network (SDN) was introduced into WLAN [25]–[27]. Zhao et al. in [25] proposed an SDN-based WLAN (SDWLAN) to support flexible and fine-grained control over enterprise WLAN. Simulation results demonstrated that AP handover operation in SDWLAN leads to negligible throughput fluctuation of the on-going connection compared to the traditional architecture with IEEE 802.11 standard handover mechanism. Dezfouli et al. in [26] conducted a comprehensive review of software-defined WLANs from the architecture and central control mechanism aspects. In addition, Gallo et al. in [27] proposed a control architecture for efficient management of dense WLAN access networks (CADWAN) to address the challenges of high-density deployments. CADWAN can separate the control plane and data plane so that the data path completely remains at the APs, while only the data path parameters that the AC has requested to monitor are forwarded to the global controller. Moreover, the decoupling of the control plane and data plane has a significant advantage in railway wireless networks [28], [29]. Because the relatively important passenger services can be kept on the control plane to handle mobility, while the corresponding data plane can be used to achieve higher throughput.

Although the above studies have developed some efficient management schemes for dense networks, most of them are focused on the traditional LF networks. Considering that the future WLAN will be multi-band (e.g., support 2.4GHz, 5GHz and 60GHz) capable [17], it is necessary to study the WLAN based on HF & LF cooperation to take full advantages of both the HF and the LF. Meanwhile, according to the centralized control architecture and the control plane and data plane decoupled WLAN architecture that are discussed above, we propose a control plane and data plane decoupled WLAN architecture that supports both the HF and the LF. In our proposed WLAN architecture, there is an AC that controls all the APs and stations (STAs) within its coverage through the control plane in the LF, because it can provide better support for users’ mobility and reduce the control plane’s handover probability, etc. [28], [29]. Each AP provides mmWave communication services for the STAs within its directional beams’ coverage through the data plane in the HF. Therefore, when the data plane is interrupted, the control plane can be still maintained for the connection. And the control plane can assist the recovery of the data plane, thus improving the reliability of mmWave communications. In addition, in dense mmWave networks, an STA can receive signals from multiple surrounding APs. Therefore, in our proposed control plane and data plane decoupled WLAN architecture, we propose a multi-beam transmission mechanism in which multiple APs can jointly provide mmWave communication services for an STA simultaneously. This mechanism can improve both throughput and reliability, since the probability of simultaneous interruption of directional beams from multiple APs is significantly lower than that of the single-beam communications. In summary, the contributions of this paper are listed as follows:

1) We propose a control plane and data plane decoupled WLAN architecture that supports both the LF and the HF, where AC controls all the APs and STAs through the control plane in the LF and each AP provides mmWave communication services for STAs through the data plane in the HF.

2) A multi-beam transmission mechanism is designed for our proposed control plane and data plane decoupled WLAN architecture, in which directional beams from
multiple APs can serve an STA concurrently to improve the throughput and reliability of mmWave communications.

3) An HF & LF cooperation mechanism is designed for our proposed control plane and data plane decoupled WLAN architecture to further enhance the reliability of mmWave communications.

The remainder of this paper is organized as follows. In Section II, we describe our proposed control plane and data plane decoupled WLAN architecture. In Section III, we present the mathematical models. Then, Section IV introduces our proposed multi-beam transmission mechanism and HF & LF cooperation mechanism for control plane and data plane decoupled WLAN. Next, Section V shows the performance evaluation and simulation. Finally, Section VI concludes this paper.

II. CONTROL PLANE AND DATA PLANE DECOUpled WLAN ARCHITECTURE

For the traditional WLAN architecture, all the APs work in a distributed manner. Meanwhile, each STA chooses an AP for association, and then carries out data transmission under the control of this AP. Fig. 1 shows the logic view of the traditional LF WLAN and HF WLAN architectures. It can be seen that each AP and STA has complete medium access control layer protocol (MAC) and physical layer protocol (PHY). There is no explicit concept of control plane and data plane in both logical and physical channels. For example, in the traditional IEEE 802.11 protocol-based WLAN, when an STA has data to be transmitted to its AP, the STA will first transmit an Request-To-Send (RTS) frame to the AP. After the AP responds a Clear-To-Send (CTS) frame to the STA, the STA starts transmitting data to the AP, and then the AP feeds back an Acknowledgement (Ack) frame to the STA. In the above processes, RTS, CTS and Ack frames are control messages (i.e., “control frame” and “management frame” in the IEEE 802.11 protocol). However, data belong to “data frame” in the IEEE 802.11 protocol. All the control messages and data frames are coupled to be transmitted in the same physical channel. In addition, control messages are usually transmitted under the lowest modulation and coding scheme (MCS, i.e., MCS0), and the transmission of control messages will suspend the transmission of data frames. This will result in throughput reduction, which will be even worse in the HF WLAN. Moreover, when WLANs are densely deployed in dense user scenarios (e.g., stadium and airport), the coupling of control messages and data frames is not conducive to the deployment and design of efficient centralized control WLAN architecture. With the aggravation of user competition conflicts, the system performance of the traditional distributed WLAN will become worse.

Centralized network architecture with control plane and data plane decoupling is widely adopted in the advanced mobile communication systems (e.g., LTE and 5G), because it can flexibly utilize the global information to achieve optimal radio resource management and network optimization. Moreover, the decoupling of the control plane and the data plane can easily facilitate the network management and mobility management [28], [29]. In view of the aforementioned shortcomings of the traditional WLAN architecture, and considering that the future WLAN is multi-band capable [17], to make full use of this feature, this paper proposes a centralized WLAN architecture that supports both the HF and the LF. As shown in Fig. 2, APs no longer work independently in this architecture, while they are controlled and managed by the AC. Each AP provides mmWave communication services for STAs. This centralized network architecture is conducive to achieving better radio resource management and network optimization [10]. In addition, to better distinguish AC’s management task from APs’ data transmission tasks, the concept of control plane and data plane, which are similar to that of the advanced mobile communication systems [26], [27], are also introduced into our proposed control plane and data plane decoupled WLAN architecture. Since the data transmission between AP and STA is managed and scheduled by AC, the control plane can be separated to AC, and then the data plane can be kept at the AP side. Therefore, the decoupling between control plane and data plane is realized. Similar to the concept of control plane and data plane decoupling in [26] and [27], we can define the data plane and the control plane of WLAN as follows:

- **Data plane**: Responsible for the data transmission tasks among WLAN nodes. Data frames are transmitted and received through the data plane.
- **Control plane**: Responsible for the channel access, data transmission scheduling and network management tasks, etc. Control messages, including “control frames” (e.g., RTS frame, CTS frame, Ack frame, beamforming frame, etc.) and “management frames” (e.g., Beacon frame, etc.), are transmitted and received through the control plane.

In addition, according to the different functions of the MAC in the IEEE 802.11 protocol, we can further divide the MAC of the traditional WLAN into sub-MACs of control MAC (cMAC) that only supports control messages (i.e., “control frame” and “management frame” in the IEEE 802.11 protocol) and data MAC (dMAC) that only supports data frames (i.e., “data frame” in the IEEE 802.11 protocol). Fig. 2 illustrates the proposed WLAN architecture in physical view, in which AC, APs and STAs are capable of multi-band operations. Since the LF can guarantee wider signal coverage and higher reliability than the HF, and it does not have to support data transmission since the HF can provide ultra-high-speed data transmissions, we can configure the control plane into the LF. Meanwhile, the LF is responsible for controlling APs...
The proposed control plane and data plane decoupled WLAN protocol structure in logical view is shown in Fig. 3, in which both of the logical decoupling of the control plane and data plane, and the physical channels separation of the control plane and data plane are realized. In this architecture, AC controls APs and STAs through the control plane in the LF, while APs exchange data with STAs through the data plane in the HF. In addition, the dash line of the data plane between AC and AP indicates that only when STA switches to another AP, AC assumes the role of data transfer between the two APs, thus avoiding the bottleneck of aggregating all data to AC [27]. In addition, the IEEE Extreme High Throughput (EHT) Working Group is now considering introducing the 6GHz band into the next generation IEEE 802.11 standard [30]. However, the 6GHz band is the shared access spectrum with other wireless communication services, such as fixed access or satellite service. Those are the primary services in this band. An EHT as the secondary wireless access service shall support the shared access with the primary wireless communication services in 6GHz via dynamic or semi-dynamic spectrum management [30]. Therefore, when the 6GHz band is introduced into the future WLAN, our proposed control plane and data plane decoupled WLAN architecture can adopt dynamic or semi-dynamic spectrum management mechanisms through the control plane at AC side, which can make better use of the 6GHz band within the scope of compliance with the specifications.

As shown in Fig. 2, it is assumed that there are \( m \) APs and \( n \) STAs within the AC’s coverage. We mark the set of \( m \) APs as \( \mathbf{M} = \{ \text{AP 1}, \text{AP 2}, \ldots, \text{AP } i, \ldots, \text{AP } m \} \) and the set of \( n \) STAs as \( \mathbf{N} = \{ \text{STA 1}, \text{STA 2}, \ldots, \text{STA } j, \ldots, \text{STA } n \} \). In addition, we assume that STAs and APs are equipped with multiple antennas, then STA \( a \) can establish the control plane with AC by omni-directional link in the LF and the data plane with multiple APs (marked as \( \mathbf{S} = \{ \text{AP } i, \text{AP } j, \ldots \} \)) by directional mmWave beams in the HF to achieve higher throughput and reliability.

### III. Mathematical Models

According to \[2\], \[14\], \[31\], in order to simplify the analysis, we just consider the two most important fading factors (i.e., the shadow fading and the pathloss) in the LF channel model. As shown in Fig. 2, the signal power received by STA
a from AC in the LF can be determined by

\[ p_{r,LF}^{a,AC} = p_{t,LF}^{AC} - P_{LF}(d^{a,AC}) - \varepsilon, \]  

(1)

where \( p_{t,LF}^{AC} \) is the transmit power of AC in the LF; \( \varepsilon \) is the log-normal shadow fading with mean zero and standard deviation \( \sigma, \sigma = 7\text{dB} \); \( P_{LF}(\cdot) \) is the path loss in the LF [31], and it can be expressed as

\[ P_{LF}(d_{a,AC}) = P_{LF}(d_0) + 10\beta \cdot \log \left( \frac{d_{a,AC}}{d_0} \right), \]  

(2)

where \( P_{LF}(d_0) \) denotes the path loss at the reference distance \( d_0 = 1\text{m} \) and \( P_{LF}(d_0) = 30\text{dB}. \beta \) is the path loss coefficient, \( \beta = 2.68 \) [31]. \( d^{a,AC} \) is the distance between AC and STA \( a \).

For analytical tractability, we assume that there is only one AC, which means there is no interference from other ACs in the LF. Then the Signal-to-Noise-Ratio (SNR) of STA \( a \) in the LF can be derived by

\[ SNR_{LF}^{a,AC} = \frac{p_{t,AC}^{a,AC}}{W_{LF} \cdot N_1}, \]  

(3)

where \( W_{LF} \) and \( N_1 \) represent the bandwidth and background noise power spectrum density of the LF, respectively.

For the HF mmWave, we adopt the commonly used switched analog beam pattern [8]–[10], [32]. Then, the normalized beamforming gain \( G \) is

\[ G(\alpha, \theta) = \begin{cases} \frac{2\pi(\alpha - \theta)}{\alpha}, & \text{if } |\theta| \leq \frac{\alpha}{2}, \\ 0, & \text{otherwise}, \end{cases} \]  

(4)

where \( \alpha \) is the beamwidth of the mainlobe in radian. \( \theta \) is the beam offset angle to the mainlobe in radian. \( v \) is the gain of the sidelobes and \( 0 < v \ll 1 \).

Considering the scenario that AP \( i \) transmits signal to STA \( a \), the signal power received by STA \( a \) from AP \( i \) in the HF [2], [10] is

\[ p_{r,HF}^{a,i} = p_{t,HF}^{i} \sum_{ch=1}^{CH} G_{t}^{a,i} G_{c}^{a,ref} G_{r}^{a,i}, \]  

(5)

where \( p_{t,HF}^{i} \) is the transmit power of AP \( i \) in the HF. \( CH \) is the number of paths, and the superscript "(ch)" stands for the \( ch \)-th path. \( G_{c}^{a,ref} \) is the channel gain between AP \( i \) and STA \( a \). \( G_{t}^{a,i} \) and \( G_{r}^{a,i} \) are the directional transmit gain of AP \( i \) and the directional receive gain of STA \( a \), respectively. Then, based on eq. (4), we can obtain \( G_{t}^{a,i} \) and \( G_{r}^{a,i} \) as

\[ G_{t}^{a,i}(\alpha_{t}^{a,i}, \theta_{t}^{a,i}) = \begin{cases} \frac{2\pi(\alpha_{t}^{a,i} - \theta_{t}^{a,i})}{\alpha_{t}^{a,i}}, & \text{if } |\theta_{t}^{a,i}| \leq \frac{\alpha_{t}^{a,i}}{2}, \\ 0, & \text{otherwise}, \end{cases} \]  

(6a)

\[ G_{r}^{a,i}(\alpha_{r}^{a,i}, \theta_{r}^{a,i}) = \begin{cases} \frac{2\pi(\alpha_{r}^{a,i} - \theta_{r}^{a,i})}{\alpha_{r}^{a,i}}, & \text{if } |\theta_{r}^{a,i}| \leq \frac{\alpha_{r}^{a,i}}{2}, \\ 0, & \text{otherwise}. \end{cases} \]  

(6b)

According to [33], the channel between AP \( i \) and STA \( a \) in the HF is given by

\[ h_{HF}^{a,i}(\tau) = \sum_{ch=1}^{CH} \chi_{ch}^{a,i} \delta \left( \tau - \tau_{ch}^{a,i} \right), \]  

(7)

where \( \tau_{ch}^{a,i} \) is the propagation delay of the \( ch \)-th path, and \( \tau_{ch}^{a,i} = \frac{d_{ch}^{a,i}}{c}, \quad d_{ch}^{a,i} \) is the distance of the \( ch \)-th path between STA \( a \) and AP \( i \), \( c \) is the speed of light. \( \delta(\cdot) \) is the Dirac delta function. \( \chi_{ch}^{a,i} \) is the amplitude of the \( ch \)-th path that includes both path loss and reflection coefficients. According to [33], \( \chi_{ch}^{a,i} \) can be derived by

\[ \chi_{ch}^{a,i} = \frac{\lambda_{HF}(ch))}{4\pi d_{ch}^{a,i} f_{HF}(ch)} \prod_{ref} \Omega(ref), \]  

(8)

where \( \lambda_{HF} \) is the wavelength of the carrier in the HF and \( \lambda_{HF} = \frac{c}{f_{HF}} \) is the carrier frequency in the HF. \( REF \) is the number of reflections of the path. \( \Omega(ref) \) is the reflection coefficient of the ref-th reflection for the \( ch \)-th path.

Since the line-of-sight (LOS) path (i.e., \( ch = 1 \)) does not exist reflections (i.e., \( REF = 0 \)), the reflection coefficient of the LOS path is \( \Omega(0) = 1 \). Then, the amplitude of the LOS path is given by

\[ \chi_{1}^{a,i} = \frac{\lambda_{HF}(1)}{4\pi d_{1}^{a,i}}. \]  

(9)

In addition, HF mmWave signal can be easily absorbed by reflectors, and it shows poor reflectivity [33]. Therefore, we only consider one reflection (i.e., \( REF = 1 \)) for a given path (i.e., \( ch \in [2,CH] \)). Then, \( \chi_{ch}^{a,i} \) can be simplified as

\[ \chi_{ch}^{a,i} = \frac{\lambda_{HF}(ch)}{4\pi d_{ch}^{a,i}} \Omega(1), \quad ch \in [2,CH]. \]  

(10)

According to [34], we can get the channel gain between AP \( i \) and STA \( a \) as

\[ G_{c}^{a,i} = \left| \chi_{ch}^{a,i} \delta \left( \tau - \tau_{ch}^{a,i} \right) \right|^2. \]  

(11)

From eq. (5), eq. (6a), eq. (6b), eq. (9), eq. (10) and eq. (11), we can finally obtain the signal power (i.e., \( p_{r,HF}^{a,i} \)) received by STA \( a \) from AP \( i \) in the HF. Similarly, the interference received by STA \( a \) from other APs (e.g., AP \( j \)) and STAs (e.g., STA \( b \)) can be derived by

\[ p_{r,LF}^{b,a,i} = p_{t,LF}^{i} \sum_{ch=1}^{CH} G_{t}^{j,a,i} G_{c}^{a,j} G_{r}^{b,a,i}, \quad j \in \mathcal{M}\setminus i, \]  

(12a)

\[ p_{r,LF}^{b,a,i} = p_{t,LF}^{i} \sum_{ch=1}^{CH} G_{t}^{j,a,i} G_{c}^{a,j} G_{r}^{b,a,i}, \quad b \in \mathcal{N}\setminus a, \]  

(12b)

where \( G_{t}^{j,a,i} \) and \( G_{r}^{b,a,i} \) stand for the transmit gains from AP \( j \) and STA \( b \) to STA \( a \), respectively; \( G_{c}^{a,j} \) and \( G_{r}^{b,a,i} \) stand for the receive gains of STA \( a \) from AP \( j \) and STA \( b \), respectively.

Finally, we can obtain the Signal-to-Interference-plus-Noise-Ratio (SINR) between STA \( a \) and AP \( i \) in the HF as follows [13], where \( W_{HF} \) and \( N_2 \) represent the bandwidth and the background noise power spectrum density of the HF, respectively.
IV. MULTI-BEAM TRANSMISSION AND HF & LF COOPERATION MECHANISMS

In this section, we will design a multi-beam transmission mechanism and an HF & LF cooperation mechanism for our proposed control plane and data plane decoupled WLAN architecture, including the establishment of multi-beam transmission and the update of multi-beam links.

A. The Establishment of Multi-Beam Transmission

In Section II, we assumed that APs and STAs are equipped with multiple antennas, so they can generate multiple directional beams concurrently. Then, one STA can connect to multiple surrounding APs by beamspaces multi-user multiple-input multiple-output (MU-MIMO) [35]. This improves not only the throughput, but also the link reliability of mmWave communications. Therefore, we can design a multi-beam transmission mechanism in the proposed control plane and data plane decoupled WLAN architecture. The following descriptions and Fig. 4 show the process steps of establishing multi-beam transmission:

(1) If STA $a$ wants to establish multi-beam links with multiple APs, it will transmit “multi-beam transmission request” frame to AC through the control plane in the LF.

(2) AC transmits “multi-beam transmission command” frame through the control plane in the LF to STA $a$’s surrounding APs (e.g., AP $i$, AP $j$, . . .). This frame informs these APs that STA $a$ wants to perform beamforming training with them, and it also informs STA $a$ to be ready to start beamforming training.

(3) STA $a$ performs beamforming training with its surrounding APs through the control plane (i.e., HF-scMAC) in the HF. In order to improve the efficiency of beamforming training, we can adopt our proposed Efficient Beamforming Training Mechanism in [10].

(4) After finishing beamforming training, STA $a$ will feed back a “beam training report” frame that contains the quality of directional links (i.e., SNR values in IEEE 802.11ad/ay) to the AC via the control plane in the LF.

(5) AC selects $^1$ appropriate APs to form a set $S$ (i.e., $S = \{\text{AP } i, \text{ AP } j\}$), and all the APs in $S$ provide multi-beam transmission services for STA $a$. The selected results will be contained in the “multi-beam transmission confirm” frame and transmitted to STA $a$ and all the APs who are involved in beamforming training via the control plane in the LF. After receiving the “multi-beam transmission confirm” frame, the selected APs can point their transmit beams to STA $a$ according to the results of beam training report, while STA $a$ points its receive beams to the selected APs specified in the “multi-beam transmission confirm” frame.

(6) The selected APs start directional communication with STA $a$ according to the time indicated by the “multi-beam transmission confirm” frame.

In the above steps, the AC is responsible for controlling APs and STA $a$ through the control plane in the LF. The HF is responsible for the data transmission between APs and STA $a$ through the data plane. In addition, the HF is also responsible for beamforming training between APs and STA $a$ through the control plane. After finishing the above steps, the establishment of multi-beam transmission is completed.

B. The Update of Multi-Beam Links

When the multi-beam communication links are established, if an STA moves around, it may lead to the misalignment of the initial beam pairs, which will affect the throughput and even cause the interruption of communications. Therefore, in order to provide continuous and high-quality mmWave communication services for users, it is necessary to update the multi-beam links in real time. The update of multi-beam links can be divided into two situations: 1) Beam tracking within AP’s coverage: STA moves only apart a short distance, but it is still within the coverage of the serving AP. Thus, simple beam tracking between the STA and AP can achieve beam realignment [8], [9]. 2) Serving AP handover: STA moves apart a long distance, thereby it needs to disconnect from the old AP(s) and update the serving AP(s).

1) Beam tracking within AP’s coverage: Considering the fact that directional mmWave communication is very sensitive to mobility, the tiny movement between the transmit and the receive beam pair will probably lead to a dramatic change of communication link’s quality [9], [10]. Therefore, when user moves, frequent beam tracking operations are needed to recover the directional links, which will incur huge signaling overhead [8]–[10]. In addition, there are many APs in the network and there are also many STAs within the coverage of each AP. In order to avoid the bottleneck that all the beam tracking signaling of APs and STAs are forwarded to AC, we adopt the local beam tracking mechanism proposed in [9], [17], which can be implemented in the data plane.

As shown in Fig. 5, if relative movement occurs between the beam tracking initiator (i.e., STA $a$) and the beam tracking

$$SINR_{HF}^{a,1} = \frac{\sum_{b \in \mathcal{N}_a} (L_{HF}^{a,1} G_{C_r}^{a,b} + \sum_{c \in \mathcal{M}_a} (L_{HF}^{a,1} G_{C_r}^{a,b,c} + \sum_{d \in \mathcal{M}_a} (L_{HF}^{a,1} G_{C_r}^{a,b,c,d}))) + \sum_{j \in \mathcal{M}_a} (L_{HF}^{a,1} G_{C_r}^{a,b,j} + \sum_{c \in \mathcal{M}_a} (L_{HF}^{a,1} G_{C_r}^{a,b,c,j} + \sum_{d \in \mathcal{M}_a} (L_{HF}^{a,1} G_{C_r}^{a,b,c,d,j}))) + W_{HF} \cdot N_2.$$
Fig. 4. The establishment of multi-beam transmission in our proposed control plane and data plane decoupled WLAN.

Fig. 5. An example of transmit beam tracking within an AP’s coverage.

As the beam tracking mechanism mentioned above, beam realignment can be achieved through several simple interactions between an STA and its AP in the data plane. All the overhead of beam tracking is processed at the AP side, instead of being transferred to AC. Thus, it eliminates the burden of AC dealing with the overhead of frequent beam tracking.

2) Serving AP handover (update S): When an STA moves continuously and is far from the coverage of its AP, the beam tracking mechanism mentioned above cannot recover the directional link by switching to other beam directions any more. At this time, it is necessary for the STA to connect to new serving AP(s) to achieve high-speed and stable communications. In our proposed control plane and data plane decoupled WLAN architecture, we can use the control plane in the LF to assist the data plane in the HF to perform serving AP handover. The detailed process steps are shown in Fig. 6 and described below:

1) AP and APj in the initial serving AP set S transmit data i and data j to STA a through the data plane in the HF, respectively. If AP j does not receive the Ack from STA a for a specified period of time, the directional link between AP j and STA a can be considered as outage [9], [17].

2) AP j transmits a “update request” frame through the control plane in the LF to inform AC that STA a wants to initiate serving AP handover. At the same time, AP j forwards data j through the data plane in the HF to AC.

3) AC transmits a “update command” frame through the control plane in the LF to STA a’s surrounding APs (e.g., AP x, AP y, ...). This frame informs these APs that STA a wants to perform beamforming training with them, and it also informs STA a to be ready to start beamforming training.

4) STA a performs beamforming training with its surrounding APs through the control plane (i.e., H-F_scMAC) in the HF. In order to improve the efficiency of beamforming training, we can also adopt our proposed Efficient Beamforming Training Mechanism in [10].
Fig. 6. Serving AP handover (update S) in our proposed control plane and data plane decoupled WLAN.

(5) After finishing beamforming training, STA a will feed back a "beam training report" frame that contains the quality of directional links (i.e., SNR value in IEEE 802.11ad/ay) to AC via the control plane in the LF.

(6) AC selects appropriate APs (e.g., the SINR value is higher than the predefined threshold $\Gamma_{HF}$ [2], [9]) to form a new serving AP set $S'$ (i.e., $S' = \{AP_i, AP_j, \ldots \}$). The selected results will be contained in the "update confirm" frame and transmitted to STA a, AP j and all the other APs (e.g., AP x, AP y, . . .) who are involved in beamforming training via the control plane in the LF. In addition, AC forwards data j to the selected AP(s) (e.g., AP x) through the data plane in the HF. After receiving the "update confirm" frame, the selected AP(s) (e.g., AP x) will point its transmit beams to STA a, and STA a will point its receive beams to the selected APs specified in the "update confirm" frame. Meanwhile, AP j will be excluded from the updated serving AP set $S'$ according to the "update confirm" frame.

(7) All the APs in the updated serving AP set $S'$ start directional communications with STA a according to the time indicated in the "update confirm" frame. In addition, AP x will continue to transmit data j to STA a.

After finishing the above steps, the update of multi-beam links is completed. The LF is responsible for the control plane, while the HF is responsible for both the data transfer between APs (i.e., $AP_j \rightarrow AC \rightarrow AP_x$) and the beamforming between APs and STA. However, if APs work at LF band to carry the separated C-plane for in-service STAs, the control command from the AC should be transmitted to the AP first, and then the AP relays the command to STAs. This kind of two-hop control mechanism will incur significant overhead that will result in much latency. It is worth noting that the control plane in the LF always remains connected, and the data plane in the HF also stays connected with the AP(s) in $S$ (i.e., $AP_i$) who is(are) not involved in the handover. The above-mentioned serving AP handover operation can also be performed periodically, thus ensuring that there are always multiple suitable APs serving one STA. For simplicity, we take one STA and multiple STAs as an example in the proposed mechanisms above. Note that our proposed mechanisms can also be applied into the scenario that contains multiple STAs and multiple APs. Please refer to [10] for more details. In addition, to better understand the overall scheme, Fig. 7 shows the relationship of the sub-schemes in Fig. 4, Fig. 5 and Fig. 6.

C. Performance Modelling of the Proposed Multi-Beam Transmission and HF & LF Cooperation

1) Throughput Improved by Multi-Beam Transmission: As shown in Fig. 2, an STA can receive signals from multiple surrounding APs due to the dense deployment of APs. In addition, we assume that STAs and APs are equipped with multiple antennas, thus an STA can connect to multiple APs in $S$ (or updated $S'$) simultaneously through multiple directional beams in the HF. When compared with the traditional mmWave WLAN architecture (i.e. STA a just connects to AP $i$), the throughput of STA a in our proposed control plane and data plane decoupled WLAN architecture is increased from $W_{HF}^{\alpha_i} \log_2 \left(1 + SINR_{HF}^{\alpha_i}\right)$ to

$$T_{HF}^{\alpha_i} = \sum_{i \in S} W_{HF}^{\alpha_i} \log_2 \left(1 + SINR_{HF}^{\alpha_i}\right),$$

where $W_{HF}^{\alpha_i}$ represents the bandwidth of the HF between AP $i$ and STA a.

2) Reliability Improved by Multi-Beam Transmission and HF & LF Cooperation: In order to evaluate the reliability of communications in our proposed control plane and data plane decoupled WLAN architecture, we adopt the outage
probability as the indicator, which means the higher the outage probability is, the lower the reliability will be. We set the outage threshold of SNR in the LF as $\Gamma_{LF}$, then the outage probability of STA $a$ in the control plane is

$$P_{CP,\text{outage}}^a = \text{Prob} \left( \text{SNR}_{\text{LF}}^{a,\text{AC}} < \Gamma_{LF} \right).$$ (15)

Similarly, we set the outage threshold of SINR for the directional mmWave links in the HF as $\Gamma_{HF}$. When STA $a$ connects to the APs in $S$ (or updated $S'$) through directional links in the HF, the outage probability in the data plane can be considered as all the directional links are interrupted simultaneously, which can be expressed as

$$P_{DP,\text{outage}}^a = \prod_{i \in S} \text{Prob} \left( \text{SINR}_{\text{HF}}^{a,i} < \Gamma_{HF} \right).$$ (16)

For the traditional coupled mmWave WLAN architecture, control and data frames are transmitted in the HF. Therefore, the reliability can be considered as there is no outage with both control frames and data frames, which is shown as

$$P_{\text{coupled, reliability}}^a = \left( 1 - \text{Prob} \left( \text{SINR}_{\text{HF}}^{a,i} < \Gamma_{HF} \right) \right)^2.$$ (17)

Accordingly, the reliability of our proposed control plane and data plane decoupled WLAN architecture is improved to eq. (18).

V. PERFORMANCE EVALUATION AND SIMULATION

In this section, we first introduce the network topology used in the simulation, and then provide the simulation results and corresponding analyses. It is worth noting that we mainly focus on the (protocol) design of new multi-beam transmission and HF & LF cooperation schemes under the proposed control plane and data plane decoupled WLAN architecture. We believe that effective radio resource management algorithms (e.g., flexible power control, innovative channel assignment) can remarkably improve the overall system performance in the proposed architecture. For example, Takahashi et al. in [36] proposed an adaptive power resource allocation scheme with multi-beam directivity control mechanism to improve the allocation efficiency of communication resources. Simulation results showed that the proposed allocation scheme achieves higher traffic accommodation rate than the conventional ones. Recently, machine learning algorithms are becoming a promising tool to deal with the traditional radio resource management problems [37]. Liu et al. in [38] formulated an energy efficiency-based optimization problem in nonorthogonal multiple access (NOMA)-based heterogeneous Internet-of-Things (IoT) system to pair the users and allocate the radio resource. Then they obtained the optimal solution by using a deep recurrent neural network-based method. Huang et al. in [39] considered a weighted sum-rate maximization problem under the total power constraint. Then they proposed an unsupervised learning-based fast beamforming design method to reduce the radio resource allocation complexity. We will consider how to obtain the optimal system performance in the proposed architecture through effective radio resource management algorithms in our future work.

A. Network Topology Used in the Simulation

For analytical tractability, we adopt the network topology as shown in Fig. 8. APs are distributed in grid shape, in which the distance between two adjacent APs is 100m. AC is located in the center of this grid, and it is also a co-located AP (i.e., AP $i+1$). It is noteworthy that our proposed control plane and data plane decoupled WLAN architecture, multi-beam transmission mechanism and HF & LF cooperation mechanism are also suitable for an arbitrary network topology. In Fig. 8, STA $a$ moves along a straight line (i.e., the blue line in Fig. 8) from the center (i.e., $D_1$) of AP $i$ and AP $j$ to the center (i.e., $D_2$) of AP $i+2$ and AP $j+2$. Since $D_1$ and $D_2$ are on the same horizontal line, we can set the abscissa of $D_1$ to “$D = 0m$”, and then the abscissa of $D_2$ should be “$D = 200m$” in one-dimensional horizontal coordinates. Therefore, if STA $a$ is in position $D_2$ (i.e., $D = D_2$), the distance from STA $a$ to AP $i$ or AP $j$ is

$$d_{a,i}^a = d_{a,j}^a = \sqrt{50^2 + D_2^2}.$$ (19)
Then, the distance from STA $a$ to AP $i+1$ or AP $j+1$ (i.e., AC) is
\[
d^a_{i+1} = \sqrt{50^2 + (D_a - 100)^2}. \tag{20}
\]
Accordingly, the distance from STA $a$ to AP $i+2$ or AP $j+2$ is
\[
d^a_{i+2} = \sqrt{50^2 + (200 - D_a)^2}. \tag{21}
\]

Based on eq. (19), eq. (20), eq. (21), Section III and Section IV.C, we can analyze the performance of multi-beam transmission mechanism and HF & LF cooperation mechanism in our proposed control plane and data plane decoupled WLAN architecture. The remaining simulation parameters are listed in Table I.

### B. Simulation Results

We simulate the performance of multi-beam transmission mechanism and HF & LF cooperation mechanism in our proposed control plane and data plane decoupled WLAN architecture based on the network topology shown in Fig. 8. Meanwhile, we adopt periodic multi-beam links update method to ensure that there are always multiple suitable APs serving one STA. We can see from Fig. 9 that the average SNR between AC and STA $a$ is always higher than that of the SINR between STA $a$ and each AP. There are two reasons, on one hand, the path loss of the LF is much smaller than that of the HF mmWave. On the other hand, only one AC is considered in the network topology, and there is no interference in the LF. However, there are many APs in the HF, which will cause directional interference at STA $a$ side. Therefore, the two facts make the SNR of the control plane between AC and STA $a$ much higher than that of the SINR of the data plane between STA $a$ and each AP. In addition, we can see that the variation trend of SINR in the HF (or SNR in the LF) is closely related to the distance from STA $a$ to each AP (or AC). The longer the distance is, the lower the SINR (SNR) value will be. We also provide the performance comparison when the beamwidths in the HF are different. For example, when the beamwidth is narrower (i.e., beamwidth = $10^\circ$), the SINR in the HF is about 5 dB higher than that when the beamwidth is wider (i.e., beamwidth = $20^\circ$), because narrower beamwidth not only brings larger directional transmit gain and receive gain, but also alleviates the interference.

Fig. 10 shows the changes of throughput between STA $a$ and each AP during STA $a$ moving from $D_1$ to $D_2$. Similar to the results as shown in Fig. 9, the throughput between STA $a$ and AP $i$ & AP $j$ decreases slowly when STA $a$ moves from $D_1$ to $D_2$, because the communication distance becomes longer. When the beamwidth is $10^\circ$, the throughput between STA $a$ and AP $i$ & AP $j$ becomes zero at $D = 170$m. This is because we have set a threshold $\Gamma_{HF}$ in Section IV, if the SINR of directional link is lower than $\Gamma_{HF}$, this link will be disconnected. However, when the beamwidth is $20^\circ$, the throughput between STA $a$ and AP $i$ & AP $j$ becomes zero at $D = 80$m. Because a wider beamwidth will bring smaller directional transmit gain and receive gain, and also severer interference, then the SINR will be lower than $\Gamma_{HF}$ at $D = 80$m. The SINR between STA $a$ and AP $i+2$ & AP $j+2$ is increasing.

### TABLE I

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
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</thead>
<tbody>
<tr>
<td>LF carrier frequency: $f_{LF}$</td>
<td>2.4GHz</td>
</tr>
<tr>
<td>HF carrier frequency: $f_{HF}$</td>
<td>60GHz</td>
</tr>
<tr>
<td>LF bandwidth: $W_{LF}$</td>
<td>20MHz</td>
</tr>
<tr>
<td>HF bandwidth: $W_{HF}$</td>
<td>2.16GHz</td>
</tr>
<tr>
<td>LF transmit power: $P_{AC,LF}^i$</td>
<td>12dBm</td>
</tr>
<tr>
<td>HF transmit power: $p_{HT,HF}$</td>
<td>12dBm</td>
</tr>
<tr>
<td>LF SNR threshold: $\Gamma_{LF}^i$</td>
<td>3dB</td>
</tr>
<tr>
<td>HF SNR threshold: $\Gamma_{HF}$</td>
<td>3dB</td>
</tr>
<tr>
<td>STA position: $D$</td>
<td>$0 \sim 200$m</td>
</tr>
<tr>
<td>HF mmWave beamwidth: $\alpha$</td>
<td>$10^\circ$, $20^\circ$</td>
</tr>
<tr>
<td>Sidelobe gain: $\psi$</td>
<td>0.1</td>
</tr>
<tr>
<td>Background noise power spectrum density: $N_1, N_2$</td>
<td>-174dBm/Hz</td>
</tr>
</tbody>
</table>
while STA $a$ is moving from $D_1$ to $D_2$. Then, the SINR values of the links with beamwidth = $10^\circ$ and beamwidth = $20^\circ$ exceed $\Gamma_{HF}$ at $D = 40m$ and $D = 130m$, respectively. After that, the directional links between STA $a$ and AP $i+2$ & AP $j+2$ are established, and the throughput keeps rising. For the directional links between STA $a$ and AP $i+1$ & AP $j+1$, when the beamwidth is $10^\circ$, the SINR is always higher than $\Gamma_{HF}$, which means the directional links always exist. Therefore, the throughput changes according to the distance between STA $a$ and AP $i+1$ & AP $j+1$. However, when the beamwidth is $20^\circ$, the SINR is lower than that when the beamwidth is $10^\circ$. When STA $a$ is far from AP $i+1$ and AP $j+1$ (i.e., $D<30m$ and $D>170m$), the directional links are disconnected. When STA $a$ is close to AP $i+1$ and AP $j+1$ (i.e., $30m<D<170m$), the throughput will increase first and then decline according to the communication distance.

However, if the beamwidth is $20^\circ$, the variation tendency of sum-throughput is different from that when the beamwidth is $10^\circ$. For the multi-beam transmission mechanism, STA $a$ just connects to AP $i$ and AP $j$ when $D<20m$. Then, the sum-throughput goes down as STA $a$ moving away. When $30m<D<70m$, STA $a$ will connect to AP $i$, AP $j$, AP $i+1$ and AP $j+1$ simultaneously, so the sum-throughput will increase significantly. But when $80m<D<120m$, STA $a$ is too far from AP $i$ and AP $j$. Thus, STA $a$ will disconnect from AP $i$ and AP $j$, and then the sum-throughput will decrease significantly. Similarly, STA $a$ will connect to AP $i+1$, AP $j+1$, AP $i+2$ and AP $j+2$ simultaneously when $130m<D<170m$. Therefore, the sum-throughput increases dramatically. However, STA $a$ will disconnect from AP $i+1$ and AP $j+1$ and only connect to AP $i+2$ and AP $j+2$ when $D>180m$, so the sum-throughput...
witnesses a big drop. After that, the sum-throughput will increase slowly as STA $a$ moving closer to the center of AP $i+2$ and AP $j+2$. For the traditional coupled mechanism, the sum-throughput shares the similar trend to that when the beamwidth is 10° as described above. We will not provide the redundant details here.

Fig. 12 shows the changes of outage probability between STA $a$ and each AP during STA $a$ moving from $D_1$ to $D_2$. We can see that the outage probability of the LF is almost zero (less than 0.5%), which means STA $a$ has almost no outage in the LF. This is very important for our proposed control plane and data plane decoupled WLAN architecture, since the control plane in the LF needs ultra-high reliability to provide control messages for both APs and STAs. However, since the outage probability in the HF is greatly influenced by the beamwidth and the communication distance. For example, if the beamwidth is 10°, the outage probability in the HF ranges from 8% to 60% according to the distance between STA $a$ and the serving AP. In fact, such a high outage probability (i.e., about 60%) means that this AP is not suitable for providing communication services for STA $a$ any more, and it is necessary to reconnect to other suitable APs (i.e., update S).

If the beamwidth is 20°, the outage probability in the HF is greatly increased by 20% ∼ 30%, since the wider beamwidth incurs lower SINR (or SNR). Meanwhile, with the increase of the distance between STA $a$ and AP, the outage probability increases from 25% (when STA $a$ is close to AP) to 85% (when STA $a$ is far away from AP). We can also see from Fig. 12 that, as the distance between STA $a$ and AP $i+1$ & AP $j+1$ first getting closer and then farther, the outage probability in the HF first becomes lower and then higher accordingly.

Fig. 13 shows the reliability comparison between our proposed multi-beam transmission mechanism and HF & LF cooperation mechanism in the decoupled architecture (i.e., abbreviated as “Decoupled” in Fig. 13) while STA $a$ is moving from $D_1$ to $D_2$. For the traditional mechanism in the coupled architecture, STA $a$ will connect to the AP with the best link quality (i.e., highest SINR). It can be seen in Fig. 13 that the reliability in the traditional mechanism is relatively low. For example, when the beamwidth is 20°, with the increase of the distance between STA $a$ and AP, the reliability decreases from 58% to 38%. However, the narrower the beamwidth is, the higher the directional transmit gain and receive gain will be, and the lower the interference will be, so the reliability will increase. When the beamwidth is 10°, the reliability ranges from 75% to 88% according to the distance between STA $a$ and the serving AP. In the decoupled architecture, with the proposed multi-beam transmission mechanism and HF & LF cooperation mechanism, the reliability can be greatly promoted to higher than 98%. Moreover, with narrower beamwidth (i.e., beamwidth = 10°), the reliability can achieve almost 100%.

Therefore, the above results verify that the proposed multi-beam transmission mechanism and HF & LF cooperation mechanism can greatly improve the reliability of mmWave communications in our proposed control plane and data plane decoupled WLAN architecture.

![Fig. 12. The changes of outage probability between STA $a$ and each AP with respect to different HF mmWave beamwidths.](image)

![Fig. 13. The reliability comparison between traditional single AP transmission in the coupled architecture and the proposed mechanisms in the decoupled architecture.](image)

**VI. CONCLUSIONS**

In this paper, a new control plane and data plane decoupled WLAN architecture is proposed to solve the problems of inefficient management and poor reliability of the existing distributed mmWave WLAN. The WLAN architecture we proposed is a centralized control network architecture with control plane and data plane decoupling, in which AC, as the central controller, controls and manages all the APs and STAs through the control plane in the LF, and the AP provides data transmissions for STAs through the data plane in the HF. Then, we proposed the multi-beam transmission mechanism and HF & LF cooperation mechanism in our proposed network.
architecture to improve the throughput and reduce the outage probability of mmWave communications. Performance analysis and simulation have shown that the throughput has been greatly improved by using our proposed multi-beam transmission mechanism. Meanwhile, the proposed multi-beam transmission mechanism and HF & LF cooperation mechanism have significantly improved the reliability of mmWave communications.

REFERENCES

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