mmWave IEEE 802.11ay for 5G Fixed Wireless Access

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Abstract

Fixed wireless access (FWA) utilizing both licensed and unlicensed millimeter wave (mmWave) spectrum is considered a key technology that can lead to the early deployment of the fifth-generation new-radio (5G-NR) networks. 5G FWA can provide easy installation of network infrastructure and ubiquitous high-speed Internet access at low cost compared to the conventional broadband fixed access networks. In this article, we investigate the mmWave distribution network (mDN) use case that has been standardized recently by the IEEE 802.11ay standard as an alternative 5G FWA solution. Specifically, we provide a comprehensive tutorial view of the considered new protocol specifications and design elements of the mDN. We also highlight some challenging research issues in the field of the mDN. Finally, we provide a case study based on the investigation of the mDN where a low-complexity concurrent transmission protocol is proposed to enhance the network performance while mitigating the interference.

Introduction

In the emerging next-generation networks era, such as fifth-generation (5G) and the IEEE 802.11ay, data-intensive applications and a wide range of use cases have become feasible as a result of the high speeds and low latency provided by millimeter wave (mmWave) technology. Due to the vast spectrum swath, mmWave technology can dramatically improve wireless application experiences by providing multi-gigabit data-rate services. Heterogeneous networks with very diverse requirements are supported in the 5G where different technologies are employed with different use cases, such as enhanced mobile broadband (eMBB). Fixed wireless access (FWA) is a specific case of the eMBB, where it can exceed the quality of service of most current fixed broadband networks when either licensed or unlicensed mmWave spectrum is exploited. The 5G FWA is viewed as one of the potential services that can be enabled in early 5G deployment.

Although the concept of FWA was previously used in the past cellular generations and standards derived from the Wi-Fi family, the speeds and latency provided are not comparable to the service provided by fiber broadband networks. Thanks to mmWave technology, the 5G FWA can provide Internet access with enhanced quality of service and seamless user experience due to the high speeds, low latency, low cost, and faster time-to-market that it can provide. Due to these advantages, several service providers around the globe, e.g., Verizon and Facebook, have adopted 5G FWA or plan to exploit this technology. Even though 5G FWA can be adopted by utilizing the technologies available in the 5G (3GPP standard) using licensed mmWave spectrum, the mmWave distribution network (mDN) use case of IEEE 802.11ay that operates on the unlicensed 60 GHz band is an alternative low-cost solution for operators to provide similar 5G performance.

The mDN allows operators to provide fiber-replacement broadband services, where it has the potential to build denser urban networks with the support of various emerging applications. In addition to the unlicensed 60 GHz band benefit, the enhanced technologies considered in the IEEE 802.11ay standard can provide a promising high network performance [1]–[3]. Moreover, the mDN can provide a similar user experience as 5G in terms of capacity, efficiency and flexibility at a fraction of the cost of equivalent 5G small cell infrastructure. The primary purpose of the mDN is to realize both wireless backhauling and point-to-multipoint (P2MP) mmWave access, which is based on the concept of mesh networking topology. Therefore, the mDN can offer a multi-Gbps fiber-like speed and low-cost solution for 5G FWA.

This article aims to investigate the mDN in order to deliver a comprehensive tutorial view of the new protocol specifications and design elements that have been proposed recently by IEEE 802.11ay, where 5G FWA and IEEE 802.11ay standard are first reviewed. Then, future research directions to address the challenges associated with the mDN are highlighted. Finally, a case study is conducted to elaborate on how to improve the network performance by taking advantage of the spatial reuse in a dense network.

An Overview of 5G FWA and IEEE 802.11ay

5G Fixed Wireless Access

FWA is a broadband network that provides Internet access to customers utilizing wireless technology instead of the wired network, such

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Digital Object Identifier: 10.1109/MWC.001.1900174

1536-1284/20/$25.00 © 2020 IEEE

as the fiber broadband network. In the past, previous cellular generations and standards derived from the Wi-Fi family have been utilized for the FWA. However, the speeds and latency provided in these approaches cannot compete with the fiber broadband networks. With the new advanced technologies, such as mmWave beamforming (BF) and small cell base stations [4]–[7], 5G FWA can deliver Internet access to homes with fiber-like speeds. Another reason that makes 5G FWA essential is that many houses around the globe do not have reliable broadband access, where it can be expensive and time-consuming to deploy fiber broadband network everywhere. Therefore, this raises an opportunity for operators and service providers to adopt the 5G FWA.

5G FWA Deployments: Several 5G FWA trials have been conducted by the industry to demonstrate the potential of both licensed and unlicensed mmWave technologies. In 2017, Verizon started pre-standard 5G trials to provide 5G FWA and thereby launched this service, called 5G-Home, in limited locations in the United States. Another 5G FWA trial was launched recently by Huawei and TELUS in Canada by using Huawei 5G products that are based on entirely 3GPP standards. Facebook, Deutsche Telekom, and Qualcomm are working together on Facebook's Terragraph project which is based on the mDN that operates in the unlicensed 60 GHz band. Furthermore, SiKlu launched a P2MP mmWave system which is another 5G FWA trail that is based on the unlicensed 60 GHz band.

5G FWA Advantages: The main advantages of the 5G FWA based on either licensed or unlicensed mmWave spectrum are summarized as follows:
- High speeds and very low latency can be provided due to the mmWave spectrum.
- Reduced cost of network infrastructure can be realized compared to the fiber broadband networks.
- Faster time-to-market can be achieved, where quick and cheap Internet access can be enabled.
- Ubiquitous connectivity to rural areas can be delivered, where wired access infrastructure is unavailable.

IEEE 802.11ay

The IEEE 802.11ay standard is an advanced communication system that operates on the unlicensed 60 GHz band to enhance the user experience, where point-to-point (P2P) and P2MP are considered for indoor and outdoor communications. The IEEE 802.11ay standard has been established to improve the legacy 802.11ad standard while guaranteeing backward compatibility for legacy users. IEEE 802.11ay utilizes BF training and specific directional medium access control (MAC), where multi-user (MU) multiple-input multiple-output (MIMO) and channel bonding and aggregation are supported to improve the spectrum efficiency and system throughput.

Channel Bonding and Aggregation: In order to enhance the channel utilization and achieve significant throughput gain, the IEEE 802.11ay standard supports the multi-channel approach by transmitting data over channels simultaneously [1]–[3]. Channel bonding and aggregation are utilized to create a wider channel from multiple channels by combining two or more channels, where there are up to six 2.16 GHz channels in the unlicensed 60 GHz frequency band. The client-nodes (CNs) with enhanced directional multi-gigabit (EDMG) ability can use channel bandwidth containing 4.32, 6.48, or 8.64 GHz by combining two, three, or four 2.16 GHz channels, respectively.

MIMO Channel Access: IEEE 802.11ay supports the downlink MU-MIMO to enable simultaneous transmissions for multiple CNs such that the spatial reuse and transmission robustness to link-outage can be enhanced [1]–[3]. To enable MIMO channel access, physical carrier sensing, virtual carrier sensing or clear channel assessment are implemented with specific MIMO backoff procedure. Thus, a transmitter (TX) is permitted to gain a transmission opportunity for a downlink MU-MIMO transmission when all the MIMO beams are sensed to be idle while the backoff procedure is satisfied.

Directional MAC: The IEEE 802.11ay directional MAC protocol includes a beacon interval (BI) access time that has four main components, where the functions of each of them are described as follows. First, during the beacon transmission interval (BTI), BF training can be initiated by a distribution-node (DN) or an access point, where an Announce frame or EDMG-Beacon is transmitted. Second, during association beamforming training (A-BFT), BF training can be completed by CNs by utilizing A-BFT slots. The number of A-BFT slots in IEEE 802.11ay is increased to up to 16 slots using the extended A-BFT mechanism or up to 48 slots utilizing the multi-channel A-BFT method [1], [3]. Third, during the announcement transmission interval (ATI), exchanges in the request-response-based management and allocation information can be announced. Finally, during the data transfer interval (DTI), slot allocations are established by using either contention-based access periods or scheduled-service periods (SPs). Time division duplex (TDD) channel access allocation (TDD-SP) is another type of allocation that is utilized for the mDN use case during the DTI.

BF Training: BF training is utilized to establish a communication link between a TX and a receiver (RX) in order to overcome the challenges that result from the directional transmission. The BF training of IEEE 802.11ay is similar to the legacy 802.11ad, except that it includes new BF training stages to enhance the BF process. BF for multi-channel, BF for asymmetric links, BF for MIMO, and BF for the TDD channel access are the new BF training protocols, where the basic BF training of IEEE 802.11ay is a sector-level sweep (SLS) BF stage. The SLS is described briefly in the following which is a necessary operation before communication can be established.
- First, initiator-transmit-sector-sweep (I-TXSS) frames are transmitted by the DN in different directions in the BTI whereas quasi-omni mode is used by each CN to receive the frames.
- Second, each CN responds by transmitting a responder-transmit-sector-sweep (R-TXSS) frame in the A-BFT whereas quasi-omni mode is used by the DN to receive the frames.

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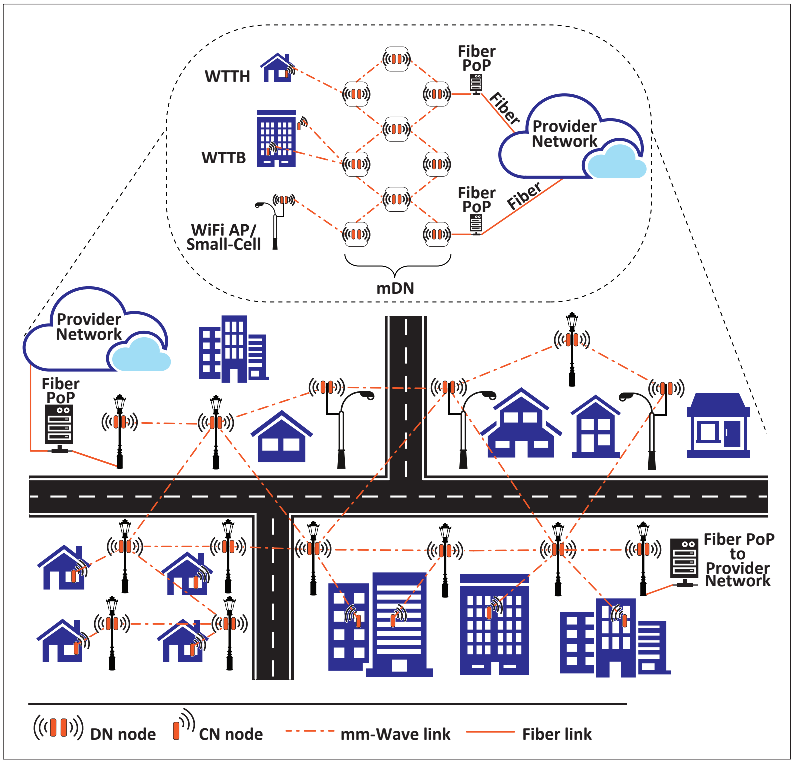


FIGURE 1. The network topology of the mDN.

- Finally, the decision for CN association is made, and the best sector identification (S_{id}) is reported by the DN when sector sweep (SSW)-Feedback is transmitted in the A-BFT.

mmWave Distribution Network

IEEE 802.11ay supports the mDN use case, which can provide a promising cost-efficient and high-performance solution to fiber broadband networks. Recently, FWA has gained considerable attention from both academia and service providers because of the reduced cost of network infrastructure and high speeds compared to the fiber-to-the x (FTTx) networks. The mDN has the potential to build denser urban networks that are capable of connecting more people everywhere in the world with the support of various emerging applications. The design elements and specific details of the IEEE 802.11ay mDN are presented in the following subsections.

mDN Architecture

As illustrated in Fig. 1, the mDN is based on the concept of mesh networking topology, where each node not only sends and receives its data (within its coverage area) but also acts as a relay node to have a direct and dynamic connection with other nodes in the network [8]. The mDN can be deployed by several outdoor DNs, where redundancy can be attained. The mDN can enable neighboring outdoor DNs over multi-hops to construct and preserve non-overlapping data transmission and control allocations dynamically. Furthermore, multi-hop communication is supported to reach destinations in the area coverage. Line-of-sight (LOS) communication is required among the DNs by considering the potential mDN challenges, such as interference and beam tracking. (This is further discussed in a later section.) Various placement options, such as rooftops, house-walls, and street poles, are supported for the DNs in the mDN. The mDN is connected to the provider network through point-of-presence (POP) using an optical fiber link. The distance between the DNs is up to 1000 m and 300 m for rooftops and street poles, respectively, while the distance between a DN and CN is up to 100 m.

mDN Applications

The primary purpose of the mDN is to achieve wireless backhaul network and perform P2MP mmWave access to CNs for the sake of realizing the 5G fiber-replacement application scenarios. These application scenarios include wireless-to-the home (WTTH) access, wireless-to.the-building (WTTB) access, WiFi DN backhauling, and small-cell backhauling. For the WTTH scenario, the DNs can deliver the Internet service to homes by using a window access point at the CN side. For the WTTB scenario, an additional wireless or fixed network inside the building is required to serve the individual units. A further and optional indoor wireless or wired network can be utilized in the WTTH and WTTB scenarios. Different frequency bands from the mmWave links for backhauling can be used for the WTTH and WTTB scenarios. For WiFi and small-cell backhauling scenario, the mDN is used to aggregate and carry the traffic of the mobile services to the mobile core. The capacity level in this scenario is less than the WTTH and WTTB scenarios.

mDN Benefits

Data traffic in communication networks in cities is growing exponentially which demands a tremendous amount of bandwidth per km^2 to support new smart city applications, such as smart utility meters, traffic cameras, a massive number of sensors and smart parking meters. Although optical fiber cable solutions can offer a tremendous amount of bandwidth, the infrastructure cost of the fiber network is expensive, and it can be slower to implement in all locations. Therefore, an efficient solution, such as the mDN, is needed in order to provide Internet access everywhere and improve quality of life. The main benefits of the mDN can be summarized as follows:
- High-speed access (fiber-like speed) can be achieved which is based on the 60 GHz of the IEEE 802.11ay.
- A significant lower-cost network infrastructure is offered for fixed access networks.
- Faster time-to-market can be delivered, where the small mDN access points (DNs) can be implemented on pre-existing street poles or buildings without the need for time-consuming permissions.
- Ubiquitous coverage with high speeds can be realized, where the service can reach areas that can be difficult for fiber network infrastructure in urban or rural areas.

mDN Protocol

The IEEE 802.11ay standard defines a distributed scheduling protocol specifically for the mDNs when two neighboring DNs or more are partially overlapped in order to enhance spatial sharing and interference mitigation, where one or more of the channels utilized in these DNs are similar [1]. The purpose of this protocol is to arrange dynamic non-overlapping allocations and assure fair resource scheduling among DNs, where a highly dynamic network is considered with delay sensitive traffic. The main aspects of the mDN scheduling protocol are summarized as follows.

•Distributed scheduling protocol can be established during an Announce frame in order to initiate the TDD channel access. The Announce frame contains two subfields called TDD-Slot-Structure-Element and TDD-Slot-Schedule-Element; they are responsible for describing the structure of the TDD channel access and addressing the access time assignments by using TDD bitmap schedule, respectively. Therefore, in order to enable the distributed scheduling protocol and identify the upcoming transmission schedules of neighboring DNs, each DN must listen for Announce frames from neighboring DNs and may need to listen in different channels.

•For a specific channel, each DN needs to divide its BI duration by the number of discovered neighboring DNs for the sake of distributing channel resources. To maintain fairness among DNs in the same coverage area with the same channel, the maximum access time allocations of each DN is (BI duration)/(number of discovered neighboring DNs + 1).

TDD Channel Access: In order to achieve fairness communication with no interference in the mDNs, a TDD-SP allocation is defined, where the TDD channel access rules are specified. As shown in Fig. 2, a TDD-SP consists of consecutive TDD-Intervals, where each TDD-Interval consists of consecutive TDD-Slots that are separated by new guard times (GTs). During both the TDD-SP and TDD-Interval, the allocation time may contain one or more slots. The TDD bitmap schedule is utilized to indicate the allocation type, e.g., TX or RX allocations, and the access permissions. The bitmap information is transmitted by each DN to its neighboring DNs in unicast messages during the Announce frame. Moreover, the allocation category, such as a control, management, or Data-only frame, is identified.

mDN BF Training Protocol

Regular BF training is not appropriate with the TDD channel access allocations because different interframes to separate the BF frames are utilized. Therefore, a new TDD BF training is defined for the mDNs by considering the new GT interframes. The TDD individual and group BF training procedures are described in the following.

TDD Individual BF: To establish a communication link between a CN and a DN, the TDD individual BF is utilized by performing a sequential BF training. In this process, only one CN can perform BF training with a DN during assigned TDD-Slots by using unicast TDD BF frames, and these frames are repeated for each CN in order to be trained. As illustrated in Fig. 3(a), the procedure of the TDD individual BF is given as follows.

i) A DN sends several TDD-SSW frames while a CN uses all of its receive sectors during this time. The TDD-SSW frame is sent repeatedly to span all of DN's S_{id}.

ii) A CN transmits a TDD-SSW-Feedback frame by using the sector that has the best quality.

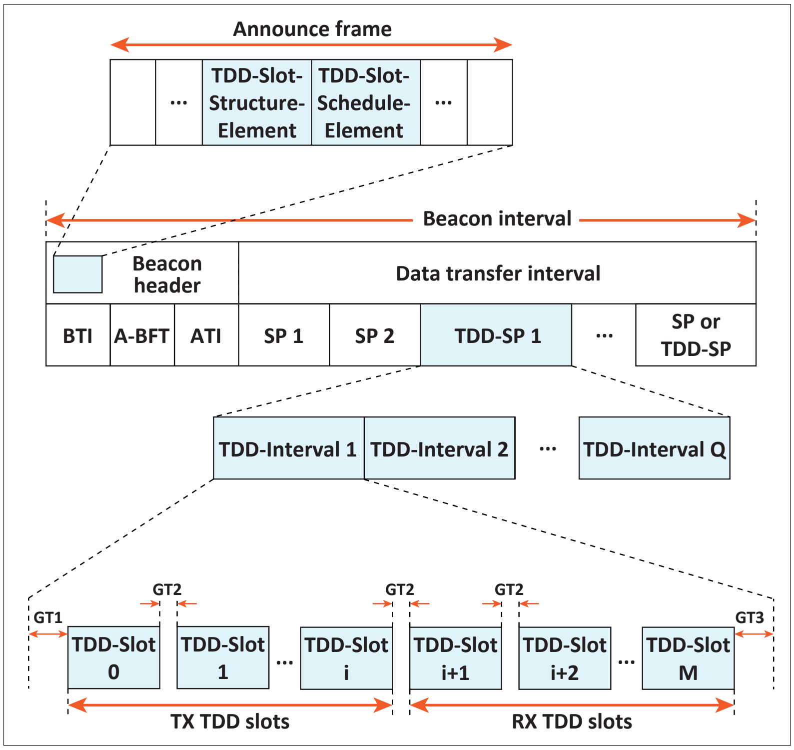


FIGURE 2. The allocation structure of the TDD channel access.

iii) A TDD-SSW-Ack frame is sent by the DN after the reception of a TDD-SSW-Feedback in order to acknowledge the received configuration.

This process can be repeated if needed unless it is specified by the DN to end the TDD individual BF during the TDD-SSW-Ack.

TDD Group BF: In order to increase the TDD BF efficiency by reducing the BF training overhead, TDD group BF is introduced by performing BF training for multiple CNs. Hence, the BF training time is reduced since a certain number of CNs are trained simultaneously. As shown in Fig. 3(b), the procedure of the TDD group BF is similar to the TDD individual BF with the following modifications.

i) A DN sends multiple TDD-SSW frames for multiple CNs by using broadcast the MAC address subfield in order to initiate the TDD group BF. In the TDD-SSW frames, the number of CNs to be trained is specified.

ii) TDD-SSW-Feedback frames are sent by each CN in different time allocations using the sector with the best link quality.

iii) After receiving TDD-SSW-Feedback frames, the DN transmits several TDD-SSW-Ack frames to each CN in different time allocations in order to transmit the sector used by the DN, the sector used by the CN, and whether the BF training is completed or not.

mDN Challenges

Despite the attractive benefits of the mDN, many open questions, problems, and limitations remain. In this section, we identify some future research directions based on the challenges that are associated with the mDN.

Beam Tracking: The overhead generated from beam tracking is a challenge related to mmWave communication that arises because of the need for tracking the changes that occur in analog and

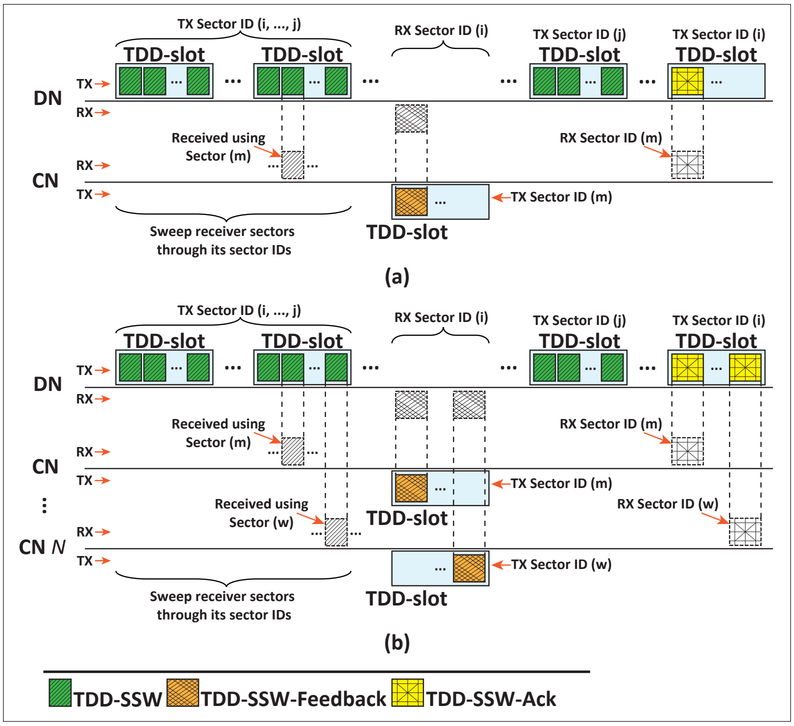


FIGURE 3. TDD BF training procedure: (a) TDD individual BF (b) TDD group BF.

baseband beams, e.g., due to mobility, RX rotation, or blockage. In order to track beam changes between a TX and RX while keeping overhead at an acceptable level, an efficient mechanism is required by employing analog tracking with limited digital baseband channel tracking.

Blockage Effect: Blockage effect is one of the main challenges associated with beam alignment in mmWave communications which can be a result of many causes, including low-emissivity glass and high-density tree foliage. To overcome this challenge, new and efficient beam tracking approaches are needed in order to guarantee the link robustness and quality of user experience. For example, machine learning approaches can be utilized to find the optimal transmit-receive beam pair while considering the beam alignment latency.

Interference Management: Maintaining efficient utilization of the mDN concept with ultra-dense deployment requires spatial and spectrum reuse, which negatively affects the end-user experience at cell boundaries due to co-channel interference (CCI) [9], [10]. Furthermore, interference can be a crucial issue and difficult to be managed especially for IEEE 802.11ay implementation since it is a distributed network. New and efficient methods with low complexity for managing interference and radio resources must be developed for the ultra-dense 5G FWA networks.

Uplink MU-MIMO Transmission

In the mmWave uplink MU-MIMO, a large number of users is expected to be handled in dense deployment scenarios and applications, such as the Internet of Things (IoT) and vehicular communications. Although uplink MU-MIMO transmission is a promising technology, the user selection algorithm needs to be considered in a mmWave system with a large user population. To overcome this challenge, power selection allocation or priority-based resource allocation is required to handle large numbers of users in the multi-hop scenario and to reduce the energy consumption of the system while keeping the complexity reasonably low for practical utilization.

Case Study

In the foreseeable future, emerging data-hungry applications and the proliferation of wireless devices will substantially increase wireless data traffic. To further improve spectrum efficiency of mmWave systems with a large number of users, massive MIMO can be exploited to utilize concurrent transmission. Due to the narrow beams of mmWave directional antennas, concurrent transmissions are possible based on the employment of a spatial reuse mechanism. The IEEE 802.11ay standard supports the MU-MIMO transmission to achieve significant throughput gain [1].

This section presents a case study where a low-complexity concurrent transmission protocol, utilizing one channel frequency, is employed to mitigate the interference and support the mDN use case by exploiting the spatial reuse characteristic. The network performance can be affected by the CCI and adjacent channel interference, in which multiple neighboring nodes are partially overlapped in a dense scenario. This case study focuses on exploiting spatial reuse while mitigating the interference in the dense mDN by implementing an efficient MAC protocol. Specifically, we propose a low-complexity concurrent transmission protocol to attain concurrent downlink transmissions and mitigate the CCI in a wireless mDN without employing digital BF.

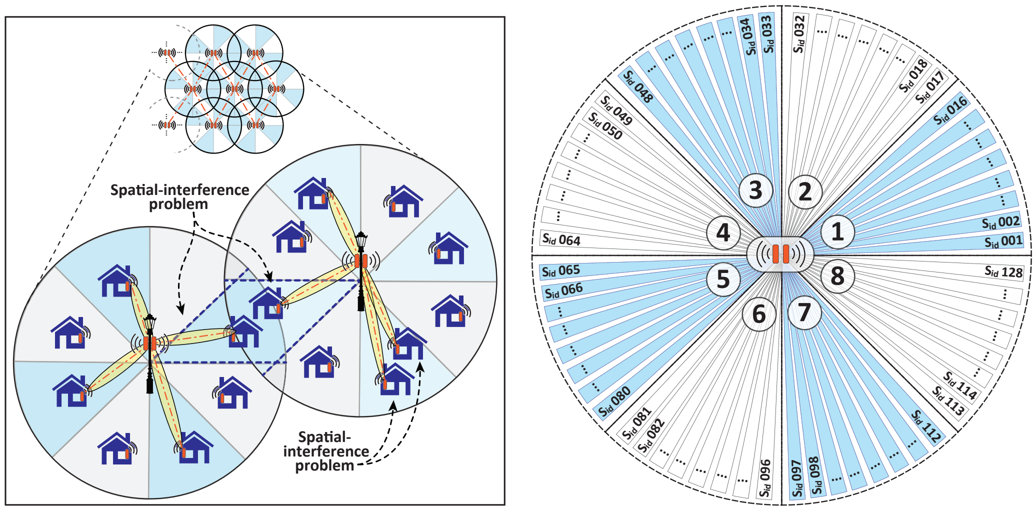
It is worth noting that in order to mitigate the CCI using traditional lower frequency systems, numerous mechanisms have been proposed in the literature by mainly using digital BF methods, such as zero-forcing BF [11]. Nevertheless, for mmWave communications, these methods introduce significant overhead and extreme computational complexity [12] because the size of the channel state information feedback increases with the number of antennas and the number of devices. Furthermore, extra antennas are needed on each TX node for digital BF to mitigate the CCI.

Considered Scenario

As shown in Fig. 4(a), CNs are densely deployed in an mDN, where they can communicate with DNs with directional antennas by performing BF training of the IEEE 802.11ay system. TDD BF training is considered in order to realize an appropriate link budget between a TX and RX before transmitting data, where antenna reciprocity is assumed for both the TX and RX. Highly dynamic topologies are assumed for the mDN use case for the sake of plug and play mechanism to lower the operating expense even though the DNs are fixed while the CNs are not mobile frequently, nearly static.

Low-Complexity Concurrent Transmission Protocol

As depicted in Fig. 4(b), to mitigate the MU interference and the CCI, the low-complexity concurrent transmission protocol divides the coverage area of each DN into virtual sectors. These virtual sectors are divided based on the beam direction associated with the optimal S_{id} determined when



(a) Considered case study scenario.

(b) Virtual segmentation of the predefined antenna directional S_{id} (total S_{id} = 128, as an example).

FIGURE 4. The illustration of the concurrent transmission protocol.

In the foreseeable future, emerging data-hungry applications and the proliferation of wireless devices will substantially increase wireless data traffic. To further improve spectrum efficiency of mmWave systems with a large number of users, massive MIMO can be exploited to utilize concurrent transmission.

the CNs report their S_{id} during the TDD BF training. Then, these virtual sectors are divided into two orthogonal groups (G_1 and G_2) so that concurrent transmission can be achieved in separate time slots for each group [13]–[15]. For the sake of canceling interference among CNs that overlap in the same active virtual sector, a Spatial-Reuse condition is proposed as an essential pre-requisite criterion to meet before transmission can be granted where the spatial-interference problem can be avoided. As illustrated in Fig. 4(a), the spatial-interference problem happens when more than one CN is reported in the same virtual sector within a single hop or when the used virtual sector will incur CCI to any active CNs in other DNs. Specifically, the concurrent transmission can start when the Spatial-Reuse condition is fulfilled, and otherwise, it is terminated from the concurrent transmission and schedule the intended CN sequentially in a different time slot if necessary. The details of the proposed low-complexity concurrent transmission protocol are outlined as follows.

1) A DN initiates an Announce frame to establish a TDD channel access while each DN must listen to identify the upcoming transmission schedules of neighboring DNs, where the maximum permitted BI duration and bitmap information can be exchanged.
2) After the BF training is completed, all DNs check and announce the best S_{id} information that is exchanged from all the associated CNs.
3) Both the MU interference and CCI will be examined by a DN upon reception of the best S_{id} information before granting concurrent data transmission allocations as follows.
   a) If Spatial-Reuse condition is not satisfied when more than one CN are reported in the same virtual sector within a single hop, one CN with the highest signal-to-noise ratio (SNR) will be picked for concurrent transmission. During the TDD-Interval, the selected CN will be allocated in time slot t or $t+1$ if it is located in G_1 or G_2, respectively. The un-selected CNs will be allocated in a different time slot sequentially.

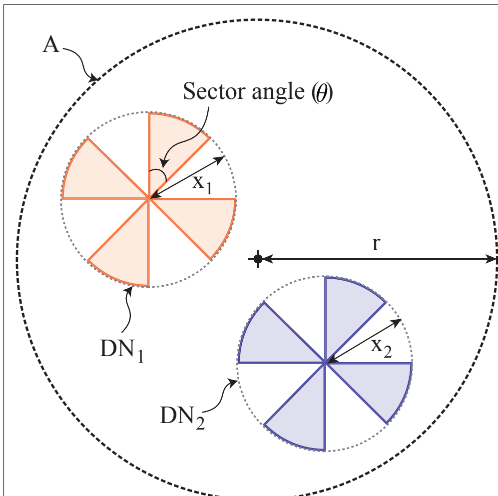
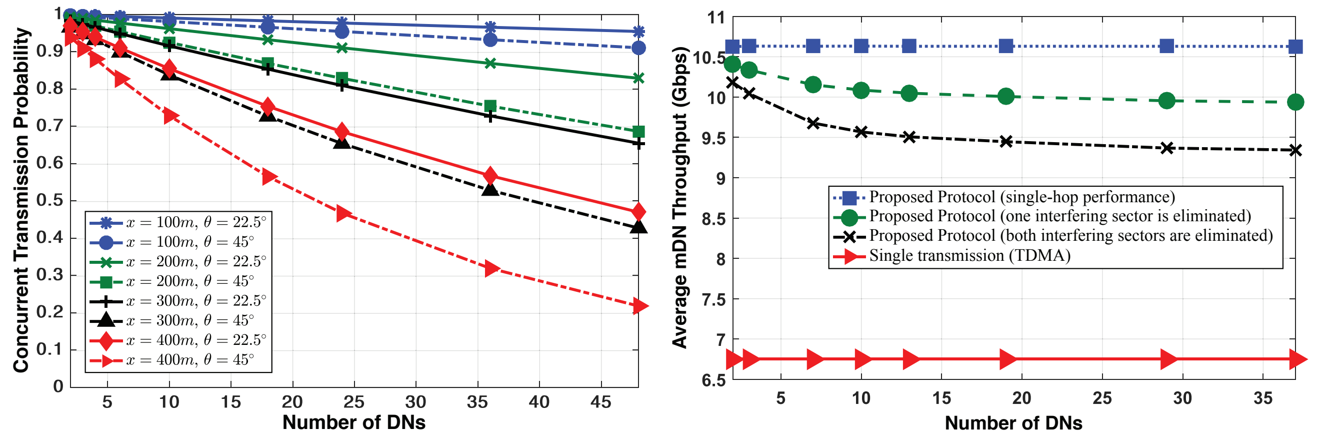


FIGURE 5. Example of the concurrent transmission scenario in an mDN.

   b) If Spatial-Reuse condition is not satisfied when the used virtual sector will incur CCI to any active CNs in partially overlapped DNs, the intended concurrent transmission in this specific virtual sector for the corresponding CN will be terminated and then be rescheduled in a different time slot sequentially.
4) Finally, Data-only TDD-Slots are utilized for concurrent and sequential data transmissions during the TDD-Interval allocations, where these allocations are announced.

Performance Evaluation

We evaluate the performance of the low-complexity concurrent transmission protocol by analyzing the spatial multiplexing gain. The spatial multiplexing gain represents the number of concurrent transmissions allowed over the same mmWave channel in a given area from the perspective of spatial reuse. Moreover, the probability of achieving concurrent transmissions depends on the coverage area and the virtual sector angle,



(a) Probability Q versus the number of DNs ($r = 1600m$). (b) Average network throughput.

FIGURE 6. Low-complexity concurrent transmission protocol performance.

where interference occurs when the active virtual sectors are overlapped.

For simplicity, we consider a traceable case as shown in Fig. 5, where A is a circle area with radius r. There are two or more DNs that have coverage area with radius x_i, where they are randomly distributed in A. Let a_1 and a_2 denote the areas of the active virtual sectors of DN_1 and DN_2, respectively. Then, the probability (P_1) that a_2 does not overlap with a_1 is $1-(x_1^2/2r^2)$ while the probability (P_2) that a_1 does not overlap with a_2 is $1-(x_2^2/2r^2)$. Thus, the probability that both DN_1 and DN_2 do not interfere with each other is $Q = P_1P_2$. Fig. 6(a) shows the numerical results of the probability Q versus the number of DNs when different values of virtual sector angle (θ) and radius coverage (x) are considered, assuming all DNs have the same x in every time. Fig. 6(a) shows how the concept of the proposed protocol by separating the coverage zone into virtual sectors can increase the channel utilization efficiency and interference mitigation as long as the coverage area of each DN is small enough.

Fig. 6(b) shows how the unique spatial reuse of the low-complexity concurrent transmission protocol can be exploited to realize concurrent downlink transmission compared to the time-division multiple access (TDMA) method. We simulate nearly two-million BIs taking different network topologies into account to show the average mDN throughput performance per data time slot. As shown in Fig. 6(b), significant average network throughput can be achieved due to the two-time slots of G_1 and G_2 that can realize concurrent transmission. Simulation results demonstrate that both interference mitigation and simultaneous transmission can be realized without the need for complex precoding methods.

Conclusions

This article has investigated the new protocol specifications and design elements of the mDN by providing a comprehensive picture to adopt an alternative solution to conventional fixed networks that can be a strong business case to provide Internet access to households worldwide. Some of the mDN challenges have also been highlighted for future research and improvement. Finally, a case study on realizing concurrent downlink transmissions in the mDN has demonstrated the potential of concurrent transmission on enhancing network performance while mitigating the interference.

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