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Research Article

Performance Evaluation of IEEE 802.11ad in Evolving Wi-Fi Networks

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The IEEE 802.11ad technology, which allows wireless devices to communicate in the unlicensed 60 GHz ISM band, promisingly provides multi-Gbps data rates for bandwidth-intensive applications. After years of research and development, we are now observing an increasing number of commodity IEEE 802.11ad radios that motivate researchers to exploit the IEEE 801.11ad capability for applications. This work first conducts an empirical study on the IEEE 802.11ad performance. In particular, we characterize the performance of IEEE 802.11ad links considering the variation of network parameters and interference. Secondly, we investigate the possibility of introducing IEEE 802.11ad to an evolving Wi-Fi network. The evaluation results show that our off-the-shelf IEEE 802.11ad hardware can achieve the Gbps level throughput of the transmission control protocol (TCP) and user datagram protocol (UDP). However, the evolvement is not trivial since the hardware can not well maintain the 60 GHz link. The main reason is lacking the fast switchover function between an IEEE 802.11ad and a legacy Wi-Fi link. We then seek the potential of multipath TCP (MPTCP) for the expected switchover. The default MPTCP, which enables data transmissions on both the IEEE 802.11ad and Wi-Fi links, is harmful to the IEEE 802.11ad throughput. Meanwhile, the backup mode of MPTCP, in which the Wi-Fi link acts as a backup for IEEE 802.11ad one, can maintain the comparable performance. Therefore, we propose to adopt MPTCP with the backup mode in the evolving Wi-Fi networks. The efficiency of MPTCP-based switchover is confirmed by conducting real experiments.

1. Introduction

In recent years, the popularity of wireless devices and the explosion of wireless traffic require ever-increasing demands on better network performance [1]. Accordingly, there are ongoing efforts in realizing the next generation of mobile wireless networks (i.e., 5G), which is expected to provide significantly high peak performance indicators (i.e., 1000 times better than the current 4G) [2, 3]. The new network is also envisioned to support the next generation of bandwidth-intensive applications such as 4K, 8K video streaming, real-time gaming, and virtual and augmented reality. It is widely agreed that leveraging the underutilized radio spectrum of millimeter wave (mmWave) band (i.e., between 30 GHz and 300 GHz) is one of the most promising approaches to satisfy the bandwidth demand [4–6]. Within the mmWave band, there is a vast amount of bandwidth (up to 14 GHz) that is allocated as the unlicensed 60 GHz band (i.e., 57-71 GHz spectrum). The 60 GHz band communication is supported by the IEEE 802.11ad standard [7, 8], which aims to bring multi-Gbps data rates to the next generation Wi-Fi network.

The IEEE 802.11ad physical layer uses 2.16 GHz-width channels that theoretically provide data rate up to 6.76 Gbps per single channel. Moreover, the IEEE 802.11ad radio with directional beams can improve the spatial use. The IEEE 802.11ad signal, however, incurs much higher attenuation than the one of legacy Wi-Fi. To compensate for the path loss, the IEEE 802.11ad device uses high gain antenna arrays, which on the other hand introduces a new challenge of link maintenance (e.g., when blockage exists). The maintenance is expected to be realized by switching to a legacy Wi-Fi link when the IEEE 802.11ad link is not available. Accordingly, numerous efforts in research and development have led to the advent of low-cost, low power, off-the-shelf IEEE 802.11ad devices [9]. The advent motivates many experimental studies that aim to exploit the 60 GHz opportunity in evolving

Wi-Fi networks. The previous works provide not only valuable insights of 60 GHz communication and IEEE 802.11ad features [10, 11] but also new use cases of IEEE 802.11ad [12, 13]. Although much has been understood, there is a lack of common understanding about the characterization of IEEE 802.11ad performance (esp. the feasible multi-Gbps throughput), as well as, evolvability of IEEE 802.11ad on Wi-Fi networks.

This work first addresses the issue of performance characterization; we empirically evaluate an off-the-shelf IEEE 802.11ad hardware in a typical office environment towards the achieved multi-Gbps throughput. The performance metrics of IEEE 802.11ad links have been extensively investigated under the variation of different network parameters and interference. In particular, we consider the existence and nonexistence of two typical types of IEEE 802.11 interferences (i.e., cochannel and adjacent channel). Moreover, we also scrutinize the network parameters such as signal strength, modulation and coding scheme (MCS), Maximum Transmission Unit (MTU), and traffic types (i.e., TCP and UDP). Thanks to the support of the IEEE 802.11ad driver and associated tools, we can find the multi-Gbps throughput (for both TCP, UDP) following the conditions of modulation and coding scheme (MCS) set, signal strength, and MTU. We also quantify the traditional interference effects on the throughput and lost packet metrics.

Secondly, targeting the evolvability issue, thoroughly investigate the capacity of link maintenance (i.e., the most significant challenge of 60 GHz communication). Our evaluation shows that the IEEE 802.11ad link itself can neither bypass the blockage nor handle the change of antenna direction. That is because there is a lack of the function of fast switchover between the IEEE 802.11ad and a legacy Wi-Fi link. We then seek the possibility of multipath TCP (MPTCP), which is capable of exploiting multiple wireless links concurrently, for the switchover. Our investigation points out that the default MPTCP (i.e., full mesh mode) that simultaneously uses the IEEE 802.11ad and Wi-Fi links for data transmission is not efficient. The overall throughput is largely varied and is always smaller than the TCP throughput of IEEE 802.11ad link. On the other hand, the backup mode of MPTCP, in which the IEEE 802.11ad and Wi-Fi links are in an active/standby state, guarantees the comparable throughput. Therefore, we propose to adopt MPTCP with the backup mode for the switchover. The efficiency of MPTCP-based switchover has been confirmed by conducting the real experiments.

The remainder of this paper can be outlined as follows. The following section presents related works. In Section 3, we introduce the imperial investigation on IEEE 802.11ad. Section 4 introduces an evolving Wi-Fi network with MPTCP. Finally, Section 5 concludes the paper.

2. Related Works

The experimental study is a popular method for understanding the performance characterization in IEEE 802.11 (Wi-Fi) networks. The method has shown its usability with different IEEE 802.11 versions such as IEEE 802.11n [14] or IEEE 802.11ac [15]. Additionally, the same technique is also efficient in finding the conditions of significant IEEE 802.11 features (e.g., channel bonding in IEEE 802.11n [16]). With IEEE 802.11ad, there have been several early works, which use the experimental study [17–20]. Those works focus on modeling channel propagation characteristics using dedicated hardware for 60 GHz communications. In [10], the authors investigate the performance of 60 GHz links under conditions of introducing blockage and different antenna orientations. However, they use the non-802.11ad hardware and measure the performance of IP-over-wireless-HDMI. Hence, the results do not adequately reflect the characteristics of IEEE 802.11ad link. The work in [11] has profiled the indoor 60 GHz links by using a software-defined radio platform. Although the work offers many valuable insights (e.g., about the potential capabilities and limitations of flexible beams), it may not reflect the behavior of the real IEEE 802.11ad hardware (because of using a channel width of 245 MHz).

On the other hand, the off-the-shelf IEEE 802.11ad hardware is gaining popularity after years of efforts in R & D. That attracts the experimental studies on the IEEE 802.11ad performance. The most related one to ours is [21], in which the authors experiment IEEE 802.11ad radios in an indoor environment. Their results indicate the advantages of IEEE 802.11ad development in overcoming blockage and establishing suitable communication ranges. However, the feasibility of multi-Gbps IEEE 802.11ad link has not been fully confirmed. In fact, the measured throughput values are all below 1 Gbps. The reason may be the effects of autorate algorithm, which can not be disabled on the investigated hardware. Moreover, the authors use TCP traffic; hence the TCP congestion control may affect the performance. Additionally, some throughput values are reported indirectly via the PHY rates, which may not reflect the real ones correctly. We aim to complement the work [21] in the context of introducing the multi-Gbps IEEE 802.11ad link on evolving Wi-Fi networks. The difference in ours which initiated from the previous work [22] is that we consider the other influenced factors including interference, packet size, as well as, both the UDP, TCP traffic. Comparing to [22], this paper additionally includes more results such as the performance of interferer links under TCP and UDP.

The link maintenance capability, which is critical for the evolvement of IEEE 802.11ad, has been investigated in several related works. In [23, 24], the authors present the implementation and evaluation of Fast Session Transfer (FST) within the IEEE 802.11ad standard. The evaluation results have shown the successful switch of continuous UDP flow between the 60 GHz and 5 GHz bands. However, those works are all simulation-based (i.e., [23] is with the OPNET environment while [24] is with ns-3), they may not correctly reflect the real IEEE 802.11ad hardware. On the other hand, MPTCP that simultaneously utilizes multiple wireless links for data transmission is a candidate for the expected switchover. In fact, the MPTCP-based switchover has been useful in many use cases such as Wi-Fi/LTE [25], virtual Wi-Fi/virtual Wi-Fi [26], Wi-Fi/Wi-Fi [27]. This work deeply investigates the capability of MPTCP in bypassing the problem of 60 GHz link maintenance. The feasibility of switching back-and-forth a multi-Gbps transmission between an IEEE 802.11ad and a legacy Wi-Fi link has been initially presented in [28]. This work provides the detailed comparison with a new performance metric aiming to affirm the efficacy of MPTCP further.

3. Empirical Study on IEEE 802.11ad Performance

In this section, we first describe the overview of IEEE 802.11ad. After that, we present the experiment environment and the measurement results.

3.1. IEEE 802.11ad Overview. The IEEE 802.11ad standard supports peer-to-peer and infrastructure connections. In an IEEE 802.11ad link, each end's physical layer executes a beamforming mechanism to form directional transmit/receive beams using a phased-array antenna. There are four types of PHY layers in the standard (i.e., control PHY, OFDM PHY, Single Carrier (SC) PHY, and Low Power SC PHY), each of which supports a set of MCSs. In the 2012 version, the channel list for IEEE 802.11ad operation in the 57-63 GHz band includes four channels as presented in Table 1. Recently, the Federal Communication Commission (FCC) of the US has announced that the 7 GHz band between 64 and 71 GHz is unlicensed aiming to be used by IEEE 802.11ad [29].

The 60 GHz link has a problem with blockage vulnerability. Moreover, the antenna direction may change in operation. Therefore, the link maintenance is vital to efficiently evolve IEEE 802.11ad on Wi-Fi networks. For that purpose, the IEEE 802.11ad standard defines the Fast Session Transfer (FST) protocol [7]. The protocol is supposedly equipped with multiband devices that have an IEEE 802.11ad and a legacy Wi-Fi radio. FST concurrently manages the radios, which are either in a transparent or nontransparent mode (i.e., having the same MAC address or different MAC addresses, respectively). FST defines a procedure of switching traffic between two links operating on different bands. The standard also specifies another mode of FST, in which the data transmission can concurrently happen over two bands (i.e., for link aggregation).

3.2. Experiment Environment. We conduct our investigation using a testbed deployed in a typical office environment. Each IEEE 802.11ad link is constructed by a pair of radio modules, which are produced by Panasonic Inc., Japan. Each module is connected to an Ubuntu 14.04 LTS machine that includes the supporting drivers and monitoring utilities. The radio module can run in the client or personal basic service set (PBSS) control point (PCP)/access point (AP) modes. The IEEE 802.11ad defines antenna beams as narrow as 2.86-degree. However, the investigated IEEE 802.11ad module uses 50-degree beam width [9]. Therefore, the throughput measurements in our study are probably the lower bounds of achievable performance of IEEE 802.11ad link. The module contains an implementation of single carrier PHY, that supports nine transmission rates (i.e., MCS indices 1 to 9). The basic information and theoretical PHY rate of MCSs are presented in Table 2. In the 60 GHz band, the module can operate on channel 2 and channel 3 indicated in Table 1. The maximum value of supported MTU is 7912 bytes. We use the popular tool *iperf3* [30] for generating and collecting TCP and UDP traffic flows. The *iperf3* server, client runs on the machine associated with IEEE 802.11ad AP/PCP, client mode, respectively. The traffic flow typically lasts ten seconds. *iperf3* supports storing traffic information in the *json* format that is easy to parse for further processing and analysis. In order to conveniently experiment, we wrote custom scripts for easily controlling the settings of MCS, MTU, and collecting, extracting, and processing the measurement data such as Received Signal Strength Indicator (RSSI) provided by the IEEE 802.11 driver, etc.

3.3. Investigation of IEEE 802.11ad Capability. The investigation begins with checking the signal quality of IEEE 802.11ad link (i.e., ranges of RSSI values) in our environment. To identify the range of RSSI, we record the RSSI values every 0.1 seconds while varying the distance and direction between the pair of IEEE 802.11ad radios. We found that the IEEE 801.11ad link can communicate within the signal range of (-41 dBm, -69 dBm). In the following experiments, we define the strong signal scenario where the RSSI value is kept within (-41 dBm, -43 dBm) and the RSSI value in the weak one is within (-65 dBm, -69 dBm).

We then investigate the TCP and UDP throughput of IEEE 802.11ad link under the combination of all supported MCSs and the link quality scenarios. We also consider different sizes of MTU since they largely affect the throughput. For the high throughput purpose, the link should use the maximum supported MTU. Besides, there are cases of communicates to a far destination (e.g., more than one hop or accessing the Internet). In such cases, the communication is likely limited by a common MTU on the end-to-end path. Therefore, we select the value of 1500-byte MTU, which is typical on Wi-Fi networks and the Internet. We then evaluate the maximum supported MTU (7912 bytes) to observe the full capability provided by the hardware. The evaluation results expose distinct patterns in the behavior of throughput concerning different traffic types, MCSs, and MTUs. We provide a representative subset of our results that show the patterns as mentioned earlier in Figures 1, 2, 3, and 4. In each figure, the average throughput value at each MCS collected and calculated from ten measurements is shown. Moreover, the error bar shows the distance between maximum and minimum values.

The measured throughput of UDP and TCP traffic with 1500-byte MTU in the different signal scenarios are shown in Figures 1 and 2, respectively. Comparing the UDP throughput in the two figures, we can draw a common observation; that is, the UDP throughput is not directly affected by the signal strength. When the IEEE 802.11ad sends at the same speed (i.e., the same MCS value), the results are comparable in the two scenarios. We also have another important observation; that is, the UDP throughput reaches around 1 Gbps with MCS8 and MCS9. On the other hand, the weak signal negatively affects the TCP transmission, especially at the high transmission rates. That is indicated by the visible error bars

Table 1: IEEE 802.11ad channel list.

Channel	Center (GHz)	Minimum (GHz)	Maximum (GHz)	Bandwidth (GHz)
1	58.32	57.24	59.4	2.16
2	60.48	59.4	61.56	2.16
3	62.64	61.56	63.72	2.16
4	64.8	63.72	65.88	2.16

Table 2: Supported single carrier PHY modulation and coding scheme.

MCS Index	Modulation	Repetitions	Coding Rate	Rate (Mbps)
1	$\pi/2$ BPSK	2	1/2	385.0
2	$\pi/2$ BPSK	1	1/2	770.0
3	$\pi/2$ BPSK	1	5/8	962.5
4	$\pi/2$ BPSK	1	3/4	1155.0
5	$\pi/2$ BPSK	1	13/16	1251.0
6	$\pi/2$ QPSK	1	1/2	1540.0
7	$\pi/2$ QPSK	1	5/8	1925.0
8	$\pi/2$ QPSK	1	3/4	2310.0
9	$\pi/2$ QPSK	1	13/16	2502.0

on the right side of Figure 2. Moreover, the TCP throughput values are much smaller than not only the ones of UDP but also the level of 1 Gbps. The reasons include the limitation of MTU size and the sequencing transmissions of TCP. It is obvious that the IEEE 802.11ad link is not able to achieve the multi-Gbps performance with the 1500-byte MTU.

However, we have a different observation in the case of 7912-byte MTU as shown in Figures 3 and 4, which include many multi-Gbps values in both the strong and weak signal scenarios. In the former situation (Figure 3), the TCP and UDP throughput monotonically increase along with the higher transmission rates within each MCS set. The throughput values of UDP and TCP become higher than 1Gbps with the rate provided by MCS6 and MCS7, respectively. In the latter scenario (Figure 4), the increasing trend of UDP throughput is similar except for the case of the maximum supported rate (MCS9). In that case, the big MTU size gets more negative effects than the small MTU. However, it may be efficiently fixed by an algorithm of rate selection that never sends at the maximum speed with the weak signal. On the other hand, the negative effects of the weak signal on TCP are more severe than the ones on UDP. The TCP throughput starts to be significantly degraded from MCS8. That is caused by the behavior of TCP congestion control, which reduces the transmission rate due to lost packets.

From the above observations, we can conclude that the multi-Gbps throughput of IEEE 802.11ad link has been achievable with both the TCP and UDP traffic. However, those high throughput values depend on the signal strength, PHY rates, and MTU on the system.

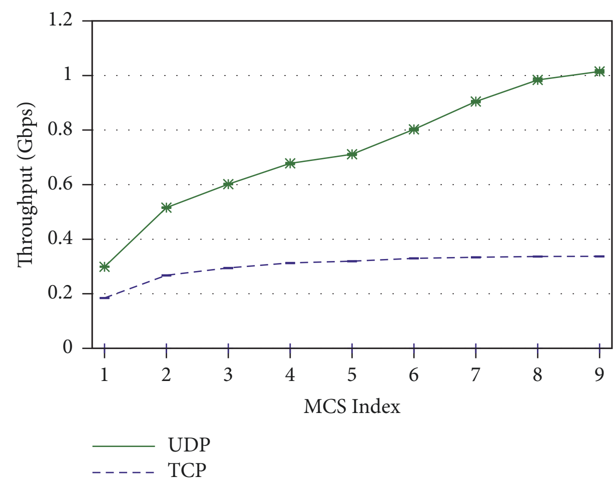

Figure 1: Throughput in strong signal and 1500-byte MTU scenario.

3.4. Impact of Adjacent Channel and Cochannel Interference. This section investigates the effects of conventional interference factors (i.e., adjacent channel interference (ACI) and cochannel interference (CCI)) on the IEEE 802.11ad performance. ACI means wireless transmission on a specific channel suffers interference from channel leakage of its adjacent channels. Meanwhile, CCI indicates the effect of two communications that share a channel without being aware due to the known hidden terminal problem. The hidden terminal problem occurs when two transmitters are not in the transmission range of each other but the carrier sensing range. Due to the beamforming, the nearby position of am IEEE 802.11ad transmitter is within the carrier sensing range if it is outside of the directional transmission.

We set up an additional IEEE 802.11ad link with the strong signal as the interferer to evaluate the interference effects. An *iperf3*'s UDP flow over the link runs at the maximum

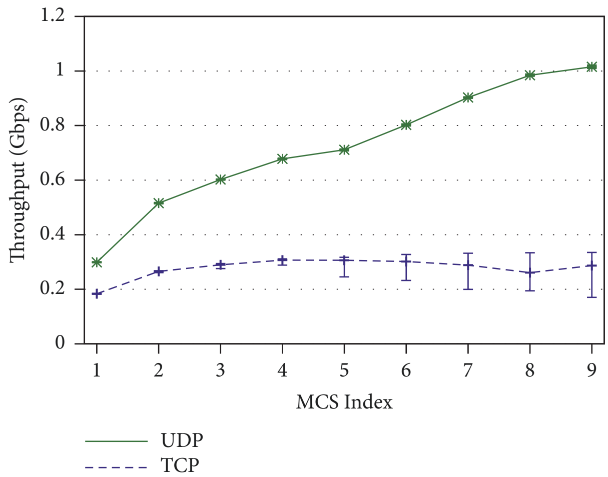

Figure 2: Throughput in weak signal and 1500-byte MTU scenario.

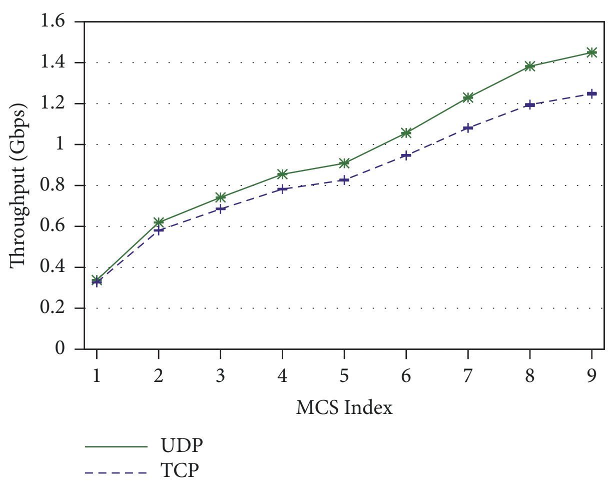

Figure 3: Throughput in strong signal and 7912-byte MTU scenario.

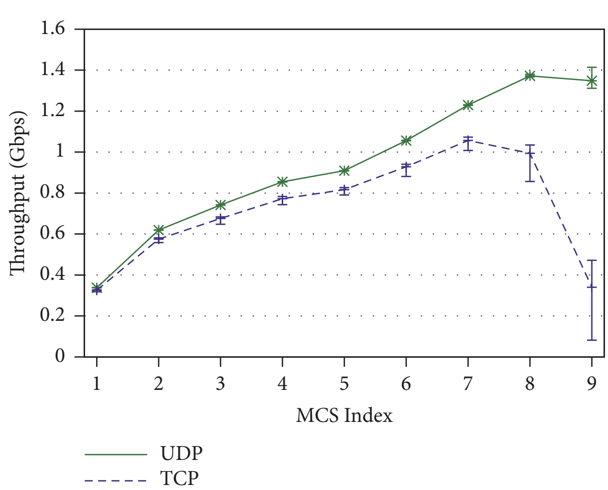

Figure 4: Throughput in weak signal and 7912-byte MTU scenario.

speed. The link is therefore supposed to fully occupy the wireless medium when there is no other transmission. The interference link is configured to operate on channels 3 and 2 for the investigation of ACI and CCI respectively. We use the 7912-byte MTU aiming to observe the variation of the multi-Gbps link. Similar to the previous experiments, we run our custom scripts, which enable the use of all supported MCSs. With each MCS, the associated experiment is also repeated ten times. We make the comparison with two metrics: the normalized throughput and the percentage of lost packets. The normalized throughput is defined as follows:

$$Th_{normalized} = \frac{Th_{measured}}{Th_{expected}} \quad (1)$$

in which $Th_{measured}$ and $Th_{expected}$ are the measurement throughput and the expected throughput, respectively. At each MCS, we choose $Th_{expected}$ as the maximum throughput derived from the previous section. The average, minimum, and maximum values of normalized throughput and the percentage of lost packets are plotted in Figures 5 and 6.

In Figure 5, the normalized throughput values are all less than 1. That means ACI and CCI have negative impacts on the performance of IEEE 802.11ad link. Moreover, the average value (i.e., in the box plots) decreases along with the increase of data rates provided by MCSs; meanwhile, the values of measured throughput in fact increase. That indicates the higher transmission rates, the more serious impacts of interference. In the ACI scenario, the normalized throughput becomes less than 80% when the MCS index is higher than 5. On the other hand, similar degradation happens at MCS2 in the CCI scenario. CCI obviously has heavier influence than ACI. More specifically, the measured throughput in the ACI scenario is approximately 1 Gbps with MCS8 and MCS9. However, in the CCI scenario, the throughput values regardless of MCSs are all under the 1Gbps level. Another observation (in Figure 5) is that the interference effects cause big fluctuations in the IEEE 802.11ad throughput in different runs (i.e., in the error bars), especially in the CCI scenario. In order to avoid the fluctuations, the algorithms of careful network planning or interference mitigation may be necessary.

In Figure 6, the percentage of lost packets also shows a similar trend. When transmitting at low data rates (i.e., up to MCS5), the percentage values in the ACI and CCI scenarios are as small as the ones in the no-interference situation. However, when the data is transmitted at the higher rates, more lost packets appear in the two interference scenarios. The maximum percentage of the lost packet in the ACI scenario is about 1%. In the CCI scenario, the value of the maximum one is nearly 5%. The values are seemingly reasonable in comparing to the existing IEEE 802.11 networks in terms of percentage. The absolute amount of lost traffic, however, needs to be considered when deploying the multi-Gbps capability.

We further investigate ACI and CCI with the same setup of two IEEE 802.11ad links (i.e., strong signal, 7912-byte MTU); the traffic characteristic over the two links is however different. In this case, we try to start the traffic flows on the

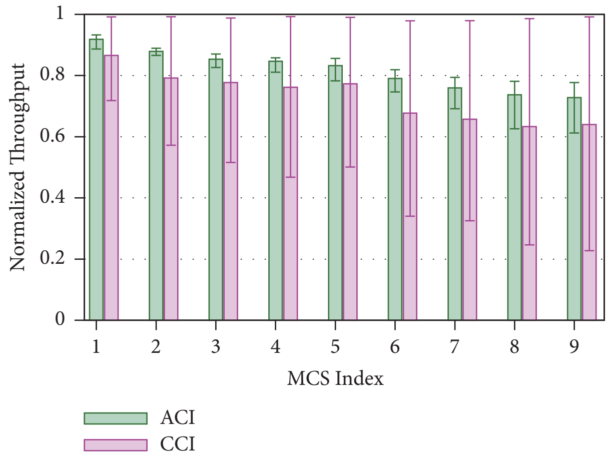

Figure 5: Comparison of UDP normalized throughput.

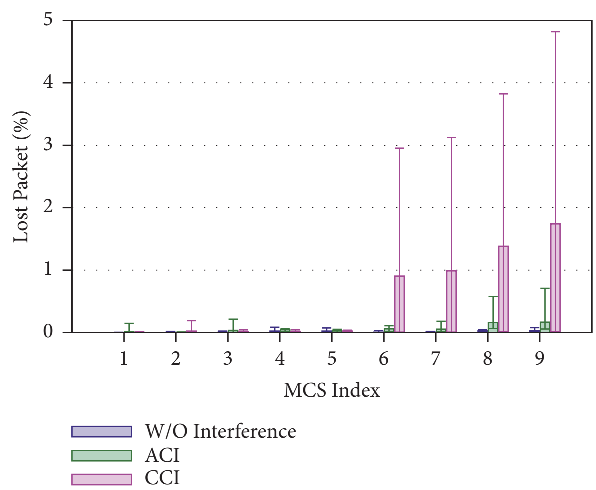

Figure 6: Comparison of lost packets.

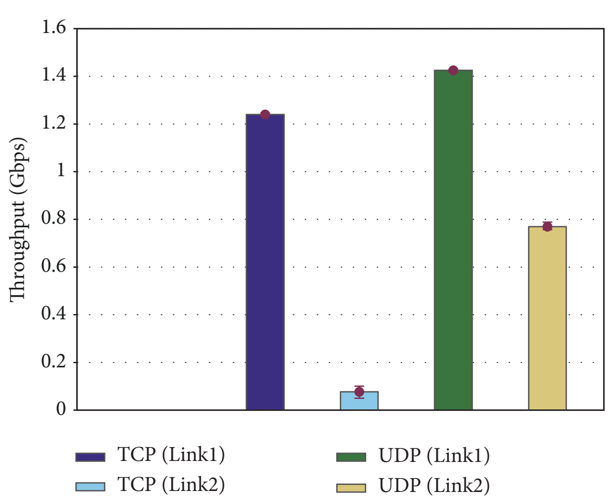

Figure 7: Throughput comparison in ACI scenario with concurrent start of two flows.

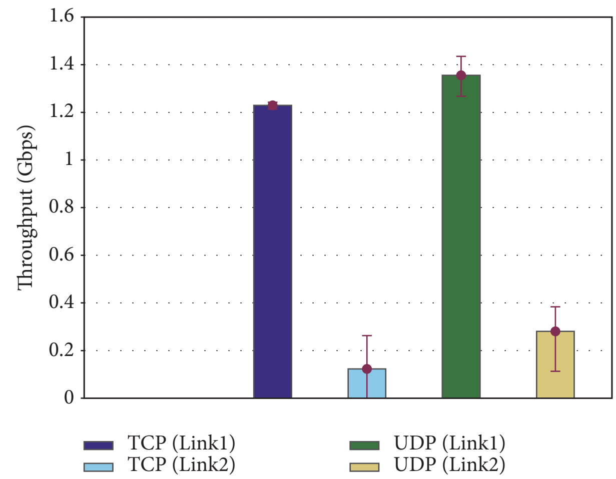

Figure 8: Throughput comparison in CCI scenario with concurrent start of two flows.

two links concurrently with both TCP and UDP traffic. In each experiment, when the *iperf3* process starts on Link1, it will enable remote access that initiates a similar *iperf3* process on Link2. In the same condition, an experiment is repeated ten times. We then plot the average, minimum, and maximum throughput values of UDP and TCP over the two IEEE 802.11ad links in the ACI and CCI scenarios in Figures 7 and 8. We can again observe that ACI and CCI cause significant degradation of the throughput of Link2. There is seemingly no fairness between the two links, probably due to a slower initialization of *iperf3* on Link2. In both ACI and CCI, the lost packets on the Link2 are severe that even makes the TCP traffic inefficient. The UDP throughput of Link2 is better than the TCP one. However, comparing to the noninterference scenario, the UDP throughput of Link2 equals half and one-fourth in case of ACI and CCI, respectively. Therefore, an efficient interference mitigation algorithm is necessary to guarantee the throughput performance.

4. Evolving IEEE 802.11ad on Wi-Fi Networks with MPTCP

This section first investigates the capability of link maintenance in IEEE 802.11ad. We then present a method of realizing the link maintenance using MPTCP.

4.1. Link Maintenance Capability and MPTCP Potential. The link maintenance is critical in IEEE 802.11ad since the antenna may temporarily change directions or incur blockage. We hence check the ability of link maintenance on our hardware. We set up a traffic flow running over the IEEE 802.11ad link in 60 seconds. During the period, we observe the variation of traffic under two events: temporary introducing blockage and turning antenna directions. The throughput variation is plotted in Figure 9, which shows a common behavior in both cases. When the events occur the IEEE 802.11ad link is disabled and the throughput goes to zero; the link maintenance problem has not yet solved.

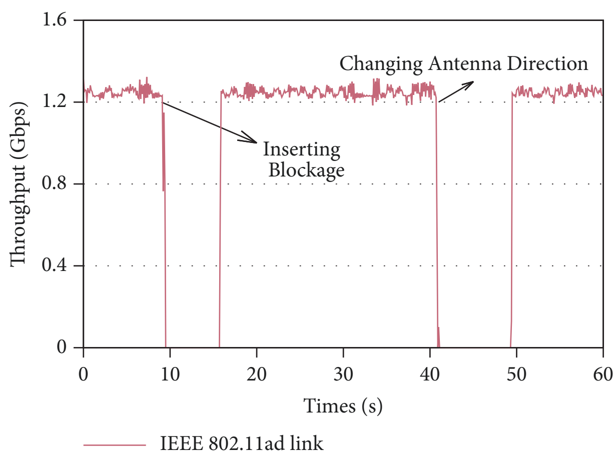

Figure 9: Throughput variation with introducing blockage and changing antenna direction.

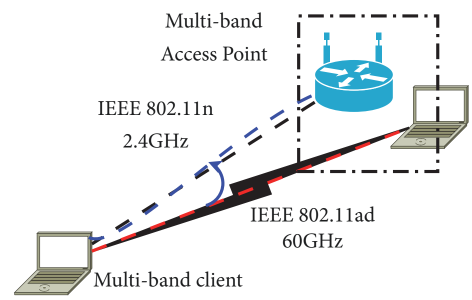

Figure 10: Evolving Wi-Fi network.

It is necessary to bypass that problem to introduce the IEEE 802.11ad link in evolving Wi-Fi networks. The standard approach is getting the assistance from a legacy Wi-Fi link on the same device since the Wi-Fi link does not insist the mentioned events. However, the Fast Session Transfer (FST) function, which cooperates with IEEE 802.11ad and Wi-Fi links, is not supported by the hardware. Therefore, a replacement method is expected with the primary goal of achieving a fast switchover function between an IEEE 802.11ad link and legacy Wi-Fi link. MPTCP, which has recently standardized by IETF, shows a lot of potential in providing the switchover.

MPTCP introduces an additional layer between the application layer and the transport layer in the networking stack. MPTCP does not require any modification in the application or lower layers. MPTCP divides the application data into several subflows (i.e., similar to TCP connections), each of which contains data packets following a different path from a sender to a receiver. The received packets at the receiver are restructured based on their data sequence number. The default operation mode of MPTCP (i.e., full mesh) aims to maximize the usage of all available paths for throughput improvements. In the other modes, MPTCP can use a subset of available paths while putting the remaining paths in a standby condition. With the different modes of operation, as well as two levels of sequencing (i.e., subflow and data), MPTCP theoretically supports the automatic switching and shifting traffic between paths.

MPTCP is however designed for the LTE/Wi-Fi environment. Its potentiality and applicability in the evolving Wi-Fi network (i.e., with IEEE 802.11ad) in practice are not yet known. Besides, the legacy Wi-Fi and IEEE 802.11ad link have the significant difference in characteristics, which may cause unexpected harmful behaviors (e.g., bad packet reordering, inflated or false retransmission timeout, link overshoot, etc.) during the switchover. Addressing those, we investigate two possible operational modes of MPTCP (i.e., namely, full mesh and backup) in the evolving Wi-Fi network. In the former mode, the Wi-Fi and IEEE 802.11ad links are concurrently used for transmitting data (i.e., supporting active/active switchover). In the latter, one link is a backup for the other (i.e., active/standby switchover).

4.2. Evolving Wi-Fi Network with MPTCP. We construct an evolving Wi-Fi network that includes IEEE 802.11ad, legacy Wi-Fi link, and MPTCP to investigate the capability of MPTCP. The network is shown in Figure 10 in which the multiband (MB) client has an IEEE 802.11n radio (i.e., on the 2.4 GHz band) and an IEEE 802.11ad radio. The MB can communicate with the multiband access point (AP) via both the 2.4 GHz and 60 GHz links. The AP and the MB client are equipped with the MPTCP kernel version 0.90 [31]. The appropriate routing policy has been configured to route packets correctly over two wireless links. In each experiment, we use *iperf3* to generate a TCP flow from the MB client to the AP in 60 seconds.

We initially explored the MPTCP's two modes in normal conditions (without link error) in the network. The performance metric under investigation is inherited from the aggregation benefit function, which has been proposed in the literature [32]. We slightly modify the function to include this case, where MPTCP uses two links IEEE 802.11ad and 802.11n. If we denote *Ben*(*mode*) as the aggregation benefit function in an operation *mode* of MPTCP, the function is as follows.

$$Ben\,(mode) = \begin{cases} \dfrac{T_{mode} - L_{max}}{\sum_{i=1}^{2} L_i - L_{max}}, & \text{if } T_{mode} \geq L_{max} \\ \\ \dfrac{T_{mode} - L_{max}}{L_{max}}, & \text{if } T_{mode} < L_{max} \end{cases} \tag{2}$$

where L_i is the link capacity of the link i, L_{max} is the highest capacity among all links, and T_{mode} is the measured throughput value of MPTCP with *mode*. In the investigated network, L_{max} is always the throughput over the IEEE 802.11ad link. We denote L_{11ad} and L_{11n} as the link capacity of IEEE 802.11ad and IEEE 802.11n link, respectively. *Ben*(*mode*) in (2) can be transferred to

$$Ben\,(mode) = \begin{cases} \dfrac{T_{mode} - L_{11ad}}{L_{11n}}, & \text{if } T_{mode} \geq L_{11ad} \\ \\ \dfrac{T_{mode} - L_{11ad}}{L_{11ad}}, & \text{if } T_{mode} < L_{11ad} \end{cases} \tag{3}$$

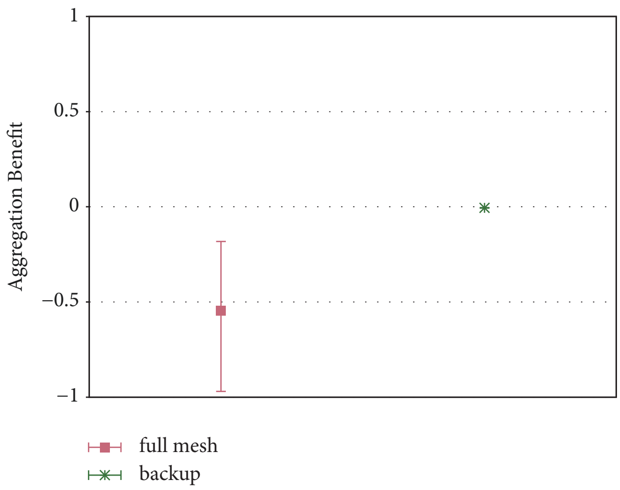

Figure 11: Comparison of aggregation benefit.

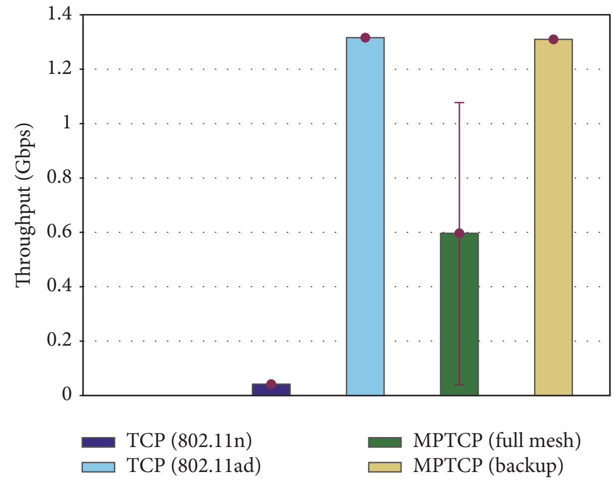

Figure 12: Throughput comparison between MPTCP in two modes and TCP.

It is obvious that the values of $Ben(m)$ are in the range $[-1, 1]$. If $Ben(m) \geq 0$, MPTCP has a positive benefit and vice versa.

To identify L_{11ad} and L_{11n} in (3), we run *iperf* 3 with TCP over each wireless link; each experiment is repeated ten times. In this case with the maximum supported speed at MCS9 of IEEE 802.11ad, we selected the maximum throughput among all runs, which is 1.316 Gbps. Similarly, we got the IEEE 802.11n's maximum throughput at 46.16 Mbps. In the MPTCP experiment, either the full mesh or backup mode, a batch of ten experiments is executed and we collect all the measured MPTCP throughput. We calculate and show the average, minimum, and maximum values of $Ben(fullmesh)$ and $Ben(backup)$ in Figure 11. In the figure, the values of $Ben(fullmesh)$ are not only always negative but also largely varied. On the other hand, the values of $Ben(backup)$ are stable around zero, which means the performance is comparable to the TCP throughput over the IEEE 802.11ad. We also calculate the average, minimum, and maximum throughput of TCP and two different modes of MPTCP in the investigated cases. The comparative values are shown in Figure 12. We can see that the throughput values of TCP on IEEE 802.11ad and the MPTCP backup are almost similar. That is because the difference between the twos is only the handshaking period. However, the full mesh mode has a bad performance compared to the others and the Gbps level. While the backup mode's throughput values are always at the multi-Gbps level, the full mesh's ones are unstable. The worst value of the full mesh throughput approximates the throughput of IEEE 802.11n. In this case, the reason is mainly due to the different characteristics of two wireless links. The MTU of IEEE 802.11ad is 7912 bytes, while the IEEE 802.11n's MTU is 1500 bytes. The MTU sizes confuse the packet scheduler of MPTCP full mesh at the high transmission rate, consequently reducing the overall throughput.

We then explore the effects of MTU size on the throughput performance of MPTCP. We aim to change the MTU value on each wireless link and to repeat the previous *iperf3* experiments. We have modified our previous scripts to include the MTU configuration using the *ip* utility (e.g., change the MTU of wigig0 to the size 3000 bytes: *ip link set dev wigig0 mtu 3000*). Since the maximum supported MTU for the transmission between the Wi-Fi card and AP is 1500 bytes, we can not have a bigger value of MTU on the IEEE 802.11n link. We hence decided to vary the MTU on the IEEE 802.11ad link for the performance evaluation. More specifically, we consider the MTU size in the set of $\{1500, 3000, 4500, 6000\}$ (bytes). We collect and plot the throughput values in Figure 13. In the figure, we show the average throughput of MPTCP backup since the collected values are quite stable. Meanwhile, we show the maximum values of the MPTCP full mesh. In both modes, the throughput increases along with the MTU size. At the 1500- and 3000-byte MTU, we have a different observation as the previous comparison. The full mesh performance is better than the one of backup with the small MTU sizes. That means the aggregation benefit of MPTCP has been positive due to the efficient operation of the scheduler. However, the aggregate throughput is far less than the 1 Gbps level. Additionally, the wireless resource of both link has been used in the full mesh mode. Therefore, the usage of such MTU sizes for applications should take into consideration that trade-off. On the other hand, when the MTU values are either 4500 or 6000 bytes, it is seen that the MPTCP backup mode's performance is better. Therefore, the backup mode is likely adopted for the sakes of high throughput and resource efficiency.

We further observe the throughput of MPTCP full mesh with all the supported MCSs in comparison to the one of TCP over IEEE 802.11ad link, which is similar to the MPTCP backup throughput. At each PHY rate, we collect and calculate the average, minimum, and maximum values of measured throughput of ten runs. We show the values in Figure 14. The figure indicates that except MCS1, with all other PHY rates in our experiment, the MPTCP full mesh's average throughput is smaller than the TCP throughput. In particular, the higher the physical rate is, the worse the measured throughput becomes. With MCS1,

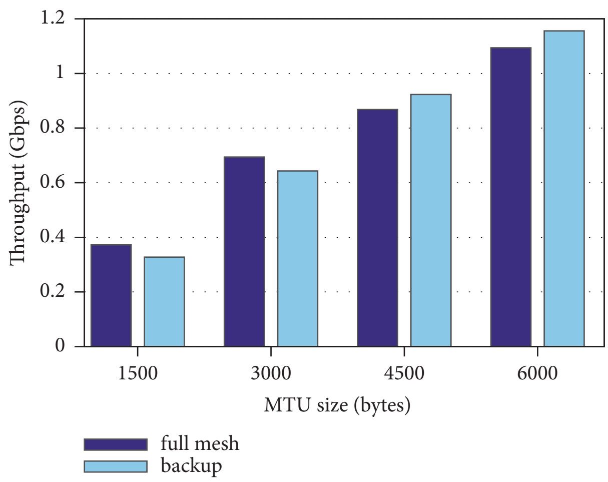

Figure 13: Throughput comparison between the full mesh and backup modes with different MTU sizes.

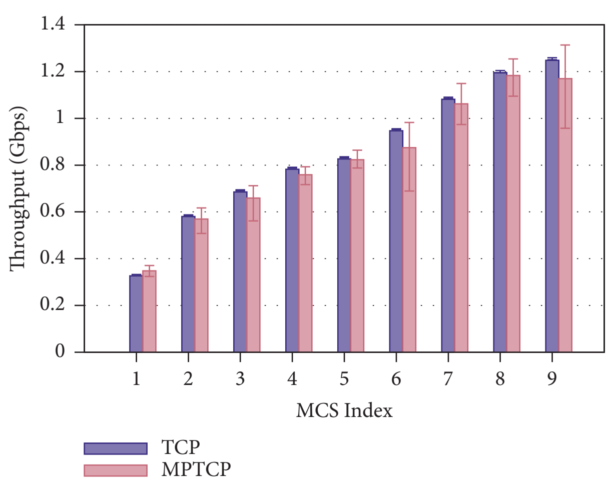

Figure 14: Comparison of TCP/MPTCP backup and MPTCP full mesh.

the MPTCP throughput is slightly better than the TCP throughput. On the other hand, MPTCP with the full mesh mode uses more networking resources than TCP since the two wireless links are both active for data transmissions. Therefore, we conclude that MPTCP full mesh (with the 7912-byte MTU of IEEE 802.11ad link) is not suitable for the expected switchover in the evolving Wi-Fi network.

In the following, we investigate the performance of MPTCP with the backup mode in the context of achieving the switchover in the evolving Wi-Fi network. The backup mode lets the IEEE 802.11n link be in a standby state for MPTCP packets in a normal condition. The IEEE 802.11n link will be active for MPTCP transmission when the IEEE 802.11ad link is not available. In this investigation, we keep the traffic condition similar to the previous one in the MPTCP evaluation. However, we additionally introduce the events of inactive, reactive links as follows. A period after starting the experiment, we change the direction of the

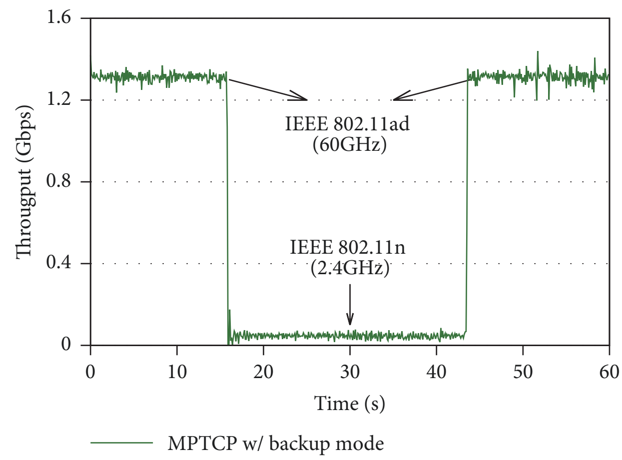

Figure 15: Achieving switchover with MPTCP backup.

IEEE 802.11ad radio on the MB until the IEEE 802.11ad link becomes inactive (i.e., note that this event is considerably similar to inserting blockage). After another period, we turn the radio back to the original direction for reactivating the IEEE 802.11ad link. During the experiment, we track the instantaneous throughput values at every 0.1 seconds; we then show them in Figure 15. The figure shows that the *iperf3* traffic is automatically switched from the IEEE 802.11ad link (i.e., in the 60 GHz band) to the IEEE 802.11n link (i.e., in the 2.4 GHz band) when the IEEE 802.11ad link is unavailable. Furthermore, after the recovery of IEEE 802.11ad link, the traffic is shifted back to the IEEE 802.11ad link and the application enjoys the higher bandwidth. In other words, MPTCP with the backup mode has efficiently achieved the expected switchover of IEEE 802.11ad.

5. Conclusion

With the advent of new off-the-shelf IEEE 802.11ad wireless devices, which can provide Gbps "wire like" experience to Wi-Fi networks, it is necessary to investigate the capacity of IEEE 802.11ad hardware to introduce the multi-Gbps capability to evolving Wi-Fi networks efficiently. This work first provides an in-depth experimental study on IEEE 802.11ad links in a typical office environment under the variation of network and interference conditions. We confirm the multi-Gbps throughput of both the UDP and TCP traffic with the constraints of signal strength, MCSs, and MTUs. Secondly, we verified that the link maintenance problem (e.g., due to blockage or changing antenna directions) still exists. To solve the problem, we propose to use MPTCP as a mean that provides a fast switchover between an IEEE 802.11ad to a legacy Wi-Fi link. Our evaluation results show that the IEEE 802.11ad radios can evolve on an existing Wi-Fi network. In particular, MPTCP with the backup mode could efficiently switch the multi-Gbps traffic on IEEE 802.11ad to a legacy Wi-Fi (i.e., IEEE 802.11n) link and vice versa.

Data Availability

The experimental data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

The preliminary results of this research have been presented in the 2017 IEEE International Conference on Communications Workshops (ICC Workshops) [22] and the 2017 IEEE 86th Vehicular Technology Conference (VTC2017-Fall) [28]. Mirza Golam Kibria is now with SIGCOM Research Group, SnT, University of Luxembourg.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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