Measurement-Based Study of the Performance of IEEE 802.11ac in an Indoor Environment

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Abstract—We present results from a measurement-based study of the performance of the emerging IEEE 802.11ac Wi-Fi standard in an indoor environment. The measurements were conducted in a typical office building, and show that for small distances IEEE 802.11ac offers significantly improved performance compared to IEEE 802.11n. However, these performance improvements were also found to be quite sensitive to channel conditions, with the achieved data rates rapidly declining as the distance between the transmitter and the receiver is increased. We also studied the coexistence properties of IEEE 802.11ac through measurements, observing that adjacent channel interference from legacy Wi-Fi devices can have a severe performance impact. For co-channel interference, the medium access control mechanism of IEEE 802.11ac allows it to share the channel effectively with other Wi-Fi devices.

I. INTRODUCTION

The rapid increase in data traffic is imposing ever higher efficiency requirements not only for mobile networks, but for Wi-Fi access points and terminals as well. The relatively simple spread spectrum design combined with basic CSMA/CA MAC in IEEE 802.11b has largely been replaced by the OFDM based IEEE 802.11a/g devices over the last decade to accommodate for this increase. The introduction of MIMO in IEEE 802.11n together with further MAC and PHY enhancements have enabled further increases in Wi-Fi system capacities. The work is currently ongoing in the IEEE 802.11ac task group to further improve the efficiency of Wi-Fi networks by incorporating support for multi-user MIMO as well as higher order modulation and coding schemes combined with further MAC layer enhancements [1], [2]. While the work on the IEEE 802.11ac standard amendment is still ongoing, first products based on version 2.0 of the draft standard have already become available in the market. However, despite the availability of IEEE 802.11ac devices, performance evaluation studies for this emerging standard have until now focused almost exclusively on simulations [3]–[8].

In this paper we provide first results from an extensive measurement-based performance evaluation of IEEE 802.11ac access points in a typical office environment. Our main objective is to study whether the extremely high theoretical maximum throughputs are actually achievable in practice, and how severely interference from legacy Wi-Fi systems and other ISM band transmitters degrades the performance of IEEE 802.11ac networks. As was observed already for IEEE 802.11n in several measurement studies (see, for example, [9]–[12]) the large gains from use of MIMO are expected to be heavily dependent on the actual propagation environment, and it is not clear if the high predicted throughputs are achievable even in the absence of interference.

II. OVERVIEW OF THE IEEE 802.11AC AMENDMENT

As currently envisaged, IEEE 802.11ac mainly introduces physical layer changes compared to IEEE 802.11n. Support for 80 MHz channel bandwidths is now mandatory, with options introduced to support 160 MHz bandwidth in either contiguous or discontiguous manner. This also implies that IEEE 802.11ac is supported only on the 5 GHz ISM band, since the maximum available bandwidth in the 2.4 GHz band is insufficient even for the 80 MHz channels (dual band IEEE 802.11ac access points typically operate as IEEE 802.11n devices on the 2.4 GHz band). The highest order modulation type is changed from 64-QAM to 256-QAM, with maximum optional coding rate of 8/9, whereas the mandatory coding rate remains at 5/6. The use of MIMO is also enhanced by increasing the maximum number of supported spatial streams from four to eight, and adding support for multi-user MIMO together with standardized approach to beamforming. In fact the latter was already in place for many IEEE 802.11n devices, but vendor-specific implementations severely hampered interoperability.

The combined effect of these changes vastly increased the theoretical maximum throughput compared to IEEE 802.11n. With 256-QAM, coding rate of 5/6 and short guard interval being used, physical layer bitrate of 867 Mbps per spatial stream is achievable. Given the maximum of eight spatial stream supported by IEEE 802.11ac access points, this could result in aggregate physical layer bitrate of 6.7 Gbps in an individual hotspot. Of course, the actual capacity is expected to be much lower, both due to non-idealities in MIMO operation as well as smaller number of antennas expected in typical
access points and terminals compared to the numbers needed to support eight spatial streams.

III. MEASUREMENT SETUP

We shall now introduce our measurement setup in detail, first describing the equipment and software used in the measurements, followed by the detailed description of the measurement environment and layout of measurement locations therein.

A. Equipment and Software Used

For our tests two Asus RT-AC66U wireless routers were used. We chose to use two routers, one functioning as an access point and another one as a wireless bridge towards a computer due to the lack of availability of IEEE 802.11ac compliant terminals\(^1\). The devices are based on Broadcom BCM4360 chipset offering simultaneous three-stream operation based on draft 2.0 of the IEEE 802.11ac amendment. The 5 GHz radio comes equipped with a Skyworks SE50003 23 dBm power amplifier with power detector.

The Asus RT-AC66U offers the support for all the mandatory IEEE 802.11ac features, such as the possibility to use up to 80 MHz channel bandwidth, 256-QAM and 802.11ac compliant transmit and receive beamforming. It also implements LDPC codes and short guard intervals from the optional features, and offers up to 1.3 Gbps theoretical aggregate throughput using three spatial streams. These are supported by three RP-SMA detachable antennas with a 9 dBi gain. The devices can be used in three operating modes. When set up as a wireless router, the device connects directly to the Internet and provides internet network access to connecting clients. In access point mode, the device can connect to a wireless router through an Ethernet cable in order to extend the wireless signal coverage. Finally, a Media Bridge operating mode can be set up, giving multiple entertainment devices the opportunity to use the fast 802.11ac Wi-Fi connection. In our tests, we used one Asus device set up as a wireless router and acting as the transmitter, whereas the second device was set up in media bridge mode and was acting as a client.

Traffic in our network was generated using Iperf \([13]\), an open-source traffic generation software running on multiple platforms. It is a commonly used tool for network testing that can create both TCP and UDP data streams and measures the end-to-end achievable throughput together with delay statistics. When used in UDP mode, Iperf allows the user to specify the datagram size and provides the results for datagram throughput and packet error rate, whereas when running in TCP mode, Iperf measures the throughput for the given payload size. In our tests, we mainly used the UDP mode. As TCP uses end-to-end congestion control mechanisms for managing the sending rate, the results presented here therefore give upper bounds on the expected TCP performance over IEEE 802.11ac links, but actually achieved throughput can remain significantly lower with details heavily depending on the channel conditions and the TCP version used.

In order to capture the packets sent between the two 802.11ac devices, we used Wireshark \([14]\), an open-source packet analyzer used for network troubleshooting and analysis. Wireshark enables detailed logging of network traffic, and for our tests we were particularly interested in the packet number, time stamp information, identification flag of the IP packet and the fragment offset. This information allowed us to keep track of the sent and received packets, enabling us to calculate the throughput and packet error rate and see the behavior of error occurrence in the IEEE 802.11ac network.

To monitor the 5 GHz ISM band and to ensure there was no unwanted source of interference at the time or our measurements, we used the WiSpy DBx, a portable USB spectrum analyzer. In order to generate interference we used two different approaches. First, an AirHorn dual-band signal generator was used to generate interference on various channels of the 5 GHz band. The AirHorn operates on 20 MHz wide channels, has a transmit power of 17 dBm, and is capable to work in three transmission modes, generating traffic either on a single channel, all channels in the frequency band sequentially, or transmit pulses at regular intervals. Second test scenario was then focused on the impact of legacy devices on the IEEE 802.11ac network performance. For this purpose we set up a network using IEEE 802.11n capable devices and generated traffic at different data link rates using Iperf. We chose an Asus RT-N56U wireless router as the transmitter connected to a PC, and the client was another PC equipped with an Asus USB N53 Dual-Band WLAN Adapter. The control channel of the IEEE 802.11n network was set to channel 44, same as the control channel of the IEEE 802.11ac network. The bandwidth of the IEEE 802.11n network was set to 40 MHz.

B. Measurement Environment and Configuration Summary

The measurements were conducted in a typical office building of the RWTH Aachen University, with individual offices combined with lecture rooms and computer laboratory rooms, all separated by a mixture of soft partitions and supporting walls. The measurement setup and the positions of the Asus routers are shown in Fig. 1. In the figure “S” denotes the position of the wireless router acting as the sender, whereas the points denoted by “R” represent the different positions chosen for the receiver. In order to maintain a uniform configuration between different test scenarios, the same locations and orientations in a given receiver position were used throughout all measurements. For measurements with interference, the interfering devices were placed either close to the 802.11ac transmitter or receiver, respectively, at a distance of 1 m. The overall test setup with interferers is shown in Fig. 2. The measurement configurations used are summarized in Table I.

IV. RESULTS

In this section we present the results from our measurement campaign. We first focus on achievable performance in condi-
A. IEEE 802.11ac Performance without Interference

First, we measured the saturation throughput of the IEEE 802.11ac connection in order to establish the higher performance we can expect to achieve. We placed the two devices in a small office with multiple computers and other reflectors, creating a rich multipath environment for MIMO. The sender and receiver locations correspond to positions S and R1 in Fig. 1. This setup also provides a strong line-of-sight path between the two communicating end-points. The UDP link rate generated in Iperf was slowly increased until the packet error rate (PER) reached a value of 1%. The measured saturation throughput was $618 \pm 2$ Mbps with a PER of $0.35 \pm 0.25\%$.

We then repeated the measurement at different locations, increasing the distance between the sender and the receiver. We were interested both in measuring the maximum communication range as well as the degradation of throughput over distance. With proper antenna orientation, the maximum range achieved was of 24.3 meters, with a throughput of 90.1 Mbps. Going beyond this distance added one more wall as attenuator, after which connection could no longer be established. Up to a distance of 17.1 meters the throughput was above 500 Mbps with a PER lower than 1%. Fig. 3 shows the maximum saturation throughput results as a function of range. The very low throughput value obtained at the location marked with R5 at a distance of 24.3 meters can be explained by the high attenuation added by a supporting wall, made of concrete, between locations R4 and R5. In our subsequent measurements when interference was added we did not consider this measurement.
Fig. 4. Packet error rate as a function of distance when the Sender transmits with a data link rate of 600 Mbps.

Fig. 5. Time variation of throughput with offered UDP rate of 700 Mbps, 10.1 m distance.

location further, since the communication link was completely lost when other interference sources were present on the 5 GHz band.

Fig. 4 shows the variation in packet error rate over the distance between the IEEE 802.11ac devices and with a UDP transmission rate of 600 Mbps. The PER value stays below 5% up to a distance of 15 meters and then increases to almost 40% for 20 m separation between the client and the AP. We will use these results as a baseline for the PER performance when performance in the presence of interferers will be discussed.

Finally, Fig. 5 shows the variation in throughput over a 30 seconds measurement duration at a distance of 10.1 m between devices and when the sender transmits with an user datagram rate of 700 Mbps. We see from the figure that the achieved performance is highly stable, with very few significant drops in throughput. Note that the achieved throughput is higher than the above-mentioned saturation throughput as the packet error rate was allowed to exceed 1% for these results.

B. Impact of Interferers on IEEE 802.11ac Performance

We shall now study the impact of interference on the IEEE 802.11ac performance, beginning with interference coming from a signal generator transmitting on 20 MHz wide channels. Fig. 6 shows throughput and packet error rate for two of the measurement positions in the presence of interference on channels 36, 44 and 52. The IEEE 802.11ac transmitter sends packets at the optimal link rate in each position. We can immediately observe the high variation in both throughput and packet error rate compared to the interference-free case. The impact of the channel used by the 20 MHz interferer is also substantial, both with respect to the median value of throughput or packet error rate, as well as the variability of the measurements around these values.

Further interesting result is that at distances of separation longer than 15 meters, the performance of the 802.11ac WLAN is highly influenced even if the interference is present on an adjacent channel, namely channel 52. This can be explained by the fact that at higher separation distances, the signal power that arrives at the receiver is low and the adjacent channel rejection is poor. The receiver will thus use a lower modulation and coding scheme, or will not be able to demodulate the signal at all. Another contributing cause for this behavior would probably be the poor implementation of both transmit and receive spectrum masks on the used devices. At a distance of 19.7 meters, the IEEE 802.11ac link was completely lost when the signal generator was active on channel 52 and could not be recovered even if transmitting with lower link rates.

Fig. 7 shows the variation of throughput over time for a measurement with 10.1 meter distance between sender and receiver. We see that compared to the interference free case, the throughput is no longer constant, but has rather high degree of variability instead. This can be explained by combination of
5.2. Effects of Interference

Fig. 7. Time variation of throughput for offered UDP data rate of 600 Mbps, 10.1 meter distance, artificial interference close to the sender on the control channel.

Fig. 8. Throughput and packet error rate in the presence of interference from an 802.11n WLAN (UDP data rate of 600 Mbps and 400 Mbps, 10.1 meter distance, interference placed close to the sender and close to the receiver).

Lost packets as well as rapid changes of the used modulation and coding scheme due to interference. The number of correctly received packets between packet errors was measured to have a much lower mean value (500 compared to 1000) with an increased standard deviation. The mean error burst length also increased to over 180 in the presence of interference, compared to the value of 40 measured in the interference-free case.

We next discuss the results in the case of interference arising from IEEE 802.11n transmitter/receiver pair. In the presence of interference transmitting with different link rates (50 to 150 Mbps), the throughput and packet error rate results of the 802.11ac WLAN are significantly lower and are characterized by a high variation over the transmission time as shown in

We also studied the joint coexistence properties of the two networks. For this purpose, we analyzed the throughput values of the IEEE 802.11n network in stable and saturation conditions while slowly increasing the data link rate of the IEEE 802.11ac transmission. We repeated the saturation measurement setup used in the optimum conditions case. The IEEE 802.11n devices were placed 1 meter apart and at varying distances from the interfering 802.11ac transmitter. We measured the saturation throughput of the IEEE 802.11n WLAN as being 130 Mbps and afterwards started transmitting on the 802.11ac network, beginning with a low data link rate and keeping the PER on both networks below the 1% threshold.

The results shown in Fig. 9 are characterized by a linear dependence in terms of throughput performance of the two IEEE 802.11 WLANs. As can be expected, the less optimal case is when the two networks are at close range. In our measurement environment, a distance of 10 meters between the 802.11ac devices guarantees the least amount of interference on the 802.11n connection. Throughout the measurement campaign, we could observe that each network was maintaining a throughput of roughly half the value each was capable of in saturation and stable conditions and with no interference, which is very close to optimum for networks using CSMA/CA as the MAC protocol.
In this paper we have studied the performance of the emerging IEEE 802.11ac Wi-Fi standard in an indoor environment through extensive measurement campaign. Our results have shown that for connection distances IEEE 802.11ac offers significantly improved performance compared to IEEE 802.11n in a typical office environment, with data rates exceeding 700 Mbps for a $3 \times 3$ MIMO configuration. However, these performance improvements are sensitive to channel conditions, with the achieved data rates rapidly declining as the distance between the transmitter and the receiver is increased. Two supporting concrete walls were sufficient to prevent a connection from being established. We also saw that other wireless technologies using the 5 GHz ISM band can also have a significant performance impact on IEEE 802.11ac. The CSMA/CA medium access control mechanism allowed effective sharing of the channel with legacy Wi-Fi technologies, but other types of interference severely reduced the throughput and increased packet error rate for the IEEE 802.11ac link.

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REFERENCES