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Experimental Evaluation of Performance Anomaly in Mixed Data Rate IEEE802.11ac Wireless Networks

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Abstract—**IEEE 802.11 wireless local area networks (WLANs) are shared networks, which use contention-based distributed co-ordination function (DCF) to share access to wireless medium. The performance of DCF mechanism depends on the network load, number of wireless nodes and their data rates. The throughput unfairness also known as performance anomaly is inherent in the very nature of mixed-data rate Wi-Fi networks. This unfairness exhibits itself through the fact that slow clients consume more airtime to transfer a given amount of data, leaving less airtime for fast clients. In this paper, we evaluate the performance anomaly of mixed rate wireless networks and present the results of practical experiments benchmarking throughput of a mixed rate 802.11ac wireless network. These results clearly show that even the most recent wireless standard still suffers from the airtime consumption unfairness. At the end of the paper we analyse related works offering possible solutions and discuss our approach to evade performance degradation in mixed data rate Wi-Fi environments.**

Keywords—IEEE802.11ac; wireless networks; Wi-Fi; DCF; CSMA/CA; mixed data rate; airtime consumption unfairness; performance anomaly; throughput; benchmarking.

I. Introduction

The IEEE 802.11 wireless local area network (WLAN) standard is one of the most widely deployed wireless technologies. There has been huge growth of WLANs deployments in offices, homes, hot-spots, commercial and public organizations [1]. The popularity of WLAN is driven by tremendous proliferation of wireless enabled devices, such as, laptops, tablets, smartphones and many IoT smart devices like wireless cameras, sensors, etc.

Supporting different data rates is in the very nature of wireless technologies. Due to dynamic environment and mobile nature of wireless communication, IEEE 802.11 nodes use different modulation and encoding schemes to provide reliable transmission. Wireless nodes use rate adaptation mechanism to dynamically change their data rate depending on the RF signal quality and condition of the channel.

Equally, IEEE 802.11 standards provide backward compatibility to support legacy and low-data rate devices such as laptops, tablets, smartphones, wireless cameras and Wi-Fi enabled domestic appliances.

Besides, it is anticipated that millions of IoT devices and sensors will be connected to networks [2]. These devices are usually limited in hardware resources, energy and are not capable of supporting high data rates. As a result, the difference in data rates between low and high data rate stations in the same wireless local area networks (WLAN) can reach hundreds of times.

The diversity of data rate in a wireless network could lead to the performance anomaly because 802.11 distributed coordination function (DCF) makes sure every node, whether high-rate or low-rate has the same opportunity to access the shared channel [3]. When a low-data rate node gains access to the medium, it takes longer time to transmit its frame. Thus, low-rate nodes will occupy the channel much longer and penalize higher rate nodes.

There have been several studies benchmarking throughput of wireless networks [3, 4, 5, 6] and evaluating performance anomaly [6, 7, 8, 9]. Even though these works are important for understanding IEEE 802.11 performance overheads and uncovering the nature of the throughput unfairness in mixed data rate Wi-Fi networks they mostly rely on analytical modeling or simulation without verifying them experimentally. Besides, studying legacy 802.11b/a/g standards these works do not offer quantitative results useful for users of the most recent 802.11n/ac WLANs.

This paper presents the results of experimental evaluation of the throughput unfairness in a mixed data rate 802.11ac wireless network. Moreover, we compare our experimental findings with the theoretical models proposed in [7, 9] and discuss a deviation between them.

The rest of the paper is organized as follows. In the next section we briefly discuss the Wi-Fi distributed coordination function and uncover a phenomenon of the airtime consumption unfairness arisen in mixed data rate wireless networks. Section III presents the performance measurement results of experiments conducted in a mixed data rate 802.11ac wireless network. We discuss related researches in Section IV and conclude our work in Section V.

II. Wi-Fi Medium Access Control and Airtime Consumption Unfairness

The fundamental medium access control mechanism used by IEEE 802.11 standard is called distributed coordination function (DCF). DCF is a contention-based, best effort mechanism based on carrier sense multiple access with collision avoidance (CSMA/CA) protocol [12].

In general, DCF provides a random pseudo-fair multiply access to a wireless media. This means a statistically equal

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number of chances that each computer get to transfer its data frames over a shared media. However, low data-rate wireless stations consume more airtime to transfer a given amount of data, leaving less airtime for other stations. This decreases the overall network throughput and significantly degrades performance of high data rate devices. Thus, DCF becomes unfair toward high-speed stations working in mixed data rate Wi-Fi networks.

Fig. 1 helps in understanding a nature of the problem. It depicts an example of a channel access cycle in case of two stations: low data rate station A and high data rate station B. Please note that stations A and B get access to the channel with the same probability, and A and B frames are of the same size. In Fig. 5, it is finally assumed that A has half of the link speed of B which doubles the transmission time compared to B.

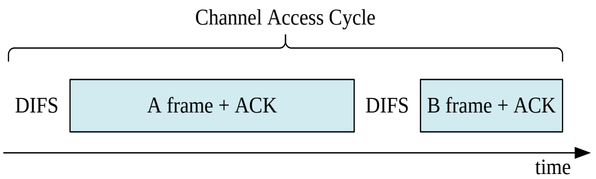


Fig. 1. Time allocation of a channel access cycle.

Thus, the high data rate client spends more time waiting for the slow client to release the media than transmitting its own frame. This means that even a single client connected to the wireless network at a low data rate can dramatically slow down all high data rate clients.

This performance anomaly has been studied in a series of works, e.g. [8, 10, 11]. Authors of [9] proposed a lightweight analytical model, which was further improved in [7] to estimate throughput of wireless stations U_i with regard to their data rates:

$$U_i \approx \frac{\alpha}{\sum_{j=1}^{n} \frac{1}{V_j}}. \quad (1)$$

where U_i – is the throughput available to the i-th station; V_j – is a data rate of the j-th station connected to the same access point; n – is the total number of wireless stations connected to the same access point; α – is an overhead coefficient ($0 < \alpha \leq 1$).

The model (1) roughly predicts the maximal throughput available to each station in the Wi-Fi network with mixed data rates where all stations are busy transmitting and receiving data. It shows that all station would have approximately the same throughput independently on their individual data rate. Moreover, this throughput would approximate to the data rate of the slowest station, which is in-line with another study [8].

Finally, the overall bandwidth of a wireless network with n stations could be estimated as:

$$U_\Sigma = n \cdot U_i = n \cdot \frac{\alpha}{\sum_{j=1}^{n} \frac{1}{V_j}}. \quad (2)$$

A coefficient α ($0<\alpha<1$, $\alpha \approx 0.5$) was introduced in [5] to take into account such a decrease caused by many reasons including inter-frame gaps and CSMA/CA contention windows, numerous Wi-Fi control frames, collisions and retransmissions of corrupted frames. Many practical studies, e.g. [4, 6], show that a throughput practically achieved at the OSI Level-7 (or Level-4) is substantially lower than the data rate at which a client is connected to the wireless network at the Level 1 and takes approximately 50% at best even in case of a single client connected to an access point.

Moreover, if two wireless stations communicate via the access point, the same message goes over the air twice (from the source STA to the AP and then from the AP to the destination STA) which additionally reduces the throughput half as much. Detailed consideration of the wireless networks overheads is given in [5], but it is out the scope of this paper.

III. Throughput Benchmarking in Mixed Data Rate IEEE 802.11ac Wi-Fi Networks

A. Methodology and Experimental Setup

We conducted a number of experiments to investigate performance anomaly in mixed data rates Wi-Fi networks. The testbed network configuration is depicted in Fig. 2. It includes one desktop computer C connected directly to the Linksys WRT 1200AC (802.11ac) access point via the Gigabit Ethernet wired connection.

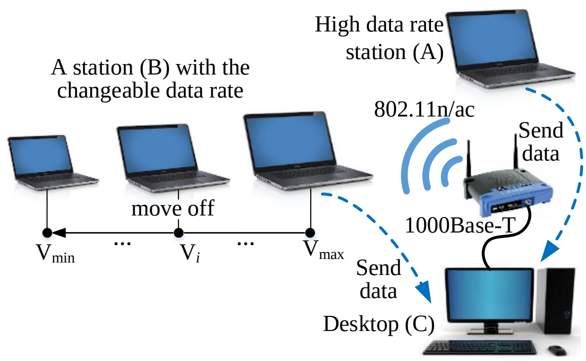


Fig. 2. CSMA/CA airtime distribution between two clients depending on their data rates.

Two wireless laptops (A and B) were equipped with the TP-Link Archer AC600 (802.11ac) network adapters supporting one spatial downstream. These wireless laptops established connections to desktop computer C via the access point.

The wireless stations and access point were configured to work in the 5GHz band and use 80 MHz channel width. The single spatial stream between station and access point allows to reach the maximal data rate of 433.3 Mbps.

IxChariot tool[1] has been used to benchmark wireless network throughput under realistic load conditions. Using IxChariot we created two simultaneous data streams between endpoints A and C and B and C running the same throughput benchmarking script (see Fig. 3). The script sends a series of files via the TCP connections established between endpoints. The file size was set to 1 MB. IxChariot estimates throughput by measuring how fast a file is transferred between two endpoints of the data stream. Our script transferred a series of 1000 files in a loop, which gives 1000 throughput measures.

[1] http://www.ixchariot.com/products/datasheets/ixchariot.html

The core idea of the our experiments was to create a mixed data rate environment by having one of the wireless laptops connected to the access point at the maximal data rate while forcing the second laptop to use a lower data rate.

Laptop A was placed close to AP throughout the whole experiment which enabled the maximal data rate of its wireless connection.

One should note that users cannot directly control and set the certain data rate of a wireless network adapter. It is selected automatically depending on the signal strength and noise level. To force the second laptop (laptop B) to switch to lower data rate, it was moved away from the access point until its data rate dropped down to the next discrete value (see Fig. 2). Our experiments were run in an open area environment with no other wireless networks installed nearby.

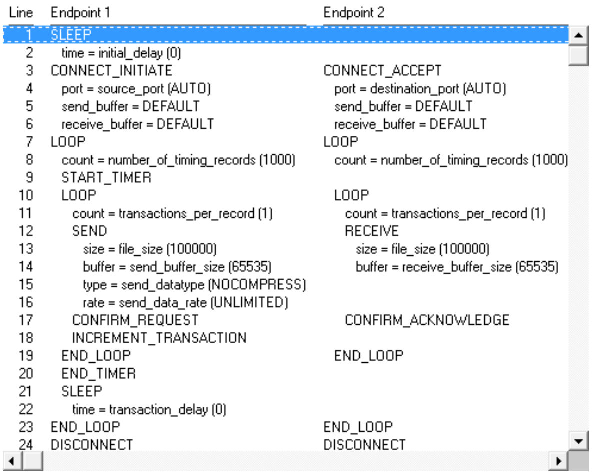


Fig. 3. IxChariot throughput benchmarking script.

We performed a series of benchmarks at different data rates of laptop B, starting from the maximum supported value (433.3 Mbps) and decreasing it down to the minimal one (6 Mbps). The whole range of data rates supported by 802.11ac standard can be found in [13].

The data rate at which a station is connected to an access point and sends data can be noticed by using OS APIs. On Windows 10 PC one can use the following WMC (Windows Management Instrumentation) command:

```
>wmic NIC where "Manufacturer='TP-LINK'"
get "Speed" >> net-speed.txt
```

In addition, we used the *CommView for Wi-Fi*[2] to capture packets and display the data rate at which each packet is sent and other physical-layer metadata: signal level, noise level, etc. (see Fig. 4).

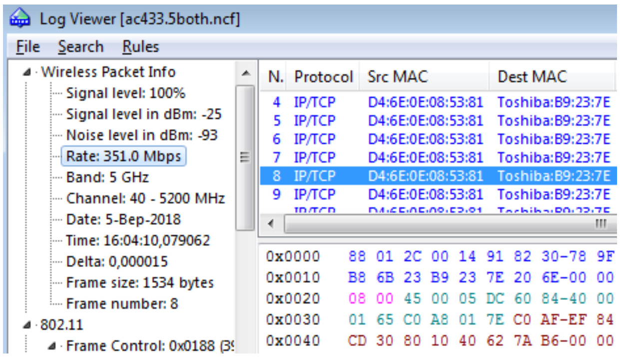


Fig. 4. Packets and physical-layer data captured by *CommView for Wi-Fi*.

The most important experimental settings are summarised in Table I. A frequency range, channel width and wireless mode were configured via adapter/access point settings.

TABLE I. THROUGHPUT UNFAIRNESS IN MIXED WI-FI NETWORKS

Parameter	Value
Mode	802.11ac mixed
Frequency band, GHz	5
Channel Width, MHz	80
MIMO configuration	2x1:1
Maximal data rate, Mbps	433.3
Minimal data rate, Mbps	6
File size, KB	1000
Transmission protocol	TCP
No of loop cycles	1000

B. *Throughput Benchmarking Results and Their Comparison with the Theoretical Models*

Fig. 5 summarizes the experimental results and compares them with the theoretical modeling using (1). It shows how the average throughput of two independent data streams (A→C) and (B→C) changes depending on data rate of station B.

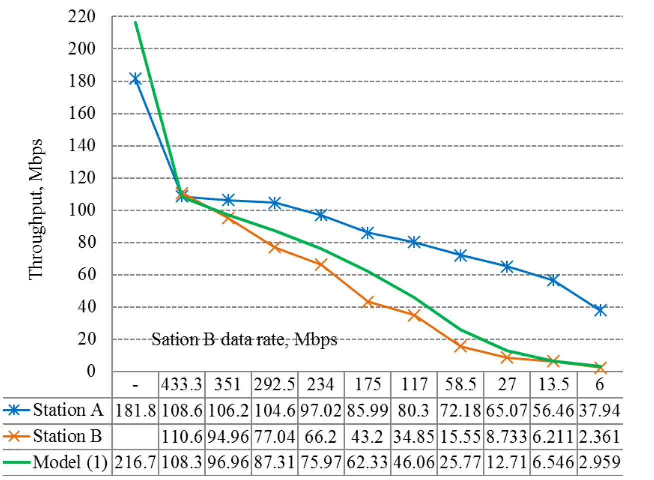


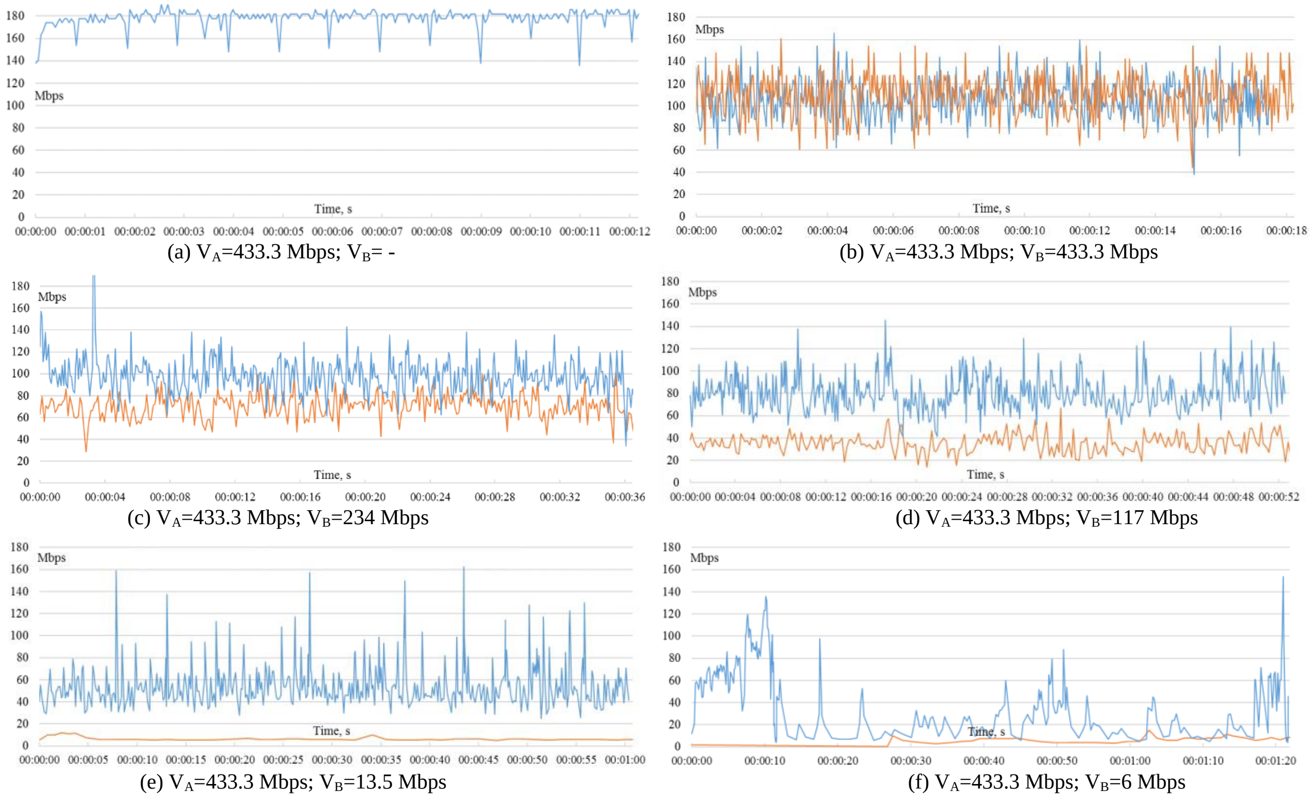
Fig. 5. Stations throughput depending on the data rate of Station B.

When Station A solely occupies the wireless media the maximal achieved throughput is equal to 181.8 Mbps on average which is considerably less than 50% of its data rate (433.3 Mbps). It witnesses to the significant overheads existed even in the most recent 802.11ac standard.

[2] https://www.tamos.com/products/commwifi/

When Station A shares the media with Station B which also sends data at the maximal data rate the two stations share the network throughput almost equally (108.6 vs 110.6 Mbps).

It can be clearly noted, that the throughput of both data streams dropped down due to decrease in the data rate of Station B. At the same time, the theoretical model (1) slightly overestimates the throughput of slow data rate station B and considerably underestimates the throughput of the high-speed station A.



(a) V_A=433.3 Mbps; V_B= -

(b) V_A=433.3 Mbps; V_B=433.3 Mbps

(c) V_A=433.3 Mbps; V_B=234 Mbps

(d) V_A=433.3 Mbps; V_B=117 Mbps

(e) V_A=433.3 Mbps; V_B=13.5 Mbps

(f) V_A=433.3 Mbps; V_B=6 Mbps

Fig. 6. Results of experimental throughput evaluation depending on stations' data rates: IEEE802.11ac; 80 MHz channel width; MIMO 2x1:1.

Fig. 6 explains this phenomenon. It presents examples of raw throughput estimates measured by IxChariot at different data rate of Station B. One can notice two different patterns corresponding to slow and high data rate stations especially when a difference between their data rates becomes significant (Figs. 6, e-f).

Despite the fact that the data rate of Station A remains maximal, its throughput is decreasing on average. However, in Fig. 6 we can notice throughput peaks regularly experienced by Station A. Analysing packet traces captured by *CommView for Wi-Fi*, we have found out the throughput of Station A sharply increased when station B made pauses in data transfer.

In turn, these pauses occurred because of the TCP protocol slowed down its transmission rate reacting to packets loss (by reducing transmission window) or when station B lost a wireless connection and was trying to reconnect. The fact that TCP protocol works non-optimally over unstable wireless connections is widely accepted and have been studied by many authors, e.g. [5]. However, deep investigation of this phenomenon is out of the scope of this paper.

Non-optimal settings of the retransmission timer and wrong congestions detection cause unnecessary retransmissions and unfoundedly reduce TCP congestion windows that additionally degrades throughput of the low data-rate station B.

However, this gives an additional opportunity to the high-data rate station A to overrun the theoretical throughput suggested by (1). Nevertheless, our experimental results clearly show that slow data rate stations actively transmitting data, can significantly degrade throughput of high data rate stations connected to the wireless network.

During our experiments we noticed that network adapters and access point tend to use long guard intervals when the signal strength is not maximal. Hence, some of the data rates defined by 802.11ac standards have been never used by them.

IV. RELATED WORKS

Since Martin Heusse et al [8] pointed out that the diversity of data rate in a wireless network could lead to the performance anomaly in IEEE 802.11b networks, there have been a number of works investigating throughput of mixed data rate Wi-Fi networks using different assessment techniques. They are summarized in Table II.

TABLE II. RELATED WORKS STUDYING PERFORMANCE ANOMALY IN MIXED DATA RATES WI-FI NETWORKS

Paper	IEEE standard	Evaluation technique	Verification technique
A.M. Abdul-Hadi, et al. [7]	802.11g	Analytical modelling	IxChariot benchmarking
M. Heusse, et al. [8]	802.11b	Analytical modelling	Proprietary simulator; tcpperf benchmark
F. Miki, et al. [9]	802.11a/g	Analytical modelling	Proprietary simulator
O. Abu-Sharkh and A. H. Tewfik [10]	802.11b	Markov chain modelling	-
D.-Y. Yang, et al. [11]	802.11b	Markov chain modelling	-

As we discussed earlier, the vast majority of that studies proposed analytical equations or Markov chain models without any practical experiments to verify their proposals. Equally, their work were focused on legacy 802.11b/a/g standards, reporting quantitative results which cannot be applied to most recent 802.11n/ac standards.

To address the performance anomaly in multi-rate WLANs a number of solutions/mechanisms have been proposed recently (see Table III). There are two basic ideas put forward by these works: either enlarging the Contention Window (CW) of the low-data rate stations or reducing their MTU size. Efficiency of the proposed techniques are verified using NS2 simulator.

TABLE III. RELATED WORKS PROPOSING SOLUTIONS TO MITIGATE PERFORMANCE ANOMALY IN MIXED DATA RATE WI-FI NETWORKS

Paper	IEEE standard	Proposed solution	Optimality	Verification technique
Y. Liu, et al. [13]	802.11b	Nodes initialize their CWmin based on the ratio of their own data rates to their competitive nodes' data rates	Sub-optimal	Simulation, NS2
H. Kim, et al. [14]	802.11b	Nodes initialize their CWmin inversely proportional to their bit-rates; the highest bitrate stations retain the current default value	Sub-optimal	Simulation, NS2
S.-H. Yoo, et al. [15]	802.11b	Nodes decrease the MTU size proportionally to their bit rates; the highest bitrate stations retain the current default value	Optimal for high data rate stations; decreases utilization rate for slow stations	Simulation, NS2
J.-S. Kim and T.-J. Lee [16]	802.11b	Modifying RTS/CTS mechanism limits transmission opportunities of low rate stations to the half of the transmission opportunities of high data rate stations	Sub-optimal	Analytical modelling
A. Banchs, et al. [17]	802.11b	1. slower nodes initialize their CWmin as a function of the CW of the fastest station which is taken as reference; 2. Slower nodes decrease the MTU size down to fixed values identified empirically	Sub-optimal	Proprietary event-driven simulator written in C++
D.-Y. Yang, et al. [11]	802.11b	Different initial backoff window size, frame size and maximum backoff stage are used for different transmission rates. Their values are static and should be identified empirically	Sub-optimal	Markov chain modelling

For example, in [15] authors propose a contention window (CW) adaptation scheme by adjusting the size of CW inversely proportional to node's transmission rate. The principle of suggested scheme is to assign smaller CW to high rate nodes and larger CW to low rate nodes. Thus, a probability of slow rate nodes gaining access to medium is reduced. Another approach to achieve a channel utilization fairness via adjusting the packet size proportionally to node's transmission rate was proposed in [16]. Despite the fact that the proposed techniques can mitigate the performance anomaly existed in mixed-data rates wireless networks neither of them offers an optimal solution. Besides, they do not consider the problem in a comprehensive manner and do not take into account the trade-offs exist between throughput, latency, utilization and reliability.

V. CONCLUSION AND FUTURE WORK

In the paper we investigate a problem of unfair airtime distribution between wireless stations with different data rates and its implication on stations throughput. The problem is manifested by the fact that slow stations consumes considerably more airtime than high-speed ones to send the same amount of data. As a result, in heavy-loaded wireless networks even a single low-data rate station can significantly degrade performance of the whole network and dramatically decrease throughput of its high-data rate neighbors.

This performance anomaly was examined experimentally using a series of benchmarks. In our work, we analyze the most recent IEEE802.11ac standard using 80MHz channels to achieve the maximal data rate of 433.3 Mbps for a single spatial stream.

Our experimental results have confirmed the significance of the issue and showed that the airtime consumption unfairness decreases the throughput of high-data rate stations, Most of the theoretical models proposed to evaluate performance anomaly in Wi-Fi networks suggest that both low and high-data rate stations get the same throughput. However, experimental results have demonstrated, that despite a significant performance degradation, the high-data rate station still over performs the low-data rate one (see Fig. 5). For example, it was shown that the analytical model (1) proposed in [9, 7] to evaluate performance of wireless stations depending on their data rates slightly overestimates the throughput of a low data rate station and considerably underestimates the throughput of a high-speed station. This finding is discussed in more details in Section III.B.

Ultimately, our work clearly shows that airtime consumption unfairness still exists even in the most recent wireless standard IEEE802.11ac. It remains one of the major stumbling blocks in achieving the full potential of modern Wi-Fi networks. Despite the fact that many techniques have been proposed recently to mitigate this issue, none of them offers a complex approach and provides an optimal solution.

In future work, we are planning to study a wider range of application scenarios including 20MHz and 40MHz setups and to complement our practical experiments with simulation results. Besides, to cope with the performance anomaly we will put forward a complex approach considering fundamental trade-offs between throughput, latency, utilization and reliability.

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