UDC 004.732.051 **doi: 10.32620/reks.2022.4.06**

Fash SAFDARI[1], Anatoliy GORBENKO[1,2]

[1] *Leeds Beckett University, Leeds, UK*
[2] *National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine*

THEORETICAL AND EXPERIMENTAL STUDY OF PERFORMANCE ANOMALY IN MULTI-RATE IEEE802.11AC WIRELESS NETWORKS

IEEE 802.11 wireless local area networks (WLANs) are shared networks, which use contention-based distributed coordination function (DCF) to share access to wireless medium among numerous wireless stations. The performance of the distributed coordination function mechanism mostly 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 using the distributed coordination function. 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 comprehensively examine the performance anomaly in multi-rate wireless networks using three approaches: experimental measurement, analytical modelling and simulation in Network Simulator v.3 (NS3). The results of our practical experiments benchmarking the throughput of a multi-rate 802.11ac wireless network clearly shows that even the recent wireless standards still suffer from airtime consumption unfairness. It was shown that even a single low-data rate station can decrease the throughput of high-data rate stations by 3–6 times. The simulation and analytical modelling confirm this finding with considerably high accuracy. Most of the theoretical models evaluating performance anomaly in Wi-Fi networks suggest that all stations get the same throughput independently of the used data rate. However, experimental and simulation results have demonstrated that despite a significant performance degradation high-speed stations still outperform stations with lower data rates once the difference between data rates becomes more significant. This is due to the better efficiency of the TCP protocol working over a fast wireless connection. It is also noteworthy that the throughput achieved by a station when it monopolistically uses the wireless media is considerably less than 50 % of its data rate due to significant overheads even in most recent Wi-Fi technologies. Mitigating performance anomaly in mixed-data rate WLANs requires a holistic approach that combines frame aggregation/fragmentation and adaption of data rates, contention window and other link-layer parameters.

Keywords: *IEEE802.11ac; wireless networks; Wi-Fi; distributed coordination function; multi-rate network; airtime consumption unfairness; performance anomaly; throughput; benchmarking; simulation, modelling.*

Introduction

There has been tremendous proliferation of Wi-Fi enabled devices and huge growth of wireless communication deployments in public hot-spots, homes, and commercial organizations [1]. The proliferation of wireless local area networks (WLANs) and explosive growth in wireless data traffic led to a surge in demand for more bandwidth. This has motivated the development of new 802.11 Wi-Fi standards promising high data rate and low latency. However, the actual data rate and throughput available to wireless stations depend on many factors and are usually considerably less than the maximal data rate defined by the standard.

IEEE 802.11 series of standards provide backward compatibility to support legacy and low-data rate devices. Heterogeneous Wi-Fi enabled devices and IoT sensors have varied hardware resources, processing power, bandwidth configurations, employing different PHY and MAC layer techniques and capable of different data rates [2]. As a result, the difference in data rates between low and high data rate stations in the same wireless local area network (WLAN) can reach hundreds of times.

Furthermore, supporting different data rates is in the very nature of wireless technologies. Due to the 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 condition of the channel, relative position of the nodes in the wireless network, and MAC layer retransmission of frames.

The diversity of data rate in a wireless network could lead to performance anomaly [3] because IEEE 802.11 wireless local area networks (WLANs) use contention-based medium access control mechanism where every node, whether high-rate or low-rate, has the opportunity to access the shared channel. 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, penalizing high-rate nodes [2, 4] and can severely degrade overall performance of the network and

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

in particular the performance of high-data rate devices [5-7]. This issue is becoming especially critical for video streaming services in future smart systems, e.g. vehicular networks [8], UAV-enabled [9] wireless networks, etc.

A number of enhancements at both PHY and MAC layers have been introduced in 802.11n, 802.11ac and the most recent IEEE 802.11ax standard [10] to improve performance and mitigate the impact of performance anomaly in multi-rate wireless networks. However, performance anomaly has not been resolved and the results of our practical experiments benchmarking throughput of mixed rate 802.11n/ac wireless networks clearly show that even the most recent wireless standards still suffer from airtime consumption unfairness.

There have been several studies benchmarking [11-13] and modelling [14, 15] throughput of wireless networks and evaluating performance anomaly [16-18]. Even though these works are important for understanding IEEE 802.11 performance overheads and uncovering the nature of throughput unfairness in mixed data rate Wi-Fi networks, but they mostly rely on analytical modelling or simulation without verifying them experimentally. Besides, their findings are mostly based on legacy 802.11b/a/g standards which do not offer quantitative results useful for users of more recent WLAN specifications. Despite the fact that the weak TCP performance over wireless networks is a well-known problem, TCP is widely used as a standard transport in smart systems and IoT application to carry sensor data and even for video streaming [8-9]. Thus, in our study we focus on examining TCP performance over mixed data rate Wi-Fi network.

In this paper, we present the results of a comprehensive study of performance anomaly in mixed rate 802.11n and 802.11ac wireless networks using three approaches: experimental measurements, analytical evaluation and simulation in Network Simulator v.3 (NS3). In addition to our earlier work [19], we considered three possible scenarios of using 20, 40, and 80 MHz-width wireless channels and complement the experimental findings with analytical modelling and simulation of complex multi-node scenarios in NS3.

The rest of the paper is organised 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 2 describes evaluation methodology, scenarios and experimental setup. In Section 3 we report results of the throughput experimental measurements performed in a test-bed Wi-Fi network. Section 4 examines performance anomaly in mixed data rate wireless networks via simulation in NS3. Accuracy of theoretical throughput modelling and simulation are discussed in Section 5. Performance anomaly in a multi-node setup is studied in Section 6. The last section discusses main findings and concludes our work.

1. Wi-Fi medium access control and airtime consumption unfairness

1.1. Distributed Coordinated Function

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. DCF treat all traffic with the same priority.

In general, DCF provides a random pseudo-fair multiple access to a wireless media. This means statistically each computer gets an equal number of chances 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. Station A has half of the link speed of Station B which doubles its transmission time compared to B. It is also assumed that stations A and B get access to the channel with the same probability, and A and B frames are of the same size.

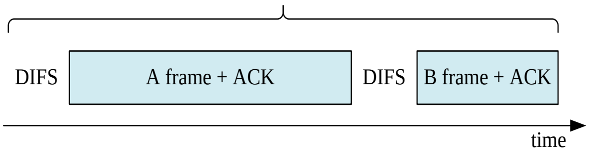


Fig. 1. Time allocation of a channel access cycle

Thus, the high data rate client spends more time waiting for the slow client to release the media then 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 [3, 17, 18]. Authors of [16] proposed a lightweight analytical model, which was further improved in [13] to estimate throughput of wireless stations U_i with regard to their data rates:

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

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 stations 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 [3]. Finally, the overall bandwidth of a wireless network with *n* stations could be estimated as:

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

A coefficient α ($0<\alpha<1$, $\alpha \approx 0.5$) was introduced in [20] 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 showed that a real throughput achieved at OSI layer7 (or layer4) is substantially lower than the data rate at which a client is connected to the wireless network and takes approximately 50% in Ad-hoc networks. Moreover, if wireless stations communicate via the access point (i.e. in the Infrastructure mode), 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 by half as much. A detailed consideration of wireless networks overheads is given in [20], but it is out of the scope of this paper.

1.2. Enhanced distributed channel access

802.11n and 802.11ac standards use an enhanced variation of DCF for channel access called Enhanced Distributed Channel Access (EDCA). EDCA mechanism provides differentiated access to wireless medium by dividing traffic into four main access categories: background, best effort, video and voice. Instead of a constant distributed coordination function interframe space (DIFS) value, each traffic access category is assigned a distinct arbitration interframe space (AIFS) and using different values for minimum and maximum contention windows [10]. Although, despite the improvements provided, EDCA does not seem to solve the throughput unfairness issue.

2. Methodology and experimental setup

We conducted a number of experiments to investigate performance anomaly in mixed data rate Wi-Fi networks. The test-bed 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. Two wireless laptops (A and B) were equipped with the TP-Link Archer AC600 (802.11ac) network adapters supporting one spatial stream. These wireless laptops established connections to the desktop computer C via the access point. Evaluation version of *IxChariot* tool 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, 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 100 KB (default value) in case of 20 MHz and 40 MHz channel width setups. For the 80 MHz channel width scenario we increased the file size up to 1 MB.

IxChariot estimates throughput by measuring how fast a file is transferred between two endpoints of the data stream. The script transferred a series of 1000 files in a loop, which gives 1000 throughput measures.

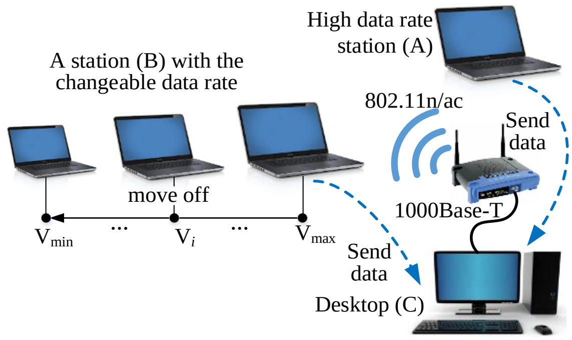
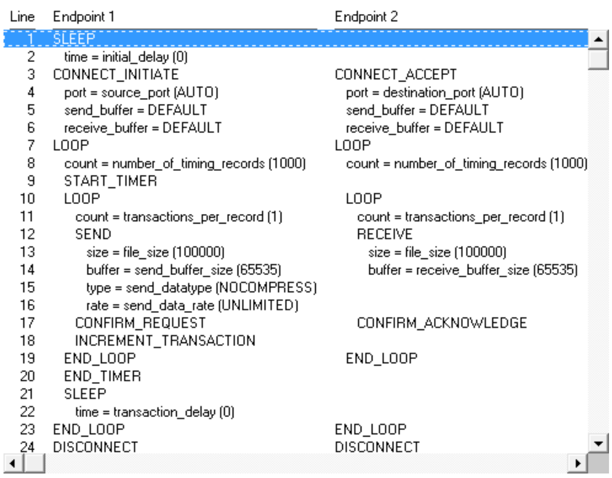


Fig. 2. Experimental setup



Endpoint 1	Endpoint 2
SLEEP	
time = initial_delay (0)	
CONNECT_INITIATE	CONNECT_ACCEPT
port = source_port (AUTO)	port = destination_port (AUTO)
send_buffer = DEFAULT	send_buffer = DEFAULT
receive_buffer = DEFAULT	receive_buffer = DEFAULT
LOOP	LOOP
count = number_of_timing_records (1000)	count = number_of_timing_records (1000)
START_TIMER	
LOOP	LOOP
count = transactions_per_record (1)	count = transactions_per_record (1)
SEND	RECEIVE
size = file_size (100000)	size = file_size (100000)
buffer = send_buffer_size (65535)	buffer = receive_buffer_size (65535)
type = send_datatype (NOCOMPRESS)	
rate = send_data_rate (UNLIMITED)	
CONFIRM_REQUEST	CONFIRM_ACKNOWLEDGE
INCREMENT_TRANSACTION	
END_LOOP	END_LOOP
END_TIMER	
SLEEP	
time = transaction_delay (0)	
END_LOOP	END_LOOP
DISCONNECT	DISCONNECT

Fig. 3. IxChariot throughput benchmarking script

The experiments were conducted in an open area environment with no other wireless networks installed nearby. The core idea of our experiments was to create a mixed data rate environment by having one of the wireless laptops connected to access point at maximal data rate while forcing the second laptop to use a lower data rate. With this in mind, Station A was placed close to AP throughout the whole experiment which enabled the maximal data rate of its wireless connection.

Radioelectronic and Computer Systems, 2022, no. 4(104)
ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

One should note that users cannot directly control and set certain data rate for a wireless network adapter. It is selected automatically by the station depending on signal strength and noise level. To force the second laptop (Station 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).

The full range of data rates supported by 802.11ac standards can be found in [21].

We performed a series of throughput benchmarks at different data rates of Station B, starting from maximum supported rate and decreased it down to lowest rate. We consider three different scenarios corresponding to different channel width: 20 MHz, 40 MHz and 80 MHz.

A single spatial stream theoretically supports maximal data rates of 72.2, 150 and 433.3 Mbps correspondingly (see Table 1). If the signal strength is very low, 802.11n/ac devices can even switch over to 1 or 2 Mbps data rate (supported by the legacy 802.11b standard) when they work in the 2.4GHz band. The actual data rate at which station A was sending data frames was extracted from the radiotap header of sent packets captured by *Wireshark* packet analyser. The most important experimental settings are summarised in Table 1. A frequency range, channel width and wireless modes were configured via adapter/access point settings.

Table 1

Parameters for experimental evaluation of throughput unfairness in mixed Wi-Fi networks

Parameter	**Scenario 1**	**Scenario 2**	**Scenario 3**
Mode	802.11n/ac mixed		
Frequency band, GHz	2.4	2.4	5
Channel Width, MHz	20	40	80
MIMO configuration	2x1:1	2x1:1	2x1:1
Maximal data rate	72.5	150	433.3
Minimal data rate	1	1	6
File size, KB	100	100	1000
Transmission protocol	TCP	TCP	TCP
No of loop cycles	1000	1000	1000

3. Throughput benchmarking and their comparison with the theoretical model

3.1. Throughput benchmarking results: 20MHz-width channel scenario

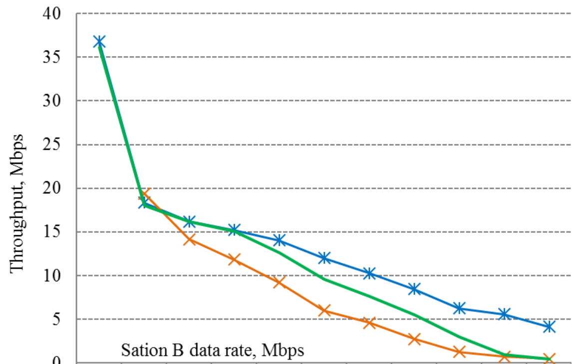
In this scenario the maximal data rate of a wireless connection established between laptops and an access point can reach 72.2 Mbps using one spatial stream. The single data stream established between A and C occupies the whole available throughput of a wireless network. It reached 36.823 Mbps on average (varying between 14.286 and 47.059 Mbps) which is 51% of the data rate at which A was connected to wireless access point. This observation is in line with a series of other experimental works. Fig. 4 shows how the average throughput of two independent data streams (A→C) and (B→C) is changed depending on the data rate of Station B. When B also sends data at the maximal data rate the two data streams share the network throughput almost equally (18.343 vs 19.403 Mbps). It can be noted that the throughput of both data streams decreased due to drop in Station B data rate.

At the same time, it is clear that the theoretical model (1) overestimates throughput of slow data rate (station B) and underestimate throughput of high data rate (station A). Fig. 5 explains this phenomenon. It presents examples of raw throughput estimates measured by *IxChariot* at different data rates of Station B.

One can notice two different patterns corresponding to slow and high data rate stations, especially when the difference between their data rates becomes significant (Figs. 5,c-d). Even though the data rate of Station A remains maximal, its throughput is decreasing on average. However, in Fig. 5 we can notice throughput peaks regularly experienced by Station A.

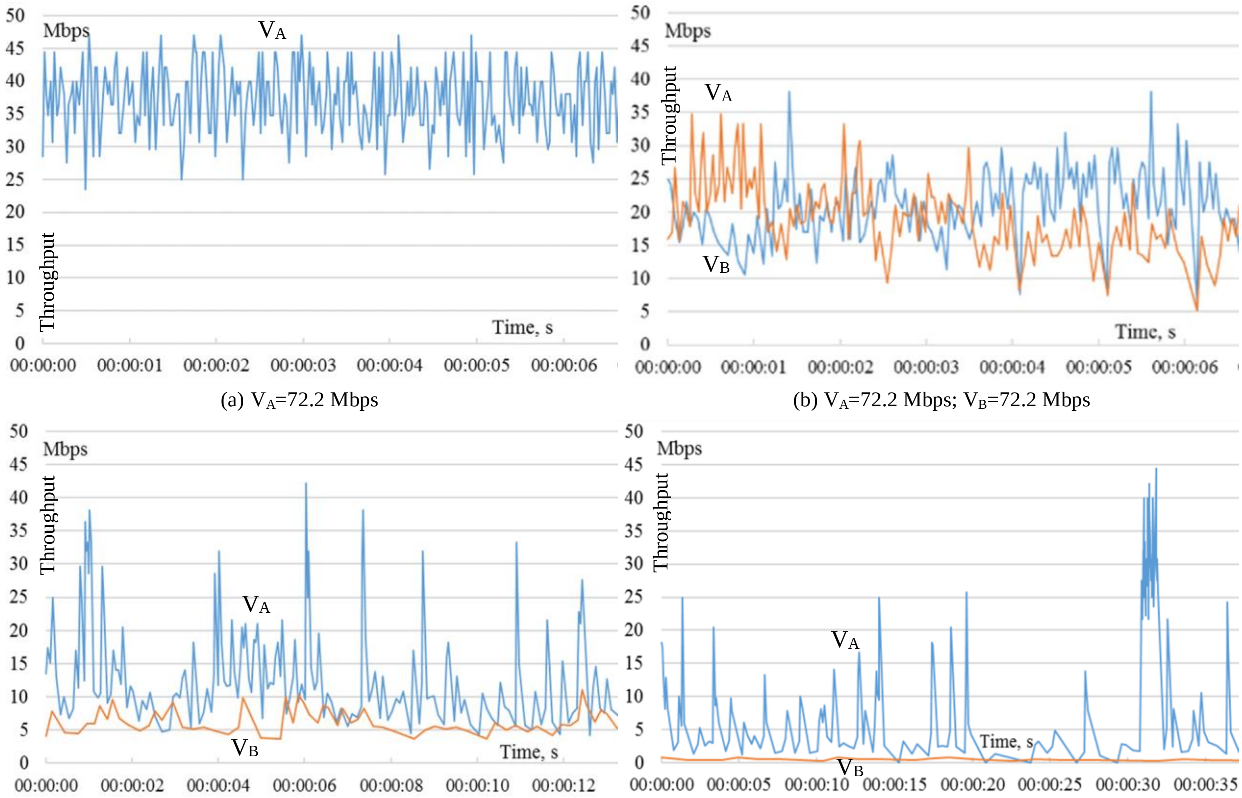
Analysing packet traces captured by *Wireshark*, we have found out that throughput of Station A sharply increased when Station B paused in data transfer. In turn, these pauses occurred because of TCP protocol slowed down its transmission rate reacting to packets loss (by reducing transmission window) or when Station B lost wireless connection and was trying to reconnect. The fact that TCP protocol works non-optimally over unstable wireless connections is widely accepted and has been studied by many authors [20, 22, 23].

Non-optimal settings of retransmission timer, wrong congestions detection cause unnecessary retransmissions, and reduced TCP congestion window also additionally degrades throughput of low data-rate Station B. However, this gives an additional opportunity to high-data rate Station A to overrun the theoretical throughput suggested by (1). However, deeper investigation of this phenomenon is beyond the scope of this paper.



	-	72.2	58.5	52	39	26	19.5	13	6.5	2	1
Station A	36.82	18.34	16.22	15.22	14.03	12.03	10.27	8.48	6.261	5.615	4.152
Station B		19.4	14.16	11.87	9.232	6.024	4.639	2.75	1.276	0.751	0.479
Model (1)	36.1	18.05	16.16	15.11	12.66	9.558	7.677	5.508	2.982	0.973	0.493

Fig. 4. Station throughputs depending on the data rate of Station B: 20 MHz scenario



(a) V_A=72.2 Mbps (b) V_A=72.2 Mbps; V_B=72.2 Mbps

(c) V_A=72.2 Mbps; V_B=26 Mbps (d) V_A=72.2 Mbps; V_B=1 Mbps

Fig. 5. Throughput patterns of stations with different data rates: 20 MHz scenario

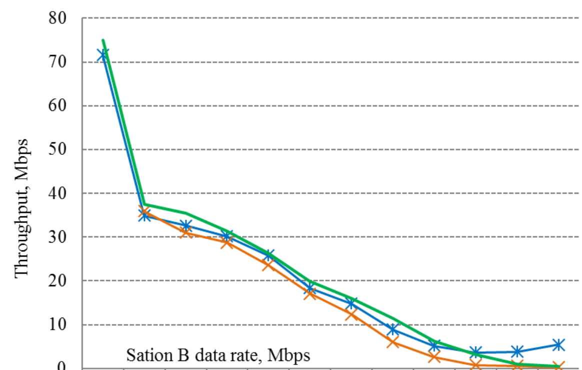
Nevertheless, our experimental results clearly show that slow data rate stations actively transmitting data can significantly degrade throughput of high data rate stations connected to wireless network.

3.2. Throughput benchmarking results: 40MHz-width channel scenario

In this scenario the maximal data rate of wireless connection was 150 Mbps. The single data stream established between A and C reaches 71.624 Mbps on average varying between 16 and 80 Mbps. It is 48% of the maximal data rate at which A was connected to wireless access point. Figures 6 and 7 show that the theoretical model (1) approximates stations throughput with a good accuracy. Only when a data rate of Station B drops down to 1 Mbps (which can happen when a Wi-Fi network uses 2.4 GHz range), Station A considerably outperforms Station B due to non-optimal behavior of TCP protocol (see Fig. 7). This phenomenon was considered in previous scenario.

3.3. Throughput benchmarking results: 80MHz-width channel scenario

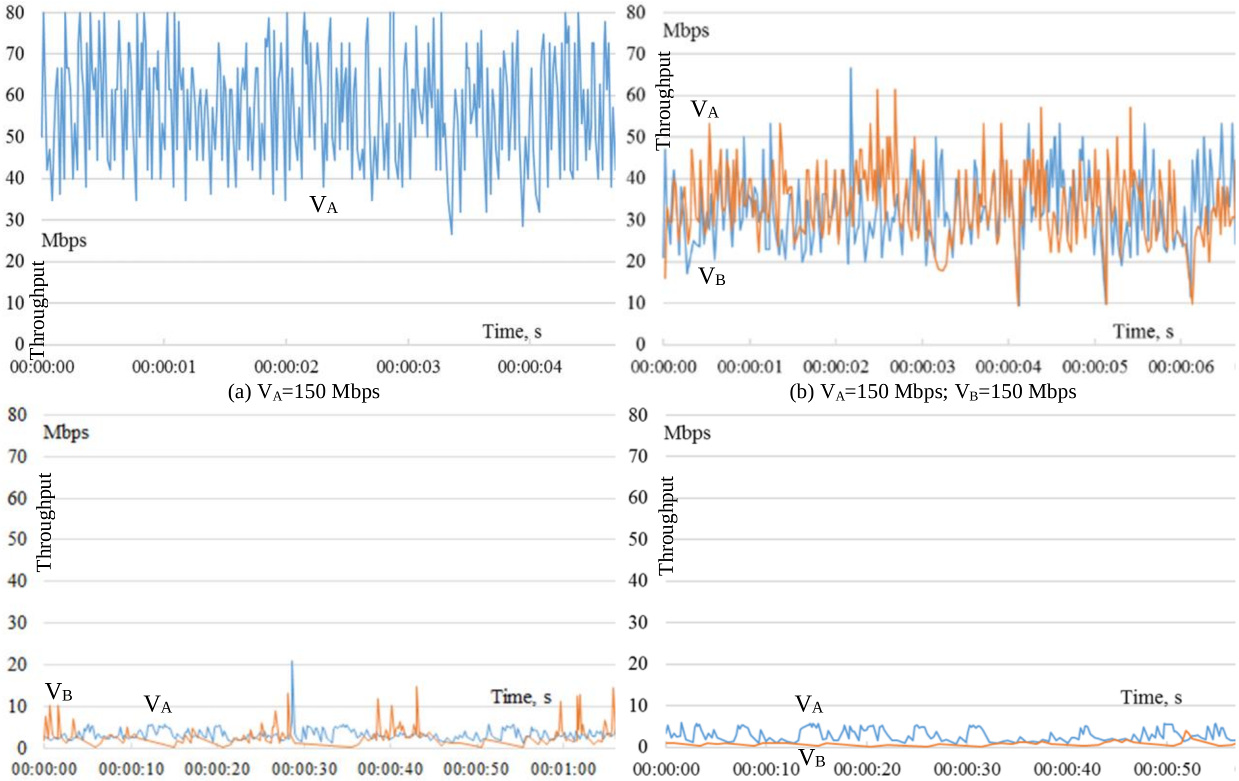
This scenario is only possible in pure 802.11ac wireless networks working in 5GHz range. The maximal allowed data rate in the case of single spatial stream is equal to 433.3 Mbps. The lowest supported data rate is 6 Mbps. Figs. 8 and 9 show the drop in Station B data rate affects throughput of both stations. However, the theoretical model (1) considerably underestimates the average throughput of Station A especially when difference between stations data rates becomes significant. It is also noteworthy that the throughput achieved by Station A when it monopolistically uses the wireless media is equal to 181.8 Mbps on average, which is considerably less than 50% of its data rate. This is due to significant overheads, even in most recent Wi-Fi technologies. During our experiments we noticed that network adapter and access point tend to use long guard intervals if the signal strength is not maximal.



	-	150	135	108	81	54	40.5	27	13.5	6.5	2	1
Station A	71.62	34.93	32.63	30.18	25.81	18.35	14.79	8.87	5.182	3.595	3.817	5.403
Station B		35.93	31.04	28.74	23.61	17.05	12.32	5.997	2.63	0.717	0.623	0.224
Model (1)	75	37.5	35.53	31.4	26.3	19.85	15.94	11.44	6.193	3.115	0.987	0.497

Fig. 6. Station throughputs depending on the data rate of Station B: 40 MHz scenario

Radioelectronic and Computer Systems, 2022, no. 4(104)
ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

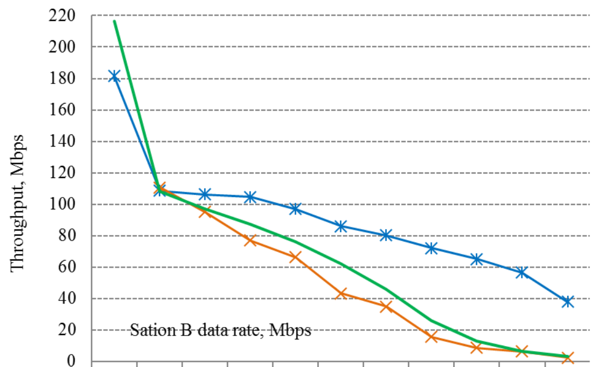


(a) V_A=150 Mbps (b) V_A=150 Mbps; V_B=150 Mbps

(c) V_A=150 Mbps; V_B=13.5 Mbps (d) V_A=150 Mbps; V_B=1 Mbps

Fig. 7. Throughput patterns of stations with different data rates: 40 MHz scenario

Hence, some of the data rates defined by 802.11n/ac standards have never been used by station B.



	-	433.3	351	292.5	234	175	117	58.5	27	13.5	6
Station A	181.8	108.6	106.2	104.6	97.02	85.99	80.3	72.18	65.07	56.46	37.94
Station B		110.6	94.96	77.04	66.2	43.2	34.85	15.55	8.733	6.211	2.361
Model (1)	216.7	108.3	96.96	87.31	75.97	62.33	46.06	25.77	12.71	6.546	2.959

Fig. 8. Station throughputs depending on the data rate of Station B: 80 MHz scenario

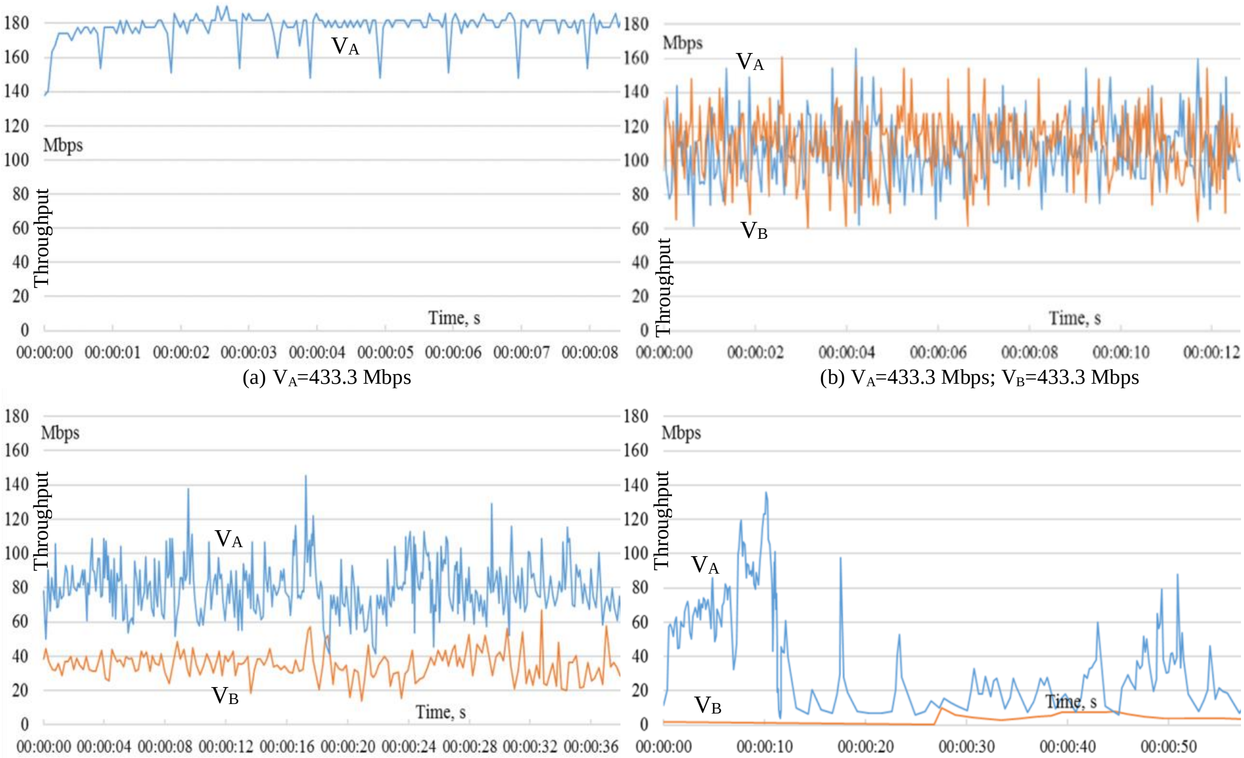
4. NS3 simulation of mixed data rate Wi-Fi networks

4.1. NS3 simulation model and setup

NS3 (Network Simulator v.3) is an open source network simulation tool which has been used extensively by research community and recognised to be a reliable network simulator [24]. It is a discrete-event computer network simulator which runs high-level C++ models. In simulation models we reproduced the same WLAN infrastructure and topology used for experimental throughput measurements (see Fig. 2).

The simulation model was created as per following sequence of operations:

1. Create network nodes and connections between them according to Fig. 2.
2. Setup Gigabit Ethernet channel between Access Point and Server C.
3. Setup Wi-Fi channel and physical layer between Access Point and two wireless stations A and B:
    a. Wi-Fi standard;
    b. channel width;
    c. number of antennas;
    d. number of Tx and Rx spatial streams;
    e. guard interval;
    f. modulation code scheme;
4. Setup Wi-Fi mac layer:
    a. network SSID;
5. Install protocol stack on all devices.
6. Configure IP settings on all devices.
7. Configure the application layer settings:
    a. Create TCP sockets between wireless stations A and B and server C;
    b. Setup packet size;
    c. Setup the application data rate for both stations;
    d. Setup simulation time;
8. Run the simulation.
9. Collected the wireless nodes applications throughputs.



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

(c) V_A=433.3 Mbps; V_B=117 Mbps (d) V_A=433.3 Mbps; V_B=6 Mbps

Fig. 9. Throughput patterns of stations with different data rates: 80 MHz scenario

We run a series of simulations for each of the scenarios reported in Table 1. In each simulation, data rate of station A was set to maximal supported rate and never changed. Instead of moving Station B away from access point, we configured Station B settings to use the data rates from the range obtained experimentally and reported in Section 3.

4.2. NS3 simulation results and their comparison with experimental and theoretical data

Tables 2-4 report throughputs of high and low data rate stations A and B depending on differences in their data rates estimated theoretically (1), measured experimentally and simulated in NS3. Reported data show that NS3 simulation results are in line with results obtained experimentally and estimated using (1). They confirm the general finding that low speed stations can significantly degrade throughput of high data rate stations and drop the overall network efficiency. Moreover, simulation results confirm our practical observations that high data rate station starts to over perform the low data rate station once the difference between their data rates becomes more significant. Packet traces generated by NS3 showed that TCP protocol of low-data rate station sends data with the lower intensity even despite statistically equal transmission opportunities at the MAC layer. Round trip time (RTT) measured by low data rate station is significantly higher than RTT of high-data rate station.

Table 2

Scenario 1: a deviation between throughput modelling, measurement and simulation

Data rates, Mbps		Throughput, Mbps				
		Theoretical	Experimental		ns3 Simulation	
St. A	St. B	St. A=B	St. A	St. B	St. A	St. B
72.2	-	36.10	36.82	-	50.02	-
72.2	72.2	18.05	18.34	19.40	23.25	23.34
72.2	58.5	16.16	16.22	14.16	22.85	21.24
72.2	52	15.11	15.22	11.87	21.74	19.66
72.2	39	12.66	14.03	9.23	21.36	15.67
72.2	26	9.56	12.03	6.02	20.23	11.23
72.2	19.5	7.68	10.27	4.64	19.44	9.33
72.2	13	5.51	8.48	2.75	18.20	5.62
72.2	6.5	2.98	6.26	1.28	16.05	2.55
72.2	2	0.97	5.62	0.75	13.74	0.98
72.2	1	0.49	4.15	0.48	10.23	0.60

Table 3

Scenario 2: a deviation between throughput modelling, measurement and simulation

Data rates, Mbps		Throughput, Mbps				
		Theoretical	Experimental		ns3 Simulation	
St. A	St. B	St. A=B	St. A	St. B	St. A	St. B
150	-	75.00	71.62	-	103.98	-
150	150	37.50	34.93	35.93	52.84	53.14
150	135	35.53	32.63	31.04	50.28	47.25
150	108	31.40	30.18	28.74	41.31	42.85
150	81	26.30	25.81	23.61	37.99	36.44
150	54	19.85	18.35	17.05	32.08	26.80
150	40.5	15.94	14.79	12.32	26.10	22.60
150	27	11.44	8.87	6.00	20.59	14.40
150	13.5	6.19	5.18	2.63	17.23	7.22
150	6.5	3.12	3.60	0.72	15.67	1.72
150	2	0.99	3.82	0.62	14.52	0.95
150	1	0.50	5.40	0.22	13.04	0.59

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

Table 4
Scenario 3: a deviation between throughput modelling, measurement and simulation

Data rates, Mbps		Throughput, Mbps				
		Theoretical	Experimental		ns3 Simulation	
St. A	St. B	St. A=B	St. A	St. B	St. A	St. B
433.5	-	216.75	181.778	-	279.62	-
433.5	433.5	108.38	108.613	110.6	132.26	135.08
433.5	351	96.98	106.242	94.962	128.61	122.62
433.5	292.5	87.33	104.551	77.037	122.64	108.71
433.5	234	75.98	97.02	66.2	109.96	99.26
433.5	175	62.34	85.993	43.197	92.00	85.30
433.5	117	46.07	80.303	34.848	72.57	65.16
433.5	58.5	25.77	72.175	15.546	46.91	42.21
433.5	27	12.71	65.068	8.733	37.86	22.04
433.5	13.5	6.55	56.176	6.211	36.27	9.96
433.5	6	2.96	37.937	2.361	35.84	4.84

This affects retransmission timer settings and causes considerable pauses in TCP data flow which are used by high data rate station to transmit its data. However, one should note that NS3 simulation considerably overestimates the initial stations' throughputs (by 45% on average – see Tables 2-4) compared to experimental results. This means that NS3 simulator does not take into account all overheads of wireless networks.

Ultimately, the simulation results confirm that NS3 does take into account airtime consumption unfairness that occurred in mixed data rate Wi-Fi networks with adequate accuracy.

5. Accuracy of theoretical throughput modelling and simulation

In this section we evaluate how well the experimental data are replicated by the simulation and analytical models. With this purpose we use the coefficient of determination (R-squared) and a standard deviation between predicted and measured throughput values (see Table 5).

In addition to analytical model (1) and NS3 simulations, we also consider a *conservative approach* which estimates station's throughput as inversely proportional to number of stations. This estimate is used to roughly predict station's throughput in half-duplex CSMA/CA networks where all stations in the same collision domain use the same data rate (e.g. 10 Mbps in Ethernet networks or 100 Mbps in Fast Ethernet networks).

Table 5 shows that the conservative estimate is not appropriate for wireless networks. In all three scenarios R-squared estimated between the experimentally observed and predicted throughput of high-data rate station approximates to zero. Though, this approach is still applicable for predicting throughput of stations with lower data rate sharing common media with high-speed stations.

The theoretical model (1) gives a good approximation of experimental data in case of both high and low data rate stations. However, the model assumes that high and low data rate stations would have the same throughput approximate to data rate of the slowest station. This is not generally true. Experimental results (see Figs. 4, 6, 8) show that in all scenarios the high-data rate station always outperforms the low data rate station, especially when the difference between their data rates is increasing. As a result, model (1) slightly overestimate throughput for low data rate station (the average standard deviation is equal to 5 Mbps) and considerably underestimate throughput of high-speed station (the average standard deviation is equal to 13.5 Mbps).

Table 5 also shows that NS3 simulator predicts stations throughput with a considerably high accuracy, close to theoretical modelling. It does take into consideration airtime consumption unfairness between high and low data rate stations and also accurately simulates behavior of the TCP protocol. Simulation results correlate with experimental observations showing that the high-speed station outperforms the slow one on average (see Tables 2-4). However, as mentioned above, it seems NS3 does not take into account all overheads existed in wireless networks.

Table 5
Accuracy of theoretical throughput modelling and simulation

		R-squared		Std. Dev.	
		St. A	St. B	St. A	St. B
Conservative estimate	Scenario 1	0.00	0.99	9.15	11.99
	Scenario 2	0.00	0.98	25.06	2.09
	Scenario 3	0.00	0.99	36.94	4.43
Analytical model (1)	Scenario 1	0.99	0.93	2.78	2.59
	Scenario 2	0.98	0.99	2.45	3.26
	Scenario 3	0.97	0.97	35.18	9.57
NS3 Simulation	Scenario 1	0.89	0.95	8.37	12.06
	Scenario 2	0.98	0.99	13.50	11.03
	Scenario 3	0.90	0.95	19.52	28.01

Therefore, throughputs of both high and low data rate stations are considerably overestimated which results in a significant standard deviation despite high R-squared values (especially for station B).

6. Simulation of throughput degradation in a multi-node setup using NS3

In this section we considered multi-node scenarios. Running real experiments with multi-node Wi-Fi network is expensive and not practical. Our simulations results reported in previous sections demonstrated that NS3 does take into consideration airtime consumption unfairness that exists in mixed data-rate networks with good accuracy.

Therefore, we carried out a series of multi-node simulations to investigate how the overall network throughput and the average throughput available to each station vary depending on the number of stations and the impact of presence of even a single low data rate station on stations' throughputs and network throughput. Two setups are considered:

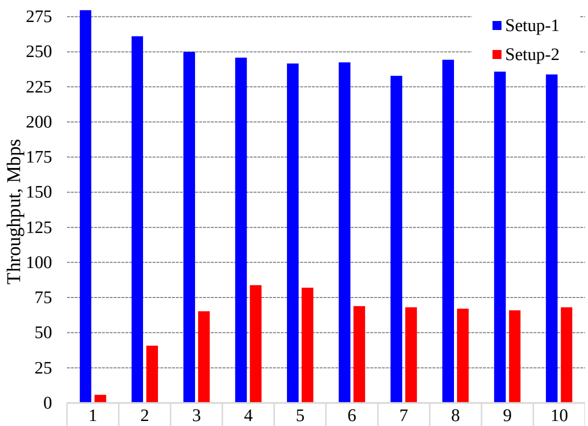
Setup-1: all wireless stations are connected to an access point at the maximal data rate of 433.5 Mbps;

Setup-2: there is one low data rate station in the networks which is connected to an access point at the minimal data rate of 6Mbps; the rest of the stations are connected at the maximal data rate of 433.5 Mbps.

Fig. 10 shows how the overall network throughput depends on the number of stations in both setups. If all stations transmit data at the maximal data rate, we observe only slight throughput degradation with the increase of number of stations. This is explained by CSMA/CA overheads appearing when two or more stations share the media. Finally, the overall network throughput stabilizes around 238 Mbps, which is 55% of the maximal data rate 433.5 Mbps. This aligns with our experiments and simulation model. Fig. 10 also shows that even a single low data rate station significantly affects the overall network throughput.

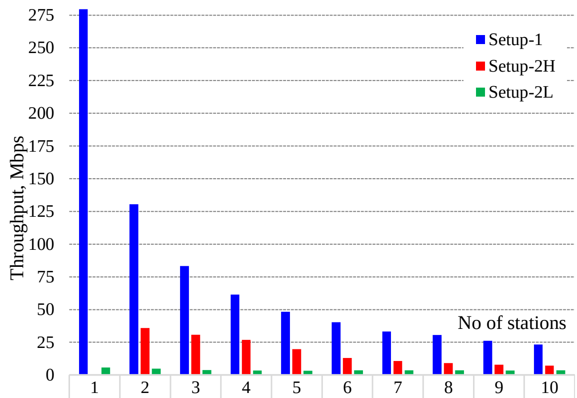
On average, it decreases the overall network throughput by a factor of 3.5. Further increasing the number of stations will increase the probability of collision occurring and number of retransmissions. This, in turn, will cause network throughput degradation for both setups.

Fig. 11 demonstrates how the average station's throughput depends on the total number of stations in the network. When all stations use the same maximal data rate, their average throughput is decreasing proportionally to the number of stations. Histogram *Setup-2L* on Fig. 11 represents a throughput of a single low data rate station.



	1	2	3	4	5	6	7	8	9	10
Setup-1	279.62	261.09	249.87	245.78	241.64	242.51	232.85	244.33	235.83	233.83
Setup-2	5.78	40.68	65.21	83.81	81.99	68.94	68.08	67.14	66.00	68.11

Fig. 10. Overall network throughput depending on the number of stations



	1	2	3	4	5	6	7	8	9	10
Setup-1	279.62	130.54	83.29	61.44	48.33	40.42	33.26	30.54	26.20	23.38
Setup-2H		35.84	30.70	26.81	19.68	13.08	10.74	9.07	7.82	7.17
Setup-2L	5.78	4.84	3.82	3.39	3.26	3.56	3.63	3.64	3.42	3.59

Fig. 11. Average station throughput depending on the number of stations

It remains almost constant irrespective of number of high data rate stations it shares the media with. At the same time, average throughput of high data rate stations in the second setup (*Setup-2H*) is approximately three times less compared to *Setup-1*.

Finally, it can be seen that with the increase of number of high data rate stations, their average throughput is approximating to the throughput of the slow data rate station. These results highlight the importance of solving performance anomaly that existed in mixed data rate Wi-Fi networks and clearly demonstrate that even a single low data rate station can dramatically degrade throughputs of high data rate stations and significantly reduce the overall performance of the wireless network.

Conclusions and Lessons Learnt

In this paper we investigated the 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 consume considerably more airtime than high speed stations 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 the performance of the whole network and dramatically decrease throughput of high data rate stations. This performance anomaly was examined (i) experimentally, (ii) via simulation and (iii) analytical modelling. In our work we considered three scenarios, using different Wi-Fi standards and channel widths: 802.11n 20MHz, 802.11n 40MHz, and 802.11ac 80 MHz. Our experimental results have confirmed the significance of the issue and indicated that the airtime consumption unfairness dramatically decreases the throughput of high data rate stations. It was shown that airtime consumption unfairness degrades the throughput of high data rate station by a factor of 3–6 times (depending on

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

the scenario) when a single low data rate station transmits data at the lowest supported data rate.

Simulation results and analytical modelling using (1) have certain limitations as discussed in Sections 3-4. Nevertheless, they give considerably high approximation of the experimental results and confirm experimental findings.

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 and simulation results have demonstrated, that despite a significant performance degradation, the high-data rate station still outperforms the low data rate station. This finding is discussed in more details in Section 3.

Ultimately, our work clearly shows that airtime consumption unfairness still exists in recent wireless standard IEEE802.11n/ac and there are no signs that the situation changed in the new IEEE802.11ax. It remains one of the major stumbling blocks in achieving the full potential of modern Wi-Fi networks. Even though many techniques have been proposed to mitigate this issue, none of them offers a complex approach and provides an optimal solution. We believe that mitigating performance anomaly in mixed-data rate WLANs requires a holistic approach that combines the frame aggregation/fragmentation and adaptation of station's data rate, contention window and other link-layer parameters [25]. Therefore, in the future work, we plan to design models and techniques allowing to take into account some of these parameters considering fundamentals trade-offs between throughput, latency, utilization and reliability.

Contributions of authors: conceptualization – **Anatoliy Gorbenko**; methodology – **Anatoliy Gorbenko, Fash Safdari**; formulation of tasks and literature review – **Anatoliy Gorbenko, Fash Safdari**; development of models – **Anatoliy Gorbenko, Fash Safdari**; software development – **Fash Safdari**; verification – **Anatoliy Gorbenko**; analysis of results – **Anatoliy Gorbenko, Fash Safdari**; visualization – **Anatoliy Gorbenko**; writing – original draft preparation – **Anatoliy Gorbenko, Fash Safdari**; writing – review and editing – **Anatoliy Gorbenko**.

All the authors have read and agreed to the published version of the manuscript.

References (GOST 7.1:2006)

1. Revisiting Wireless Internet Connectivity: 5G vs Wi-Fi 6 [Text] / E. J. Oughton, W. Lehr, K. Katsaros, I. Selinis, D. Bubley and J. Kusuma // Telecommunications Policy. – 2021. – Vol. 45, No. 5. – P. 1-15. DOI: 10.1016/j.telpol.2021.102127.

2. Naik, G. Coexistence of Wireless Technologies in the 5 GHz Bands: A Survey of Existing Solutions and a Roadmap for Future Research [Text] / G. Naik, J. Liu, J.-M. J. Park // IEEE Communications Surveys & Tutorials. – 2018. – Vol. 20, No. 3. – P. 1777-1798. DOI: 10.1109/COMST.2018.2815585.

3. Performance Anomaly of 802.11b [Text] / M. Heusse, F. Rousseau, G. Berger-Sabbatel, A. Duda // Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM'2003). – 2003. – P. 836-843. DOI: 10.1109/INFCOM.2003.1208921.

4. Performance Evaluation of WiFi Direct for Data Dissemination in Mobile Social Networks [Text] / Z. Mao, J. Ma, Y. Jiang, B. Yao // IEEE Symposium on Computers and Communications (ISCC'2017). – 2017. – P. 1213-1218. DOI: 10.1109/ISCC.2017.8024690.

5. The Impact of Channel Bonding on 802.11n Network Management [Text] / L. Deek, E. Garcia-Villegas, E. Belding, S. Lee, K. Almeroth // Conference on emerging Networking Experiments and Technologies (CoNEXT '2011). – 2011 – P. 1-12. DOI: 10.1145/2079296.2079307.

6. Zeng, Y. A first look at 802.11ac in action: energy efficiency and interference characterization [Text] / Y. Zeng, P. H. Pathak, P. Mohapatra // IFIP Networking Conference. – 2014. – P. 2-9. DOI: 10.1109/CSNDSP.2018.8471865.

7. Abu-Sharkh, O. The impact of multi-rate operation on A-MSDU, A-MPDU and block acknowledgment in greenfield IEEE802.11n wireless LANs [Text] / O. Abu-Sharkh, M. Abdelhadi // Conference on Wireless Advanced (WiAD'2011). – 2011. – P. 116-121. DOI: 10.1109/WiAd.2011.5983297.

8. Performance Analysis of Video on Demand in an IEEE 802.11p-based Vehicular Network [Text] / T. Begin, A. Busson, I. Guérin-Lassous, A. Boukerche // Computer Communications. – 2019. – Vol. 146. – P. 174-185. DOI: 10.1016/j.comcom.2019.08.006.

9. Kliushnikov, I.M. Scheduling UAV fleets for the persistent operation of UAV-enabled wireless networks during NPP monitoring [Text] / I.M. Kliushnikov, H.V. Fesenko, V.S. Kharchenko // Radioelectronic and computer systems. – 2020. – Vol. 1. – P. 29-36. DOI: 10.32620/reks.2020.1.03.

10. IEEE Std 802.11ax-2021. Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Amendment 1: Enhancements for High-Efficiency WLAN [Text]. – IEEE, 2021. – 767 p. DOI: 10.1109/IEEESTD.2021.9442429.

11. Sandoval, J. Performance Evaluation of IEEE 802.11ax for Residential Networks [Text] / J. Sandoval, S. Cespedes // IEEE Latin-American Conference on Communications (LATINCOM'2021). – 2021. – P. 1-7. DOI: 10.1109/LATINCOM53176.2021.9647762.

12. Performance Analysis of a Novel TCP Protocol Algorithm Adapted to Wireless Networks [Text] / G. Olmedo, R. Lara-Cueva, D. Martínez, C. de Almeida // Future Internet. – 2020. – Vol. 12, No. 101. – P. 1-17. DOI:10.3390/fi12060101.

13. Throughput estimation with regard to airtime consumption unfairness in mixed data rate Wi-Fi networks [Text] / Abdul-Hadi, O. Tarasyuk, A. Gorbenko, V. Kharchenko, T. Hollstein // Communications. – 2014. –

Vol. 16, No. 1. – P. 84-89. DOI: 10.26552/com.C.2014.1.84-89.

14. Natkaniec, M. A Performance Analysis of IEEE 802.11ax Networks [Text] / M. Natkaniec, Ł. Prasnal, M. Szymakowski // International Journal of Electronics and Telecommunications. – 2020. – Vol. 66, No. 1. – P. 225-230. DOI: 10.24425/ijet.2020.131867.

15. Implementation and Evaluation of WLAN 802.11ac for Residential Networks in NS-3 [Text] / Y. Xu, A.B. Amewuda, F.A. Katsriku, J.-D. Abdulai // Journal of Computer Networks and Communications. – 2018. – Vol. 9, Issue 25. – P. 1-10. DOI: 10.1155/2018/3518352.

16. Performance Evaluation of Multi-Rate Communication in Wireless LANs [Text] / F. Miki, D. Nobayashi, Y. Fukuda, T. Ikenaga // IEEE Consumer Communications and Networking Conference (CCNC'2010). – 2010. – P. 1-3. DOI: 10.1109/DESSERT.2019.8770038.

17. Abu-Sharkh, O. Multi-Rate 802.11 WLANs [Text] / O. Abu-Sharkh, A. Tewfik // IEEE Global Telecommunications Conference (CLOBECOM’2005). – 2005. – P. 3128-3133. DOI: 10.1109/GLOCOM.2005.1578333.

18. Performance Enhancement of Multirate IEEE 802.11 WLANs with Geographically Scattered Stations [Text] / D.-Y. Yang, T.-J. Lee, K. Jang, J.-B. Chang, S. Choi // IEEE Transaction on Mobile Computing. – 2006. – Vol. 5, No. 7. – P. 906-919. DOI: 10.1109/TMC.2006.101.

19. Safdari, F. Experimental Evaluation of Performance Anomaly in Mixed Data Rate IEEE802.11ac Wireless Networks [Text] / F. Safdari, A. Gorbenko // IEEE International Conference on Dependable Systems, Services and Technologies (DESSERT’2019). – 2019. – P. 82-87. DOI: 10.1109/DESSERT.2019.8770038.

20. TCP Performance Issues over Wireless Links [Text] / G. Xylomenos, G. Polyzos, P. Mahönen, M. Saaranen // IEEE Communications Magazine. – 2001. – Vol. 39, No. 4. – P. 52-58. DOI: 10.1109/35.917504.

21. 802.11ac-2013. Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Amendment 4: Enhancements for Very High Throughput for Operation in Bands below 6 GHz [Text]. – IEEE, 2013. – 485 p. DOI: 10.1109/IEEESTD.2013.7797535.

22. Goswami, C. Transport Control Protocol (TCP) enhancement over wireless environment: Issues and challenges [Text] / C. Goswami, R. Shahane // Proceedings of the IEEE International Conference on Inventive Computing and Informatics (ICICI). – 2017. – P. 742-749. DOI: 10.1109/ICICI.2017.8365234.

23. V-TCP: A Novel TCP Enhancement Technique for Wireless Mobile Environments [Text] / D. Nagamalai, D.-H. Kang, K.-Y. Moon, J.-K. Lee // Information Networking: Convergence in Broadband and Mobile Networking (ICOIN’2005). – 2005. – P. 122-131. DOI: 10.1007/978-3-540-30582-8_13.

24. Kamoltham, N. From NS-2 to NS-3 – Implementation and evaluation [Text] / N. Kamoltham, K. Nakorn, K. Rojviboonchai // Computing, Communications and Applications Conference. – 2012. – P. 35-40. DOI: 10.1109/ComComAp.2012.6153999.

25. Contention window adaptation to ensure airtime consumption fairness in multirate Wi-Fi networks [Text] / O. Tarasyuk, A. Gorbenko, V. Kharchenko, T. Hollstein // 10th International Conference on Digital Technologies (DT’2014). – 2014. – P. 344-349. DOI: 10.1109/DT.2014.6868737.

References (BSI)

1. Oughton, E. J., Lehr, W., Katsaros, K., Selinis, I., Bubley, D. and Kusuma, J. Revisiting Wireless Internet Connectivity: 5G vs Wi-Fi 6. *Telecommunications Policy*, 2021, vol. 45, no. 5, pp. 1-15. DOI: 10.1016/j.telpol.2021.102127.

2. Naik, G., Liu, J. and Park, J.-M. J. Coexistence of Wireless Technologies in the 5 GHz Bands: A Survey of Existing Solutions and a Roadmap for Future Research. *IEEE Communications Surveys & Tutorials*, 2018, vol. 20, no. 3, pp. 1777-1798. DOI: 10.1109/COMST.2018.2815585.

3. Heusse, M., Rousseau, F., Berger-Sabbatel, G. and Duda, A. Performance Anomaly of 802.11b. *22nd Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM’2003)*, 2003, pp. 836-843. DOI: 10.1109/INFCOM.2003.1208921.

4. Mao, Z., Ma, J., Jiang, Y. and Yao, B. Performance Evaluation of WiFi Direct for Data Dissemination in Mobile Social Networks. *IEEE Symposium on Computers and Communications (ISCC'2017)*, Heraklion, Greece, 2017. DOI: 10.1109/ISCC.2017.8024690

5. Deek, L., Garcia-Villegas, E., Belding, E., Lee, S. and Almeroth, K. The Impact of Channel Bonding on 802.11n Network Management. *Conference on emerging Networking Experiments and Technologies (CoNEXT '2011)*, 2011, pp. 1-12. DOI: 10.1145/2079296.2079307.

6. Zeng, Y., Pathak P. H. and Mohapatra, P. A first look at 802.11ac in action: energy efficiency and interference characterization. *IFIP Networking Conference*, 2014, pp. 2-9. DOI: 10.1109/CSNDSP.2018.8471865.

7. Abu-Sharkh, O. and Abdelhadi, M. The impact of multi-rate operation on A-MSDU, A-MPDU and block acknowledgment in greenfield IEEE802.11n wireless LANs. *Proceedings of the Conference on Wireless Advanced (WiAD'2011)*, 2011, pp. 116-121. DOI: 10.1109/WiAd.2011.5983297.

8. Begin, T., Busson, A., Guérin-Lassous, I. and Boukerche, A. Performance Analysis of Video on Demand in an IEEE 802.11p-based Vehicular Network. *Computer Communications*, 2019, vol. 146, pp. 174-185. DOI: 10.1016/j.comcom.2019.08.006.

9. Kliushnikov, I.M., H.V. Fesenko, H.V., Kharchenko, V.S. Scheduling UAV fleets for the persistent operation of UAV-enabled wireless networks during NPP monitoring. *Radioelectronic and computer systems*, 2020, vol. 1, pp. 29-36. DOI: 10.32620/reks.2020.1.03.

10. *IEEE Std 802.11ax-2021. Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY)*

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

Specifications Amendment 1: Enhancements for High-Efficiency WLAN, IEEE, 2021, 767 p. DOI: 10.1109/IEEESTD.2021.9442429.

11. Sandoval, J., Cespedes, S. Performance Evaluation of IEEE 802.11ax for Residential Networks. *IEEE Latin-American Conference on Communications (LATINCOM'2021)*, 2021, pp. 1-7. DOI: 10.1109/LATINCOM53176.2021.9647762.

12. Olmedo, G., Lara-Cueva, R., Martínez, D., de Almeida, C. Performance Analysis of a Novel TCP Protocol Algorithm Adapted to Wireless Networks. *Future Internet*, 2020, vol. 12, no. 101, pp. 1-17. DOI:10.3390/fi12060101.

13. Abdul-Hadi, A., Tarasyuk, O., Gorbenko, A., Kharchenko, V. and Hollstein, T. Throughput estimation with regard to airtime consumption unfairness in mixed data rate Wi-Fi networks. *Communications*, vol. 16, no. 1, pp. 84-89, 2014. DOI: 10.26552/com.C.2014.1.84-89.

14. Natkaniec, M., Prasnal, Ł., Szymakowski, M. A Performance Analysis of IEEE 802.11ax Networks. *International Journal of Electronics and Telecommunications*, 2020, vol. 66, no. 1, pp. 225-230. DOI: 10.24425/ijet.2020.131867.

15. Xu, Y., Amewuda, A.B., Katsriku, F.A., Abdulai, J.-D. Implementation and Evaluation of WLAN 802.11ac for Residential Networks in NS-3. *Journal of Computer Networks and Communications*, 2018, vol. 9, issue 25, pp. 1-10. DOI: 10.1155/2018/3518352.

16. Miki, F., Nobayashi, D., Fukuda, Y. and Ikenaga, T. Performance Evaluation of Multi-Rate Communication in Wireless LANs. *IEEE Consumer Communications and Networking Conference (CCNC'2010)*, 2010, pp. 1-3. DOI: 10.1109/DESSERT.2019.8770038.

17. Abu-Sharkh, O. and Tewfik, A. Multi-Rate 802.11 WLANs. *IEEE Global Telecommunications Conference (CLOBECOM'2005)*, 2005, pp. 3128-3133. DOI: 10.1109/GLOCOM.2005.1578333.

18. Yang, D.-Y., Lee, T.-J., Jang, K., Chang, J.-B. and Choi, S. Performance Enhancement of Multirate IEEE 802.11 WLANs with Geographically Scattered Stations. *IEEE Transaction on Mobile Computing*, 2006, vol. 5, no. 7, pp. 906-919. DOI: 10.1109/TMC.2006.101.

19. Safdari, F. and Gorbenko, A. Experimental Evaluation of Performance Anomaly in Mixed Data Rate IEEE802.11ac Wireless Networks, *Proceedings of the 10th IEEE International Conference on Dependable Systems, Services and Technologies (DESSERT'2019)*, 2019, pp. 82-87. DOI: 10.1109/DESSERT.2019.8770038.

20. Xylomenos, G., Polyzos, G.C., Mahonen, P., Saaranen, M. TCP Performance Issues over Wireless Links. *IEEE Communications Magazine*, 2001, vol. 39, no. 4, pp. 52-58. DOI: 10.1109/35.917504.

21. *802.11ac-2013. Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Amendment 4: Enhancements for Very High Throughput for Operation in Bands below 6 GHz*, IEEE, 2013, 485 p. DOI: 10.1109/IEEESTD.2013.7797535.

22. Goswami, C. and Shahane, R. Transport Control Protocol (TCP) enhancement over wireless environment: Issues and challenges. *Proceedings of the IEEE International Conference on Inventive Computing and Informatics (ICICI'2017)*, 2017, pp. 742-749. DOI: 10.1109/ICICI.2017.8365234.

23. Nagamalai, D., Kang, D.-H., Moon, K.-Y. and Lee, J.-K. V-TCP: A Novel TCP Enhancement Technique for Wireless Mobile Environments. *Proceedings of the Information Networking: Convergence in Broadband and Mobile Networking (ICOIN'2005)*, 2005, pp. 122-131. DOI: 10.1007/978-3-540-30582-8_13.

24. Kamoltham, N., Nakorn, K. and Rojviboonchai, K. From NS-2 to NS-3 - Implementation and evaluation. *Proceedings of the Computing, Communications and Applications Conference (COMCOMAP'2012)*, 2012, pp. 35-40. DOI: 10.1109/ComComAp.2012.6153999.

25. Tarasyuk, O., Gorbenko, A., Kharchenko, V., Hollstein, T. Contention window adaptation to ensure airtime consumption fairness in multirate Wi-Fi networks. *10th International Conference on Digital Technologies (DT'2014)*, 2014, pp. 344-349. DOI: 10.1109/DT.2014.6868737.

Надійшла до редакції 25.09.2022, розглянута на редколегії 20.11.2022

ТЕОРЕТИЧНЕ ТА ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ АНОМАЛІЇ ПРОДУКТИВНОСТІ У БЕЗДРОТОВИХ МЕРЕЖАХ IEEE802.11ac З АБОНЕНТАМИ З РІЗНОЮ ШВИДКІСТЮ ПЕРЕДАЧІ ІНФОРМАЦІЇ

Феш Сафдарі, Анатолій Горбенко

Бездротові локальні мережі (wireless local area networks, WLAN) стандарту IEEE 802.11 – це мережі, які використовують функцію розподіленої координації (distributed coordination function, DCF) для організації спільного доступу до бездротового середовища багатьох бездротових станцій. Продуктивність механізму розподіленої координації з випадковим доступом в основному залежить від навантаження на мережу, кількості бездротових вузлів, а також їхньої швидкості передачі даних. Відомо, що у мережах Wi-Fi які обслуговують бездротових абонентів зі змішаною швидкістю передачі даних виникає несправедливість розподілу пропускної здатності між цими абонентами. Цей феномен, також відомий як аномалія продуктивності, властивий самій функції розподіленої координації спільного доступу. Аномалія продуктивності проявляється через те, що клієнти з меншою швидкістю споживають значно більше ефірного часу для передачі певного обсягу даних, залишаючи менше ефірного часу для більш швидких абонентів. У статті всебічно досліджується аномалія продуктивності, що виникає в бездротових мережах з абонентами з різною швидкістю передачі даних, використовуючи три підходи: експериментальне вимірювання, аналітичне дослідження та імітаційне моделювання в Network Simulator v.3 (NS3). Результати експериментального дослідження та порівняння пропускної здатності абонентів у бездротовій мережі 802.11ac показують, що проблема несправедливого споживання ефірного часу залишається актуальною навіть для найбільш сучасних стандартів бездротового зв’язку. Було показано, що навіть одна станція з низькою швидкістю передачі даних знижує пропускну здатність станцій з високою швидкістю передачі даних у 3–6 разів. Імітаційне та аналітичне моделювання підтверджують цей висновок із значною точністю. Більшість теоретичних моделей, що оцінюють аномалію продуктивності в мережах Wi-Fi, передбачають однакову пропускну здатність вузлів незалежно від швидкісті передачі. Однак експеримені дані та результати моделювання показують, що, незважаючи на значне погіршення продуктивності, високошвидкісні станції починають випереджувати низькошвидкісні, коли різниця між їхніми швидкостями передачі даних стає значною. Це пов’язано з кращою ефективністю протоколу TCP при роботі через високошвидкісні бездротові з’єднання. Варто також відзначити, що пропускна здатність, яка може бути досягнута станцією, коли вона монопольно використовує бездротовий канал зв’язку, є значно меншою за 50% від її швидкості передачі через значні накладні витрати навіть у найновіших технологіях Wi-Fi. Вирішення аномалії продуктивності в бездротових мережах Wi-Fi вимагає цілісного підходу, який має поєднувати агрегацію/фрагментацію кадрів і адаптацію швидкості передачі даних, вікна конкуренції та інших параметрів канального рівня.

Ключові слова: IEEE802.11ac; бездротові мережі; Wi-Fi; CSMA/CA; змішана швидкість передачі; несправедливого споживання ефірного часу; аномалія продуктивності; пропускна здатність; експериментальне вимірювання; аналітичне дослідження; імітаційне моделювання.

Сафдарі Феш – старший викладач Університету Лідс Бекетт, Лідс, Великобританія.

Горбенко Анатолій Вікторович – д-р техн. наук, проф., проф. каф. комп’ютерних систем, мереж та кібербезпеки, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна; Університет Лідс Бекетт, Лідс, Великобританія.

Fash Safdari – Senior Lecturer, School of Built Environment, Engineering and Computing, Leeds Beckett University, Leeds, United Kingdom,
e-mail: f.safdari@leedsbeckett.ac.uk.

Anatoliy Gorbenko – Doctor of Science on Engineering, Professor; School of Built Environment, Engineering and Computing, Leeds Beckett University, Leeds, United Kingdom,
e-mail: a.gorbenko@leedsbeckett.ac.uk, ORCID: 0000-0001-6757-1797, ResearcherID: X-1470-2019,
https://scholar.google.com/citations?user=nm8TOtEAAAAJ Scopus Author ID: 22034015200.