KnE Engineering
ICEUBI2019
International Congress on Engineering — Engineering for Evolution
Volume 2020

Knowledge E
enriching | engaging | empowering

Conference Paper

Performance Evaluation of IEEE 802.11 ac WPA2 Laboratory Links

José A. R. Pacheco de Carvalho, Cláudia F. F. P. Ribeiro Pacheco, Antonio D. Reis, and Hugo Veiga

Universidade da Beira Interior

Abstract

The increasing importance of wireless communications, involving electronic devices, has been widely recognized. Performance is a fundamental issue, resulting in more reliable and efficient communications. Security is also crucially important. Laboratory measurements are presented about several performance aspects of Wi-Fi IEEE 802.11ac WPA2 point-to-point links. Our study contributes to performance evaluation of this technology under WPA2 encryption, using available equipment (Cisco 2702i access points and TP-Link AC1900 USB 3.0 adapters). New results are given from TCP and UDP experiments concerning TCP throughput versus TCP packet length, jitter and percentage datagram loss versus UDP datagram size. Comparisons are made to corresponding results for WPA2 802.11n. Conclusions are drawn about the comparative performance of the links.

Keywords: Wi-Fi, WLAN, IEEE 802.11ac, Wireless network laboratory performance, Point-to-Point WPA2 links

Corresponding Author:
José A. R. Pacheco de Carvalho
pacheco@ubi.pt

Received: 26 November 2019
Accepted: 13 May 2020
Published: 2 June 2020

Publishing services provided by Knowledge E

© José A. R. Pacheco de Carvalho et al. This article is distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use and redistribution provided that the original author and source are credited.

Selection and Peer-review under the responsibility of the ICEUBI2019 Conference Committee.

OPEN ACCESS

1. Introduction

Electromagnetic waves in several frequency ranges, propagating in the air, permitted the development of contactless communication technologies. Wireless fidelity (Wi-Fi) and free space optics (FSO) are typical examples of wireless communications technologies, using microwaves and laser light, respectively. Their importance and utilization have been growing worldwide.

Wi-Fi uses microwave technology, giving versatility, mobility and favourable prices. The importance and utilization of Wi-Fi have been increasing. It is a complement to traditional wired networks. The chief use is infrastructure mode where a wireless access point, AP, provides communications of Wi-Fi electronic devices with a wired based local area network (LAN) through a switch/router. By this means a wireless local area network (WLAN), based on the AP, is set. At the home level personal devices can

How to cite this article: José A. R. Pacheco de Carvalho, Cláudia F. F. P. Ribeiro Pacheco, Antonio D. Reis, and Hugo Veiga, (2020), "Performance Evaluation of IEEE 802.11 ac WPA2 Laboratory Links" in *International Congress on Engineering — Engineering for Evolution*, KnE Engineering, pages 182–194. DOI 10.18502/keg.v5i6.7033

communicate through a wireless personal area network (WPAN). Essentially, point-to-point (PTP) and point-to-multipoint (PTMP) microwave links are used in the 2.4 and 5 GHz frequency bands, with IEEE 802.11a, 802.11b, 802.11g, 802.11n and 802.11ac standards [1]. The increasing use of the 2.4 GHz band has resulted in strong electromagnetic interference. Therefore, the use of the 5 GHz band is interesting, in spite of larger absorption and shorter ranges. Wi-Fi communications are not very affected by rain or fog, as wavelengths are in the range 5.6-12.5 cm. However, rain or fog significantly degrades FSO communications, as the typical wavelength range for the laser beam is 785-1550 nm.

Wi-Fi has nominal transfer rates up to 11 (802.11b), 54 Mbps (802.11 a, g), 600 Mbps (802.11n) and 6.9 Gbps (802.11ac). The medium access control of Wi-Fi is carrier sense multiple access with collision avoidance (CSMA/CA). 802.11n offers higher data rates than 802.11a,g. These provide a multi-carrier modulation scheme called orthogonal frequency division multiplexing (OFDM) that allows for binary phase-shift keying (BPSK), quadrature phase-shift keying (QPSK) and quadrature amplitude modulation (QAM) of the 16-QAM and 64QAM density types. One spatial stream (one antenna) and coding rates up to 3/4 are possible and a 20 MHz channel. 802.11n also uses OFDM, permitting, BPSK, QPSK, 16-QAM and 64-QAM. Up to four spatial streams are possible (four antennas), using multiple-input multiple-output (MIMO). MIMO permits to increase the capacity of a wireless link using multiple transmit and receive antennas to take advantage of multipath propagation. Antenna technology also favours 802.11n by introducing beam forming and diversity. Beam forming can be used both at the emitter and the receiver to achieve spatial selectivity to focus the radio signals along the path. Diversity uses, from a set of available multiple antennas, the best subset to obtain the highest quality and reliability of the wireless link. Coding rates up to 5/6 are possible and a 20/40 MHz channel. The standard guard interval (GI) in OFDM is 800 ns. Additional support for 400 ns GI provides an increase of 11% in data rate. Modulation and coding schemes (MCS) vary from 0 to 31. 600 Mbps are possible using MCS 31, four spatial streams, 64-QAM modulation, 5/6 coding rate, 40 MHz channel and 400 ns GI. 802.11n is suitable for transmitting e.g. high definition video and voice over IP (VoIP). Both the 2.4 and 5 GHz microwave frequency bands are usable. 802.11ac has been intended for the 5 GHz band, multi user (MU) MIMO, up to 6.9 Gbps, channel widths 20, 40, 80, 80-80, 160 MHz, 256-QAM modulation and up to eigth spatial streams. It has ten modulation encoding schemes (MCS 0 to MCS 9). 802.11ac Wave1 features single user (SU) MIMO, up to 1.3 Gbps, 20, 40, 80 MHs channel widths, and three spatial streams. 802.11ac

Wave2 has MU MIMO, up to 2.3-3.5 Gbps, 20, 40, 80, 80-80, 160 MHz channel widths, and 3-4 spatial streams [2].

Studies have been published on wireless communications, wave propagation [3, 4], practical accomplishments of WLANs [5], performance analysis of the effective transfer rate for 802.11b PTP links [6], 802.11b performance in crowded indoor environments [7].

Performance gain has been a central issue, giving more reliable and efficient communications. Requirements have been presented [8]. New telematic applications are especially sensitive to performances when compared to traditional applications.

Wi-Fi security is very important for privacy reasons. Several security methods have been developed to provide authentication such as, by increasing order of security, wired equivalent privacy (WEP), Wi-Fi protected access (WPA) and Wi-Fi protected access II (WPA2). Several performance measurements have been published for 2.4 and 5 GHz Wi-Fi Open [9, 10], WEP [11], WPA[12] and WPA2 [13] links, as well as very high speed FSO [14]. Performance evaluation of IEEE 802.11 based Wireless Mesh Networks has been given [15]. Studies are published on modelling TCP throughput [16]. A formula that bounds average TCP throughput is available [17].

It is significant investigating the effects of TCP packet size, UDP datagram size, network topology, increasing levels of security encryption, on link performance and compare equipment performance for several standards. Performance studies have been published for 5 GHz 802.11n WPA2 links [18]. In the present work new Wi-Fi results are given from measurements on 802.11ac WPA2 links, namely through OSI level 4 from TCP and UDP experiments. Performance is evaluated in laboratory measurements of WPA2 two-node (PTP) links using available equipments. TCP throughput is measured versus TCP packet length. Jitter and percentage datagram loss are evaluated versus UDP datagram size. Comparisons are made to results obtained for 802.11n WPA2 links. In relation to previous work [18], an extended research on performance is carried out in the present work.

In prior and actual state of the art, several Wi-Fi links and technologies have been investigated. Performance evaluation has been stated as a crucially important criterion to assess communications quality. The motivation of this work is to evaluate performance in laboratory measurements of WPA2 PTP 802.11ac links using accessible equipments and compare the results to those obtained for WPA2 PTP 802.11n links. Thus enlarging the knowledge about performance of Wi-Fi (IEEE 802.11 ac) links. The problem basis is that performance needs to be evaluated under several TCP and UDP parameterizations, link topologies and security encryption. The constructed solution uses an experimental setup and method, to monitor signal to noise ratios (SNR) and noise levels (N), and measure TCP throughput (from TCP connections) versus TCP packet size, and UDP jitter and percentage datagram loss (from UDP communications) versus UDP datagram size.

The paper is structured as follows: Section 2 gives the experimental conditions i.e. the measurement setup and procedure. Results and discussion are presented in Section 3. Conclusions are drawn in Section 4.

2. Experimental Details

The experiments were made during the second quarter 2019. We have used a Cisco 2702i access point supporting 802.11ac Wave1 [19], with 2.4 GHz 4 dBi gain and 5 GHz 6 dBi gain, internal omni directional antennas providing 3x4 MIMO technology with three spatial streams, IEEE 802.11 a/b/g/n/ac, software version 15.3(3)JI3. A 1000-Base-T/100-Base-TX/10-Base-T layer 2 3Com Gigabit switch 16 and a 100-Base-TX/10-Base-T layer 2 Allied Telesis AT8000S/16 switch were available [20]. We had two PCs and one Edimax AC1200 Wireless DualBand USB 3.0 Adapter [21], to enable a PTP link to the access point. Interference free communication channels were used (chs 52, 56, 60, 64). This was ensured through a portable monitoring computer, equipped with a Wi-Fi 802.11 a/b/g/n/ac adapter, running Acrylic WiFi software [22]. WPA2 encryption with AES-CCMP was activated in the AP and the wireless adapters of the PCs, with a pass phrase resulting in an encryption key of 256 bits. The experiments were conducted under far-field conditions. No power levels above 50 mW (17 dBm) were used, as the wireless equipments were nearby. In fact, the distances involved were large in comparison to the wavelength used (5.8 cm).

A versatile laboratory setup has been planned and realized for the experiments, as shown in Figure 1. Up to three wireless links to the AP are possible. At OSI level 4, measurements were made for TCP connections and UDP communications using Iperf software [23]. For a TCP client/server connection (TCP New Reno, RFC 6582, was used), TCP throughput was obtained for a given TCP packet size, varying from 0.25k to 64k bytes. For a UDP client/server communication with a given bandwidth parameter, UDP jitter and percentage loss of datagrams were determined for a given UDP datagram size, in the range 0.25k to 64k bytes.

The Wi-Fi network was as follows. One PC, with IP 192.168.0.2 was the Iperf server and the others, with IPs 192.168.0.6 and 192.168.0.50, were the Iperf clients (client1 and client2, respectively). Jitter, which is the root mean square of differences between consecutive transit times, was continuously computed by the server, according to the real time protocol RTP, in RFC 1889 [24]. A control PC, with IP 192.168.0.20, was mainly used to control the settings of the AP. The net mask was 255.255.255.0. Three types of experiments are possible: PTP (two nodes), using the client1 and the control PC as server; PTMP (three nodes), using the client1 and the 192.168.0.2 server PC; 4N-PTMP (four nodes), using simultaneous connections/communications between the two clients and the 192.168.0.2 server PC.

The PCs had Intel Core i7-3770-CPUs at 3.4 GHz and 8 Gbytes RAM. Windows 7 Enterprise-64 bits SP1 was the operating system. The PCs were arranged to provide maximum resources to the present work. Batch command files have been re-written for the new TCP and UDP experiments.

The results were obtained in batch mode and recorded as data files to the client PCs disks. Every PC had a second Ethernet network adapter, to permit remote control from the IP APTEL (Applied Physics and Telecommunications) Research Group network, via switch.

3. Results and Discussion

WPA2 encryption was activated in the AP and every wireless network adapter of the PCs. Nominal communication rates were monitored during the experiments. They were typically 1.3 Gbps. For every TCP packet size in the range 0.25k-64k bytes, and for every corresponding UDP datagram size in the same range, data were acquired for WPA2 PTP links at OSI levels 1 (physical layer) and 4 (transport layer) using the setup of Figure 1. For every TCP packet size an average TCP throughput was calculated from a set of experiments. This value was fed in as the bandwidth parameter for every corresponding UDP test, giving average jitter and average percentage datagram loss.

At OSI level 1, signal to noise ratios (SNR, in dB) and noise levels (N, in dBm) were obtained in the AP. Signal gives the strength of the radio signal the AP receives from a client PC, in dBm. Noise means how much background noise, due to radio interference, exists in the signal path between the client PC and the AP, in dBm. The lower the value is, the weaker the noise. SNR indicates the relative strength of client PC radio signals versus noise in the radio signal path, in dB. SNR is a good indicator for the quality of the radio link between the client PC and the AP. The measured data were similar for all types of experiments. Typical values are shown in Figure 2. The links have shown good, high, SNR values.

The main average TCP and UDP results are summarized in Table 1, for WPA2 PTP for both 802.11ac and 802.11n links. The statistical analysis, including calculations of confidence intervals, was made as in [25].

In Figs. 3 and 4 polynomial fits were made (shown as y versus x), using the Excel worksheet, to the TCP throughput data both for 802.11ac and 802.11n links, respectively, where R^2 is the coefficient of determination. It indicates the goodness of fit. If it is 1.0 it means a perfect fit to data. It was found that, on average, the best TCP throughputs are for 802.11ac links (Table 1). There are fair increases in TCP throughput with packet size. For small packets there is a large overhead, as there are small amounts of data that are sent in comparison to the protocol components. The role of the frame is very heavy in Wi-Fi. For larger packets, overhead decreases; the amount of sent data overcomes the protocol components.

In Figs. 5-8, the data points representing jitter and percentage datagram loss were joined by smoothed lines. It was found that, on average, the best jitter performances are for 802.11ac links (Table 1). For small sized datagrams, jitter is small. There are small delays in sending datagrams. Latency is also small. Jitter increases for larger datagram sizes.

Concerning average percentage datagram loss, performances were found better for 802.11ac links (Table 1). There are larger percentage datagram losses for small sized datagrams, for 802.11n, when the amounts of data to send are small in comparison to the protocol components. There is considerable processing of frame headers and buffer management. For larger datagrams, percentage datagram loss is lower. However, large UDP segments originate fragmentation at the IP datagram level, leading to higher losses. TCP throughput, jitter and percentage datagram loss were found best for 802.11ac.

Table 1: Average Wi-Fi WPA2 PTP results: 802.11 ac; 802.11 n

Link type	802.11 ac	802.11 n
TCP throughput (Mbps)	108.3+-3.3	50.8+-1.5
UDP-jitter (ms)	1,0+-0.0	3.0+-0.6
UDP-% datagram loss	1.3+-0.1	1.5+-0.2

4. Conclusions

In the present work a versatile laboratory setup arrangement was devised and realized, that permitted systematic performance measurements of available wireless equipment

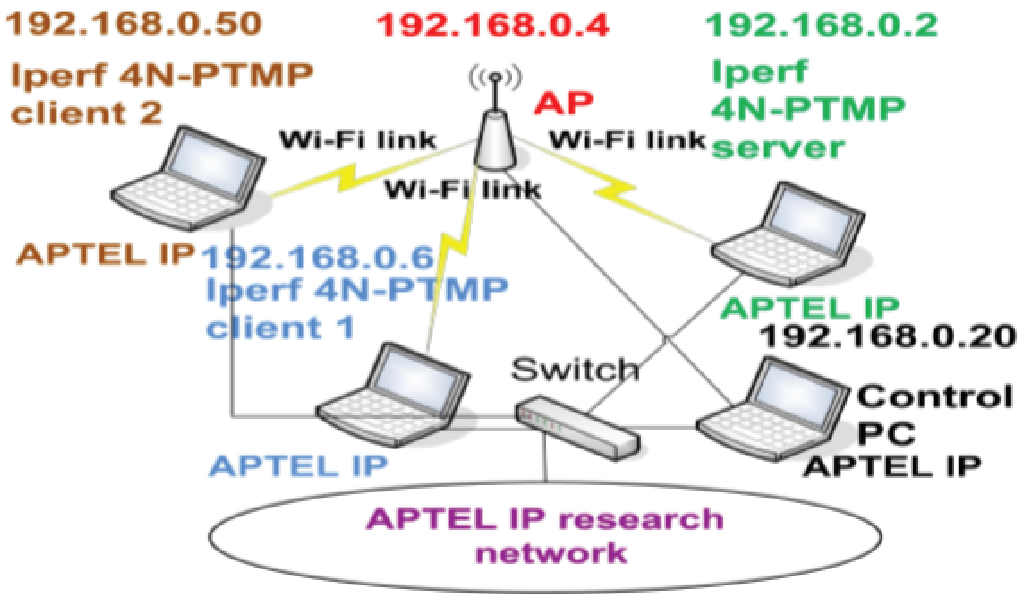

Figure 1: Laboratory setup scheme.

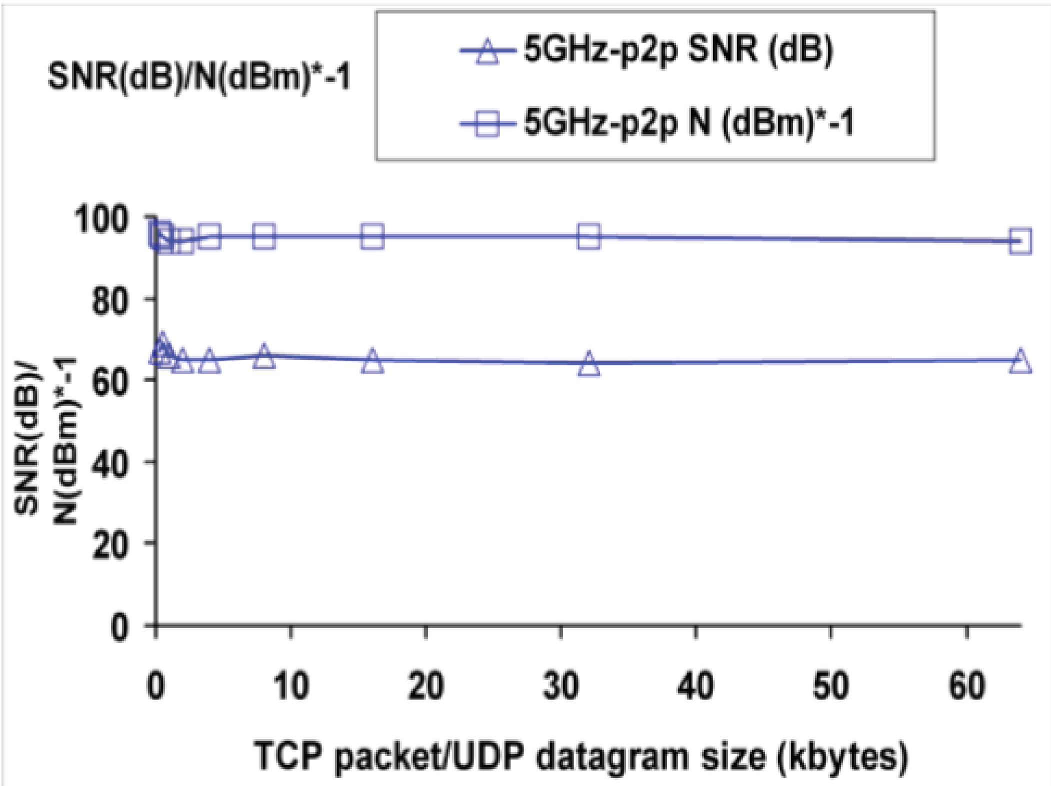

Figure 2: Typical SNR (dB) and N (dBm). 802,11 ac links.

(Cisco 2702i access points and Edimax AC1200 USB 3.0 adapters) for Wi-Fi (IEEE 802.11 ac) in WPA2 PTP links.

For OSI layer 4, TCP and UDP performances were measured versus TCP packet size and UDP datagram size, respectively. TCP throughput, jitter and percentage datagram

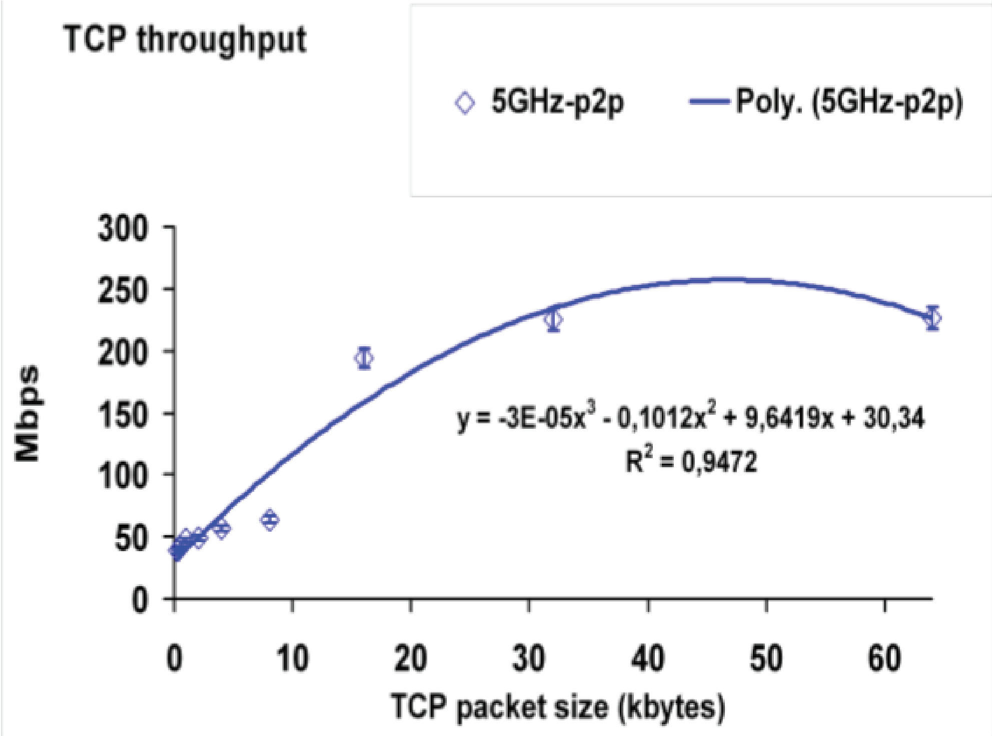

Figure 3: TCP throughput (y) versus TCP packet size (x). 802.11 ac links.

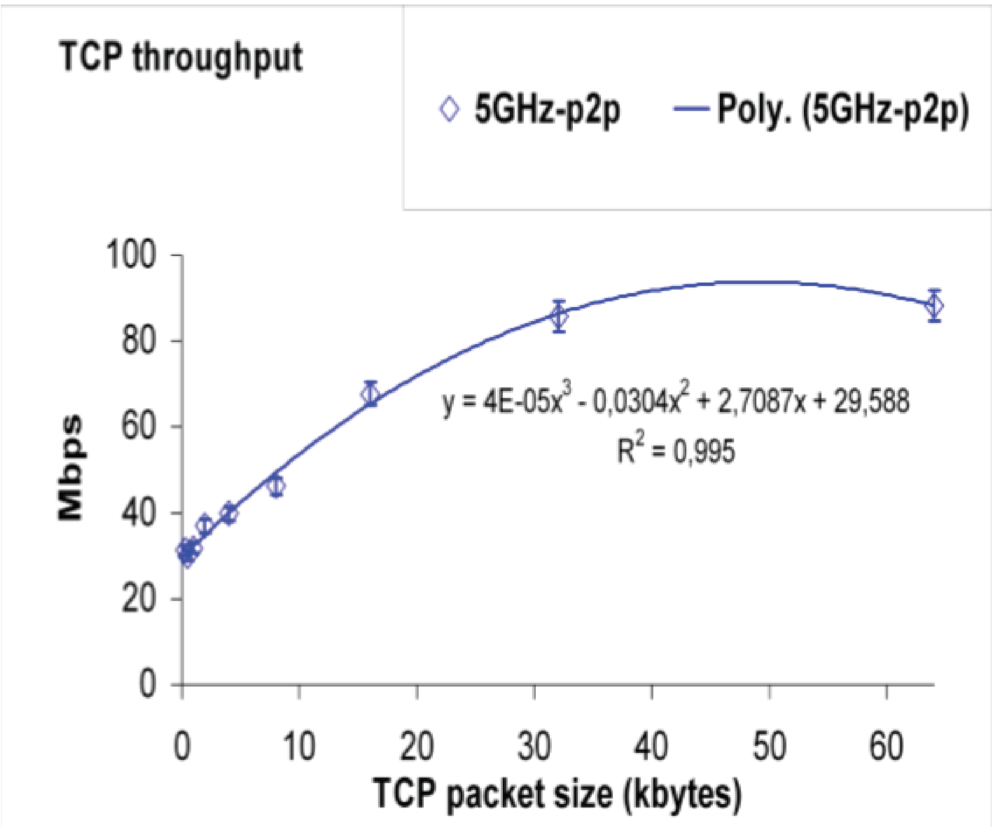

Figure 4: TCP throughput (y) versus TCP packet size (x). 802.11 n links.

loss were measured and compared for WPA2 PTP 802.11ac and 802.11n links. TCP

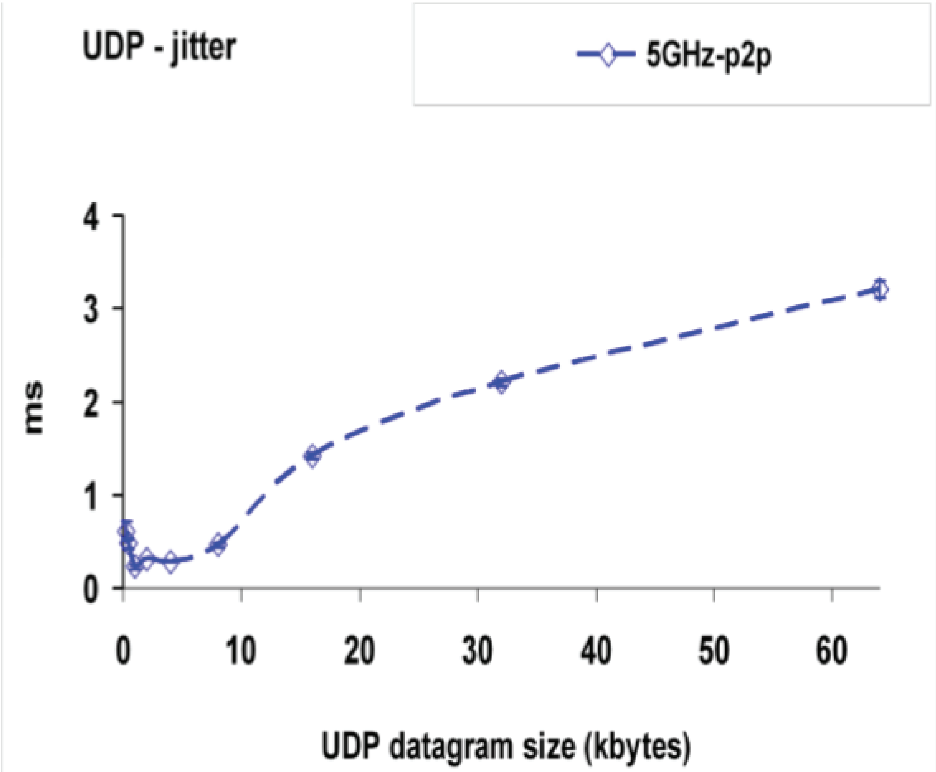

Figure 5: UDP jitter versus UDP datagram size. 802.11 ac links.

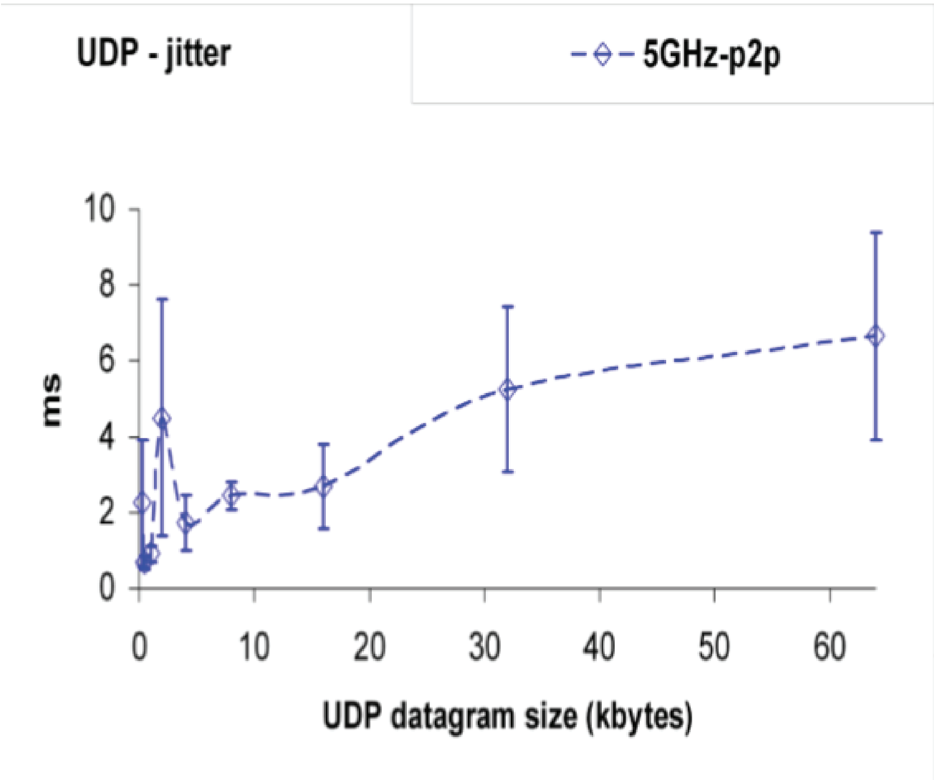

Figure 6: UDP jitter versus UDP datagram size. 802.11 n links.

throughput was found to increase with packet size. For small sized datagrams, jitter is

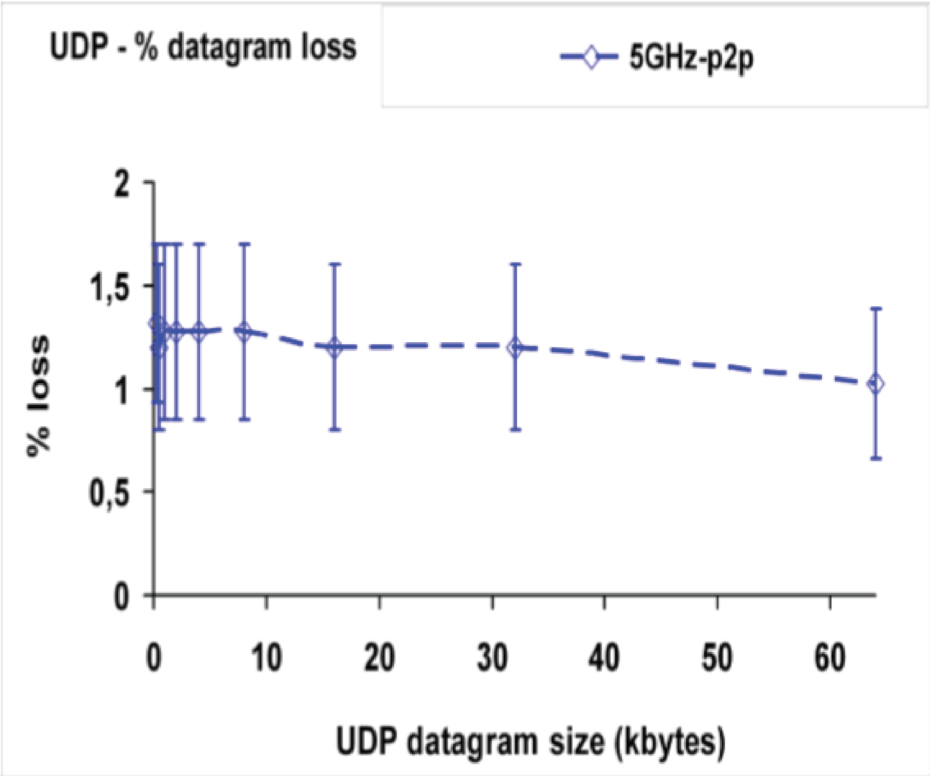

Figure 7: UDP percentage datagram loss versus UDP datagram size. 802.11ac links.

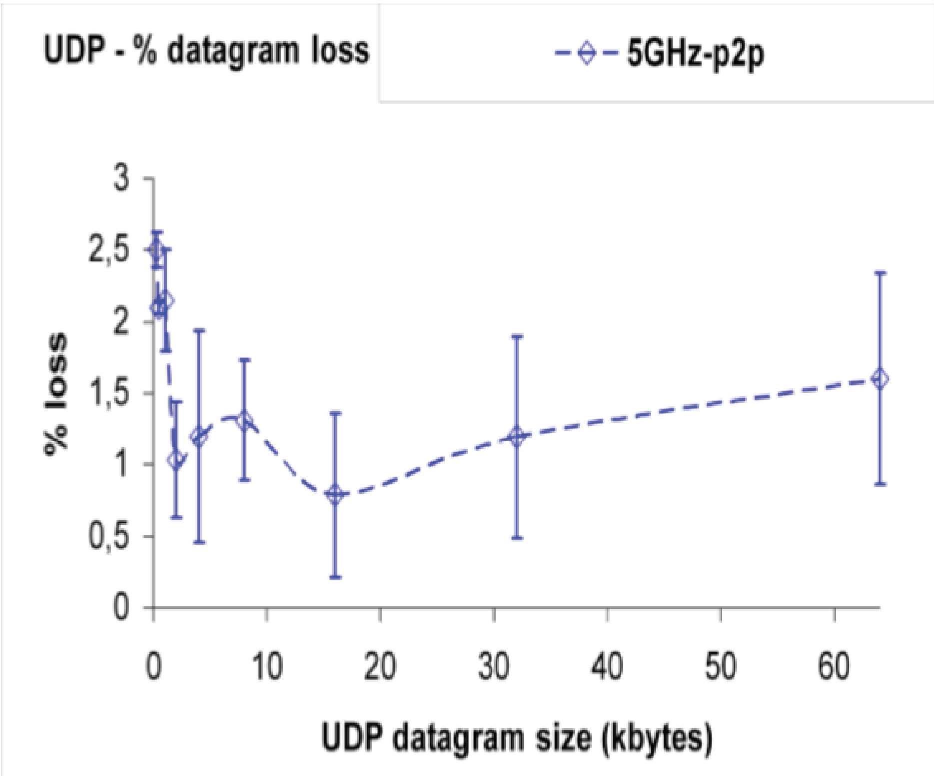

Figure 8: UDP percentage datagram loss versus UDP datagram size. 802.11 n links.

small. There are small delays in sending datagrams. Latency is also small. Jitter increases for larger datagram sizes. Concerning percentage datagram loss, it was found high for small sized datagrams, for 802.11n links. For larger datagrams it diminishes. However, large UDP segments originate fragmentation at the IP datagram level, leading to higher losses.

The present results show that 802.11ac has given better TCP throughput, jitter and percentage datagram loss performances than 802.11n.

Further performance investigations are outlined using several standards, equipment, topologies, security settings and noise conditions, not only in laboratory but also in outdoor environments involving, mainly, medium range links.

Acknowledgments

Support from University of Beira Interior and FCT (Fundação para a Ciência e a Tecnologia)/ PEst-OE/FIS/UI0524/2014(ProjectoEstratégico-UI524-2014) is acknowledged.

References

[1] Web site http://standards.ieee.org; IEEE 802.11a, 802.11b, 802.11g, 802.11n, 802.11i, 802.11ac standards.

[2] 802.11ac wireless throughput testing and validation guide (2018). http://www.cisco.com accessed 3 Sept 2019.

[3] Mark, J. W. and Zhuang, W. (2003). *Wireless Communications and Networking*. (New Jersey: Prentice-Hall).

[4] T Rappaport, T. S. (2002). *Wireless Communications Principles and Practice*. (New Jersey: Prentice-Hall).

[5] Bruce W. R. and Gilster, R. (202). *Wireless LANs End to End*. (New York: Hungry Minds).

[6] Schwartz, M. (2005). *Mobile Wireless Communications*. (Cambridge: Cambridge University Press).

[7] Sarkar, N. and Sowerby, K. (2006). High Performance Measurements in the Crowded Office Environment: a Case Study. *ICCT '06-International Conference on Communication Technology*. (Guilin, China), pp. 1-4.

[8] Boavida, F. and Monteiro, E. (2011). *Engenharia de Redes Informáticas*, (Lisbon: FCA-Editora de Informática Lda).

[9] Pacheco de Carvalho, J. A. R., Veiga, H., Gomes, P. A. J., *et al* (2010). Wi-Fi Point-to-Point Links- Performance Aspects of IEEE 802.11 a,b,g Laboratory Links. *Electronic Engineering and Computing Technology, Series: Lecture Notes in Electrical Engineering*, (Netherlands: Springer), vol. 60, pp. 507-514.

[10] Pacheco de Carvalho, J. A. R., Veiga, H., Ribeiro Pacheco, C. F., and Reis, A. D. (2016). Extended Performance Research on Wi-Fi IEEE 802.11 a, b, g Laboratory Open Point-to-Multipoint and Point-to-Point Links. *Transactions on Engineering Technologies*. (Singapore: Springer), pp. 475-484.

[11] Pacheco de Carvalho, J. A. R., Veiga, H., Marques, N., *et al* (2011). Wi-Fi WEP Point-to-Point Links- Performance Studies of IEEE 802.11 a,b,g Laboratory Links. *Electronic Engineering and Computing Technology, Series: Lecture Notes in Electrical Engineering*. (Netherlands: Springer), vol. 90, pp. 105-114.

[12] Pacheco de Carvalho, J. A. R., Veiga, H., Ribeiro Pacheco, C. F., and Reis, A. D. (2014). Extended Performance Studies of Wi-Fi IEEE 802.11a, b, g Laboratory WPA Point-to-Multipoint and Point-to-Point Links. *Transactions on Engineering Technologies: Special Volume of the World Congress on Engineering 2013*, (Gordrecht: Springer), pp. 455-465.

[13] Pacheco de Carvalho, J. A. R., Veiga, H., Ribeiro Pacheco, C. F., and Reis, A. D. (2014). Performance Evaluation of IEEE 802.11 a, g Laboratory WPA2 Point-to-Multipoint Links. *Lecture Notes in Engineering and Computer Science: Proceedings of the World Congress of Engineering 2014*, (London: WCE 2014), pp. 699-704.

[14] Pacheco de Carvalho, J. A. R., Veiga, H., Marques, N., *et al* (2010). Performance Measurements of a 1550 nm Gbps FSO Link at Covilhã City, Portugal. *Proc. Applied Electronics 2010 - 15th International Conference* (University of West Bohemia, Czech Republic), pp. 235-239.

[15] Bansal, D., Sofat, S., Chawla, P., and Kumar, P. (2011). Deployment and Evaluation of IEEE 802.11 based Wireless Mesh Networks in Campus Environments. *Lecture Notes in Engineering and Computer Science: Proceedings of the World Congress on Engineering 2011*, (London: WCE 2011), pp. 1722-1727.

[16] Padhye J., Firoiu, V., Towsley, D., and Kurose, J. (1998). Modeling TCP Throughput: A Simple Model and its Empirical Validation. S*IGCOMM Symposium Communications, Architecture and Protocols*, pp. 304-314.

[17] Mathis, M., Semke, J. and Mahdavi, J. (1997). The Macroscopic Behavior of the TCP Congestion Avoidance Algorithm. *ACM SIGCOMM Computer Communication Review*, vol. 27, issue 3, pp. 67-82.

[18] Pacheco de Carvalho, J. A. R., Veiga, H., Ribeiro Pacheco, C. F., and Reis, A. D. (2019). Extended Performance Research on 5 GHz IEEE 802.11n WPA2 Laboratory Links. *Transactions on Engineering Technologies* (Singapore: Springer), pp. 313-323.

[19] Cisco Aironet 2700 Series Access Points (2014). http://www.cisco.com accessed 3 Jun 2019.

[20] AT-8000S/16 level 2 switch technical data (2009). http://www.alliedtelesis.com accessed 10 Dec 2018.

[21] AC1900 High Gain Wireless Dual Band USB Adapter Archer T9UH (2018). http://www.tp-link.com accessed 10 Jun 2019.

[22] Acrylic WiFi software (2016). http://www.acrylicwifi.com accessed 8 Jan 2019.

[23] Iperf software (2019). http://iperf.fr accessed 16 Feb 2019.

[24] Network Working Group. RFC 1889-RTP: A Transport Protocol for Real Time Applications. http://www.rfc-archive.org accessed 3 Jan 2019.

[25] Bevington, P. R. (1969). Data Reduction and Error Analysis for the Physical Sciences (New ork: McGraw-Hill).