Performance Evaluation of 5 GHz IEEE 802.11n WPA2 Laboratory Links

J. A. R. Pacheco de Carvalho, H. Veiga, C. F. Ribeiro Pacheco, A. D. Reis

***Abstract*—The increasing importance of wireless communications, involving electronic devices, has been widely recognized. Performance is a crucial issue, leading to more reliable and efficient communications. Security is also critically important. Laboratory measurements were performed about several performance aspects of Wi-Fi IEEE 802.11n WPA2 5 GHz links. Our study contributes to performance evaluation of this technology, using available equipments (HP V-M200 access points and Linksys WPC600N adapters). New detailed results are presented and discussed, namely at OSI level 4, from TCP and UDP experiments. TCP throughput is measured versus TCP packet length. Jitter and percentage datagram loss are measured versus UDP datagram size. Results are compared for both point-to-point and point-to-multipoint links. Comparisons are also made to corresponding results obtained for Open links. Conclusions are drawn about performance of the links.**

***Index Terms*—Wi-Fi; WLAN; IEEE 802.11n; TCP packet size; UDP datagram size; Point-to-Point and Point-to-Multipoint WPA2 Links; Wireless Network Laboratory Performance.**

I. Introduction

Contactless communications techniques have been developed using mainly several frequency ranges of electromagnetic waves, propagating in the air. The importance and utilization of wireless fidelity (Wi-Fi) and free space optics (FSO) have been growing. They are relevant examples of wireless communications technologies.

Wi-Fi is based on microwave technology. It gives versatility, mobility and reachable prices. The importance and utilization of Wi-Fi have been increasing. It complements traditional wired networks. It works both in ad hoc and infrastructure modes. In this latter case an 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 communicate through a wireless personal area network (WPAN). Point-to-point (PTP) and point-to-multipoint (PTMP) 2.4 and 5 GHz microwave links are used, with IEEE 802.11a, 802.11b, 802.11g and 802.11n standards [1]. The heavy use of the 2.4 GHz band has led to considerable 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 significantly affected by rain or fog, as wavelengths are in the range 5.6-12.5 cm. On the contrary, FSO communications have been found sensitive to rain or fog, 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) and 600 Mbps (802.11n). 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 64-QAM 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.

Studies are available on wireless communications, wave propagation [2,3], practical realizations of WLANs [4], performance analysis of the effective transfer rate for 802.11b PTP links [5], 802.11b performance in crowded

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J. A. R. Pacheco de Carvalho is with the APTEL (Applied Physics and Telecommunications) Research Group and the Physics Department, University of Beira Interior, 6201-001 Covilha, Portugal (phone: +351 275 319 703; fax: +351 275 319 719; e-mail: pacheco@ ubi.pt).

H. Veiga is with the APTEL Research Group and the Informatics Centre, University of Beira Interior, 6201-001 Covilha, Portugal, and with the PT Data Center, Covilha, Portugal (e-mail: hveiga@ubi.pt).

C. F. Ribeiro Pacheco is with the APTEL Research Group, University of Beira Interior, 6201-001 Covilha, Portugal (e-mail: a17597@ubi.pt).

A. D. Reis is with the APTEL Research Group and the Physics Department, University of Beira Interior, 6201-001 Covilha, Portugal, and with the Department of Electronics and Telecommunications/ Institute of Telecommunications, University of Aveiro, 3810 Aveiro, Portugal (e-mail: adreis@ubi.pt).

indoor environments [6].

Performance increase has been a fundamental issue, giving more reliable and efficient communications. New telematic applications are specially sensitive to performances when compared to traditional applications. Requirements have been published [7].

Wi-Fi security is critically important. Microwave radio signals travel through the air and can be very easily captured. 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).

Various performance measurements have been published for 2.4 and 5 GHz Wi-Fi Open [8-9], WEP [10], WPA [11] and WPA2 [12] links, as well as very high speed FSO [13]. Performance evaluation of IEEE 802.11 based Wireless Mesh Networks has been given [14]. Studies are published on modelling TCP throughput [15]. A formula that bounds average TCP throughput is available [16].

It is relevant to investigate 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. In the present work new Wi-Fi (IEEE 802.11 n) results arise from measurements on WPA2 5 GHz links, namely through OSI level 4. Performance is evaluated and compared in laboratory measurements of WPA2 PTP and three-node point-to-multipoint (PTMP) links using new available equipments. TCP throughput is measured versus TCP packet length. Jitter and percentage datagram loss are measured versus UDP datagram size. Comparisons are made to corresponding results obtained for Open links [17].

In prior and actual state of the art, several Wi-Fi links and technologies have been researched. Performance evaluation has been pointed out as a crucially important criterion to assess communications quality. The motivation of this work is to evaluate and compare performance in laboratory measurements of WPA2 PTP and PTMP 5 GHz links using new available equipments. This contribution permits to increase the knowledge about performance of Wi-Fi (IEEE 802.11 n) links. The problem statement is that performance needs to be evaluated under several TCP and UDP parameterizations, link topologies and security encryption. The solution proposed uses an experimental setup and method, permitting to monitor signal to noise ratios (SNR) and noise levels (N), 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 rest of the paper is structured as follows: Section II is about the experimental conditions i.e. the measurement setup and procedure. Results and discussion are given in Section III. Conclusions are drawn in Section IV.

II. Experimental Details

Here we have used a HP V-M200 access point [18], with three external dual-band 3x3 MIMO antennas, IEEE 802.11 a/b/g/n, software version 5.4.1.0-01-16481, 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 AT-8000S/16 switch [19]. Two out of three PCs were used having a PCMCIA IEEE.802.11 a/b/g/n Linksys WPC600N wireless adapter with three internal antennas [20], to enable three-node PTMP (PTMP) links to the access point. In every type of experiment, interference free communication channels were used (ch 36 for 802.11n). This was mainly checked through a portable computer, equipped with a Wi-Fi 802.11 a/b/g/n adapter, running Acrylic WiFi software [21]. WPA2 encryption with AES was activated in the AP and the wireless adapters of the PCs, with a key composed of twenty six hexadecimal characters. The experiments were made under far-field conditions. No power levels above 30 mW (15 dBm) were used, as the wireless equipments were close.

A versatile laboratory setup has been planned and implemented for the PTMP measurements, as shown in Fig. 1. Up to three wireless links to the AP are usable. At OSI level 4, measurements were made for TCP connections and UDP communications using Iperf software [22]. 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, varying from 0.25k to 64k bytes.

One PC, with IP 192.168.0.2 was the Iperf server and the others, with IP 192.168.0.6 and 192.168.0.50, were the Iperf clients (client1 and client2, respectively). Jitter, which represents the smooth mean of differences between consecutive transit times, was continuously calculated by the server, as specified by the real time protocol RTP, in RFC 1889 [23]. A control PC, with IP 192.168.0.20, was mainly used to control the settings of the AP. Three types of experiments could be made: PTP, using the client1 and the control PC as server; PTMP, using the client1 and the 192.168.0.2 server PC; 4N-PTMP, using simultaneous connections/communications between the two clients and the 192.168.0.2 server PC.

The server and client PCs were HP nx9030 and nx9010 portable computers, respectively. The control PC was an HP nx6110 portable computer. Windows XP Professional was the operating system. The PCs were prepared so as to allocate the maximum resources to the present work. Batch command files have been re-written to enable the new TCP and UDP tests.

The results were obtained in batch mode and written as data files to the client PCs disks. Every PC had a second network adapter, to permit remote control from the official IP APTEL network, via switch.

III. Results and Discussion

The wireless network adapters of the PCs were manually configured for best rate. WPA2 encryption with AES was activated with a key having twenty six hexadecimal characters. MCS was monitored in the AP along the experiments. It was typically MCS 15 both for transmit and receive. 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 PTMP and PTP links at OSI levels 1 (physical layer) and 4 (transport layer) using the setup of Fig. 1. For every TCP packet size an average TCP throughput was calculated from a set of experiments. This value was included 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 measured in the AP. Signal indicates 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 (more negative) 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 Fig. 2. The links had good, high, SNR values.

The main average TCP and UDP results are summarized in Table I, both for WPA2 and Open PTMP and PTP links. The statistical analysis, including calculations of confidence intervals, was carried out as in [24].

In Fig. 3 polynomial fits were made (shown as y versus x), using the Excel worksheet, to the TCP throughput data for PTMP and PTP links, where R2 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 PTP links (Table I). There is a very significant degradation of 46% in passing from PTP to PTMP. This is due to increase of processing requirements for the AP, so as to maintain links between two PCs. In comparison to Open data (Table I) PTP results are within the experimental error. For WPA2 and PTMP there is a decrease of 8% in TCP throughput, larger than the experimental error. Fig. 3 shows that there is a fair increase in TCP throughput with packet size. For small packets the overhead is large, 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. 4-5, the data points representing jitter and percentage datagram loss were joined by smoothed lines. It was found that, on average, jitter performances are not very significantly different between PTP and PTMP links, considering a large error bar in the 32k data point of the PTMP curve (Fig. 4). For Open links jitter performance degrades, on average, in passing from PTP to PTMP. This is due to increase of processing requirements for the AP, so as to maintain links between two PCs. For PTMP, in passing from Open to WPA2 jitter performance decreases. For PTP it can be seen that, for small sized datagrams, jitter is small. There are small delays in sending datagrams. Latency is also small. Jitter increases for larger datagram sizes. For PTMP and both for Open [20] and WPA2 links there are initial oscillations of the jitter curves that are so far unexplained.

Concerning average percentage datagram loss, performances were found on average better for PTP than for PTMP links (Table I). This is due to increase of processing requirements for the AP, for maintaining links between two PCs. The best performance is on average for PTP links, both for WPA2 and Open links. For PTMP links percentage datagram loss gets degraded. The degradation is larger for WPA2. Fig. 5 shows larger percentage datagram losses for small sized datagrams, 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 generally found to show performance degradations due to link topology, in passing from PTP to PTMP, where processing requirements for the AP are higher so as to maintain links between PCs. As CSMA/CA is the medium access control, the available bandwidth and the air time are divided by the nodes using the medium. WPA2, where there increase in data length due to encryption, did not show significant influence in our study.

TCP and UDP performance aspects versus TCP packet size and UDP datagram size were found as given above.

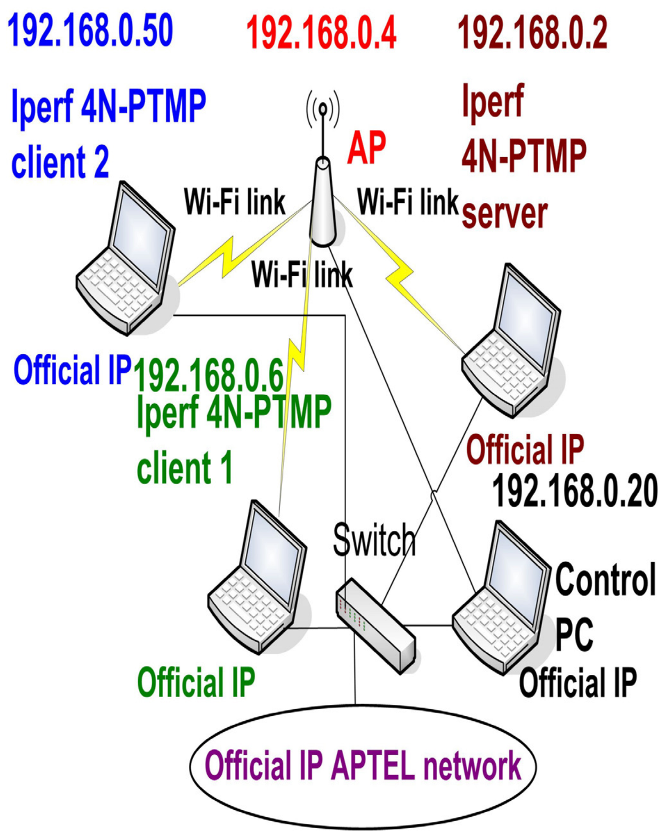

Fig. 1- Laboratory setup scheme.

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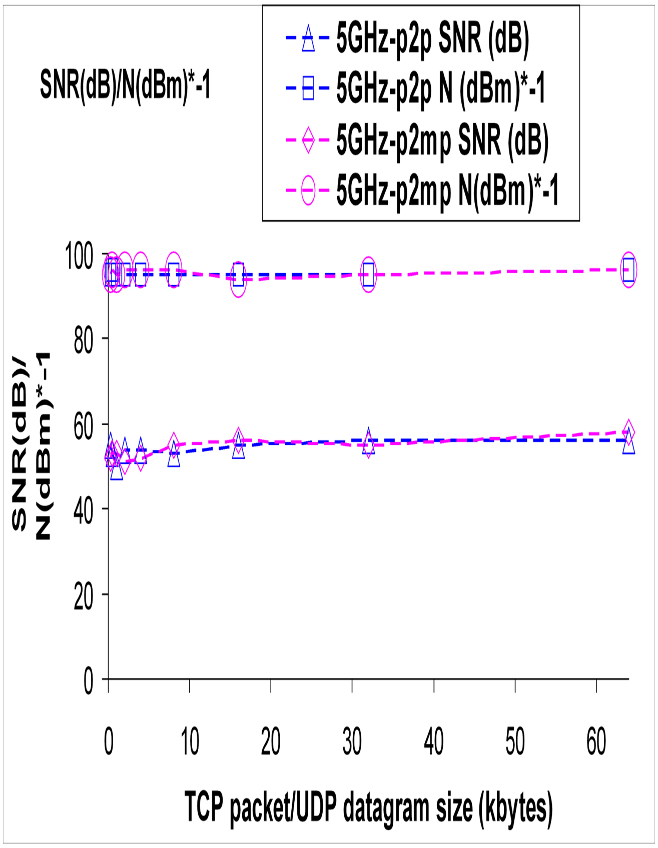

Fig. 2- Typical SNR (dB) and N (dBm).

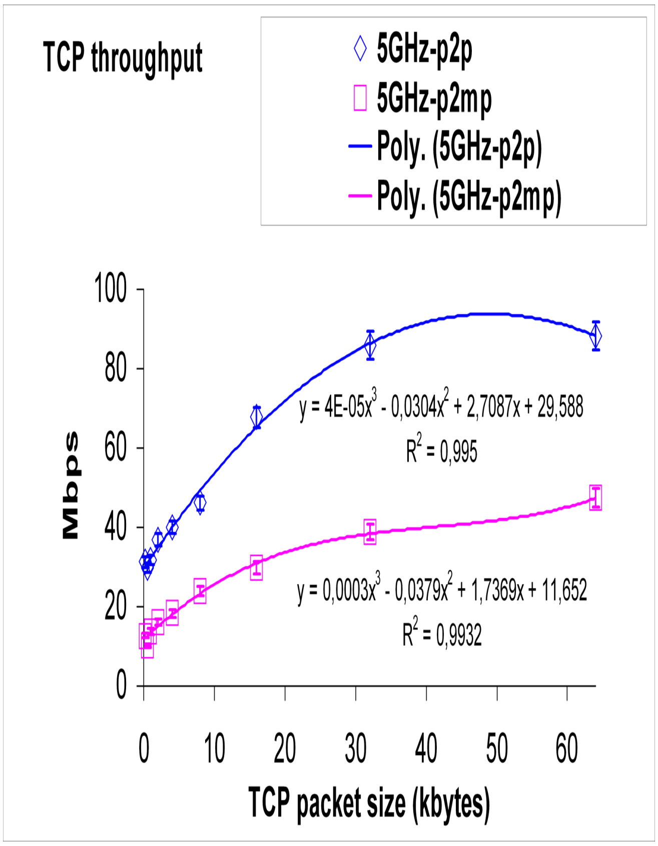

Fig.3- TCP throughput (y) versus TCP packet size (x).

TABLE I
AVERAGE IEEE 802.11N 5 GHZ OPEN AND WPA2 RESULTS

Link type	**WPA2 PTP**	**WPA2 PTMP**
TCP throughput (Mbps)	50.8+-1.5	23.4+-0.7
UDP-jitter (ms)	3.0+-0.6	2.2+-0.9
UDP-% datagram loss	1.5+-0.2	6.4+-0.2
Link type	**Open PTP**	**Open PTMP**
TCP throughput (Mbps)	51.2+-1.5	25.3+-0.8
UDP-jitter (ms)	2.1+-0.1	2.5+-0.2
UDP-% datagram loss	3.1+-0.3	5.1+-0.2

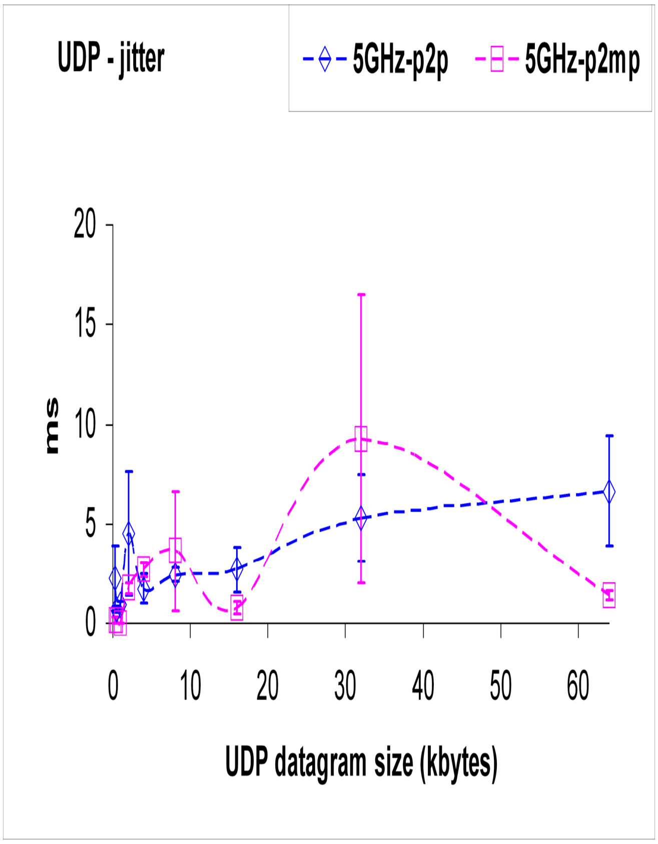

Fig. 4- UDP - jitter versus UDP datagram size.

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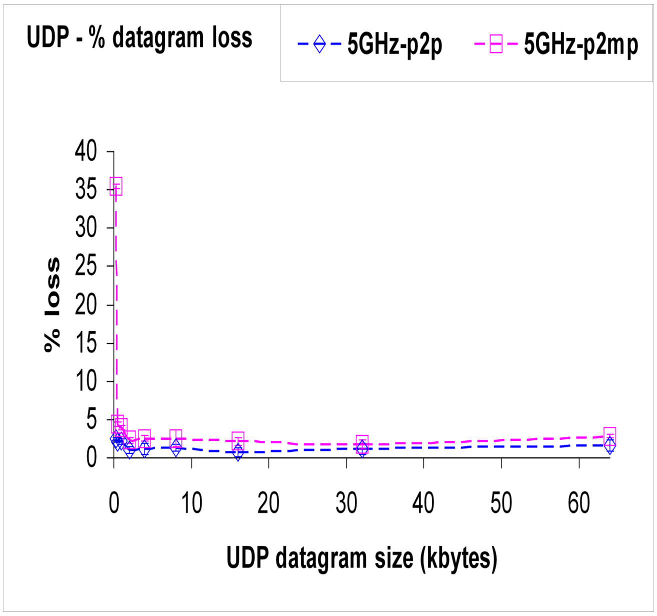

Fig. 5- UDP – percentage datagram loss versus UDP datagram size.

IV. Conclusion

In the present work a versatile laboratory setup arrangement was devised and implemented, that permitted systematic performance measurements using new available wireless equipments (V-M200 access points from HP and WPC600N adapters from Linksys) for Wi-Fi (IEEE 802.11 n) in 5 Ghz WPA2 PTP and PTMP links.

Through OSI layer 4, TCP and UDP performances were measured versus TCP packet size and UDP datagram size, respectively. TCP throughput, jitter and percentage datagram loss were measured and compared for WPA2 PTP and PTMP links. Comparisons were also made to corresponding results obtained for Open links. TCP throughput was found to increase with packet size. Generally jitter, for small sized datagrams, is found small. It increases for larger datagrams. Concerning percentage datagram loss, it was found high for small sized datagrams. For larger datagrams it diminishes. However, large UDP segments originate fragmentation at the IP datagram level, leading to higher losses. In comparison to PTP links, TCP throughput, jitter and percentage datagram loss were found to show significant performance degradations for PTMP links, where the AP experiments higher processing requirements for maintaining links between PCs. WPA2, where there is increase in data length due to encryption, did not show significant influence in our study.

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

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