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Extended Performance Research on IEEE 802.11a WPA2 Multi-Node Laboratory Links

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Abstract—**Wireless communications, involving electronic devices, are increasingly important. Performance is a fundamental issue, leading to more reliable and efficient communications. Security is also, no doubt, most important. Laboratory measurements were achieved about several performance aspects of Wi-Fi IEEE 802.11a 54 Mbps WPA2 links. Our study enriches performance evaluation of this technology, using accessible equipments (HP V-M200 access points and Linksys WPC600N adapters). New accurate results are given, namely at OSI level 4, from TCP and UDP experiments. TCP throughput is measured against TCP packet length. Jitter and percentage datagram loss are evaluated versus UDP datagram size. Results are examined for point-to-point, point-to-multipoint and four-node point-to-multipoint links. Comparisons are also made mainly to related data obtained for Open links. Conclusions are extracted about performance of the links.**

Index Terms—**IEEE 802.11a, Multi-Node Links, TCP packet size, UDP datagram size, Wi-Fi, Wireless Network Laboratory Performance, WLAN, WPA2.**

I. INTRODUCTION

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

Wi-Fi adopted microwave technology. Versatility, mobility and favourable prices are provided. Wi-Fi has seen its importance and utilization enlarging. It enhances traditional wired networks. Both ad hoc and infrastructure modes are used. In this second case, a wireless access point, AP, provides communications of Wi-Fi electronic devices with a wired based local area network (LAN) through a switch/router. Thus, a wireless local area network (WLAN), based on the AP, is set. At the home level, personal devices are permitted to communicate through a wireless personal area network (WPAN). Point-to-point (PTP) and point-to-multipoint (PTMP) microwave links are used in the 2.4 and 5 GHz 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 led to strong electromagnetic interference. Therefore, the use of the 5 GHz band is very convenient, although absorption is larger and ranges shorter. Wi-Fi communications are not significantly influenced by rain or fog, as wavelengths are in the range 5.6-12.5 cm. On the contrary, rain or fog indubitably degrade 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). 802.11a,g 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. 802.11a and 802.11g work in the 5 and 2.4 GHz bands, respectively.

Studies have been published on wireless communications, wave propagation [2,3], practical implementations of WLANs [4], performance analysis of the effective transfer rate for 802.11b PTP links [5], and 802.11b performance in crowded indoor ambiances [6].

Performance increase has been a crucial issue, giving more reliable and efficient communications. Requisites have been published both for traditional and new telematic applications [7].

Wi-Fi security is critically important for secretiveness reasons. Microwave radio signals travel through the air and can be quickly captured. Security methods have been developed to provide certification such as, by increasing order of safeness, 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 [8-9], WEP [10], WPA[11] and WPA2 [12,13] 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 worthwhile investigating the effects of TCP packet

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size, UDP datagram size, network topology, increasing levels of security encryption, on link performance and compare equipment performance for several standards. Studies have been published for 5 GHz 802.11n WPA2 links [18]. In the present work new Wi-Fi results arise from measurements on 802.11a WPA2 multi-node links at 54 Mbps, namely through OSI level 4 from TCP and UDP experiments. Performance is evaluated and compared in laboratory measurements of WPA2 PTP, three-node point-to-multipoint (PTMP) and four-node point-to-multipoint (4N-PTMP) links using available equipments. TCP throughput is measured against TCP packet length. Jitter and percentage datagram loss are evaluated versus UDP datagram size. In comparison to previous work [12] extended investigations on performance are realized.

In prior and actual state of the art, several Wi-Fi links and technologies have been examined. Performance evaluation has been identified as a centrally important criterion to determine communications quality. The incentive to this work is to evaluate and compare performance in laboratory measurements of WPA2 multi-node 802.11a links at 54 Mbps using available equipment. Thus permitting to increase the expertise about Wi-Fi (IEEE 802.11 a) link performance. The problem statement is that performance needs to be evaluated under several TCP and UDP parameterizations and link topologies under security encryption. The proposed solution uses an experimental setup and method, permitting to check 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) against UDP datagram size.

The structure for the rest of the paper is as follows: Section II is about the experimental conditions i.e. the measurement setup and procedure. Results and discussion are given in Section III. Section IV presents Conclusions.

II. EXPERIMENTAL DETAILS

The experiments were made during the second quarter 2019. Here a HP V-M200 access point [19] was used, 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 [20]. Three PCs were used having a PCMCIA IEEE.802.11 a/b/g/n Linksys WPC600N wireless adapter with three internal antennas [21], to enable 4N-PTMP links to the access point. In every type of experiment, an interference free communication channel was used (ch. 36). This was mainly found out through a portable computer, equipped with a Wi-Fi 802.11 a/b/g/n adapter, running Acrylic WiFi software [22]. WPA2 encryption with AES was activated in the AP and the wireless adapters of the PCs, with a pass phrase giving an encryption key of 256 bits. The experiments were conducted under far-field conditions. No power levels above 30 mW (15 dBm) were used, as the wireless equipments were neighbouring. The distances concerned were much larger than the wavelength used (5.8 cm).

A functional laboratory arrangement has been planned and set up for the measurements, as shown in Fig. 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 collected 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 obtained for a given UDP datagram size, varying from 0.25k to 64k bytes.

The Wi-Fi network was the following. 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 constantly computed by the server, conforming to the real time protocol RTP, in RFC 1889 [24]. A control PC, with IP 192.168.0.20, was mainly used to set the configuration 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 server and client PCs were HP nx9030 and nx9010 portable computers, respectively. The control PC was an HP nx6110 portable computer. Windows XP Professional SP3 was the operating system. The PCs were arranged to enable maximum resources to the present work. Batch command files have been re-written for the new TCP and UDP research.

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

III. RESULTS AND DISCUSSION

WPA2 encryption and a nominal rate of 54 Mbps were manually configured in every wireless network adapter of the PCs. Nominal transmit and receive rates were monitored in the AP along the experiments. They were regularly 54 Mbps. 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 collected for the WPA2 multi-node links at OSI levels 1 (physical layer) and 4 (transport layer) using the arrangement of Fig. 1. For every link type and TCP packet size an average TCP throughput was calculated from a set of experiments. This value was taken as the bandwidth parameter for every related 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 collected 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 collected data were similar for all types of experiments. Typical values are given in Fig. 2. The links had good, high, SNR values.

The main average TCP and UDP results are compiled in Table I, for WPA2 and Open links, and every link topology (PTP, PTMP and 4N-PTMP). The statistical analysis, including computations of confidence intervals, was performed as in [25].

In Fig. 3, polynomial fits were made (shown as y versus x), using the Excel worksheet, to the TCP throughput data for WPA2 multi-node links, where R^2 is the coefficient of determination. It provides the goodness of fit. A value of 1.0 implies a perfect fit to data. It was found that, on average, the best TCP throughputs are for PTP, both for WPA2 and Open links (Table I). In passing from PTP to PTMP, throughput reduces to 45%. In comparison to PTMP, 4N-PTMP throughput falls to 51%. Similar trends are visible for Open links. This is due to increase of processing requirements for the AP to maintain links between PCs. Fig. 3 puts forward a fair increase 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 contrast to the protocol components. The role of the frame is very heavy in Wi-Fi. For larger packets, overhead reduces; the amount of sent data overcomes the protocol components. WPA2 802.11n results [18] show better TCP throughput performances and similar trends than WPA2 802.11a data. WPA2 802.11ac TCP throughput results [13] show the best performance.

In Figs. 4-5, the data points representing jitter and percentage datagram loss for WPA2 links were joined by smoothed lines. In Figs. 6-7, log 10 based scales were applied to the horizontal axes, for providing further details. Similar data are given in Figs. 8-9 for Open links. It was found that, on average, the best jitter performances are for PTMP and 4N-PTMP, for both WPA2 and Open links (Table I). This is surprising, and so far unexplained. We would expect a degradation of jitter performance due to link topology with increased number of nodes, where processing requirements of the AP increase for providing links between PCs. There are unusual oscillations in the PTMP and 4N-PTMP jitter curves (Figs. 4, 5 and 8). For PTP and small sized datagrams, jitter is small. There are small delays in sending datagrams. Latency is also small. Jitter increases for larger datagram sizes. WPA2 did not show a visible effect on jitter performance. Jitter performances are not very significantly different, considering the experimental error, between WPA2 and Open links

Concerning average percentage datagram loss, performances were generally found, on average, to degrade due to link topology by increasing the number of nodes (Table I). This is due to increase of processing requirements for the AP to keep links between PCs. Generally, Figs. 6, 7 and 9 show 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, resulting in higher losses. WPA2, where data length increases due to encryption, shows the effect of increasing average percentage datagram loss performance, for all link topologies.

TCP throughput and percentage datagram loss have generally shown performance degradations due to link topology. As CSMA/CA is the medium access control, the available bandwidth and the airtime are divided by the nodes using the medium. WPA2 has shown to degrade datagram loss performances.

Further experiments were made under similar conditions with 128-bit WEP multi-node links. It was found that TCP throughput and percentage datagram loss exhibit performance degradations due to link topology, in increasing the number of nodes. Here, processing requirements of the AP are higher to ensure links between PCs. WEP, where there is increase of data length due to encryption, was found not to decrease TCP throughput within the experimental error. Nevertheless to degrade, mainly, datagram loss performance.

Present results show that 5 GHz 802.11n WPA2 [18] gives better performances than 802.11a WPA2 for both TCP and (for PTP) jitter and datagram loss.

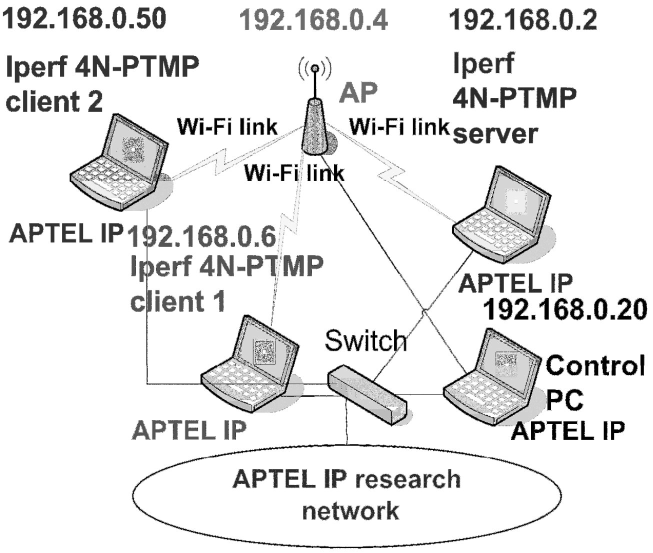

Fig. 1- Laboratory setup arrangement.

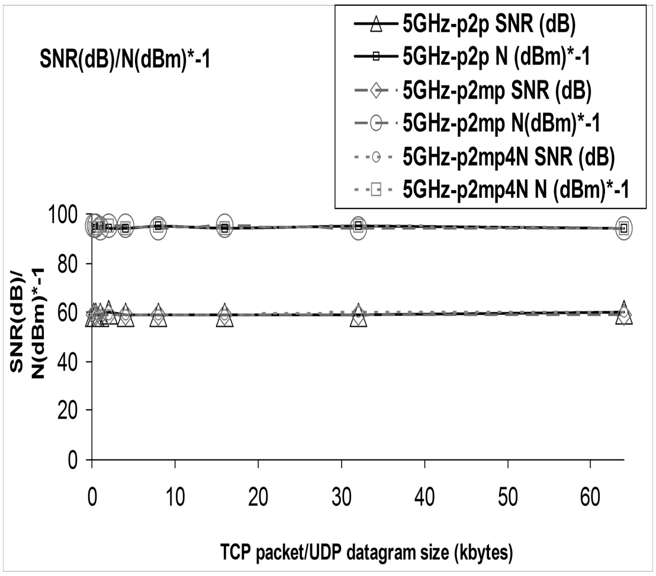

Fig. 2-SNR (dB) and N (dBm). WPA2 links.

TABLE I
Average Wi-Fi (IEEE 802.11a) WPA2 and Open results: PtP, PtMP, 4N-PtMP

Link type	**WPA2 PTP**	**WPA2 PTMP**	**WPA2 4N-PTMP**
TCP throughput (Mbps)	22.9 +-0.7	10.3 +-0.3	5.3 +-0.2
UDP-jitter (ms)	3.2 +-0.1	2.1 +-0.2	2.6 +-0.3
UDP-% datagram loss	2.5 +-0.2	8.4 +-0.1	5.9 +-0.9
Link type	**OPEN PTP**	**OPEN PTMP**	**OPEN 4N-PTMP**
TCP throughput (Mbps)	23.1 +-0.7	10.5 +-0.3	5.4 +-0.2
UDP-jitter (ms)	3.5 +-0.2	2.6 +-0.4	2.6 +-0.6
UDP-% datagram loss	1.9 +-0.2	7.5 +-0.4	4.7 +-0.2

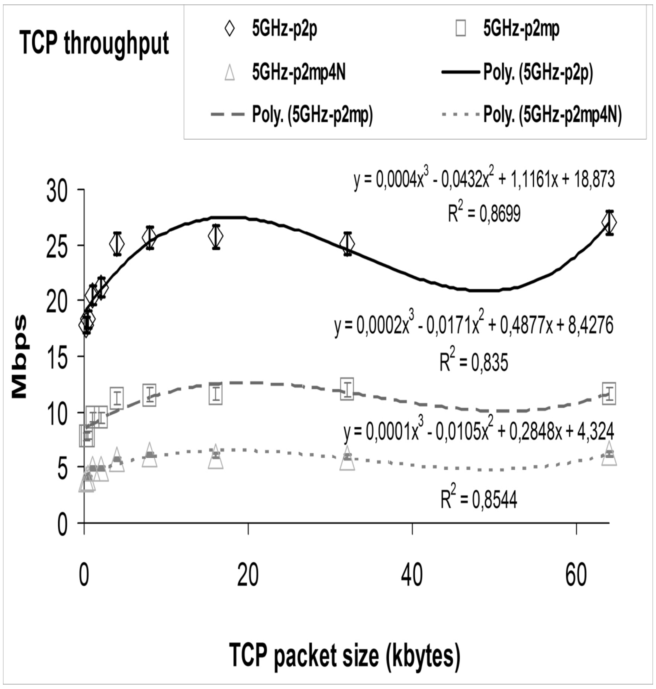

Fig.3- TCP throughput (y) versus TCP packet size (x). WPA2 links.

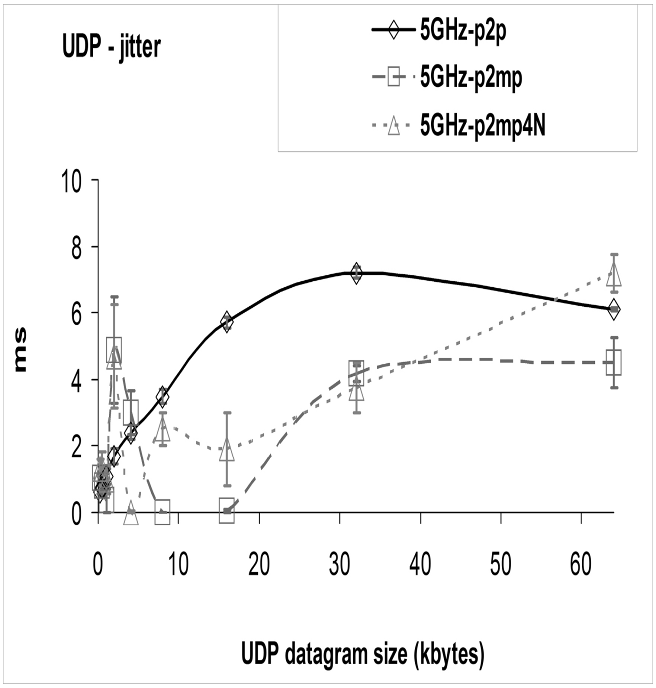

Fig. 4- UDP - jitter versus UDP datagram size. WPA2 links.

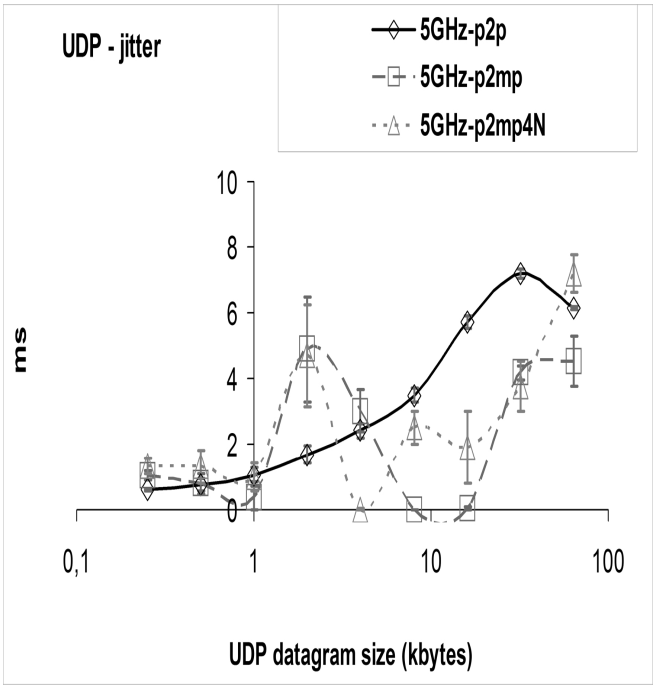

Fig. 5- UDP - jitter versus UDP datagram size. WPA2 links. Horizontal axis log scale.

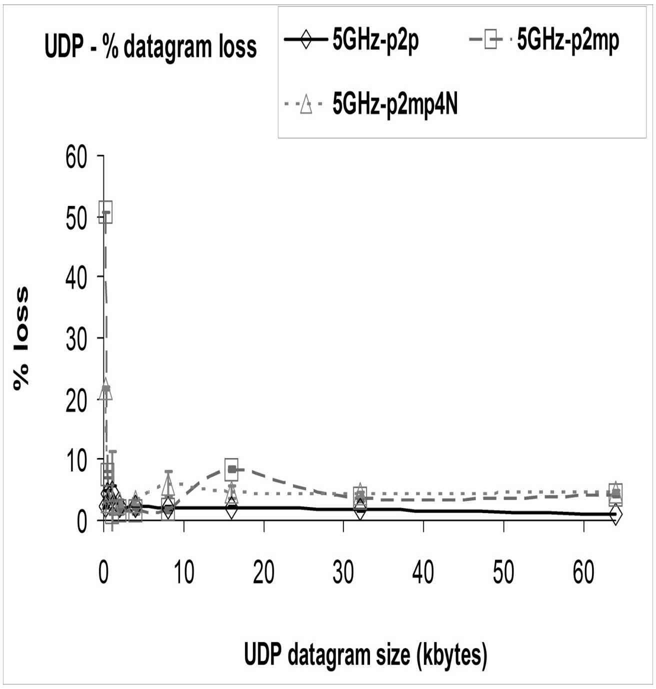

Fig. 6- UDP – percentage datagram loss versus UDP datagram size. WPA2 links.

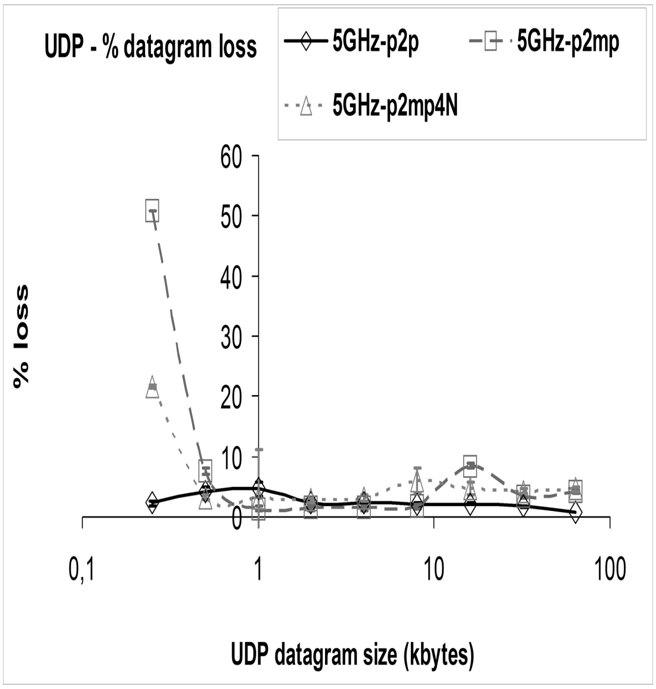

Fig. 7- UDP – percentage datagram loss versus UDP datagram size. WPA2 links. Horizontal axis log scale.

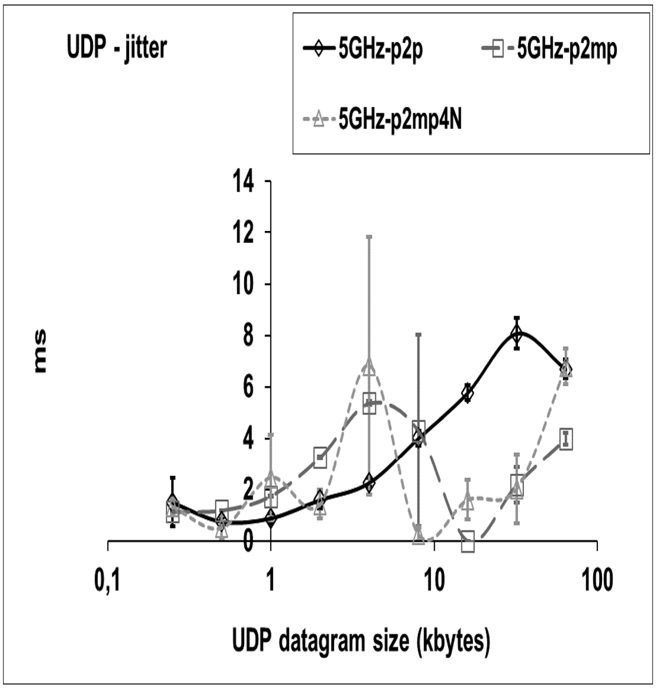

Fig. 8- UDP – jitter versus UDP datagram size. Open links. Horizontal axis log scale.

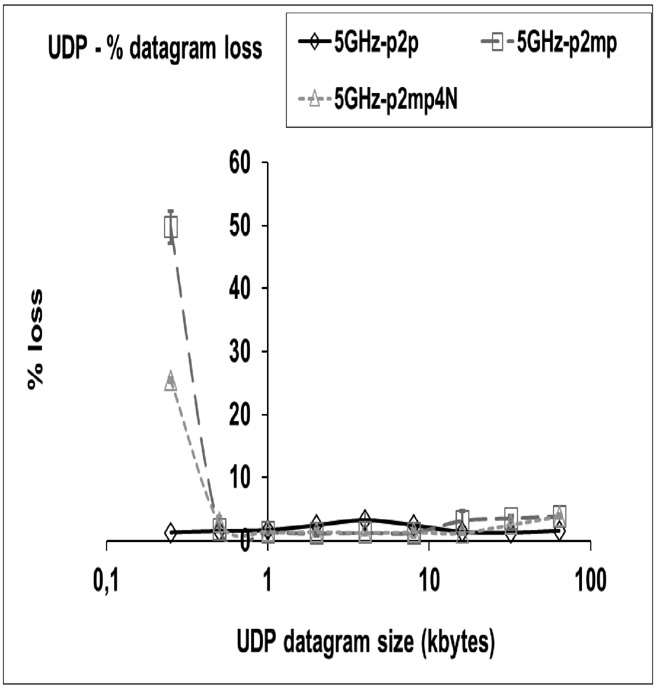

Fig. 9- UDP – percentage datagram loss versus UDP datagram size. Open links. Horizontal axis log scale.

IV CONCLUSION

In the present work a versatile laboratory setup arrangement was planned and realized, that permitted systematic performance measurements using available wireless equipments (V-M200 access points from HP and WPC600N adapters from Linksys) for Wi-Fi (IEEE 802.11 a) in WPA2 multi-node (PTP, PTMP and 4N-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 and Open links, for all link topologies. TCP throughput was found to increase with packet size. No significant sensitivity to WPA2 was found within the experimental error. As for jitter, for PTP and small sized datagrams, it is found small. It increases for larger datagrams. WPA2 did not show a visible effect on jitter performance. Concerning percentage datagram loss, it was found high for small sized datagrams, chiefly for PTMP. For larger datagrams, it diminishes. However, large UDP segments originate fragmentation at the IP datagram level, leading to higher losses. TCP throughput and percentage datagram loss were found, generally, to show performance degradations due to link topology, in increasing the number of nodes. Processing requirements of the AP are higher, to ensure links between PCs. As CSMA/CA is the medium access control, the available bandwidth and the airtime are divided by the nodes using the medium. WPA2 has shown to degrade datagram loss performances, for all link topologies. WEP was found not to decrease TCP throughput within the experimental error. Nevertheless to degrade, mainly, datagram loss performances. The present results show that 5 GHz 802.11n WPA2 gives better performances than 802.11a WPA2 for both TCP and (for PTP) jitter and datagram loss.

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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