Cross-Layer Measurements for a Comprehensive Characterization of Wireless Networks in the Presence of Interference

Leopoldo Angrisani and Michele Vadursi

***Abstract*—Assessing the overall performance of wireless communication networks is of key importance for optimal management and planning. With special regard to wireless networks operating in an unlicensed band, evaluating overall performance mainly implies facing the coexistence issues, which are associated with the contemporaneous presence of true and interfering signals at the physical layer. This task is difficult to fulfill only on the basis of single-layer measurements, if not prohibitive; a partial perspective of network behavior would, in fact, be gained. With this concern, a cross-layer approach is presented hereinafter. It provides for several measurements to be concurrently carried out at different layers through a proper automatic station. It aims to correlate the values of the major physical-layer quantities (e.g., channel power and signal-to-interference ratio) exhibited by those characterizing the key higher layers' parameters (e.g., packet-loss ratio and one-way delay) in the presence of interference. A first step toward a full characterization of how the effects of a problem, which is experienced at the physical layer, propagates along the whole protocol stack, can thus be taken.**

***Index Terms*—Coexistence issues, cross-layer measurements, interference measurements, one-way-delay (OWD) measurements, packet-loss-ratio (PLR) measurements, timing-jitter measurements, Wi-Fi, wireless networks.**

I. Introduction

OVERALL performance of any communication network is strictly connected to the functionalities of each layer in its International Organization for Standardization/Open System Interconnect stack. In particular, it depends on the characteristics of data link and physical layers, which are mandated to manage data transmission in all physical channels involved. With regard to wired channels, mechanical, electrical, and protocol characteristics of the aforementioned layers prove appropriate to reach such a signal-integrity level as to transmit and receive data safely. In wireless channels, on the contrary, this is not true. Unpredictable and uncontrollable interference can severely degrade the signal integrity and ultimately compromise the performance perceived by the final user, which is generally quantified through objective parameters peculiar to transport and application layers (higher layers) such as packet-loss ratio (PLR), timing jitter, one-way delay (OWD), and throughput.

The notable reliability of typical higher layer protocols makes the overall performance of wireless or hybrid communication networks significantly depend on signal integrity on the wireless channel. However, characterizing only the physical layer does not prove appropriate to determine how the possible signal degradations affect the behavior of higher layers and, ultimately, the perceived performance. Dually, evaluating only the key higher layer parameters, although they are very close to an overall performance assessment, does not provide any useful information to fix possible problems at the vulnerable physical layer.

Therefore, research activity aimed at going beyond a single-layer measurement approach in order to establish how and in what measure the presence of interference can influence the overall performance of typical wireless or hybrid networks seems to be relevant and should be encouraged. This is particularly true for the communication networks operating in the unlicensed industrial-scientific-medical (ISM) band like Wi-Fi, Bluetooth, ZigBee, and WiMAX networks. Coexistence issues, which are related to the superposition of the desired and interfering signals in the same band, are, in fact, of major concern in such cases [1]–[5].

To give a proper answer to the cited measurement need, this paper aims at correlating the values of the major physical quantities in the wireless channel to those characterizing the key higher layer parameters. In a word, the research activity can be said to take advantage of the cross-layer measurements, which are intended to assess the performance of a network layer as a function of that of another or several other ones. The proposed cross-layer approach can be of great help both in the design and maintenance stages of a wireless-network life cycle. In the design stage, measurements conducted at the physical layer are useful to characterize the wireless channel that the network has to exploit; on the basis of measurement results, the characteristics of the network can be optimally tailored to meet user desiderata. Once the network is operative, physical-layer measures can be profitably exploited to infer possible causes of quality-of-service (QoS) degradation when the latter is experienced at higher layers.

Whereas a number of papers on wireless network performance evaluation are present in the literature [5]–[13], few works seem to face the problem of experimentally assessing the cross-layer performance. Analytical approaches based on

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L. Angrisani is with the Dipartimento di Informatica e Sistemistica, Università degli Studi di Napoli Federico II, 80125 Napoli, Italy (e-mail: angrisan@unina.it).

M. Vadursi is with the Dipartimento per le Tecnologie, Università degli Studi di Napoli "Parthenope", 80133 Napoli, Italy (e-mail: vadursi@uniparthenope.it).

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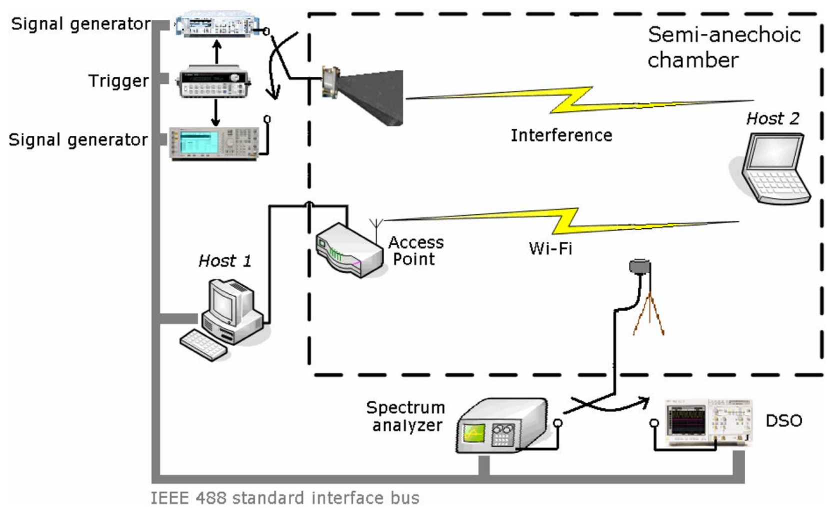

Fig. 1. Experimental testbed adopted in the first scenario.

a propagation model are presented in [8] and [9], whereas cross-layer simulations are proposed in [11]. Other works aim to evaluate the performance of IEEE 802.11 networks with Bluetooth interference using analytical approaches that take into consideration the typical parameters of different layers [5], [12], [13]. Furthermore, cross-layer approaches are also adopted in the design of wireless sensor networks, with the aim of optimizing their performance [14], [15].

In the following, two measurement scenarios are designed, each of which provides for a proper testbed and operative procedure. The wireless channel of the network under test is located inside a protected environment, in which the controlled interference is generated. The first scenario enlists the interfering signals with known characteristics, while the second one accounts for the interference produced by real communication equipment.

This paper is organized as follows. Section II describes the proposed cross-layer approach, giving details both of the testbed and operative procedure of the two measurement scenarios. Sections III and IV are mandated to show the results of a number of experiments conducted on a wireless network compliant with IEEE 802.11b standard; the efficacy and reliability of the proposal are highlighted. Concluding remarks are drawn in Section V.

II. Cross-Layer Approach

Stemming from the past experience documented in [16], a cross-layer measurement approach is proposed to correlate the major physical-layer quantities to the key higher layer parameters. With regard to the physical layer, channel power and signal-to-interference power ratio (SIR) are enlisted. Concerning higher layers, PLR, timing jitter, OWD, and throughput, which have direct influence on the quality perceived by the final user in a variety of heterogeneous applications, are taken into consideration.

Two different measurement scenarios, involving a real testbed and a proper operative procedure, are presented. They can act as alternatives or as a complementary pair. In each of them, in fact, signal integrity is degraded by the controlled interference; a protected environment, which embraces the wireless channel, keeps the unpredictable interference out. Higher layer parameters can thus be evaluated for different types and levels of interference, and a suitable correlation can be established. Without losing generality, the first and second scenarios are described with references both to the testbed and operative procedure adopted in the experiments accounted for in Sections III and IV, respectively. In these experiments, a wireless network compliant with IEEE 802.11b standard (Wi-Fi) is analyzed, and a semianechoic chamber acts as the protected environment.

A. First Measurement Scenario

1) Testbed: The only interfering signal in wireless channel is emitted from a signal generator suitably commanded, whereas possible uncontrolled interference from outside the chamber does not affect the communication. Specifically, the adopted testbed, shown in Fig. 1, consists of the following:

1) three hosts;
2) an IEEE 802.11 access point (AP) D-link DI-624+;
3) a signal generator Rhode&Schwarz SML03 (9 kHz–3.3 GHz output frequency range and pulse modulation capability), which provides sinusoidal interference;
4) another signal generator that is the Agilent Technologies E4403B (9 kHz–3.0 GHz output frequency range), which provides modulated interference;
5) an arbitrary waveform generator (AWG) Agilent Technologies 33120A (15 MHz maximum output frequency);
6) a microwave horn antenna Amplifier Research AT4002A (0.8–5 GHz frequency range);
7) an omnidirectional antenna EM-6865 (2–18 GHz frequency range and 10.16 cm diameter);
8) a spectrum analyzer Anritsu MS2687B (9–30 GHz input frequency range and up to 20 MHz resolution bandwidth);
9) a digital storage oscilloscope (DSO) Agilent Technologies 54833D (1 GHz bandwidth, 4 GS/s sampling frequency, and 8.2 megasample memory depth).

The dashed box in Fig. 1 encloses instruments that are inside the semianechoic chamber. The three generators, spectrum analyzer, DSO, and one of the hosts, which is the processing and control unit of the measurement testbed, are all interconnected through an IEEE 488 standard interface bus.

The signal inside the chamber is captured by the omnidirectional antenna, which is connected to the spectrum analyzer through a coaxial cable. Besides providing the power spectrum of the signal captured by the antenna, the spectrum analyzer can be utilized in zero span mode to attain the evolution versus time of signal envelope power. Moreover, it can act as a downconverter to an intermediate frequency equal to 66 MHz; owing to this feature, the DSO can acquire the evolution versus time of the downconverted signal, whose significant spectral content is totally included inside the DSO bandwidth.

2) Measurement Procedure: Communication occurs between a pair of hosts, which is, in the following, referred to as Hosts 1 and 2. Host 1 is connected via a wired 100 Mb/s link to the AP, which represents its default gateway. Wireless communication, which is compliant with the IEEE 802.11b standard, actually takes place between AP and Host 2, which are inside the chamber. An active measurement approach is adopted. Synthetic user-datagram-protocol traffic is generated through the distributed Internet traffic generator (D-ITG) [17], [18], whose architecture allows measuring several QoS parameters at both the sender and receiver sides, and reporting a complete digest of measured parameters over the entire measurement time. Specifically, PLR, OWD, and timing jitter are measured by analyzing the D-ITG log files. Although any packet hit and degraded by interference is rejected at datalink layer, higher layer parameters are enlisted to assess the effects of interference on QoS, due to their better suitability in quantifying the QoS perceived by the final user. Moreover, the simple topology of the considered wireless network makes the performance degradation introduced by network and transport layers unrealistic.

Controlled interference is generated according to the procedure exploited in [13]. Interference is emitted by the two signal generators, which are outside the semianechoic chamber and feed the microwave horn antenna located inside. Several types of both continuous and bursty interfering signals are taken into consideration. To emit bursty interference, particularly, the pulse modulation capability of the signal generators is exploited, while AWG, which is used as the trigger source, is commanded to generate either a periodic or frequency-modulated square wave signal.

As stated previously, the channel power and SIR measurements are carried out at the physical layer. Channel power is measured through the spectrum analyzer, in the absence of interference. It is worth noting that spectral analysis on Wi-Fi signals through a spectrum analyzer places some constraints, due to the limited duration of transmitted packets. Transmission of long packets, in fact, requires no more than few milliseconds, and the minimum allowed sweep time covers several packets. A synchronization with the transmitted packets would prevent from sweeping when no signal is present in the channel; signal power spectrum could therefore be reconstructed by joining the power spectrum segments of successive packets. This solution is implemented by setting the spectrum analyzer in gate mode and performing the sweep over the selected frequency span at intervals synchronized with the transmission of packets. D-ITG has, in fact, been provided with a triggering feature, which has already been exploited in [19], which is very useful to the purpose at hand. In particular, when the sender starts the transmission of each packet, a voltage pulse is generated on a certain pin of its serial port. The EIA232-to-TTL converter has been designed by the authors to use the pulse emitted on the serial port of the sender host as trigger signal for the spectrum analyzer (and/or the DSO). An external trigger source is, in fact, needed, because beacon frames, which are periodically generated by the AP, could induce wrong triggers. Although this technique has the disadvantage that measurement time grows inversely with packet transmission rate, it allows analysis of the signal power spectrum with the sensibility typical of a spectrum analyzer, rather than performing a fast-Fourier-transform-based analysis. Interference power is similarly measured through the spectrum analyzer, in order to evaluate SIR.

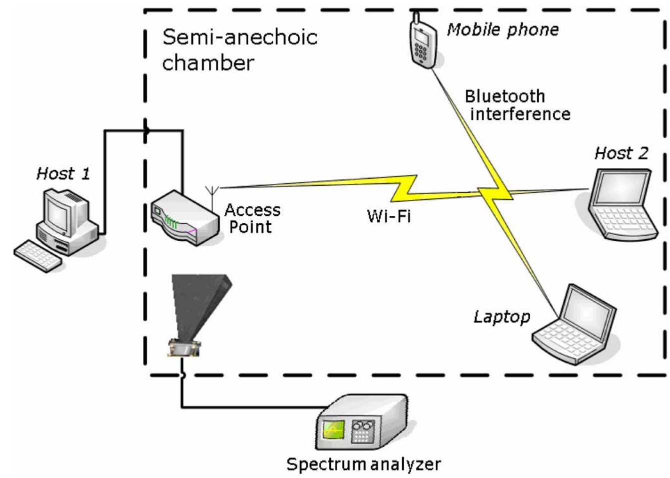

Fig. 2. Experimental testbed adopted in the second scenario.

B. Second Measurement Scenario

1) Testbed: The interference produced by real communication equipment is present in the wireless channel. Specifically, it refers to file-transfer activity occurring between a mobile phone and a laptop via Bluetooth in the semianechoic chamber. The experimental testbed is shown in Fig. 2; it consists of the following:

1) three hosts;
2) an IEEE 802.11 AP D-link DI-624+;
3) a horn antenna Schwarzbeck Mess-Elektronik BBHA9120D (0.8–18 GHz frequency range);
4) a spectrum analyzer Anritsu MS2687B (9–30 GHz input frequency range and up to 20 MHz resolution bandwidth);
5) a mobile phone Nokia 6230i.

The dashed box in Fig. 2 encloses the devices inside the semianechoic chamber. The signal inside the chamber is captured by the antenna, which is connected to the spectrum analyzer through a coaxial cable.

TABLE I
PLR VALUES FOR THE DIFFERENT SINUSOIDAL INTERFERENCE LEVELS AND TRANSMISSION RATES; d IS EQUAL TO 0.1

		Interference power level [dBm]														
	S_M	-49.3	-46.2	-45.6	-44.1	-43.1	-42.1	-41.1	-40.2	-39.2	-38.2	-37.2	-34.1	-33.6	-33.1	-32.0
	S_{BURST}	-59.3	-56.2	-55.6	-54.1	-53.1	-52.1	-51.1	-50.2	-49.2	-48.2	-47.2	-44.1	-43.6	-43.1	-42.0
250 packet/s	**SIR**	14.4	11.3	10.7	9.2	8.3	7.2	6.2	5.3	4.3	3.3	2.3	-0.8	-1.3	-1.8	-2.9
	PLR	2.7%	4.1%	6.3%	24%	30%	31%	35%	38%	35%	35%	36%	38%	37%	34%	32%
750 packet/s	**SIR**	14.2	11.1	10.5	9.0	8.0	7.0	6.0	5.1	4.1	3.1	2.1	-1.0	-1.5	-2.0	-3.1
	PLR	58%	63%	65%	67%	70%	74%	76%	77%	78%	78%	78%	78%	78%	78%	79%
1000 packet/s	**SIR**	14.7	11.6	11.0	9.5	8.5	7.5	6.5	5.6	4.6	3.6	2.6	-0.5	-1.0	-1.5	-2.6
	PLR	70%	73%	75%	72%	79%	81%	83%	83%	84%	84%	84%	84%	84%	84%	83%

TABLE II
PLR VALUES FOR THE DIFFERENT SINUSOIDAL INTERFERENCE LEVELS AND TRANSMISSION RATES; d IS EQUAL TO 0.15

		Interference power level [dBm]														
	S_M	-46.8	-45.9	-45.3	-43.8	-42.8	-41.9	-40.9	-39.9	-38.9	-37.9	-36.9	-33.9	-33.3	-32.8	-31.8
	S_{BURST}	-55.1	-54.4	-53.6	-52.1	-51.1	-50.1	-49.1	-48.2	-47.2	-46.2	-45.2	-42.1	-41.6	-41.1	-40.1
250 packet/s	**SIR**	10.1	9.2	8.7	7.2	6.2	5.2	4.2	3.2	2.2	1.2	0.2	-2.8	-3.3	-3.9	-4.9
	PLR	7.8%	34%	38%	48%	50%	55%	56%	53%	57%	58%	56%	55%	54%	57%	57%
750 packet/s	**SIR**	9.9	9.0	8.5	7.0	6.0	5.0	4.0	3.1	2.1	1.1	0.1	-3.0	-3.5	-4.0	-5.1
	PLR	65%	70%	72%	76%	79%	82%	83%	84%	86%	85%	85%	85%	85%	85%	85%
1000 packet/s	**SIR**	10.5	9.6	9.0	7.5	6.5	5.5	4.5	3.6	2.6	1.6	0.6	-2.5	-3.0	-3.5	-4.5
	PLR	73%	77%	78%	81%	84%	86%	88%	89%	88%	89%	90%	89%	89%	89%	89%

2) Measurement Procedure: Communication occurs between Hosts 1 and 2, as in the first scenario. Specifically, a file-transfer-protocol (FTP) server (Golden FTP Server v.1.92) runs on Host 1, and an FTP client (WS_FTP Professional) runs on Host 2. The interfering signal is due to a file transfer, which is performed through Bluetooth connection, from the mobile phone to the host in the semianechoic chamber.

Throughput measurements are performed at the application level by analyzing the log files of the FTP client. As for the physical-layer measurements, channel power of the interfering Bluetooth signal is considered. When the Wi-Fi communication is shut down, the Bluetooth channel power is measured through the spectrum analyzer by exploiting the maxhold function. The maxhold function is needed because the frequency hopping [20] is activated in the Bluetooth communication, and the signal periodically changes its carrier among 79 allowed values that are 1 MHz apart from one another.

III. EXPERIMENTAL RESULTS: FIRST SCENARIO

Experiments have been conducted in the presence of different types of interfering signals, such as sinusoidal, frequency-shift keying (FSK), and Bluetooth signals, and taking into consideration both the continuous and bursty interferences.

A. Sinusoidal Interference

For the sake of brevity, only results related to PLR, in the presence of bursty sinusoidal interference characterized by random occurring times, are given.

For an easier comprehension of the results, the following parameters have to be clarified:

- T_{ON} — duration of a single burst of interference;
- T — average time interval between the two successive bursts;
- $d = T_{ON}/T$ — duty cycle;
- S_M — power of the continuous interfering sinusoidal signal, hereinafter named as peak power, which is measured through the spectrum analyzer;
- $S_{BURST} = d \cdot S_M$ — average power of interference;
- C_P — channel power of the Wi-Fi signal, which is measured through the spectrum analyzer in the absence of interference;
- $\mathrm{SIR} = C_P/S_{BURST}$ — SIR.

The interfering signal carrier frequency has been fixed at 2.427 GHz, and PLR has been evaluated over a 60 s transmission, in order to be able to confidently assume S_{BURST} as the average power of interference. Moreover, values of S_M and C_P, which are measured through the spectrum analyzer, have been averaged over 100 successive measurements to mitigate the repeatability problems of power measurements on (wideband) RF signals [21]. All power values have been expressed in decibels referenced to 1 mW, SIR in decibels, PLR in percentage relative terms, and packet rate and length have been given in packets per second and byte, respectively. Tables I–III show the PLR for different interfering signal power levels and different transmission packet rates. They are related to a duty cycle d that is equal to 0.1, 0.15, and 0.2, respectively.

From the analysis of the results, the following considerations can be drawn.

1) Since the channel power of Wi-Fi signal does not vary significantly with the transmission rate, SIR and S_{BURST} are equivalent figures of merit in the analyzed cases.
2) A threshold SIR value can always be singled out, which separates a variation region, in which the lower the SIR (or the higher the S_{BURST}), the worse the PLR, from a saturation region, in which the worst PLR is reached.

TABLE III
PLR VALUES FOR THE DIFFERENT SINUSOIDAL INTERFERENCE LEVELS AND TRANSMISSION RATES; d IS EQUAL TO 0.2

		Interference power level [dBm]														
	S_M	-49.3	-46.3	-45.7	-44.2	-43.2	-42.2	-41.4	-40.7	-40.1	-39.5	-39.1	-34.2	-33.7	-33.2	-32.1
	S_{BURST}	-56.3	-53.3	-52.7	-51.2	-50.2	-49.2	-48.4	-47.7	-47.1	-46.5	-46.1	-41.2	-40.7	-40.2	-39.2
250 packet/s	**SIR**	11.4	8.4	7.8	6.3	5.3	4.3	3.5	2.8	2.2	1.6	1.2	-3.7	-4.3	-4.7	-5.9
	PLR	12%	19%	27%	33%	39%	44%	54%	61%	64%	63%	64%	65%	66%	64%	65%
750 packet/s	**SIR**	11.2	8.2	7.6	6.1	5.1	4.1	3.3	2.6	2.0	1.4	1.0	-3.9	-4.4	-4.9	-6.0
	PLR	71%	75%	78%	80%	83%	85%	88%	88%	88%	87%	89%	88%	88%	88%	88%
1000 packet/s	**SIR**	11.7	8.7	8.1	6.6	5.6	4.6	3.8	3.1	2.5	1.9	1.5	-3.4	-3.9	-4.4	-5.5
	PLR	79%	82%	83%	85%	88%	89%	90%	91%	91%	91%	91%	92%	92%	92%	91%

3) Maximum PLR is not necessarily equal to 100%, but it depends on the packet transmission rate and T. Once SIR has gone below the aforementioned threshold, given a certain value of T (or packet transmission rate), PLR is not affected by further SIR degradation but mainly depends on the packet transmission rate (or T).

B. FSK and Bluetooth Interference

A set of experiments has been carried out in the presence of 2-FSK interfering signals, which are characterized by frequency deviation equal to 170 kHz and bit rate equal to 1 Mb/s. Different values of carrier frequency and average power of the 2-FSK interfering signal have been considered. In all cases, the carrier frequency has fallen within the Wi-Fi signal bandwidth (the AP has been configured to utilize the Wi-Fi channel number 4, i.e., the carrier frequency is equal to 2.427 GHz). Experiments have also been repeated for the different values of packet rate and length. Hosts 1 and 2 have been synchronized through the network time protocol [22].

Fig. 3 shows the results achieved with the continuous 2-FSK interference when the interference and the Wi-Fi signal have the same carrier frequency, for the different values of interfering signal level and transmitted packet length and rate. Results are expressed in terms of PLR [Fig. 3(a)] and average jitter J [Fig. 3(b)], where the latter is defined as

$$J = \sum_{i=1}^{n-1} \frac{|D_i|}{n-1} \qquad (1)$$

where n is the number of transmitted packets, and

$$D_i = (R_{i+1} - R_i) - (S_{i+1} - S_i) \qquad (2)$$

is the difference between the interarrival $(R_{i+1} - R_i)$ and the interdeparture times $(S_{i+1} - S_i)$ and the delay experimental standard deviation [Fig. 3(c)].

Please note that the interference-power levels have been chosen in order to prevent from compromising the Wi-Fi communication. Values of interference power higher than those shown in Fig. 3 would, in fact, make the establishing 802.11b communication impossible, as the transmitter would sense the channel and find it continuously busy.

The results have shown that degradation increases (as expected) upon the interference level's increasing. No significant dependence of degradation on packet size or length can be highlighted, although Wi-Fi transmission seems to be slightly more sensitive to interference when longer packets are transmitted.

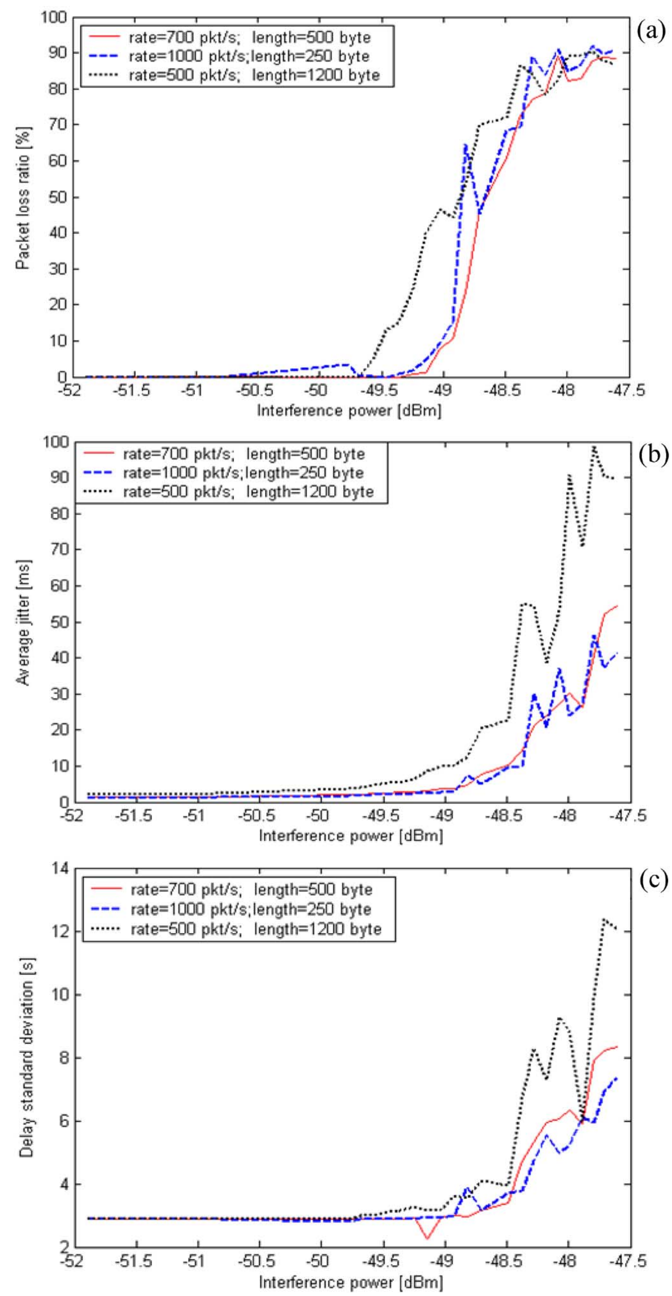

Fig. 3. (a) PLR, (b) average jitter, and (c) delay experimental standard deviation versus 2-FSK interference level for the different values of transmission rate and packet length.

It is notable that it is possible to single out a threshold for the interference power value over which the three parameters that are taken into consideration jump up to very high values. With

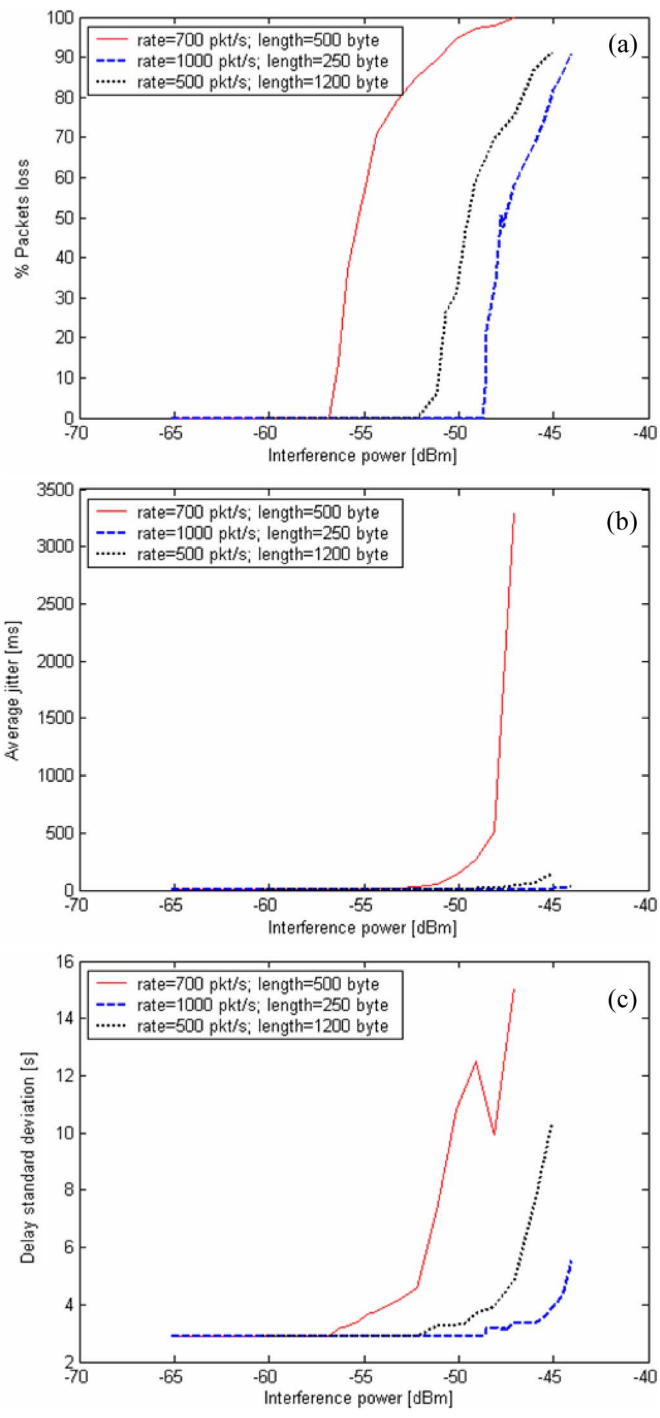

Fig. 4. (a) PLR, (b) average jitter, and (c) delay experimental standard deviation versus Bluetooth interference level for the different values of transmission rate and packet length.

regard to the transmission of 500-byte packets at a rate equal to 700 packet/s, for example, less than a 1-dB increase in the interference power can make the PLR jump from 0% to more than 60%. Similarly, the average jitter is increased from less than 5% to more than 50%, upon a 1.5-dB increase of interference power. A further increase of interference power, which is lower than 1 dB, would make the Wi-Fi communication impossible, as already stated.

Fig. 4 shows the results achieved with continuous Bluetooth interference, with random payload, when the interference,

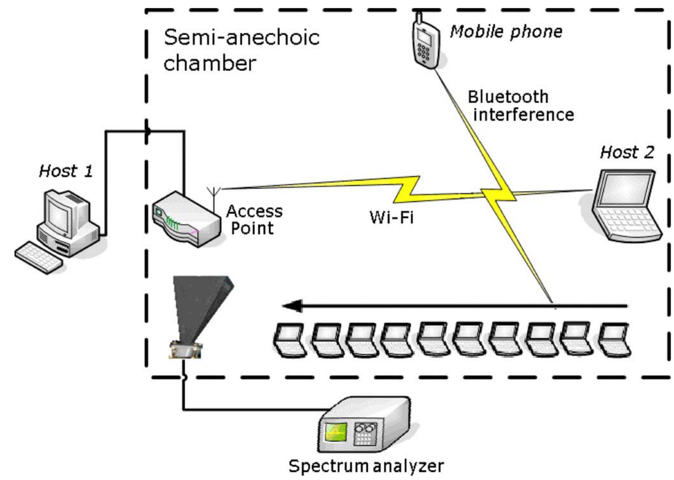

Fig. 5. Experimental testbed adopted in the second scenario for the measurements in different positions.

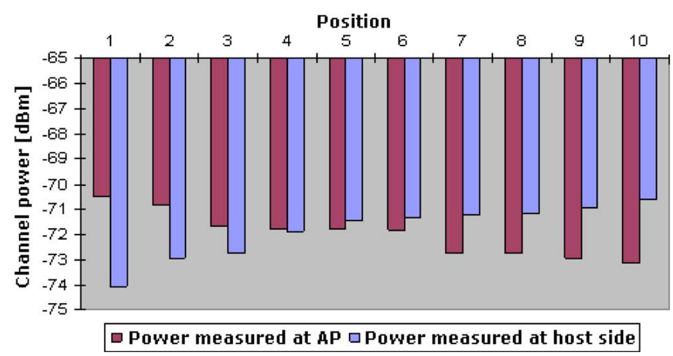

Fig. 6. Interfering signal power measured at the AP and Host 2 sides.

and the Wi-Fi signal have the same carrier frequency for the different values of interfering signal power and transmitted packet length and rate. Evolution versus interference power of each parameter is practically the same as that experienced with the 2-FSK interference. The Wi-Fi communication is not affected by interference as long as the interference-power level is below a certain power threshold; when interference power is increased over such threshold, the performance degrades very rapidly, until communication is totally precluded. Similar outcomes have been experienced when the carrier frequency of the interfering signal is 5 or 10 MHz greater than that of the Wi-Fi signal, but the power values, in correspondence of which interference degrades the network performance, are significantly lower.

C. Critical Analysis of the Results

By analyzing the experimental results and considering the standard wireless medium access control (MAC) and physical-layer specifications, the reason for such behavior can be inferred. Stations regularly perform clear channel assessment to check the status (busy/idle) of the channel. Interference has practically no effect as long as its power does not pass a threshold Θ over which the AP starts to consider the physical channel busy. This is consistent with the wireless

TABLE IV
THROUGHPUT (IN KILOBYTES PER SECOND) ACHIEVED IN THE ABSENCE OF INTERFERENCE AND FOR THE DIFFERENT LAPTOP POSITIONS

File size [byte]	NO interference	Interference position									
		1	2	3	4	5	6	7	8	9	10
1 k	33.81	31.67	32.64	32.85	33.38	32.72	32.64	32.91	32.69	32.76	32.64
10 k	73.10	67.50	70.02	71.62	73.31	72.36	73.11	72.28	72.22	70.77	67.69
100 k	519.75	407.83	446.15	447.30	467.73	472.86	478.02	470.81	457.02	456.35	417.42
1 M	567.98	445.58	463.09	481.09	482.16	489.44	485.61	481.53	479.48	468.40	454.26

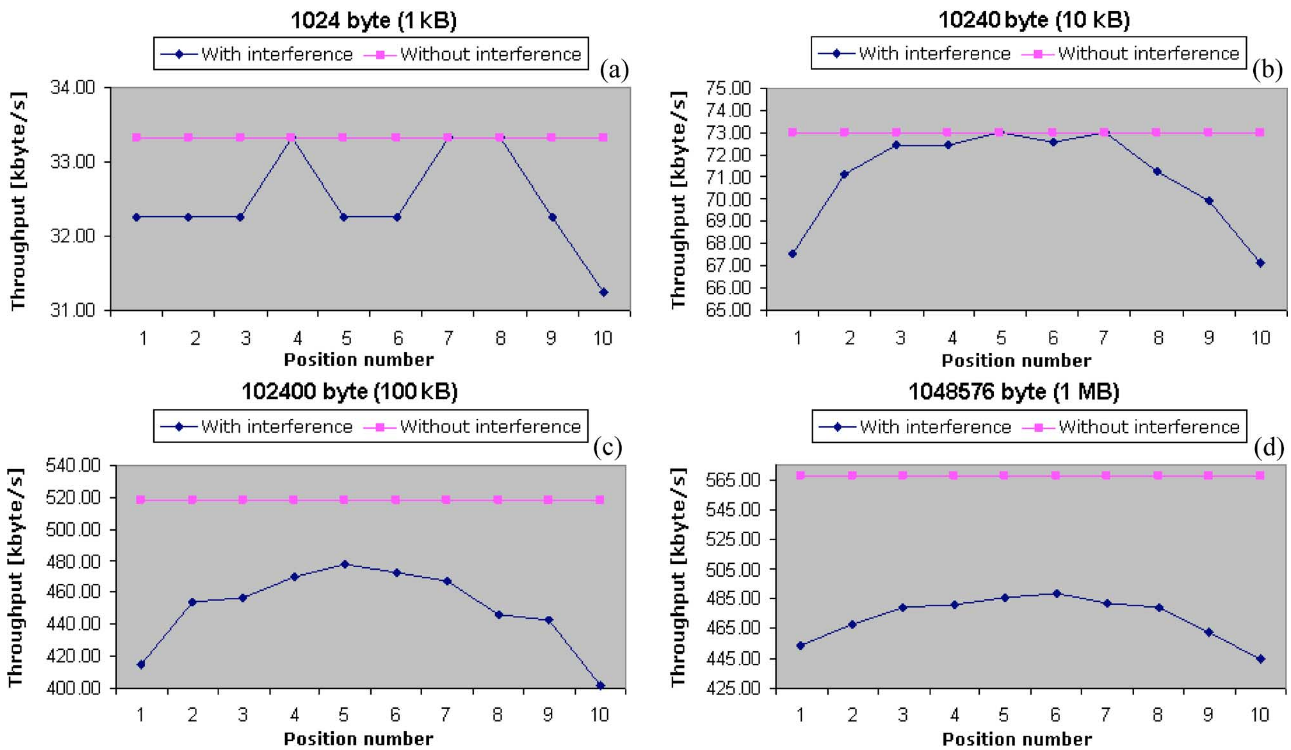

Fig. 7. Comparison between the throughput achieved with and without an interfering signal present in the Wi-Fi channel for different file sizes. (a) 1 kB, (b) 10 kB, (c) 100 kB, and (d) 1 MB.

local-area-network (WLAN) Bluetooth coexistence evaluation model proposed in [13]. When the interference power goes over Θ, transmission is blocked, and a queue overflow is experienced at the AP. Such two-state behavior is, however, only ideal. A transition region can be singled out for power values very close to Θ, where the channel is sensed sometimes busy and idle, and the transmission goes by fits and starts. The width of such transition region depends both on the receiver sensitivity and the characteristics of the signals, but the experimental results show that it is very narrow. For the Bluetooth interferer (Fig. 4), an increase of some decibels is enough to make the PLR pass from 0% to 80%. In particular, when the Wi-Fi signal consists of 500-byte packets, which are transmitted at 700 packet/s, a 5-dB increase in the interference power, from -57 to -52 dBm, causes an increment of PLR from 0% to 80%. The same happens with longer Wi-Fi packets (1200 byte), which are transmitted at a rate equal to 500 packet/s, when the interference power increases from -52 to -47 dBm. For higher Wi-Fi packet rate (1000 packet/s), a 3-dB increase in the interference power is enough to make the PLR jump from 0% up to 80%.

An alternative explanation for such a quick degradation could be the following: the interference damages packets, which are therefore retransmitted even more than once, according to the MAC protocol, thus causing a queue overflow at the AP side. Besides being not realistic, as the Wi-Fi networks are robust with respect to the narrowband interference (whereas the behavior under discussion has been observed with sinusoidal interference as well), such a hypothesis has been discarded after analyzing the results of further experiments. In particular, single packets have been transmitted, and interference has been triggered immediately after the packet has occupied the channel; the evolution versus time of the signal in the wireless channel, which is recorded by the DSO, has shown that MAC-layer acknowledgment is delayed one Short InterFrame Space (SIFS) with respect to the end of the transmitted packet, which means that no retransmission has occurred, proving that interference has not damaged the packet. In conclusion, although the Wi-Fi modulation is robust with regard to narrowband interference, its MAC protocol strongly suffers from the presence of interference, because of the sensitivity of carrier sensing mechanism, which leads to the queue overflow at the sender side and consequent possible packet loss.

IV. Experimental Results: Second Scenario

To evaluate the effects of different interfering-power levels, measurements have been repeated for ten different positions of the laptop (see Fig. 5). Moreover, interference power has always been measured both at the AP and host sides to investigate whether one of the devices is more sensitive to the disturbance. Fig. 6 shows the interference-power levels measured at the AP and Host 2 sides. The evolution of interference power versus laptop position is actually the same in both cases.

Table IV shows the throughput experienced for files of different sizes, for all the considered positions of the laptop. The throughput achieved in the absence of interference is also given. The effects of interference on higher layer measures are highlighted by Fig. 7, which shows the variation of throughput for the ten positions where the laptop has been placed. The following considerations arise.

1) The transmission of small files does not seem to suffer from the interference [Fig. 7(a) and (b)]. The throughput reduction is, in fact, lower than a few percent with regard to 1- and 10-kbyte files.
2) On the contrary, the transmission of large files is more affected by the presence of interference. Degradation can reach the peaks of 20%.
3) When the mutual distances between laptop and Host 2 and laptop and AP are comparable, the lowest throughput degradations are verified (regarding small files, throughput is practically unaffected).
4) Network behavior is symmetric with regard to the laptop position. This implies that the two transceivers (AP and 802.11b WLAN card on Host 2) are equally affected by the equal interfering-power levels.

V. Conclusion

A cross-layer approach has been presented to assess the performance of wireless networks operating in the ISM band. Two application examples related to a Wi-Fi network in the presence of in-channel interference have been presented. Owing to the original proposed approach and to the suitable measurement testbed setup for the scope, it has been possible to correlate the values of the major physical-layer quantities to those characterizing the key higher layer parameters. The cross-layer approach has also been decisive in inferring the causes of the observed performance degradation on higher layer parameters and discarding the hypotheses that have not been supported by the experimental evidence. The obtained results have shown that, when the interference level is below a certain threshold, the channel is sensed as idle, and interference does not affect the Wi-Fi communication. On the contrary, when the interference level passes such a threshold, the transmission is blocked as the channel is sensed to be busy; packets are consequently lost, which is due to the buffer overflow, and not because they are damaged by the interference.

Future research activities will investigate the relation between the AP receiver sensitivity and the width of the observed transition region and extend the application of the proposed testbed to more complex networks, as well as networks that are compliant with different standards.

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Leopoldo Angrisani was born in Nocera Superiore, SA, Italy, on April 16, 1969. He received the M.S. degree (*cum laude*) in electronic engineering from the University of Salerno, Salerno, Italy, in 1993 and the Ph.D. degree in electrical engineering from the University of Napoli Federico II, Napoli, Italy, in 1997.

Since 2002, he has been an Associate Professor with the Dipartimento di Informatica e Sistemistica, Università degli Studi di Napoli Federico II, Napoli. He is currently involved in research into new digital signal-processing methods for assessing the performance of wireless or wired digital communication systems and apparatuses, testing and troubleshooting communication networks, detecting, measuring, and classifying nonstationary signals, and evaluating uncertainty in indirect measurements.

Michele Vadursi was born in Naples, Italy, on May 9, 1978. He received the M.S. degree in telecommunication engineering and the Ph.D. degree in electrical engineering from the University of Naples Federico II in 2002 and 2005, respectively.

Since 2006, he has been an Assistant Professor with the Dipartimento per le Tecnologie, Università degli Studi di Napoli "Parthenope", Naples. His research activity is focused on RF transmitter testing and troubleshooting, power measurement of RF signals, and performance evaluation in both wired and wireless LANs.