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Research Article

Cross-Layer Measurement on an IEEE 802.11g Wireless Network Supporting MPEG-2 Video Streaming Applications in the Presence of Interference

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The performance of wireless local area networks supporting video streaming applications, based on MPEG-2 video codec, in the presence of interference is here dealt with. IEEE 802.11g standard wireless networks, that do not support QoS in according with IEEE 802.11e standard, are, in particular, accounted for and Bluetooth signals, additive white Gaussian noise, and competitive data traffic are considered as sources of interference. The goal is twofold: from one side, experimentally assessing and correlating the values that some performance metrics assume at the same time at different layers of an IEEE 802.11g WLAN delivering video streaming in the presence of in-channel interference; from the other side, deducing helpful and practical hints for designers and technicians, in order to efficiently assess and enhance the performance of an IEEE 802.11g WLAN supporting video streaming in some suitable setup conditions and in the presence of interference. To this purpose, an experimental analysis is planned following a cross-layer measurement approach, and a proper testbed within a semianechoic chamber is used. Valuable results are obtained in terms of signal-to-interference ratio, packet loss ratio, jitter, video quality, and interference data rate; helpful hints for designers and technicians are finally gained.

1. Introduction

Wireless local area networks (WLANs) compliant with the family of IEEE 802.11 standards (also known as Wi-Fi standards) are nowadays one of the most successful emerging network technologies in the wireless communication scenario [1]. They are commonly used to provide wireless access to the Internet and network connectivity for personal digital assistants, laptops, and modern consumer electronics. In particular, they are widely available worldwide, through thousands of public hotspots located anywhere, in millions of homes, factories, and university campuses.

A great interest in Wi-Fi technology is also rapidly growing in the field of real-time multimedia, for applications such as audio/voice and video streaming over a wireless link. With regard to video streaming, although new applications are very likely to appear soon with upcoming WiMAX or DVB-H enabled devices [2, 3], the research community is in-depth studying new protocols, able to make Wi-Fi apparatuses overcome some notable drawbacks, thus allowing them to satisfy the stringent real-time unicast and multicast requirements [4–6]. Some fundamental drawbacks are related to the occurrence of phenomena in the propagation channel such as multipath, shadowing, echoes, and fading. Other ones are instead associated to the simultaneous presence of interfering signals within the same bandwidth deployed by the network. For instance, the IEEE 802.11b and g standards are allowed to operate in the unlicensed and crowded 2.4 GHz industrial scientific medical (ISM) band, in which several different devices may operate simultaneously, like, for instance, IEEE 802.15.4 (Zig-Bee) [7] and IEEE 802.15.1 (Bluetooth) [8] apparatuses, microwave ovens, cordless phones, baby monitors, security cameras, and so forth, [9]. All these sources may add significant interference to a Wi-Fi network supporting video streaming, provoking various classes of effects such as: collisions, delays, jitter and loss of data packets, reduced signal-to-interference ratio, final video quality degradation, and so forth.

To mitigate these effects a suitable standard, namely, IEEE 802.11e standard, has been developed. It relies on the classification of the incoming packet flows and association of a service class to each of them. Each service class offers different performance in terms of available bandwidth, delay, and jitter, succeeding in providing both best effort and high quality services. Although the IEEE 802.11e standard has been issued since 2005, only few companies have developed devices according to it. In actual scenarios, it is nowadays extremely unusual finding devices that operate according with the cited standard. Hence, most of current installed Wi-Fi networks do not provide QoS mechanisms but they are however exploited for sharing and spreading video. In these cases, the most efficient way to face the problem is to achieve information about the radio link characteristics and to take them into account at the early stages of a wireless network (in the following simply referred to as WLAN) design. Such information is not easy to obtain, and often requires to perform ad hoc laboratory and on-the-field measurements, through the use of proper testbeds. To this aim, crosslayer measurements can prove to be very helpful to detect key problems, solve the related drawbacks [10], and allow also a Wi-Fi network to provide reliable video streaming services without QoS.

As mentioned above, in the literature, a number of papers aim at investigating on the feasibility of video streaming over Wi-Fi networks [4–6, 11–13], and in some cases efficient solutions are also proposed. Nevertheless, only few of them face the problem from an experimental point of view. In [13], interesting experimental results are given, but they concern only free-from-interference multicast video streaming. In [9, 14–17], major effects of some kinds of interference on a WLAN as well as coexistence issues are analyzed theoretically and experimentally. In particular, in [9] the coexistence impact of an IEEE 802.15.4 network on IEEE 802.11b devices is investigated analytically, and a predicting model is proposed. In [14], the interference effects of IEEE 802.15.4 networks over IEEE 802.11b WLANs and vice versa are analyzed both analytically and through simulations. In [15–17], coexistence issues between wireless networks (IEEE 802.15.4, 802.11b and 802.15.1) are investigated through measurements. Although very interesting, the few given results do not specifically refer to the critical case of real-time video streaming applications under interference, which, to the best of the authors' knowledge, has not been dealt with in the literature yet.

Stemming from the past experience documented in [17] and specifically oriented to an IEEE 802.11g wireless network, major effects of interference in the wireless channel on unicast and multicast video streaming, based on MPEG-2 video codec, are experimentally assessed in the paper. In fact, MPEG-2 is still the most used video/audio codec for sharing video on internet, even though new video codecs, such as H.264AVC and MPEG-4, have been developed to better compress the information, but they are principally exploited for data storing.

To assess the performance of the network, a cross-layer approach is applied through a purposely developed testbed. The goal is twofold: from one side, experimentally assessing and correlating the values that some performance metrics assume at the same time at different layers of an IEEE 802.11g WLAN supporting video streaming applications in the presence of in-channel interference, from the other side, deducing helpful and practical hints for designers and technicians, in order to efficiently assess and enhance the performance of an IEEE 802.11g WLAN supporting video streaming, in some suitable setup conditions and in the presence of interference. With respect to the available literature, the proposed work can be considered original in that the use of IEEE 802.11g for supporting video streaming applications is analyzed, (i) from an experimental point of view, (ii) in both unicast and multicast scenarios, (iii) in the presence of interference, and (iv) through a cross-layer approach.

The paper is organized as follows. Section 2 provides preliminary notes on the IEEE 802.11 standard, streaming video, and cross-layer measurements. In Section 3, the adopted testbed as well as measurement procedures are described in detail. In Sections 4 and 5, experimental results are given, and helpful considerations are drawn.

2. Preliminary Notes

2.1. IEEE 802.11 Family Standards. The family of IEEE 802.11 standards concerns wireless connectivity for fixed, portable, and moving stations within a local area. It applies at the lowest two layers of the Open System Interconnection (OSI) protocol stack, namely, the physical layer and the data link layer [1].

The physical layer (PHY) essentially provides three functions. First, it interfaces the upper media access control (MAC) sublayer for transmission and reception of data. Second, it provides signal modulation through direct sequence spread spectrum (DSSS) techniques or orthogonal frequency division multiplexing (OFDM) schemes. Third, it sends a carrier sense indication back to the upper MAC sublayer, to verify activity in the wireless bandwidth.

The data link layer includes the MAC sublayer, which allows the reliable transmission of data from the upper layers over the PHY media. To this aim, it provides for a controlled access to the shared wireless media, called *carrier-sense multiple access with collision avoidance* (CSMA/CA). It also protects the data being delivered through proper security policies.

The 802.11 family currently includes multiple extensions to the original standard, based on the same basic protocol and essentially different in terms of modulation techniques. The most popular extensions are those defined by the IEEE 802.11a/b/g amendments (also referred to as standards), on which most of the today's manufactured devices are based.

Nowadays, IEEE 802.11g is becoming the WLAN standard more widely accepted worldwide. It involves the license-free 2.4 GHz ISM band (2.4–2.4845 GHz), like the IEEE

802.11b standard, and supports a maximum data rate of 54 Mbps, like the IEEE 802.11a. IEEE 802.11g devices are backwards compatible with IEEE 802.11b ones. They use the OFDM modulation scheme for the data rates of 6, 9, 12, 18, 24, 36, 48, and 54 Mbps and revert to complementary code keying (CCK, as in the case of the IEEE 802.11b standard) for 5.5 and 11 Mbps and differential binary phase shift keying (DBPSK)/differential quadrature phase shift keying (DQPSK) + DSSS for 1 and 2 Mbps.

In the 2.4 GHz ISM band, the IEEE 802.11g standard defines a total of 14 frequency channels, each of which is characterized by 22 MHz bandwidth. In USA, channels 1 through 11 are allowed, in Europe channels 1 through 13 can be used, and in Japan only channel 14 is accessible. Due to the available bandwidth, channels are partially overlapped, and the number of nonoverlapping usable channels is only 3 in USA and Europe (e.g., channels 1, 6, and 11).

Rate adaptation mechanisms are not defined into the standards family, but they are commonly implemented into manifold Wi-Fi devices. They allow to adapt transmission bit-rate (R_t) and relatived modulation scheme according to physical channel conditions in order to provide more reliable communications. To this aim, three main mechanisms are today exploited (i) *Auto Rate Fallback (ARF)* [18], (ii) *Sample Rate (SR)* [19], and (iii) *SNR-based rate* (SBR) [20]. Due to the satisfactory performance [21] exhibited by ARF mechanism, it is commonly used in all devices present on the market. It attempts to transmit the packet with the highest possible bit-rate. If the packets are lost, the transmitter will reattempt its transmission with a lower bit-rate, until the Binary Back-off algorithm (BBA) decides to drop the packet. Otherwise, if for ten consecutive times the transmitter succeeds to send a packets with a bit-rate, the consecutive packet will be sent with higher bit-rate, and so on.

2.2. Video Streaming. Video streaming can be delivered via a wireless link in unicast or multicast mode. In unicast mode, a single client receives its own dedicated stream through an access point within the wireless network. With regard to WLANs, the task is carried out with the support of the MAC sublayer, which adjusts the radio transmission in such a way as to optimize the link, and through retransmission most lost or corrupted packets can ultimately be received. This mechanism makes WLANs a reliable and robust solution for video streaming, even though it is not scalable to multiple users.

In multicast or broadcast mode, a large number of clients (potentially hundreds) may simultaneously receive the stream from a single access point. Examples of this scenario include applications like online gaming, distributed television, and so forth. Different from the unicast case, the quality of a transmission is not regulated by the MAC sublayer, and the multicast packets are delivered in open-loop without any possible acknowledgment. The open-loop transmission mechanism causes two main problems. First, without any feedback mechanism, the PHY layer setup of the transmitter cannot dynamically be adapted to the radio link characteristics, thus making the packets be broadcasted over the air at the same rate (one of the rates included in the basic set). Second, lost packets are not retransmitted at the MAC sublayer, so, more data losses than those observable in unicast case can be experienced, to the detriment of performance and reliability.

In the literature, alternatives aimed at improving real-time multicast video streaming are presented [4–6]. They are mainly based on link adaptation and cross-layer signaling techniques. Leader-based mechanisms are also proposed in [11].

Basically, link adaptation consists of tuning a number of radio/MAC parameters in such a way as to outperform the quality of packet transmission. The most important parameter commonly adjusted is the transmission rate, which can be varied changing the modulation scheme or code rate (automatic rate control). Cross-layer signaling operates at the application layer directly on the video encoder, which is adjusted by changing the video compression degree. In both the cases, the feedback of the link quality is derived at the transmitter side (without feedback from the client stations), from signal-to-noise ratio measurements and throughput statistics. Leader-based mechanisms use one of the receivers to send acknowledgment frames back to the sender. As with regular unicast transmissions, a PHY transmission rate selection mechanism is then applied and lost packets are thus retransmitted [5].

2.3. Cross-Layer Measurement Approach. A cross-layer measurement approach allows an efficient assessment of communication networks performance. It provides for several measurements to be concurrently carried out on parameters belonging to different levels of the International Organization for Standardization/Open Systems Interconnection (ISO/OSI) stack. Its main goal is to give the opportunity of experimentally correlating the values that characterize major physical layer quantities to those assumed by key higher layer parameters (e.g., network/transport layer, application layer) at the same time [10, 17].

3. Measurement Setup

Experiments are conducted involving a proper testbed, operating in two different common scenarios. The testbed includes a WLAN compliant with the IEEE 802.11g standard and supporting video streaming applications, and some interference sources in the proximity of it aimed at emulating some typical interference phenomena of a real-world environment.

Measurements are carried out according to a cross-layer approach. In particular, the following parameters are considered: channel power and signal-to-interference power ratio (SIR) at PHY layer, packet loss ratio (PLR) at transport layer, jitter at network layer, and objective video quality at application layer.

Tests are conducted inside a protected and controlled environment, that is, a shielded semianechoic chamber compliant with electromagnetic compatibility requirements

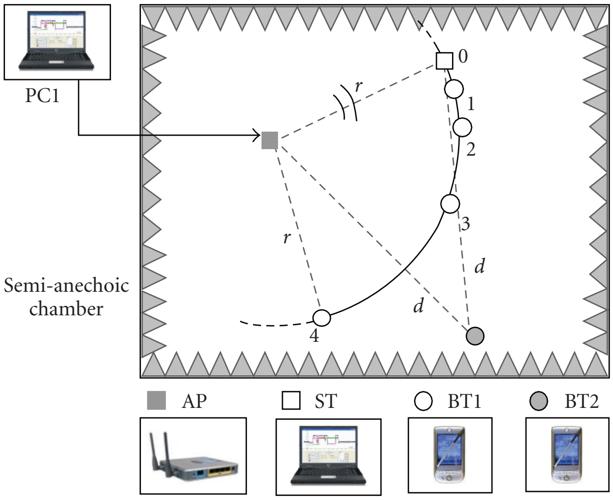


Figure 1: First measurement scenario: adopted testbed.

for radiated emission tests [22]. The wave absorption characteristics of the chamber make the influence on measurements of perturbing phenomena in the propagation channel like fading, shadowing, and multipath negligible. To the same aim, reduced distances (in the order of few meters) are considered among the various radiating elements of the testbed. The analysis can thus be focused only on the effects caused by the superposition of the in-channel interference over the useful signal, at the same time and at the WLAN receiver input connector.

3.1. First Measurement Scenario. The considered WLAN operates in the close proximity of an interfering Bluetooth network; its performance is experimentally assessed.

3.1.1. Testbed. The adopted testbed, sketched in Figure 1, consists of the following components:

1. a WRT54GR access point, AP, by *Linksys*, compliant with the IEEE 802.11g standard and using ARF mechanism,
2. a notebook, ST, by ACER, equipped with 1.4 GHz Intel Centrino processor, 512 MB RAM, and a DWL-G650 adapter, by *D-link*, compliant with the IEEE 802.11g standard,
3. two mobile phones: a *Nokia* 6600, BT1, and a *Nokia* 6630T, BT2, each of which equipped with a 1.1/class 2 Bluetooth transmitter,
4. a personal computer, PC1, equipped with 1.4 GHz Intel Pentium IV processor and 1 GB RAM.

All the enlisted devices operate inside the semianechoic chamber, with the exception of PC1, which communicates with AP at a rate of 100 Mbps and through a 5 m length UTP category 3 cable. Specifically, it delivers to AP the video streaming under test, to be forwarded to ST according to the IEEE 802.11g wireless format. AP and ST exploit channel 11 (2.462 GHz), according to a distributed coordination function (DCF) MAC layer access method along with CSMA/CA protocol, operate at fixed positions, represented by grey and white squares in Figure 1, and are characterized by a reciprocal distance r equal to 2.25 m. Moreover, the AP implements the ARF mechanism for adapting the bit-rate.

Bluetooth terminals, BT1 and BT2, are represented as white and grey circles in Figure 1. BT2 is placed at a fixed distance $d = 4.15$ m from both AP and ST. The position of BT1 is instead varied along an imaginary circumference of radius r, with AP in the center. Five different positions along the circumference, numbered from 0 to 4, are assumed by BT1; 0 matches the position of ST, while 1, 2, 3, and 4 refer to a distance, respectively, of 0.5, 1, 2, and 4 m from ST. In this way, a variety of interference and SIR levels are sensed by ST, without varying the interference conditions affecting AP. Upon the moving of BT1 along the circumference, the distance between BT1 and ST changes, while the distance between BT1 and AP remains the same.

The positions of WLAN and Bluetooth terminals are suitably chosen, (i) according to the dimensions of the available semianechoic chamber, (ii) in order to emulate as well as possible a typical scenario in an actual office/home environment, in which a WLAN terminal is located at a few meters from the nearest access point, and Bluetooth devices can operate very close to or at few meters from a WLAN station.

3.1.2. Measurement Procedure. Experiments are conducted emulating a real-world unidirectional video streaming from AP to ST, with regard to the IEEE 802.11g standard. The features of the video used in the tests are chosen according to a typical configuration exploited for sharing and spreading video contents over the Internet. In particular, the video is MPEG-2 compliant characterized by, (i) "main" profile, (ii) "low" level, (iii) CIF (Common Intermediate Format, 352×288) picture format, (iv) mean data rate of nearly 300 kbit/s (R_V), and (v) MPEG-TS (Transport Stream) as communication protocol over RTP/UDP. Furthermore, the RTP/UDP packet size is fixed to 1316 bytes by the VideoLAN software emulator according to the specification given in [23].

A bidirectional file-transfer activity occurring between BT1 and BT2 is then activated in order to emulate the presence of Bluetooth interference.

The transmission is analyzed both in unicast and multicast mode at the highest data rate available, that is, 54 Mbps for the IEEE 802.11g standard. In both the cases, and for any considered point $\{0, \dots, 4\}$, the following parameters are measured close to ST: PLR, jitter, video quality, and SIR. PLR and jitter are estimated through the software *Wireshark* [24], and video quality is assessed through the tool Video Quality Metric (VQM) [20], running on ST. In particular, video streaming characteristics are purposely adjusted through the distributed internet traffic generator (DITG) running on PC1 [25]. SIR estimates are achieved in two steps, through a preliminary measurement campaign carried out with the support of a microwave horn antenna Schwarzbeck BBHA9120D (1–18 GHz frequency range) connected to a real-time spectrum analyzer, *Tektronix* RSA 3408 (0–8 GHz frequency range). In the first step, the useful signal power inside channel 11 is measured with the only WLAN on, the horn antenna located in 0 position (the same as ST) and oriented toward AP. In the second step, the interference power level, again inside channel 11, is measured with the only Bluetooth network on, the horn antenna located in 0 and oriented toward BT1. The measured values of useful, P_U and interference power levels, P_I, at the various positions considered, are finally used to determine the SIR (i.e., SIR = P_U/P_I).

3.2. Second Measurement Scenario. The considered WLAN operates in the absence/presence of background data traffic and with a superimposed additive white Gaussian noise (AWGN); its performance is experimentally assessed. The background data traffic is considered in order to emulate those typical interference situations occurring at network/transport layer, in which a WLAN video streaming traffic has to coexist with ordinary WLAN data traffic, needed for traditional applications like web or email. In this condition, the aim is to investigate the amount of data packets lost due to AP buffer in managing different packet flows at its highest nominal bit-rate (i.e., 54 Mbit/s). In fact, any packet will be transmitted to 54 Mbit/s and will not be subject to collision phenomena due to other interference sources. Hence, the only cause, for which a packet can be lost, is the AP buffer overflow.

The AWGN is instead generated in order to emulate those typical interference effects occurring at PHY layer when the interference belongs to the class of modulated signals having wide bandwidth and noise-like spectrum, like for example code division multiple access (CDMA) and OFDM modulated signals. The addition of AWGN signal to background traffic gives rise also to packets collision phenomena causing a packets retransmission through one of the aforementioned rate adaptive mechanisms. Retransmission phenomena further increases the packet loss for two main reasons: (i) buffer overflow and (ii) maximum number of retransmissions for each corrupted packet because of multiple collisions. In fact, the BBA, exploited by CSMA/CA mechanism for managing the retransmission, drops a packet if after seven times it does not succeed to transmit [1].

3.2.1. Testbed. The adopted testbed, sketched in Figure 2, consists of the following components:

(1) a WRT54GR access point, AP, by *Linksys*, compliant with the IEEE 802.11g standard and using ARF mechanism,

(2) a notebook, ST, by ACER, equipped with 1.4 GHz Intel Centrino processor, 512 MB RAM, and a DWL-G650 adapter, by *D-link*, compliant with the IEEE 802.11g standard,

(3) a microwave horn antenna *Schwarzbeck* BBHA9120D (1–18 GHz frequency range),

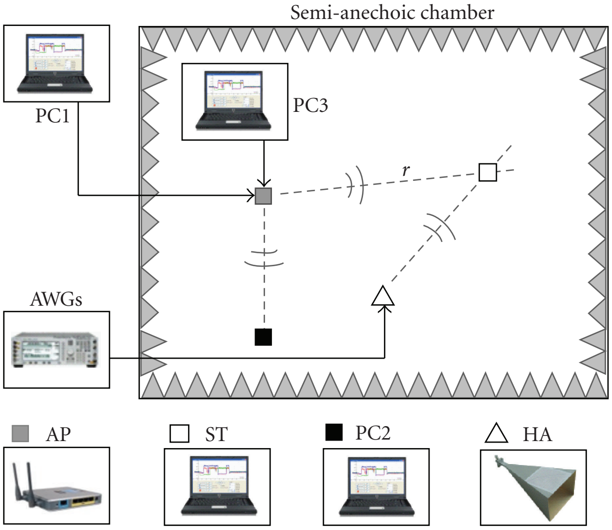


Figure 2: Second measurement scenario: adopted testbed.

(4) an arbitrary waveform generator (AWG), *Agilent Technologies* E4431B ESG-D (250 kHz–6 GHz frequency range),

(5) an arbitrary waveform generator (AWG), *Agilent Technologies* E4438C ESG (250 kHz–6 GHz frequency range),

(6) a personal computer, PC1, equipped with a 1.4 GHz Intel Pentium IV processor and 1 GB RAM,

(7) a notebook, PC2, by Hewlett Packard, equipped with Intel Pentium III processor, 192 MB RAM, and a DWL-G650 adapter, by *D-link*, compliant with the IEEE 802.11g standard,

(8) a notebook, PC3, IBM ThinkPad, equipped with Intel Pentium IV processor.

PC1 operates outside the semianechoic chamber and communicates with AP at a 100 Mbps rate and through a 5 m length UTP category 3 cable. Specifically, it delivers to AP the video streaming under test, to be forwarded to ST according to the IEEE 802.11g wireless format. AP and ST exploit channel 11 (2.462 GHz), according to a DCF MAC layer access method along with CSMA/CA protocol, operate at fixed positions, represented by grey and white squares in Figure 2, and are characterized by a reciprocal distance r equal to 2.25 m. Moreover, AP adapts the rate through ARF mechanism.

As above mentioned, two further notebooks, PC2 (black square) and PC3, are utilized in such a way as to emulate the presence of data traffic in the network. In particular, PC3 generates data traffic to be sent to AP through a 2 m length UTP category 3 cable and to be radiated by AP toward the receiver PC2.

Two arbitrary signal generators provide the controlled interference according to the procedure stated in [10]. Specifically, the AWG E4431B ESG-D generates a band-base AWGN signal, which is translated to the 2.4 GHz ISM band by the AWG E4438C ESG that acts as frequency upconverter;

both generators operate outside the semianechoic chamber. The output signal is a continuous 20 MHz bandwidth AWGN interference, centered at the same frequency of the considered channel (2.462 GHz) and radiated by the horn antenna, in the figure denoted as HA and represented as a white triangle. The antenna is oriented toward ST and placed at a distance of 1.5 m from it. Also in this case, the position of WLAN terminals is chosen (i) according to the physical dimensions of the available semianechoic chamber, (ii) in order to emulate as well as possible a typical WLAN scenario in a real-office/home environment. The position of the antenna HA is chosen (i) according to the physical dimensions of the chamber, (ii) in order to provide the desired levels of SIR at the ST input connector.

3.2.2. Measurement Procedure. In this second scenario, a video MPEG2 compliant is transferred from AP to ST. The video has the same features described in the first measurement scenario, that is, (i) "main" profile, (ii) "low" level, (iii) CIF (Common Intermediate Format, 352 × 288) picture format, (iv) mean data rate of nearly 300 kbit/s (R_V), and (v) MPEG-TS (Transport Stream) as communication protocol over RTP/UDP. Furthermore, the RTP/UDP packet size is fixed to 1316 bytes by the VideoLAN software emulator according to the specification given in [23].

Interference power is suitably varied in order to test the WLAN at different levels of SIR (measured close to ST). Different levels of WLAN load are also emulated through D-ITG running on PC3. Specifically, a synthetic user-datagram-protocol (UDP) traffic is generated and sent to PC2 via AP, at a data rate, R_A from 18 up to 46 Mbps, which includes the maximum throughput (31 Mbps) that an IEEE 802.11g network can efficiently manage at MAC layer [26].

As in the first scenario, PLR and jitter are estimated through the software *Wireshark*, and video quality is assessed through the software tool VQM, running on ST. Video streaming characteristics are purposely adjusted through the software D-ITG, running on PC1.

3.3. Measurement Tools. The whole set of software tools used in the experiments are open source, free available in the public domain. Specifically, VideoLAN that is a free cross-platform media player released under the GNU General Public License [27]. It supports a large number of audio and video formats, without the need for additional codecs. It can also be used as a multicast and unicast streaming generator of files, and requires the choice of the receiver buffer length. VideoLAN is, in particular, used both by PC1, to generate a MPEG-2 video stream, and PC2, to decode the received data flow. The chosen length of the receiver buffer matches a time interval equal to 300 ms.

Wireshark is a complete tool for multilevel packet analysis [24]. It allows in-depth investigation about network problems and performance and accurate testing of new protocols. It provides meaningful information of the incoming packets characteristics and contents. *Wireshark* is, in particular, used both to assess the correct operation of the WLAN and to measure the PLR and jitter experienced by ST.

D-ITG is a distributed Internet traffic generator [25], whose architecture allows the generation of traffic and the regulation of key parameters such as packet interdeparture time and length. It also allows measuring several QoS parameters at both sender and receiver sides and obtaining a complete report of measured parameters over the whole measurement time. D-ITG is, in particular, used to generate WLAN traffic in the second scenario.

VQM is a Video Quality Metric (VQM) algorithm, based on the models referred to by ITU Recommendation BT.1683 [28, 29]. It provides video quality estimates rather close to those achievable from subjective analysis. It requires two input video streams: the original one, taken as reference, and the effectively displayed one, corrupted, to be analyzed. As final results, VQM provides an overall quality score, mapped on a scale from 0 up to 1, where 0 means that no impairment is perceivable and 1 means that a maximum level of impairment is visible.

4. First Scenario Results

The first experiments have aimed at measuring the level of SIR at the five positions $\{0, \ldots, 4\}$ assumed by BT1 in Figure 1. The following results have been obtained SIR ≅ 4, 10, 16, 20, and 25 dB, for BT1 in the positions 0, 1, 2, 3, and 4, respectively.

The case of WLAN in multicast mode has initially been investigated. A preliminary analysis has been conducted in order to verify the correct operation of the WLAN in the delivery of packets. Specifically, the length of delivered packets has been monitored through a digital signal oscilloscope (DSO) connected to a receiving antenna positioned in the chamber.

Afterwards, measurements have iteratively been repeated ten times for any considered SIR. The obtained mean values, μ, of PLR and VQM score and the related experimental standard deviations, σ, are summarized in Figure 3.

In Figure 3, as well as in the rest of the section, the dashed lines represent the obtained mean values, while the horizontal solid lines indicate, for any SIR, the interval $(\mu - \sigma, \mu + \sigma)$.

Obtained results conduct to the following considerations.

(i) strict relation between SIR values and all metrics can be extracted. In particular, PLR,VQM, and jitter vary according to a monotone threshold trend.

(ii) PLR grows suddenly for decreasing values of SIR in the range 4−10 dB, because of many corrupted packets for which it is not possible to receive a feedback by MAClayer because the ACK strategy is deactivated,

(iii) PLR is negligible (≅0%) for SIR in the range 16−20 dB; negligible values are also expected for SIR > 20 dB, for which all packets are correctly received,

(iv) VQM rapidly degrades for decreasing values of SIR in the range 4−10 dB; a decreasing trend is also expected for SIR < 4 dB,

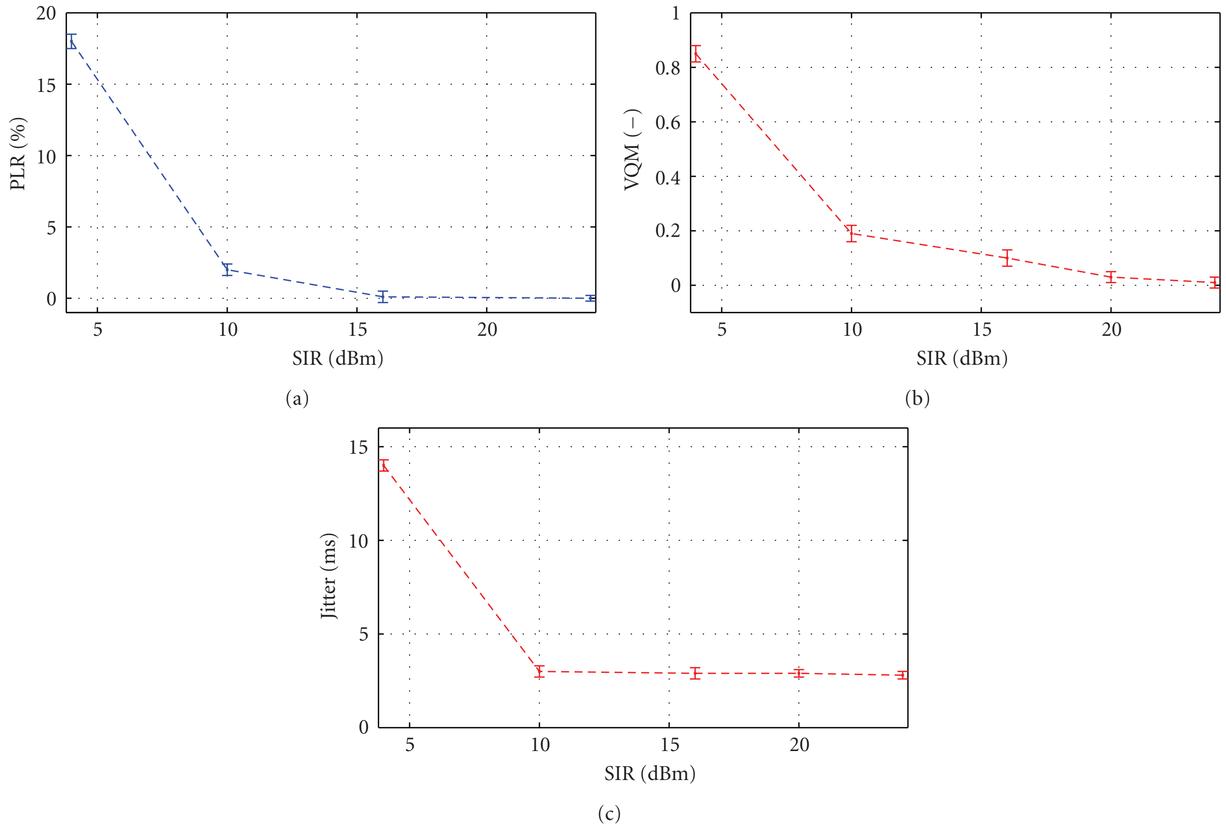


FIGURE 3: Bluetooth interference and multicast video streaming: PLR (a), VQM (b), and jitter (c) versus SIR.

(v) VQM is lower than 0.1 (i.e., good video quality) for SIR in the range 12−24 dB; VQM scores close to 0 (i.e., full video quality) are expected for SIR > 24 dB,

(vi) For 4 < SIR < 7 dB, the obtained values of PLR and VQM are, respectively, included in the intervals 10%–20% and 0.45−0.85,

(vii) VQM = 0.1 for SIR and PLR equal to 13.5 dB and 1%, respectively, while VQM = 0.2 for SIR and PLR equal to 9.5 dB and 3%, respectively,

(viii) Jitter rapidly decreases upon the increasing of SIR from 4 dB up to 10 dB, reaching the highest value of nearly 14 ms,

(ix) Jitter is negligible for SIR values nearly greater than 10 dB, in correspondence of which it never exceeds 3 ms,

(x) Jitter is completely compensated by the VideoLAN buffer configured at the receiver side.

An example of quality degradation in the case of SIR = 4 dB (BT1 position 0) is given in Figure 4. The figure shows the original frame (a), compared to the corrupted one (b).

A second measurement campaign has been conducted with the WLAN operating in unicast mode, with IEEE 802.11g format and 54 Mbit/s as bit-rate. With respect to the multicast case, a null effect of interference has been measured, that is, PLR = 0% and VQM = 0 for any considered SIR value. The reason of this fact is that in unicast mode the retransmission mechanism along with adaptive bit-rate mechanism succeeds to manage corrupted packets obtaining a considerable reduction of PLR.

The following considerations and hints can be drawn.

(a) A Bluetooth terminal operating in the proximity of a WLAN receiver can significantly damage the video quality perceived by final users when a multicast transmission is received; no effect is experienced in unicast connection, obtaining always high video quality.

(b) A minimum SIR of 12 dB is needed to obtain good video quality scores when a multicat connection is used. Full video quality levels, instead, require SIR values greater than 24 dB. In other words, if multicast video is being received through the wireless channel, during a videoconference, then bluetooth sources, such as cellular phones and mouse, should be turned off or moved for a few meters from the receiving laptop in order to correctly see the incoming video. In fact, beyond these thresholds (i.e., moving the bluetooth sources for a few meters), the values of VQM do not significantly decrease anymore. On contrary, no corruption effects are noted on the video if it is streamed from a video server through a peer-to-peer link (unicast connection) also in presence of bluetooth interferences next to the receiving


(a) (b)

Figure 4: First scenario, multicast video streaming, SIR = 4 dB: (a) original frame, (b) corrupted frame.

laptop. This different behaviour can be explained as follows. For SIR values greater than 10 dB, the intensity of the Bluetooth signal is so low with respect to the useful one (received WLAN signal) as to not significantly affect the demodulation process of the latter, that is, the received constellation diagram is still sufficiently "clean" and the information can be extracted. Instead, when the SIR reaches values below 10 dB, the Bluetooth interference gives rise to impairment phenomena on constellation diagram that impair the correct demodulation process of the useful one, that is, the received constellation diagram is so "dirty" that most of packet bits are incorrectly demodulated causing the packets loss and consequently the video quality decrease. To overcome the problem, in the unicast mode a suitable strategy, relying on ARF mechanism, is applied. In fact, the transmitter mitigates the bluetooth interference effects reducing the data rate at every packet lost and selecting a more robust modulation scheme that allows the correct demodulation of all packets at receiver side and providing null PLR. More specifically, every retransmission causes R_t reduction, reaching the lowest possible value equal to 6 Mbit/s for IEEE 802.11g standard, when many retransmissions occur (worst case). Hence, in the worst case most packets will always be transmitted to 6 Mbit/s, which is however sufficient to manage the R_{BV} associated with the video. Further retransmissions are compensated by the AP buffer. This strategy cannot be utilized in multicast mode because the ACK strategy is deactivated, and each packet lost strongly influences the final video quality.

(c) An apparent acceptable PLR within the interval $10\%-20\%$ does not imply an acceptable video quality. In this range, in fact, the obtained VQM scores are rather high, that is, between 0.45 and 0.85, which means a quite completely degraded video stream (see Figure 4). Instead, acceptable video quality levels (i.e., $0.1 < \mathrm{VQM} < 0.2$) can be obtained with SIR in the interval $9.5-13.5$ dB or, equivalently, with PLR in the range $1\%-3\%$.

(d) Good video quality levels (i.e., $0 < \mathrm{VQM} \leq 0.1$) can be obtained with SIR > 13.5 dB or, equivalently, PLR < 1%.

(e) Thanks to the results shown in Figure 3, a user can assess the final perceived quality without the need for measurements at application layer, which are not simple to be carried out. In fact, in actual operating scenarios the original video, used as reference in VQM score evaluation, is always unavailable, thus video quality assessment is a difficult task. On contrary, it suffices to determine SIR or PLR through traditional measurements at PHY layer or analytical models at network/transport layer, and verify that the obtained SIR or PLR values satisfy the above deduced cross-layer conditions to obtain acceptable ($0.1 < \mathrm{VQM} < 0.3$) or good video quality ($\mathrm{VQM} < 0.1$).

(f) Moreover, such relationships can be considered general for any other layouts of the testbed terminals in the same assumed conditions (i.e., in the absence of perturbing phenomena in the propagation channel like shadowing, echoes, multipath, and fading). Under this assumption, the only parameter that changes upon the varying of the testbed terminals position is just the SIR.

5. Second Scenario Results

Experiments have been conducted in the presence of AWGN interference and with different levels of WLAN background data traffic, flowing from PC3 to PC2 via AP. AWGN noise has been emulated through vector signal generator (ESG), namely, Agilent Technologies *ESG E4438C* (250 kHz–6 GHz output frequency range), with arbitrary waveform generation capability (80 MHz modulation bandwidth, 16 bit vertical resolution, and 8 MSample memory depth) connected to a horn antenna via RF cable.

Preliminary measurements have been performed forcing the WLAN to operate in multicast mode and with AWGN interference and SIR within the interval 6–20 dB. The obtained results have highlighted unacceptable video quality levels (i.e., $\mathrm{VQM} > 0.2$) for any of the considered setups.

Further measurements have been carried out in unicast mode. The preliminary results have been achieved without additional data traffic from PC3 to PC2, and upon the varying of SIR within the interval 6–20 dB. The lower bound of the range represents the lowest experimented SIR value for which it is possible to establish and assur a stable wireless connection. Below this value, the wireless link always breaks down. In this scenario, null values of all metrics have been measured. That is, independently of SIR values, the video flow does not suffer the critical channel condition due to the presence of AWGN, succeeding in correct delivery of all packets. This phenomenon is justified through two main factories: (i) low R_v value (i.e., 300 kbit/s), and (ii) the use of the ARF mechanism. In fact, the critical conditions in channel, due to AWGN source, causes many collisions for low SIR values, entailing the reduction of R_t at most up to 6 Mbit/s. This R_t value is both lower than R_v and sufficient for allowing the correct forwarding of video packets. Moreover, the employment of a different modulation scheme, binding to lower R_t, allows demodulation packets that have suffered collision.

From these results, a first consideration can be drawn. AWGN noise has threshold effect on video streaming. SIR values below 6 dB cause an abrupt reduction of wireless connection quality, while SIR values slightly greater than 6 dB grant a high quality video. This outcome can be very helpful in wireless planning stage. In particular, the level both of useful signal and noise has to be measured at all receiver points, and SIR values greater than 6 dB must be experienced in order to allow an acceptable video quality. If lower values are measured, a different place of the AP has to be chosen for improving useful signal strength or a reduction of the noise level has to be pursued.

A second set of measures is shown in Figure 5; it refers to different levels of the overall traffic load, T_O, from PC3 to PC2 via AP, in the absence of external interference.

T_O is the sum of R_v and the additional traffic load, R_A. The vertical solid lines indicate the maximum overall data rate $T_{O,\max}$ (32 Mbps) that an IEEE 802.11g WLAN can efficiently manage at MAC layer [30], that is, without saturating the AP output buffer. The diagrams highlight the following results.

(i) Both PLR and VQM are strictly related to T_O, and vary according to a monotone threshold relationship.

(ii) The effect of additional data traffic in terms of both PLR and VQM is quite null in the interval $20 \leq T_O \leq 26$ Mbps; negligible values of both PLR and VQM are expected for $T_O < 20$ Mbps.

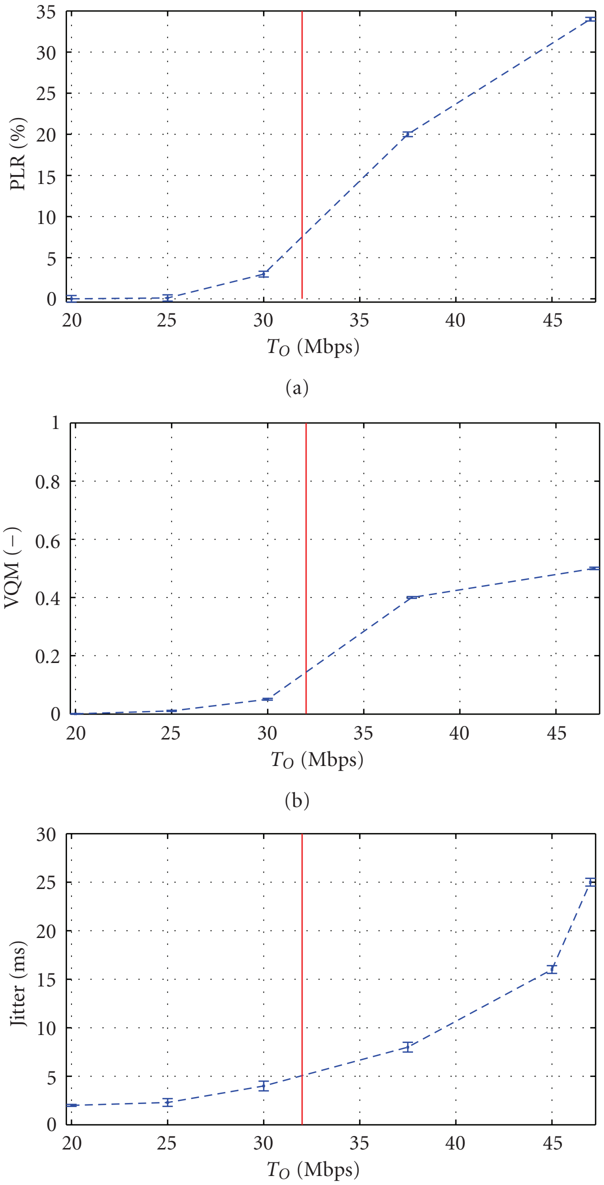
(iii) PLR and VQM slightly increase within the interval $26 < R_A < 30$ dB, but remain well below quite negligible values, that is, 3% and 0.3, respectively.

(iv) Beyond 30 Mbps, in the interval $30 \leq T_O \leq 45$ Mbps, the two parameters as well as T_O suddenly increase; worse values of both PLR and VQM are expected for $T_O > 45$ Mbps.

(v) VQM = 0.1 for T_O and PLR nearly equal to 31 Mbps and 4%, respectively, while VQM = 0.2 for T_O and PLR equal to 32.5 Mbps and 7.5%, respectively.

(vi) Jitter is quite constant for T_O within the interval 20–32 Mbps; its value never exceeds 4 ms.

(vii) Jitter grows up suddenly for T_O greater than 32 Mbps, reaching the highest value of nearly 24 ms in correspondence of a traffic load equal to 47 Mbps. For instance, upon the decreasing of T_O from 40 Mbps down to 25 Mbps, the jitter rapidly falls from 24 ms down to 4 ms and consequently both VQM and PLR assume negligible values.



(a)

(b)

(c)

FIGURE 5: Unicast video streaming, additional data traffic, and no interference: (a) PLR, (b) VQM, and (c) jitter versus the overall network load, T_O.

(viii) Jitter values lower than 4 ms allow VQM $\leq$ 0.1 and PLR $\leq$ 5%, that is, a good quality of the received video.

Thanks to the result shown in Figure 5(b), a relation between the data traffic and video quality is obtained. This relation can be exploited by the network for extracting information about video quality, due to the actual amount of data traffic presented in the network. A proper control strategy of data traffic flow can be implemented for assuring a defined quality to video steaming applications. Moreover, the relation between VQM and PLR allows at video receiver to implement a suitable feedback procedure towards the AP,

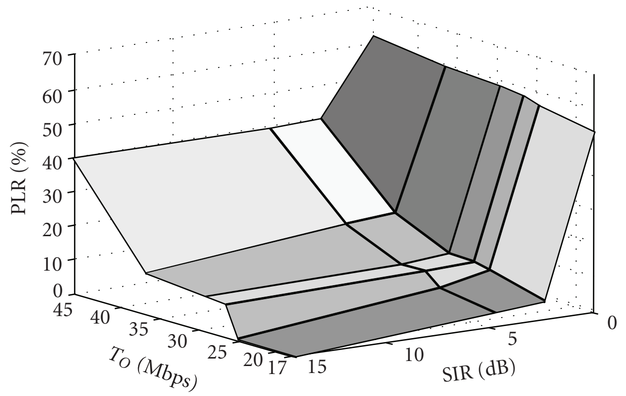


Figure 6: Unicast video streaming, additional data traffic, and AWGN interference: PLR versus SIR and T_O.

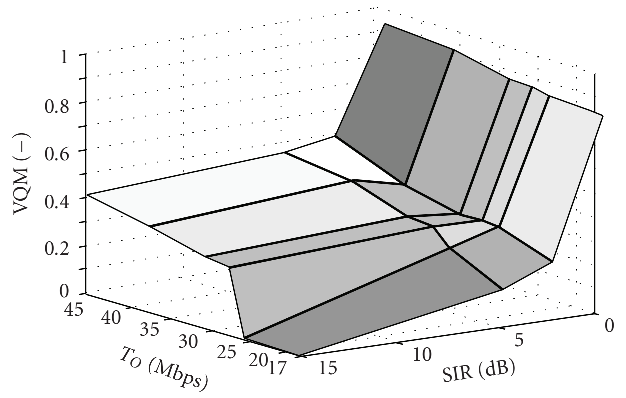


Figure 7: Unicast video streaming, additional data traffic, and AWGN interference: VQM versus SIR and T_O.

for reducing the data traffic into the network as long as the desired video quality is achieved.

A final set of experiments has been carried out emulating the presence of both additional traffic over the WLAN and AWGN interference. The obtained results are given in Figures 6 and 7, where the evolution of PLR and VQM is plotted upon the varying of SIR and T_O.

The following details can, in particular, be noted.

(i) In the range $6 \leq \text{SIR} \leq 11$ dB, PLR is always above 20%, for any considered T_O, in the interval 17–45 Mbps.

(ii) In the same interval of SIR and T_O, VQM is always above 0.4.

(iii) In the case of SIR $>$ 15 dB, PLR is expected to be null for any considered overall traffic level, T_O, in the range 17–25 Mbps.

(iv) In the same interval of SIR and T_O, VQM is expected to be null (full video quality).

(v) In the bidimensional interval $17 \leq T_O \leq 20$ Mbps and $11 \leq \text{SIR} \leq 15$ dB, PLR and VQM are always lower than 5% and 0.1, respectively. In this interval, the highest PLR and VQM values occur at the following setup: $T_O = 25$ Mbps and SIR = 11 dB.

From the above results obtained, the following hints can be drawn.

(a) AWGN interference can seriously degrade the quality of video streaming in the presence of additional data traffic in the network in the unicast mode. Therefore, its presence in a real-life environment should always be accounted for. In particular, it is advisable to measure both the useful signal and noise level before installing a wireless network, in order to establish if the measured SIR value matches the desiderated video quality. In fact, acceptable video quality is obtained for SIR values greater than 8 dB and network data traffic below 25 Mbps, while SIR values lower than 8 dB, independent of data traffic amount, have to be avoided. Analogous considerations can be drawn also using the PLR, when the SIR values are not available. In fact, the correlation shown in Figures 6 and 7 suggests that for assuring sufficient video quality, PLR values lower than 20% have to be experienced.

(b) In the case of SIR values greater than 8 dB, the attention has to be paid only to additional data traffic as interference. That is, the network must assure that a data traffic is always below 27 Mbps for providing acceptable VQM score (i.e., $0.1 < \text{VQM} < 0.3$). For this reason, a control strategy of data traffic flow could be implemented in the AP by exploiting the results given in Figure 7.

(c) So that a full video quality (VQM = 0) is achieved, care should be taken in order to keep SIR $\geq$ 15 dB and the traffic load, T_O, lower than 25 Mbps. In this case, PLR values equal to 0 are measured.

(d) The obtained results can be utilized for estimating the performance of video streaming applications in presence of AWGN noise and cross-traffic, that is, the typical actual conditions in which WLAN operate. In fact, once a WLAN is installed, the SIR level can be measured in all receiver points and for each of them both VQM and PLR versus data traffic can be extracted. This way, due to the amount of data traffic, the relative VQM and/or PLR value can be estimated in real-time. Moreover, combining the two aforementioned curves, VQM versus PLR can be obtained, thus providing a quick estimation of the final video quality due to the experienced PLR.

6. Conclusions

The paper has focused on WLANs delivering video streaming in the presence of interference. In particular, it has been demonstrated that WLAN final performance strongly depends on the (i) adopted streaming protocol (unicast or multicast), (ii) signal-to-interference ratio (Bluetooth signals and AWGN have been considered as interferes), and (iii) additional data traffic competing in the wireless channel. To this aim, a comprehensive experimental analysis has been conducted and some critical threshold values have been measured. Such values can play a key role in design and installation stages of a WLAN, in order to forecast its realistic performance in terms of network/transport and application layer parameters. Indications and suggestions on how to measure such parameters in a reproducible way have been given, along with a description of possible testbeds to be used. Final comments and practical hints have also been drawn for two investigated scenarios.

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