Maximum Throughput of IEEE 802.11 Access Points: Test Procedure and Measurements

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Abstract

Performance measurements of IEEE 802.11 access points are becoming increasingly important since it is the predominant choice for high-speed wireless LAN networks. Among the different possible access point's figures of merit, we focus our investigation on throughput performance. In particular, in this work we present measurements of the access point's maximum saturation throughput. The saturation throughput is achieved when the access point always has a frame ready to transmit, and it reaches the maximum for optimal transmission conditions and appropriate offered traffic. We show that the maximum saturation throughput is the key figure of merit to characterize the performance of the access points.

Several different standards are currently part of the 802.11 family, but we restrict our investigation to IEEE 802.11b devices. This standard is currently the most mature, with the largest number of devices, and with the most complete set of tools. Nevertheless, since the newer 802.11a and 802.11g are rapidly increasing their importance, we designed our measurement method in a way that it is possible to use it with others 802.11 technologies.

The first contribution of this work is a methodology to produce and measure the maximum saturation throughput of any 802.11b access point. The proposed procedure includes the testbed setup, the software tools and the mathematical support for processing the results. All these aspects were investigated in order to define a unique and repeatable test procedure. The main effort was invested maximising and stabilising the access point performance. It was necessary to limit the impact of external factors that interfered with the access point optimal status and produced large throughput instability. We use the average value of the maximum saturation throughput as the figure of merit for 802.11 APs, and the test procedure allowed computing such a value with a defined confidence level and accuracy. The instant value of the saturation throughput even in optimal conditions has a too large variance to be significant.

The second contribution of this work is the measurement results obtained following our proposed methodology from five different IEEE 802.11b access points. The purpose of the tests was to validate our methodology, and this result was successfully achieved. Moreover, the analysis of the test results suggests some conclusions about the performance of current access points. The downlink maximum saturation throughput is often limited by the access point performance, while the uplink maximum saturation throughput is rarely compromised. Therefore, the downlink saturation throughput is the key figure of merit of the access point, and the generic maximum saturation throughput of any access point is the 802.11 link capacity. On the other hand, increasing the offered load to the access point's Ethernet interface does not always increase the downlink throughput; some access points present a downlink throughput reduction when the offered load exceeds their bridging capabilities. Finally, despite all the access points claim to use omni-directional antennas, some of them exhibit better performance

in certain orientations with respect to the mobile stations.

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Chapter 1

Introduction

In the last years, Wireless Local Area Network (WLAN) technologies have reached a large popularity that is still growing. This kind of access network solution has been deployed for several different usages, from home personal applications to large public access systems, as well as point-to-point backbone radio links. The large popularity has generated an increasing demand for improving their features, mainly in terms of higher capacity and increased security. The technological and commercial development of wireless LANs have been helped by the results of different studies that offered different models for predicting their behaviour.

Despite that different standards have been proposed, the most widely used WLAN technologies are the different evolutions of the original IEEE 802.11 standard: 802.11b, 802.11a and 802.11g. The wide usage of IEEE 802.11 based WLANs has generated a large interest in modelling their behaviour. Examples of the various published studies are [13, 15].

WLAN models were often validated with simulations and rarely supported by real performance measurements. The few studies including real measurements were based on tests with a single solution: one access point model with one kind of wireless client interface. Moreover, the real system measurements are generally limited to a specific and restricted aspect of the proposed model. In order to get information about the performance of real devices in a real scenario, the only available source has been the performance analysis provided by the different device producers. These reports are made to advertise specific products and are often incomplete. In fact, the goal of such white papers is to demonstrate the efficiency of a specific implementation under some specific, and not always well-defined circumstances [9, 10].

In this thesis, we complete the previous work on IEEE 802.11 performance, by providing maximum saturation throughput measurements in a real scenario. Our tests were performed on different commercial devices in a controlled testbed. This work has two main goals: to propose a WLAN APs test procedure, and to show the results we found with the commercial devices we could test. The large number of different available WLAN solutions, the continuous and fast development of new implementations and the new standards make it impossible to present a complete and definitive performance evaluation. Instead, we propose our test methodology for performing tests on any AP implementation. Therefore, it is possible to create a well-defined platform for performance evaluation and cross comparisons. Note that our purpose has never been to grade different commercial products in order to find the best devices. The aim of our tests were more general, despite of the fact that we found many interesting results related to the characteristics of specific AP models which could be used to justify a purchase.

Our work has been completely focused on 802.11b devices. However, the proposed procedure involves simple tests on basic functionality that is common to APs of other wireless standards. For this reason, we are confident that our test procedure can be successfully adapted to APs of any kind of WLAN technologies. Anyhow, an exhaustive extension of the proposed test procedure to standards different from 802.11b is left to future work.

The performance of a single AP is a key factor in order to design and tune wireless LAN systems. The results from previous work based on mathematical models and simulations, are often not sufficient when planning for real systems. Theoretical models show the performance and limitations of algorithms and mechanisms defined by the standard. These kinds of results are essential to propose improvements to the standard itself, but of little application to network planning and deployment. On the other hand, real measurements include the effects of the specific implementation policies and of the environment. The results from tests on real devices are more useful for real system analysis and development.

In particular, our approach to the wireless LAN performance evaluation comes from the need of developing and improving an existing large WLAN access system. Since the beginning of year 2000, we have developed a large wireless access network based on IEEE 802.11 technology for the IT-University in Kista[1] (Stockholm, Sweden). The initial aim of this project was to offer wireless connectivity to a large group of students, and then we evolved it to a Campus wireless system [1]. Nowadays, we are growing our solution to a metropolitan area wireless system [2] due to the StockholmOpen Project[2]. In order to predict the behaviour of such a large system, we have often faced the problem of estimating the local wireless cell performance. The study of the available WLAN literature shows the need of making new and different tests. We found the need to identify a reference value of maximum throughput for the APs and to justify some anomalous behaviours. In order to fulfill our goal we had to create our proposed test procedure. This document presents the final result of this process.

The remainder of the report is structured as follows. Chapter 2 introduces the important aspects of the IEEE 802.11 standard and related work. After this, chapter 3 defines the target of our measurement, and chapter 4 presents the challenges to perform such measurements. Chapter 5 presents the statistical framework necessary for a correct performance analysis producing results with a defined precision. Chapter 6 describes our recommended test procedure providing more details about general 802.11 AP behaviours. Chapter 7 shows the performance of the different AP models we tested. Chapter 8 contains our conclusions and chapter 9 addresses some suggested future work to extend our test methodology.

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[1] IT-University in Kista: http://www.it.kth.se

[2] The StockholmOpen Project: http://www.stockholmopen.net

Chapter 2

Background and Related Work

In this section we present the necessary background and related work. The chapter is divided into two main sections: the first section presents the most important aspects of the IEEE 802.11 family standards, with a special focus on the Media Access Control system (MAC). The second section presents related work on IEEE 802.11 performance. In particular, we firstly examine some articles and academic works. Secondly, we present some white papers on 802.11 performance provided by different WLAN vendors.

2.1 IEEE 802.11 Overview

In this section, we present an overview of the IEEE 802.11 standard with particular emphasis on the Medium Access Control (MAC) part. The 802.11b and 802.11a differences with respect to the original standard will be presented as well, and the 802.11g will be pointed as a newer alternative. The main references on this section will be the original IEEE standard documents [4, 5, 6].

2.1.1 Highlights

The original IEEE 802.11 standard was published in June 1997[4], and it was the final result of a long process of integration and standardization of previous wireless LAN technologies. The IEEE 802.11 scope is to develop a Medium Access Control (MAC) and physical layer (PHY) specification for wireless connectivity for fixed, portable, and moving stations within a local area [4]. Several wireless communication aspects are covered in this standard. In particular IEEE 802.11

- Describes functions and services required by compliant devices. Note that two main operational modes are defined: Ad-Hoc (peer-to-peer) and Infrastructure (managed).
- Defines the MAC procedures to support asynchronous data unit delivery within the wireless system.
- Defines several physical signalling techniques and interface functions that are controlled by the IEEE 802.11 MAC.
- Permits the operation of several multiple overlapping IEEE 802.11 wireless LANs.

- Describes the requirements and procedures to provide authentication of 802.11 stations and user data transmission privacy.

The IEEE 802.11 standard has a wide scope and includes alternative MAC modes and protocols to support a large range of applications. We focus our attention on the infrastructure mode that was especially designed for implementing wireless access networks. In this kind of applications the access points found their utility.

IEEE 802.11 defines two alternative MAC protocols: the Distributed Coordination Function (DCF), and the Point Coordination Function (PCF). The first protocol is the largely used and defines a distributed medium access arbitration mechanism. The second protocol has been used only for particular applications; for example point to multi-points wireless links. This protocol defines a centralized medium access arbitration mechanism. In the next section we present with more details the DCF. No more information is given regarding the PCF, because it is not usually implemented in the devices we study in this document.

The original IEEE 802.11 standard defines a physical layer including two possible data transmission rates: 1 Mbps and 2Mbps. A maximum transmission speed of 2 Mbps was found too low compared to the users requirements. Therefore, different groups developed alternative physical layers to increase the data transmission rates. The work of the different groups produced at different times alternative extensions to the original 802.11 standard. We examine with more details the three existing IEEE 802.11 extension regarding the physical layer in section 2.1.3. Other groups defined different IEEE 802.11 extensions to propose new functionalities and/or services. We will not examine these different extensions because they are outside the scope of our work.

2.1.2 Distributed Coordination Function

The largely used IEEE 802.11 medium access control protocol is the distributed coordination function. This protocol defines a distributed medium access arbitration that can be used in both the two fundamental IEEE 802.11 operational modes: ad-hoc (peer-to-peer) and infrastructure (managed). It is important to remind that the different IEEE 802.11 physical layer extensions did not modify the access protocol.

The DCF implements the *carrier sense multiple access with collision avoidance* (CSMA/CA) method. Any wireless stations must implement this protocol in order to successfully transmit data on the radio link. The aim of this protocol is to avoid that a station transmits a frame when another one is already using the medium, and minimize the probability that two stations start to transmit a frame at the same time. The IEEE 802.11 defines a basic access system and an extra method (RTS/CTS) to minimize the collision probability and/or consequences. We first examine the basic access, and then we explain how RTS/CTS works.

According to the CSMA/CA any station with a frame ready to be transmitted senses the radio channel to determine if another station is already transmitting. If the channel is idle for a defined time (Distributed Interframe Space, DIFS), the station starts to transmit the frame. If any transmission is detected during this initial gap, the station must defer to the end of the current transmission. Note that the IEEE 802.11 defines a minimum gap between two consecutive frame transmissions. After deferral or before transmitting a new frame directly following a successful transmission, the station must select a random backoff interval and decrease the backoff interval counter while the medium is idle. The station that first uses up the backoff time can start to transmit

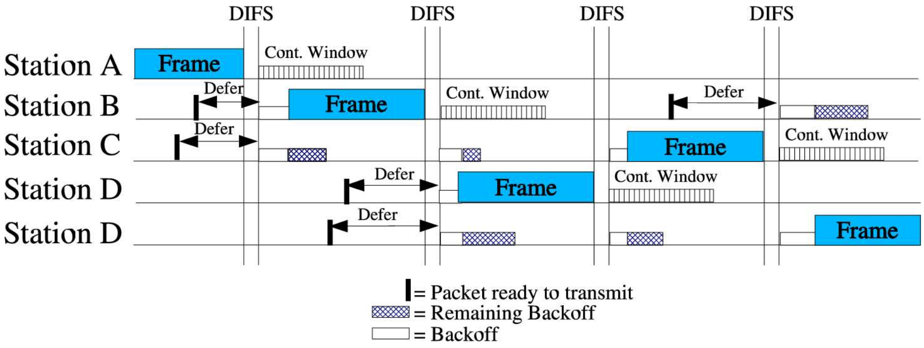

Figure 2.1: Backoff procedure according to IEEE 802.11.

the frame. The other stations sense that the channel was busy and defer at the end of the current transmission. Note that when the channel is idle again, after a new DIFS interval, the stations that still need to transmit start decrementing the backoff counter from the value at which it was previously stopped. Figure 2.1 illustrates this mechanism.

It is important to understand how the backoff time is determined. The IEEE 802.11 standard defines a contention window where the station backoff time must be. Each station has is own contention window with a dimension that can change in a defined range according to the working conditions. The minimum contention window is defined by IEEE 802.11 and its initially used by any station that wants to transmit a packet. If a collision happens, the stations that produced it must increase their contention windows. After each consecutive collision the contention windows is exponentially extended up to a maximum value also defined in IEEE 802.11. When a station successfully transmits a frame, it resets its contention window to the minimum value.

The IEEE 802.11 defines a time slot to use as a unit for the contention widows. The minimum and maximum dimension of the contention windows is defined through the minimum and maximum number of time slots to use for it. After a collision, the station doubles the number of slots of its contention widows up to the maximum possible value. The station's backoff time is chosen by randomly taking a number of slots in the current range of the contention window.

The IEEE 802.11 requires that any unicast frame must be acknowledged. This mechanism enforces transmission reliability in the radio link allowing the station knowing if the frame transmission succeeds and taking proper countermeasures when failing (i.e. to increase the contention window and retransmission of the frame). A special acknowledgment-frame must follow any unicast frame. This frame is sent from the frame destination to the sender in a prioritized way, thus it directly follows the original frame transmission. In order to implement this mechanism the acknowledged frame is sent directly after the original frame without any backoff time and with a shorter interval (Short Interframe Space, SIFS) than the DIFS to anticipate any other stations that want to transmit. The basic access mechanism is illustrated in Figure 2.2 .

The basic access performs well as long as all the stations can listen to all the others and therefore can accurately determine when the channel is busy. If one or more stations are out of the range of some of the others ones, the system might fail. For example, using infrastructure mode, two wireless clients are at two opposite edges of the

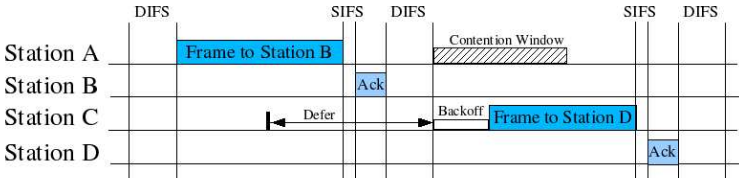

Figure 2.2: Basic Access Mechanism according to IEEE 802.11.

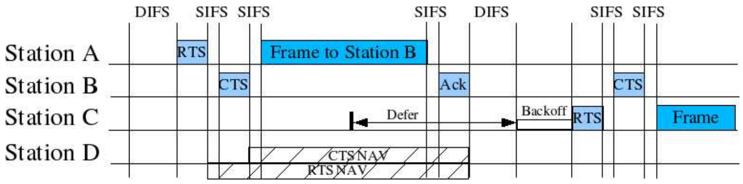

Figure 2.3: RTS/CTS access according to IEEE 802.11.

AP coverage area. In this case the two clients cannot hear each other, therefore their transmissions might collide at the AP. To prevent such a problem, the IEEE 802.11 allows adding some extra signalling to the basic access method. A station with a data frame to transmit first sends a Request-To-Transmit (RTS) frame using the basic access to request channel. The RTS includes the time that the client needs the medium for transmitting the data. The AP reply to a RTS with a Clear-To-Transmit (CTS) message that includes the time the channel is reserved to the granted transmission (Network Allocation Vector, NAV). The client that sent the original request starts to transmit the data frame after receiving the CTS and waiting a short gap (SIFS). All the other nodes in the AP's range get the CTS frame; therefore they defer any transmission until the end of reserved time (NAV). Figure 2.3 shows the RTS/CTS mechanism. It is important to note that the RTS/CTS reduces the hidden nodes collision probability with respect to the basic access, but does not completely avoid it. The collision can still happen when the station try to transmit the RTS frame. However, this frame has a small dimension and a collision produce a lower impact to the link throughput. The IEEE 802.11 allows using a mixed mechanism where long frames are sent using the RTS/CTS system, but not short ones. In the same radio cell might coexist clients using RTS/CTS and not.

2.1.3 IEEE 802.11 Extensions

The original IEEE 802.11 standard defines different physical layers: 2.4 GHz using Direct Sequence Spread Spectrum (DSSS) or Frequency Hopping (FH), and infrared. However, the highest physical transmission rate was 2 Mbps. Different groups proposed extensions to the original 802.11 physical layer to support higher transmission speed.

The first group that completed its work was the IEEE 802.11b in September 1999 [5]. The IEEE 802.11b defines a new physical layer using the 2.4 GHz radio band and DSSS or FH. Four data transmission rates are allowed: the two original 802.11 (1 and 2Mbps) plus two new ones (5.5Mbps and 11Mbps). The IEEE 802.11b does not modify the 802.11 MAC, but for the introduction of the minimum parameters for supporting the new data rates. Note that 802.11b guarantees backward compatibility with legacy 802.11 devices.

The IEEE 802.11a [6] was published together with the IEEE 802.11b, but only recently compliant devices were available. This group produced a completely different physical layer with respect to the 802.11 and 802.11b. IEEE 802.11a uses a radio spectrum in the range of 5 GHz and Orthogonal Frequency Division Multiplexing (OFDM). This standard is not backward compatible with 802.11/802.11b devices, but offers several different higher data rates: 6, 9, 12, 18, 24, 36, 48 and 54 Mbps. The 802.11a MAC is the same of the previous standards, but for the support for different data rates and the value of different parameters; for example DIFS, SIFS, contention window slot, etc...

Recently IEEE 802.11g was published providing a new physical layer for IEEE 802.11 [7]. This standard was designed to provide high speed (up to 54Mbps) and backward compatibility with the currently largest used IEEE 802.11b devices. This standard defines a physical layer based on 2.4 GHz radio frequency spectrum and uses two different transmission type: DSSS and OFDM. The available data rates include the 802.11b and 802.11a ones; IEEE 802.11g uses: 1, 2, 5.5, 6, 9, 11, 12, 18, 24, 36, 48 and 54 Mbps. Note that the data rates corresponding to the 802.11a ones use OFDM, the others use DSSS. Devices using 802.11b cannot sense OFDM transmissions. In order to make working together devices using not compatible radio transmission modes, 802.11g enforces the usage of a hybrid solution between 802.11 basic access and RTS/CTS. The 802.11b devices cannot sense 802.11g high rate transmissions, thus CTS frame are sent using 802.11b transmission to notify to legacy devices that the channel is taken by other stations. IEEE 802.11g can reach the same performance of 802.11a only when no 802.11 backward compatibility is enforced. In this last case the normal basic access or RTS/CTS are used. Note that the 802.11g and 802.11a devices cannot share the same radio cell because they use a different radio frequency spectrum.

2.2 Summary of previous work on IEEE 802.11 performance

The performance of the IEEE 802.11 protocol has been deeply studied in the last years. In this section, we present related work in this topic and we underline important results and the limitations that made our investigation necessary.

2.2.1 Papers on 802.11 performance analysis

Performance analysis has always taken an important part of IEEE 802.11 related work for proving the different theories or validating new proposed models or improvements. In all the papers we present, performance is studied by using simulation or by running tests on a specific wireless LAN implementation. Simulation has been the best option to compare the performance of different algorithms. This approach allows skipping device implementation details and the effects of a real environment. Instead, tests on a specific implementation are used to verify the performance or specific behaviours in complex situation (i.e. the performance of higher level protocols over IEEE 802.11 protocols) or in a real environment.

We are going to present five different papers related to three different aspects of IEEE 802.11 performance. The first group of two papers will show different analytical models of 802.11 access mechanism. The two works proposed two level of analysis with different approximation. G. Bianchi [13] used a Markov chain based model to study the performance of the 802.11 Medium Access Control technique. Bianchi's model works on any 802.11 mode over any available physical layer. Y.C Tay and K.C. Chua [14] proposed a simpler model using average values for stochastic variables. This second model only works when using the 802.11 basic access system.

The second aspect of 802.11 we are going to present is related to the performance of different higher-level protocols over a wireless link. G. Xylomenos and G.C. Polyzos [16] showed interesting behaviours of a legacy wireless link technology that anticipated the IEEE 802.11 and had the same main characteristics. A. Kamerman and G. Aben [15] used a very simple model of the 802.11 MAC layer to study the performance of TCP/IP and IPX over IEEE 802.11b. The proposed approach is also used to estimate the performance of IEEE 802.11a.

The third aspect of 802.11 we are going to present is about IEEE 802.11 AP performance evaluation. I. Al Khatib [17] proposed an analytical model for the IEEE 802.11 access points evaluation, this model is based on queuing theory.

2.2.1.1 IEEE 802.11 Medium Access Control performance

G. Bianchi in [13] proposed an analytical study of the 802.11 Medium Access Control (MAC) performance based on Markov chains. The goal of the proposed model was to estimate the throughput of the 802.11 MAC. In this article, throughput was defined as the fraction of the time the channel is used to successfully transmit payload bits [13]. The complexity of the system imposed the author to restrict the scope of his model. The most important assumption was to concentrate the work on the "*Saturation Throughput*". Bianchi defined this concept as: "*the limit reached by the system throughput as the offered load increases*"[13]. This value represents the maximum load the system can carry in stable conditions [13]. Bianchi's model is valid with the assumption of ideal channel conditions (i.e. no hidden terminals, good signal quality). Thus, during the analysis, the author assumed a fixed number of stations in a short range that always have a packet to transmit.

The 802.11 Medium Access Control analysis is divided into two parts. First, Bianchi studied the behaviour of a single station. A Markov chain based model was used to compute the stationary probability that a specific station transmit a packet in a generic slot time. The throughput is expressed by studying the possible events within a generic slot time as a function of the probability previously modelled. The proposed model is true when using both 802.11 access methods: basic and RTS/CTS and even in the case of a combination of the two systems. Bianchi's model was validated using the results of several simulations. For simplicity, the article presented investigations about different cases where either the basic access system or RTS/CTS were used. Hybrid solutions, using basic access and RTS/CTS together were not studied. Moreover, all the investigations supposed the transmission of packets of a fixed size (1500 bytes).

Bianchi's analytical model features parameters to model the different aspects of the MAC layer, in particular the contention window. The IEEE 802.11 standard fixes the values of many physical and link layer protocol parameters. Depending on the physical medium in use (Infrared, Direct Sequence Spread Spectrum (DSSS), or Frequency Hopping Spread Spectrum (FHSS)) specific values are defined for the minimum and maximum number of slots for the contention window, and the length of a single slot. Unfortunately, the author decided to use for his analysis the values relative to the FHSS. Thus, the contention window is larger in terms of number of slot and time length of the slot than the DSSS case. Nowadays, the most commonly used physical medium is DSSS. As a consequence, the results and analysis reported in Bianchi's articles [13] cannot be used to predict the behaviours of current 802.11 networks. Bianchi's analytical model is still valid, but a re-computation of the results with the DSSS parameters is necessary.

We would like to underline two interesting general results of Bianchi's paper. First: small changes in the contention window strongly affect the overall performance in relation to the number of stations. Those parameters are fixed in the 802.11 standard. However, some current AP implementations[1] allow the change of the contention window characteristics in order to provide a sort of quality of service to different packet types. A second result is that RTS/CTS has better performance than the basic access control system. This result seems to be contradictory to the results of other studies, but Bianchi analysis in [13] was focused on a different physical layer and it was applied to specific working conditions.

Y.C. Tay and K.C. Chua in [14] proposed a simple analytical model of the 802.11 Medium Access Control mechanism. Instead of using stochastic analysis, this model presets the average values for variables when possible. The proposed model can be used under almost the same conditions as the Bianchi one [13]. However, Tay and Chua restricted their model validity to only the basic access system. Multiple stations were supposed to share the wireless channel without a coordinating base station (peer-to-peer mode was used) and without hidden nodes. The saturation throughput was analyzed. Thus, each wireless station always had a packet to transmit.

In order to validate the new model, Tay and Chua used the same simulation tool developed and used by Bianchi in the article presented above. The resulting model is much simpler than the Bianchi one. However, it provided accurate results according to performed simulations and compared to Bianchi's results. The fundamental assumptions of the Tay and Chua model are that the collision probability is very low (maximum 0.5) even in saturation condition, and the back-off time is approximated to half of the contention window (average value of the uniform probability distribution) [14]. Even in this case, this throughput analysis cannot be used for current 802.11 APs. The authors computed the throughput on a FHSS physical medium in order to compare the result of their model to Bianchi's. A new throughput computation of the results of [14] is necessary to get a DSSS throughput analysis.

Tay and Chua showed the utility of their model demonstrating some characteristics of the 802.11 medium access control. In particular, they showed that:

- The probability of a collision only depends on the number of transmitting stations and the minimum and maximum dimensions of the contention window. However, the choice of the maximum window size has minimal effect on the collision rate and saturation throughput,

- The saturation throughput depends on both the number of transmitting stations and the minimum contention window in equal amounts. Thus halving the initial contention window size (minimum size) is similar in effect to doubling the number of transmitting stations. In general, the maximum saturation throughput is a trade-off between bandwidth wastage by collisions and backoff. For a large number of transmitting stations, the saturation throughput can be approximated by a simple formula which only includes the number of stations, the initial con-

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[1] For instance Cisco Aironet 1200 series 802.11 APs. http://www.cisco.com

tention window and the time used for the protocol overhead such as the time to send acknowledgments, DIFS, SIFS, etc...

- For throughput maximization: the initial value of the contention window should linearly increase with the number of transmitting stations and be proportional to the square root of the packet size (in number of time slots).

2.2.1.2 Network and transport protocols performance on IEEE 802.11

G. Xylomenos and G.C. Polyzos in [16] investigated the performance of TCP and UDP transport protocols over Lucent WaveLAN radio technology. Lucent WaveLAN products were first released in the early '90s, before the IEEE 802.11 standard was approved. The initial WaveLAN products used 900MHz radio frequency, then a 2.4GHz DSSS at 2Mbps version was also released before the IEEE 802.11 publication. This second kind of device is the one used for the tests presented in [16]. The first 2Mbps 2.4GHz WaveLAN used a radio and link layer very similar to the IEEE 802.11 final release, but with some important differences. Firstly, Lucent WaveLAN did not use link layer frame acknowledgments. The transport layer instead of the MAC layer handled transmission errors and undetected collisions therefore the radio link was not reliable. This important difference makes the performance measurements provided by G. Xylomenos and G.C. Polyzos in [16] not comparable with the performance of current IEEE 802.11 compliant devices. Moreover, many effects described and measured in [16], especially for TCP are not exportable to the IEEE 802.11 technology.

Despite the big difference in the technology, there are many valid aspects in Xylomenos and Polyzos article regarding the test procedure. Their focus was on performance measurements on real devices. Thus, tests were performed in order to measure the effective throughput in different and realistic scenarios. Particular or unexpected behaviours were further analyzed and then explained by parsing the test results and logs. The WaveLAN devices utilized peer-to-peer (Ad-Hoc) mode; no APs were used. Xylomenos and Polyzos tried to mix different kinds of hardware platforms using stationary computers and laptops, and several radio device implementations (PCMCIA and ISA radio interfaces). The problem of the repeatability of the tests was addressed with the chosen solution being one of the most commonly used (see section 2.2.2: IEEE 802.11 White Papers). Tests were performed in a few different selected places in a real environment (some rooms in a university building). Moreover, the radio link status was monitored during the different sessions and the recorded values are provided in [16] to show the global radio signal quality during the tests. Because the high variance of the test results, each single test session was repeated five times and the mean, the maximum and the minimum values reported. Note that, Xylomenos and Polyzos measured and analyzed the end-to-end UDP and TCP throughput over the radio link. This implies, the performance of the end machines (sender and receiver), the different drivers, operating system and even the specific transport and network protocol implementations were included into the analysis. This kind of approach is understandable, but forced the authors to consider many factors into the interpretation of the results. According to this kind of approach, the overall end-to-end performance of the wireless system is studied, not only the specific wireless part.

A. Kamerman and G. Aben in [15] analyzed the performance of TCP/IP and IPX over IEEE 802.11b using the basic access system and RTS/CTS. The authors studied the 802.11 medium access control mechanism and provided a raw model of the wireless link capacity. Kamerman and Abel's model only considers the different overheads and payload transmission time. The backoff time is always zero producing an unrealistic continuous packet transmission stream. The authors ran some tests to validate their model. The tests were performed sending TCP or IPX data from a server connected to an Ethernet link to one or more wireless stations through an AP. The tests were done transferring a large file using a tool called Chariot[2]. Note that, not many details are provided in [15] about the performed tests. However, the tests were run in an optimal environment and the effects of the produced traffic were examined on both sides of the AP: Ethernet and 802.11b radio link. The screening of the traffic on the wireless link was performed with a network analyzer. This technique allowed Kamerman and Aben to study the behaviour of the radio link and integrate the first raw MAC model results. Unfortunately, no details are given in [15] about the tools used to monitor the radio link.

Kamerman and Aben measured the performance of IEEE 802.11 using their model and comparing the results with real measurements on a specific 802.11 system. In particular, they simulated and measured TCP/IP 802.11b cell's throughput using 1, 3 and 5 clients. They separately simulated the behaviour of each 802.11b available data link. Therefore, during the measurements they forced the AP and wireless clients to use only one data link rate: 1 then 2, 5.5 and 11 Mbps. The tests and simulations were repeated for the two different 802.11 access protocols: basic access and RTS/CTS. Kamerman and Abel do not provide any exact value of the throughput they measured, but some figures. The pictures shows that for the available data link rates (1, 2, 5.5 and 11 Mbps) using the basic access the respective measured throughput was around: 0.8 Mbps, 1.5 Mbps, 3.3 Mbps and 5 Mbps. When using RTS/CTS, they measured an approximate throughput of: 0.9 Mbps, 1.4 Mbps, 2.9 Mbps and 4.1 Mbps. Note that in both cases the aggregate throughput only slightly increased with the number of clients and that measured and simulated values were very closed.

The test that Kamerman and Abel performed generated not symmetric bidirectional traffic on the wireless link. The downstream (AP to wireless station) was made of big packets (almost all of 1500 bytes of link payload). Only small TCP Acknowledge packets were sent into the other direction. Note that, using 802.11b at 2.4 GHz DSSS physical level, the performance of a transport protocol as TCP is better using the basic access system than RTS/CTS.

The authors run the same kind of test and simulation using IPX instead of IP network protocol. In this case each single packet at transport protocol needs an acknowledgment; IPX does not use transmission windows techniques as TCP/IP. The performance in this case is different compared to the previous one. Mainly, the channel capacity could not be saturated using a single wireless station.

An interesting result by Kamerman and Abel is the analysis of the 802.11b bandwidth usage. This analysis is generated integrating the proposed MAC model and the 802.11b traffic analysis during the performed tests. This analysis shows that the overhead of the different network layers of the wireless link quickly increases with the data link rate. Therefore, the percent of the raw data bandwidth used by real payload transmission decreased with faster data link rates. The authors extended the results of their investigation on 802.11b to the case of 5GHz 802.11a. Even in this case the different overheads due to link layer 802.11 protocol takes an increasing percent of the available bandwidth with faster link rate. According to Kamerman and Abel results, IEEE 802.11a using 54 Mbps link rate cannot produce more than around 28 Mbps TCP/IP throughput. No 802.11a implementation was available at the time the paper was pre-

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[2] Chariot 3.1, Ganymede Software Inc., http://www.ganymede.com/html/chariot.html .

sented, so no validation was provided for this last result.

2.2.1.3 Performance of 802.11 Access Points

Al Khatib presented an interesting study on the 802.11b AP performance [17]. The aim of his work was to design a simple analytical model of an IEEE 802.11 AP. The result was a single FIFO (First In First Out) queue model with a single server system. According to this scheme, all the packets coming from both interfaces (Ethernet and 802.11) go into a single queue. The packets are served one by one and send out to the appropriate media. Different APs have different performance that produces different values for the system parameters. The main focus of this work was to study the packet delay introduced by the AP. In a second step, the system throughput was computed from knowledge of the packet delays.

Experimental measurements were made to obtain the total delay introduced on the packets when passing through an AP. This total delay, Response time (R) according to Al Khatib's notation in [17], is the time difference between the departure time and the arrival time of the packet. The departure time is the time instant when the last bit of the packet leaves the system. The arrival time is the time instant when the last bit of the packet enters the system. Note that the response time is the sum of two main terms: the Waiting Time (W) and the Service Time (S). W is the time a packet spends in the service queue. S is the time the system needs to handle the packet and forward it. According to the previous definitions, the time spent by the packet to enter the system is not considered. Instead, the time to transmit the packet on the destination media is included into the response time. This transmission time adds to the service time. Al Khatib estimated the waiting and service times of each packet by studying the arrival and departure time of all the packets sent during a test session. The service time of a specific packet has been approximated as the difference of the departure time of the packet and the departure time of the previous one. The conclusion of this work was that the service time is a linear function of the packet payload [17].

According to Al Khatib's analysis, the large difference of the Medium Access Control of the two media used by the AP, Ethernet and 802.11, produces different service times. The higher complexity of the IEEE 802.11 MAC makes the downlink (Ethernet to 802.11b) service time longer than the uplink (802.11b to Ethernet) one. Al Khatib's measurements in [17] showed this kind of behaviour and underline an interesting phenomenon. The difference between the uplink service time and the downlink service time is not a constant value but depends on the packet size. Al Khatib defined the *uplink-downlink Contrast* (UDC) as: "*the absolute value of the difference between the uplink and downlink service time in relation to the packet size*"[17]. There are important differences in the service time and UDC due to specific AP implementations. Packet service times vary from AP to AP. Moreover the UDC behaviour changes on different APs. Some kinds of AP show a convergent UDC that means the UDC decreases when the packet size increases. Other APs show an opposite behaviour. In particular, Al Khatib showed that the Lucent WaveLAN Point-II has a convergent UDC, the Orinoco AP2000 a divergent one.

In order to study the AP throughput, Al Khatib proposed a different model of the system. The AP was modelled as a data link with variable bandwidth. The instant bandwidth was defined as the link layer dimension in bits of a packet divided by its time of arrival to destination minus the time of arrival to destination of the preceding packet. Al Khatib showed that the bandwidth could be computed with knowledge of the service time. The service time of a packet into the AP depends on the packet size. Thus the AP bandwidth is not constant, but depends on the packet size. Moreover, the bandwidth depends on the stream direction: downlink or uplink. After studying the bandwidth, Al Khatib studied the maximum throughput of the APs defined as the user payload data over the time needed to transmit it on the link. Al Khatib showed that the throughput is directly proportional to the bandwidth. The purpose of Al Khatib work was not to exactly measured the uplink and/or downlink throughput of different APs, but study their behaviours. However, according to Al Khatib's results Lucent WaveLAN Point-II produced a maximum downlink throughput around 3.9 Mbps. Instead the Orinoco AP 2000 produce and maximum throughput of 5.4 Mbps. Note that Al Khatib produced an analysis of the throughput versus packet size.

2.2.2 IEEE 802.11 White Papers

The main source for IEEE 802.11 device performance measurements are product brochures and white papers provided by device producers. Product brochures are too concise and partial whilst white papers are usually more complete and often propose interesting methodologies. In this section we are going to present white papers from different 802.11 producers, these documents show the performance of different evolutions of the main 802.11 standard.

The first paper is taken from the Proxim Inc. web site [8] and presents the performance of the Lucent Inc. WaveLAN 802.11 products[3]. This document aims to demonstrate that WaveLAN 802.11 products can be successfully used to provide wireless network connectivity in different scenarios. At the time the report was first published, 802.11 devices had just been marketed and were not well known. Many technicians worried about the real usability of the 802.11 technologies. The main reservation was that interferences and different environmental effects could prevent the use of such radio technology in many situations. The Lucent report shows WaveLAN products performance in normal and critical scenarios. Moreover, throughput measurements were taken to quantify the normal performance and the effect of different forms of noise and interference. The second paper is taken from the Atheros Inc. web site [9]. Atheros Inc. was the first manufacturer providing integrated circuits implementing IEEE 802.11a. This paper was published before the commercial 802.11a devices were available on the market. The radio spectrum around 5GHz used by 802.11a was expected to provide a much smaller cell than the 2.4GHz used by 802.11b. Because of the used radio spectrum, 802.11a real throughput was also expected to quickly decrease with the distance making 802.11b better performing already in a medium range. This report aims to demonstrate that the previous convictions were wrong and to show the better performance of 802.11a compared to 802.11b. Intersil Inc. published on its web site [10] a white paper on the newest IEEE 802.11g standard performance. Throughput versus range measurements are presented to compared the performance of the 2.4 GHz Orthogonal Frequency Division Multiplexing (OFDM) 802.11g radio technology with the 5 GHz still OFDM 802.11a one. The last white papers we examine are taken form Atheros Inc. web site and were later published with respect to the previous one [11, 12]. These last paper focus on 802.11b, 802.11a and 802.11g performance analyses and they present a general test methodology and some test result providing cross comparisons of the different technologies.

All papers we examine have some common aspects. All of them try to demonstrate

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[3] Proxim Inc. bought in August 2002 Orinoco. Before Orinoco was part of Agere that was a spin off of Lucent Inc. developing the original WaveLAN products.

the good performance of a specific 802.11 related standard and performance is mainly throughput versus range. The study of the throughput versus the range for WLAN technologies presents many difficulties. Throughput can be measured using different methodologies, but the range is something much harder to model. The papers we present use a common test procedure to measure the throughput at different ranges. In a realistic environment, as an office area in a building, different locations are selected spread in a uniform mode around the test area. An AP is placed in a fix position, that usually is one corner of the test area, and a client is placed at the previously selected positions. A throughput measurement test is performed once per selected location for each technology. Finally, statistical indexes of the test results are presented to show the different behaviours. This approach aims to prevent common objections regarding the fact that is almost impossible to define and fix the radio signal quality at the test time. The area layout (dimension, shape and characteristics of the rooms), the building materials (different kind of walls, glass, etc...), the natural variance of the radio signal in the gigahertz range, and possible radio sources of interferences make impossible to define standard and repeatable test condition. By using a realistic environment (i.e. office areas) and selecting in a pseudo stochastic way the test locations, the authors try to show that the test was objective. However, the described approach does not provide a repeatable testbed. It is not possible to repeat the measurement in any other place and exactly reproduce the same test conditions. Note that in the studied white papers no indication of the radio signal quality in the different test location was given. Thus the range remains an ambiguous quantity.

The testbeds used in the different experiments were similar, but completely different were the system used to measure the data throughput. In the first case [8], the AP was connected to a Novel NetWare server and a NetWare client run the corresponding client. The available wireless throughput was measured using a Novel NetWare tool called *perform3.exe.* No more information is given about the generated traffic. The Atheros paper proposes a different system to estimate the 802.11 throughput. By knowing the link layer Packet Error Rate (PER) is possible to calculate the maximum throughput using a specific mathematical model of the 802.11 standard. This model includes the performance of the 802.11 standard, the radio performance of the devices in use and the environmental condition. Other effects due to the specific device implementation, packet collisions and multiple clients are not considered, so the result is one maximum possible throughput. In order to calculate the PER, 100 broadcast (i.e. not acknowledged frames in the 802.11 link layer) packets were sent to the client. The percentage of lost packet during the test session gives the necessary PER value. Note that no information is provided about the total time of a test session (i.e. the sender packet rate). The Intersil white paper does not provide any information about how the throughput was measured.

The white papers we present show two common limitations that affect the credibility of the results. Firstly, each single test is performed only once, or only one result is considered and no many details are given about the duration of the performed tests. This kind of experiment usually generates results with a high variance. Thus, the decision of using a single sample of unknown characteristics per test is open to criticism. Related work such as articles or academic works shows an alternative approach. For example: in [16] each test session was repeated five times to estimate the variance between runs. The second limitation is that the performance of the different wireless standards is analysed measuring the performance of a single, often not well-identified, commercial solution.

In the Atheros paper [9], the throughput samples taken at the selected positions for the different radio technologies were elaborated to provide a cross comparison of the tested solutions. This paper [9] firstly compares the 802.11a physical layer and available data links with the 802.11b ones. Secondly, it compares the produced throughput of the 802.11a and 802.11b. The first goal is achieved comparing of best data link rate versus range for 802.11a and 802.11b. The authors compare the throughput median over the measured samples versus the range per available data link. The conclusion is that 802.11a is more performing than 802.11b because the different available data link rates are more performing at each range. However, many details are not reported, the median index may be appropriate, but without any further information cannot be used as an absolute performance index. The Atheros paper compares the produced throughput versus range of 802.11b and 802.11a. The document shows diagrams where the different throughput values are shown, and it says that the reported throughput samples were *"binned and averaged"*[9] to produce the shown results. Thus, we can consider the reported throughput as a sort of best possible performance at any range. The highest 802.11a throughput (at close distance) is around 27Mbps. Instead, 802.11b has a maximum throughput of around 6 Mbps. The throughput of both standards decrease with the range, and the 802.11a throughput decreases faster than the 802.11b one, but it is always the higher.

The Intersil [10] white papers use an approach to compare the performance of 802.11a and 802.11g similar to the previous Atheros paper, but no explanation is given about the throughput measurement procedure. This paper provides the results of the throughput measurement at different locations in an office area using 802.11a and 802.11g devices. The 802.11g showed overall better performance than and 802.11a. The maximum measured value of the 802.11g throughput was around 22Mbps. Instead, the 802.11a had a maximum throughput of 17 Mbps. The performance of the two technologies decrease with the range, but the 802.11a performance decreases faster than the 802.11g one. Despite the maximum throughput measured values, the authors concluded that the two technologies have the same performance in a short distance range [9]. Note that the authors of this paper presented a second remarkable conclusion: 802.11a provides the highest system throughput, 802.11g provides the best coverage with comparable throughput. This conclusion is supported by the fact that 802.11a provides 9 radio independent channels versus only 3 channels for 802.11g. Therefore, the small 802.11a cells made this technology more suitable for large system providing service to many users. IEEE 802.11g is more suited for smaller system where few users are spread around a large area.

During the Summer 2003, Atheros Inc. published in its Internet home page[4] two more white papers about IEEE802.11 a/b/g performance evaluation and test methodology. The first paper "Methodology for Testing Wireless LAN Performance" [11], provides some guidelines for testing 802.11 devices. The second paper "802.11 Wireless LAN Performance" [12], provides some test results produced using the methodology presented in the previous paper. Because of the clear relations between the two papers, we are going to examine them together. Note that, the two Atheros papers focus on 802.11 system throughput versus range.

The main organization of the papers is the following. First, the authors introduced the factors affecting the 802.11 throughput and coverage. Second, the authors present an estimation of the maximum theoretical 802.11 throughput. Finally, they provide a methodology to benchmark a real system. In the second paper, different Atheros based 802.11 solutions are compared using the proposed methodology.

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[4] Atheros Inc. http://www.atheros.com

According to Atheros's white papers, the factors that limit the 802.11 throughput and coverage are:

1. 802.11 Protocol: the effective protocol throughput is lower than the available link rates because:
    (a) Protocols headers (802.11 frames header, IP headers, TCP/UDP headers, etc...)
    (b) 802.11 acknowledgment packets
    (c) Medium Access Control protocol (i.e. contention window and back-off time).
2. Radio environment:
    (a) Radio energy attenuation with propagation
    (b) Antenna's design (i.e. antenna performance)
    (c) Fading effects due to radio scattering and multi-path
    (d) Radio interferences because other devices using an overlapping spectrum or other sources of radio noise.
3. Frequency (2.4GHz for 802.11b/g, 5GHz for 802.11a):
    (a) Antenna design. In general antennas of the same physical size tend to get more directional as the frequency increases (Advantage 5GHz)
    (b) Absorption due to propagation through objects tends to increase with frequency. (Advantage 2.4GHz)
    (c) Scattering around objects might have a positive or negative effect on signal strength as a function of frequency (Advantage Neutral)
    (d) Noise generated by other electronic/radio devices (Advantage 5GHz), and
    (e) Cable loss increases with the frequency making more critical the link between the radio modem and the antenna. (Advantage 2.4GHz).
4. Vendor equipment design, and interoperability.

The Atheros white papers provide an estimation of the maximum theoretical throughput when using different 802.11 standards, see Table 2.1 from [11, 12]. Unfortunately, the documents do not give details about how these values were computed. The authors explain that the maximum throughput is relative to a stream of IP packets of 1500 bytes transmitted using 802.11 basic MAC protocol (not RTS/CTS) in optimal radio channel conditions (close range, no radio interferences) without any transmission errors.

The Atheros white papers proposed the following test methodology. As first step, it is necessary to identify the kind of area where the tests should be conducted. Three different scenarios were identified:

- outdoor
- open office
- closed office.

	Number of channels	Modulation	Maximum Link Rate	Maximum TCP Rate	Maximum UDP Rate
802.11b	3	CCK	11 Mbps	5.9 Mbps	7.1 Mbps
802.11g (with 802.11b)	3	OFDM/CCK	54 Mbps	14.4 Mbps	19.5 Mbps
802.11g (only g)	3	OFDM/CCK	54 Mbps	24.4 Mbps	30.5 Mbps
802.11a	19	OFDM	54 Mbps	24.4 Mbps	30.5 Mbps

Table 2.1: Atheros Inc. estimation of the maximum theoretical application-level throughput provided by the different IEEE 802.11 standards. The values are taken from [11, 12].

The 802.11 capacity is expected to vary a lot when changing between the different possible areas. The authors recommend identifying the most likely scenario and focusing on it. The relative performance and throughput for different products should be similar across the different environments. Therefore, if AP1 is significantly better than AP2 outdoor, most probably, AP1 is better than AP2 even in an open or close office.

In order to practically perform the tests, the Atheros papers address a large set of well-known tools for throughput measurement. For example: Chariot or Qcheck from NetIQ, a generic ftp client/server system, or Netperf from HP labs. The throughput should be measured in 4 different conditions related to the two possible main traffic directions: uplink or downlink, using TCP over IP or UDP over IP. However, the most important kind of test was identifying the downloading throughput using TCP. The authors recommend this test because it is the most common scenario in real systems.

To produce an exhaustive comparison of different 802.11 systems, the authors recommend running tests mixing devices from the same vendor and not according to a predefined scheme. First AP and clients from the same vendor, then AP from one vendor and clients from a different one. Finally, APs from different vendor with the tested client. In order to compare performance of different products from several vendors, it is necessary to run a large number of tests.

The final step for the test preparation is to choose the set of test locations. First the location of the AP is selected inside the test area. The AP location must be the same for all the APs to test. Second, an unused and radio interferences free channel is selected for the test. Finally it is necessary to select a set of locations for the 802.11 client. The minimum recommended number of different locations is eight. The range should vary from a minimum value of three feet (the authors recommended five feet as minimum distance), up to the coverage edge. At least one location should be fixed on the range borders.

A throughput test session has to be performed according to the recommend procedure of testing tool in use. However, each single test session should be short, but the test has to be repeated at least 3 times per client location. After each test session, the authors recommend to slightly move the client and/or turn it 45 degrees or more. It is recommended to test throughput with TCP/IP using both traffic directions: downloading or uploading. Tests using UDP/IP are considered optional.

The presented results are significant, and it is important to note the effort the authors invested proposing a general, easy and reproducible method for testing 802.11 products. Despite the large improvement compared to the test methodologies proposed by the previously examined white papers, this paper proposed methodology is not novel, and presents some problems. The use of general purposes throughput measurements tools, plus the choice of recommending the use of TCP/IP demonstrate the intention of treating 802.11 as a wire-based technology. We believe that the 802.11 specific characteristics, and its general performance instability cannot be completely addressed in this way. The Atheros white paper recommended to repeat the same test session at least three times and to move the client after each test session. This was done in order to try to include in the standard throughput measure procedure some of the stochastic behaviour of the 802.11 link. However, the test reproducibility is limited by the fact that any environment is unique. Running the proposed kind of tests in two different buildings, you will result in two different measured values.

We found important two notes reported in these Atheros papers. The first one is about 802.11g. This standard provides backward compatibility with previous 802.11b. When using 802.11g with 802.11b back-compatibility, 802.11g stations use a special MAC protocol sending CTS messages before transmitting a packet to notify to 802.11b clients that the channel will be used to avoid collision. This procedure is necessary because 802.11g stations use OFDM radio channel modulation that 802.11b stations cannot decode. An alternative solution is to use normal RTS/CTS protocol, but the authors of the Atheros paper believe it will affect the performance even more. The second note is about the maximum throughput of some 802.11b products. Using some specific vendor solutions, it might happen to measure a throughput higher than the maximum theoretical one. The high performance happens because some producers reduce the standard 802.11b back-off time to increase performance risking interoperability problems. We are going to analyze the behaviour of some APs that implement this kind of solution.

Chapter 3

Maximum Saturation Throughput

In this chapter, we provide the definition of the maximum saturation throughput of an 802.11 AP. This quantity is a key figure of merit of the IEEE 802.11 AP and is the goal of our measurements. The chapter is divided in three sections. The first section presents the definition of maximum saturation throughput. The second section describes the necessary conditions to produce the maximum saturation throughput on an AP and how to achieve them. The third section explains why the maximum saturation throughput is an important figure of merit for the 802.11 APs.

3.1 Saturation Throughput definition and importance

3.1.1 Access Point's Throughput

The throughput in data communication systems is traditionally defined as the ratio of an amount of data over the time needed to transfer it. We aim our investigation to the performance analysis therefore data is the successfully received (i.e. usable) amount of information. Thus, we use the general formula:

$$Throughput = \frac{Received\ Data}{Transmission\ Time} \tag{3.1}$$

The previous general formula needs to be further clarified by detailing what we consider "Received Data" and "Transmission Time".

We define *"Received Data"* as the amount of 802.11 payload data successfully received by the destination node expressed in number of bits. The IEEE standard 802.11 specifies a link layer protocol and regular AP devices are bridges between two different link layers: Ethernet and IEEE 802.11. The payload transported in the link layer frames represents the service the AP offers, therefore we aim to measure a quantity commonly defined as *goodput*.

Despite the fact that we want to measure the link layer throughput, we need to use some kind of network and transport protocol for generating the test stream and performing the experiments. We decided to use UDP over IP. TCP over IP uses end-to-end control mechanisms and produces bi-directional traffic. The TCP/IP and 802.11 link characteristics combine producing complex results. UDP/IP is a simpler and lighter protocols combination that better matches our requirements.

The "Transmission Time" is the unit of time used for computing the throughput, and we measure it in seconds. Using a small time unit, you might expect to measure throughput values with a large variance. On the contrary, using large time units, you measure an average behaviour. In the first case, you get sharp values close to the edges of AP capacity range, but you have to collect a large population of samples to compute the average behaviour of an AP. In the second case, you already measure an average capacity of the AP, but loosing short time behaviours of the 802.11 system. Both the previous kinds of results are useful to characterise the AP performance. We do not further investigate this problem in this chapter. Instead, we deeply analyse the optimal time unit dimension to measure the throughout of 802.11 APs in chapter 5.

3.1.2 Saturation Throughput Definition

The previous sub-section provided a generic throughput definition. In this sub-section we express the specific kind of throughput that we aim to measure.

In our work we concentrate on the "Saturation Throughput" of the 802.11 access points. This is a performance figure define as the throughput produced by the AP in saturation and stable conditions, i.e. the AP's transmission queue is always non-empty and it is working in a not transient condition. Thus, the AP continuously transmits and its transmission queue has always at least on packet ready to be transmitted.

The value of the saturation throughput of a particular 802.11 AP is not a constant value independent from external conditions. In fact, many factors might influence the saturation throughput performance of an 802.11 APs making its value varying in a large range. We focus our work on measuring and analysing the maximum saturation throughput of the APs. Therefore we need to enforce all the necessary conditions in order to maximise the saturation performance of the 802.11 APs. We investigate the conditions to maximise the saturation throughput in section 3.2. The next sub-section illustrates why the maximum saturation throughput is a key figure of merit for 802.11 APs.

3.2 Conditions to maximise the AP's saturation throughput

The IEEE 802.11 AP and radio-link performances depend on different factors related to the environmental conditions and the IEEE 802.11 Medium Access Control protocol's modes and configuration parameters. In this subsection we present the most important factors that might influence the system saturation throughput and we illustrate how it is possible to maximise the performance.

3.2.1 IEEE 802.11 Radio Performance Maximisation

The performance of the IEEE 802.11 radio data link depends on many environmental factors:

- Distance between the different radio stations (i.e. radio signal attenuation with propagation).

- Presence of noise or radio channel interference sources.
- Physical obstacles like walls, windows, furniture, etc...
- Radio signal reflections (radio signal multi-paths and scattering).

All these factors are important contributors to the entire system behaviour. In order to maximise the AP's saturation throughput, it is necessary to create the best possible environmental conditions:

- No 802.11 radio channel interferences.
- Short distance between the different wireless nodes (but higher than the minimum recommended one).
- A small environment to minimise radio multi-paths effects. Note that the optimal test environment should be an open outdoor space with no obstacles, but it is not practically achievable. Instead, a small and close environment represents a good compromise. In fact large indoor environment maximize the effect of radio multi-paths [8].

To achieve the previous conditions, we recommend running the experiments in an environment with no active APs, except the one under test. The radio spectrum needs to be previously scanned using proper 802.11 software tools. Non-802.11 radio devices may still interfere with the AP under test. For example: microwaves-ovens, cordless phones, etc... Unfortunately, the presence of this kind of radio sources cannot be directly detected with normal 802.11 site surveillance software tools. Radio frequency analysers are expensive and difficult to use. Therefore, we recommend monitoring the 802.11 signal and noise levels using 802.11 software tools during the test sessions. Anomalous noise or signal levels during a specific test could indicate the presence of different radio sources interfering with the tested system, and suggest invalidating the results of the test session in progress. In the next section we examine again this problem providing more details and test results.

All the wireless nodes used for the test have to be placed in a single small room, such as an office. No obstacles should be between the radio stations and their relative distance must be short, but higher than the minimum recommended by the vendor. In such conditions you can presume optimal radio performance: maximum signal level, minimum signal multi-paths and scattering effects.

Despite the effort we put to find and achieve the best possible test condition, it is important to note that there is no set of recommendations that can absolutely guarantee the best condition at any time. In fact the radio spectrum used by 802.11 devices is extremely sensitive to many environmental factors, even to small objects present in the test environment. The signal quality changes in an unpredictable way with location and time, and even air and temperature conditions. Our test environment recommendations aim to provide a general framework to select a proper location for measuring the APs performance. However, preliminary tests are always recommended to verify that the chosen environment has the proper characteristics.

3.2.2 IEEE 802.11 Medium Access Control Performance Maximisation

The 802.11 Medium Access Control protocol's characteristics impose additional constraints to maximise the AP's saturation throughput.

The IEEE 802.11 standard defines two different modes for the access control medium protocol: basic access and RTS/CTS (Request-To-Transmit/Clear-To-Transmit) [6].

In order to achieve the maximum saturation throughput, we recommend performing the test using the basic access mechanism. According to the related work (Kamerman [15]), using 802.11b the basic access system provides higher performance in a comparable test condition. Moreover, related work about others 802.11 standard uses the basic access system because it is considered the best for performance [15].

Related work also shows that the 802.11 throughput depends on the packets size. Under optimal radio conditions, the larger are the packets, the higher the throughput (see Bianchi [13] and Al Khatib [17]). Thus, in order to maximise the throughput, the data streams must be made of IP packets of 1500 bytes. This is the largest possible packet size when using AP between the 802.11 medium and Ethernet.

Commercial IEEE 802.11 APs provide the administrator the possibility to customize the system configuration by selecting alternative kinds of profiles. A large set of options is available and may produce different performance under different conditions. The target of this document is to analyse the maximum IEEE APs performance, but many times the set of possible AP options is too large to be extensively examined. Thus, we suggest using the vendor recommend configuration that guarantees full interoperability between different 802.11 implementations. We examine with details this problem in chapter 4.

3.3 Importance of the Maximum Saturation Throughput

The related work presents several throughput performance analyses regarding different AP models. Throughput versus range is probably the most commonly use figure of merit for 802.11 APs; for example it was used in [9, 10, 11, 12]. Instead, we prefer to focus our investigation on the maximum saturation throughput. There are several reasons for such a choice:

- The maximum saturation throughput is a very important performance figure. It provides an absolute upper value for the performance of the AP useful for different purposes, such as dimensioning wireless LAN systems.

- Many of the conditions to produce and maximise the saturation throughput can be almost exactly defined and reproduced. Therefore, it is possible to recreate with an acceptable precision the same test environment almost everywhere at any time. Note that it is not possible to do the same operation when measuring throughput versus range in a real scenario (See [9, 10, 11, 12]). In this case many fundamental conditions cannot be exactly defined and reproduced. For example the characteristics of the test area: dimension of the test area, walls material, obstacle etc...

- To measure the maximum saturation throughput means to stress the AP, thus making it to work at its full capacity. This condition magnifies good behaviours or imperfections of each AP model.

- In general, a device that shows a relative level of performance under specific conditions produces performance of the same level under different conditions too. A

> high quality device has very high throughput in optimal conditions, large coverage, and relative high throughput at the coverage edge. Vice-versa, a low quality device has relative low performance in any scenario. This kind of behaviour was also noticed in the related work, see [11, 12].

It is important to note that maximum saturation throughput does not indicate the performance of the AP in a real environment. The test data streams and environmental conditions to achieve are not comparable to the normal conditions where an AP usually works. However, this figure of merit can be use to compare the behaviour of different devices and to identify their possible weaknesses or good characteristics.

Chapter 4

Challenges in measuring the APs throughput

This chapter presents the general behaviour of generic IEEE 802.11b APs and its main purpose is to motivate and introduce the test procedure we present in the next chapters. It is important to note that the focus of this chapter tests is only to show some specific behaviours of the 802.11 APs, not to produce valid throughput measurements.

The 802.11 APs show a general high performance variance and many peculiar characteristics that make challenging measuring their throughput. In order to provide a significant set of examples, we performed several tests on two AP models, the Avaya RG-II and the Cisco Aironet 1200. These two devices belong to two complete different classes of systems: the RG-II is a low price device designed for home applications. The Cisco Aironet 1200 is a high price AP model designed for large WLAN systems. We chose these two AP models because they target completely different users, and show distinct behaviours and performance. Thus they are appropriated for providing an example of the large existing variety of devices.

The chapter is divided in three sections. The first one describes the simple test procedure we follow for performing tests. The second section reports the results of our tests. The last section report some important notes suggested by the analyses of the tests results.

4.1 Preliminary Tests Procedure

The goal of the tests we present in this chapter is to produce significant examples of the possible behaviours of 802.11b access points. The test procedure is intentionally simple and the values of some parameters are partially arbitrary. However, the behaviours of the APs coming from these tests are accurate. In fact they were validated with the results shown in chapter 7 and performed according to the more accurate test procedure illustrated in chapter 3 and 6.

The preliminary tests were performed in the following way. We measured the maximum saturation throughput of the two APs sending packets from a transmitter on the Ethernet side to a wireless node (downlink test). According to section 3.2 points, we used UDP/IP packets of 1472 bytes of UDP payload (i.e. 1500 bytes IP). The offered load at the AP was 800 packets per second. This kind of stream produces the wanted saturation condition to the AP. In fact, the traffic stream is higher than the AP capacity and lower than the Ethernet link capacity. The tests were run for one hour producing a record for each received packet at the destination machine. The packet records were completed with the relative packet reception time-stamp. Note that all the received packets were included in our analysis, without leaving any warm-up period to skip possible initial transients.

We decided to run the tests on the APs for exactly one hour solely for practical reasons. The related work does not provide any specific and clear indication about the optimal test time length. A test-session time of one-hour is a reasonably large interval with respect to the frequency of the saturation throughput changes. Transient effects and other short time effects should not largely influence the overall results. Moreover, the amount of data produced by a one-hour test is small enough to be simply stored and analysed with a reasonable amount of resources (i.e. disk space and time for parsing the test record). In the next chapter, we present a new and better approach to estimate the test session length.

The sender and the receiver were both running a Linux 2.4.x kernel and we used an Orinoco Silver card as 802.11b client interface. To generate the test packet stream we used MGEN[1], and tcpdump[2] was used to record the received traffic. All the tests were performed in an environment as described in section 3.2.

Note that during the test sessions, the receiver was sampling the value of signal and noise as reported by the WLAN interface driver with a period of 100ms. The results of this radio monitoring process is shown together with the instant saturation throughput of the AP to show possible relations between the signal and noise level and the instant throughput value.

4.2 Preliminary tests results

In this section we show the behaviour of the two selected 802.11b APs when working in saturation conditions, but in different scenarios

4.2.1 Saturation downlink throughput behaviours

Figure 4.1 shows the measured downlink saturation throughput using the Cisco Aironet 1200. Figure 4.2 shows the Avaya RG-II measured saturation throughput. Note that the diagrams use exactly the same axes scales. Figures 4.1 and 4.2 clearly show that the APs performance difference is large, both in terms of maximum value and sample variance. The single throughput sample values can vary in a defined range and often between well-defined levels. In general, it is possible to observe that there are some factors that produce high frequency changes in the throughput. In fact, the instant throughput seems to continuously changing on both APs. Other factors produce low frequency changes, at least in some kind of APs, as the Avaya RG-II.

The results we got with the tests stimulated us to repeat the measurements to verify that the results we got really represent the different APs behaviours and not the result of a particular temporary set of conditions. In particular, we focused on the Avaya RG-II performance. The instantaneous throughput of the RG-II can vary around few levels. A change in the throughput level variation pattern can produce quite different values of the resulting average. From figure 4.2 it is not possible to understand if the

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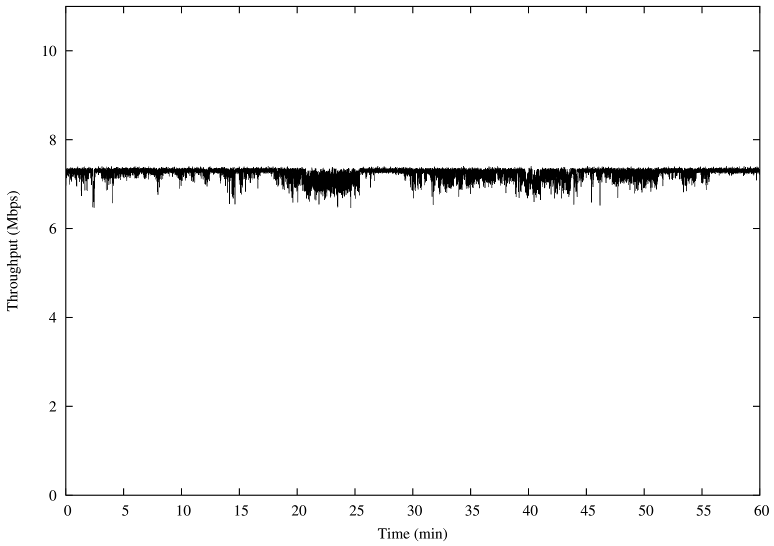
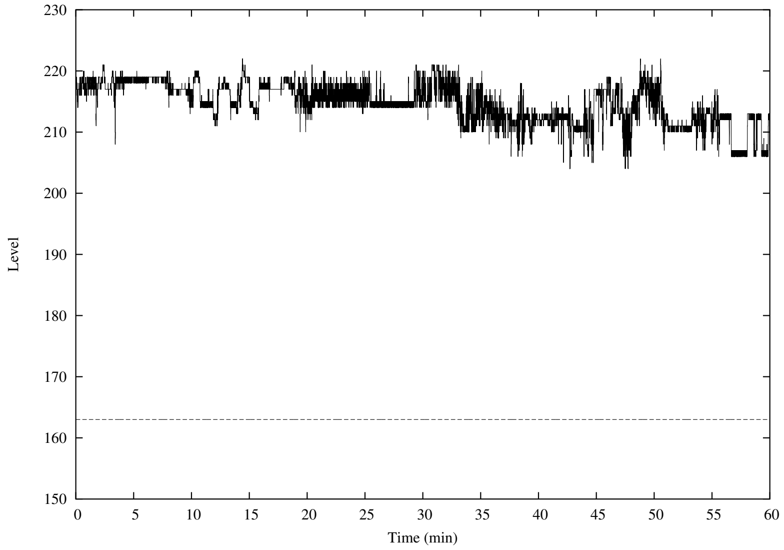
[1] MGEN: The Multi-Generator Toolset. http://manimac.itd.nrl.navy.mil/MGEN/

[2] http://www.tcpdump.org

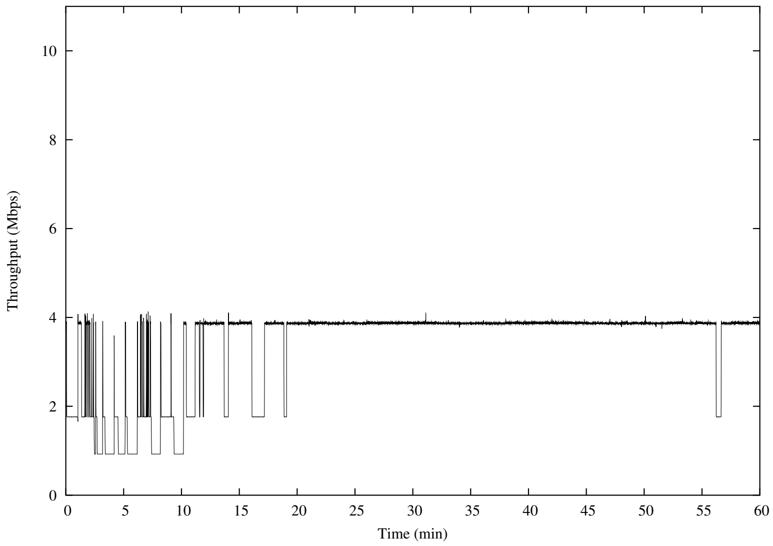


(a) AIR 1200 instant throughput

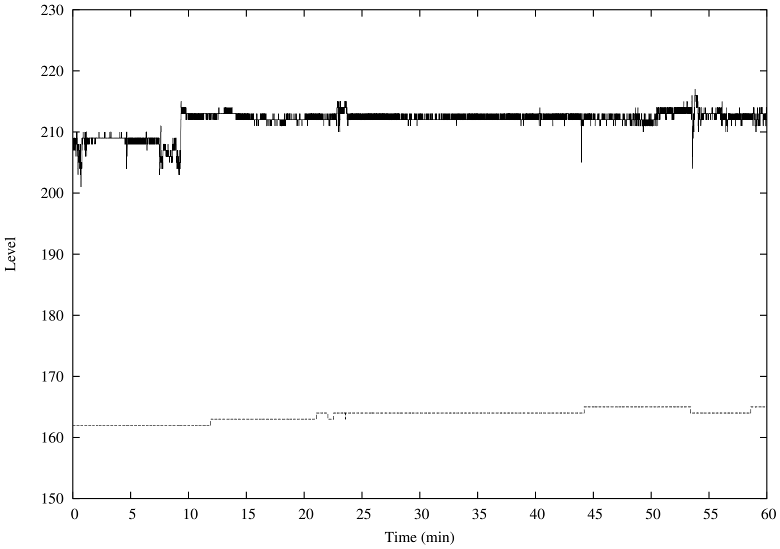


(b) AIR A1200 Signal and Noise levels during throughput test

Figure 4.1: Cisco Aironet 1200 instant throughput and radio signals over a 1-hour test.



(a) RGII instant throughput



(b) RGII Signal and Noise Levels during throughput test

Figure 4.2: Avaya RG-II throughput and radio signals over a 1-hour test.

AP performance has a regular and reproducible pattern. Moreover, it was not possible to identify the cause of the specific pattern we got in our test.

Figure 4.3 shows the result of a second test we performed on the Avaya RG-II. This test was performed according the same procedure and in the same environment as the first test. Despite of the effort we put to reproduce the same conditions, the second test shows different performance. In particular, the AP shows a general behaviour close to the Cisco Aironet A1200 one, but with a lower average throughput value. Note that the signal and noise values during the second test (figure 4.3) were worse than during the first one (see figure 4.2).

The described behaviour of the AP can be explained with the possibility that the Avaya RG-II would produce different levels of performance according to a regular pattern. If the pattern time period length is much longer than our test time (1 hour), the result of different tests could look random. Figure 4.4 shows the result of a test of 8 hours we performed on the Avaya RG-II. The test conditions were the same as in the previous tests, except for the test time length. No kind of pattern is recognisable even with respect to the previous test results. Note in Figure 4.4 that the AP performance decreases after 1.5 hours even if the signal level increases. Apparently, the Avaya RG-II AP has different behaviours in similar conditions.

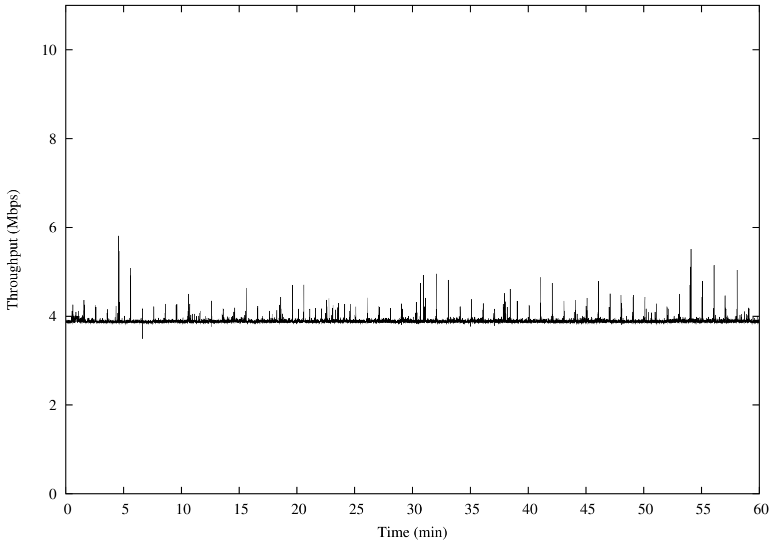
In order to find the factors that may influence the AP's performance, we repeated the test changing some characteristics of the testbed, but respecting all the test procedures we had already defined.

In section 3.2 we recommended to run the test in a small environment placing the radio devices in close range. No constraints were defined regarding the mutual position and/or orientation of the devices, except their respective distance. Figure 4.5 shows the result of two new tests on the Avaya RG-II. The first test (Figure 4.5.a) was performed orienting the AP's front side to the client. The second test (Figure 4.5.b) was performed after turning the AP 180 degrees. The difference of performance between the two tests is clear and similar results were found by repeating the tests. Despite the fact the AP's antenna is supposed to be omni-directional, the device shows a relation between the throughput behaviour and orientation. The maximum value of the AP's saturation throughput does not change with the orientation, but the performance stability. When the AP is not oriented in an optimal way, the instant throughput varies around different levels related to the different available link rates. The instantaneous throughput values produce a random pattern related to the relative transmission error probability that is higher with not optimal orientations. Note that different environmental conditions may always produce different result despite the AP's orientation. We observed that non-optimal orientations might produce good or bad performance. However, the optimal AP's orientation always produces the best performance.

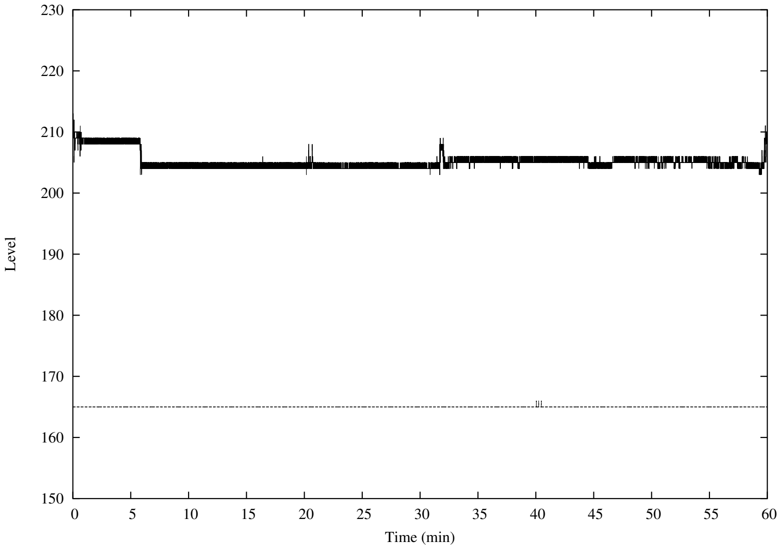
Different types of AP have different behaviours. For example: Cisco Aironet 1200 produces much more stable and reproducible behaviours than Avaya RG-II. Figure 4.6 shows the result of a second test we ran on Cisco Aironet 1200. The result of this second test is close to the result of the first one. All the tests we ran on the Cisco Aironet 1200 show similar results independently of the AP's orientation.

4.2.2 Effects of different AP configurations

Any kind of AP provides the administrator the possibility to select different configurations. Configurable parameters allow optimising the AP performance according to the specific work conditions or customer needs. Different configurations may therefore change the performance and behaviours of the AP.

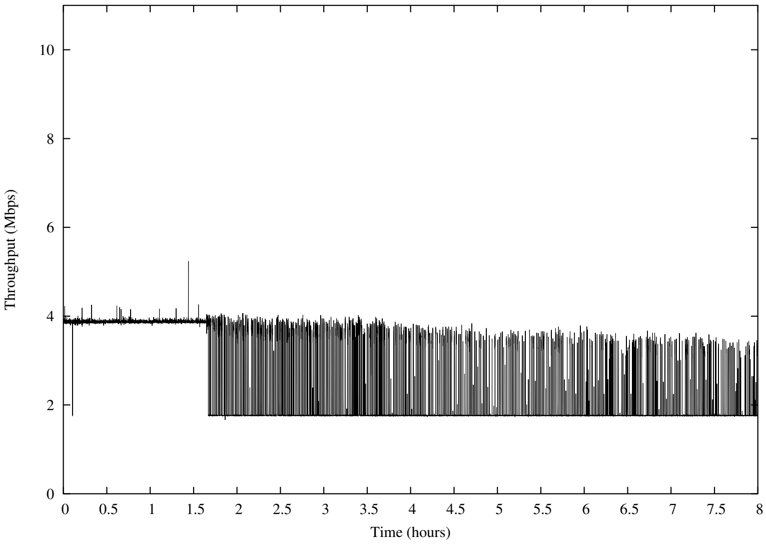


(a) RGII throughput

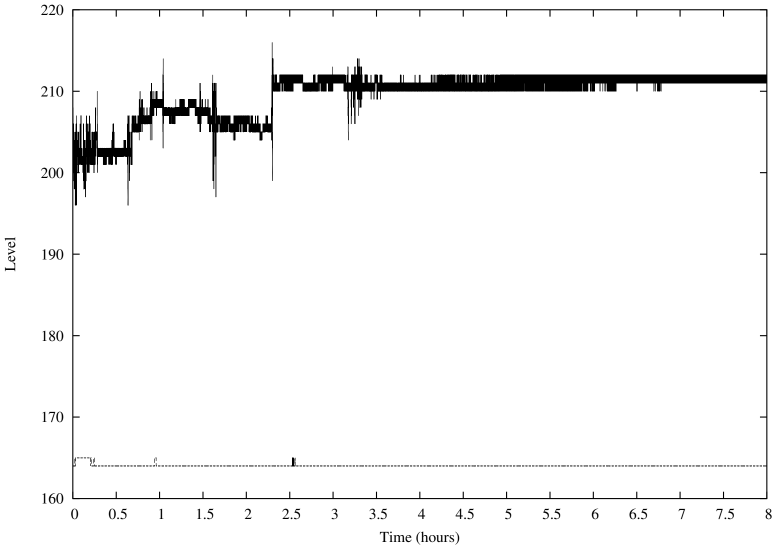


(b) RGII Signal and Noise Levels during throughput test

Figure 4.3: Avaya RG-II throughput and radio signals over a 1-hour test (test repetition).

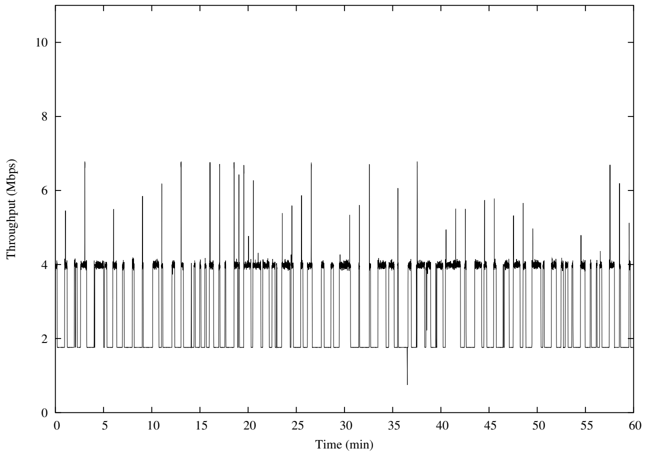


(a) RGII throughput

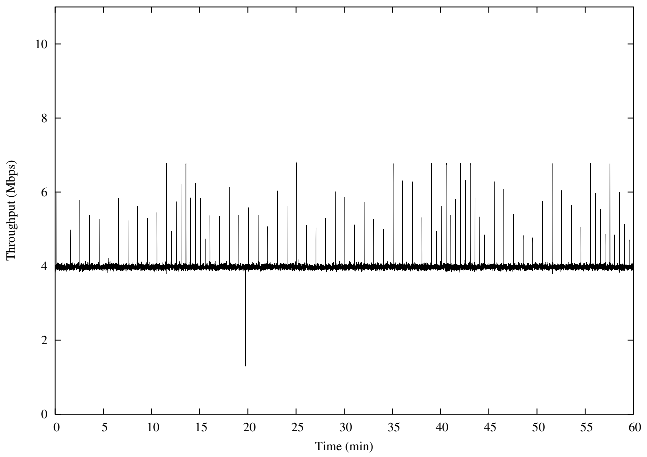


(b) RGII Signal and Noise Levels during throughput test

Figure 4.4: Avaya RG-II throughput and radio signals over 8 hour test.

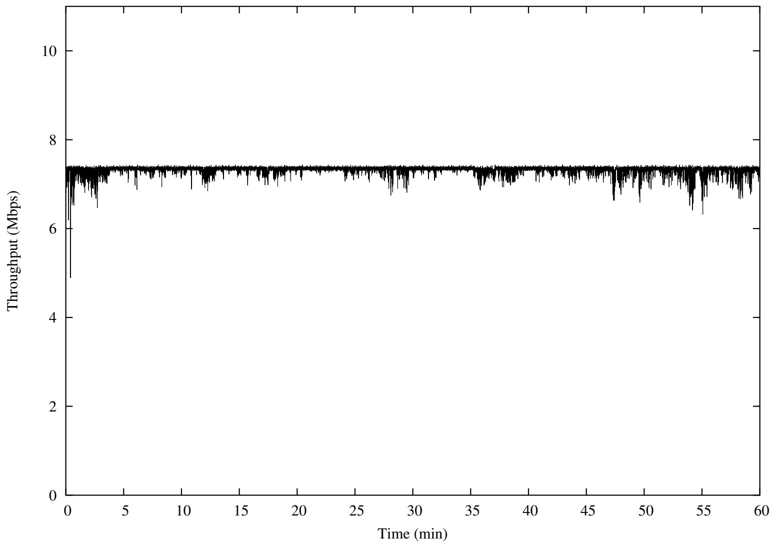


(a) RGII throughput with the AP front side pointing to the client

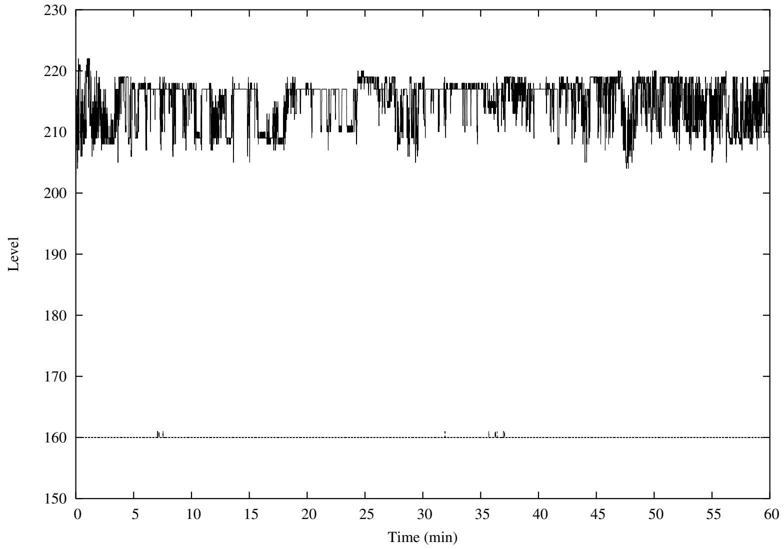


(b) RGII throughput with the AP back side pointing to the client

Figure 4.5: Avaya RG-II throughput and radio signals over a 1-hour test with different AP orientation.



(a) Cisco AIR A1200 instant throughput.



(b) AIR A1200 Signal and Noise level during Throughput test

Figure 4.6: Cisco AIR 1200 instant throughput and radio signals over a 1-hour test (Second Test).

4.2.2.1 The Cisco Aironet 1200 Case

Figure 4.1 shows the high performance of the Cisco Aironet 1200. This AP produced an average saturation throughput of over 7.1 Mbps. How could the Cisco Aironet 1200 be so fast? The answer came parsing the AP configuration and reading the relative documentation. The Cisco A1200 configuration interface offers a special option (active by default) to use no better specified "*Aironet Extensions*". When this option is not active the maximum throughput of the AP is around 6.2 Mbps. Figure 4.7 shows the Cisco Aironet 1200's behaviour without the "Aironet Extensions" and enforcing legacy 802.11 client compatibility. We did not have the appropriate tools to analyse what exactly happens when the "Aironet Extensions" are active. However, the Cisco Aironet 1200 always works properly in any conditions with the different kind of clients we tried. Thus, the "Aironet Extensions" seem to not break the basic 802.11b constraints. A reasonable, but not directly verifiable, explanation of the higher performance is that the "*Aironet Extensions*" option disregards the standard 802.11 contention window by using smaller values. This conclusion is supported from the information reported in the Atheros white papers [11, 12] about the use of such a solution on some commercial 802.11b AP models.

4.2.2.2 Avaya RG-II Case

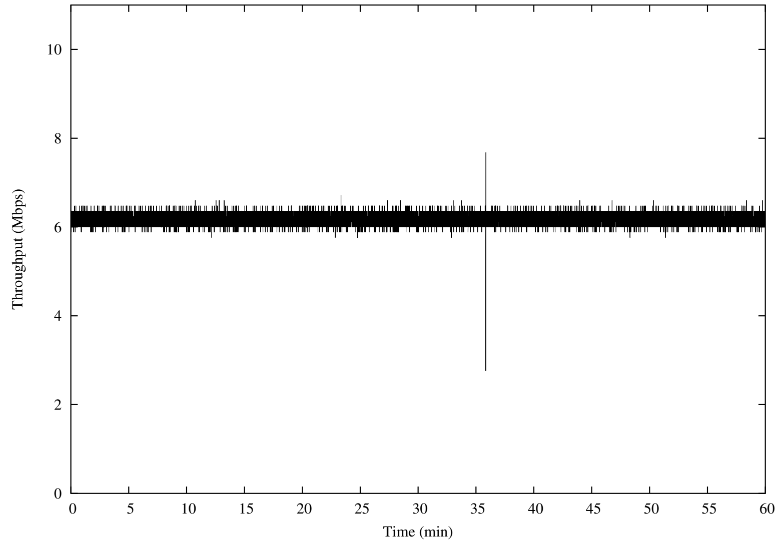
This AP model offers five different profiles to optimise the performance according to the customer WLAN cell characteristics. The available options are: Large cells, Medium cells, Small cells, Mini cells and Micro cells. Note that the tests shown in the previous sub-section were performed using the default configuration (Large cell). For example: figure 4.2 shows the saturation throughput of the Avaya RG-II with optimal orientation using Large cell profile. When changing the configuration profile, the Avaya RG-II saturation throughput changes. Figure 4.8 shows the performance of the same AP in the same conditions using the same test procedure, when the Micro cell profile is used.

Different configurations produce different behaviours. However, the performances of the alternative configuration profiles are all affected by some hardware characteristics of the AP, i.e. the antenna orientation. For example: figure 4.9 shows the result of a test on an Avaya RG-II using Micro cell profile and non-optimal AP's orientation.

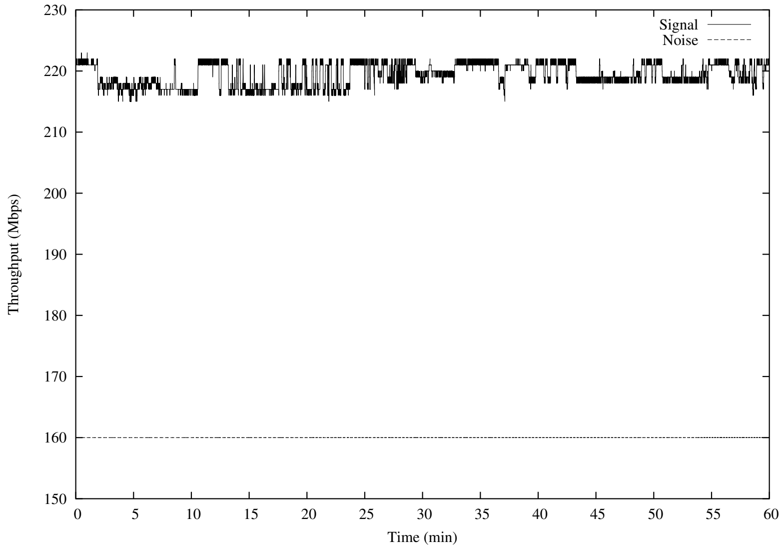
The Avaya RG-II documentation does not specify if the different profiles are associated to different radio transmission signal power levels. Many kinds of AP allow the administrator to set different levels of transmission power for the radio producing different physical dimensions of the AP's cell. No significant changes of the radio cell dimension and/or of the signal and noise levels were noticed when changing between the different profiles of the Avaya RG-II. The different cell profiles seem to do not enforce different levels of radio transmission power.

4.2.3 Offered Load versus AP throughput

The aim of this work is to measure the AP's saturation throughput. In the downlink test, this constraint implies that the AP always has a packet to transmit. This condition can be practically achieved by sending to the AP as many packets as it can bridge to the 802.11 link plus one. A way of assuring this condition during the test is to send to the AP Ethernet interface as many packets as possible. During our tests, we always used data streams slightly lower than 10 Mbps (800 pkt/sec with 1500 bytes



(a) AIR A1200 throughput



(b) AIR A1200 Signal and Noise levels during throughput test

Figure 4.7: Cisco Aironet A1200 instant throughput and radio signals over a 1-hour test when enforcing legacy 802.11 client compatibility and no proprietary Aironet extensions.

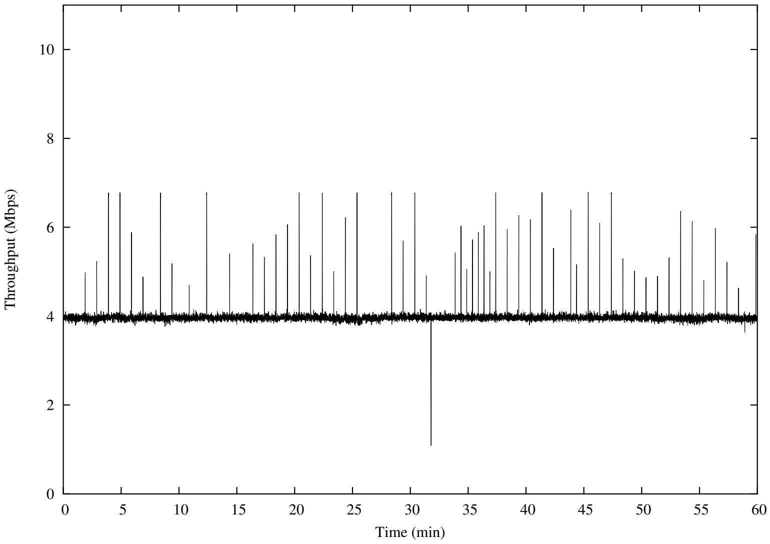


Figure 4.8: Avaya RG-II throughput over a 1-hour test using Micro Cell profile.

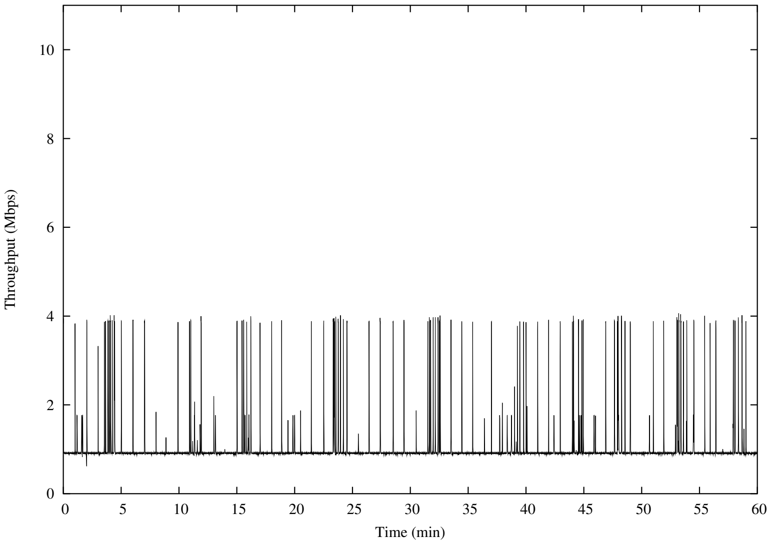


Figure 4.9: Avaya RG-II throughput over a 1-hour test using Micro Cell profile and not optimal AP orientation.

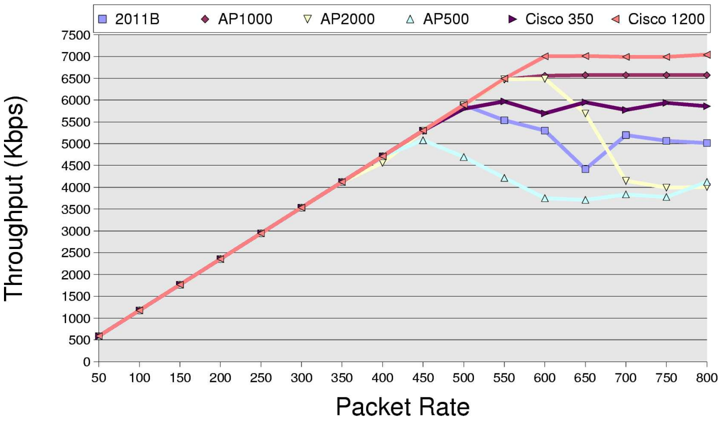


Figure 4.10: Different APs downlink throughput performance when increasing the offered load. Each point represents the best throughput on 5 minutes interval over 5 independent tests.

IP packets) to be able to produce exactly the same offered load to APs using 10 or 100 Mbps Ethernet interfaces. However, not all the APs could manage this amount of incoming traffic without loosing performance. Figure 4.10 shows the results we obtained running tests on several AP models. The test procedure we used for this test was different with respect to the one proposed earlier in this chapter (see 4.1). The purpose of this test was to analyse the behaviour of the 802.11 APs with different amounts of offered load. We selected 16 levels of offered load, from 50 up to 800 packets per seconds using UDP over IP packets of 1472 bytes of payload each. The data stream was sent from an Ethernet node downlink to an 802.11b station. A complete test on an AP was made by different independent sessions, each test session was run for 5 minutes using a specific level of offered load and it was repeated 5 times. The tested AP's maximum throughput for each offered load level was the maximum value of the measured throughput between the 5 independent measurements. Figure 4.10 shows the result we obtained. Note that the offered load influences the performance of many AP models. Therefore, in order to find the maximum throughput of a specific 802.11b AP model it is necessary to identify the offered load producing the best performance.

4.2.4 Conclusions

The different test results we presented in this chapter show three main factors that might influence the maximum saturation throughput of an 802.11b access points. These factors are:

1. The characteristics of the AP's radio antenna.
2. The AP's configuration.
3. The offered load.

The first factor shows that to measure the maximum saturation throughput of an AP it is important to verify if there is an optimal orientation of the tested device with respect to the radio client. The second factor introduces an interesting kind of problem. Some APs, such as the Cisco Aironet 1200, allow the administrator to change a very large number of 802.11 parameters making difficult to identify the optimal configuration in the test conditions. Thus, we recommend to use the default AP's configuration as long as the solution is WiFi certified [3] and there is not a specific configuration profile recommended for the particular test conditions. Finally, the third factors shows that not all the AP models can efficiently handle an extreme saturation condition without loosing performance. Therefore it is necessary to verify the optimal offered load that maximises the AP's saturation throughput.

4.3 Important Notes

4.3.1 Initial Transient

Access Points are not simple systems and use large internal buffers to handle input and/or output packet queues. According to Al Khatib's results, some APs have the capability of adapting their buffer dimension to the actual traffic characteristics [17]. Moreover, the APs can reach buffer sizes larger than 100 KBytes. Different AP models have different buffer dimension and apply different policies to them. Al Khatib proposed a procedure to estimate the buffer dimension of a specific AP [17], but it requires running extra specific tests to be performed.

The results of the preliminary tests we described in the previous section also show the initial transient behaviour of the APs. Despite the complexity of the AP system, we could not observe any special transient time, except for the first milliseconds. Figure 4.11 provides more details of the behaviour of the two APs we have examined in the first 200 ms of the test. To have little larger view of the first second of the test, you can look at figures 5.1 and 5.2 in the next chapter. Note that all the previous pictures show a little part of the same tests that we showed in figures 4.1 and 4.2 in the previous section.

The conclusion we got from the analysis of all our preliminary tests is that the transmission initial transient time of any AP is limited to the first milliseconds of the test. After a few instants, the AP performance already reaches a saturation regime.

4.3.2 Measurement of the Signal and Noise Levels

In the previous sections we show the results of many different tests on different APs. The instant throughput sample values were shown together with the correspondent signal and noise levels measured at the receiver. The purpose of showing together the instant throughput value of the AP and the signal and noise level at the receiver was to point possible relations between the two plots. After analysing the different plots, we concluded that it was not possible to note any general and clear relationship between the signal and noise levels and the measured value of the instant AP's throughput. There are several explanations for such a result:

- The signal and noise levels are related to the encoded and modulated signal. These values are linked to the probability of success or failure when transmitting a bit of information, not to the real radio signal level. For example: by changing the radio transmission power of the AP, the signal and noise values at the receiver do not change if the radio channel performance is not compromised. The signal and noise levels are the consequence of possible transmission failures, not the

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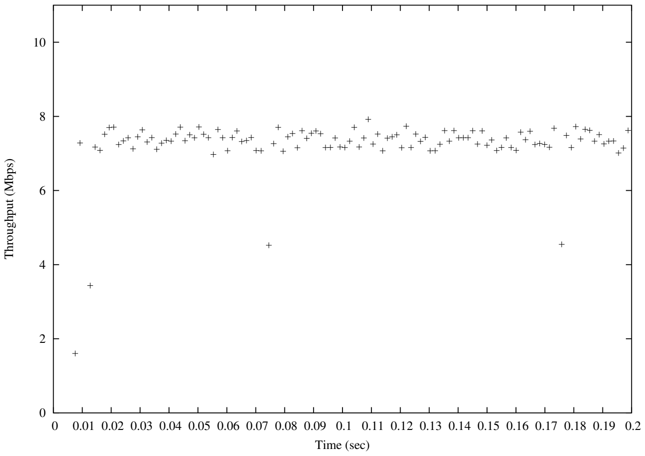
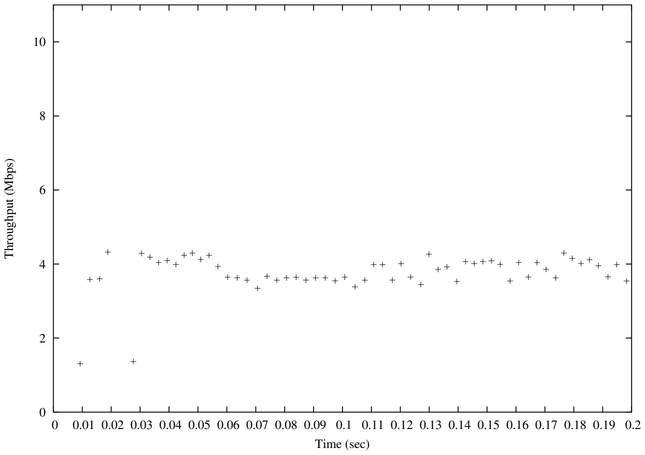
[3] The Wireless Fidelity Alliance; http://www.wi-fi.org



(a) Cisco AIR 1200



(b) Avaya RG II

Figure 4.11: Per packet throughput relative to the first 200 ms of activity.

reason. Note figure 4.4, the signal level increases when the throughput decreases. One likely way to explain such a result is that the AP lowers its transmission speed by encoding the packet using a lower link rate (i.e. 5.5 Mbps instead of 11 Mbps) when many transmission errors are detected. In the initial part of the test, the APs tries to send data at a high speed producing many transmission errors, therefore the receiver reports a low signal level. When the AP slows down the transmission to a lower data link rate, the transmission errors decrease and the signal level at the receiver increases.

- The signal and noise levels were sampled at the client, not at the AP. It is not always possible to get the instant values of noise and signal from the AP. When this information is available, you have to disturb your test environment by sending a large number of SNMP requests to the AP for retrieving the information.

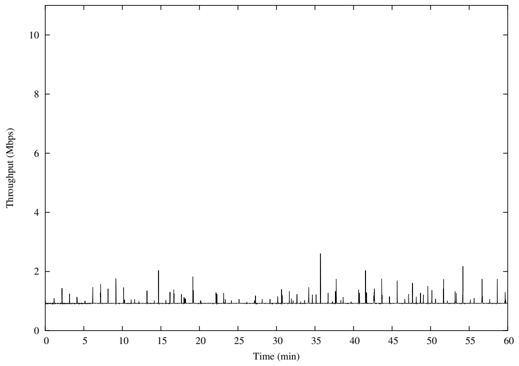
- The signal and noise levels were sampled at a different and lower frequency compared to the AP's throughput.

- The values of signal and noise levels are not an absolute measurement. Different 802.11 cards report these values on a different scale. Only a few kinds of wireless interfaces allow an accurate conversion of the provided values into decibel (dB). Therefore, it is important to use the same kind of wireless card for all the tests to compare the results.

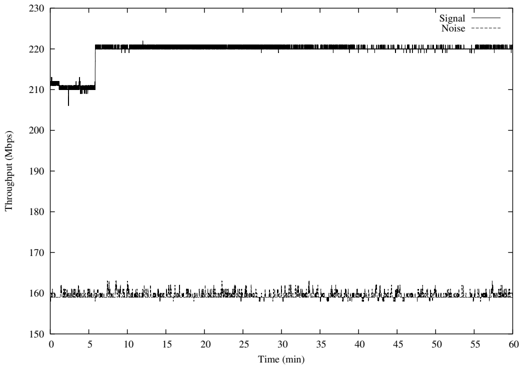
Despite the previous problems, the screening of the signal and noise levels allows controlling the general status of the test environment. In this way it is possible to verify that the general test conditions were good. Figure 4.12 shows a particular behaviour we observed with an Avaya RG-II. The extremely low throughput performance is associated with a very unstable noise level. The unusual behaviour of the noise allowed us to discard the result of this test. Most probably, external factors altered the test environment and made the test invalid.

Figure 4.13 shows a second example taken from a test from the Cisco Aironet 1200. Note that in this case it is also possible to identify a clear relation between throughput and noise level.

Our conclusion is that the signal and noise levels measured at the wireless client cannot be used to justify all the possible behaviours of the AP's throughput. However, they can give an indication about the overall test environment condition. In particular, the test results produced with levels of noise with high variance or high peaks have to be discarded. In fact, an unstable and/or unusual noise level behaviour might indicate not optimal test conditions.

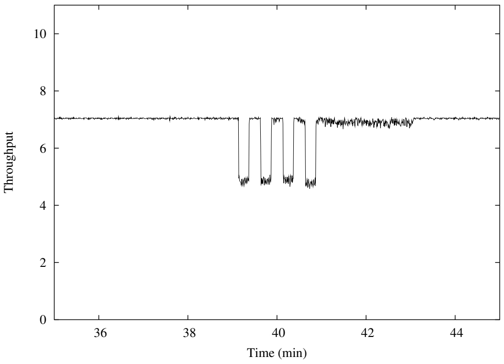


(a) Avaya RG-II throughput

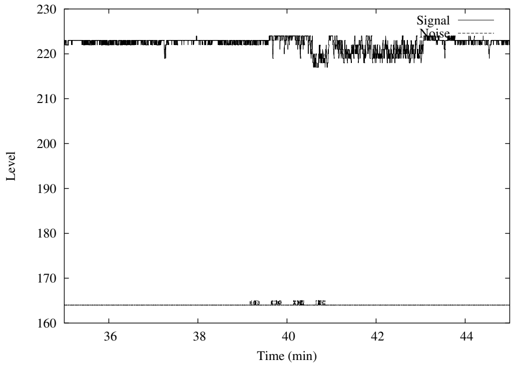


(b) Avaya RG-II Signal and Noise level during Throughput test

Figure 4.12: Avaya RG-II instant throughput and radio signals over a 1-hour test.



(a) AIR A1200 throughput



(b) AIR A1200 Signal and Noise level during Throughput test

Figure 4.13: Cisco/Aironet A1200 instant throughput and radio signals. Detail of 10 minutes over a one-hour test.

Chapter 5

A Statistical Framework for Throughput Analysis

In this chapter we present a statistical framework for testing and studying the maximum throughput of IEEE 802.11b access points.

In the first section we select the statistical indexes appropriate for summarising the AP's saturation throughput performance. In the second section, we investigate the optimal characteristics for the saturation throughput samples. In the third section, we illustrate an approach to produce saturation throughput measurements with a defined minimum accuracy.

5.1 Significant Statistical Indexes for Saturation Throughput

The target of our investigation is the maximum saturation throughput of an IEEE 802.11 AP as defined in section 3.1. The adjective *maximum* could be interpreted as the AP's throughput peak. The performance peaks are not relevant because they are very short in time, therefore do not characterise the general performance of an AP. On the contrary, we want to focus on stable saturation throughput performance in optimal conditions, therefore maximum.

We have seen that a proper approach to measure the saturation throughput of an AP is to collect and analyses a population of throughput samples (see chapter 3). Therefore, the use of some basic statistical indexes became important to produce a significant performance analysis for the studied APs. In particular, we focus our interest on the mean throughput.

Others statistical indexes are also important. The standard deviation is very useful to quantify the performance stability of a specific system. The maximum and minimum values of the throughput samples provide information about the limit of the AP performance and its throughput range variation. However the maximum and minimum values of the AP saturation throughput samples are largely influenced by the specific test session. Therefore, repeating the same tests it is quite possible to get different results despite a stable average throughput.

The conclusion is that we use as the index of the AP's maximum saturation throughput performance its average value and we report the saturation throughput standard deviation and range as complementary information.

5.2 Characteristics of the Saturation Throughput Samples

A single throughput sample is the AP's throughput computed at a specific and constant time interval. In this subsection, we investigate the optimal time interval length of a single throughput sample for an 802.11b AP.

We first investigate the general bounds for the sample time length. In general a long throughput sample time length prevents to capture short time behaviours of the APs and analyse the real range of the throughput performance. An upper limitation for the time length of the sample can be found by studying some practical limitations for the test, in particular:

- Necessary resources to successfully complete the test (total time to run the whole test, amount of disk for storing the received packet information and necessary time for the test result analysis),
- The measurement error probability of the throughput samples. We observed that some 802.11 frames could be dropped by the recording system during the test. When this happens, the relative sample has to be discarded. Thus, the longer is the sample time, the higher is the probability that an error occurs and the sample is dropped. More information can be found in section 6.2.3.

The minimum time length of an 802.11 throughput sample is related to the instantaneous throughput measurement error. We identified two main factors that can influence this parameter:

- General behaviour of IEEE 802.11 compliant APs.
- The maximum measurement error due to the measurement system.

The 802.11 APs send beacons at regular intervals (usually 100ms) to advertise their presence [4]. The beacons are always sent at a fixed and usually low speed (commonly 2Mbps). After sending a beacon, the APs schedule a set of special operations, i.e. the transmission of special data sent as multicast packets. One of the reasons of the large variance of the very small samples is the alteration produced on the normal data flow by the beacon transmissions. Figure 5.1 shows the throughput of the Cisco AIR 1200 calculated using samples of a single packet. The diagram shows the first second of the test. In Figure 5.1 one can easily identify the beacons and understand their potential influence on throughput sample values. Note that the effect of the beacon is much lower with slower AP, i.e. Avaya RG-II. Figure 5.2 shows this case.

Observe the results of a downlink traffic test on the two APs we used for our preliminary tests. Table 5.1 shows different statistical indexes of the results produced by the downlink test on the Avaya RG-II computed using different sample sizes. Table 5.2 shows a similar result with the Cisco Aironet 1200.

Despite the use of different sample sizes, in both cases the resulting average value is the same. Figure 5.3 shows the maximum, average and minimum downlink throughput for the two AP models computed for different sample sizes (from 0.05 to 2 seconds). Note that the range of throughput samples varied largely whilst the average throughput

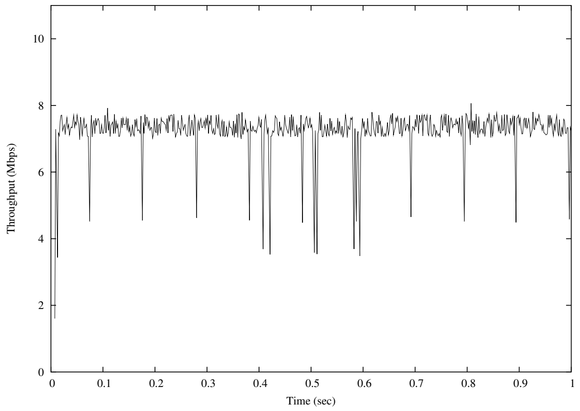


Figure 5.1: Instantaneous throughput of the Cisco/Aironet A1200 in the first second of the test. Each throughput sample is made of a single packet.

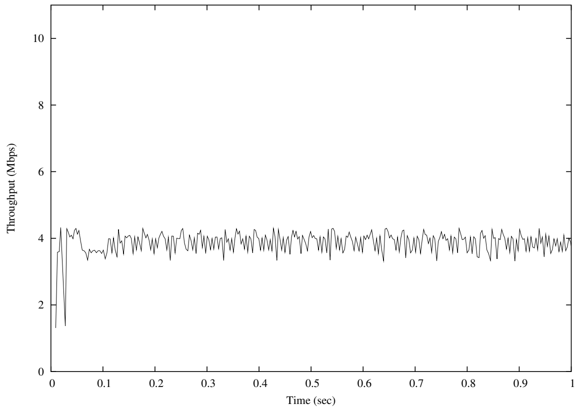


Figure 5.2: Instantaneous throughput of the Avaya RG-II in the first second of the test. Each throughput sample is made of a single packet.

Samples Size	**0.05 sec**	**0.1 sec**	**0.15 sec**	**0.2 sec**	**0.3 sec**	**0.5 sec**	**1 sec**	**2 sec**
Sample Mean (kbps)	3978	3978	3979	3978	3979	3978	3979	3977
Std. Deviation (kbps)	162	105	85	71	59	44	32	23
Maximum (kbps)	4560	4320	4240	4200	4160	4104	4068	4032
Minimum (kbps)	1440	2040	2640	2940	3320	3552	3744	3876
Range (kbps)	3120	2280	1600	1260	840	552	324	156

Table 5.1: Avaya RG-II preliminary test 1, statistical analysis with different time length samples.

Samples Size	**0.05 sec**	**0.1 sec**	**0.15 sec**	**0.2 sec**	**0.3 sec**	**0.5 sec**	**1 sec**	**2 sec**
Sample Mean (kbps)	7019	7019	7019	7019	7019	7019	7019	7019
Std. Deviation (kbps)	151	85	69	55	46	38	31	27
Maximum (kbps)	9840	8400	7200	7140	7120	7080	7068	7062
Minimum (kbps)	4320	5760	6560	6600	6680	6744	6816	6882
Range (kbps)	5520	2640	640	540	440	336	252	180

Table 5.2: Cisco Aironet 1200 preliminary test 1, statistical analysis with different time length samples.

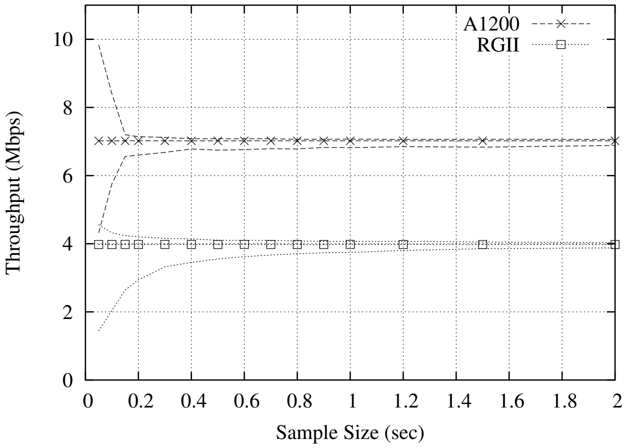


Figure 5.3: Maximum, average and minimum downlink throughput using Avaya RG-II and Cisco AIR1200 computed for different sample length.

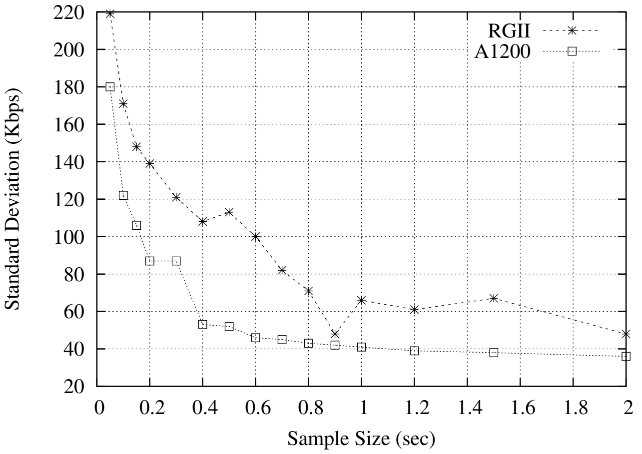


Figure 5.4: Average behaviour of the downlink standard deviation with different sample size using Avaya RG-II and Cisco AIR 1200.

remained constant. Very small samples vary in a large range and the throughout range quickly decreases as the sample size grows.

Figure 5.4 shows the average behaviour of the downlink standard deviation with different sample sizes.

The previous diagrams show that the computed average throughput does not depend on the sample size. However the sample size strongly influences the resulting throughput range and the throughput sample standard deviation. In particular note that using very small samples (i.e. 5 ms), the packet time-stamp measurement error can produce throughput samples with non-realistic values. For example: the Cisco Aironet 1200 maximum throughput value using samples of 5ms is 9840 Kbps. This value is very high compared to the expected 802.11b performance. Most probably extreme throughput sample values are produced by erroneous packet reception time-stamps.

Usage of very large sample times does not show short time behaviours. For example: computing the throughput on 2 seconds samples, it is not possible to note possible interruption in the traffic flow for periods shorter than 2 seconds. In fact, a complete AP stop produces a set of low throughput samples that looks as if the AP temporary slows down. If large sample times are used, the effect of short time throughput behaviours is re-distribute between more samples. Therefore, the throughput samples have to be small to report any kind of behaviour. However, the minimum sample time length has to be long enough to have an acceptable measurement error and including at least one beacon transmission. It is necessary to have at least on beacon per sample, thus to include this 802.11 protocol characteristic into each sample avoiding confusing a protocol characteristic with device instability.

The network analyser tools only report the packets completely received on a defined time interval. An incomplete packet transmission during the interval (i.e. the packet transmission ends just after the end of the sample interval) is not reported and produces a throughput measurement error. It is not possible to avoid such an error, but it is possible to estimate it. In the worse case, the error is equal to a single packet. For example: if an AP transmits packets at a constant speed, using a sample time interval slightly larger than the transmission time of a single packet, one observes that all the

Bit Rate	**DIFS**	**Contention window**	**PHY Preamble/Header**	**MAC Overhead**	**Payload** (1500 Bytes)	**SIFS**	**Ack. PHY Preamble/Header**	**Ack. MAC overhead**	**Total**
1 Mbps	50μs	320μs	192μs	272μs	12000μs	10μs	192μs	112μs	13148μs
2Mbps	50μs	320μs	192μs	136μs	6000μs	10μs	192μs	56μs	6956μs
5.5Mbps	50μs	320μs	192μs	49μs	2182μs	10μs	192μs	56μs	3052μs
11Mbps	50μs	320μs	192μs	25μs	1091μs	10μs	192μs	56μs	1936μs

Table 5.3: IEEE802.11b maximum frame transmission cycle-time at different link rate.

samples include zero, one or two received packets, with an average of 1 packet.

When the AP transmits packets at constant speed, the larger the sample time interval, the lower the absolute sample's throughput error. In the previous example you have a maximum error equal to 100% (two or zero received packets instead of one). Using a sample time interval equal to the average time for transmitting 100 packets, you reduce the relative maximum error to 1%. Real APs do not transmit packets at a unique and constant speed. However, this approach produces an estimation of the minimum sample time per acceptable measurement error.

The packet transmission time on an 802.11 link depends on the packet dimension, the link layer transmission rate, the contention window, and the time to get the necessary acknowledgment packet [4]. This time is the overall 802.11 transmission cycle-time. In order to maximise the AP throughput we use a test data stream made of packets with dimension equal to the IP packet maximum size (1472 bytes of UDP/IP payload) Table 5.3 shows the estimated transmission time at the different 802.11b link rates [4]. The delay introduced by the contention windows is a stochastic value with a uniform distribution [4]. In table 5.3 this delay is supposed to be always equal to its mean. Tay in [14] used the same approximation for his mathematical model. Note that we assume the link to be free of collisions. Therefore, the contention window is always minimal (i.e. up to 32 slots of $20\mu s$) and the 802.11 MAC protocol waits an average of 320 μs before sending a packet. In case of a single 802.11b station in a cell, a 1500 IP packet is completely transmitted in less than 13.15 ms (using the 1 Mbps link rate).

It is important to note that several kinds of control and management packets are defined in the IEEE 802.11 standard. These packets are transmitted at regular times, or in particular situations by the AP or by the clients and can interrupt the test data stream. However, we can simplify the analysis only including the 802.11 data packets with their acknowledgment.

The number of packets that arrived in a time interval equal to T ms depends on the link rate in use. This number is the floor or the ceiling of T divided by the time to transmit the packet at the link rate in use. In fact, a partially transmitted packet will not be included in the sample. Whatever the sample time length, the maximum absolute error is always equal to the contribution of an entire packet to the sample value. Therefore, if T is the throughput sample time length, the maximum throughput sample measurement error can be estimated as:

$$error_{max} = \frac{1}{floor(T/T_{transmission-cycle-time})} \tag{5.1}$$

	1 Mbps	**2 Mbps**	**5.5 Mbps**	**11 Mbps**
1%	1315 ms	696 ms	306 ms	194 ms
3%	439 ms	233 ms	103 ms	65 ms
5%	263 ms	140 ms	62 ms	39 ms
10%	132 ms	70 ms	31 ms	20 ms

Table 5.4: Sample's minimum time length to get a specific maximum measurement error at the different 802.11b link rate.

Table 5.4 shows the different sample time to guarantee a theoretical maximum sample measurement error at the different 802.11b link rates.

In order to study the maximum throughput of an 802.11b AP, we recommend using throughput samples of 150 ms. Under optimal conditions, we can assume the AP will never use link rates lower than 2Mbps. In case of a lower performance, the single throughput error could be up to 10%.

The sample length of 150ms represents a compromise between the different possibilities we examined. This length of sample is short enough to capture almost instantaneous behaviours of the 802.11 APs. However, it always includes at least one beacon transmitted by the AP and produces a throughput with a maximum error that is estimated lower than 5%. Note that different lengths of sample might be used, 150 ms represents the optimal option according to our experience. In particular we observed that using throughput samples up to 150 ms the 802.11 traffic analyser's packet lost probability is low enough to generate an acceptable low probability of discarding samples.

5.3 Throughput measurement accuracy and number of samples

In order to measure the maximum saturation throughput of an 802.11 AP it is necessary to collect a set of throughput samples. The AP performance is measured as the average of the collected samples. Using simple statistical analysis, it is possible to guarantee a minimum measurement precision.

The previous section defined the characteristics of the throughput samples we recommend. In this section we estimate the number of samples (i.e. the test-session time) in order to achieve a pre-defined measurement precision.

5.3.1 Background

Statistical analysis provides an approach to solve the 802.11 maximum throughput measurement problem. The confidence level gives probabilistic bounds to the throughput measurement. By fixing a confidence level, it is possible to define a symmetric interval around the measured average (confidence interval) where the real system average lies with the probability expressed by the confidence level. For example: a confidence level of 95% allows calculating a symmetric interval round the computed average where the real average value lies within a probability of 95%.

The confidence interval can be very large, but it decreases when the number of samples grows. The accuracy of the measurement is the ratio between the confidence interval and the average value. For example, an accuracy of 10% means that the confidence interval of a measurement is equal to 10% of the measured average.

The number of throughput samples one needs to collect during a test session depends on the desired measurement precision. Knowing the mean and standard deviation of a stochastic distribution, it is possible to estimate the necessary number of samples to collect in order to measure the mean at a certain confidence level and with a specific accuracy. The formula 5.2 from [3] allows estimating the necessary number of samples:

$$NSamples = Ceiling\left(\left(\frac{100 \cdot z \cdot \sigma}{r \cdot x}\right)^2\right) \tag{5.2}$$

Where:

- x: Distribution mean,
- σ: Standard Deviation of the distribution,
- z: Quantiles of the Unit Normal Distribution (this value depends on the selected confidence level),
- r: Desired mean accuracy percent.

We recommend using a high accuracy level and confidence level for measuring the AP's maximum saturation throughput. The high accuracy and confident interval are necessary to be able to easily distinguish and compare the different performance of the APs. The lower the accuracy, the larger the performance range where it will not be possible to distinguish the behaviours.

We suggest using a confidence level of 95%. We chose such a confident level because it represents a good compromise between provided precision and amount of necessary resources. The necessary accuracy is investigated in the next subsection.

5.3.2 Estimation of the number of necessary samples

The previous sub-section introduced a statistical approach for the analyses of the throughput performance of any 802.11 AP. Unfortunately it is not possible to know in advance the throughput's mean and standard deviation of a specific AP under certain conditions. Therefore, in order to determine the necessary number of throughput samples we investigate the worse case. This methodology produces an over-estimation of the necessary number samples, but it achieves a pre-defined minimum accuracy with a unique procedure for any AP without running preliminary tests on each device.

Equation 5.2 shows that the necessary number of samples is proportional to the square power of the ratio between standard deviation and the mean; this ratio is called Coefficient Of Variation (C.O.V). The proportional factor depends on the desired confident level (through the quantiles of the Unit Normal Distribution, z) and the desired mean accuracy. In our analyses, the worse possible case corresponds to the AP producing saturation throughput with the highest C.O.V.

The throughput samples of an 802.11 AP cannot have values outside the limit of the 802.11 link capacity. Thus the average throughput and its standard deviation are limited within the 802.11 capacity range (i.e. from 0 to 11Mbps for IEEE 802.11b). The analyses of preliminary tests suggested estimating the maximum C.O.V equal to 1. This

Accuracy	N. Samples	Test time (using 150ms samples)
1%	38416	5763 sec (96 min)
2%	19208	2882 sec (49 min)
3%	12805	1921 sec (33 min)
4%	9604	1441 sec (24 min)
5%	7683	1153 sec (19 min)
7%	5489	824 sec (13 min)
10%	3842	577 sec (10 min)

Table 5.5: Number of necessary samples and estimate time to complete a test session to measure the throughput with a confidence level of 95% and different levels of accuracy.

value represents a reasonable maximum upper bound with a good margin with respect to the measured saturation throughput's C.O.V. of the tested 802.11 APs. Moreover, a maximum C.O.V. equal to one represents a realistic scenario where the throughput samples of the different APs have a standard deviation lower than their mean. Note that the theoretical maximum value of the C.O.V. for the 802.11 AP's saturation throughput is higher. Thus, in order to validate any measurement, it will be always necessary to verify the C.O.V. Our assumption might fail when measuring the throughput of devices with extremely low and instable performance. However, we consider such behaviour a failure of the tested system to be treated as an exception.

Under the hypothesis that the maximum C.O.V. is equal to one, the number of necessary samples to pick up is equal to:

$$MaxN.Samples = Ceiling((\frac{100 \cdot z}{r})^2) \tag{5.3}$$

The equation 5.3 shows that with a fixed value of the confidence level, the number of samples grows with the accuracy. It is recommendable to achieve a high accuracy, but also keeping the number of necessary samples as low as possible (i.e. the time to complete a test session). Table 5.5 shows the number of necessary samples for a confident level of 95% and different accuracy values. This table also reports an estimation of the time to complete a test session.

It is not possible to provide here the optimal accuracy to use for all kind of tests. The optimal value depends on the specific target of the test you want to run. The next chapter describes the maximum saturation throughput measurement procedure for 802.11b APs. Different kinds of tests are recommended as part of the general procedure, for each specific test we recommend an appropriate accuracy.

Chapter 6

Measurement of AP Maximum Throughput

This chapter presents our recommended procedure to measure the IEEE 802.11 AP's maximum saturation throughput. The first section details the general throughput definition according to the 802.11 AP's characteristics and surveys the different options. The second section presents our recommended test procedure. The last section describes the necessary testbed to successfully perform the measurements according to our recommendation.

6.1 Particularities of the IEEE 802.11 AP Throughput

In chapter 3, we provided a general definition of the maximum saturation throughput (see 3.1). Despite the general validity, the previous definition needs to be better detailed. The first throughput definition does not include important aspects necessary to study the IEEE 802.11 APs throughput. In particular, it is necessary to consider the data stream direction and the number of nodes and/or data streams to use. The following subsections demonstrate that the previous points represent important issues.

A generic AP can bridge data packets into four different directions:

1. Downlink (Ethernet to wireless),
2. Uplink (wireless to Ethernet),
3. Wireless-to-Wireless, and
4. Ethernet-to-Ethernet.

The last two cases need further explanation. The wireless-to-wireless case refers to different wireless stations exchanging packets in the AP's radio cell. In this scenario the AP works as a repeater. The Ethernet-to-Ethernet case refers to stations exchanging packets when connected to the same Ethernet link of the AP. This case is not significant for our investigation. No actions are required to the AP.

Note that more kinds of traffic streams can be generated combining the previous four different basic ones. Moreover, data packets can be exchange between two or more nodes. Therefore, the previous different traffic scenarios can be further subdivided according to the numbers of streams and/or stations involved.

Avaya RG-II	**1 Receiver**			**2 Receivers**		
	Test1	**Test2**	**Test3**	**Test1**	**Test2**	**Test3**
Average (Kbps)	3940	3979	3977	3981	3933	3978
Maximum (Kbps)	6720	6720	4320	7200	4240	4320
Minimum (Kbps)	0	0	0	3624	2560	2240
Std. Dev. (Kbps)	223	130	126	284	73	91

Table 6.1: Avaya RG-II downlink test results. The throughput was computed on sequential samples of 150 ms each. The measurements confidence level is 95% and the accuracy is 3%.

Cisco AIR1200	**1 Receiver**			**2 Receivers**		
	Test1	**Test2**	**Test3**	**Test1**	**Test2**	**Test3**
Average (Kbps)	6945	7024	7025	6956	7030	6957
Maximum (Kbps)	8320	7200	7200	7200	7200	7760
Minimum (Kbps)	0	4240	0	3840	4160	0
Std. Dev. (Kbps)	368	69	98	125	68	411

Table 6.2: Cisco AIR 1200 downlink test results. The throughput was computed on sequential samples of 150 ms each. The measurements confidence level is 95% and the accuracy is 3%.

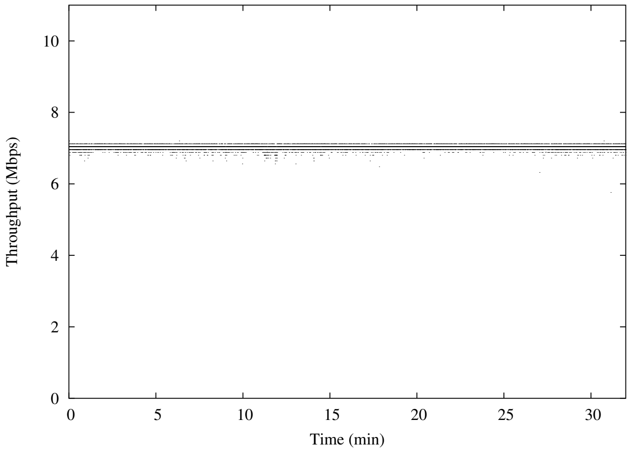
This section investigates the AP saturation throughput generated by the different kinds of test traffic to identify the one producing the highest result. In the following sub-sections we examine the AP general performance when handling traffic in different directions. All tests were performed according to the recommendations provided in the previous chapter. The tests were made on the two AP models we used for studying the general behaviour of 802.11 devices (Cisco Aironet 1200 and Avaya RG-II). The Avaya RG-II uses the default configuration (Large cell profile). The Cisco Aironet uses the standard configuration (Aironet extension on), but enforcing back compatibility with legacy IEEE 802.11 devices. This is necessary to explain the difference in performance with respect to the preliminary tests.

6.1.1 AP's downlink Throughput

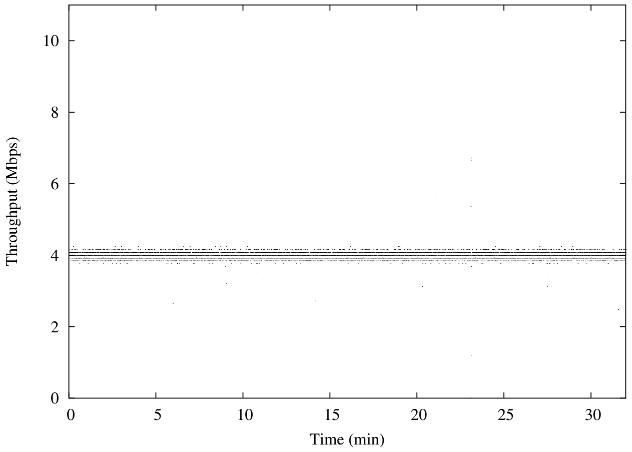
During this test a station in the Ethernet link sent streams of UDP packets to one or more stations in the 802.11 radio cell. According to our general test procedure, the test data stream is made of UDP/IP packets of 1472 bytes of payload. The total amount of offered load to the AP is always 800 packets per second. When running tests with more receivers, the total offered load is equally redistributed between the different streams. Note that, all tests were run up to collect 12805 consecutive samples of 150 ms each. Therefore, the shown saturation throughput measurements have a confidence level of 95% and an accuracy of 3%.

Figure 6.1 shows an example of the instantaneous downlink throughput behaviour of Cisco Aironet 1200 and Avaya RG-II. The test was run with one sender and one receiver.

The previous test was repeated 3 times per AP model using one wireless station as a receiver, and 3 times more with two wireless stations and sending an equal data stream per receiver. Table 6.1 shows the results of the test on the Avaya RG-II. Table 6.2 shows the results of the test on the Cisco Aironet 1200. Figure 6.2 shows the downlink average

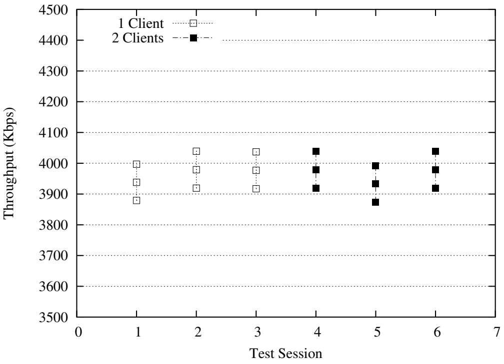


(a) Cisco AIR 1200 Downlink Throughput

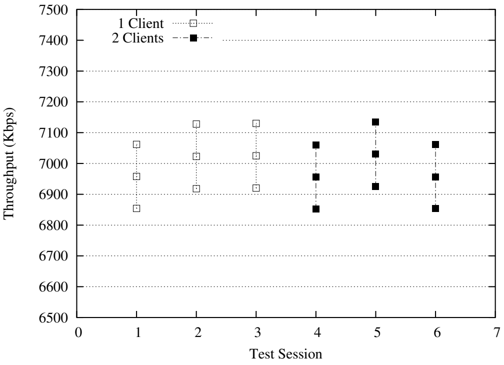


(b) Avaya RGII Downlink Throughput

Figure 6.1: Cisco AIR 1200 and Avaya RG-II downlink test results. The graphs show the specific AP throughput computed on sequential samples of 150 ms each. The two different tests were run the time necessary to collect 12805 samples.



(a) Avaya RGII



(b) Cisco AIR 1200

Figure 6.2: Avaya RG-II and Cisco AIR 1200 downlink test results. Average throughput and confidence intervals for the different test sessions with 1 and 2 receivers.

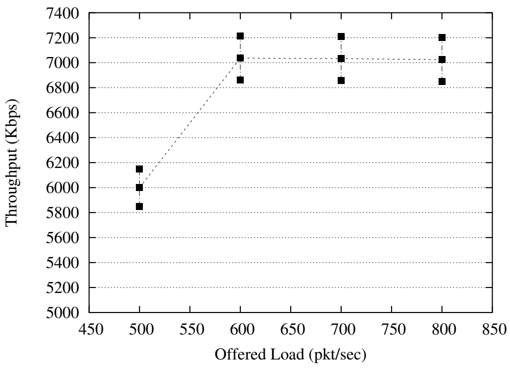


Figure 6.3: Cisco AIR 1200 downlink throughput with different offered load: from 500 to 800 pkt/sec. The measurements confidence level is 95% and 5% accuracy.

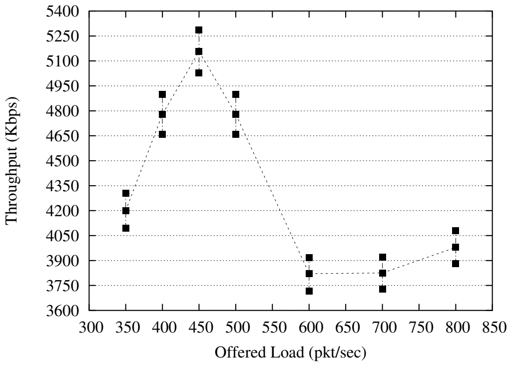


Figure 6.4: Avaya RG-II downlink throughput with different offered load: from 350 to 800 pkt/sec. The measurements confidence level is 95% and 5% accuracy.

throughput computed at each test repetition and the relative confidence interval of the different measurements. Figure 6.2a shows the Avaya RG-II behaviour, Figure 6.2b the Cisco Aironet 1200. Note that the saturation throughput is different for different APs, and it remains within the same confidence interval with one or two wireless stations.

In order to complete the analysis of the downlink behaviour of the APs, it is necessary to verify their behaviour with differing offered loads. The Cisco Aironet 1200 already produces a very high throughput with the maximum offered load (800pkt/sec). Figure 6.3 shows that the downlink throughput does not change with lower offered load as long as it is higher then the AP's maximum downlink throughput.

Instead, the Avaya RG-II produces a lower throughput and requires further investigation. Figure 6.4 shows the downlink saturation throughput of the Avaya RG-II with different offered loads and relative confidence intervals (accuracy 5%). The highest Avaya RG-II saturation throughput is reached with an offered load of 450 pkt/sec and its average is 5158 Kbps (confidence level 95%, 3% accuracy). The AP can bridge the entire offered load up to 350 pkt/sec, then it starts to drop packets. Up to 450 pkt/sec the throughput grows, then decreases.

The downlink test shows large performance difference between the AP models. The

Avaya RG-II	**1 Sender**			**2 Senders**		
	Test1	**Test2**	**Test3**	**Test1**	**Test2**	**Test3**
Average (Kbps)	6168	6161	6159	6386	6494	6442
Maximum (Kbps)	6480	6400	6400	6642	6645	6645
Minimum (Kbps)	5840	5600	5120	2640	3360	3360
Std. Dev. (Kbps)	75	80	84	272	175	224

Table 6.3: Avaya RG-II uplink test results. The throughput was computed on sequential samples of 150 ms each. The measurements confidence level is 95% and 3% accuracy.

Avaya RG-II produces a maximum downlink throughput of 5158 Kbps, Cisco Aironet 1200 produces 7024 Kbps. The Cisco Aironet 1200 is 36% faster than the Avaya RG-II. Moreover, Avaya RG-II degrades its performance when overloaded, thus its maximum saturation throughput depends on the offered load.

It is important to note that in the downlink test the only active node in the 802.11 radio cell is the AP itself. The wireless stations receive the packets and return the necessary 802.11 acknowledgment frames. Since, they never send packets in the radio cell, the 802.11 link throughput only depends on the AP. Therefore the aggregate throughput does not change with the number of wireless receivers and data streams.

6.1.2 AP's Uplink Throughput

During this test one or two wireless stations sent a streams of UDP/IP packets to one station on the Ethernet link. The test data stream was made of UDP packets of 1472 bytes of payload. The maximum total amount of offered load to the AP is 800 packets per second. Note that the wireless clients sent packets as fast as they can up to a total offered load of 800 packets per second. Therefore, the channel load was always lower. In fact it is not possible to send such a large stream on the 802.11 link. When running tests with more wireless stations, the total data stream is equally distributed between the different senders, i.e. up to 400 packets per second per sender.

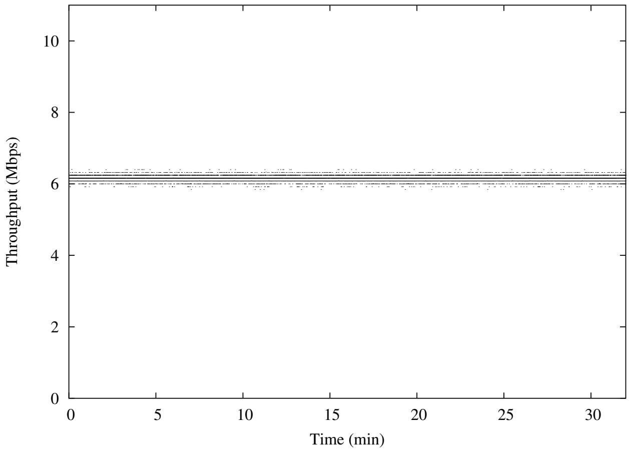
The tests were run the time to collect 12805 consecutive throughput samples of 150 ms each. Therefore the uplink saturation throughput measurements have a confidence level of 95% and an accuracy of 3%.

Figure 6.5 shows an example of the uplink throughput behaviour on a Cisco Aironet 1200 and on an Avaya RG-II. The test was run with one sender (wireless station) and one receiver (Ethernet station).

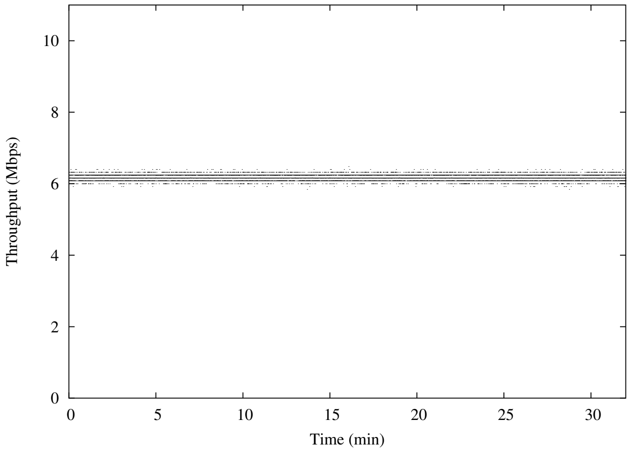
The previous test was repeated 3 times per AP model using one wireless station as a sender and 3 more times using two wireless stations. Note that the same 802.11 client wireless interface (Orinoco Silver 802.11b PC-card) with the same driver was used for all the tests and all the wireless clients.

Table 6.3 shows the results of the test on the Avaya RG-II. Table 6.4 shows the results of the test on the Cisco Aironet 1200. Figure 6.6 shows the uplink average saturation throughput computed for each test repetition and the relative confidence intervals. Figure 6.6a shows the Avaya RG-II behaviour, Figure 6.6b the Cisco Aironet 1200. Figure 6.7 compares the uplink throughput of Cisco Aironet 1200 and Avaya RG-II when using 1 and 2 senders. Note that the two APs behave exactly in the same way with one and with two wireless stations.

The uplink test produces different results with respect to the downlink test. Note



(a) Cisco AIR 1200 Uplink Throughput

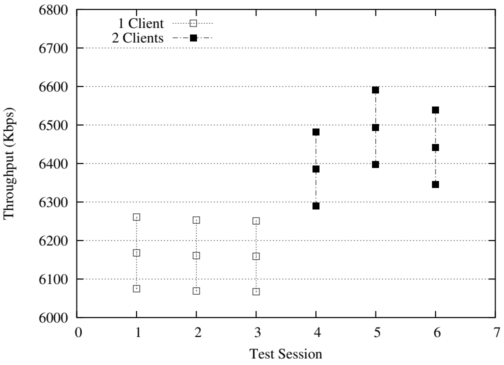


(b) Avaya RGII Uplink Throughput

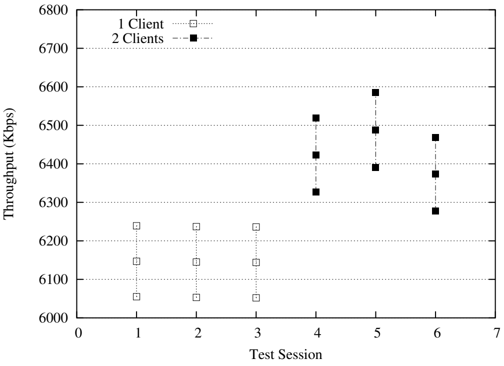
Figure 6.5: Cisco AIR 1200 and Avaya RG-II uplink test results. The graphs show the AP throughput computed on sequential samples of 150 ms each. The two different tests were run the time necessary to collect 12805 samples.

Cisco AIR1200	**1 Sender**			**2 Senders**		
	Test1	**Test2**	**Test3**	**Test1**	**Test2**	**Test3**
Average (Kbps)	6147	6145	6144	6423	6488	6373
Maximum (Kbps)	6403	6403	6403	6883	6880	6880
Minimum (Kbps)	5840	5600	5760	2720	2000	1760
Std. Dev. (Kbps)	80	80	82	293	262	328

Table 6.4: Cisco AIR 1200 uplink test results. The throughput was computed on sequential samples of 150 ms each. The measurements confidence level is 95% and 3% accuracy.

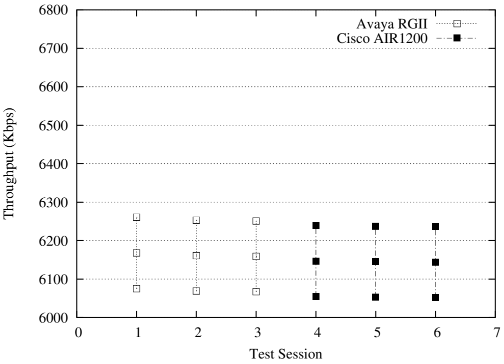


(a) Avaya RGII

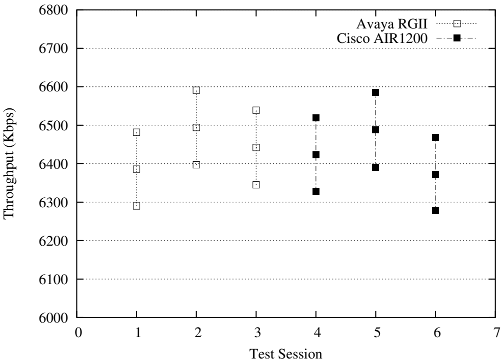


(b) Cisco AIR 1200

Figure 6.6: Uplink test results. Average throughput and confidence intervals for the different test sessions with 1 and 2 senders.



(a) 1 Sender up-link throughput



(b) 2 Senders up-link throughput

Figure 6.7: Avaya RG-II and Cisco AIR 1200 uplink aggregate average throughput and confidence interval with one (a) and two (b) senders. The throughput was computed on sequential samples of 150 ms each. The measurements confidence level is 95% and 3% accuracy.

that:

- Different AP models produce the same uplink saturation throughput.
- The number of senders strongly influences the resulting aggregate saturation throughput. The uplink average aggregate saturation throughput is 6237 Kbps with one sender and 6522 Kbps with two. The increment is equal to 4.6%.

The characteristics of 802.11 Medium Access Control can explain the observed difference between the uplink and the downlink throughput. The Distributed Coordination Function concentrates into the sender all the critical decisions that determine the speed of the packet transmission on the radio link. Generally, an 802.11 receiver is simpler than the transmitter. The receiver station listens to the channel and when a packet is received, it has a well-determined time (SIFS) to return an acknowledgment frame at a fixed data rate (usually 2Mbps with 802.11b).

During the downlink test the AP has to perform several operations. It manages the Ethernet input queue, applies the packets-bridging algorithm to the received packets, and transmits them on the 802.11 link. The faster the AP, the higher the resulting throughput.

During the uplink test, the AP receives packets from the 802.11 media and bridges them to the Ethernet. This second kind of operation is easier. All the tested APs could manage to bridge all the packets coming from the 802.11b media. Therefore, the uplink throughput is limited by the sender speed (wireless clients). When using more than one wireless sender, the 802.11 link throughput increases, thus the AP throughput increases also.

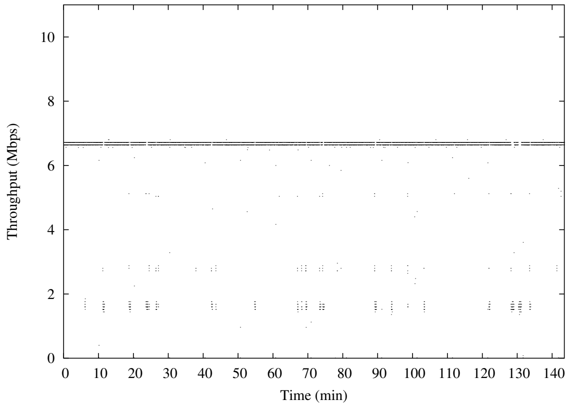
The uplink test allows studying the general IEEE 802.11b cell and wireless station's characteristics more than the behaviour of the AP. The test with one sender shows the wireless sender's speed. Increasing the number of wireless senders, the aggregate throughput increases. This behaviour is coherent with the general characteristics of the 802.11 link. In fact, the throughput of an 802.11 link increases with the number of senders up to the maximum 802.11 capacity. According to the related work, further increments to the number of senders decreases the aggregate throughput [13].

6.1.3 Wireless-to-Wireless Throughput

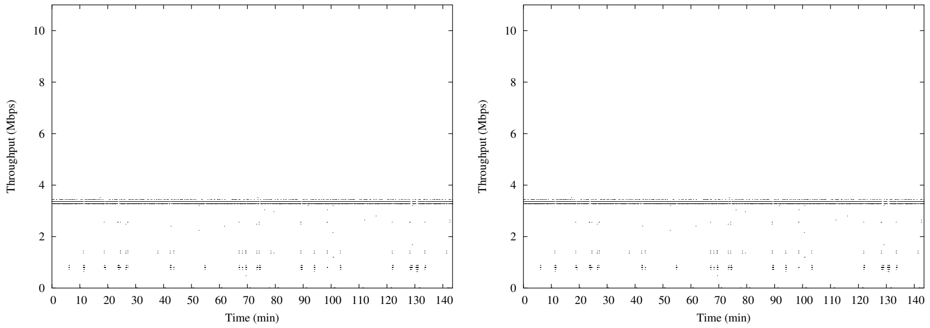
According to the IEEE 802.11 standard [4] when two wireless stations are in the same AP cell, they always exchange packets through the AP. The AP works as a repeater in order to guarantee that the two wireless stations can communicate even if they are at opposite edges of its radio cell.

We run the wireless-to-wireless test in order to verify the 802.11 AP behaviour when acting as a repeater. In this case the AP must forward to the destination the packets just received from the sender. Note that all the packets are transmitted on the same radio channel. Thus the wireless sender and the AP have to compete to obtain access to the same medium. However, the offered load to the AP is limited by the wireless station speed and the 802.11 link capacity with two senders. Only the data stream that reaches the destination contributes to the real test throughput.

Figure 6.8 shows the 802.11 throughput when one wireless station sends to a second one a stream of 800 UDP packets per second (packet size equal to 1472 bytes of UDP/IP payload). The test was conduct using the Avaya RG-II. Table 6.5 shows the statistical indexes for the aggregate throughput and the throughput of each stream. Figure 6.9 and Table 6.6 show the result of the same test on a Cisco AIR 1200. All the



(a) Avaya RGII wireless-to-wireless aggregate throughput on the 802.11 link



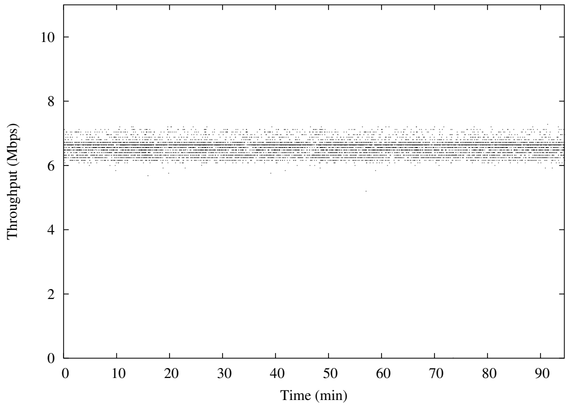
(b) Sender to AP throughput

(c) AP to receiver throughput

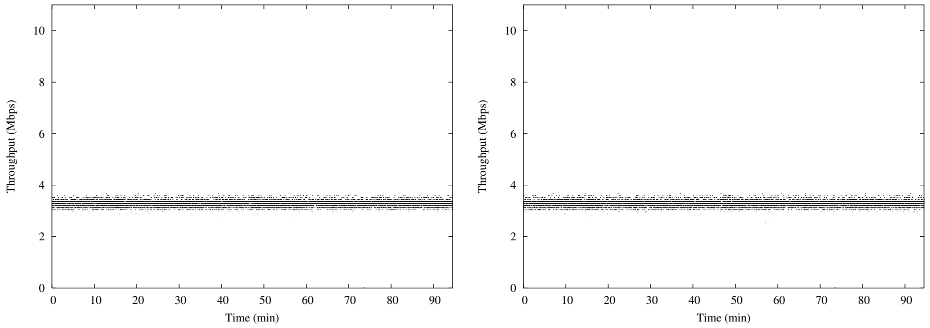
Figure 6.8: Avaya RG-II throughput for wireless-to-wireless communications. The test was run up to collect 7683 consecutive throughput samples of 150 ms.

	WS1 to AP	AP to WS2	Aggregate
Average (Kbps)	2895	2882	5776
Maximum (Kbps)	6240	3520	6800
Minimum (Kbps)	0	0	0
Std. Dev. (Kbps)	1059	1065	2109

Table 6.5: Avaya RG-II Wireless-to-Wireless test result. The throughput was computed on sequential samples of 150 ms packets each. The measurement confidence level is 95% with 5% accuracy.



(a) Avaya RGII wireless-to-wireless aggregate throughput on the 802.11 link



(b) Sender to AP throughput

(c) AP to receiver throughput

Figure 6.9: Cisco AIR 1200 throughput for wireless-to-wireless communications. The test was run up to collect 7683 consecutive throughput samples of 150 ms.

	WS1 to AP	**AP to WS2**	**Aggregate**
Average (Kbps)	3265	3264	6529
Maximum (Kbps)	3680	3680	7280
Minimum (Kbps)	0	0	0
Std. Dev. (Kbps)	176	180	346

Table 6.6: Cisco AIR-1200 Wireless-to-Wireless test result. The throughput was computed on sequential samples of 150 ms packets each. The measurement confidence level is 95% with 5% accuracy.

	Avaya RG-II			**Cisco AIR 1200**		
	Uplink	**Downlink**	**802.11**	**Uplink**	**Downlink**	**802.11**
Average (Kbps)	4610	579	5791	1975	4806	6920
Maximum (Kbps)	6720	5920	6640	2480	6000	7200
Minimum (Kbps)	0	0	0	400	0	0
Std. Dev. (Kbps)	1173	832	128	163	218	293

Table 6.7: Uplink/downlink test results. The throughput was computed on sequential samples of 150 ms each. The measurements confidence level is 95% and 5% accuracy.

measurements have a confidence level of 95% and 5% accuracy.

6.1.4 Uplink/downlink Throughput

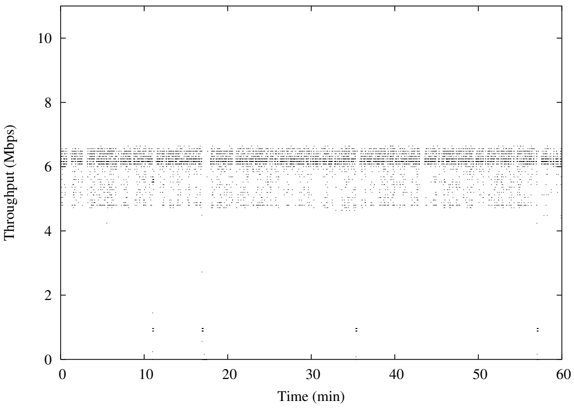
The previous sub-sections illustrate the behaviours of different APs when bridging packets into one of the three directions: downlink, uplink, wireless-to-wireless. In this section we examine the behaviour of the same APs when simultaneously bridging traffic in different directions.

We only examine the case of simultaneous uplink/downlink traffic. For simplicity, we limit our investigation to only two nodes: one Ethernet station and a wireless station. Each node sends to the correspondent node a stream of 400 UDP packets per second (total AP offered load is 800 pkt/sec). More nodes on the Ethernet link do not change the traffic characteristics in both directions. On the wireless side, more nodes imply slightly higher uplink traffic, there is no change in the downlink stream. The fact that the AP has to handle a few more MAC addresses for different destinations should not have a significant impact on performance.

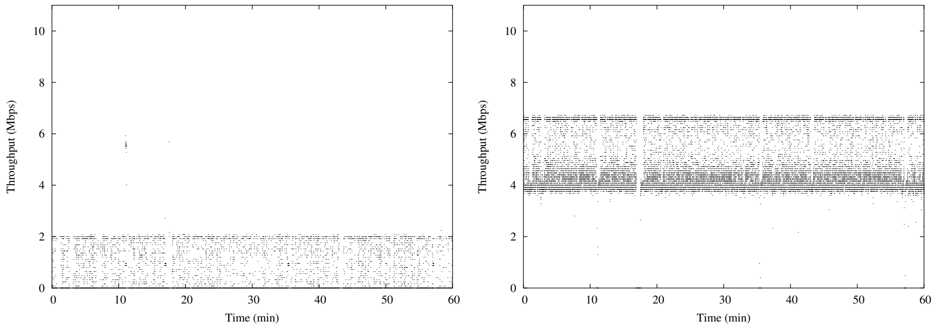
Figure 6.10 shows the behaviour of the Avaya RG-II. Figure 6.11 shows the behaviour of the Cisco Aironet 1200. Table 6.7 shows the average uplink and downlink throughputs of the two APs. The average values are calculated with a confidence level of 95% and an accuracy of 5%. Note that the downlink throughput average of Avaya RG-II has a coefficient of variation larger than 1! The specific result most probably has a lower confidence level and accuracy than the other ones. We did not consider important to repeat the measurement taking more samples. in this section t is more important to underline the anomalous low performance of the downlink throughput more than its absolute correct value.

The result of this test quotes the results of the previous ones with some peculiarities. Table 6.7 shows the aggregate throughput of the 802.11 cell. The Avaya RG-II 802.11 throughput is much higher than the sum of the uplink and downlink average throughput. The downlink throughput is measured on the radio link and is low. Thus, a large part of the 802.11 throughput is enforced by the wireless client transmitting data. However, a part of this traffic is not bridged in the Ethernet link, but dropped by the AP (the AP was connected to the Ethernet node with a cross-over cable using Ethernet in full-duplex mode).

The Avaya RG-II has limited downlink capacity. Therefore, when different stations transmit on the 802.11 medium together with the AP, they take a larger bandwidth partially compensating for the low AP performance. Note that the Avaya RG-II uplink throughput with one sender was 6162 Kbps, higher than the 802.11 throughput measured in this test. This result is partially explained by the several 802.11 data flow



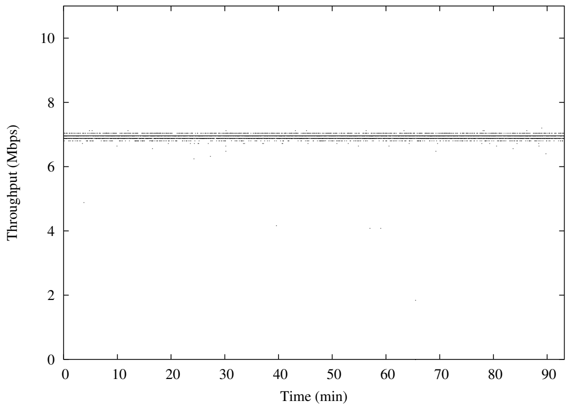
(a) 802.11 aggregate link throughput



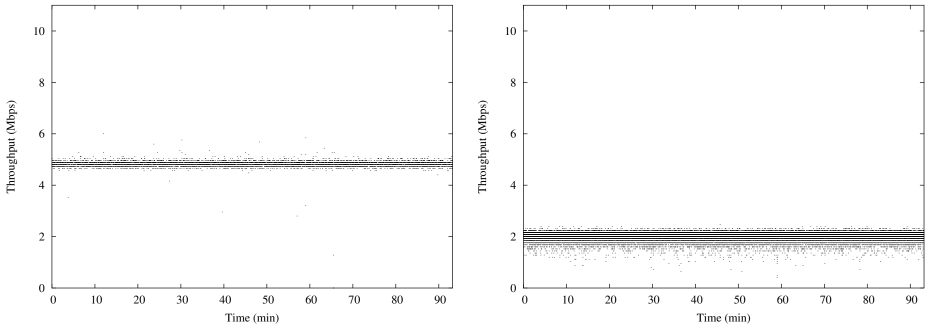
(b) Down-link Throughput

(c) Up-Link Throughput

Figure 6.10: Avaya RG-II uplink/downlink throughput behaviour. The test was run the necessary time to measure the throughput with a confidence level of 95% and with 5% accuracy.



(a) 802.11 aggregate link throughput



(b) Down-link Throughput (c) Up-Link Throughput

Figure 6.11: Cisco AIR 1200 uplink/downlink throughput behaviour. The test was run the necessary time to measure the throughput with a confidence level of 95% and with 5% accuracy.

interruptions (2.5% of samples have a null throughput value). A second factor might be the different data link rate used to transmit the packets by the client and by the AP.

The Cisco Aironet 1200 has a different behaviour. Uplink and downlink streams share the available 802.11 bandwidth in almost fair way. Moreover, almost all the transmitted uplink packets reach the destination Ethernet node.

The 802.11 throughput (6920 Kbps) is higher than the highest measured in the uplink test (6488 Kbps), and lower than the throughput of the downlink test (7000 Kbps). By default, Cisco Aironet 1200 uses a non IEEE 802.11 compliant contention window. The use of a smaller contention window allows improving the downlink throughput reducing the average idle time between two consecutive packets sent by the AP. This special configuration produces the highest throughput when only the AP is transmitting (see Cisco AIR 1200 downlink test). Instead, it does not give any benefit when the AP is only receiving data (Cisco AIR 1200 has the same uplink performance as the Avaya RG-II). The uplink/downlink test produces an intermediate result. However, note that the downlink throughput in this test is higher than the uplink test.

6.1.5 Conclusions

The aim of this work is to measure the maximum saturation throughput of different 802.11 APs. In the previous sub-sections we examined a set of tests and we underlined the general results. Now, it is possible to identify which test or tests combination can be used to measure the maximum saturation throughput of any 802.11 AP model.

Figure 6.12 shows the average aggregate throughput and confidence interval resulting from the previous tests on Avaya RG-II and Cisco Aironet 1200. Note that the uplink test result is for the 2 wireless senders case. The aggregate throughput reported for the uplink/downlink test is the aggregate throughput of the 802.11 cell. This value is an approximation of the up/down link aggregate throughput value.

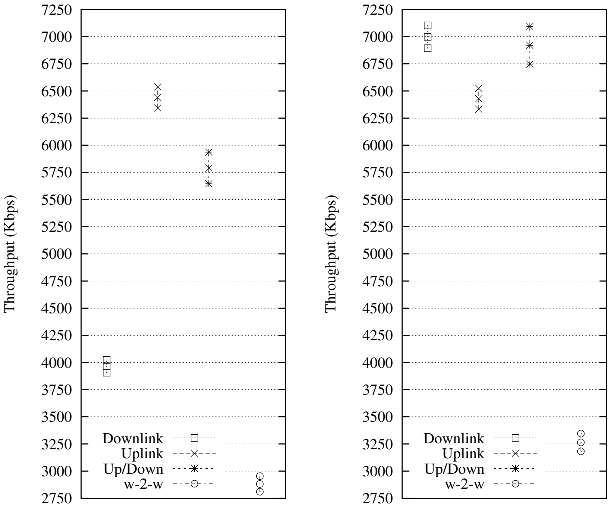
Figure 6.12 shows that there is not a unique test that always produces the maximum saturation throughput with any AP model. For example, the Avaya RG-II produces the highest throughput when performing the uplink test. Instead, Cisco Aironet 1200 produces the highest throughput with the downlink test.

We showed that the uplink test throughput is linked to the wireless station transmission speed (see section 6.1.4). In fact, different AP models produce the same uplink throughput when using the same clients. It is very important to note that the uplink test produces an aggregate throughput that is close to the maximum capacity of the 802.11 medium (in optimal condition and with the proper number of wireless stations). The consequence of this is that the maximum throughput of any AP model is the maximum capacity of the 802.11 link.

Our first conclusion is supported by all our test results. However, it cannot be generally extended to any given AP model. It is always necessary to verify the uplink capacity of any AP model that will not reach the 802.11 link capacity with other kinds of tests. However, an AP that never reaches the maximum 802.11 link throughput is clearly an example of a broken or not properly designed device.

Two important issues still need to be solved:

- The Cisco Aironet 1200 has downlink throughput higher than uplink one.
- Different AP models have different performance despite the fact that they produce the same maximum throughput.



(a) Avaya RGII (b) Cisco AIR 1200

Figure 6.12: Avaya RG-II and Cisco AIR1200 compared test results. The graphs show the aggregate throughput average and confidence intervals for uplink, downlink and uplink/downlink tests. Note that the uplink shows the case of 2 wireless senders and the up/down link test throughput is the aggregate throughput in the 802.11 link that is slightly higher than the AP real aggregate throughput.

The first point is related with the fact that the Cisco Aironet 1200 does not use an IEEE 802.11 compliant contention window. See the uplink/downlink test result explanation (section 6.1.4). Access Points using this kind of solution will not meet our general conclusion, but they are exceptions.

The second point shows the fact that the generic maximum saturation throughput is not a figure of merit for the 802.11 APs. In fact, we already concluded that all the AP models should be able to get the same maximum performance level. The results of all our previous tests show that the AP's key performance index is the downlink maximum saturation throughput. Different AP models have different downlink maximum saturation throughput.

For the rest of this document we focus on the downlink maximum saturation throughput. However, if an AP model does not provide an appropriate maximum downlink saturation throughput, we verify the maximum AP uplink throughput as well. This operation is necessary in order to validate our general conclusions that the maximum saturation throughput of any given AP is however equal to the maximum 802.11 capacity.

6.2 Maximum Saturation Throughput Measurement Procedure

This section describes our recommend procedure for measuring the IEEE 802.11 AP maximum saturation throughput.

Chapter 3 presented the general definition of saturation throughput and the different conditions necessary to maximise it when working with 802.11 devices. In the same chapter, we presented a set of 802.11 AP behaviours that can make difficult to determine the real maximum throughput. Chapter 5 defined the statistical framework for performing the measurement. In the section above different kinds of AP's throughput were examined and a set of necessary tests were defined.

In this section we describe a throughput measurement procedure that allows testing any kind of 802.11 APs. The first sub-section presents the necessary steps to perform a complete test on an AP. The second sub-section describes the recommended testbed for performing the test.

6.2.1 Test Procedure

According to the conclusion of section 6.1, two kind of analysis are necessary on each IEEE 802.11 AP model:

- Measurement of the AP performance, and
- Validation of the AP maximum saturation throughput.

The first step is performed with the downlink throughput test. The second step is performed running the uplink test. The expected test result of the last test is that the uplink maximum saturation throughput is equal the 802.11 link maximum capacity. The second step will be performed only when the AP cannot reach the maximum 802.11 link capacity when downloading data.

We can describe the entire procedure as a sequence of four steps:

1. Set up of the test environment

2. Identification of the optimal AP orientation
3. Measurement of the AP throughput performance (downlink test)
    (a) Optimal offered load measurement
    (b) Maximum downlink throughput measurement
4. (Optional) Verification of the maximum AP throughput (uplink test)

Our recommended testbed, described in the section 6.2.2 covers the first step. The following sub-sections describe the other steps.

6.2.1.1 Optimal AP orientation

The goal of this specific test is to discover the AP radio interface characteristics. If an AP performs differently depending on the antenna orientation, the best orientation needs to be identified. Unfortunately, an exhaustive and accurate investigation needs a very large amount of time and resources.

An AP can be turned in an almost infinite number of ways. However, any AP model has always a clear top and bottom. Many times the vendor recommends an optimal mounting direction for the AP. Therefore it is always possible to restrict the investigation to the AP rotation around its vertical axis.

The most appropriate test to perform is the downlink one. In fact we need to stress the radio interface and verify the AP performance with different orientations.

We recommend to run at least 4 tests turning the AP 90 degrees around the vertical axis after each test, without moving the wireless clients. Note that this procedure does not allow exactly measuring the optimal AP orientation, but only allows discovering the main antenna characteristics and selecting a proper AP orientation.

The downlink throughput measurements still require a confidence level of 95%, but we use an accuracy of 5% instead of 3%. In this way the number of necessary samples is 7683 saving 60% of the test time per session with respect to the time for achieving an accuracy of 3%.

It is important to note that this kind of test often does not produce clear unique results. The effect of the antenna's orientation is not always clear because it is related with unpredictable and not controllable environmental conditions. For example: the Avaya RG-II often has unstable performance with instant throughput changing around different levels (See the result of preliminary tests, figures: 4.2, 4.3, 4.5). It was observed that tests performed with a non-optimal orientation produced the highest level of throughput also. Therefore, the antenna orientation produces measurable effect only in combination with other not reproducible environmental conditions. In general a not optimal orientation increase the performance instability.

We recommend to run this kind of test and to use the resulting best AP's orientation. In case no specific orientation is found, any can be used. In this case it might be possible that performing other tests, a result instability will be observed. In this case, it necessary to run again the antenna orientation test to verify if it is possible to find an optimal orientation in the current environmental conditions.

6.2.1.2 Measurement of the AP throughput performance

This test is performed in two separate steps:

- Optimal offered load measurement
- Maximum downlink saturation throughput measurement

Some APs experience performance degradation when the offered load is higher than the AP bridging capacity. For example, the Avaya RG-II produces the highest downlink throughput with an offered load of around 450 packets per second and then the throughput decreases.

In order to find the optimal offered load, the AP should be tested with all the possible loads. Because the test data stream is made of UDP packets of a fixed dimension (1472 bytes of UDP payload), the only possibility is to change the packet transmission rate from 1 to 900 packets per second (about 11 Mbps).

An exhaustive investigation requires a long time and many resources. Therefore we recommend restricting the offered load test range in order to make practically possible the measurement of the optimal offered load. This is possible by defining appropriate test granularity and optimising the test procedure.

In order to minimise the number of necessary test sessions, we recommend starting the test from the highest possible offered load supported by the Ethernet link and then decreasing it. Using IEEE 802.11b, the APs may have legacy Ethernet (10Mbps) or Fast Ethernet (100Mbps) interfaces. In order to have a fair test condition, it is necessary to run the test with offered loads up to 10Mbps (800 packet per second using packet size equal to the standard Ethernet MTU of 1500 bytes). After a first test session with an offered load of 800 packets per second, the test is repeated several times decreasing the offered load by 100 packets per second each session. The procedure is repeated as long as the measured AP throughput increases or up to the offered load that is completely bridged. In the first case, when the AP throughput decreases, a final test with an offered load of 50 packets per second more and less than the last tested offered load should be conducted. We recommend measuring the AP throughput with a confidence level of 95% and an accuracy of 5%. The approximation used for determining the optimal offered load suggests the opportunity of using a lower accuracy.

The optimal offered load is the one producing the highest saturation throughput within the performed tests. In the case of different offered loads producing the same AP throughput, the highest of those values is selected as the optimal one for performing the following test.

The result of this test already produces a measurement of the downlink maximum saturation throughput but with an accuracy of 5%. We recommend repeating the downlink test with the optimal offered load, but achieving a confidence level of 95% and 3% accuracy.

6.2.1.3 Maximum AP throughput verification

If the previous tests produce a maximum AP's throughput lower then the 802.11 link capacity, the uplink test is necessary. The aim of this test is to validate our conclusion that the maximum saturation throughput of any given 802.11 AP is equal to the maximum 802.11 link capacity.

The uplink test may be performed with one or more wireless clients sending UDP/IP streams to an Ethernet node. In order to reach the maximum 802.11 link capacity several wireless client are necessary. An acceptable approximation can be reached by using two clients, but even a single one is significant if the downlink maximum saturation throughput of the AP was low. During this test, we recommend achieving a measurement confidence level of 95% with 3% accuracy.

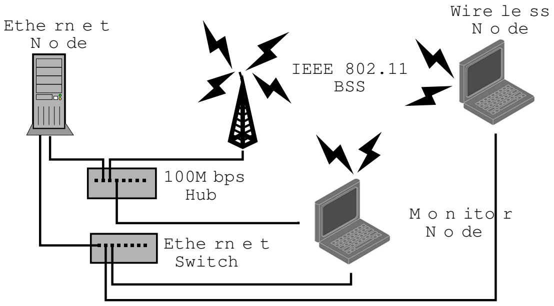


Figure 6.13: Testbed for IEEE802.11 AP throughput Measurements.

6.2.2 Testbed for Maximum Throughput measurements

This section describes our recommended testbed for measuring the IEEE 802.11 AP throughput.

Several times we recommended measuring the 802.11 APs throughput in an optimal environment. The general recommendations of section3.2 can be practically implemented in the following way:

- The test area has to be a small room, such as an office. All the wireless stations are placed in a close range without any obstacles in between.
- The distance between the different radio stations (AP and wireless clients) have to be small and must be constant during the test session. Note that the wireless stations distance must be larger than one meter to respect the vendor's recommendations.
- No other APs and/or BSS (i.e. peer-to-peer cells) should be active in the area to avoid radio interferences. In case other 802.11 channel are in use, they must not overlap the channel in use for the test.

The last point is not always easy to verify. The radio spectrum can be scanned using specific tools designed for this purpose and usually distributed with IEEE 802.11 client interfaces. For example: we used the Orinoco Client Manager[1]. Unfortunately, this kind of tool reports the presence of different APs in the area, but they do not always show the presence of IEEE 802.11 peer-to-peer (Ad-Hoc) cells. Moreover, software tools cannot produce a complete scan of the radio spectrum to identify different radio noise sources. For example: it is not possible to find non IEEE 802.11 devices using an overlapped radio spectrum.

The presence of a different radio noise source might be discovered by analysing the performance of a well-known AP and with a screening of the signal and noise levels as reported by the 802.11 client cards.

Figure 6.13 shows our basic testbed.

In order to perform the test, at least three different computers are necessary:

- Ethernet Node. This machine is used to generate and/or receive the test packet stream on the Ethernet link

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[1] Orinoco Wireless, Proxim Inc.: http://www.orinocowireless.com

- Wireless Node. This machine is used to generate and/or receive the test packet stream on the wireless link. Multiple machines are optional
- Monitor Node. This machine listens both links: Fast Ethernet and 802.11. The traffic on both networks is recorded for a later traffic analysis

One Ethernet link is used to transport the test packet stream to the AP and a second independent one for distributing test management information, for example time synchronization between all the nodes. The Monitor node records the traffic on both interfaces. This is a completely passive node in both tested links. Using a separate machine for recording the traffic, we completely separate the measurement system from the measured one. Moreover, we can minimise the time synchronization problems. In fact, the reception time stamps of the packets on the two networks in the monitor machine are always relative to the same system clock. Note that not all the tests need to dump traffic on both sides of the AP.

The packet stream was generated using an open source tool called MGEN[2]. This tool allows generating and/or receiving UDP/IP streams of packets with a configurable dimension and transmission rate.

For our 802.11b AP tests, we used Linux on the different stations and the following set of wireless cards:

- Wireless Sender/Receiver. Orinoco 802.11b Silver card with orinoco_cs Linux driver distributed with the 2.4.x kernel
- Wireless recorder. Symbol LA 2141 or ZoomAir 4100 with host-AP[3] driver

In order to record the network traffic on both 802.11 link and the Ethernet, we used tcpdump[4]. Note that only the packet header and size need to be recorded.

The throughput calculation and traffic analysis were done using special tools we created for parsing the packet-dumped files generated with tcpdump. Three different programs were made. The first program parses the 802.11 packet dump. The second tool parses the Ethernet packet dump. These two programs extract the different throughput sample set from the trace files discarding the initial transient (first second of the test) and reporting general statistical information (i.e. number of parsed packets, and for 802.11 the number of frame retransmission, beacons, etc...). The third program parses the sample set produced by the previous tools and computes the different statistical indexes (i.e. average, maximum, minimum and standard deviation).

Two different programs are necessary for parsing the trace files. In fact, tcpdump produces different packet traces for the two different mediums: 802.11 and Ethernet. In particular, the 802.11 traffic was dumped using the 802.11 monitoring mode that shows management frames not available on the Ethernet link (i.e. acknowledgments, probing, beacons, etc...). Note that different tcpdump versions may produce different trace files. Moreover, different 802.11 cards in monitoring mode may show more or less frame details. For all these reasons, our tools cannot be used in different testbed, but they need to be adapted to the specific case.

It is important to note that the proposed testbed potentially introduces some measurement errors. A systematic error may be introduced because of the different delays due the packet propagation times. Building our testbed, we assumed that the hub was

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[2] MGEN: The Multi-Generator Toolset. http://manimac.itd.nrl.navy.mil/MGEN/

[3] Host AP driver for Intersil Prism2/2.5/3. http://hostap.epitest.fi/

[4] http://www.tcpdump.org/

able to transmit the packets on the different ports simultaneously. Similarly, we assumed that the packets arrived at the same time to the monitor and to the destination node. These errors are relatively very small and did not influence our measurement. In fact, we measured the throughput, not the delay of the packets.

We measure the throughput using software tools running on standard Linux installations. Thus, the measurement errors are related with the software and system performance. In particular, the precision of the packet time stamp can be critical with respect to the measurement precision. In Chapter 3, section 5, we already analysed this problem. The single packet reception time-stamp can be influenced by a relatively large error. However, by using throughput samples made of several packets and collecting a large sample size we can reduce this kind of error to an acceptable range.

A different problem is due to the usage of an Ethernet Hub to connect the Ethernet node with the AP and the Monitor node. The hub may leak packets affecting the correct execution of the tests. Only the packets that actually reach the destination are considered in our system. However, changes to the offered load, or problems in the Ethernet packets transmission can influence the measured results. Preliminary tests were run to verify the correct behaviour of the hub when handling the load produced by the test streams and the general correct behaviour of the device. However, we observed several problems when using multi-directional streams. Therefore, we used a crossover cable connection between Ethernet node and the AP during such a test. Thus the Ethernet node recorded the data stream in the Ethernet link during these kinds of tests.

6.2.3 Important Notes

According to the throughput definition provided in section 3.1, we computed the APs throughput at network level (level 3). All the network protocol packets transmitted on the wireless link are accounted for the throughput computation, but not the 802.11 link control and management frames.

It is possible to perform different levels of investigation:

- Throughput Analysis: basic throughput performance analysis to calculate the performance of a specific AP
- Behavioural Analysis: the purpose is not only to calculate the APs throughput performance, but also to investigate the reasons for the resulting performance

These two kinds of analysis are performed in a similar way using the same testbed and procedure. The key difference is how deeply the 802.11 link is analysed.

In order to provide a simple throughput analysis, it is only necessary to dump the packets transmitted on the 802.11 link using a tool such as tcpdump and a standard 802.11 client card with is normal driver. All the transmitted packets are visible as coming from a standard Ethernet link; no information is available about the 802.11 link.

In order to perform a deeper AP performance analysis, it is necessary to collect more information about the 802.11 link. Using particular wireless interfaces and with specific drivers is it possible to dump all the 802.11 link layer frames including the AP's beacons, 802.11 link acknowledgment frames and all management and control 802.11 frames. This deeper kind of analysis requires more resources in terms of time to set up the necessary drivers and tools and complexity of the traffic analysis compared to the standard one.

It is important to note that both approaches have some important drawbacks:

- Current 802.11b client interfaces and/or their drivers seem to not efficiently dump all 802.11b link frames in monitoring mode. Several 802.11 frames are dropped along a test. In order to avoid erroneous throughput measurements it is necessary to carefully analyse the traffic dump to identify possible errors. For example: the analysis of the traffic dump often shows consecutive 802.11 acknowledgment frames. This happens because some frames were dropped (at least one data frame). In order to avoid measurement errors, samples including possible errors have to be discarded.

- In order to make correct throughput measurement, the monitor node must be completely passive. This condition can be only achieved setting the 802.11 wireless client to monitoring mode, but this mode make many wireless card drivers returning 802.11 link frames. A possible compromise could be to use the wireless monitor interface in infrastructure (managed) mode but without assigning any IP address to it and avoiding generating any packet on the wireless link. However, some AP models deassociate the wireless client if it does not transmit packets for more than a few minutes. When the client is deassociated tcpdump does not dump any more packets and the test fails.

A solution is to set the sniffer wireless card to monitoring mode, but without forcing to dump 802.11 link frames information. This kind of configuration is only possible with some specific 802.11b cards. Moreover, using this configuration one collects a minimal set of information and it is impossible to verify if (and when) the monitor system drops packets (i.e. miss-behaviours of the wireless card in monitoring mode or even temporary radio reception failures).

We suggest to set the sniffer wireless interface to monitoring mode and to dump all the 802.11 link frames. In this way it is possible to get as much information about the AP behaviour as possible. Moreover, 802.11 frames lost can be identified during the traffic analysis and the resulting measurement errors limited.

It is important to note that the procedure to minimize the sample errors implies enlarging the different test sessions times. Because the possible invalid samples that have to be discarded, it is not possible to exactly estimate the total test session time. Therefore, it is necessary to run each test sessions for a longer time in order to collect enough data for the throughput computation.

Chapter 7

IEEE 802.11 AP's Saturation Throughput

This chapter presents the results of the tests we performed on several different AP models according to our procedure, and it has two aims. The first one is to validate our recommended test procedure. The second one is to verify the general conclusions we present in the previous chapter. In particular:

- The maximum downlink saturation throughput is the key throughput performance index of any 802.11 APs
- The maximum saturation throughput of all 802.11 APs is equal to the maximum 802.11 link capacity. Some APs reach the highest performance bridging traffic downlink and uplink, other APs only on the uplink

7.1 Former Lucent products

In this section we analyse the performance of a set of 802.11b APs with different characteristics distributed by different vendors. The common aspect of all these devices is the fact that they are different evolutions of the former Lucent Inc. WaveLAN 802.11 products.

All the APs we examine in this subsection are based on exactly the same radio implementation. All devices are made of a main unit that changes depending on the AP model, and a PCMCIA wireless card that includes the 802.11 specific hardware (MAC protocol implementation chipset, radio modem and radio antenna). The PC-Card used by the different APs is exactly the same and it can be exchanged between different units. Note that this PCMCIA wireless card is a regular former Lucent, now Proxim/Orinoco or Avaya 802.11b client card. One can take the wireless interface from the AP and plug into your notebook and vice-versa.

We examine all these APs together in order to analyse and compare the different APs behaviours knowing that all the devices use the same radio implementation.

7.1.1 Avaya RG-II

The RG-II is a low-price device for home usage. The AP is made of an electronic board with a PCMCIA interface placed on one of the sides. The radio module is an Avaya

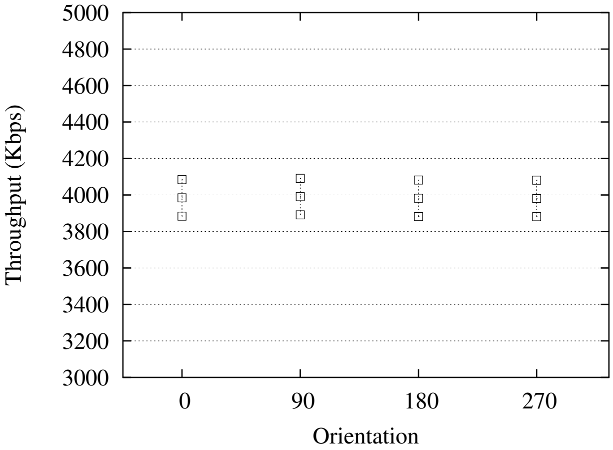


Figure 7.1: Avaya RG-II downlink throughput versus AP/Client orientation. The diagram shows the average throughput value and its confidence interval (confidence level 95%, 5% accuracy).

	0 Degrees	**90 Degrees**	**180 Degrees**	**270 Degrees**
Average	3984	3991	3982	3981
Maximum	4320	4320	6880	6480
Minimum	3760	3680	3040	3760
Sdt. Dev.	77	82	107	84

Table 7.1: Avaya RG-II downlink throughput versus orientation (average confidence level 95%, accuracy 5%).

PCMCIA wireless client.

In the previous chapter, we already examined the behaviour of the RG-II, here we briefly summarize the main characteristics adding extra details. Figure 7.1 shows the downlink saturation throughput with different AP's orientations. The 0 degrees position corresponds to the AP front side facing the client. Table 7.1 compares the statistical indexes of the different test-session results. Note that it is not possible to identify any particular orientation. During the preliminary tests, we observed a clear antenna orientation effect (see figure 4.5) with an optimal orientation of 180 degrees. There are two non-mutually exclusive possible explanations for such a result:

- The different tests were performed at the same place, in the same general conditions, but at different times. Despite all measurable parameters showing the same environment conditions, we still cannot be sure that the overall environmental conditions were exactly the same. It is possible that at the time we performed the tests there were different conditions than when we run the preliminary ones.
- Unfortunately, the AP we used for the preliminary test was accidentally broken. To perform this last test we used a second identical station (i.e. exactly same hardware and firmware). However, it could be that there was small but important differences in the two units that may explain the different antenna performance.

According to the current AP's orientation test results and our previous experience, we

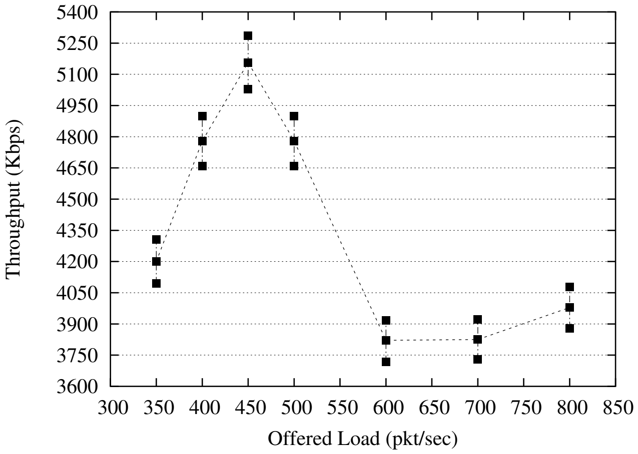


Figure 7.2: Avaya RG-II downlink throughput versus offered load. The diagram shows the average throughput value and its confidence interval (confidence level 95%, 5% accuracy).

	350pkt/sec	**400**pkt/sec	**450**pkt/sec	**500**pkt/sec	**600**pkt/sec	**700**pkt/sec	**800**pkt/sec
Average (Kbps)	4200	4779	5158	4780	3821	3825	3982
Maximum(Kbps)	5600	5840	6560	4960	3920	4000	6880
Minimum(Kbps)	2560	3440	4960	4560	3680	3604	3040
Sdt. Dev. (Kbps)	59	174	69	65	38	60	107

Table 7.2: Avaya RG-II downlink throughput versus offered load.

decided to use an AP's orientation of 180 degrees, an optimal orientation according to the preliminary tests.

Figure 7.2 shows the downlink throughput versus the offered load. Table 7.2 compares the statistical indexes of the different test-session results. The Avaya RG-II produces the highest saturation throughput with an offered load of 450 pkt/sec. Note that the performance degrades 22% with respect to the maximum value when offering a load equal to the full Ethernet link capacity (800 pkt/sec).

Figure 7.3 shows the instant saturation throughput of the Avaya RG-II in optimal conditions (180 degrees AP orientation, 450 pkt/sec offered load) and the Table 7.3 reports the relative statistical indexes. This test was run in order to collect 12805 consecutive samples of 150ms each. Therefore the average value has a confidence level of 95% and 3% accuracy.

Average (Kbps)	5158
Maximum (Kbps)	6560
Minimum (Kbps)	4960
Sdt. Dev. (Kbps)	69

Table 7.3: Avaya RG-II downlink maximum saturation throughput significant statistical indexes (confidence level 95%, 3% accuracy).

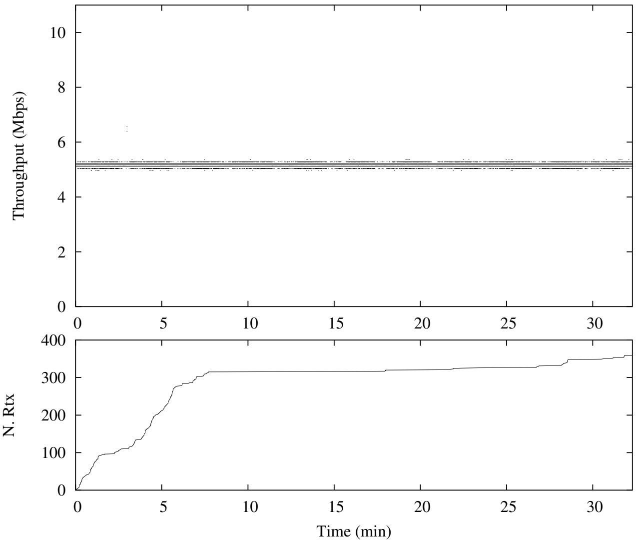


Figure 7.3: Avaya RG-II downlink instant saturation throughput in optimal conditions (180 degrees AP orientation, 450 pkt/sec offered load) and cumulate number of packet retransmissions.

Note that the Avaya RG-II downlink maximum saturation throughput is lower than the IEEE 802.11b link capacity. However, the 802.11 data link traffic analysis does not show any abnormal behaviour during the test that may explain such a result. The AP sends the beacons at regular intervals (102 ms average beacon transmission interval, no detected missing beacon). The 802.11 link packet retransmission rate is fairly low: 0.04% of 802.11 data frames were retransmitted (358 retransmissions over 834165 total packets). No 802.11 management packets were sent. Thus, no RTS/CTS messages, association request/reply, authentication request/reply or probing request/reply were sent.

A likely conclusion is that the AP cannot simply transmit packets faster, therefore the channel is not used for a large fraction of the time. The number and distribution of the 802.11 data frame retransmission events and the value of the maximum throughput could suggest the alternative possibility that this AP only sends data at 5.5 Mbps. To verify this hypothesis, we performed a short downlink test where we captured even the radio header of the 802.11 frames. This test showed that all data frames are sent at 11Mbps, so the first hypothesis was the correct one.

On the other hand, it is important to note that the Avaya RG-II uplink traffic is equal to the maximum IEEE 802.11b link, as was demonstrated in section 6.1. Thus, the Avaya RG-II confirms the hypothesis that the maximum saturation throughput of any AP model is equal to the 802.11 link capacity. However, this AP reaches the maximum link capacity only when bridging the traffic uplink.

7.1.2 Proxim/Orinoco AP1000

This device was originally developed by Lucent Inc. and distributed as WaveLAN AP1000, and then it was distributed as Orinoco AP1000 (this is the version we tested), Avaya AP1, and with different names by different OEMs. This product was recently

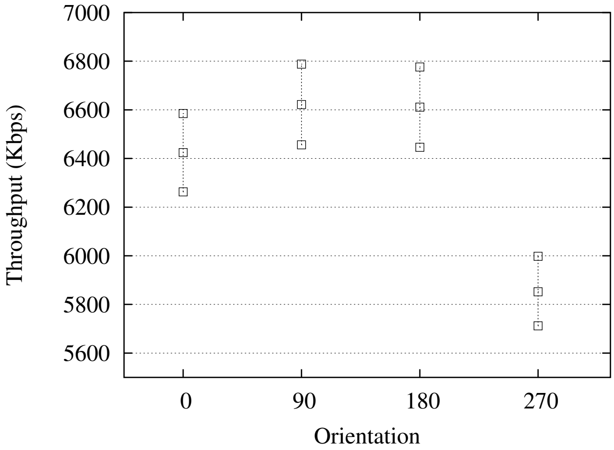


Figure 7.4: Orinoco AP1000 downlink saturation throughput versus AP/Client orientation. The diagram shows the average throughput value and its confidence interval (confidence level 95%, 5% accuracy).

	0 Degrees	90 Degrees	180 Degrees	270 Degrees
Average	6424	6622	6611	5859
Maximum	7040	6960	6960	6960
Minimum	0	5920	4000	3920
Sdt. Dev.	695	145	221	113

Table 7.4: Orinoco AP1000 downlink saturation throughput versus AP/Client orientation (average confidence level 95%, accuracy 5%).

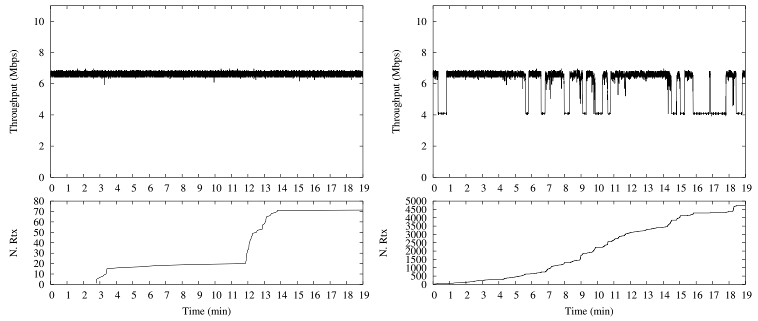
discontinued from the market.

Figure 7.4 shows the downlink saturation throughput with different AP's orientations with respect to the client. The 0 degrees position corresponds to the AP front side facing the client. Table 7.4 compares the statistical indexes of the different test-sessions results. Note that the AP's orientation has a significant impact on the performance. The test showed that with some AP orientation ranges, the antenna performs better producing more stable throughput levels. Figure 7.5 shows the instant saturation throughput produced by the Orinoco AP1000 with the best and worse AP's orientations. Note the large different number of retransmitted packets in the two cases.

Figure 7.6 shows the AP1000 downlink throughput versus offered load. Table 7.5

	500pkt/sec	600pkt/sec	700pkt/sec	800pkt/sec
Average (Kbps)	5989	6622	6621	6622
Maximum(Kbps)	6880	6960	7040	6960
Minimum(Kbps)	880	6080	6000	5920
Sdt. Dev. (Kbps)	201	143	144	145

Table 7.5: Orinoco AP1000 downlink saturation throughput versus offered load (confidence level 95%, accuracy 5%).



(a) 90 degrees orientation

(b) 270 degrees orientation

Figure 7.5: Orinoco AP1000 downlink instant saturation throughput versus AP/Client orientation and cumulative number of packet retransmissions.

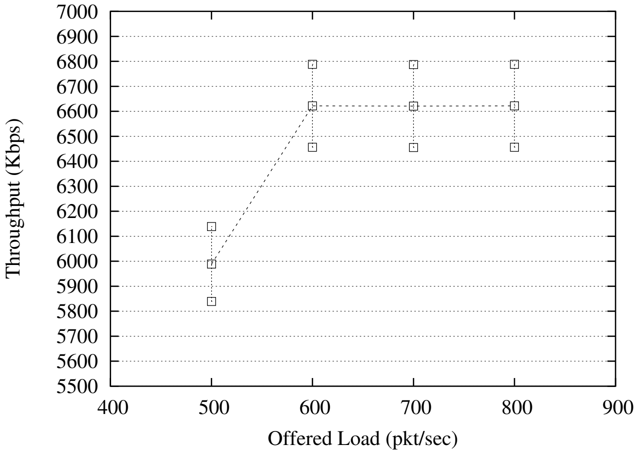


Figure 7.6: Orinoco AP1000 downlink saturation throughput versus offered load. The diagram shows the average throughput value and its confidence interval (confidence level 95%, 5% accuracy).

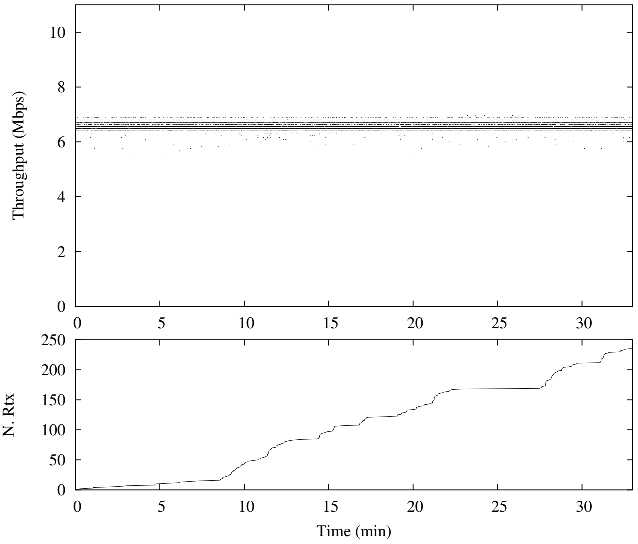


Figure 7.7: Orinoco AP1000 downlink instant saturation throughput under optimal conditions (90 degrees AP orientation, 800 pkt/sec offered load) and cumulative number of packet retransmissions.

Average (Kbps)	6609
Maximum (Kbps)	6960
Minimum (Kbps)	5520
Sdt. Dev. (Kbps)	145

Table 7.6: Orinoco AP1000 downlink maximum saturation throughput significant statistical indexes (average confidence level 95%, 3% accuracy).

compares the statistical indexes of the different test-session results. The saturation throughput of the Orinoco AP1000 is independent from the offered load.

Figure 7.7 shows the instant throughput of the Orinoco AP1000 in optimal conditions (90 degree AP orientation, 800 pkt/sec offered load) and Table 7.6 reports the relative statistical indexes. This test was run in order to collect 12805 consecutive samples of 150ms each. Therefore, the average value has a confidence level of 95% and 3% accuracy.

The Orinoco AP1000 saturates the full IEEE 802.11b link capacity when bridging the traffic form the Ethernet to the wireless link (downlink). Therefore, it was not necessary to run the uplink test to verify our conclusion that any AP's maximum saturation throughput is equal to the 802.11 link capacity.

7.1.3 Proxim/Orinoco AP2000

The Proxim/Orinoco AP2000 is the evolution of the previous model and it still available on the market. This AP uses the same radio interface (the Orinoco/Lucent wireless client) and the same device chassis as the previous model. Instead, the AP2000's internal implementation and its firmware are completely different from the AP1000 ones. According to the vendor brochures, the newer AP model has a much faster CPU and

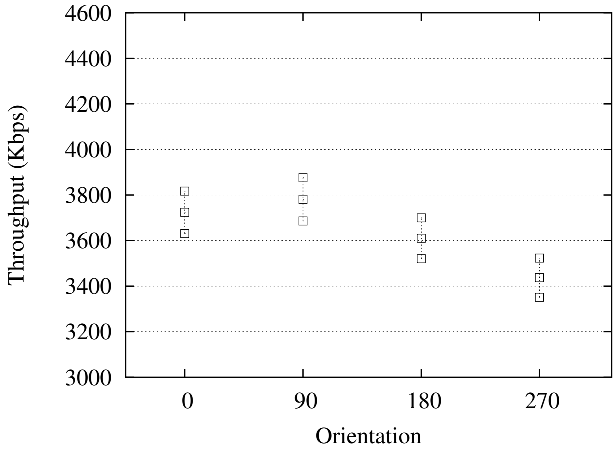


Figure 7.8: Orinoco AP2000 downlink saturation throughput versus AP/Client orientation. The diagram shows the average throughput value and its confidence interval (confidence level 95%, 5% accuracy).

	0 Degrees	**90 Degrees**	**180 Degrees**	**270 Degrees**
Average	3724	3781	3610	3610
Maximum	7280	7280	7280	7280
Minimum	0	0	0	0
Sdt. Dev.	1633	1650	1621	1621

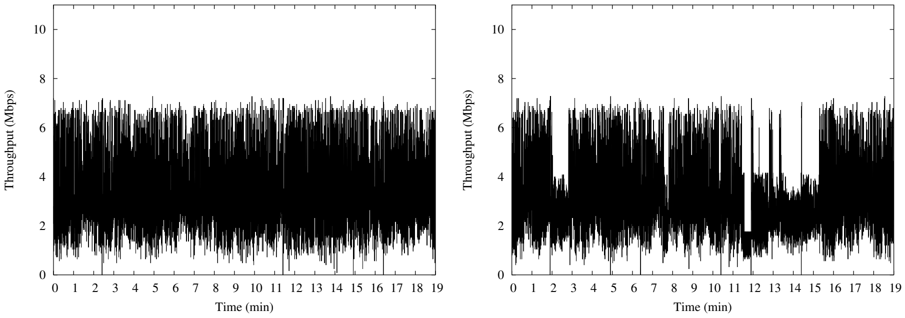
Table 7.7: Orinoco AP2000 downlink saturation throughput versus AP/Client orientation (average confidence level 95%, accuracy 5%).

much more internal memory compared to the AP1000. Moreover, more features were added to the AP2000 including the support for IEEE 802.11a and IEEE 802.11g (using different radio modules). Nevertheless, we only tested the Proxim/Orinoco AP2000 with an 802.11b interface.

Figure 7.8 shows the downlink saturation throughput with different AP/Client orientations. The 0 degrees position corresponds to the AP front side facing the client. Table 7.7 compares the statistical indexes of the different test sessions. As it was observed with the AP1000, the AP2000's orientation has a significant impact on the throughput performance.

The measured AP2000 downlink throughput is quite low and the behaviour of the instant throughput is different with respect to the AP1000. Figure 7.9 shows the instant saturation throughput produced by the Orinoco AP2000 with the best and worse AP orientations. Note the large difference of the current case compared to the AP1000 case (see Figure 7.5).

Figure 7.10 shows the AP2000's downlink saturation throughput versus the offered load. Table 7.8 compares the statistical indexes of the different test sessions. The Orinoco AP2000 performance degrades when overloaded. Moreover, despite the effort of optimizing the test environment, the AP still shows unstable throughput performance. Figure 7.11 shows the instant throughput of the test-sessions with an offered load of 550 (Figure 7.11a), 600 (Figure 7.11b) and 650 (Figure 7.11c) pkt/sec. Note



(a) 90 degree orientation

(b) 270 degree orientation

Figure 7.9: Orinoco AP2000 downlink instant saturation throughput versus AP/Client orientation.

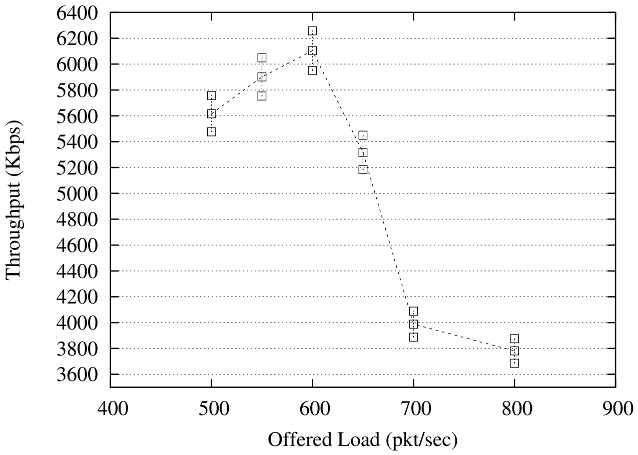
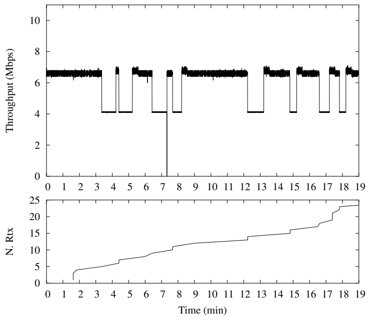


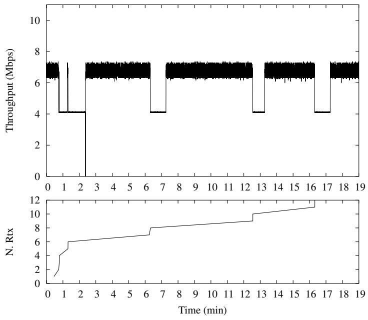
Figure 7.10: Orinoco AP2000 downlink saturation throughput versus offered load. The diagram shows the average throughput value and its confidence interval (confidence level 95%, 5% accuracy).

	500pkt/sec	**550**pkt/sec	**600**pkt/sec	**650**pkt/sec	**700**pkt/sec	**800**pkt/sec
Average (Kbps)	5616	5901	6104	5317	3988	3781
Maximum(Kbps)	6800	7120	7360	7040	7360	7280
Minimum(Kbps)	800	0	0	0	0	0
Sdt. Dev. (Kbps)	807	1147	1179	1138	1571	1650

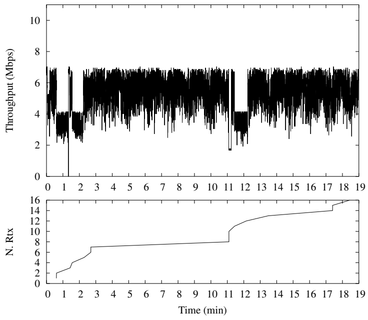
Table 7.8: Orinoco AP2000 downlink saturation throughput versus offered load (average confidence level 95%, accuracy 5%).



(a) 550 pkt/sec offered load instant throughput



(b) 600 pkt/sec offered load instant throughput



(c) 650 pkt/sec offered load instant throughput

Figure 7.11: Orinoco AP2000 downlink instant saturation throughput in an optimal environment and with optimal orientation and different offered loads. The diagrams show the throughput samples and cumulative number of packet retransmissions.

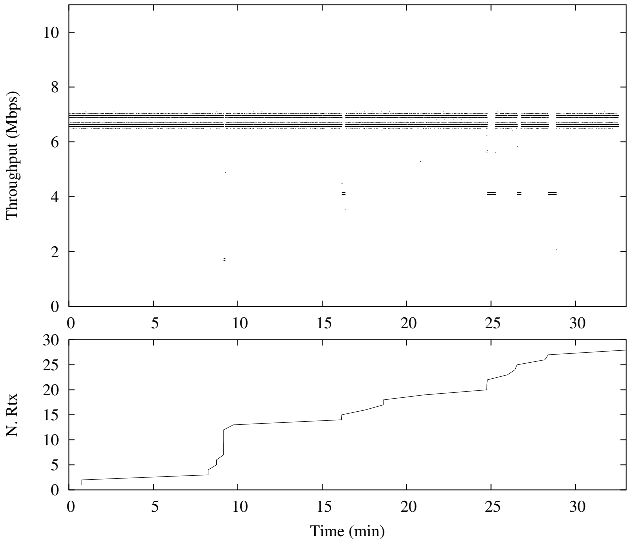


Figure 7.12: Orinoco AP2000 downlink instant saturation throughput in optimal conditions (90 degrees AP orientation, 600 pkt/sec offered load) and cumulative number of packet retransmissions.

Average (Kbps)	6636
Maximum (Kbps)	7120
Minimum (Kbps)	0
Sdt. Dev. (Kbps)	612

Table 7.9: Orinoco AP2000 downlink maximum saturation throughput significant statistical indexes (confidence level 95%, 3% accuracy).

that the saturation throughput is strongly influenced by the offered load. In 550 and 600 pkt/sec cases, the visible different levels of throughput are clearly related to the usage of at least two of the four 802.11b link rates (most probably 11Mbps and 5.5 Mbps). The changes between the different link rates may be related to consecutive packet lost. In the 650 pkt/sec case, there is the superimposition of a new kind of effect on the previously described one. The AP seems to not be able to handle the amount of incoming packets from the Ethernet link and the transmission of the data frames to the 802.11 link. The result is a large variance of the produced 802.11 link throughput (see Figure 7.11c).

Figure 7.12 shows the Orinoco AP 2000's instant throughput in optimal conditions (90 degrees AP orientation, 600 pkt/sec offered load) and Table 7.9 reports the measured statistical indexes. The test was run the necessary time to collect 12805 consecutive samples of 150ms each. Therefore, the computed average value has a confidence level of 95% and 3% accuracy. Note that, despite the fact that less than 30 data frames needed to be retransmitted on the 802.11 link, the AP changes several times the data transmission rate. This behaviour reduced the measured average saturation throughput.

It is important to note that the Orinoco AP2000 with the tested configuration seems to be extremely sensitive to the environmental conditions. Despite our effort to provide an optimal environment and to optimize the AP test conditions (i.e. optimal orientation and offered load), it was not possible to make the device work with completely stable performance over long time intervals. This behaviour could impact our measurement accuracy, but it seems to be a specific characteristic of this model.

The Orinoco AP2000 saturates the full IEEE 802.11b link capacity when bridging the traffic form Ethernet to wireless link. It was not necessary to run the uplink test to verify our assumption that any AP maximum saturation throughput is equal to the 802.11 link capacity.

7.1.4 Notes on former Lucent 802.11b APs

The analysis of the maximum saturation throughput of Avaya RG-II, Orinoco AP1000, and Orinoco AP2000 showed some common and non-common characteristics.

All the different APs use the same kind of 802.11 radio interface: the former Lucent wireless PCMCIA client. As a consequence, all the APs show a relation between performance and the device orientation. Orinoco AP1000 and AP2000 have exactly the same behaviour, since they use an identical chassis. The Avaya RG-II has a different behaviour, probably because the wireless card is mounted in a different position.

The different APs maximum downlink saturation throughput seems to be bounded by the maximum radio performance. All former Lucent products use the same radio interface, but different AP implementations may limit the performance in specific conditions. The Orinoco AP1000 and AP2000 produce the same downlink maximum saturation throughput, but they have opposite behaviours in response to increasing offered loads. Despite the fact that the AP2000 has the best hardware (CPU and Memory), the former AP1000 is clearly the most efficient AP of the tested ones. The Avaya RG-II has a similar behaviour to the previous APs, in particular to the AP2000, but with much lower maximum downlink saturation throughput. However, this last AP model has the simplest hardware implementation.

All the three different APs run different software. Specific firmware might implement different policies or offer different possible configurations. As a consequence, they produce different results under the same test conditions. In particular, the APs responses to radio link errors were very different. Note that the AP2000 seems to be much more sensitive to radio transmission errors than the other AP models. The performance degradation that was observed when increasing the offered load might be related to a non-efficient firmware implementation too.

7.2 Cisco Aironet 1200

The Cisco AIR 1200 was extensively studied in the previous chapter. In this section we apply to our complete test procedure using the same "extreme" AP's configuration we used in the first preliminary test (see section 4), but not in chapter 6. To perform the test showed in chapter 6 we used a safe configuration that enforces backward compatibility to legacy 802.11 devices. In this section we show how the performance changes without this last constraint. Note that in both cases we activated the offered "Aironet extensions" option.

Figure 7.13 shows the downlink saturation throughput with different AP orientations with respect to the client. The 0 degrees position corresponds to the AP facing client. Table 7.10 compares the statistical indexes of the different test session results. Figure 7.14 shows the instant saturation throughput and 802.11 link data frame retrans-

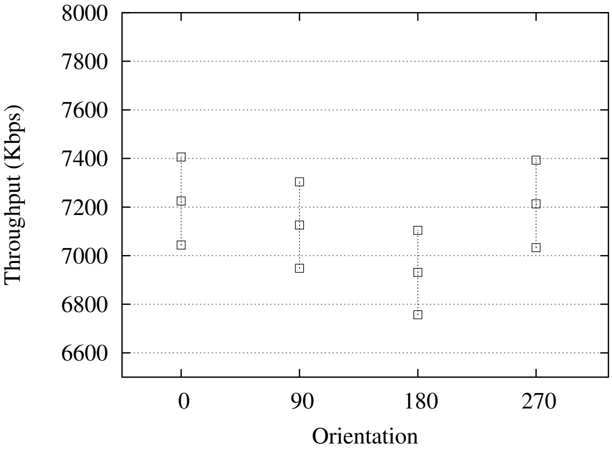
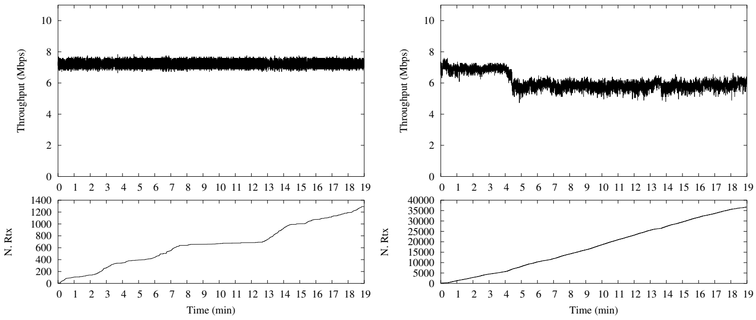


Figure 7.13: Cisco AIR 1200 downlink saturation throughput versus AP/Client orientation. The diagram shows the average throughput value and its confidence interval (confidence level 95%, 5% accuracy).

	0 Degrees	90 Degrees	180 Degrees	270 Degrees
Average	7225	7126	6080	7213
Maximum	7840	7760	7600	7760
Minimum	6640	6400	4720	6160
Sdt. Dev.	243	214	515	270

Table 7.10: Cisco AIR 1200 downlink saturation throughput versus AP/Client orientation (average confidence level 95%, accuracy 5%).



(a) 0 degrees orientation

(b) 180 degrees orientation

Figure 7.14: Cisco AIR 1200 downlink instant saturation throughput versus AP/Client orientation. The diagrams show the throughput samples (top) and cumulative number of packet retransmissions (bottom).

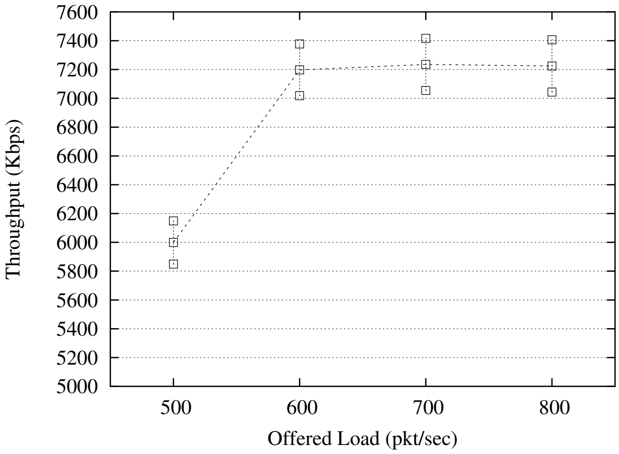


Figure 7.15: Cisco AIR 1200 downlink saturation throughput versus offered load. The diagram shows the average throughput value and its confidence interval (confidence level 95%, 5% accuracy).

	500pkt/sec	**600**pkt/sec	**700**pkt/sec	**800**pkt/sec
Average (Kbps)	5999	7198	7235	7225
Maximum(Kbps)	6240	7760	7760	7840
Minimum(Kbps)	5760	3520	6720	6640
Sdt. Dev. (Kbps)	74	253	254	243

Table 7.11: Cisco AIR 1200 downlink saturation throughput versus offered load (confidence level 95%, accuracy 5%).

mission produced by the Cisco Aironet 1200 with the best and worse AP orientations. Note the extremely high number of packet retransmissions during the 270 degrees test.

The previous test showed that there is an influence of the AP's orientation on the average saturation throughput. No relation between orientation and throughout was observed during the previous sets of tests. The reason for such a different result could be some unpredictable different test conditions, or the effects of the missing backward 802.11 compatibility. More details are given at the end of this subsection.

Figure 7.15 shows the Cisco AIR 1200 downlink throughput versus offered load. Table 7.11 compares the statistical indexes of the different test sessions. The Cisco Aironet 1200 does not degrade the saturation throughput performance when overloaded.

Figure 7.16 shows the instant throughput of the Cisco AIR 1200 in optimal conditions (0 degrees AP orientation, 800 pkt/sec offered load) and Table 7.12 reports the computed statistical indexes. This test was run in order to collect 12805 consecutive samples of 150ms each. Therefore, the average value has a confidence level of 95% and 3% accuracy.

In order to understand the different maximum saturation throughput values we measured with the Cisco Aironet 1200 running alternative configurations, we ran some short downlink tests capturing the 802.11 radio frame headers. Using "Aironet Extension" and no legacy 802.11 compatibility mode the AP transmits all the data, acknowl-

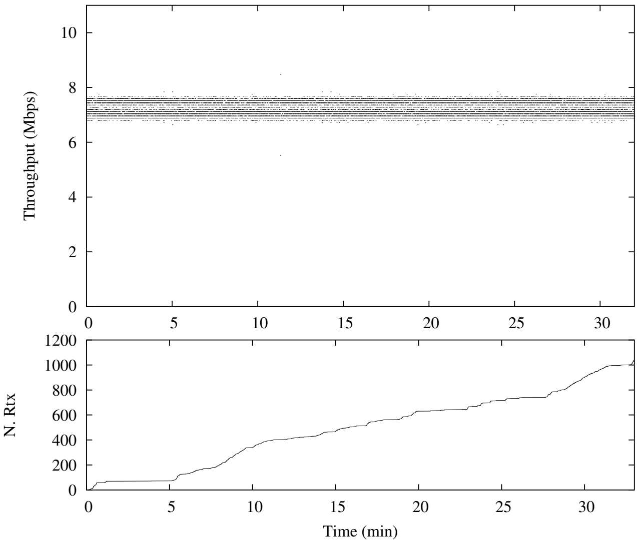


Figure 7.16: Cisco AIR 1200 downlink instant saturation throughput in optimal conditions (0 degrees AP orientation, 800 pkt/sec offered load) and cumulate number of packet retransmissions.

Average **(Kbps)**	7233
Maximum **(Kbps)**	8480
Minimum **(Kbps)**	5520
Sdt. Dev. **(Kbps)**	251

Table 7.12: Cisco AIR 1200 downlink maximum saturation throughput significant statistical indexes (confidence level 95%, 3% accuracy).

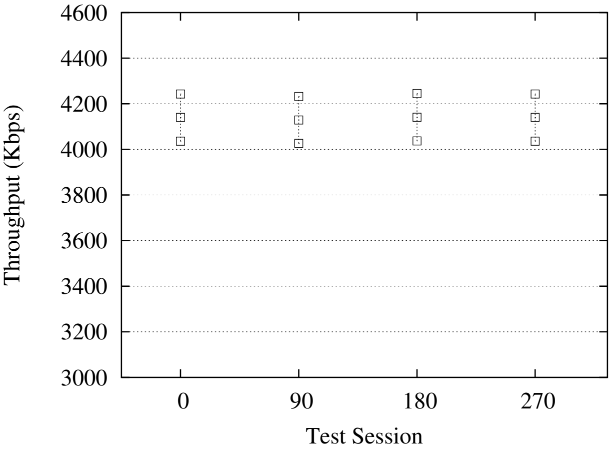


Figure 7.17: Ericsson A11d downlink saturation throughput versus AP/Client orientation. The diagram shows the average throughput value and its confidence interval (confidence level 95%, 5% accuracy).

edgment and control frames at 11 Mbps, but the beacons are always sent at 1Mbps. This configuration produces the highest and the most unstable downlink saturation throughput. In fact the acknowledgments frames are sent at 11Mbps, increasing the probability of 802.11 link data frame transmission errors. By forcing the legacy 802.11 client support, the AP starts to transmit all acknowledgment and control/management frames at 2 Mbps, but the beacons are still transmitted at 1 Mbps. It is interesting to note that in this case the maximum downlink saturation throughput decreases around 3% compared to the previous one. No difference was noticed in the 802.11 link between the previous cases and the configuration without the Aironet Extension, but a much lower throughput around 6.3 Mbps was observed (see Figure 4.7). This result supports our hypothesis that the "Aironet Extension" reduces the contention window with respect to the IEEE 802.11 standard dimension. Unfortunately, we could not completely verify it via measurements.

7.3 Ericsson A11d (Symbol AP-4121)

Ericsson distributed with its own brand a set of OEM 802.11 wireless LAN products. We had the opportunity to test the Ericsson A11d, equivalent to a Symbol AP-4121, but with an Ericsson customized firmware. This kind of AP was designed for office/business applications and is discontinued now.

Figure 7.17 shows the downlink saturation throughput with different AP orientations with respect to the client. The 0 degrees position corresponds to the AP facing the client. Table 7.13 compares the statistical indexes of the different test sessions. Note that it was not possible to observe any influence of the AP's orientation on the saturation downlink throughput. We select the orientation 0 degrees as the optimal one for continuing the test.

Figure 7.18 shows the Ericsson A11d downlink saturation throughput versus the offered load. Table 7.14 compares the different statistical indexes of the test sessions. Note the very large influence of the offered load on the saturation downlink throughput.

	0 Degrees	**90 Degrees**	**180 Degrees**	**270 Degrees**
Average	4140	4129	4141	4140
Maximum	5280	4497	4720	4480
Minimum	322	3840	3120	3920
Sdt. Dev.	79	40	63	63

Table 7.13: Ericsson A11d downlink saturation throughput versus AP/Client orientation (confidence level 95%, accuracy 5%).

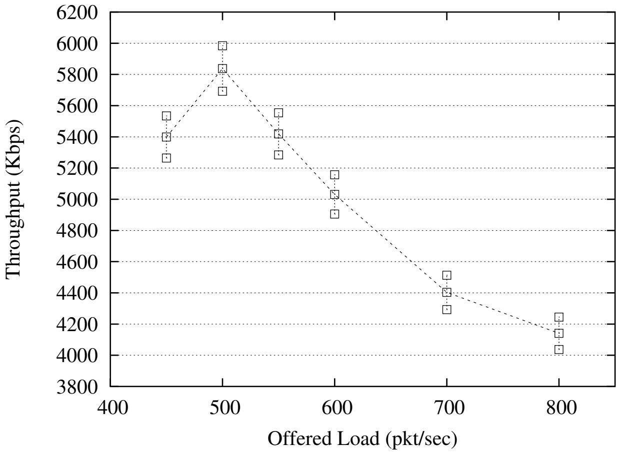


Figure 7.18: Ericsson A11d downlink saturation throughput versus offered load. The diagram shows the average throughput value and its confidence interval (confidence level 95%, 5% accuracy).

	450pkt/sec	**500pkt/sec**	**550pkt/sec**	**600pkt/sec**	**700pkt/sec**	**800pkt/sec**
Average (Kbps)	5399	5838	5419	5031	4403	4141
Maximum(Kbps)	5600	6160	5764	1248	4804	4720
Minimum(Kbps)	5040	5440	4720	4320	4080	3120
Sdt. Dev. (Kbps)	50	110	105	123	99	63

Table 7.14: Ericsson A11d downlink saturation throughput versus offered load (confidence level 95%, accuracy 5%).

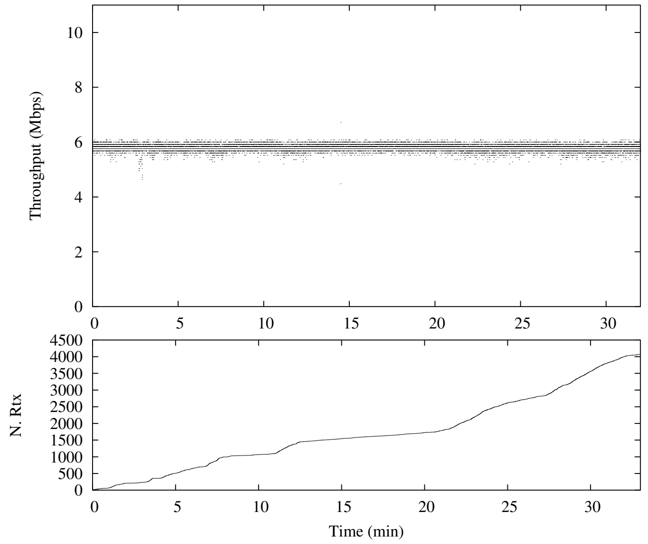


Figure 7.19: Ericsson A11d downlink instant saturation throughput in optimal conditions (0 degrees AP orientation, 500 pkt/sec offered load) and cumulate number of packet retransmissions.

Average (Kbps)	5801
Maximum (Kbps)	6720
Minimum (Kbps)	4480
Sdt. Dev. (Kbps)	132

Table 7.15: Ericsson A11d downlink maximum saturation throughput significant statistical indexes (confidence level 95%, 3% accuracy).

The maximum saturation throughput is reached with an offered load of 500 pkt/sec and is little lower than 6 Mbps.

Figure 7.19 shows the instant throughput of the Ericsson A11d in optimal conditions (0 degree AP orientation, 500 pkt/sec offered load) and Table 7.15 reports the statistical indexes of the measurement. The last test was run in order to collect 12805 consecutive samples of 150ms each. Therefore, the computed average value has a confidence level of 95% and 3% accuracy. Note that the maximum downlink saturation throughout is lower than the maximum capacity of the 802.11b link.

Figure 7.20 shows the instant uplink saturation throughput of the Ericsson A11d in optimal conditions (0 degrees AP orientation, 800 pkt/sec offered load) and Table 7.16 reports the measured statistical indexes. Note that the Ericsson A11d's maximum saturation uplink throughput with a single sender is much lower than the 802.11 link capacity.

In the previous chapter we concluded that the maximum saturation throughput of any 802.11 AP model is equal to the 802.11 link capacity. Some APs reach the maximum saturation throughput when bridging data downlink or uplink, other APs only when bridging data uplink. Despite the Ericsson A11d performance, we still consider our general conclusion valid. In fact, the analysis of the Ericsson A11d uplink satura-

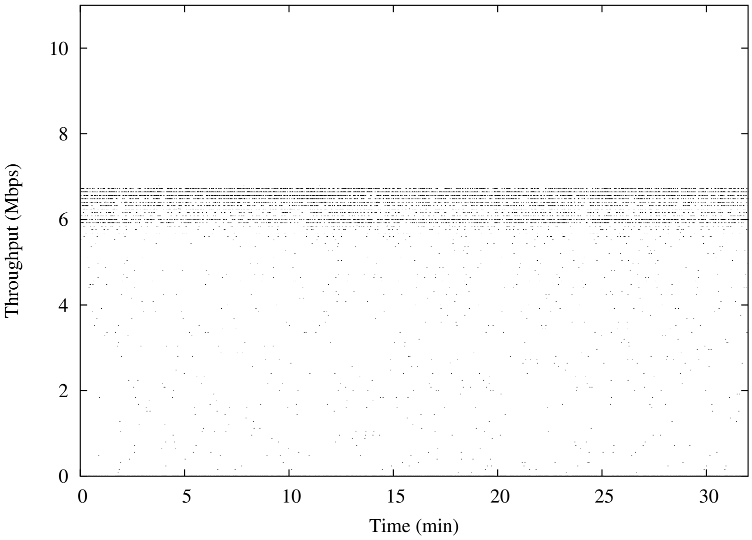
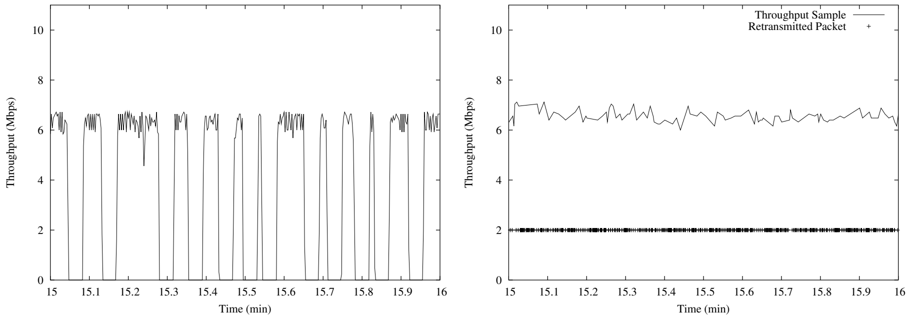


Figure 7.20: Ericsson A11d uplink instant saturation throughput in optimal conditions (0 degrees AP orientation, 800 pkt/sec offered load).

Average **(Kbps)**	4055
Maximum **(Kbps)**	6800
Minimum **(Kbps)**	0
Sdt. Dev. **(Kbps)**	3011

Table 7.16: Ericsson A11d uplink maximum saturation throughput significant statistical indexes (confidence level 95%, 3% accuracy).



(a) uplink throughput in the Ethernet link

(b) 802.11b throughput and packet retransmission events

Figure 7.21: Ericsson A11d uplink instant saturation throughput in optimal conditions. The diagrams show a single minute of the uplink test. The complete test is shown in Figure 7.20.

tion throughput explains the reason of its low uplink performance.

Figure 7.21 shows the instant uplink saturation throughput of the Ericsson A11d over a single minute of the previous test. Figure 7.21a shows the throughput measured on the Ethernet link. Figure 7.21b shows the simultaneous traffic in the 802.11b cell. Despite the large number of necessary 802.11 packet retransmissions (see Figure 7.21b), the 802.11 link throughput is almost equal to the link capacity (the test was run with a single sender). The 802.11 link behaviour is close to the ones we observed with other AP uplink tests (see 6.1.2). Note that the Ericsson A11d is not able to bridge all the 802.11 incoming packets to the Ethernet link. Figure 7.21a shows that the Ethernet throughput level is not stable as the 802.11 one. The AP produces high throughput for a short time then it stops. The result is an almost regular Ethernet traffic pattern where the Ethernet link remains idle for almost 30% of the time!

During the test, we noticed that the link status LED of the AP's Ethernet interface was always blinking. At a regular times the Ethernet link went up and then down again. Most probably, the Ericsson A11d's Ethernet driver continuously reset the network interface producing the transmission stops.

Our conclusion is that the limited uplink capacity of the Ericsson A11d is due to a failure of the AP's Ethernet interface and/or a general misbehaviour of the system. Note that the instant uplink saturation throughput when the AP transmits is approximately 6.1 Mbps according to the expected throughput level. This AP has a clear implementation error and therefore its performance cannot be compared to the others.

7.4 Conclusions

In the previous sections we presented the results of our recommended test procedure on several different AP models. Despite the large set of different performance and characteristics of the analysed APs, our procedure always produced positive results. Therefore, we can conclude that our recommended test procedure was successfully validated.

The analysis of the test results on the AP models we studied allowed explaining

	Avaya RG-II	**Orinoco AP1000**	**Orinoco AP2000**	**Cisco AIR-1200**	**Ericsson A11d**
Max. Down. Stat. Thr.	5158 kbps	6609 kbps	6636 kbps	7233 kbps	5801 kbps
Opt. Orientation	180 degrees	90 degrees	90 degrees	0 degrees	Any
Opt. Offered Load	450 pkt/sec	800 pkt/sec	600 pkt/sec	800 pkt/sec	500 pkt/sec
Notes	-	-	unstable performance	Non 802.11 Cont. Window	Broken Ethernet Int.

Table 7.17: Summary table of the downlink saturation throughput performance of the AP models tested in chapter 7.

several abnormal behaviours of the different devices. Moreover, the comparison of the APs results allows us formulating some general conclusions. In particular, we could verify the hypothesis we formulated in section 6.1.5:

- The downlink maximum saturation throughput represent the key throughput performance index of 802.11 APs, and
- The maximum saturation throughput of any 802.11 AP is equal to the maximum 802.11 link capacity. Some APs produce the maximum saturation throughput bridging traffic uplink and downlink, whilst other APs only the uplink.

According to the first point, we can compare the performance of different APs by the maximum downlink saturation throughput and the necessary condition for producing it. Table 7.17 summarizes the different performance of the AP models we tested.

Chapter 8

Conclusions

The performance of the access points is a key factor for the design and analysis of any wireless LAN. We have focused our work on IEEE 802.11 devices. Nowadays, this technology is largely the dominant one for general-purpose broadband wireless access networks.

Throughput is the main service that a generic wireless LAN user requires from APs. Different environmental and/or traffic conditions produce different AP throughput performance. Therefore, throughput can generally have a very large variance. We decided to limit the scope of our investigation to the AP's throughput produced in well-defined and repeatable conditions. This kind of approach simplifies the general test procedure and allows reproducing the tests results. Moreover, the performance of different APs in the same conditions can be compared in order to identify common or specific characteristics and to evaluate the performance. We also decided to focus our work only on the IEEE 802.11b technology. All different standards that are part of the 802.11 family (legacy 802.11, 802.11b, 802.11a and 802.11g) share the same link layer, i.e. they share the same network protocol mechanisms. Any standard differs from the others only in the physical/radio layer. For this reason, our final methodology can be successfully applied to any kind of 802.11 AP.

We identified the maximum saturation throughout as the key figure of merit of the 802.11 APs. The saturation throughput is the throughput produced by an AP in saturation conditions, i.e. when the AP has always a packet ready to transmit. In order to maximize the saturation throughput it is necessary to optimize:

- The environmental and test conditions (no radio interferences, small close test environment, no obstacles between the radio stations, maximum packet size for the test stream)
- The AP's orientation with respect to the client
- The offered load

The first optimization is achieved with a correct setup of the testbed. Note that the optimal environmental and test conditions are the same for any 802.11b AP. In order to achieve the other two optimal conditions, it is necessary to run some preliminary tests on the studied AP. In fact, the optimal orientation and offered load are peculiar characteristics of any specific AP model. Note that no technical brochure or user guide reported these behaviours for the tested APs. In particular, all the tested APs claim to have omni-directional antennas.

Our main contribution in this work is our recommended test procedure. The procedure goal is to measure the maximum saturation throughput of any 802.11b APs with a defined confidence level and accuracy. The test procedure includes a detailed description of the testbed and the set of tests to perform per AP. It also includes different recommendations on how to sample the APs instant saturation throughput and the duration of each test session.

The analysis performed on a limited set of APs to formulate the test procedure produced two conclusions:

- Any 802.11b AP reaches a maximum saturation throughput equal to the maximum capacity of the IEEE 802.11b link. Some AP can reach the highest throughput level when bridging the traffic both downlink and uplink. Some other APs reach the highest performance only in uplink.
- The key figure of merit of the 802.11 APs is the downlink maximum saturation throughput. On the contrary, the wireless clients mainly drive the uplink maximum saturation throughput.

The validation of our test and a practical verification of our general conclusions were done by measuring the maximum saturation throughput for a set of 802.11b APs. We tested 5 different models from 4 different vendors. These tests showed a large variation in results. Any part of the AP system has an important influence on the overall performance. In particular:

- Radio modem and antenna implementation
- Firmware efficiency
- Specific configuration options

Characteristics such as the CPU speed, memory and other hardware performance seem not to be critical compared to the previously presented ones. Vendors do not always release the hardware implementation details of their APs. However, we found an example of two 802.11b APs with exactly the same radio interface, but different hardware where the AP with more limited hardware had better performance.

The tests we ran validated our general conclusions regarding the maximum saturation throughput of any 802.11b APs. Moreover, it is important to note that our tests allow estimating the maximum saturation throughput of IEEE 802.11b as 6.6 Mbps. We also found two exceptions. First, the Cisco Aironet 1200 had a maximum downlink saturation throughput of 7.2 Mbps, but only when using a special configuration. It seems that this AP model can be configured to use non-compliant 802.11 parameter values that improve its performance. Second, the Ericsson A11d features a misbehaving implementation of the Ethernet interface that limits the uplink maximum saturation throughput. This AP model was the only one with a maximum saturation throughput lower than the 802.11b maximum capacity.

Chapter 9

Future Work

The work described in this document is complete for what it concerns to the IEEE 802.11b devices. The test procedure has been described with details, and validated by testing a set of different devices. Additionally, our conclusions were verified on the tested devices. More tests on different devices might show distinct behaviours of other 802.11 AP models. In fact, our experience shows that many characteristics depend on the specific AP implementation. However, we expect that all our general conclusions will hold for all access points.

The main task not completed in this work is the validation of our test procedure for other IEEE physical interfaces, namely IEEE 802.11a and IEEE 802.11g. The main structure of the test procedure needs no change. However, some details about the testbed environmental conditions, throughput sample size and number might need some tuning for different technologies.

An extension to this work could be to investigate how different access point's configuration could affect the saturation throughput. For example, to compare the performance of an 802.11 AP when using the basic access protocol and RTS/CTS, and/or when using different packet sizes for the offered load. Nevertheless, in these cases the measured throughput will not be the maximum possible one.

Bibliography

[1] A. Escudero, B. Pehrson, E. Pelletta, J.O. Vatn, P. Wiatr: ”Wireless Access in the Kista IT-University”, 11th IEEE Workshop on Local and Metropolitan Area Networks, March 2001, Boulder Co. USA.

[2] E. Pelletta, F Lilieblad, M. Hedenfalk, B. Pehrson: “The design and implementation of an Operator Neutral Open Wireless Access Network at the Kista IT-University”, 12th IEEE Workshop on Local and Metropolitan Area Networks, August 2002, Stockhom Sweden.

[3] Raj Jain, “The Art of Computer Systems Performance Analysis. Techniques for experimental design, measurement, simulation, and modelling”, John Wiley & Son Inc., 1991

[4] IEEE, “802 Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications”, June 1997

[5] IEEE ,“802 Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Higher Speed Physical Layer Extension in the 2.4GHz Band”. Supplement to the IEEE std 802.11, 1999. (IEEE 802.11b)

[6] IEEE ,“802 Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Higher Speed Physical Layer Extension in the 5GHz Band”. Supplement to the IEEE std 802.11, 1999. (IEEE802.11a)

[7] IEEE, “802 Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Amendment 4: Further Higher Data Rate Extension in the 2.4 GHz Band” (IEEE802.11g), June 2003

[8] Proxim Inc., “ORINOCO/IEEE 802.11 reviewer’s giude”, Orinoco Technical Bulletin 018/A, October 1998. http://www.proxim.com/support/techbulletins. Last visit March 2003.

[9] J. C. Chen, J. M. Gilbert, “Measured Performance of 5GHz 802.11a Wireless LAN Systems”, Atheros Communication, Inc. 2001. http://www.atheros.com/AtherosRangeCapacityPaper.pdf, last visited March 2003.

[10] J. Zyren, E. Enders, T. Edmondson, “IEEE802.11g Offers Higher Data Rates and Longer Range”, Intersil. http://www.intersil.com/data/wp/WP0555.pdf, last visited March 2003.

[11] Atheros Communications Inc., “Methodology for Testing Wireless LAN Performance”, http://www.atheros.com, September 2003.

[12] Atheros Communications Inc., “802.11 Wireless LAN Performance”, http://www.atheros.com, September 2003

[13] G. Bianchi, “Performance Analysis of the IEEE 802.11 Distributed Coordinator Function”, IEEE Journal on Selected Areas in Communications. Vol 18 no. 3, March 2000.

[14] Y.C. Tay, K.C. Chua, “A capacity Analysis for the IEEE 802.11 MAC Protocol”, Wireless Networks 7, 159-171, 2001

[15] A. Kamerman, G. Aben, “Throughput Performance of Wireless LANs Operating at 2.4 and 5GHz”, 11th IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC 2000), London Set. 2000.

[16] G. Xylomenos, G.C. Polyzos, “TCP and UDP Performance over a Wireless LAN”, INFOCOM 1999.

[17] I. Al Khatib, “Performance Analysis of Wireless LAN Access Points”, Department of Microelectronics and Information Technology, Royal Institute of Technology, Stockholm (Sweden), May 2003.