UNIVERSITÀ DEGLI STUDI DI PADOVA
DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE
TESI DI LAUREA SPECIALISTICA
INGEGNERIA DELLE TELECOMUNICAZIONI

CHARACTERIZATION AND OPTIMIZATION OF MIMO SYSTEMS

RELATORE: *Ch.mo Prof. Antonio D. Capobianco*

LAUREANDO: *Stefano Pampagnin*

Padova, 9 Marzo 2010

Abstract

In recent years demand for wireless products and networks has experienced substantial growth in the area of digital communications, evolving from novelty into necessity. The deployment has been remarkable in the new generation of IEEE 802.11n-based Wi-Fi technology, which has introduced several enhancements in wireless LAN performance.

The most significant innovation has been the introduction of *MIMO* (*multiple-input-multiple-output*) interface. MIMO employs an antenna system with multiple transmitters and receivers, improving RF signal quality and increasing efficiency, reliability and throughput. This technology implements advanced signal processing and modulation techniques, added to exploit multiple antennas and wider channels.

The potential of MIMO systems bring along several topics. One of these is the choice of design parameters, like, for example, symbol rate, modulation and coding, constellation size and many other. Since the propagation situation can quickly changes, the performance of MIMO systems is determined by its ability to adapt to the changing channel conditions. Thus sophisticated techniques have been proposed to improve the data rate by adapting some of these parameters to the time-varying channel.

Another major question is figuring out the ways multiple antennas should be positioned for uncorrelated reception. Due to the fact that antenna elements and propagation channel interact in MIMO systems, the array arrangement strongly influences performance. The configuration has to be chosen carefully with the aim of getting high efficiency in terms of power and a low correlation by exploiting various propagation paths.

Contents

Chapter 1

Introduction

This thesis resumes the results of a stage at Telsey's, a company with head quarter in Quinto di Treviso, whose activity focuses on design and production of access gateway, IP-video station and networking solutions. The paper presents an overview of the central element of the study activity, that are *MIMO* (*multiple-input-multiple-output*) wireless systems and develops this study from a theoretical and experimental point of view.

A MIMO system can be defined as a wireless communication system where the transmitting end as well the receiving end are equipped with multiple antenna elements, with the purpose of increasing the quality of the network.

After some background on the IEEE 802.11n Wi-Fi standard, the analysis highlights the potential and benefits of MIMO wireless link (chapter 2). Interest in MIMO technology has emerged and grown dramatically in recent years, since it offers significant increases in link quality and data throughput of the communication at no cost of extra spectrum or additional transmit power.

The quality of a system and its ability to satisfy promised services involves the need to identify the most significant parameters with the regard to a given requirement and define a method to assess them. Thus defining a technique able to characterize the equipment under test and give indications on its quality is the first step of a standardized procedure of analysis (chapter 3).

Afterwards, an important aspect of MIMO systems is treated in detail, the *Modulation and Coding Scheme* or *MCS* (chapter 4). 802.11n standard defines a large set of these schemes, i.e. a combination of some factors, like the type of RF modulation, the coding rate and others, that determine the physical data rate of the transmission. Since the wireless fading channel varies with time, link adaptation must be employed to sustain reliable communication and maximize throughput. Thus, in this context, the goal of the work was to improve a technique that dynamically select the best MCS based on channel conditions and on the performance requested by applications.

Finally, the effect of antenna array geometry on MIMO channel properties is investigated (chapter 5). A combination of different diversity techniques, like spatial, pattern and polarization diversity, leads to a considerable capacity gain. Propagation environment and antenna array configuration have significant effects on spatial correlation properties of MIMO wireless communication channels, thus the effect of different antenna array geometries on MIMO channel properties has a key role in the study of the performance.

The study of this technology was finalized to the characterization of some commercial products with the aim of improving their performance and this target was achieved in the optimization of the data throughput between 802.11n APs and stations.

Chapter 2

An overview of MIMO systems

2.1 802.11n standard

IEEE 802.11n is a set of specifications for high throughput enhancements to the previous 802.11 wireless LAN standard. IEEE recently announced that its Standards Boards has ratified this amendment (11 September 2009), defining mechanisms that provide significantly improved data rates and ranges for wireless local area networks (WLANs). However, since 2007 the Wi-Fi Alliance has started certifying products based on a preliminary draft that anticipated the specifications of the final standard and enterprises have begun developing products according to its technical proposals.

This new amendment to the 802.11 base standard is designed to help the data communications industry address the escalating demands placed on enterprise, home and public WLANs with the rise of higher-bandwidth file transfers and next-generation multimedia applications. As IEEE explains, the standard "defines how to design interoperable WLAN equipment that provides a variety of capabilities including a wide range of data rates, quality of service, reliability, range optimization, device link options, network management and security".

802.11n includes a number of improvements at both the Physical (PHY) and Media Access Control (MAC) layers. At the Physical layer, advanced signal processing and modulation techniques have been added to exploit multiple antennas and wider channels. At the MAC layer, protocol extensions make more efficient use of available bandwidth. In this way 802.11n differs from its predecessors in that it provides for a variety of optional modes and configurations that increase the raw physical layer data rate from 54 Mbps (supported by 802.11a and 802.11g hardware) to a maximum of 600 Mbps (i.e. more than a ten-fold improvement). And this is possible at 2.4 GHz and 5 GHz bands. Thus the primary benefit is its superior performance in terms of data rate and range.

2.2 Principles of MIMO systems

The most significant change in 802.11n is certainly the addition of MIMO air interface technology to the physical layer. But MIMO is an important innovation for several non-802.11 wireless data communications standards too, including 4G cellular. This technology introduces a smart system of multiple element antennas for signal transmission and reception, so as to improve RF signal quality, reach high spectral efficiencies and increase the data rate.

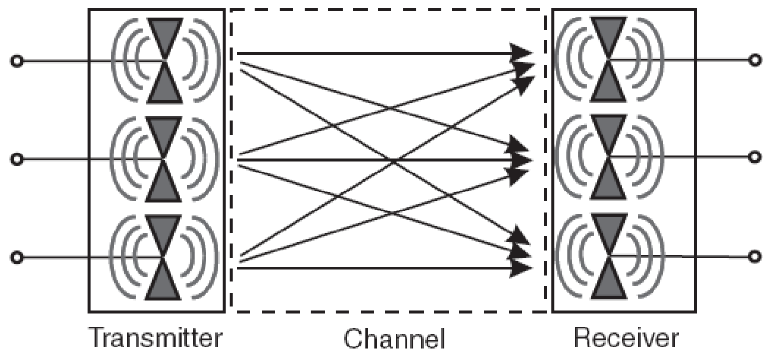

Figure 2.1: MIMO system

802.11n products are typically described in terms of their MIMO attributes, denoted by $T \times R : S$, where T is the number of transmit antennas or RF chains, R the number of antennas or RF chains at the receiving end and S the number of data spatial streams the radio can send and receive. For example, a system that can transmit and receive two spatial streams on two antennas has a configuration $2 \times 2 : 2$.

The technique, implemented by 802.11n, to multiply the data streams is called *Spatial Division Multiplexing* (*SDM*). Using multiple spatially distributed antennas, it is possible to subdivide an outgoing signal stream into multiple independent pieces and transmit these sequences of data to corresponding antennas on the receiving end simultaneously on the same channel, thereby increasing the spectral efficiency and maximum data rate. For example, assuming a clear signal, a two spatial stream link will achieve twice the throughput of a single stream in the same channel. Thus a core idea in MIMO systems is *space-time* signal processing in which the natural dimension of digital communication data, the transmission in the time, is complemented with the spatial dimension, inherent in the contemporary use of multiple streams in the same channel.

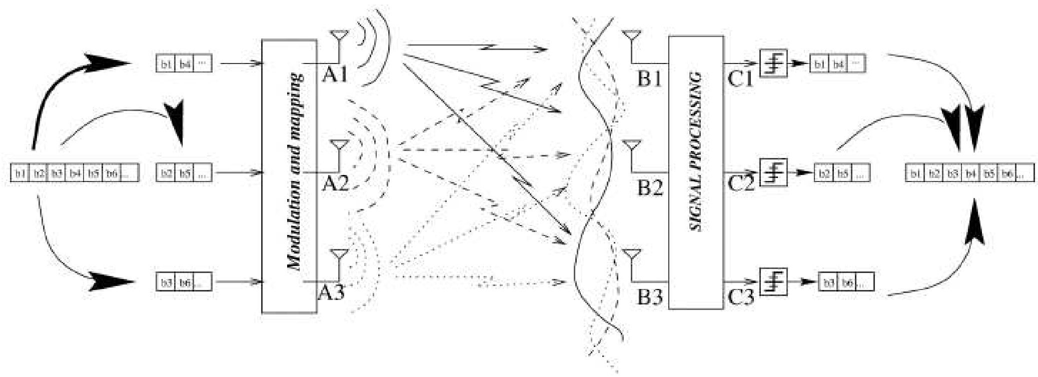

Figure 2.2: Spatial multiplexing scheme with three TX and three RX antennas

In Fig 2.2 the transmitting WLAN device splits a high-rate signal in three lower rate bit streams, each one transmitted through different antennas in the same frequency channel, thus consuming one third of the nominal spectrum. At the receiver the individual signals are accurately separated and estimated (in the same way as three unknowns are resolved from an algebraic system of three equations) and the original signal stream is reassembled. Thus multiplexing three spatial streams onto a single channel effectively triples capacity and thus maximizes data rate.

The number of simultaneous data streams is limited by the minimum number of antennas in use on both sides of the link, thus, for example, at least two antennas are required for two spatial streams; but a lot of systems have more antennas than the number of streams (a possible combination of this type is $2\times3:2$). The standard allows up to $4\times4:4$, but the most common configurations are $2\times2:2$, $2\times3:2$ and $3\times3:2$, that, having the same number of streams, offer the same maximum throughput and differ only in the amount of diversity the antenna system provides; instead a $3\times3:3$ product has a higher throughput, due to the additional data stream.

There are trade-offs, however, such as more complex hardware and consequently increased power consumption; but the standard includes a MIMO power-save mode, which limits power consumption penalty by using multiple antennas only when communication would benefit from the additional performance.

Generating multiple spatial streams requires multiples transmitters and receivers but also distinct and uncorrelated paths for each stream through the medium, so that the individual streams arrive at the receiver with sufficiently distinct spatial signatures. In this sense, MIMO systems exploit a radio-wave phenomenon known as *multipath*.

Multhipath is common in wireless channels, where the signal can reach its destination via different routes and at slightly different times as it reflects off, refracts through or diffracts around obstacles. The ability of MIMO is to turn multipath propagation, traditionally viewed as a bug for wireless transmission (because copies of a signal would interfere with each other causing signal distortions called *fading*), into a benefit for the user. Receivers in MIMO systems are able to consistently process each multipath component, thereby eliminating the mixture of out-of-phase components, which can result in signal distortion and deciphering the signal. MIMO works best if the paths are spatially distinct, resulting in received signals that are uncorrelated; multipath helps decorrelate the channels and thus enhances the operation of spatial multiplexing.

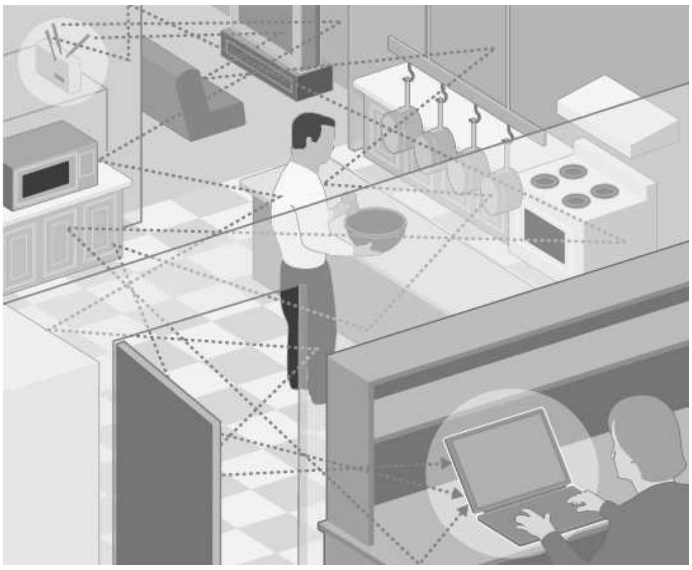

Figure 2.3: MIMO exploiting the multipath structure in an indoor scenario

Aside from spatial multiplexing, 802.11n devices can also use other techniques that aim at improving MIMO performance, like *beamforming* and *antenna diversity*.

Antenna array combining can offer a more reliable communications link in the presence of adverse propagation condition such as interference by using beamforming; it is a technique that allows to increase the signal gain and the average signal-to-noise ratio (SNR) through adapting antenna patterns to some optimum propagation paths and focusing the energy of radio signals into these desired directions, in either transmitter or receiver. This method requires the transmitting and receiving stations to perform channel sounding to optimize the shape and direction of the beam.

Because the receiver has multiple antennas, the transmit beamforming cannot simultaneously maximize the signal level at every receive antenna and thus *precoding* is used. In precoding, the multiple streams are emitted from the transmit antennas with independent and appropriate weighting per each antenna such that the link throughput is maximized at the receiver output. Thus it is necessary to estimate the response of each antenna element to a given desired signal (and possibly to interference signals) and optimally combine the elements with weights selected as a function of each element response. This allows to improving range and performance by maximizing the average desired signal or minimizing the level of noise and interference.

Beamforming can be used also in conjunction with spatial multiplexing by using several directional antenna elements and transmitting different data streams in parallel — spatially separated via different paths — by each antenna pattern.

Antenna diversity exploits multiple antennas by combining the outputs (or selecting the best subset) of a larger number of antennas than required to receive a certain number of spatial streams. For example, a client with two antennas might connect to an access point with three antennas and thus only two spatial streams can be used; but the AP can use surplus antennas to combine their outputs and achieve in this way a longer link range. The probability of losing the signal vanishes exponentially with the number of uncorrelated antenna elements available at the transmitter or receiver.

Selecting antenna mapping algorithms to provide array gain requires prior channel estimation. Where there is no channel knowledge at the transmitter, other diversity techniques can be used. *Space-time coding* (*STC*) techniques rely on spreading multiple and redundant copies of a data stream to ensure that at least some of them may be decoded at the receiver, creating a reliable link. The transmitter can use up to four differently-coded spatial streams, each transmitted through a different antenna. By comparing arrival spatial streams, the receiver has a better chance of accurately determining the original stream in the presence of destructive RF phenomena like interference and distortion. Thus this feature improves reliability by reducing the error rate experienced at a given SNR. It can be combined with spatial multiplexing, but it can only be used when the number of transmit antennas exceeds the number of receive antennas.

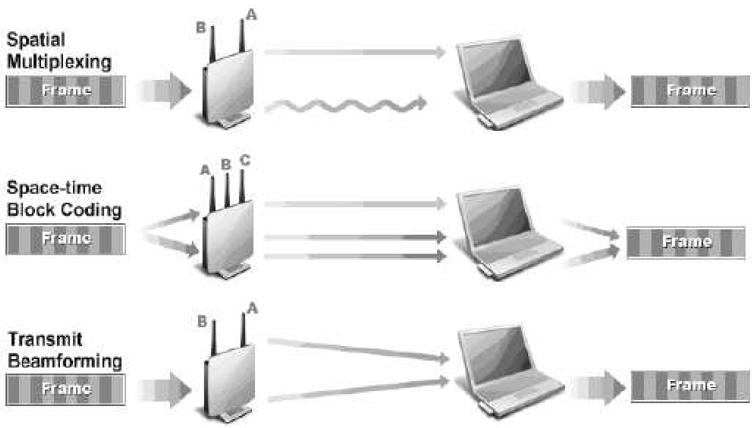

Figure 2.4: Signal processing techniques for MIMO systems (space-time block coding is an example of STC)

2.3 Other features of the standard

The first requirement for a 802.11n product is to support an OFDM (Orthogonal Frequency Division Multiplexing) implementation that improves upon the one employed in the earlier versions, using a higher maximum coding rate and slightly wider bandwidth. Originally introduced to Wi-Fi in 802.11a and 802.11g, OFDM is a modulation method which breaks the data stream up into several sub carriers that are sent in parallel; this allows more data to be reliably transmitted within the same channel.

Channel bonding is a primary feature of the standard, that doubles possible data rates by combining two adjacent 20 MHz channels to form a single 40 MHz channel. Naturally increasing the channel size decreases the total number of available non-overlapping channels.

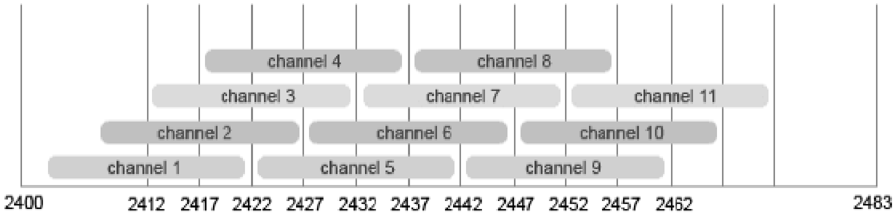

Figure 2.5: 20 MHz channels used in the 2.4 GHz band

Another option for 802.11n is the Short Guard Interval (GI). GI is the period within an OFDM symbol allocated to letting the signal settle prior to transmitting the next symbol (to ensure that a receiver is not confused by echoes). The option of pausing just 400 ns instead of 800 ns is a possible choice for 802.11n, so as to reduce the symbol time and increase the symbol rate.

The 802.11 MAC protocol has also been enhanced to allow more efficient use of the higher physical data rate.

Block acknowledgment mechanism allow multiple data frames to be transmitted in a sequence, which can be acknowledged using a single frame instead of transmitting an individual ACK for every received packet.

Packet aggregation increases the payload that can be conveyed by each 802.11 frame, bundling frames together for transmission and reducing MAC layer overhead. This option, together with block acknowledgment, reduces the protocol overhead, thus increasing the user level data rate and improves performance, particularly for voice traffic and streaming traffic such as video.

A way to further improve the efficiency is to eliminate support for 802.11a/b/g devices in the network, using High Throughput (HT) mode, also known as Greenfield mode. Greenfield preamble in the frames cannot be interpreted by legacy stations but it is shorter than the Legacy Mode or Mixed Mode preamble (a bit sequence consistent with old devices), thereby improving efficiency and performance. In fact, an 802.11n AP using Legacy Mode sends all frames in the old 802.11a/g format so that backward compatibility is ensured, but none of the new HT features is exploited. In the Mixed Mode, HT enhancements can be used simultaneously with a “protection mechanism”, that permits communication with legacy stations, while causing significant throughput penalties as compared to

Greenfield Mode.

Because it offers greater bandwidth, better range and reliability, 802.11n is advantageous in a variety of network configurations. Its capabilities serve different types of devices, including phones, personal digital assistant (PDAs), video game consoles, printers and other specialized platforms, that are increasingly adopting Wi-Fi to support current and emerging applications, like Voice over IP (VoIP), streaming video and music, gaming and network-attached storage (NAS). The expansion grows into new market segments in the home as in the enterprise environment, for indoor and outdoor networks and it testifies the success of MIMO not only in WLAN but also in other commercial standards such as 3G and 4G mobile standards.

Chapter 3

Characterization techniques for wireless systems

In this chapter a method, employed during the stage activity, to characterize wireless systems is discussed. Particularly, performance tests have been done using *Iperf*, a software tool whose features are described below. A starting point for this type of investigation has been a qualitative comparison between MIMO and *MISO* systems, degenerate cases of MIMO that have been subject of a preliminary analysis, useful to understand the testing procedure too.

3.1 Iperf

It is important verifying the ability of a network to satisfy its relative specifications, developing standardization of procedures for the measurement of the most interesting parameters for this analysis. Among the tools able to give indications on the quality of a wireless network, Iperf has been selected in conformity with the choices of the company.

Iperf (Internet Performance Working Group) is an application developed by the University of Illinois (in particular by the Distributed Applications Support Team, DAST, part of the National Laboratory for Applied Network Research, NLANR) to measure network performance. It is an open source software written in C++ and it can run on any UNIX/Linux, Microsoft Windows or Solaris platforms. The tool Jperf can be associated with Iperf to provide a graphical frontend written in Java.

Iperf is very useful for measuring the quality and the end-to-end achievable bandwidth of a network link. It can create TCP and UDP data streams, allowing the tuning of various parameters, to obtain data regarding the real transmission capacity of a channel, the number of lost packets compared to the total number of packets transmitted, as well as jitter. The term “jitter” applies here in the sense of PDV (packet delay variation), i.e. an evaluation, as statistical variance, of the latency variation over time in packet reception.

The network link is delimited by two hosts running Iperf, one set as server (to discard traffic), the other one as client (to generate traffic). Iperf uses the different capacities of TCP and UDP to provide statistics about different activities.

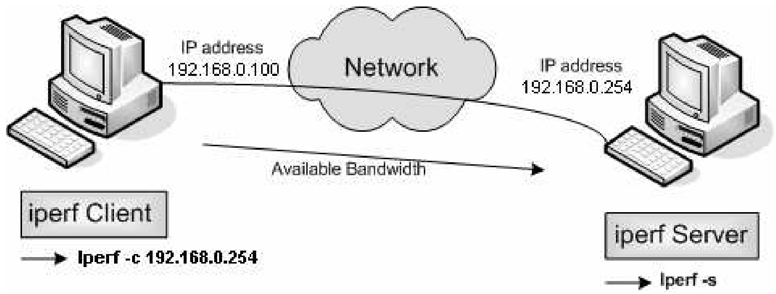

Figure 3.1: Scheme of Iperf architecture working on a network

3.1.1 TCP test

By default, the Iperf client connects to the Iperf server on the TCP port 5001 and the bandwidth displayed (the total data transferred between the end-hosts over the total transfer period) is the bandwidth from the client to the server.

The command used to start Iperf in the server (receiving end) is the following one:

```
iperf -s
```

For the operation in the client (transmitting end) the command is the this one:

```
iperf -c 192.168.0.254
```

where 192.168.0.254 is the IP address of the server machine.

TCP manages an application's network performance by controlling how much data is sent in each packet (Maximum Segment Size, MSS), how many packets are sent before receiving an acknowledgment (Window Size) and how much memory is allocated to send and receive traffic flow buffers (Buffer Length). The values of these parameters can be adjusted to see the impact the changes have on throughput.

3.1.2 UDP test

To use UDP tests rather than TCP, the "-u" argument is required in the commands on client and server sides. Iperf produces, in the case of an UDP connection, a data flow with constant bit-rate; it deals with a flow that simulates a voice communication.

The dimension of the datagram can be modified, according to the application for which the network is planned; the default value, equal to 1470 bytes, is fit for Ethernet networks. The server identifies a loss of UDP datagrams on the base of the ID number.

The calculation of the jitter is constantly performed by the server; this parameter is defined to be the mean deviation (in absolute value) of the difference in the relative time of transit for a pair of packets, that is the difference among the timestamp of a packet (recorded by the client) and the clock of the receiving station of arrival of the packet, measured in the same unities.

The monitoring of the jitter allows the control of the network performance, with particular reference to real-time applications; in VoIP, for instance, it's important to have low variation in the response time because a high jitter can break a call.

Other settings are possible with Iperf, for example it allows to do a dual-test (sequentially or simultaneously), measuring the bidirectional bandwidth, run parallel tests, creating simultaneous client threads, choose the test duration and the interval between periodic bandwidth reports.

An example of commands to start Iperf respectively in the server and client (for a recapitulation interval of 10 s, a test duration of 60 s and a bandwidth of 10 Mb/s) is the following one:

```
iperf -s -u
iperf -c 192.168.0.254 -u -i 10 -t 60 -b 10m
```

3.2 SISO, MISO and MIMO systems

A traditional radio *single-input-single-output* (*SISO*) system uses one antenna at the transmitter and one at the receiver, while in a MIMO system multiple antennas are put at both the transmitter and the receiver; but other types of multi-antenna systems are possible.

A *multiple-input-single-output* (*MISO*) device is a system which uses a single antenna at the transmitter and multiple antennas at the receiver.[1]

Naturally MIMO systems boost enhanced performance because MISO can provide only a part of the features and techniques that exploit additional antennas, i.e. receiver diversity: the receiver can either choose the best antenna to receive a stronger signal or combine signals from all antennas, in such a way that maximizes SNR, with *Maximal Ratio Combining* (*MRC*). This technique phase-aligns and adds signals received by multiple antennas to optimize signal integrity.

3.3 Testing a MISO system

In this section the results provided by testing a MISO system are presented. The equipment under test was formed by two CPVA642WA (Figure 3.2), an access gateway produced by Telsey, based on Wi-Fi 802.11b/g, with three planar internal antennas (PIFA), one for transmission and two for receiving.

Figure 3.2: CPV642WA

[1]This definition of MISO applies to a system meant as single device, for example an AP. Another definition widespread in literature refers to a system where transmitter and receiver are separated, i.e. a link network. In this case a MISO uses a transmitter with multiple antennas and a receiver with a single antenna; vice versa a system which uses a single antenna at the transmitter and multiple antennas at the receiver is named *single-input-multiple-output* (*SIMO*).

The network for which the tests have been conducted can be defined as a Wi-Fi extension of a 10/100 Ethernet. The devices were located on two writing-desks in two different rooms (at a distance of about fifteen meters), one configured as client and the other one as access point (Figure 3.3).

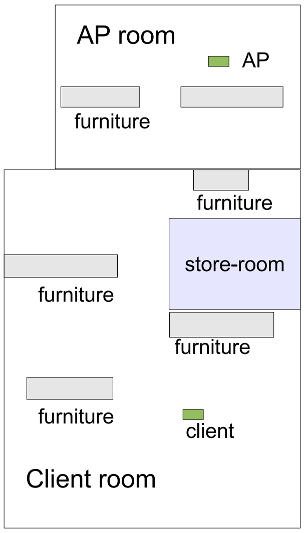

Figure 3.3: Setup layout

The first one was positioned on a flat surface in a fixed position, while the position of the server device was changed in order to verify eventual changes in the performance, due to the different position of the antennas as regards the surrounding environment and the consequent different direction of their radiation pattern. Both devices were respectively connected to a Linux box and Iperf was installed on the machines with these settings: Iperf client on the host connected to the AP and Iperf server on the one connected to the client device.

After connecting the devices, creating a radio link between the computers, both UDP and TCP tests were made to provide statistics about the connection. The measurements were done in a working environment, thus in presence of moving people and other transmitting stations in the 2.4 GHz band (like other Wi-Fi equipment, Bluetooth, wireless telephones); this “noise” could represent a source of trouble, but made the environment realistic and right for testing the features of a network of this type, destined to be used, for example, inside the house for IP TV streaming.

Theoretically the bandwidth of a 802.11g channel is equal to 54 Mb/s; in order to test the real bandwidth of the channel, a series of measurements was conducted, starting from an UDP bandwidth value equal to 2 Mb/s, in order to identify for which value of real bandwidth a percentage of lost datagrams equal to 0% was found.

To automate the procedure a script was used (see Appendix A). On the server side a simple file SH, executable via command-line, allowed to start Iperf and save the results in a CSV file; moreover, the script set a static ARP entry, i.e. it associated the IP address of the client host with its MAC address, in order not to jeopardize throughput tests with ARP broadcast traffic on the network. On the client side another script, written in Java, was started; it set the static ARP entry with the IP address that resolved to the MAC address of the server and then it created the desired data flow, allowing to choose Iperf settings (like the datagram size) and change the bit rate of the transmitted traffic periodically and automatically after a fixed time. Finally the reports on datagram loss produced by Iperf (server side) were converted in values of efficiency of the transmission and exported to a spreadsheet.

The test process was as follows: the Iperf client transmitted UDP packets ("-u") for a total time of transmission of 60 seconds ("-t 60"); the interval of recapitulation and visualization of the data was set to 10 seconds ("-i 10"). Consequently two reports were produced: one, on the client, recapitulated (for every interval of transmission) the quantity of data transferred and the relative bandwidth in transmission; the other one, on the server, showed, in relationship to how many data were received in every interval of time, the quantity of data received, the related bandwidth, the value of the jitter and the number of lost and received datagrams, expressed in percentage. Cycles of transmission with an increasing UDP bandwidth up to 54 Mb/s were performed for four dispositions of the AP (positioned horizontally or vertically and rotate to different directions as regards the client).

The results of the tests are shown here in several charts. The first chart (Figure 3.4) shows the efficiency of the link as the bit rate increases, calculated as percentage inverse to the average packet loss (for instance, if no packet of information is lost in the minute of transmission, the efficiency is equal to 100%).

One can note, when the transmission bandwidth is tuned to the theoretical maximum (54 Mb/s), the traffic flows but a high percentage of the information is lost: the efficiency is less than 70%. The diagram shows the percentage of

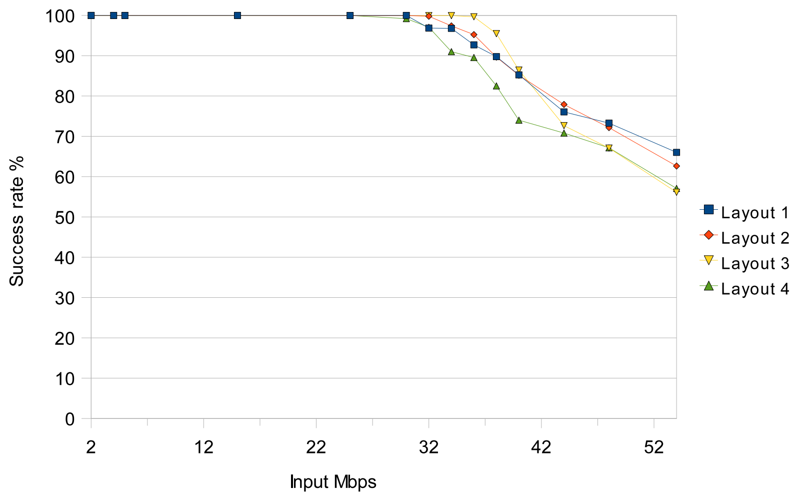

Figure 3.4: Values of efficiency

packet loss tends to zero when the bit rate in transmission is about 30 Mb/s (a little more or less according to different dispositions), that results to be the real avalaible bandwidth.

The second report (Figure 3.5) is the representation of the jitter trend: when the bandwidth overcomes 40 Mb/s, there are a lot of peaks, showing the traffic in the network does not flow in regular manner, while under this threshold variations in the jitter are less significant.

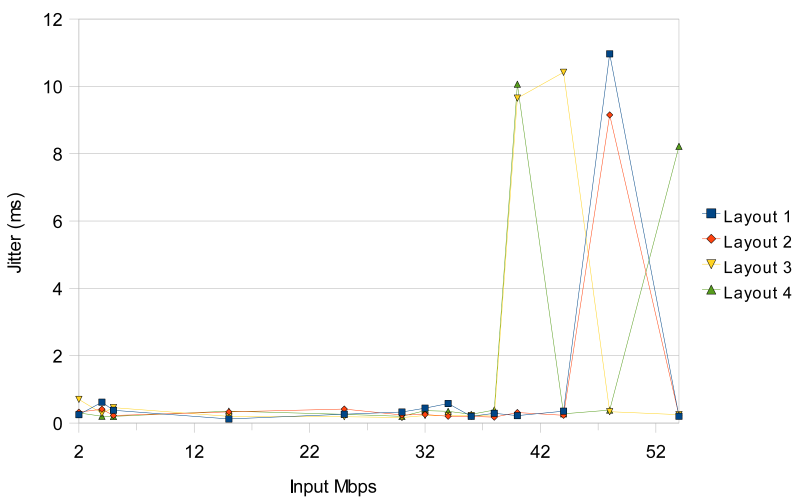

Figure 3.5: Values of jitter

The UDP tests are related to the TCP tests because a high packet loss rate will generate a lot of TCP segment retransmissions which will affect the bandwidth. This is evident in figure 3.6, which shows the evolution in the time of the achievable bandwidth, displayed running a Jperf TCP test for one of the layouts under test; from the results it can be inferred that the values of band correspond to those found previously.

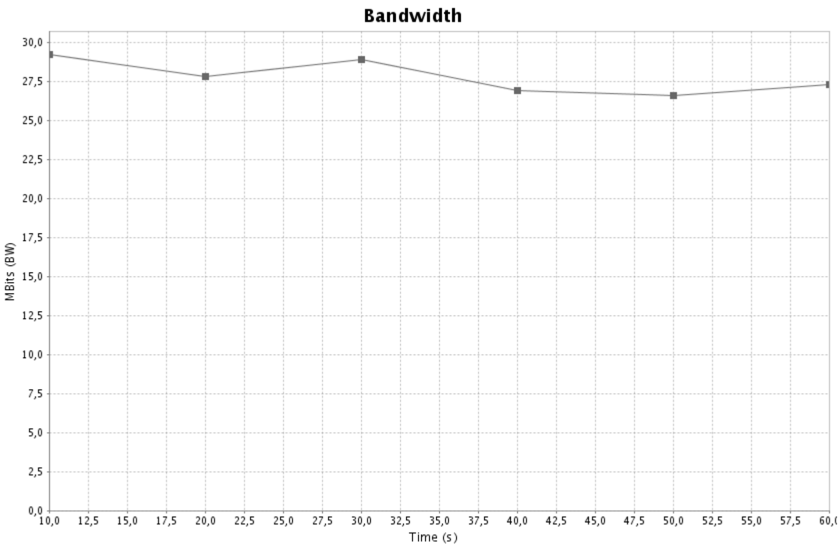

Figure 3.6: Values of bandwidth

3.4 Testing a MIMO system

The same typology of test has been made for a 802.11b/g/n network. The devices employed were two Telsey WAU11N (Figure 3.7), i.e. two 802.11n Wi-Fi adapters, configurable as access point or station; based on MIMO approach, this device has two dipole antennas, useful both to transmit and receive.

Figure 3.7: WAU11N

The network was a Wi-Fi extension of a Fast Ethernet, with a device configured as Ethernet converter (client) and the other one as access point, located according to the previous layout (Figure 3.3), thus without changing the network environment. In this case the position of the devices was fixed, while different tests were done changing frequency, or rather channel, in the 2.4 GHz band (in the previous tests the option “AutoSelect”, to choose automatically a free channel, was enabled). Besides, the configuration of the devices was in default mode (40 MHz channels and Auto Guard Interval, i.e. an option to select the best GI automatically). Cycles of transmission were performed with an increasing UDP bandwidth up to 95 Mb/s, that is the realistic limit of the rate allowed by Ethernet hardware.

The performance of the network can be evaluated in the charts representing packet loss (Figure 3.8), jitter trend (Figure 3.9) and TCP bandwidth (Figure 3.10); these measurements show the results for the first channel within the band, but similar results have been got testing other channels.

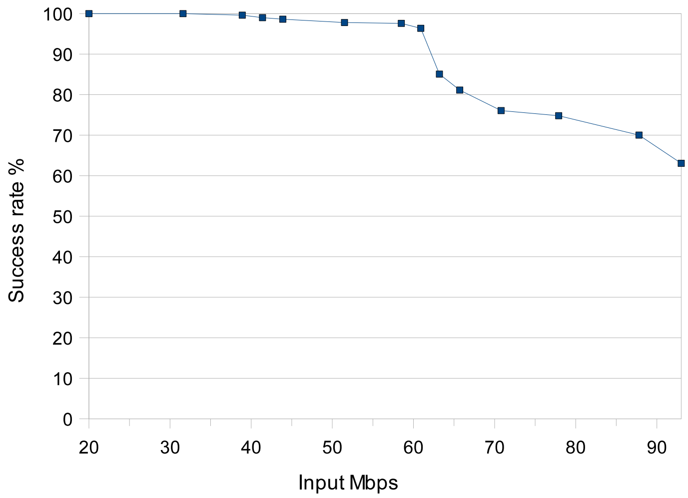

Figure 3.8: Values of efficiency

One can note the transmission is efficient as far as 40 Mb/s, then the percentage of lost datagrams begins to increase and the jitter varies about from 0 to 8 ms, showing the connection is not reliable.

Compared with the performance of the 802.11g network, throughput enhancements emerge monitoring the 802.11g/n network; but “n” features can surely support further enhancements. Thus this was a first fast analysis that explored the potential benefits guaranteed by the new standard.

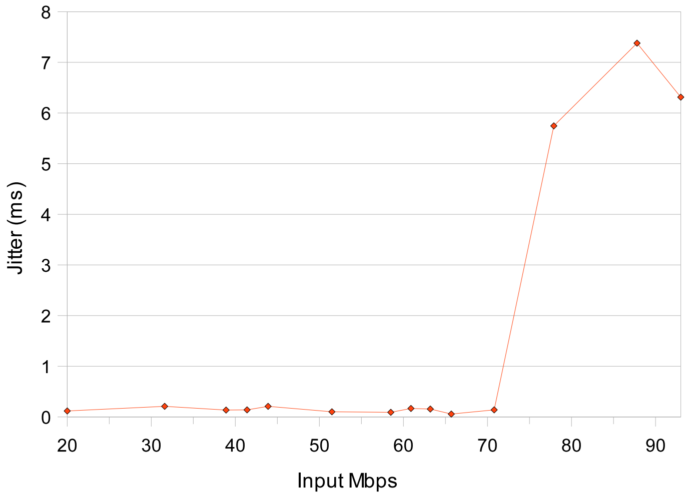

Figure 3.9: Values of jitter

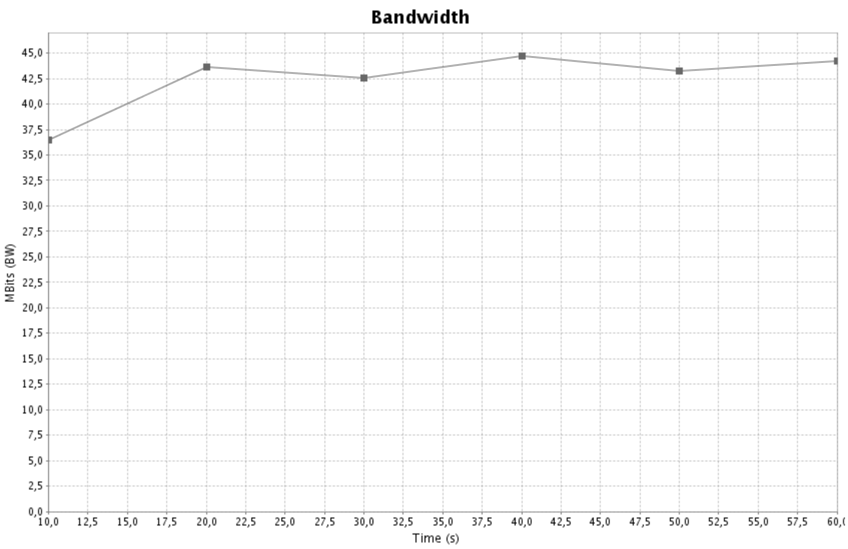

Figure 3.10: Values of bandwidth

Chapter 4

Modulation and Coding Scheme

The selection of the spatial mode together with modulation and encoding schemes based on channel condition measurements forms a basis for selecting a best transmission data rate in a MIMO wireless link in every channel conditions. In this chapter, after a theoretical analysis of the subject at issue, the results of tests done to improve a link adaptation technique are presented.

4.1 MCS (Modulation and Coding Scheme)

802.11n APs and stations need to negotiate elements like the type of RF modulation, coding rate, number of spatial streams, channel width and guard interval. The combination of all these factors determine the physical data rate, ranging from a minimum 6.5 Mbps to a maximum 600 Mbps (achieved by exploiting all possible 802.11n options).

Because the standard defines 77 possible permutations of the factors that determine data rate, a clear way is needed to communicate them. *MCS* (*Modulation and Coding Scheme*) has this function, assigning a simple integer to every possible permutation. The table 4.1 shows the relationship between some of these index values and the variables that determine the data rate.

Modulation and coding rate determine how data is sent over the air. Newer modulation methods and coding rates are generally more efficient and sustain higher data rates, but older methods are still supported for backwards compatibility. For example, Binary Phase Shift Keying (BPSK) was included in the original 802.11 standard, whereas Quadrature Amplitude Modulation (QAM)

MCS Index	Type	Coding Rate	Spatial Streams	Data Rate (Mbps) with 20 MHz CH		Data Rate (Mbps) with 40 MHz CH	
				800 ns	400 ns (SGI)	800 ns	400 ns (SGI)
0	BPSK	1 / 2	1	6.50	7.20	13.50	15.00
1	QPSK	1 / 2	1	13.00	14.40	27.00	30.00
2	QPSK	3 / 4	1	19.50	21.70	40.50	45.00
3	16-QAM	1 / 2	1	26.00	28.90	54.00	60.00
4	16-QAM	3 / 4	1	39.00	43.30	81.00	90.00
5	64-QAM	2 / 3	1	52.00	57.80	108.00	120.00
6	64-QAM	3 / 4	1	58.50	65.00	121.50	135.00
7	64-QAM	5 / 6	1	65.00	72.20	135.00	150.00
8	BPSK	1 / 2	2	13.00	14.40	27.00	30.00
9	QPSK	1 / 2	2	26.00	28.90	54.00	60.00
10	QPSK	3 / 4	2	39.00	43.30	81.00	90.00
11	16-QAM	1 / 2	2	52.00	57.80	108.00	120.00
12	16-QAM	3 / 4	2	78.00	86.70	162.00	180.00
13	64-QAM	2 / 3	2	104.00	115.60	216.00	240.00
14	64-QAM	3 / 4	2	117.00	130.00	243.00	270.00
15	64-QAM	5 / 6	2	130.00	144.40	270.00	300.00
16	BPSK	1 / 2	3	19.50	21.70	40.50	45.00
...	...	...	...	...	...	...	...
31	64-QAM	5 / 6	4	260.00	288.90	540.00	600.00

Figure 4.1: Some MCS values

was added by 802.11a.

The MCS index is from 0 to 77: values 0 through 31 define the same modulation and coding will be used on all spatial streams, while values 32 through 77 imply unequal modulation and describe mixed combinations that can be used to modulate two to four streams (different modulation type for different spatial streams). 802.11n APs are required to support at least MCS values 0 through 15, while stations must support MCS values 0 through 7.

4.2 Adaptive MCS

Throughput, defined as the data rate correctly received, is a key measure of quality of service (QoS) for wireless data transmission systems. Throughput is affected by the channel environment such as the distance between the transmitter and the receiver, the fading state of the channel and the noise and interference power characteristics. It is also influenced by the choice of some design parameters, among others the symbol rate, modulation and coding and constellation size.

Moreover, the wireless channel has a time variant and frequency selective characteristics, thus link adaptation must be employed to sustain reliable communication and maximize throughput. With fixed modulation and coding scheme, performance degrading would happen because of the high error rate in the case of bad channel state and low spectral efficiency in the case of good channel state respectively.

Thus a technique that dynamically selects the best MCS, based on channel conditions and instantaneous quality information, is a solution to solve this problem. Sender adaptively sets MCS level based on the channel quality reported by the receiver, thus performance degrading due to the channel fluctuation can be suppressed. When the channel state is bad, MCS level with higher robustness is selected to suppress error or however maintain an acceptable error rate; when the channel state is good, a MCS level with higher spectrum efficiency is chosen to maximize the average transmission rate and network capacity.

4.2.1 An example of link adaptation algorithm

A generic approach for searching and selecting the most suitable MCS for MIMO systems is proposed [5]. The technique provide for maximizing throughput while satisfying the application performance requirement for the receiver, according to the scheme of figure 4.2.

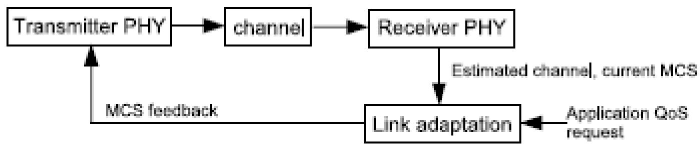

Figure 4.2: A diagram of the proposed system

Upon receiving a packet, the receiver can immediately estimate the channel for the next arriving packet (an indoor environment is supposed, thus the channel for consecutive packets undergoes a small amount of change, being a slow fading channel). The MCS of the current packet can be estimated from the HT signal field preamble. The same MCS is initially assumed for the next packet and the performance can be predicted. If the predicted performance cannot satisfy the requirements requested by the application, then the algorithm instructs the link adaptation unit to update MCS for a lower throughput. Otherwise, if the predicted performance is better than the required performance, then throughput increase should be attempted.

The MCS search algorithm consists of two parts: construction of the MCS table and the MCS search routine. The table implemented is defined by choosing the available MCS, in conformity with the features of the system (for example, a limit is represented by the number of transmit and receive antennas and maximum supportable number of spatial streams). Moreover, the table can be simplified by discarding some possible MCS in accordance with a precise design strategy.

When operating at very low SNRs, it may be necessary to reduce the number of spatial streams to sustain performance. On the contrary, if performance requirements are satisfied, a MCS with more spatial streams can be selected to increase data rate. As an example, for a maximum of two spatial streams, MCS 8 can be switched to MCS 0 or 1 if performance requirement can't be satisfied; on the other hand, if MCS 4 can be satisfied, then MCS 10 can be selected for upgrading to two spatial streams.

Fixing the number of spatial streams, modulation and constellation size represent in the choice of MCS another degree of freedom, that can be adapted under various link conditions. For example, BPSK works well in poor link condition, while 64-QAM does not; on the other hand, if the channel state is good, 64-QAM provides higher bandwidth efficiency and results in higher throughput to the system. Thus at high SNR it is possible to pack more bits per symbol into the M-QAM modulation, whereas bandwidth efficiency is sacrificed for robust communication between transmitter and receiver when link condition is poor. Finally, for the same reason, also the number of error correcting bits in a packet can be adapted to variations of the quality of transmission.

To search MCS in the MCS table, several different approaches can be implemented. The simplest one is exhaustive search; every entry in the table is tested following the direction of search and the algorithm stops until a suitable choice is found.

When MCS of identical modulation types across all spatial stream is employed, a more trivial search routine is possible. In fact, for a higher modulation level, i.e. larger number of bits per symbol, the performance achieved with the lowest coding rate is always better than the lower modulation level coded with highest rate. As a result, the search for MCS can be substantially simplified: the type of modulation can be selected separately from the rate of code.

The situation is different when unequal MCS is employed; the modulation-first approach can no longer be used. Another model instead should be considered, which is based on the product of the total bits per symbol of modulation and the coding rate (modulation-coding product, MCP). MCP indicates the equivalent bits per symbol of the combined MCS. As an example, for two spatial streams, entries of the constructed MCS table from low MCP to high MCP are shown in the table 4.1.

MCP index	Modulation Stream 1	Modulation Stream 2	Coding Rate
1	BPSK	BPSK	1/2
2	QPSK	QPSK	1/2
3	16-QAM	QPSK	1/2
4	16-QAM	16-QAM	1/2
5	64-QAM	16-QAM	1/2
6	16-QAM	16-QAM	3/4
7	64-QAM	16-QAM	3/4
8	64-QAM	64-QAM	2/3
9	64-QAM	64-QAM	3/4
10	64-QAM	64-QAM	5/6

Table 4.1: MCP

A faster search routine can be devised for the table 4.1. As an example, in a throughput increasing trend, for MCS corresponding to MCP 4, instead of moving to MCS corresponding to MCP 5, the algorithm can check directly whether a coding rate of 3/4 can be supported with four bits per symbol in both streams. If it can be supported, then the algorithm should directly check MCS corresponding to MCP 7 for the next step; otherwise the algorithm checks MCS corresponding to MCP 5.

4.3 Study of a practical case

The study of link adaptation techniques to maximize throughput has been made concrete in the analysis of a real network.

The system under examination was equipped with two transmitters and three receivers and maximum two spatial streams ($2 \times 3 : 2$ system). The device employed in the tests was a Telsey Eva, a 802.11n wireless adapter provided with three planar integrated antennas (two able both to transmit and receive, the third one only to receive). The antennas installed in the device are printed dual-band antennas, with a structure of a double-dipole right for WLAN applications, because able to resonate at the frequencies of the 5 GHz band, in addition to the overpopulated 2.4 GHz band. The type of device used can in fact operate in both bands.

Telsey Eva can be configured as access point or station, thus two devices were used to create a network similar to those of previous tests (see sections 3.3 and 3.4) and Iperf was used to test performance; the devices were located on two writing-desks at a distance of about ten meters and the scheme of the environment is shown in Figure 4.3.

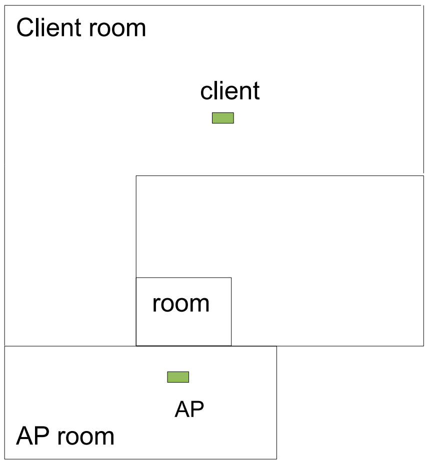

Figure 4.3: Setup layout

In this case tests have been made in the 5 GHz band, to ensure that other stations, transmitting in the 2.4 GHz band, were not a source of trouble and results were not influenced and compromised by different conditions. However, there were some obstacles like walls and furniture between AP and station to make the setting realistic.

Radios establishing and maintaining a link must negotiate a common MCS, that is decided by the AP and communicated to the station. The firmware of the device implements an algorithm designed by Telsey software engineers that automatically chooses the optimum MCS based on channel conditions and error-rate performance and then continuously adjusts the selection of MCSs as conditions change due to interference, fading and other events.

The aim of the tests was to investigate the different performance of the network by changing MCS, so as to try to improve the parameters of the automatic selection algorithm.

The device EVA is provided with a chipset that allows to select the desired MCS, besides the other options like band, channel and operating mode. The configuration of the setup of the device can be chosen via telnet, through the appropriate commands provided by the guide of the chipset, or via browser, through the graphic interface developed by Telsey.

The first step was to verify the performance of the link created between AP and station by enabling the option *Auto MCS* of the devices, that tries to provide a best transmission mode of a frame to be transmitted, in order to maximize the total transmission throughput in every channel conditions. Regarding the other most significant "HT features", Mixed Mode operating mode, 40 MHz wide channels and "Auto" guard interval (the automatic mechanism for selecting the suitable guard interval) were selected and fixed.

Iperf was used to measure UDP performance between the two endpoints, with the UDP bandwidth parameter increasing progressively from 55 to 95 Mb/s. The network under test was in fact a wireless extension of a 10/100 Ethernet (the devices were connected to the computers through their Ethernet 10/100 LAN interface), thus 95 Mb/s represented a limit to the maximum achievable bandwidth. Moreover, the same test was repeated by changing frequency channel (the table 4.2 shows the correspondence between channels and relative operative frequencies), in order to check the performance in all the spectrum.

The figures 4.4 and 4.5 are the graphic representation of the efficiency of the network in the starting conditions, achieved in the different channels.

Particularly, a network created with this type of device has to allow to support IP video streaming. Because also a Packet Error Ratio equal to 0.001% could cause visual artifacts, a reliable link (with PER near zero) is required; a PER equal to 5% would be easily handled by TCP retransmission, but it would kill UDP video. In the same time a consistent throughput is needed to transmit High Definition video too. Thus these were the performance requests.

The chart of Figure 4.5 shows that in some channels the percentage of lost

Channel	Central Frequency [GHz]
38	5.19
46	5.23
54	5.27
62	5.31
102	5.51
110	5.55
118	5.59
126	5.63
134	5.67

Table 4.2: 40 MHz channels within 5 GHz band

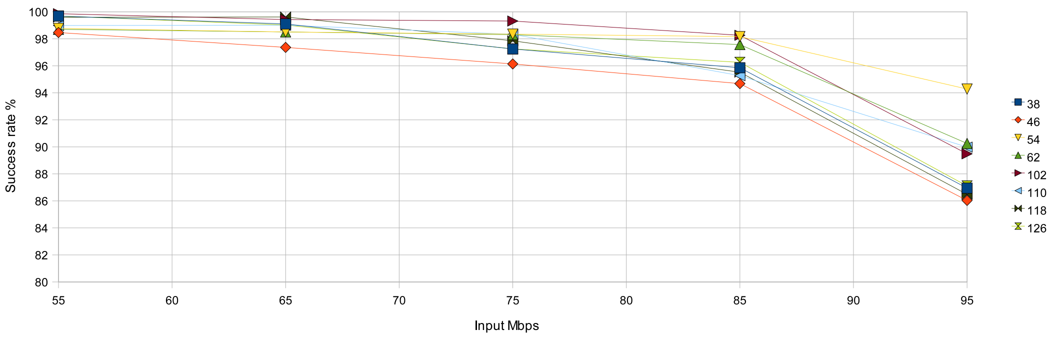

Figure 4.4: Values of efficiency

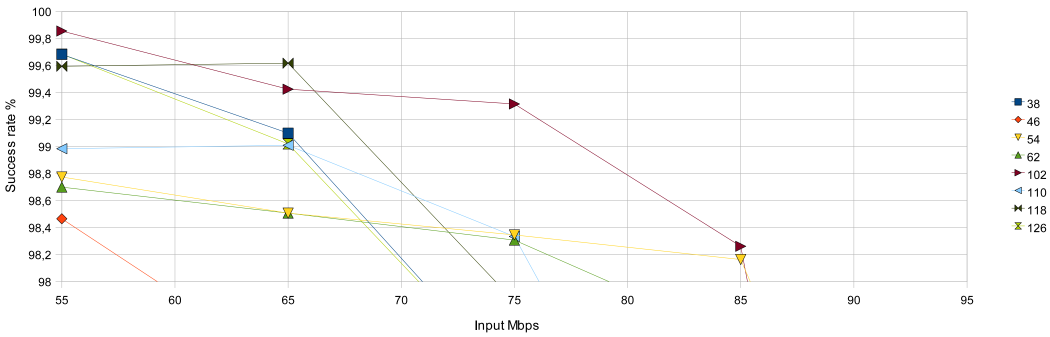

Figure 4.5: Values of efficiency: detail

datagrams is bigger than 1% already from the starting transmission bandwidth of 55 Mb/s.

With the goal of enhancing performance, an available option ("profile") that modified the mechanism of MCS selection was enabled. In this way a "minimum" modulation/coding scheme was defined and fixed: the MCS was still initially selected on the basis of the traffic to transmit, but by eliminating some possibilities of choice. Schemes with single spatial stream and phase-shift keying modulation (index values equal to 0, 1 and 2) were left out of the selection process, because their physical rate could be easily guaranteed by the corresponding schemes with two streams. Moreover, the algorithm provided for other strategic choices, particularly the passage from single to double spatial stream was facilitated by skipping the last schemes with single stream and 64-QAM modulation.

The results of tests done for this type of configuration are shown in the diagrams of Figure 4.6 and Figure 4.7; the latter represents the average among the values of efficiency of all channels.

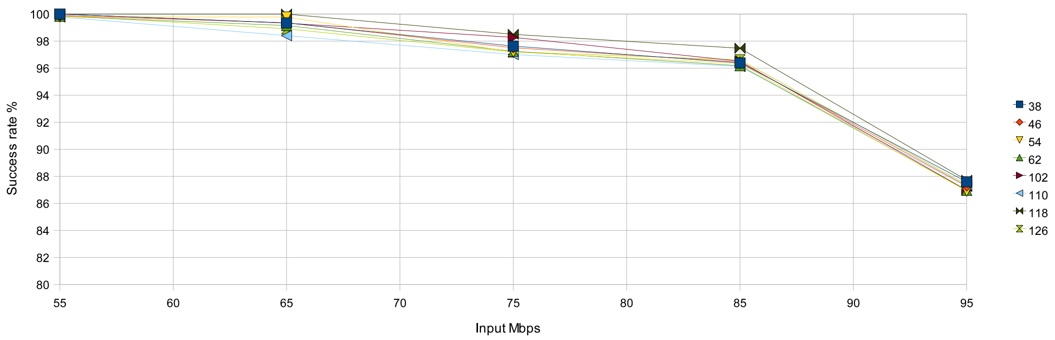

Figure 4.6: Values of efficiency with the new profile

From the charts it can be inferred that performance was better than the previous case: a bandwidth of 55 Mb/s was guaranteed. When the transmission bandwidth increased, the percentage of lost information gradually became not negligible.

The following step was to investigate the real performance of the single fixed MCSs in the environment of test, to understand if the automatic selection technique was efficient or could be improved someway. Particularly, tests were made to find the real maximum data rate achievable for every modulation and coding scheme, by remembering there was a superior limit of 95 Mb/s imposed by Ethernet connection.

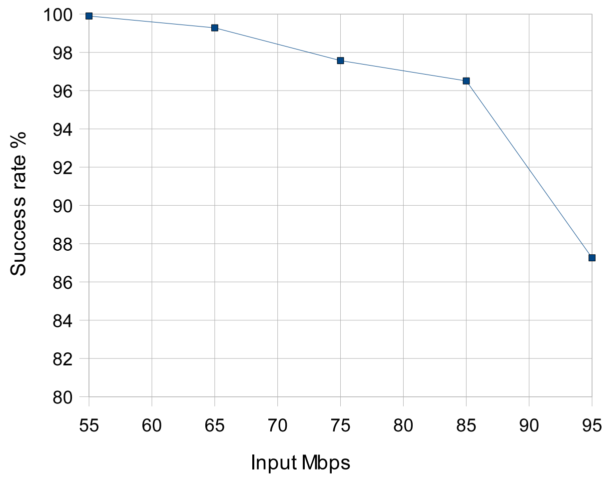

Figure 4.7: Average efficiency with the new profile

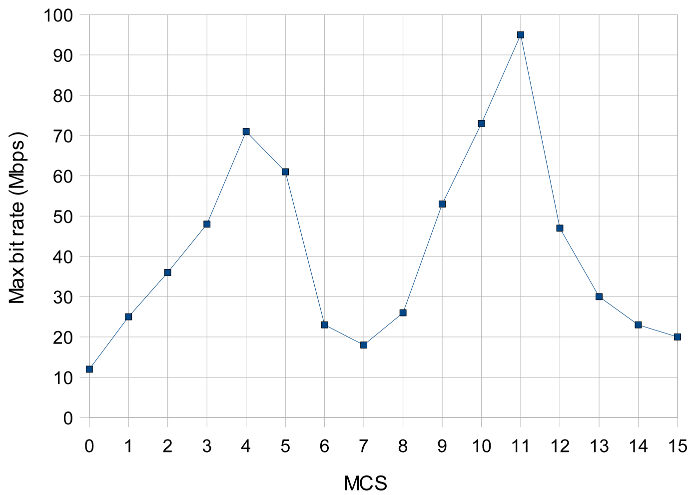

Figure 4.8: Performance with varying MCS

The chart of Figure 4.8 shows the results of this test with reference to the channel 62, chosen because central in the band; 40-MHz channels and Short Guard Interval were selected to exploit the maximum capacity of the system. The measurements display that the choice of MCSs to use and their sequence in the algorithm was the most suitable. On the other hand they show also that the algorithm was not able to select the optimal MCS for varying transmission rate. In fact, in the same conditions, the achievable bandwidth with auto-MCS mechanisms was 55 Mb/s, well below the capacity of the channel measured with fixed MCS equal to 11; the diagram of Figure 4.9 shows the average efficiency calculated by testing every channel with this modulation/coding scheme, highlighting a bandwidth of at least 85 Mb/s could be achieved (with peaks of 95 Mb/s in some channels).

A comparison between the performance of the two working modes is shown in Figure 4.10, that shows the mechanism of auto selection was not optimal. Naturally, the best solution was not to fix MCS 11, because this strategy could have been effective in this test environment but not in another one or, for example, if devices were farther. Measurements with the option Long Guard Interval were done too, but the performance was less satisfying; Short Guard Interval maintains in fact symbol separation sufficient for most environments, while a longer GI would lead to unwanted idle time in the wireless environment.

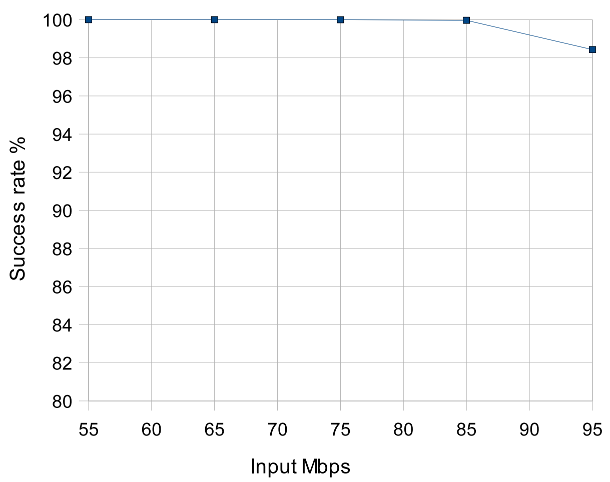

Figure 4.9: Average efficiency with MCS 11

At this point, the purpose was to understand why the auto selection algorithm did not work optimally and try to improve it. Particularly, Iperf server reports

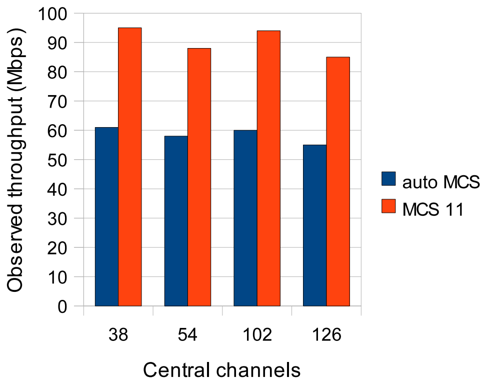

Figure 4.10: Performance with auto selection and fixed MCS

of conducted tests were carefully analyzed, because they recapitulated, for every interval of time chosen in the settings (1 s), the percentage of lost datagrams.

In this way a first problem was identified: when the transmission bandwidth was bigger than about 60 Mb/s, there was a constant high level of lost traffic concentrated in the first two seconds at the beginning of the transmission (naturally in the rest of the transmission there could be a further variable data loss, growing with increasing bandwidth). To identify the cause, a feature of the chipset was exploited, which allowed to know instantly, through an appropriate command to query the device via telnet, the modulation and coding scheme used in that moment. Reports showed that the starting MCS was equal to 12; thus this "guard-MCS", selected by the algorithm at the beginning of the transmission (before being eventually changed), was inadequate and it was lowered to the MCS index equal to 11.

The other issue was to try to remove the distributed packet loss that prevented from leading to an increase in throughput performance. An additional evaluation of test reports was carried out; a high level of lost traffic was identified when the algorithm tried to improve performance by proceeding from MCS index 11 to 12 and then back to schemes with single spatial stream because of the high packet error rate. Thus the scheme with index equal to 11 was fixed also as upper limit in the possible choices for the algorithm, because it was seen that it provided the most robust link modulation. Besides, a theoretical consideration supported this decision: Ethernet 10/100 LAN connection of devices represented the bottleneck in the network, thus the maximum achievable physical data rate could be guaranteed by MCS 11 (see the table of Figure 4.1), while the use of higher MCS values would have been inefficient.

The charts of Figure 4.11 and 4.12 show the measurements of testing the network with the modified version of auto selection algorithm. From the results it is observed that the auto rate selection scheme was in this way able to select MCS for best performance and thus the firmware of devices was updated with this final release of the algorithm.

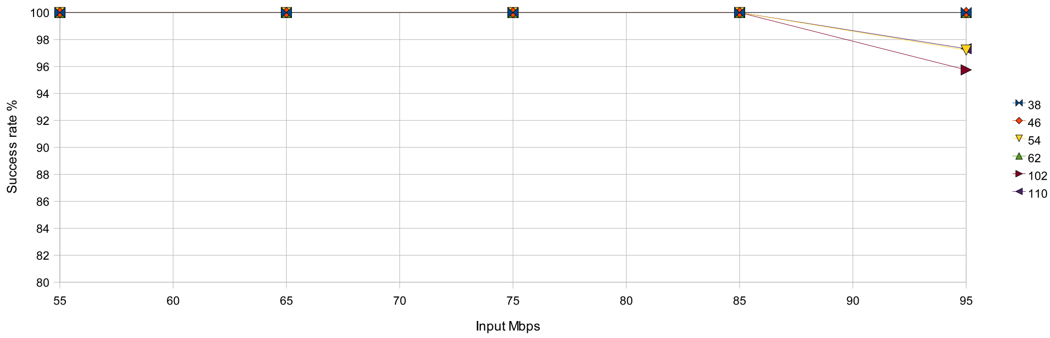

Figure 4.11: Values of efficiency for some channels with the final release of the algorithm

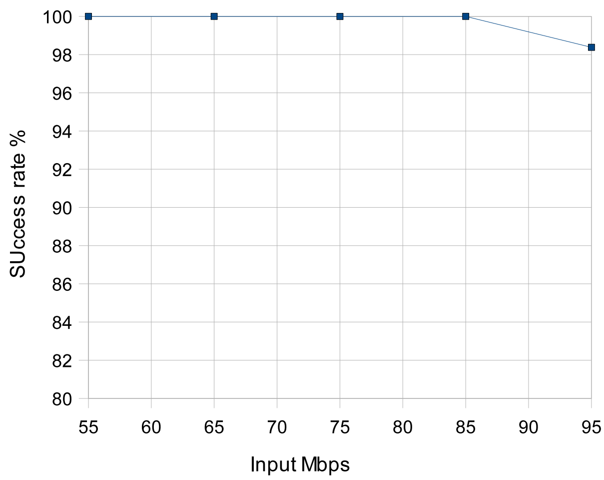

Figure 4.12: Average efficiency with the final release of the algorithm

4.3.1 Testing a multicast system

Multicast over wireless network is a more efficient method of supporting group communication than unicasting and broadcasting, as it allows transmission and routing of packets to multiple destinations using fewer network resources.

A multicast packet includes a group address so that the same packet is delivered to more than one destination. If a large group of wireless clients, for example, need to receive a particular video stream, than multicasting is really advantageous. The use of unicast packets to send the stream to each recipient individually would require many separate video streams, resulting in major performance impacts to the wireless network. With multicasting, only one stream is necessary; of course this assumes that each client needs to receive the same video at the same time.

Thus the new goal was to verify whether the algorithm of MCS selection implemented in EVA devices was the best solution in a multicast environment too. In fact, since there exist multiple receivers for a data stream in multicasting, there is much more difficulty in determining the overall MCS level which satisfies all the receiver.

The network under test consisted of one AP and two client stations (all EVA devices); the two stations were connected to the same AP and were placed according to the layout of Figure 4.13.

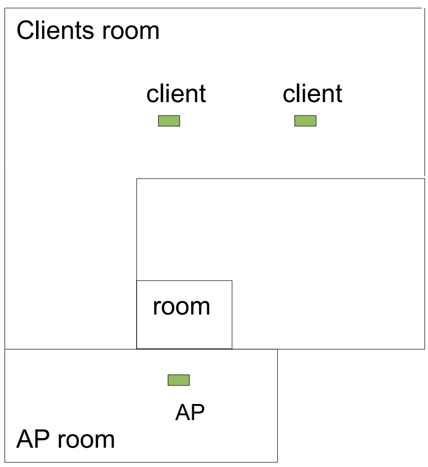

Figure 4.13: Setup layout for multicasting test

Iperf has been used to evaluate impacts on throughput with multicasting. In fact, this tool allows the monitoring of operations in a multicast environment too. A specific option of Iperf (- B) triggers the connection of the server to a multicast IP address, 224.0.55.55 for example; client will consequently transmit packets toward the same address. Thus the AP was used as Iperf client sending multicast packets and the stations (each connected to a computer) as Iperf servers joining the multicast group (see Appendix A).

The measurements of efficiency in reception for one station are reported in the diagram of Figure 4.14 (the results for the other station are identical).

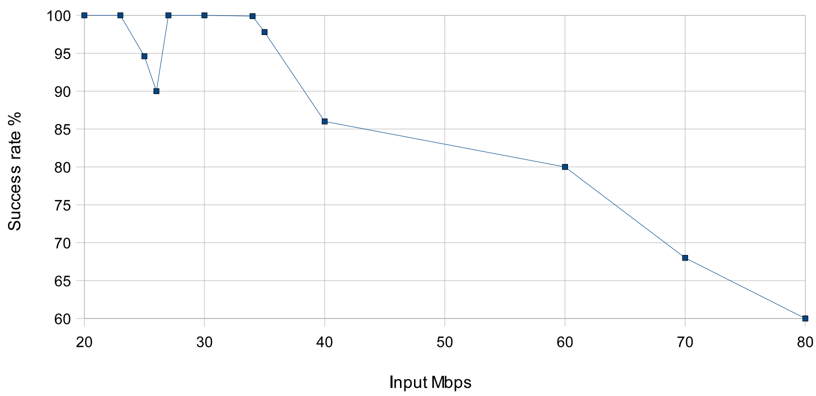

Figure 4.14: Values of efficiency in a multicast environment

The chart shows there was a negative peak around 25 Mbps. Performance was optimal up to 23 Mbps, while there was packet loss in the range from 24 to 26 Mbps. At 27 Mbps, when modulation/coding scheme increased from index value 3 to 4, efficiency was again maximum. The problem seemed to concern the need of a larger bandwidth for required transmission rates in multicast environment, because of the higher number of data streams to be managed. Thus a new profile in the MCS selection algorithm, which anticipated the passage from a MCS to the next, was tested.

Results are reported in the diagram of Figure 4.15; they show the peak was effectively eliminated, meaning this profile of working paid off in a multicast environment. However, guaranteed bandwidth for each station, a part from the negative peak in the first case, continued to be a little more than 30 Mb/s. Other tests were made to improve performance, for example by changing MCS selection, but without improvements. Thus the reason was a consequence of a "physical" limit of the system: an access point is similar to a network hub that has to handle multiple streams of information and its capacity of traffic management has a certain limit (depending on hardware and MIPS).

In any case results were satisfactory for one of main application multicasting can be addressed to, that is HD video streaming. In fact, an overall bandwidth larger than 60 Mb/s can support the transmission of four HD video streams, since one takes up to 15 Mb/s at most.

A concrete demonstration was done as final test to check the system in a

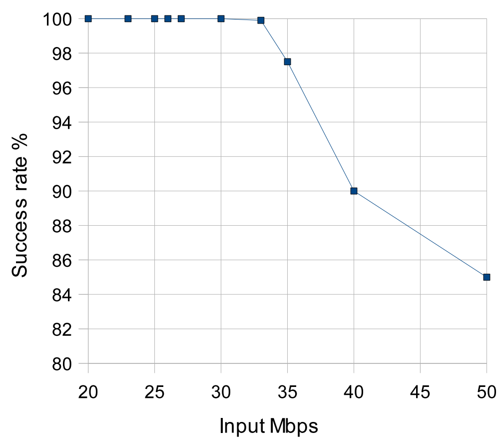

Figure 4.15: Values of efficiency in a multicast environment with the new profile of the MCS algorithm

multicast server and client environment. An AP, connected to a PC, transmitted a high-quality video by using VideoLAN, a software tool which can be used as a server or client to stream or receive videos on the network in multicast. A second device, used as client station, was connected to a set-top box, in turn connected to a television; this receiving system, associated with the multicast group, received the stream and allowed perfect viewing of the video.

Chapter 5

Antenna array design

Spatial correlation between antenna elements influence MIMO channel capacity. The primary aim of MIMO antenna design is to reduce the degree of correlation between received signal, that could affect maximum amount of data transmissible in a reliable information transfer. In this chapter a theoretical introduction about antenna array design is presented, followed by the description of testing concretely some types of antenna arrays.

5.1 Antenna array evaluation

The employment of antenna arrays is essential in a MIMO system and finding feasible configurations is an integral part of enabling the MIMO technology. Parameters such as correlation, mutual coupling and diversity have a significant influence on the MIMO system performance; therefore, they have been taken into account when evaluating a MIMO antenna array.

5.1.1 Correlation

MIMO channel capacity theoretically increases linearly with the minimum number of antennas at the transmit and receive sides, but correlation between antennas (i.e. a measure of relationship between antenna signals) can cause loss of spectral efficiency and degrade performance of a MIMO system. Thus the efficiency and the reliability of the system heavily depends on antenna correlation.

The envelope correlation (a coefficient commonly used to define correlation) is usually calculated from the three-dimensional radiation pattern of the antenna system. Following [9], the envelope correlation between two antennas in a uniform, rich scattering environment is computed as:

$$\rho_e = \frac{\left| \int \int_{4\pi} \left[\vec{F}_1(\theta, \phi) \bullet \vec{F}_2(\theta, \phi) \right] d\Omega \right|^2}{\int \int_{4\pi} \left| \vec{F}_1(\theta, \phi) \right|^2 d\Omega \int \int_{4\pi} \left| \vec{F}_2(\theta, \phi) \right|^2 d\Omega} \tag{5.1}$$

where $\vec{F}_i(\theta, \phi)$ is the active pattern of the antenna i when port j is closed on a matched load and $\bullet$ denotes the Hermitian product.

To compute (5.1), it is necessary to know the radiation pattern of the antenna system and perform numerical integrations. This is a complex process that requires advanced calculation, whether it is done numerically or experimentally.

However, in some cases the expression for the envelope correlation can be simplified. Clarke [28] derived the following relationship where dependence of ρ_e from antenna separation is pointed out:

$$\rho_e \cong \left(J_0 \left(\frac{2\pi d}{\lambda} \right) \right)^2 \tag{5.2}$$

where J_0 is the Bessel function of the first kind with order zero, d is the antenna spacing and λ the wavelength. The result is valid for a uniform angle of arrival distribution in azimuth, identically polarized omnidirectional receiving antennas, multipath components assumed to lie in the horizontal plane and last but not least mutual coupling is assumed negligible.

In other cases (uniform random field, absence of scattering objects near the antennas, interest in broadband correlation results) the envelope correlation can be fast calculated by S-parameters. This approach has the advantage that it does not require the computation nor the measurement of the radiation pattern of the system; besides, in this way, the explicit influence of mutual coupling and input match is clearly revealed. Therefore, the envelope correlation coefficient given by (5.1) can be expressed in terms of the S-parameters as:

$$\rho_e = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|^2}{\left(1 - \left(|S_{11}|^2 + |S_{21}|^2\right)\right)\left(1 - \left(|S_{22}|^2 + |S_{12}|^2\right)\right)} \tag{5.3}$$

Thus the correlation between antenna signals is an essential factor to quantify the efficiency of MIMO systems and it is required to be minimized to achieve the goal of increasing performance. In these terms, it is a fundamental criterion to asses antenna array design.

5.1.2 Mutual coupling

Correlation varies as a function of different factors, like the scattering environment, the distance between transmitter and receiver, the Doppler spread, but one is particularly significant in this analysis, that is mutual coupling.

This parameter describes the electromagnetic interactions that exist among the elements of an antenna array: when several elements are closely placed to each other, the field generated by one antenna alters the current distribution of the other antennas. By this way there is a distortion of the radiation pattern of each element of the multi-element system compared to the radiation pattern of each isolated element and the assumption of independent antennas is not justified any more. Moreover, the input impedance of each array element is influenced by the presence of the other elements. Mutual coupling effects can cause a lower antenna efficiency and decrease the total received power with a consequent decrease of SNR.

Mutual coupling have a significant influence on correlation too; it can increase or decrease correlation and thus it can reduce capacity, but also increase it. Both effects are plausible. On one hand, high mutual coupling may, by re-radiation of received power, result in higher spatial correlation between antenna signals and mean performance degradation in MIMO communication. On the other hand, since mutual coupling occurs, the individual antenna patterns may change, creating diversity (especially for antenna elements with small angular spread [7]): each antenna "sees" different portions of the surrounding scatters and this can be very useful, for example, in poor scattering environments.

Mutual coupling is typically characterized by spacing between antennas but it differs also according to each antenna's radiation pattern, even though the separation distance between antennas is similar. It can be calculated and measured from S_{ij} parameters of the scattering matrix.

5.1.3 Diversity

Antenna array design is a determining factor when designing an antenna array for MIMO systems, because an optimal array configuration allows to combine different diversity techniques, such as spatial, pattern and polarization diversity, to obtain uncorrelated signals at the antennas and enhance the performance.

Spatial diversity is the most widely implemented form of diversity combining and it consists of spacing antenna elements (that usually are antennas with the same characteristics). In order that spatial diversity works effectively, the received signals must be sufficiently uncorrelated, so that, if one of the antenna elements is in deep fade, the signal can be recovered by other antenna terminals. This can be achieved by choosing the separation distance between antenna elements appropriately. The element spacing depends upon the expected incidence of the incoming signal (and thus on the disposition of scatters causing the multipath transmission) and mutual coupling. For instance, analytical studies [7] have shown that the influence of mutual coupling (between typical antenna elements) is significant only for antenna spacings smaller than a wavelength; thus for larger distances its influence is negligible and spacings on the order of λ is sufficient in most cases.

Pattern diversity is exploited in the systems that implements different radiation patterns on the antenna elements to provide a high gain in a large portion of angle space. The use of antennas with different directive beam patterns (or the use of equal but rotated antennas) is particularly useful at a site where the waves are coming from diverse angles.

Polarization diversity use a combination of antennas with different (orthogonal) polarizations to exploit the fact that orthogonally polarized signals are uncorrelated: the improvement is granted by the uncorrelated channel provided by a polarization state made orthogonal to the existing one. Additionally this technique immunize a system from polarization mismatches caused by scattering environments.

5.2 Testing some antenna array configurations

This section presents an evaluation of the MIMO performance in an indoor environment of several candidate antenna array designs. The type of network constructed to assess the behavior of the different configurations was identical to that described in Section 4.3; thus two Telsey Eva devices were used, one configured as access point end the other as client station. The devices were placed according to the layout of Figure 3.3, thus in a *NLOS* (*non-line-of-sight*) scenario. Iperf was used to test link performance.

Telsey Eva device was particularly suited for this type of test; in fact, it allows to use either the integrated planar antennas or external antenna elements that can be connected to the device trough three "bushings". Thus the system allowed to switch from a fixed antenna array to a "mobile" array (through a command given via telnet) and test the influence of design choices on the diversity gain. Arrays consisting of three dual-band dipoles (for WLAN applications) of length $l = 8$ cm were used at the transmit and receive side of the link, where specular antenna configurations were modeled for each case. Note that dipole antennas led to worse performance in comparison with integrated planar antennas, but the purpose of this investigation was to compare the capacity gain attainable by the different array geometries, i.e. a relative and not absolute measure.

Initially tests were done in the 5 GHz band and with MCS auto-selection algorithm activated in the system configuration; regarding the other HT options, Green Field operating mode, 40 MHz wide channels and "Auto" guard interval were selected.

The first selected scheme for the antenna array was *ULA* (*Uniform Linear Array*); this configuration consists of parallel dipole antennas spaced d apart, with d that can vary (see Figure 5.1).

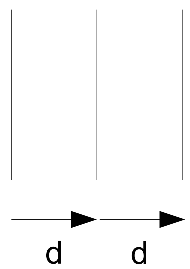

Figure 5.1: Uniform Linear Array

Inter-element spacing of 4 cm (a measure smaller than a wavelength) was fixed (system 1) and cycles of Iperf test with increasing UDP bandwidth were performed to check system efficiency; this type of test was repeated for each frequency channel, except those at the ends of the band, where the communication was not so reliable). Figure 5.2 shows the results (average efficiency).

For the second measurement campaign the antennas were positioned according to the setups of Figure 5.3 (systems 2 and 3).

These geometries require the same space of $l \times l$, but, while the first system

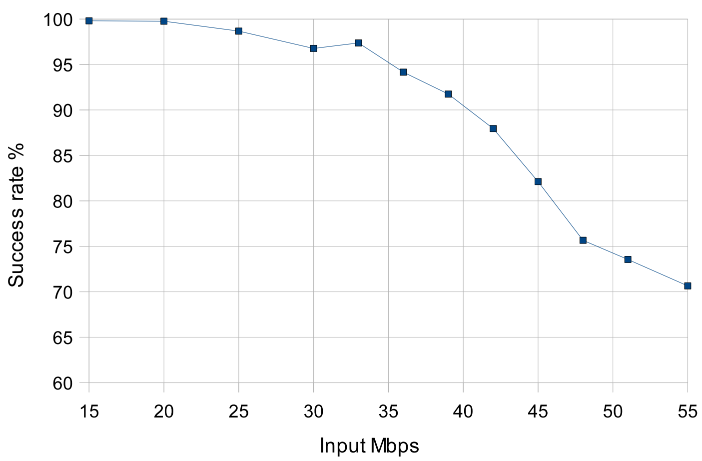

Figure 5.2: System 1: performance

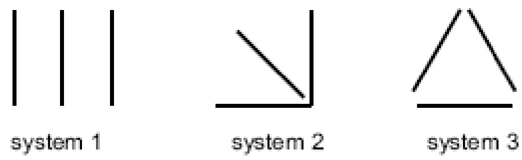

Figure 5.3: Array setups of the systems 1, 2 and 3

is a pure space diversity system, the systems 2 and 3 are based on a combination of space, pattern and polarization diversity.

The system that led to best result was the third one, where the three dipole antennas were arranged as a triangle; in fact, this antenna solution exploits the potential of combined diversity techniques — unlike the first system — and it outperforms the second one, where the antenna array geometry improve performance to a lesser extent. Figure 5.4 and 5.5 graphically represent the results of this analysis.

The following analyzed system (named system 4) was another case of ULA but with a larger inter-element spacing, that was $d = l = 8$ cm (a measure larger than a wavelength). Measured results are shown in the chart of Figure 5.6; it is evident that this configuration performed best (see also Figure 5.7 for a direct comparison). Thus the solution that exploited spatial diversity led in this case to higher capacities: by spacing antenna elements far apart, independent scattering in the propagation environment and hence a lower correlation could be ensured for received signals.

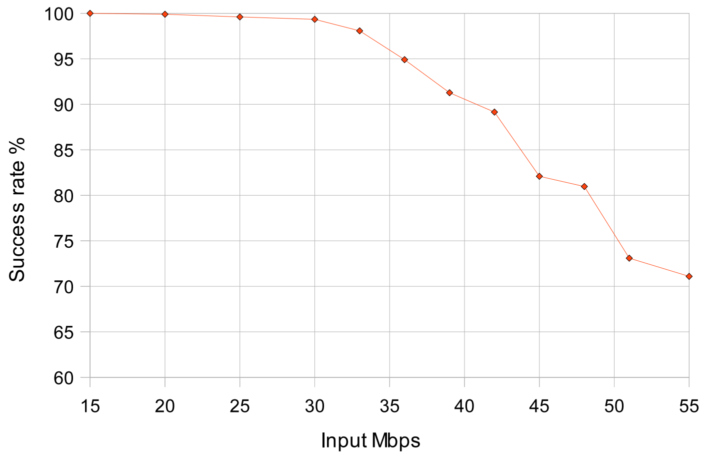

Figure 5.4: System 3: performance

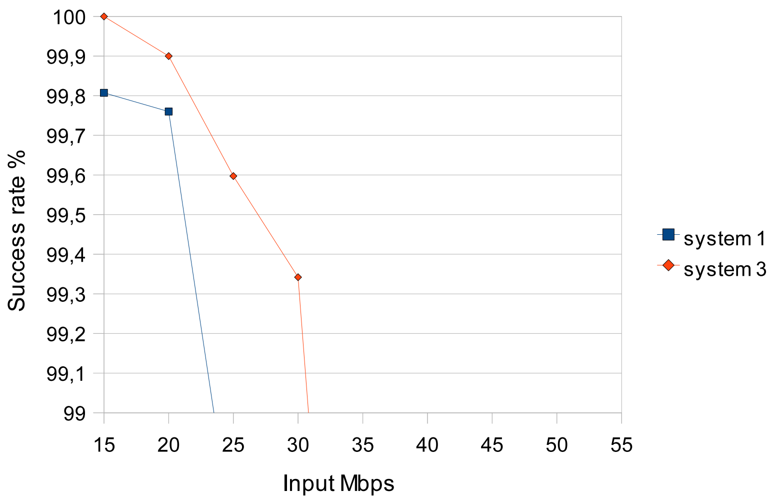

Figure 5.5: Comparison between system 1 and 3: looking for 0% - 1% packet loss

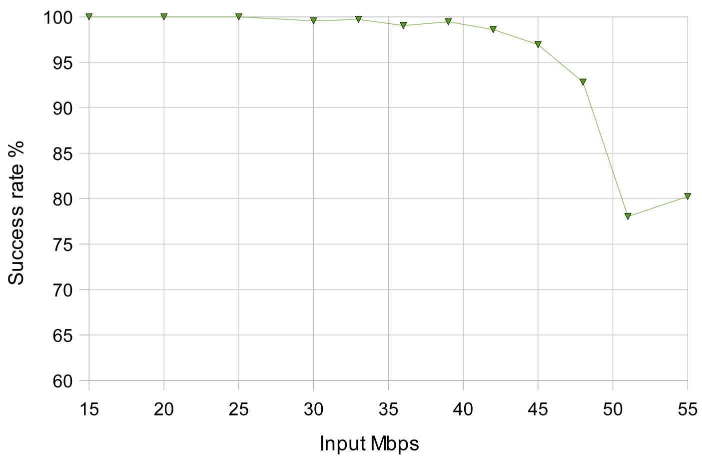

Figure 5.6: System 4: performance

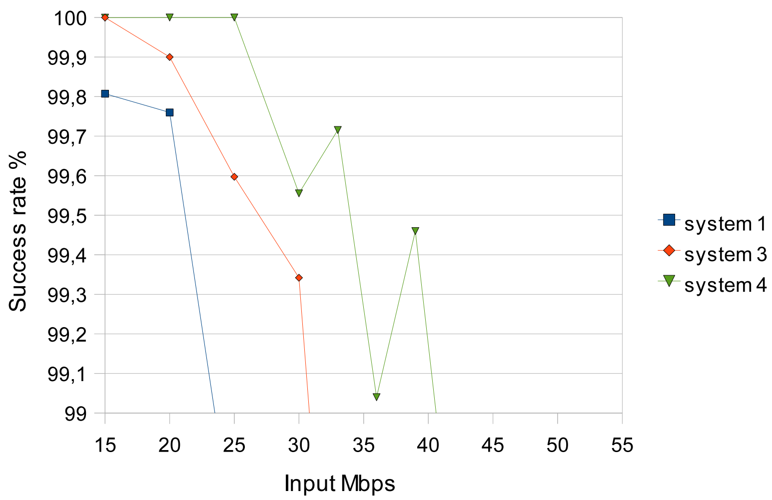

Figure 5.7: Comparison among systems 1, 3 and 4: looking for 0% - 1% packet loss

However, a clarification is necessary: this result is not a general rule but it concerns this particular situation (i.e. the system under test and its operating mode). For example, polarization and pattern diversity configurations have the advantage over spatial diversity of providing gain in *line-of-sight* (*LOS*) channels with very little multipath [13]. In fact, if the propagation environment has sufficient multipath, the channel spatial correlation is generally low; in contrast, when a strong LOS route exists between transmitter and receiver, the correlation is higher, but it can be considerably reduced, for example, by using antenna elements with orthogonal polarizations or patterns. Besides, these diversity techniques can be applied when space diversity is not an option due to the small antenna spacing, for example in small handled devices like organizers, laptops or other handsets with integrated compact arrays, where providing space saving is an indispensable condition.

Other array geometries and their impact on capacity and error rate were considered. The investigation focused on evaluating performance of array setups with inter-element spacing larger than the wavelength; thus the purpose was to look for possible geometries, based on spatial diversity, that could outperform ULA. Figure 5.8 depicts the considered antenna array geometries (the points represent dipoles orthogonal to the plane).

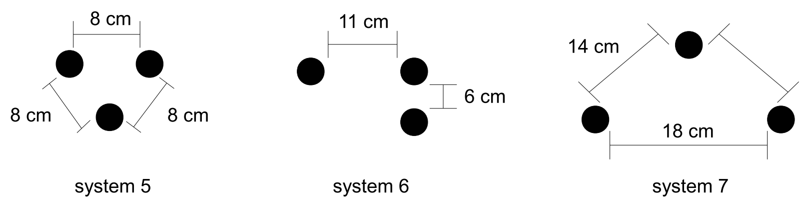

Figure 5.8: Array setups of the systems 5, 6 and 7 (top view)

The results given by testing the “star” configuration (system 5) are shown in the chart of Figure 5.9. The same inter-element spacing characterized the ULA and the star configuration, thus only the different alignment of the antenna elements in the space was the cause of the difference in the system performance. From Figure 5.10 it is seen that ULA provided better capacity. Obtained results find a positive feedback in the research described in [15]; when the channel has low correlation and at high distances between antenna elements, uniform linear arrays yield the highest capacity/diversity gains. Thus also this result is not al-

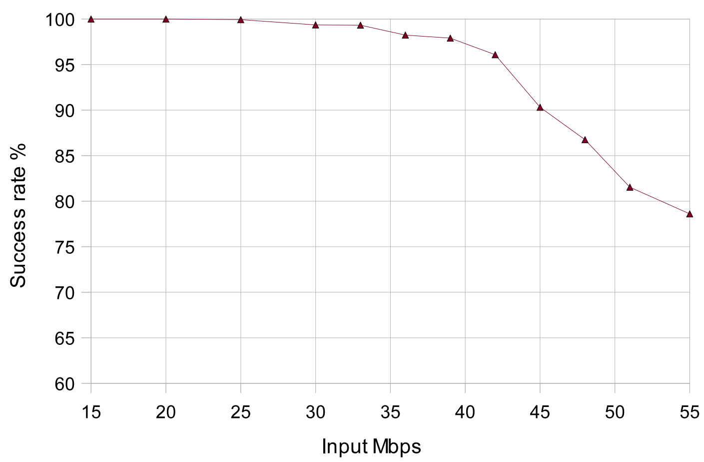

Figure 5.9: System 5: performance

ways valid and performance depends on propagation conditions; for example, the star configuration is preferable for MIMO systems characterized by high spatial correlation, hence in poor scattering environments it provides the best system performance.

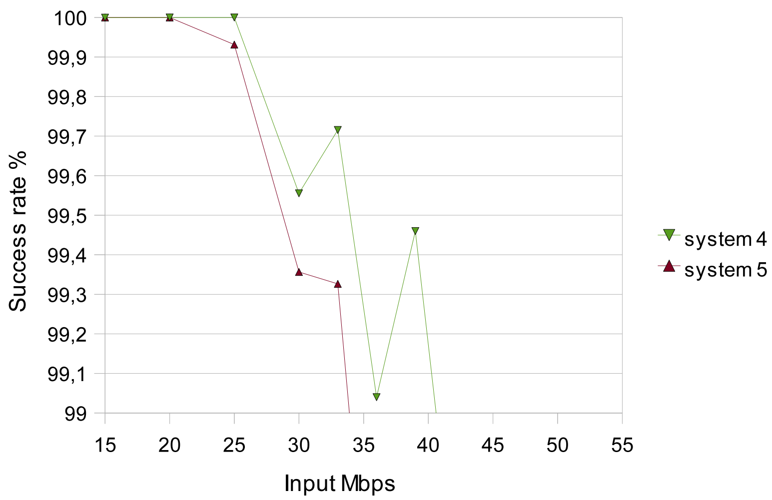

Figure 5.10: Comparison between system 4 and 5: looking for 0% - 1% packet loss

Moreover, the effect of the receive and transmit azimuthal array orientation can influence both spatial correlation and capacity of MIMO wireless channels. In [16] it is shown that in a scattering channel the maximum capacity is obtained when the ULAs at the communication ends are "broadside" oriented to each other, which means that arrays are turned to face the main direction of the radio wave propagation. This is not a problem for fixed wireless communications systems (as that one under test), where the position of AP and stations can be rotated towards the desired direction.

The performance of the systems 6 and 7 is presented in the chart of Figure 5.11 and their comparison with ULA is shown in Figure 5.12.

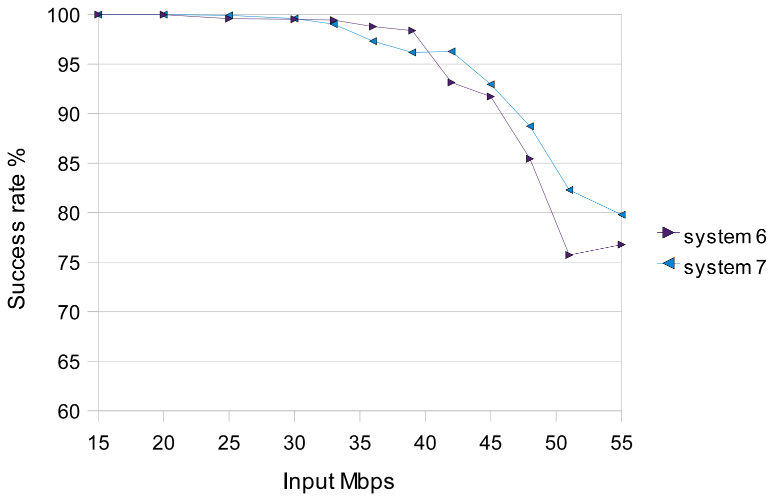

Figure 5.11: Systems 6 and 7: performance

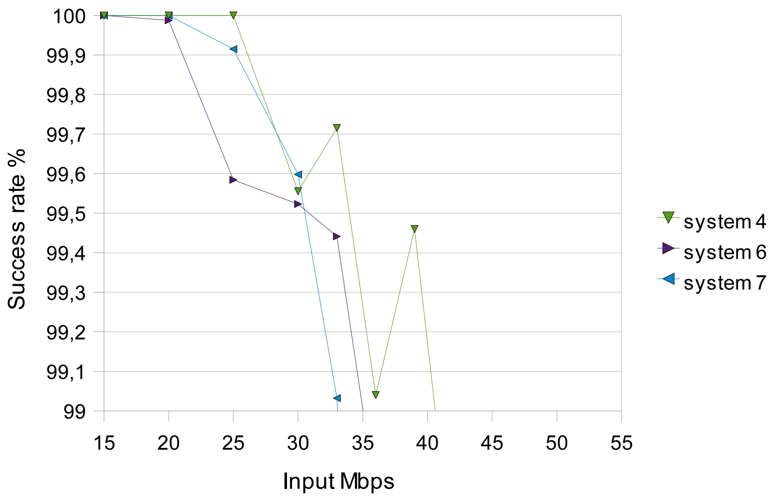

Figure 5.12: Comparison among systems 4, 6 and 7: looking for 0% - 1% packet loss

It can be noticed that these geometries did not improve system performance compared with ULA. One last attempt was make by testing another arrangement of the elements, similar to ULA of system 4 but with the lateral dipoles inclined (inclination of 45 degrees) as in Figure 5.13. From the charts of Figure 5.14 and

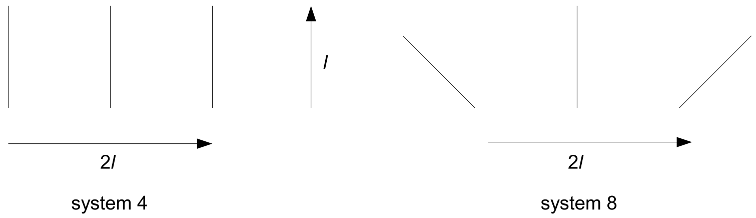

Figure 5.13: Array setups of the systems 4 and 8

5.15 it is observed that the combination of both spatial and polarization diversity did not provide advantages in terms of channel capacity and bit error rate performance; indeed, in this case (system 8), the performance deteriorated, probably due to a not optimal interaction among the radiation patterns of each antenna. Anyway, when spatial separation is large, generally the angular separation, understood as different inclination of the antenna elements, can hardly improve the diversity gain [14]; thus an evaluation of its influence on the radiation pattern of the array would be needed.

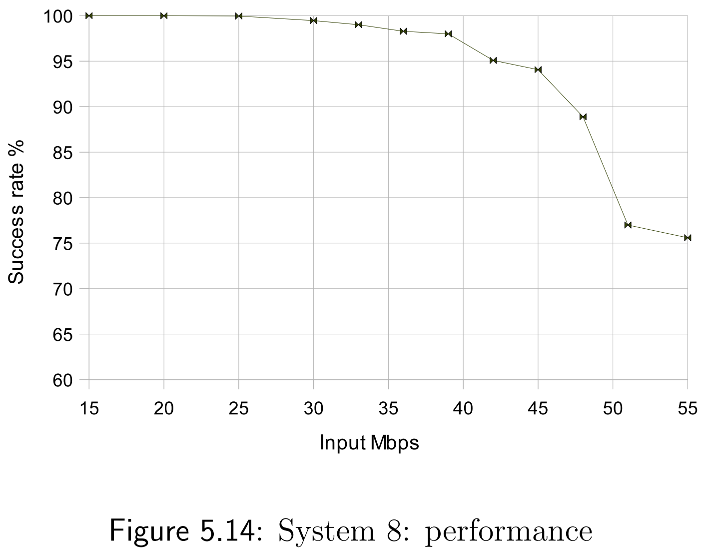

Figure 5.14: System 8: performance

To check obtained results, further investigation was done on the configurations considered up to now, with a variant in the tests. The MCS was fixed in the device configuration, so as to evaluate at every turn, for every selected MCS, the maximum data rate achievable from the system with the different array setups.

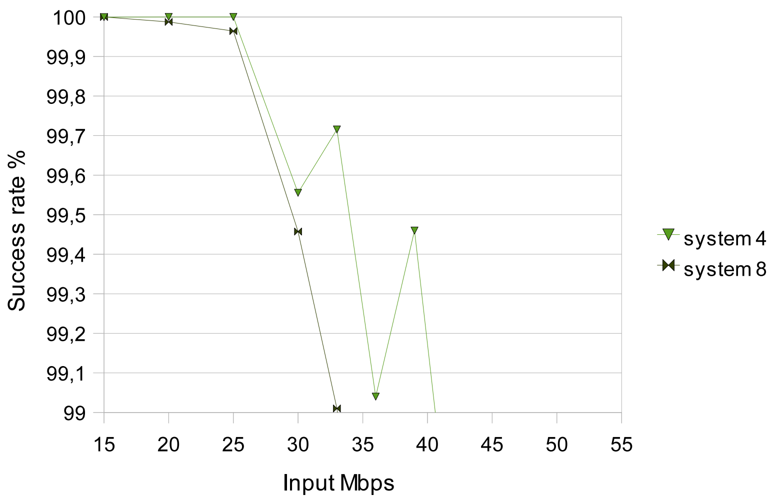

Figure 5.15: Comparison between systems 4 and 8: looking for 0% - 1% packet loss

Particularly, schemes with single spatial stream were selected; in this way the level of complexity of signal processing was further reduced and the impact of antenna array geometry on MIMO channel properties was more evident. In the diagram of Figure 5.16 the results concerning the default channel (central channel 102), where performance was better, and obtained with MCS 4 are presented.[1]

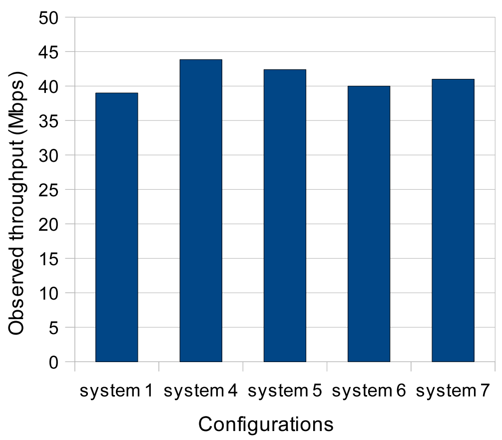

Figure 5.16: Throughput with different array configurations

It can be concluded that ULA often outperforms the other array geometries in terms of diversity gain and channel capacity performance. Particularly, it has

[1]Note that previous tests were not done with the improved version of MCS auto-selection algorithm.

been seen that in an indoor scenario under NLOS propagation conditions ULA with inter-element spacing larger than a wavelength leads to better performance than other considered setups, emerging as the preferable configuration.

Chapter 6

Conclusions

Wireless LAN advancements in terms of range, throughput and reliability introduced by IEEE 802.11n standard have made MIMO very popular in modern communications and the employment of antenna arrays at both sides of the link has become a true innovation in the area of data transmission.

In the chapter 2 the major features of MIMO are reviewed. Information theory reveals the great capacity gains which can be realized from MIMO systems. To multiply link capacity, firstly, they turn a long-time drawback for wireless transmission like multipath propagation into an opportunity to exploit the spatial dimension of the propagation channel. Naturally, they involve also combinations of digital beamforming techniques and sophisticated signal processing like, for example, spatial multiplexing.

The third chapter describes the procedures employed to characterize systems under test. Particularly, Iperf is presented, that is an open-source application to measure network performance; through this tool it is possible to measure various parameters and obtain data regarding the real transmission capacity of a channel, the number of lost packets compared to the total number of transmitted packets and the jitter delay. Iperf has been used, first of all, to compare a 802.11g network with a 802.11n network; this analysis has allowed both to describe the various types of tests later conducted for other Wi-Fi networks and check the improvements given by a MIMO system based on the last standard.

In the fourth chapter an important feature of 802.11n-based systems is presented, Modulation and Coding Scheme. The complexity of 802.11n rate adaptation has given birth to the concept of MCS, which describes, through a simple integer, the variables (number of spatial streams, modulation, coding rate) used on each transmitted stream. Wi-Fi systems can automatically choose the optimum MCS based on the required performance and channel conditions and then adjust this selection as conditions change. The study of link adaptation techniques had the practical aim of improving an algorithm of this type designed by Telsey. Particularly, several tests and measurements have been made by changing the method of MCS selection and a more efficient mechanism to maximize throughput has been obtained.

The impact of antenna array configurations on MIMO system performance in an indoor propagation environment is studied in the last chapter. Fundamentals results given by information theory show that the capacity of a MIMO system increases linearly with the number of antennas in a scattering-rich environment. However, most practical environments always exhibit some degree of spatial correlation that degrades the capacity gain. A suitable antenna array design can solve this problem and positively influence the performance of the communication system. Several tests have been made to measure the capacity gain attainable by different array geometries with three dipole elements. Measured results have demonstrated that under NLOS propagation conditions spatial diversity dominates the effect on capacity and ULA is the preferable configuration.

The tests of chapter 3 and 4 have been made with $2 \times 3 : 2$ MIMO products, which are the most common configurations with $2 \times 2 : 2$ and $3 \times 3 : 2$ systems; but 802.11n allows up to $4 \times 4 : 4$ devices able to reach data rates of 600 Mbps. Further investigations may consist in the analysis of this type of systems, to characterize their performance and try to optimize it.

Appendix A

Example of Iperf test

To start Iperf in the server (receiving end), the file *testServer.sh* is executed via command-line, allowing to save test results directly in a CSV file (*results.csv*). Here is an example of what appears on the display during the test.

```
root@pc1:/home/Iperf_server# ./testServer.sh results.csv
setting static ARP...
starting iperf test...
------------------------------------------------------------
Server listening on UDP port 5001
Receiving 1470 byte datagrams
UDP buffer size:   218 KByte
------------------------------------------------------------
[  3] local 192.168.0.100 port 5001 connected with 192.168.0.154 port 32994
[  3]  0.0- 1.0 sec  6.40 MBytes  53.7 Mbits/sec  0.323 ms    0/ 4564 (0%)
[  3]  1.0- 2.0 sec  6.40 MBytes  53.7 Mbits/sec  0.326 ms    0/ 4565 (0%)
[  3]  2.0- 3.0 sec  6.40 MBytes  53.7 Mbits/sec  0.325 ms    0/ 4567 (0%)
[  3]  3.0- 4.0 sec  6.41 MBytes  53.7 Mbits/sec  0.332 ms    0/ 4569 (0%)
[  3]  4.0- 5.0 sec  6.40 MBytes  53.7 Mbits/sec  0.321 ms    0/ 4564 (0%)
[  3]  5.0- 6.0 sec  6.40 MBytes  53.7 Mbits/sec  0.318 ms    0/ 4565 (0%)
[  3]  6.0- 7.0 sec  6.40 MBytes  53.7 Mbits/sec  0.328 ms    0/ 4566 (0%)
[  3]  7.0- 8.0 sec  6.41 MBytes  53.7 Mbits/sec  0.310 ms    0/ 4570 (0%)
[  3]  8.0- 9.0 sec  6.40 MBytes  53.7 Mbits/sec  0.337 ms    0/ 4565 (0%)
[  3]  9.0-10.0 sec  6.40 MBytes  53.7 Mbits/sec  0.321 ms    0/ 4568 (0%)
[  3] 10.0-11.0 sec  6.40 MBytes  53.7 Mbits/sec  0.327 ms    0/ 4563 (0%)
[  3] 11.0-12.0 sec  6.40 MBytes  53.7 Mbits/sec  0.322 ms    0/ 4565 (0%)
[  3] 12.0-13.0 sec  6.41 MBytes  53.7 Mbits/sec  0.335 ms    0/ 4569 (0%)
[  3] 13.0-14.0 sec  6.40 MBytes  53.7 Mbits/sec  0.330 ms    0/ 4566 (0%)
[  3] 14.0-15.0 sec  6.40 MBytes  53.6 Mbits/sec  0.322 ms    0/ 4562 (0%)
[  3] 15.0-16.0 sec  6.41 MBytes  53.7 Mbits/sec  0.329 ms    0/ 4570 (0%)
[  3] 16.0-17.0 sec  6.40 MBytes  53.7 Mbits/sec  0.332 ms    0/ 4563 (0%)
[  3] 17.0-18.0 sec  6.41 MBytes  53.7 Mbits/sec  0.323 ms    0/ 4570 (0%)
[  3] 18.0-19.0 sec  6.40 MBytes  53.6 Mbits/sec  0.330 ms    0/ 4562 (0%)
[  3] 19.0-20.0 sec  6.41 MBytes  53.7 Mbits/sec  0.326 ms    0/ 4570 (0%)
[  3] 20.0-21.0 sec  6.40 MBytes  53.7 Mbits/sec  0.331 ms    0/ 4566 (0%)
[  3] 21.0-22.0 sec  6.40 MBytes  53.6 Mbits/sec  0.332 ms    0/ 4562 (0%)
[  3] 22.0-23.0 sec  6.40 MBytes  53.7 Mbits/sec  0.330 ms    0/ 4567 (0%)
```

```
[  3] 23.0-24.0 sec  6.40 MBytes  53.7 Mbits/sec  0.335 ms    0/ 4565 (0%)
[  3] 24.0-25.0 sec  6.40 MBytes  53.7 Mbits/sec  0.314 ms    0/ 4567 (0%)
[  3] 25.0-26.0 sec  6.40 MBytes  53.7 Mbits/sec  0.321 ms    0/ 4567 (0%)
[  3] 26.0-27.0 sec  6.40 MBytes  53.7 Mbits/sec  0.330 ms    0/ 4566 (0%)
[  3] 27.0-28.0 sec  6.40 MBytes  53.7 Mbits/sec  0.333 ms    0/ 4566 (0%)
[  3] 28.0-29.0 sec  6.40 MBytes  53.7 Mbits/sec  0.337 ms    0/ 4567 (0%)
[  3] 29.0-30.0 sec  6.40 MBytes  53.7 Mbits/sec  0.327 ms    0/ 4568 (0%)
[  3] 30.0-31.0 sec  6.40 MBytes  53.7 Mbits/sec  0.327 ms    0/ 4566 (0%)
[  3] 31.0-32.0 sec  6.40 MBytes  53.7 Mbits/sec  0.326 ms    0/ 4563 (0%)
[  3] 32.0-33.0 sec  6.40 MBytes  53.7 Mbits/sec  0.327 ms    0/ 4565 (0%)
[  3] 33.0-34.0 sec  6.40 MBytes  53.7 Mbits/sec  0.330 ms    0/ 4566 (0%)
[  3] 34.0-35.0 sec  6.41 MBytes  53.7 Mbits/sec  0.328 ms    0/ 4569 (0%)
[  3] 35.0-36.0 sec  6.40 MBytes  53.7 Mbits/sec  0.323 ms    0/ 4567 (0%)
[  3] 36.0-37.0 sec  6.40 MBytes  53.7 Mbits/sec  0.323 ms    0/ 4566 (0%)
[  3] 37.0-38.0 sec  6.40 MBytes  53.7 Mbits/sec  0.323 ms    0/ 4567 (0%)
[  3] 38.0-39.0 sec  6.40 MBytes  53.7 Mbits/sec  0.326 ms    0/ 4563 (0%)
[  3] 39.0-40.0 sec  6.40 MBytes  53.7 Mbits/sec  0.337 ms    0/ 4567 (0%)
[  3] 40.0-41.0 sec  6.40 MBytes  53.7 Mbits/sec  0.333 ms    0/ 4565 (0%)
[  3] 41.0-42.0 sec  6.40 MBytes  53.7 Mbits/sec  0.316 ms    0/ 4566 (0%)
[  3] 42.0-43.0 sec  6.40 MBytes  53.7 Mbits/sec  0.320 ms    0/ 4565 (0%)
[  3] 43.0-44.0 sec  6.40 MBytes  53.7 Mbits/sec  0.328 ms    0/ 4565 (0%)
[  3] 44.0-45.0 sec  6.40 MBytes  53.7 Mbits/sec  0.340 ms    0/ 4566 (0%)
[  3] 45.0-46.0 sec  6.40 MBytes  53.7 Mbits/sec  0.328 ms    0/ 4567 (0%)
[  3] 46.0-47.0 sec  6.40 MBytes  53.7 Mbits/sec  0.333 ms    0/ 4568 (0%)
[  3] 47.0-48.0 sec  6.40 MBytes  53.7 Mbits/sec  0.328 ms    0/ 4564 (0%)
[  3] 48.0-49.0 sec  6.40 MBytes  53.7 Mbits/sec  0.325 ms    0/ 4566 (0%)
[  3] 49.0-50.0 sec  6.41 MBytes  53.7 Mbits/sec  0.326 ms    0/ 4569 (0%)
[  3] 50.0-51.0 sec  6.40 MBytes  53.7 Mbits/sec  0.328 ms    0/ 4567 (0%)
[  3] 51.0-52.0 sec  6.40 MBytes  53.7 Mbits/sec  0.322 ms    0/ 4565 (0%)
[  3] 52.0-53.0 sec  6.40 MBytes  53.7 Mbits/sec  0.323 ms    0/ 4563 (0%)
[  3] 53.0-54.0 sec  6.41 MBytes  53.8 Mbits/sec  0.310 ms    0/ 4571 (0%)
[  3] 54.0-55.0 sec  6.40 MBytes  53.7 Mbits/sec  0.323 ms    0/ 4563 (0%)
[  3] 55.0-56.0 sec  6.40 MBytes  53.7 Mbits/sec  0.334 ms    0/ 4565 (0%)
[  3] 56.0-57.0 sec  6.40 MBytes  53.7 Mbits/sec  0.321 ms    0/ 4567 (0%)
[  3] 57.0-58.0 sec  6.40 MBytes  53.7 Mbits/sec  0.323 ms    0/ 4568 (0%)
[  3] 58.0-59.0 sec  6.40 MBytes  53.7 Mbits/sec  0.327 ms    0/ 4563 (0%)
[  3] 59.0-60.0 sec  6.40 MBytes  53.7 Mbits/sec  0.335 ms    0/ 4568 (0%)
[  3]  0.0-60.0 sec    384 MBytes  53.7 Mbits/sec  0.365 ms    0/273975 (0%)
[  4] local 192.168.0.100 port 5001 connected with 192.168.0.154 port 32994
[  4]  0.0- 1.0 sec  10.6 MBytes  89.0 Mbits/sec  0.193 ms    0/ 7571 (0%)
[  4]  1.0- 2.0 sec  10.5 MBytes  87.7 Mbits/sec  0.212 ms  119/ 7578 (1.6%)
[  4]  2.0- 3.0 sec  10.4 MBytes  87.5 Mbits/sec  0.195 ms  408/ 7848 (5.2%)
[  4]  3.0- 4.0 sec  9.96 MBytes  83.5 Mbits/sec  0.227 ms  737/ 7841 (9.4%)
[  4]  4.0- 5.0 sec  9.95 MBytes  83.5 Mbits/sec  0.206 ms  813/ 7911 (10%)
[  4]  5.0- 6.0 sec  9.88 MBytes  82.8 Mbits/sec  0.210 ms  797/ 7842 (10%)
[  4]  6.0- 7.0 sec  10.0 MBytes  84.3 Mbits/sec  0.205 ms  707/ 7873 (9%)
[  4]  7.0- 8.0 sec  9.88 MBytes  82.9 Mbits/sec  0.248 ms  811/ 7857 (10%)
[  4]  8.0- 9.0 sec  9.76 MBytes  81.8 Mbits/sec  0.200 ms  881/ 7840 (11%)
[  4]  9.0-10.0 sec  10.1 MBytes  84.5 Mbits/sec  0.212 ms  759/ 7943 (9.6%)
[  4] 10.0-11.0 sec  9.58 MBytes  80.4 Mbits/sec  0.221 ms 1015/ 7848 (13%)
[  4] 11.0-12.0 sec  9.63 MBytes  80.8 Mbits/sec  0.201 ms 1028/ 7897 (13%)
[  4] 12.0-13.0 sec  9.83 MBytes  82.5 Mbits/sec  0.234 ms  884/ 7899 (11%)
```

```
[  4] 13.0-14.0 sec  10.3 MBytes  86.4 Mbits/sec  0.190 ms  541/ 7887 (6.9%)
[  4] 14.0-15.0 sec  10.6 MBytes  89.2 Mbits/sec  0.197 ms  289/ 7873 (3.7%)
[  4] 15.0-16.0 sec  10.8 MBytes  90.5 Mbits/sec  0.191 ms  177/ 7869 (2.2%)
[  4] 16.0-17.0 sec  10.7 MBytes  90.2 Mbits/sec  0.195 ms  217/ 7883 (2.8%)
[  4] 17.0-18.0 sec  10.6 MBytes  89.1 Mbits/sec  0.196 ms  274/ 7854 (3.5%)
[  4] 18.0-19.0 sec  10.5 MBytes  87.9 Mbits/sec  0.191 ms  425/ 7896 (5.4%)
[  4] 19.0-20.0 sec  10.7 MBytes  90.0 Mbits/sec  0.190 ms  187/ 7840 (2.4%)
[  4] 20.0-21.0 sec  10.7 MBytes  90.1 Mbits/sec  0.192 ms  234/ 7898 (3%)
[  4] 21.0-22.0 sec  10.7 MBytes  89.4 Mbits/sec  0.192 ms  266/ 7872 (3.4%)
[  4] 22.0-23.0 sec  10.5 MBytes  88.2 Mbits/sec  0.199 ms  350/ 7853 (4.5%)
[  4] 23.0-24.0 sec  10.4 MBytes  87.4 Mbits/sec  0.216 ms  418/ 7849 (5.3%)
[  4] 24.0-25.0 sec  10.3 MBytes  86.1 Mbits/sec  0.244 ms  579/ 7899 (7.3%)
[  4] 25.0-26.0 sec  10.2 MBytes  85.6 Mbits/sec  0.200 ms  555/ 7835 (7.1%)
[  4] 26.0-27.0 sec  10.2 MBytes  85.7 Mbits/sec  0.193 ms  597/ 7886 (7.6%)
[  4] 27.0-28.0 sec  10.1 MBytes  84.6 Mbits/sec  0.196 ms  716/ 7909 (9.1%)
[  4] 28.0-29.0 sec  10.3 MBytes  86.1 Mbits/sec  0.209 ms  570/ 7890 (7.2%)
[  4] 29.0-30.0 sec  10.2 MBytes  85.9 Mbits/sec  0.217 ms  551/ 7854 (7%)
[  4] 30.0-31.0 sec  10.3 MBytes  86.3 Mbits/sec  0.212 ms  531/ 7872 (6.7%)
[  4] 31.0-32.0 sec  10.3 MBytes  86.3 Mbits/sec  0.192 ms  526/ 7865 (6.7%)
[  4] 32.0-33.0 sec  9.91 MBytes  83.1 Mbits/sec  0.196 ms  779/ 7849 (9.9%)
[  4] 33.0-34.0 sec  10.4 MBytes  87.3 Mbits/sec  0.205 ms  481/ 7908 (6.1%)
[  4] 34.0-35.0 sec  10.3 MBytes  86.7 Mbits/sec  0.266 ms  509/ 7880 (6.5%)
[  4] 35.0-36.0 sec  10.5 MBytes  88.4 Mbits/sec  0.202 ms  356/ 7875 (4.5%)
[  4] 36.0-37.0 sec  10.5 MBytes  88.4 Mbits/sec  0.213 ms  319/ 7832 (4.1%)
[  4] 37.0-38.0 sec  10.4 MBytes  87.3 Mbits/sec  0.192 ms  451/ 7872 (5.7%)
[  4] 38.0-39.0 sec  10.4 MBytes  86.8 Mbits/sec  0.191 ms  547/ 7932 (6.9%)
[  4] 39.0-40.0 sec  10.7 MBytes  89.8 Mbits/sec  0.193 ms  233/ 7873 (3%)
[  4] 40.0-41.0 sec  10.7 MBytes  89.6 Mbits/sec  0.209 ms  240/ 7862 (3.1%)
[  4] 41.0-42.0 sec  10.3 MBytes  86.5 Mbits/sec  0.190 ms  475/ 7830 (6.1%)
[  4] 42.0-43.0 sec  10.3 MBytes  86.5 Mbits/sec  0.197 ms  522/ 7880 (6.6%)
[  4] 43.0-44.0 sec  10.6 MBytes  88.6 Mbits/sec  0.190 ms  408/ 7939 (5.1%)
[  4] 44.0-45.0 sec  10.7 MBytes  90.0 Mbits/sec  0.193 ms  206/ 7856 (2.6%)
[  4] 45.0-46.0 sec  10.6 MBytes  89.1 Mbits/sec  0.222 ms  289/ 7866 (3.7%)
[  4] 46.0-47.0 sec  10.5 MBytes  88.5 Mbits/sec  0.192 ms  351/ 7875 (4.5%)
[  4] 47.0-48.0 sec  10.7 MBytes  89.9 Mbits/sec  0.191 ms  257/ 7898 (3.3%)
[  4] 48.0-49.0 sec  10.9 MBytes  91.5 Mbits/sec  0.190 ms   98/ 7875 (1.2%)
[  4] 49.0-50.0 sec  11.0 MBytes  92.1 Mbits/sec  0.201 ms   28/ 7857 (0.36%)
[  4] 50.0-51.0 sec  10.6 MBytes  88.8 Mbits/sec  0.190 ms  302/ 7856 (3.8%)
[  4] 51.0-52.0 sec  10.5 MBytes  88.3 Mbits/sec  0.191 ms  383/ 7893 (4.9%)
[  4] 52.0-53.0 sec  10.8 MBytes  90.8 Mbits/sec  0.189 ms  154/ 7878 (2%)
[  4] 53.0-54.0 sec  10.7 MBytes  89.5 Mbits/sec  0.190 ms  281/ 7891 (3.6%)
[  4] 54.0-55.0 sec  10.9 MBytes  91.1 Mbits/sec  0.190 ms  120/ 7870 (1.5%)
[  4] 55.0-56.0 sec  10.5 MBytes  88.5 Mbits/sec  0.228 ms  281/ 7806 (3.6%)
[  4] 56.0-57.0 sec  10.6 MBytes  89.1 Mbits/sec  0.190 ms  350/ 7926 (4.4%)
[  4] 57.0-58.0 sec  10.1 MBytes  84.9 Mbits/sec  0.263 ms  592/ 7815 (7.6%)
[  4] 58.0-59.0 sec  10.5 MBytes  87.9 Mbits/sec  0.196 ms  461/ 7935 (5.8%)
[  4] 59.0-60.0 sec  10.7 MBytes  89.8 Mbits/sec  0.191 ms  240/ 7877 (3%)
[  4]  0.0-60.1 sec    625 MBytes  87.3 Mbits/sec  0.228 ms 26684/472443 (5.6%)
```

On the client side, to start the test, the file *testClient.sh* is executed via command-line (the file *bandwidth.csv* represents an input file that fixes the value of some parameters for the tests, for example the allocation of the desired bandwidth). Here is what appears on the display.

```
root@pc2:/home/Iperf_client# ./testClient.sh bandwidth.csv
setting static ARP
starting iperf client
>>>>>>>53.47222222222222 0.9722222222222222


iperf -c 192.168.0.100 -u -i 10 -t 60 -l 1470 -b 53.47222222222222m


#################################################################
#                                                               #
#              Test N.1 : 1512@53.47222222222222 [0]                      #
#                                                               #
#################################################################
------------------------------------------------------------
Client connecting to 192.168.0.100, UDP port 5001
Sending 1470 byte datagrams
UDP buffer size:  107 KByte (default)
------------------------------------------------------------
[  3] local 192.168.0.154 port 32994 connected with 192.168.0.100 port 5001
[ ID] Interval       Transfer     Bandwidth
[  3] -0.0-10.0 sec  64.0 MBytes  53.7 Mbits/sec
[  3] 10.0-20.0 sec  64.0 MBytes  53.7 Mbits/sec
[  3] 20.0-30.0 sec  64.0 MBytes  53.7 Mbits/sec
[  3] 30.0-40.0 sec  64.0 MBytes  53.7 Mbits/sec
[  3] 40.0-50.0 sec  64.0 MBytes  53.7 Mbits/sec
[  3] 50.0-60.0 sec  64.0 MBytes  53.7 Mbits/sec
[  3]  0.0-60.0 sec   384 MBytes  53.7 Mbits/sec
[  3] Server Report:
[  3]  0.0-60.0 sec   384 MBytes  53.7 Mbits/sec  0.365 ms    0/273975 (0%)
[  3] Sent 273975 datagrams
>>>>>>>63.19444444444444 0.9722222222222222


iperf -c 192.168.0.100 -u -i 10 -t 60 -l 1470 -b 92.36111111111111m


#################################################################
#                                                               #
#              Test N.2 : 1512@92.36111111111111 [0]                      #
#                                                               #
#################################################################
------------------------------------------------------------
Client connecting to 192.168.0.100, UDP port 5001
Sending 1470 byte datagrams
UDP buffer size:  107 KByte (default)
------------------------------------------------------------
[  3] local 192.168.0.154 port 32994 connected with 192.168.0.100 port 5001
[ ID] Interval       Transfer     Bandwidth
[  3] -0.0-10.0 sec   110 MBytes  92.6 Mbits/sec
[  3] 10.0-20.0 sec   110 MBytes  92.6 Mbits/sec
[  3] 20.0-30.0 sec   110 MBytes  92.6 Mbits/sec
```

```
[  3] 30.0-40.0 sec   110 MBytes  92.6 Mbits/sec
[  3] 40.0-50.0 sec   110 MBytes  92.6 Mbits/sec
[  3] 50.0-60.0 sec   110 MBytes  92.6 Mbits/sec
[  3]  0.0-60.0 sec   662 MBytes  92.6 Mbits/sec
[  3] Server Report:
[  3]  0.0-60.1 sec   625 MBytes  87.3 Mbits/sec  0.227 ms 26684/472443 (5.6%)
[  3] Sent 472443 datagrams
```

Iperf can be used also in a multicast environment. Here is an example of the commands used respectively in the receiving hosts (Iperf servers) and in the transmitting host (Iperf client).

```
iperf -s -B 224.0.55.55 -u -i 1
```

```
iperf -c 224.0.55.55 -u -b 30m -t 60 -i 10
```

Bibliography

[1] Volakis J. L. (2009), *Antenna Engineering Handbook*, 4th edition, New York, McGraw-Hill.

[2] Godara L. C. (2002), *Handbook of Antennas in Wireless Communications*, U.S.A., CRC Press.

[3] Gesbert D., Shafi M., Da-shan Shiu, Smith P. J. and Naguib A., "From Theory to Practice: An Overview of MIMO Space-Time Coded Wireless Systems", *IEEE J. Select. Areas Commun.*, vol. 21, no. 3, pp. 281-302, Apr. 2003.

[4] Yoo T., Lavery R. J., Goldsmith A. and Goodman D. J., "Throughput Optimization Using Adaptive Techniques", *IEEE Int. Conf. on Commun.*, June 2004.

[5] Fei Peng, Jinyun Zhang and Ryan W. E., "Adaptive Modulation and Coding for IEEE 802.11n", *IEEE Wireless Commun. and Network. Conf. WCNC*, pp. 656-661, March 2007.

[6] Ju Yeop Kim and Dong-Ho Cho, "Enhanced Adaptive Modulation and Coding Schemes Based on Multiple Channel Reportings for Wireless Multicast Systems", *IEEE 62nd Veh. Techn. Conf. VTCC*, vol. 2, pp. 725-729, Sept. 2005.

[7] Waldschmidt C., Hagen J. v. and Wiesbeck W., "Influence and Modelling of Mutual Coupling in MIMO and Diversity Systems", *IEEE Antennas and Propag. Soc. Int. Symp.*, vol. 3, pp. 190-193, 2002.

[8] Goldsmith A., Jafar S. A., Jindal N. and Vishwanath S., "Capacity Limits of MIMO Channels", *IEEE J. Select. Areas Commun.*, vol. 21, no. 5, pp. 684-702, June 2003.

[9] Blanch S., Romeu J. and Corbella I., "Exact representation of antenna system diversity performance from input parameter description", *IEEE Electronics Letters*, vol. 39, no. 9, pp. 705-707, May 2003.

[10] Sung Ho Chae, Se-keun Oh and Seong-Ook Park, "Analysis of Mutual Coupling, Correlations and TARC in WiBro MIMO Array Antenna", *IEEE Antennas and Wireless Propag. Lett.*, vol. 6, pp. 122-125, 2007.

[11] Vaughan R. G. and Andersen J. B., "Antenna Diversity in Mobile Communications", *IEEE Trans Veh. Techn.*, vol. 36, no. 4, pp. 149-172, Nov. 1987.

[12] Waldschmidt C., Kuhnert C., Fugen T. and Wiesbeck W., "Measurements and Simulations of compact MIMO-Systems based on Polarization Diversity", *IEEE Topical Conf. Wireless Commun. Techn.* , pp. 284-285, 2003.

[13] Dietrich C. B., Dietze K., Nealy J. R. and Stutzman W. L., "Spatial, Polarization and Pattern Diversity for Wireless Handled Terminals", *IEEE Trans. Antennas and Propag.*, vol. 49, no. 9, pp. 1271-1281, Sept. 2001.

[14] Valenzuela-Valdes J. F., Garcia-Fernandez M. A., Martinez-Gonzalez A. M. and Sanchez-Hernandez D., "The Role of Polarization Diversity for MIMO Systems Under Rayleigh-Fading Environments", *IEEE Antennas and Wireless Propag. Lett.*, vol. 5, no. 1, pp. 534-536, 2006.

[15] Forenza A. and Heath R. W. Jr., "Impact of Antenna Geometry on MIMO Communication in Indoor Clustered Channels", *IEEE Antennas and Propag. Soc. Int. Symp.*, vol. 2, pp. 1700-1703, 2004.

[16] Xin Li and Zai-Ping Nie, "Effect of Array Orientation on Performance of MIMO Wireless Channels", *IEEE Antennas and Wireless Propag. Lett.*, vol. 3, pp. 368-371, 2004.

[17] Browne D. W., Manteghi M., Fitz M. P. and Rahmat-Samii Y., "Experiments With Compact Antenna Arrays for MIMO Radio Communications", *IEEE Trans. Antennas and Propag.*, vol. 54, no. 11, part 1, pp. 3239-3250, Nov. 2006.

[18] Raj J. S. K., Arokiasamy S. P., Vikram N. and Schoebel J., "Spatial Correlation and MIMO Capacity of Uniform Rectangular Dipole Arrays", *IEEE Antennas and Wireless Propag. Lett.*, vol. 7, pp. 97-100, 2008.

[19] Browne D. W., Manteghi M., Fitz M .P. and Rahmat-Samii Y., "Experiments with Compact Antenna Arrays for MIMO Radio Communications", *IEEE Trans. Antennas and Propag.*, vol. 54, no. 11, pp. 3239-3250, 2006.

[20] Pellegrino A., "Quality Measurement in WiFi Environments", *Upgrade*, vol. 6, no. 1, pp. 57-62, Feb. 2005.

[21] Varshney U., "Multicast Over Wireless Networks", *Communications of the ACM*, vol. 45, no. 12, pp. 31-37, Dec. 2002.

[22] Abouda A. A., El-Sallabi H. M. and Häggman S. G., "Effect of antenna array geometry and ULA azimuthal orientation on MIMO channel properties in urban city street grid", *Progress In Electromagnetics Reasearch*, no. 64, pp. 257-278, 2006.

[23] Mallahzadeh A. R., Es'haghi S. and Alipour A., "Design of an E-shaped MIMO antenna using IWO algorithm for wireless application at 5.8 Ghz", *Progress In Electromagnetics Research*, no. 90, pp. 187-203, 2009.

[24] Waldschmidt C. and Wiesbeck W., "MIMO Antennas for Small Handled Devices", *Progress In Electromagnetics Research Symposyum*, Oct. 2003.

[25] Bhagavatula R., Health R. W. Jr. and Linehan K., "Performance Evaluation of MIMO Base Station Antenna Designs", *Antenna Systems & Technology Magazine*, pp. 14-17, Nov./Dec. 2008.

[26] Waldschmidt C., Kuhnert C., Fügen T. and Wiesbeck W., "Realistic antenna modeling for MIMO systems in microcell scenarios", *Advances in Radio Science*, no. 2, pp. 141-146, 2004.

[27] Pal A., Williams C., Hilton G. and Beach M., "Evaluation of Diversity Antenna Designs Using Ray Tracing, Measured Radiation Patterns and MIMO channel Measurements", *EURASIP Journal on Wireless Commun. and Network.*, no. 1, pp. 61-71, 2007.

[28] Clarke R. H., “A statistical theory of mobile-radio reception”, *Bell Syst. Tech. J.*, pp. 957-1000, July/Aug. 1968.

[29] Pesce F. and Giltrelli M., *Master Mediacom 2009 “Sistemi radio in ambienti chiusi: wireless per utenza residenziale”*, Padova, 30 April 2009.

[30] Carrigan K., Johns D., Guerci J. and Fejfar J., *Advantages of MIMO in Wireless and Radar Applications*, http://www.cst.com/Content/Showroom/, June 2009.

[31] Wi-Fi Alliance, *Wi-Fi CERTIFIED 802.11n draft 2.0: Longer-Range, Faster-Throughput, Multimedia-Grade Wi-Fi Networks*, http://www.wi-fi.org/files/kc/WFA_802_11n_Industry_June07.pdf, 2007.

[32] Broadcom Corporation, *802.11n: Next-Generation Wireless LAN Technology*, http://www.buffalo-technology.com/files/802_11n-WP100-R.pdf, Apr. 2006.

[33] Tirumala A., Cottrell L. and Dunigan T. (Jan. 2008), *Measuring end-to-end bandwidth with Iperf using Web100*, http://www.csm.ornl.gov/∼dunigan/pam.pdf.

[34] Caimi F. M., Greer K. L. and Hendler J. M. (Jan. 2002), *Antenna Diversity in Wireless Local Area Network Devices*, http://www.skycross.com/Technology/Whitepapers/Diversity_in_WLAN_Devices.pdf.

[35] Meru Networks (Aug. 2008), *Wireless Without Compromise: Delivering the promise of IEEE 802.11n*, http://www.merunetworks.com/pdf/whitepapers/WP_80211nAppDelivery_v1.pdf.

[36] AirMagnet, *802.11n Primer*, http://www.airmagnet.com/assets/whitepaper/WP-802.11nPrimer.pdf, Aug. 2008.

[37] *Iperf 2.0.4*

Acknowledgments

First of all, I would like to thank my supervisor Prof. Antonio Daniele Capobianco for his willingness and for proposing me the chance to do this thesis and his assistant Dr. Francesco Sacchetto for his advice about the paper.

It is a pleasure to thank those who make this work possible, the staff of Telsey. Particularly, I am grateful to my tutors Ing. Lucio D'Ascoli, Ing. Francesco Pesce and Ing. Simone Carnielli, whose contribution and guidance enabled me to develop my research and learn at both personal and professional level.

Special thanks to all my family, my grandparents, my uncles and my cousins, who are always ready to help me and show me their affection.

I am grateful to all my friends and "CdSA" members, who allow me to live and share wonderful experiences.

Finally, heartfelt thanks to my parents, who allowed me to get this far; they support me in everything I do and always believe in me and in my choices.
Thanks.