

Faculdade de Engenharia da Universidade do Porto



Performance Evaluation of Directional Antennas on Static Wireless Mesh Networks

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Major Telecommunications

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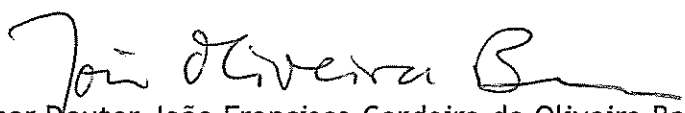
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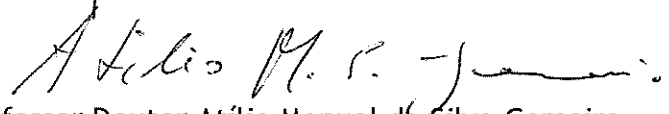
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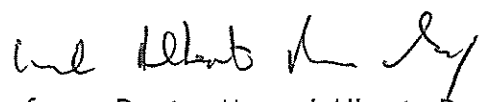
**“PERFORMANCE EVALUATION OF DIRECTIONAL ANTENNA ON STATIC WIRELESS
MESH NETWORKS”**

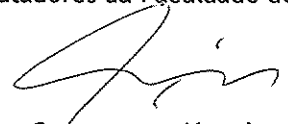
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Abstract

Previous research done in wireless mesh networks, typically assumes omni-directional antennas are used, which has the implication of when two nodes are communicating, all nodes in the vicinity must stay silent. With the use of directional antennas, two nodes can communicate without affecting communications of other nodes in the vicinity. One of the primary objectives of this dissertation is to exploit these opportunities that directional antennas can provide, and translate that into improvements of the performance of the mesh network.

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Resumo

Investigação realizada no âmbito das redes sem fios emalhadas, tipicamente assume que antenas omni-direccionais são usadas, o que implica que quando dois nós comunicam, todos os nós na vizinhança destes obrigatoriamente estão silenciados. Com a introdução de antenas direccionais, dois nós podem comunicar entre si sem afectar as comunicações de outros nós na vizinhança. Um dos principais objectivos desta dissertação consiste em explorar essas oportunidades que as antenas direccionais proporcionam, e traduzir isto em melhoramentos da performance da rede emalhada.

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Index

Abstract	iii
Resumo	v
Acknowledgements	vii
Index.....	ix
List of figures	xi
List of tables	xv
Abbreviations and Symbols	xvi
Chapter 1	1
Introduction.....	1
1.1 Background	1
1.2 Objectives	2
1.3 Relevant results and contributions	3
1.4 Structure of the dissertation	4
Chapter 2	5
State of the Art.....	5
2.1 Static wireless mesh networks	5
2.2 Directional antennas.....	7
2.3 Advantages of directional antennas in WMNs	9
2.4 Challenges of directional antennas in WMNs	11
2.5 IEEE 802.11 DCF MAC protocol in WMNs.....	14
2.6 Related work	16
Chapter 3	21
Developed Work	21
3.1 Objectives	21
3.2 Research methodology.....	22
3.3 Possible models.....	23
3.4 Devised prototype	25
3.5 Switched beam antenna radiation patterns	30
3.6 Performance characterization.....	36

Chapter 4	49
Conclusion	49
4.1 Review of developed work	49
4.2 Results and relevant contributions.....	50
Annexes.....	51
Annex A - Table of switched beam antenna radiation pattern characterization.....	51
Annex B - Configuration scripts, iwconfig and ifconfig outputs of performance measurement and comparison tests.....	53
Annex C - Tables of performance characterization tests and effective gains charts.....	69
Annex D - Airgain MaxBeam75 Product Specification Sheet.....	74
Annex E - Public Defence Presentation.....	86
Annex F - Scientific Article.....	87
References	101

List of figures

Figure 1.1 - Example of WMN [17]	1
Figure 1.2 - Using Omni-directional vs. Directional Antennas	2
Figure 2.1 - Randomly Distributed Topology [18].....	6
Figure 2.2 - 3x3 Grid Topology	6
Figure 2.3 - Spherical coordinates axis.....	7
Figure 2.4 - Radiation pattern of a switched beam antenna [18].	8
Figure 2.5 - Test scenario using a steerable beam antenna [29].	8
Figure 2.6 - Gain of omni-directional antennas vs. directional antennas	9
Figure 2.7 - Spatial reuse of omni-directional antennas vs. directional antennas.....	10
Figure 2.8 - Deafness illustration scenario [3]	11
Figure 2.9 - Hidden terminal scenario caused by asymmetric gain [4]	12
Figure 2.10 - Hidden terminal scenario caused by unheard RTS/CTS [4]	12
Figure 2.11 - Interference range without transmitted power control.....	13
Figure 2.12 - Interference range with transmitted power control.....	13
Figure 2.13 - Successful and unsuccessful RTS/CTS/DATA/ACK exchange.....	14
Figure 2.14 - Testbed setup and antenna used [13]	17
Figure 2.15 - Transmission and reception chains architecture [14]	18
Figure 2.16 - Antenna structure and configuration modes[15]	18
Figure 2.17 - MaxBeam smart antenna structure and radiation pattern[16]	19
Figure 3.1 - Research Methodology Flowchart	22
Figure 3.2 - Node Configuration - 1 st Solution.....	23
Figure 3.3 - Node Configuration - 2 nd Solution	24

Figure 3.4 - Illustrative diagram of devised prototype	25
Figure 3.5 - TP-Link TP-WN551G Wireless PCI Card [wireless_card_datasheet]	26
Figure 3.6 - Airgain MaxBeam 75 Smart Antenna [18]	26
Figure 3.7 - 6-pin connector to control switching	27
Figure 3.8 - U.FL plug [21] and RP-SMA female [22]	27
Figure 3.9 - U.FL jack to SMA plug adapter [23] and RP-SMA male to SMA female [24]	28
Figure 3.10 - Switched beam antenna inside plastic box	28
Figure 3.11 - Network analyzer and computer which controls rotating platform	30
Figure 3.12 - Transmitter antenna of the anechoic chamber	31
Figure 3.13 - Switched beam antenna to be tested over the rotating platform	31
Figure 3.14 - Orientation of switched beam antenna over the rotating platform	32
Figure 3.15 - Switched beam antenna without plastic box over the rotating platform	32
Figure 3.16 - Radiation patterns for all the possible combinations of pins and without box ..	34
Figure 3.17 - Finite state machine implemented in the driver of DA configuration	37
Figure 3.18 - First tested scenario	38
Figure 3.19 - Throughput results chart - 1 st scenario	39
Figure 3.20 - Average delay results chart - 1 st scenario	40
Figure 3.21 - RSSI results chart - 1 st scenario	41
Figure 3.22 - Link quality results chart - 1 st scenario	41
Figure 3.23 - Second tested scenario	42
Figure 3.24 - Aggregate throughput results chart - 2 nd scenario	43
Figure 3.25 - Average delay results chart - 2 nd scenario	44
Figure 3.26 - Throughput per flow results chart - 2 nd scenario	45
Figure 3.27 - Average delay per flow results chart - 2 nd scenario	45
Figure 3.28 - Fairness results chart - 2 nd scenario	46
Figure 3.29 - RSSI results chart - 2 nd scenario	47
Figure 3.30 - Link quality results chart - 2 nd scenario	47
Figure B.1 - Computer 2 iwconfig output - first scenario - SOA configuration	54
Figure B.2 - Computer 2 ifconfig output - first scenario - SOA configuration	54
Figure B.3 - Computer 3 iwconfig output - first scenario - SOA configuration	55

Figure B.4 - Computer 3 ifconfig output - first scenario - SOA configuration	55
Figure B.5 - Computer 2 iwconfig output - first scenario - OA configuration.....	56
Figure B.6 - Computer 2 ifconfig output - first scenario - OA configuration.....	56
Figure B.7 - Computer 3 iwconfig output - first scenario - OA configuration.....	57
Figure B.8 - Computer 3 ifconfig output - first scenario - OA configuration.....	57
Figure B.9 - Computer 2 iwconfig output - first scenario - DA configuration.....	58
Figure B.10 - Computer 2 ifconfig output - first scenario - DA configuration	58
Figure B.11 - Computer 3 iwconfig output - first scenario - DA configuration	59
Figure B.12 - Computer 3 ifconfig output - first scenario - DA configuration	59
Figure B.13 - Computer 2 iwconfig output - second scenario - SOA configuration	60
Figure B.14 - Computer 2 ifconfig output - second scenario - SOA configuration	60
Figure B.15 - Computer 3 iwconfig output - second scenario - SOA configuration	61
Figure B.16 - Computer 3 ifconfig output - second scenario - SOA configuration	61
Figure B.17 - Computer 4 iwconfig output - second scenario - SOA configuration	62
Figure B.18 - Computer 4 ifconfig output - second scenario - SOA configuration	62
Figure B.19 - Computer 2 iwconfig output - second scenario - OA configuration.....	63
Figure B.20 - Computer 2 ifconfig output - second scenario - OA configuration.....	63
Figure B.21 - Computer 3 iwconfig output - second scenario - OA configuration.....	64
Figure B.22 - Computer 3 ifconfig output - second scenario - OA configuration.....	64
Figure B.23 - Computer 4 iwconfig output - second scenario - OA configuration.....	65
Figure B.24 - Computer 4 ifconfig output - second scenario - OA configuration.....	65
Figure B.25 - Computer 2 iwconfig output - second scenario - DA configuration.....	66
Figure B.26 - Computer 2 ifconfig output - second scenario - DA configuration.....	66
Figure B.27 - Computer 3 iwconfig output - second scenario - DA configuration.....	67
Figure B.28 - Computer 3 ifconfig output - second scenario - DA configuration.....	67
Figure B.29 - Computer 4 iwconfig output - second scenario - DA configuration.....	68
Figure B.30 - Computer 4 ifconfig output - second scenario - DA configuration.....	68
Figure C.1 - Effective gains in throughput results chart - 1 st scenario	71
Figure C.2 - Effective gains in average delay results chart - 1 st scenario	71
Figure C.3 - Effective gains in throughput results chart - 2 nd scenario	73

Figure C.4 - Effective gains in average delay results chart - 2nd scenario	73
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List of tables

Table 3.1 – Sequence of parallel port combinations	33
Table 3.2 – Estimation of losses introduced by the box	35
Table A.1 – Full table with values of S21 parameter in dBm for all possible combinations in steps of 10°	52
Table C.1 – Performance measurements - SOA configuration	70
Table C.2 – Performance measurements - OA configuration.....	70
Table C.3 – Performance measurements - DA configuration.....	71
Table C.4 – Performance measurements - SOA configuration	72
Table C.5 – Performance measurements - OA configuration.....	72
Table C.6 – Performance measurements - DA configuration.....	72
Table C.7 – Performance measurements - Fairness	73

Abbreviations and Symbols

List of abbreviations

AP	Access Point
DA	Directional mode configuration using switched beam Antenna
ESSID	Extended Service Set IDentifier
GPL	General Public License
MAC	Medium Access Control
MAP	Mesh Access Point
MP	Mesh Point
MPP	Mesh Portal Point
OA	Omni mode configuration using switched beam Antenna
RSSI	Received Signal Strength Indication
RTT	Round Trip Time
SMD	Surface Mount Device
SOA	Standard IEEE 802.11 configuration using 2dBi Omni directional Antenna
TCP	Transmission Control Protocol
VAP	Virtual Access Point
WMN	Wireless Mesh Network

List of symbols

θ	Azimuth angle
φ	Elevation angle

Chapter 1

Introduction

1.1 Background

Wireless Mesh Networks (WMNs) are fully distributed networks which are constructed based on several nodes with wireless communicating equipment. These networks communicate according to the IEEE 802.11 MAC protocol, which has been designed assuming only omni-directional antennas are used.

In the past decade, WMNs have been increasingly used over a wide variety of applications, such as home, community and enterprise broadband networking. At this growth rate, these networks will play a crucial role in our future society, thus it is important to find new ways to improve them and overcome their limitations (see Figure 1.1).

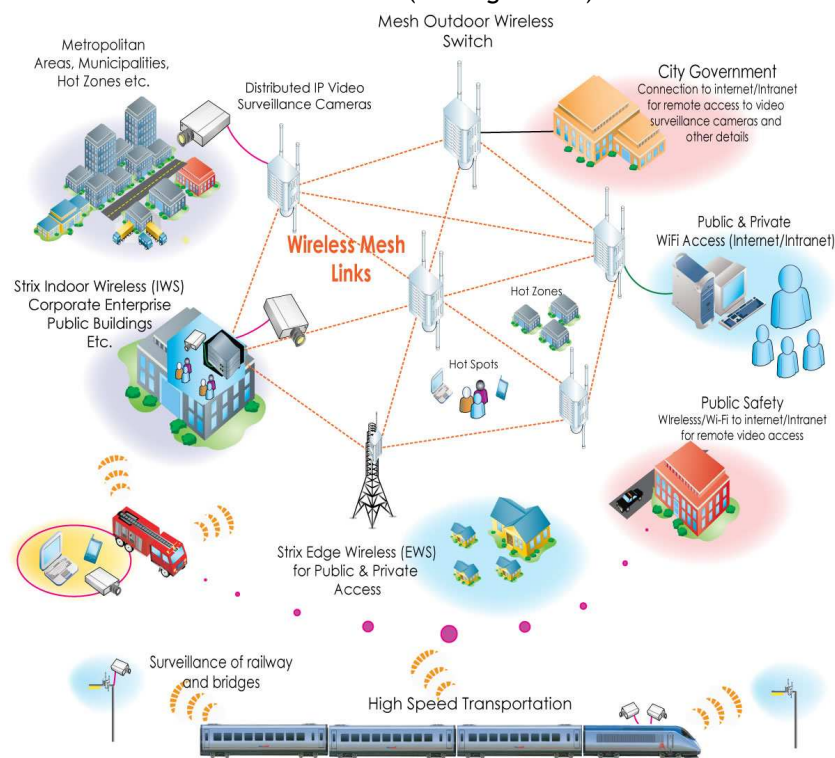


Figure 1.1 - Example of WMN [17]

The majority of WMNs established nowadays make use of omni-directional antennas, which are antennas that communicate in all directions (360 degrees) of the horizontal plane. The implication on this is that nodes placed in the vicinity of communicating nodes are silenced. By including antennas with directional beamforming, known as directional antennas, two pairs of communicating nodes in each other's vicinity may communicate simultaneously, as long as their lines of sight do not intersect (Example Figure 1.2).

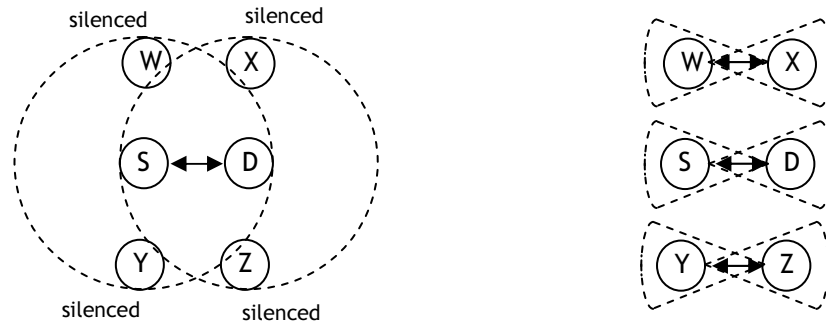


Figure 1.2 - Using Omni-directional vs. Directional Antennas

1.2 Objectives

The main objective of this dissertation is to study the impact of directional antennas in static WMNs by designing a testbed that will consist on a set of wireless nodes integrating directional antennas. The performance of the network will be measured in terms of throughput, delay, and fairness. These results will be compared with the performance of the same network configuration using omni-directional antennas. This will allow us to study the impact of directional antennas in static WMN.

1.3 Relevant results and contributions

The main relevant results and contributions of this dissertation were the following:

1.3.1. Development of prototype integrating a switched beam antenna

By developing a prototype which integrated a switched beam antenna, it was possible to use that prototype on several nodes and establish a static WMN. This allowed us to carry out radiation pattern evaluation tests and performance characterization tests to fulfill the objectives of this dissertation.

1.3.2. Identification of radiation patterns of switched beam antenna

By developing our switched beam antenna prototype, it was possible to execute a series of test in the anechoic chamber at FEUP. These tests were very important since they allowed the establishment of a direct relation between the possible combinations of the 6-pin connector, of the switched beam antenna, with the different radiation patterns the antenna forms. No information was provided regarding this issue, neither in the datasheet of the switched beam antenna [18], nor in the product specification datasheet which is printed in annex.

1.3.3. Improvement in performance of network

It has been shown in the performance characterization section of the previous chapter that, with the integration of our prototype of a switched beam antenna, we can achieve considerable gains in throughput when comparing to the same network configuration using IEEE standard 802.11 2dBi omni-directional antennas. It has also been proved that lower average delays are verified when using our prototype.

1.4 Structure of the dissertation

This dissertation is organized as follows: Chapter 1 gives an introduction about WMNs in the background section and the main objectives of the proposed thesis. Also the relevant results and contributions extracted from the work developed in this dissertation and the structure of this dissertation is presented in chapter 1. Chapter 2 comprises the State of the Art, where conceptual topics related to this dissertation are presented in sections static wireless mesh networks, directional antennas, advantages of directional antennas in WMNs, challenges of directional antennas in WMNs and the IEEE 802.11 DCF MAC protocol and also research over the past decade is presented in the related work section. Chapter 3 describes the developed work along the elaboration of this dissertation by presenting its work flow starting with the objectives of this dissertation followed by the definition of a research methodology and two possible theoretic models to fulfill the objectives of this dissertation. Then, the devised prototype to integrate in the nodes of the WMN is described in detail and, finally, the tests phase and its conclusions are presented in sections switched beam antenna pattern and performance characterization. In Chapter 4, a review of the developed work is presented and the results and relevant contributions extracted from the work of this dissertation are presented.

Chapter 2

State of the Art

This chapter presents the sections *static wireless mesh networks*, *directional antennas*, *advantages of directional antennas in WMNs*, *challenges of directional antennas in WMNs*, *IEEE 802.11 DCF MAC protocol in WMNs* and *related work*.

2.1 Static wireless mesh networks

A wireless mesh network (WMN) is a network composed of wireless communicating nodes arranged in a mesh topology. The nodes which constitute a WMN can be mesh access points (MAPs), mesh points (MPs) and mesh portal points (MPPs). MAPs are used to provide stations access to the WMN, whereas MPs are only used to connect to other mesh nodes. MPPs can be used to connect one WMN to another wireless or wired network. Differently to infrastructure wireless networks, where the control of the network is centralized in the access point (AP), in WMNs the control of the network is distributed through the mesh nodes. The MAC protocol usually used in WMNs is the distributed coordinated function variant, the IEEE 802.11 DCF MAC protocol which described afterwards in this chapter.

In WMNs, there is a panoply of topologies which can be grouped in two major categories: static WMNs and mobile WMNs. Since the title of this dissertation is about static WMNs, we only present those in detail. As its own name states, static WMNs are uniquely composed of static nodes. To deploy a static WMN two topologies can be defined: randomly distributed topology and grid topology.

2.1.1. Randomly Distributed Topology

This topology constitutes the most generic configuration that a static WMN can assume, as nodes are placed in a non-geometric arrangement. Most of the implemented WMNs have their nodes placed arbitrarily, due to the physical constraints of the place where they are established and, for that reason, this is the topology which is most widely used in real scenarios.

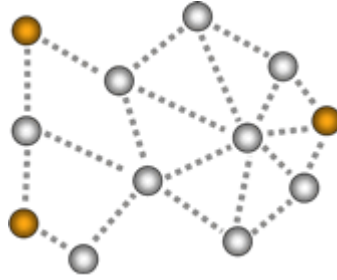


Figure 2.1 - Randomly Distributed Topology [18]

2.1.2. Grid Topology

A particular case of the previous topology is the Grid Topology, in which nodes are organized in a 90 degree grid structure. The cost of the communication between nodes can be equal or different, depending on factors such as the transmission media or the distance between them. For simplicity and symmetry reasons, this topology is the topology which is used in simulation scenarios. Therefore, we also used this topology in our simulations.

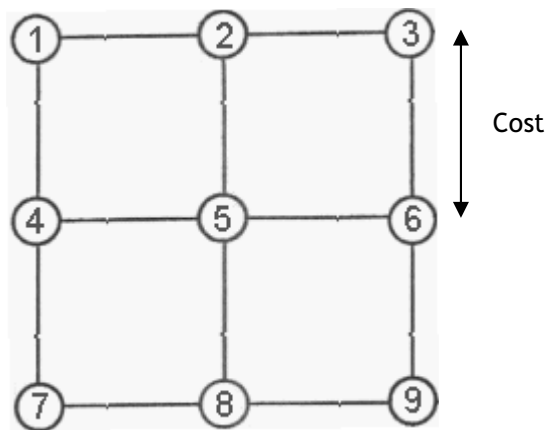


Figure 2.2 - 3x3 Grid Topology

2.2 Directional antennas

The main characteristic of directional antennas is that they concentrate the irradiated power in a certain direction, as opposed to omni-directional antennas which irradiate the power isotropically, i.e., the transmitted power is equal in all directions of the horizontal plane. To characterize an antenna we need to define its gain. Then we will overlook the different types of directional antennas.

2.2.1. Gain of an antenna

The gain of an antenna is expressed in spherical coordinates in order of the angles θ and φ , which are represented in Figure 2.3. The domain interval of the angle θ is $[0, 2\pi]$, whereas the angle φ is $[0, \pi]$.

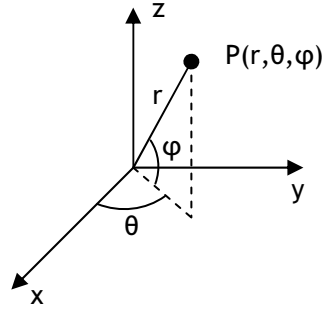


Figure 2.3 - Spherical coordinates axis.

Considering the antenna is placed in origin of the axis and the radiation power intensity $p(\theta, \varphi)$ is defined as the radiation power per unit solid angle, the total radiated power is defined as: [4]

$$p_t = \int_0^{2\pi} \int_0^\pi p(\theta, \varphi) \sin\theta d\varphi d\theta, \quad (2.1)$$

The gain of the antenna in the direction of (θ, φ) is defined as the ratio of the power density in that direction and the power density averaged over all directions. The gain in the direction (θ, φ) is mathematically expressed as: [4]

$$g(\theta, \varphi) = \frac{p(\theta, \varphi)}{\frac{1}{4\pi^2} \int_0^{2\pi} \int_0^\pi p(\theta, \varphi) d\varphi d\theta}, \quad (2.2)$$

2.2.2. Types of directional antennas

Two types of directional antenna have been identified along the research: *switched beam antennas* and *steerable beam antennas*.

2.2.2.1 Switched beam antennas

The switched beam antenna, also called sectorized antenna, is a type of directional antenna which is constituted by several sectors. Each sector forms a radiation pattern of a fraction of the horizontal plane. An example of the radiation pattern with the several beams of a switched beam antenna can be seen in Figure 2.4.

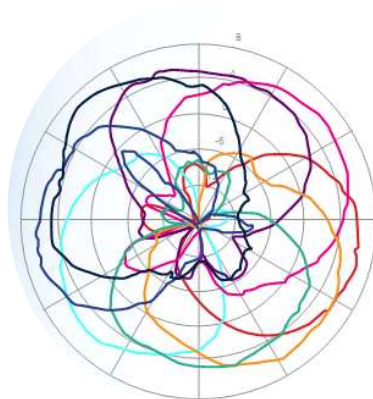


Figure 2.4 - Radiation pattern of a switched beam antenna [18].

2.2.2.2 Steerable beam antennas

The steerable beam antenna is a type of directional antenna with steerable beamforming. The steering mechanism can be electrical or mechanical. An example of a test scenario which uses a steerable beam antenna can be seen in Figure 2.5.

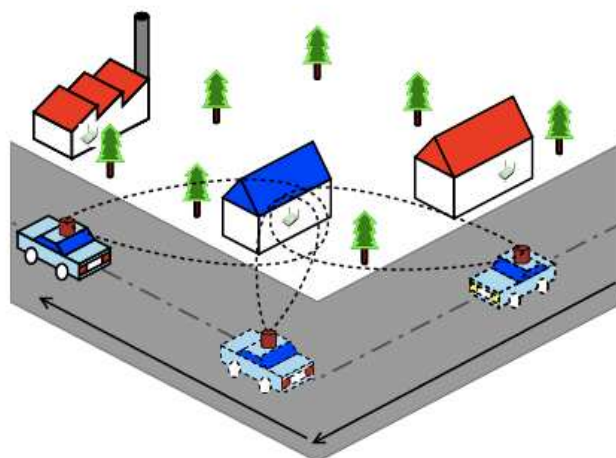


Figure 2.5 - Test scenario using a steerable beam antenna [29].

2.3 Advantages of directional antennas in WMNs

The characteristics identified directional antennas have that contribute to performance gains of a network can be classified in three categories: *higher transmission gain*, *spatial reuse* and *reduced power consumption*.

2.3.1. High transmission gain

By having a high transmission gain, directional antennas' beam range is superior in comparison to omni-directional antennas for the same power consumption, which means a communication between two distant nodes can occur simply in one hop. In Figure 2.6, if S wants to communicate with D using omni-directional antennas, the only possible way is to send the information through Y and Z, due to the fact that D is not reachable by S directly. On the other hand, if Directional Antennas are used, S can communicate directly with D.

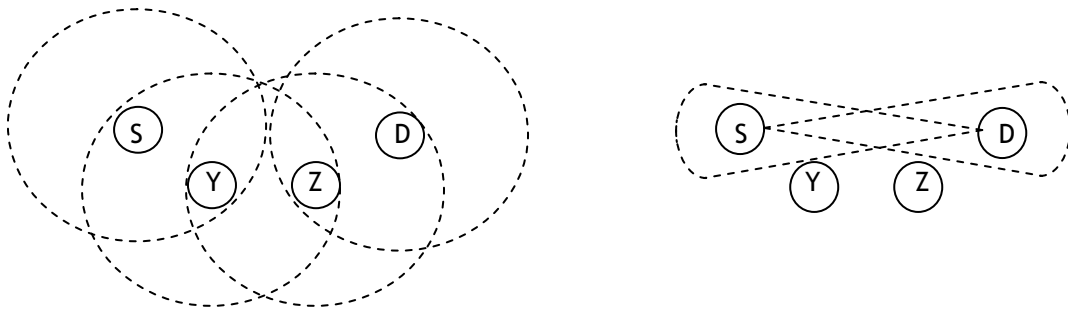


Figure 2.6 - Gain of omni-directional antennas vs. directional antennas

2.3.2. Spatial reuse

As the beamwidth of omni-directional antennas is 360 degrees, all nodes in the vicinity of two communicating nodes must be silenced to avoid unwanted collisions. With directional antennas we can take advantage of an increased network capacity, due to the fact that the transmitted power is concentrated mostly in the desired direction of communication. This means pairs of nodes in the vicinity of communicating nodes may also communicate independently without interfering with the ongoing connection. In Figure 2.7, if C wants to communicate with D using omni-directional antennas, A, B, E and F must be silenced not to disturb the communication. If directional antennas are used all nodes can establish independent connections between them, i.e., A can communicate with B, C with E and D with F.

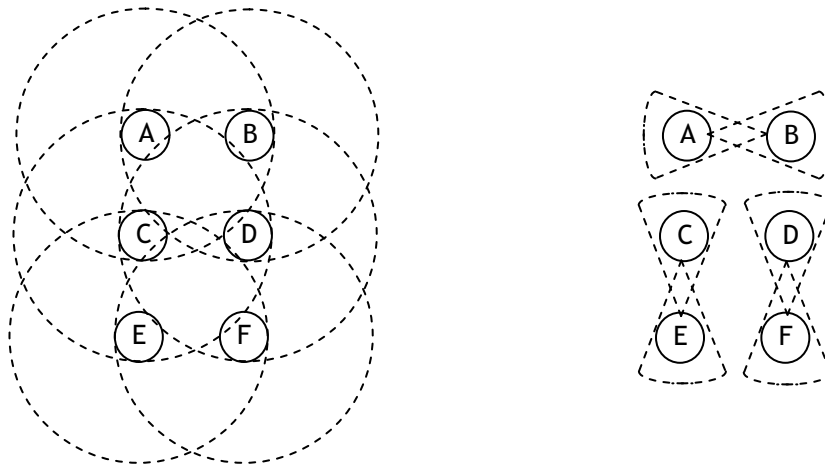


Figure 2.7 - Spatial reuse of omni-directional antennas vs. directional antennas

2.3.3. Reduced power consumption

Directional antennas have lower power consumption than omni-directional antennas for the same gain, as the energy transmitted is concentrated within a narrower beamwidth. This could be a useful characteristic when integrating in devices where efficient use of energy is a requirement, such as battery powered devices. Li et al. [4] refers a previous simulation study, which concluded the difference in power consumption is enormous - around 1-7% of the power needed for an omni-directional antenna is enough to power a directional antenna, maintaining the same link quality.

2.4 Challenges of directional antennas in WMNs

Using directional antennas in WMNs has implications which should be considered, and efforts made to minimize them. If this is not taken into account, benefits directional antennas provide may not increase the performance of the network. Three categories were identified: *deafness*, *hidden terminal* and *interference range due to directional antennas' high gain*.

2.4.1. Deafness

Deafness is consequence of the use of directional antennas in WMNs as it occurs when a third node (C) tries to establish a connection with one of two nodes which are already engaged in communication (A and B). The third node does not receive a CTS (Clear To Send) making it expire the number of RTS (Request To Send) retries and dropping the packet which was going to be sent (see Figure 2.8).

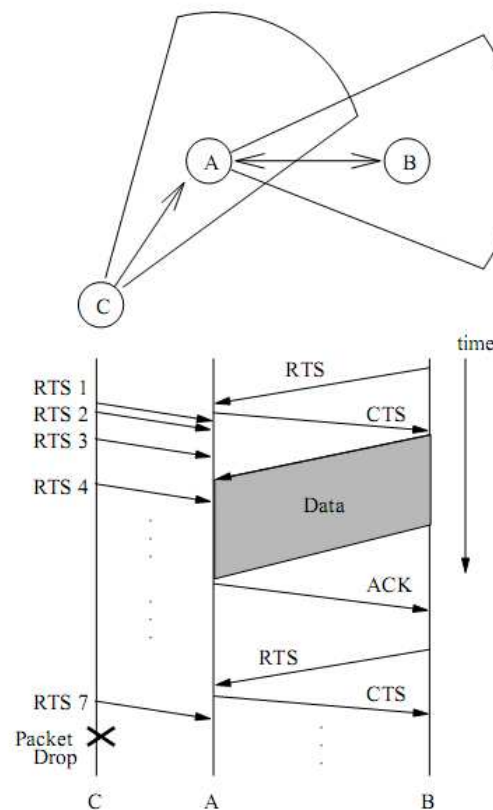


Figure 2.8 - Deafness illustration scenario [3]

If this challenge is not handled, so that its effects are minimized by the MAC protocol to be designed, the results on the performance of the network may be seriously affected.

2.4.2. Hidden terminal

The hidden terminal problem is a consequence of the use of directional antennas as a node does not sense an ongoing transmission and tries to establish a connection with a busy node. It can be caused by two different scenarios, either due to when there is an asymmetric gain, or due to unheard RTS/CTS.

2.4.2.1. Asymmetric gain

The first scenario can occur when nodes are able to operate in two modes: Omni mode and Directional mode. Often, these modes present different gains, typically $G_d > G_o$, where G_d is defined as Gain in Directional mode and G_o is defined as Gain in Omni mode. Attending to the scenario in Figure 2.9, node C is out of range of node B in Omni mode, but not when both are in Directional mode. If C is in Omni mode, it is unaware of a directional communication between A and B. When node C switches to Directional mode and send a DRTS (Directional Request To Send) to node A or node B, it interferes with the ongoing transmission.

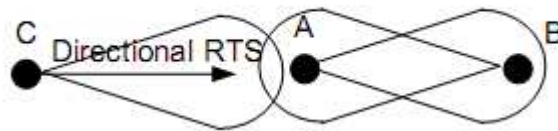


Figure 2.9 - Hidden terminal scenario caused by asymmetric gain [4]

2.4.2.2. Unheard RTS/CTS

The second scenario that can cause the hidden terminal problem is due to unheard RTS/CTS. Considering Figure 2.10, where two communications take place (B to A and C to D). If the communication between node A and node B ends first, and B wants to transmit a packet to C or D and it is in range of node D, node B is unaware of the communication between node C and node D as earlier it was communicating with A. With this, node B becomes a hidden terminal to node D.

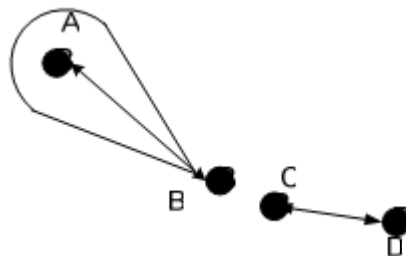


Figure 2.10 - Hidden terminal scenario caused by unheard RTS/CTS [4]

2.4.3. Interference range due to directional antennas' high gain

Given that the gain of directional antennas is greater than omni-directional antennas, a directional communication taking place between two nodes, which are close to each other, may interfere with other communications being held at a long distance, but still within range of one of the two communicating nodes. This can occur provided there is no transmitted power control (see Figure 2.11).

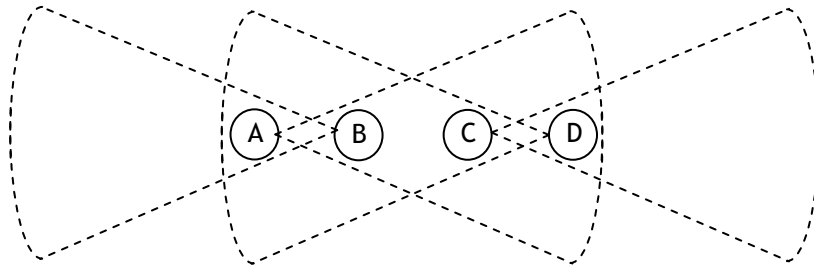


Figure 2.11 - Interference range without transmitted power control

If there is the possibility of controlling the transmitted power, this problem could be avoided (as seen in Figure 2.12).

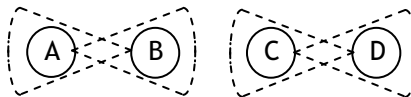


Figure 2.12 - Interference range with transmitted power control

2.5 IEEE 802.11 DCF MAC protocol in WMNs

The IEEE 802.11 DCF (Distributed Coordinated Function) is a protocol, which RTS (Request To Send), CTS (Clear To Send), DATA and ACK (ACKnowledge) frames are exchanged between pairs of nodes. RTS and CTS are optional, but are included in this description to make it as complete as possible.

Before initiating transmission, a random backoff interval limited to $[0, CW]$ is chosen by S, being CW a predefined value for the Contention Window. When the backoff counter elapses, the RTS is sent to D. If D receives the RTS, it replies with a CTS. If the CTS arrives to S within the CTS timeout, S starts transmitting DATA. After all the DATA is received by D, it replies with ACK and the transmission is completed. All transmissions are separated with SIFS (Short InterFrame Spacing), except after ACK where DIFS (DCF InterFrame Spacing) is used to separate frames from distinct dialogs (Figure 2.13a). If a collision occurs with the RTS or with the CTS, S doubles the CW and choses a new backoff interval and retransmits RTS, this is repeated until the Contention Window reaches its maximum value CW_{max} (Figure 2.13b). In backoff mode, if the channel is sensed busy, the node pauses its backoff counter. When the channel is cleared for a for a DIFS duration the backoff counter resumes from its previous value.

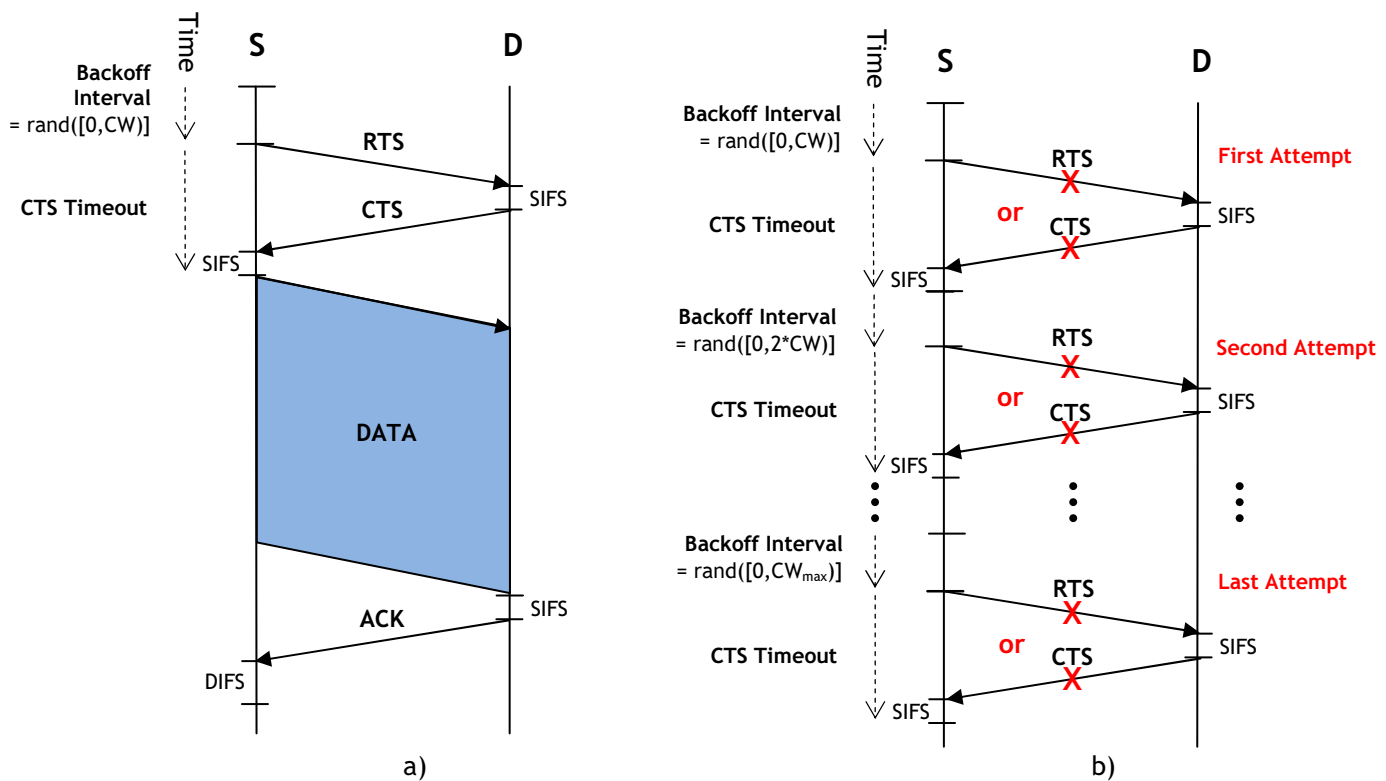


Figure 2.13 - Successful and unsuccessful RTS/CTS/DATA/ACK exchange

When used with directional antennas, the IEEE 802.11 DCF MAC protocol can give birth to some problems namely those mentioned in the “Challenges of directional antennas in WMNs” section such as: deafness, hidden terminal due to asymmetric gain or unheard RTS/CTS.

A significant amount of the previous research work done on integrating directional antennas in WMNs, focuses on proposing new Medium Access Protocols to exploit the benefits of the advantages of directional antennas and overcome the challenges introduced by them. E.g. [1], [3], [5] and [6] propose protocols based on the IEEE 802.11 DCF protocol.

2.6 Related work

From the previous work analyzed related to the area under discussion on this dissertation, the most significant topics identified to construct a review of the state of the art were *MAC protocols*, *performance evaluation using directional antennas*, *analytical study of directional antennas* and evaluation of *hardware implementations* integrating directional antennas.

2.6.1. Proposed MAC protocols

Choudhury et al. [1] proposed a MAC protocol that takes advantage of higher transmission gain and spatial reuse by establishing links between distant nodes and allowing simultaneous communications of node in each other's vicinity, depending on the directions of transmission. However, the proposed MAC protocol does not incorporate power control, which could help improving even more on the spatial reuse characteristic.

Gossain et al. [5] proposed two directional antenna MAC protocols - DAMA and enhanced DAMA - aiming to exploit the advantages of directional antennas. They conducted a simulation study which shows performance improvement over previously developed solutions such as CRM (Circular RTS MAC). However power control of directional antennas is not investigated, which could benefit even more the deployed solution on the performance of the network.

Ko et al. [6] attempt to design a new MAC protocol suitable for ad-hoc networks based on directional antennas - D-MAC - to improve bandwidth efficiency of previous MAC protocols and performance by allowing simultaneous transmissions.

2.6.2. Performance evaluation using directional antennas

ElBatt et al. [2] focus on evaluating the performance of a network considering different reservation schemes and highlight the trade-off between spatial reuse and control/data packet collisions. They concluded those reservation schemes fail to balance that trade-off, and due to this, a new algorithm is introduced. The simulation study conducted shows performance gains of the introduced algorithm over the previously existing reservation schemes. It is assumed the transmission range of the directional antenna is the same of omni-directional antennas and so, the proposed solution, does not benefit from the higher transmission range directional antennas provide.

2.6.3. Analytical study of directional antennas

Li et al. [4] identified the potential benefit directional antenna provide in ad-hoc/mesh networks namely increased signal quality, improved routing performance and better networks connectivity, which are consequences of the higher transmission gain of directional antennas. Increased network capacity is also mentioned, which is a direct result of the spatial reuse directional antennas provide.

2.6.4. Researched hardware implementations

[9], [10] and [11] refer to a type of antenna which could be considered to implement in the testbed, which is the ESPAR antenna. ESPAR means Electronically Steerable Passive Array Radiator, but our latest research showed it was not being produced so we will not consider it for our implementation.

Subramanian et al. [13] deploys a 6 node testbed in an office environment. Each node is equipped with Atheros IEEE a/b/g mini-PCI wireless card slotted to a laptop computer, which a four-sector Vivaldi antenna is connected (Figure 2.14). The main conclusion obtained by this study is if a correct sector combination is achieved, an improvement of the relative aggregate throughput up to 200% in comparison to omni-mode configuration can be obtained, due to the reduction of the directional hidden terminal problem and benefiting from the greater spatial reuse from the sectorized antenna.

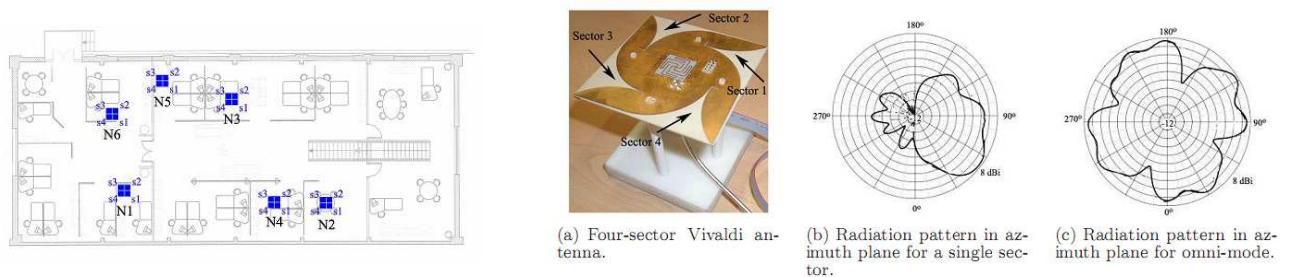


Figure 2.14 - Testbed setup and antenna used [13]

Buettner et al. [14] has as most important information for our concern, the transmission and reception chains architecture (Figure 2.15). The hardware used is a Senao 5345MP MiniPCI wireless adapter connected to a phased array 8-dipole antenna from Fidelity Comtech. There is no information about the setup of the topology used to set the testbed.

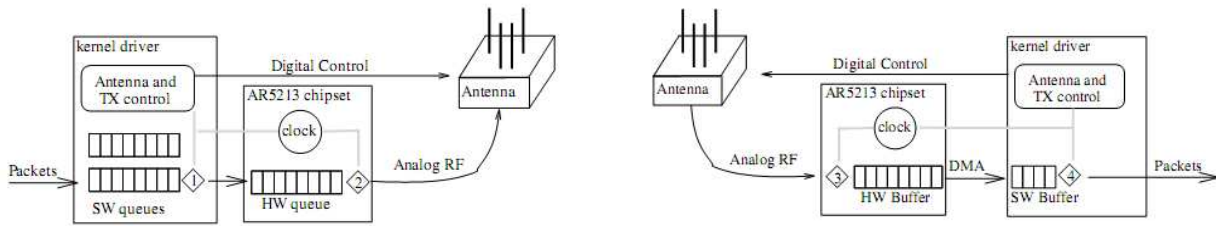


Figure 2.15 - Transmission and reception chains architecture [14]

Lai et al. [15] describe the design of an antenna which could be used in our hardware configuration. It consists in a switched beam antenna employing a four-element slot antenna array. It provides 10 configuration modes - 8 beamforming modes and 2 omni-directional modes (Figure 2.16).

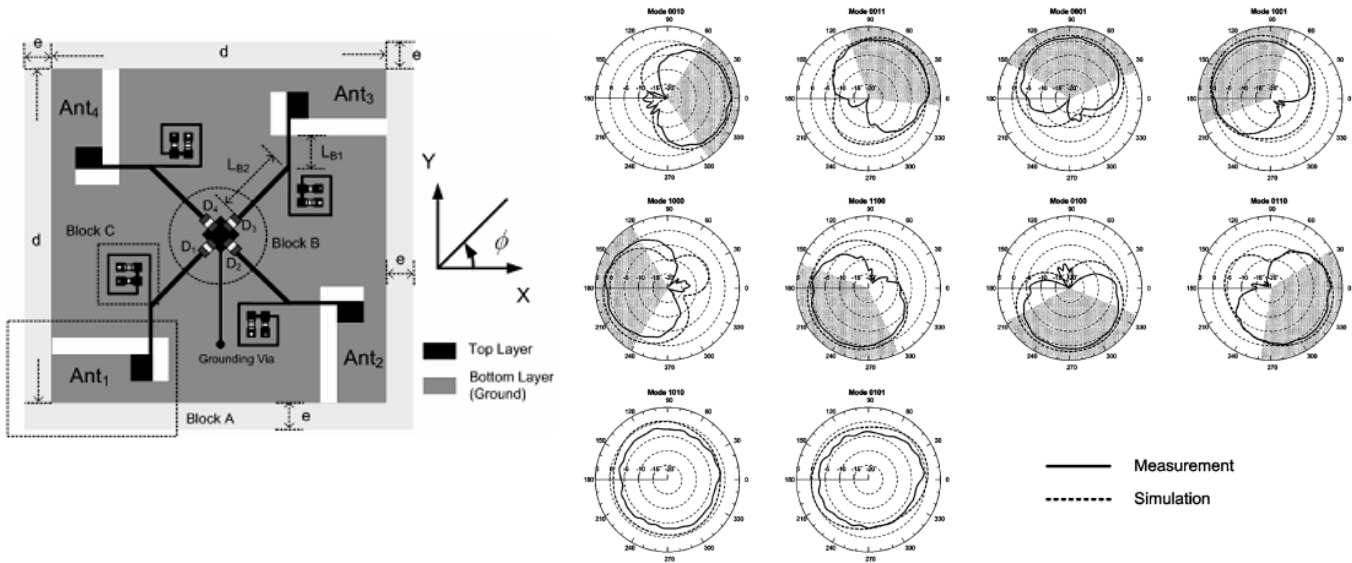


Figure 2.16 - Antenna structure and configuration modes[15]

Dunlop et al. [16] analyze the impact of a switched beam antenna in a sensor network. The only provided information relative to hardware setup is the antenna used, which is a MaxBeam smart antenna. The main conclusion of this study is that using the switched beam antenna and evaluating its performance, a positive impact is verified, with main improvements in throughput, delay and power consumption.

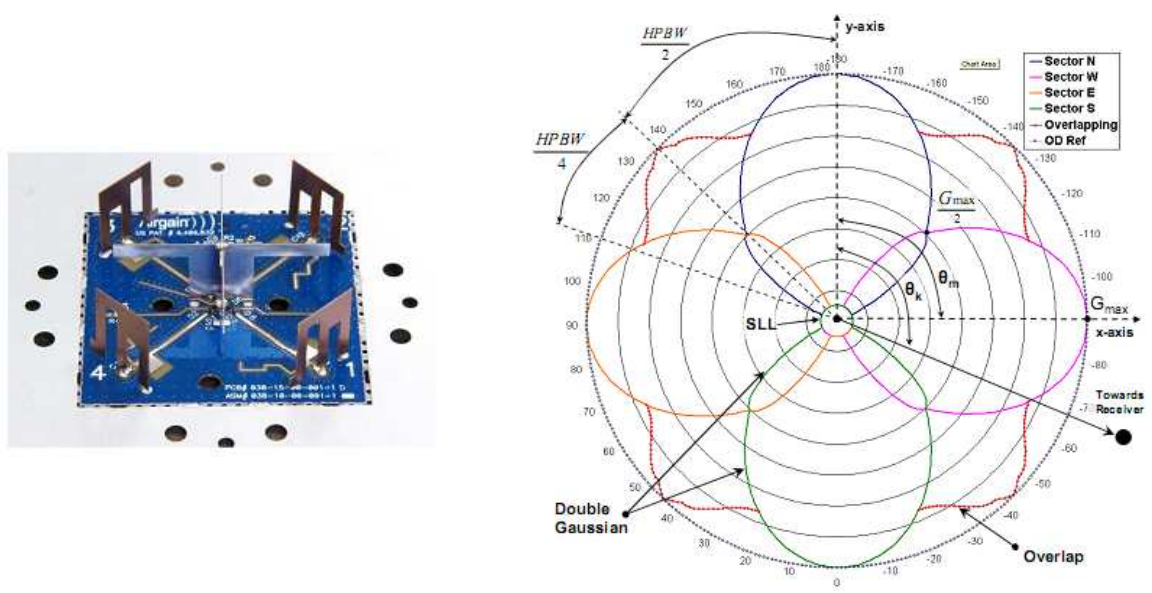


Figure 2.17 - MaxBeam smart antenna structure and radiation pattern[16]

Chapter 3

Developed Work

This chapter presents the topics related to the structure of the research work which has been developed, including the *detailed objectives* of this dissertation, the *research methodology* followed, the *proposed models* which consist in two possible solutions to fulfill this dissertation's objectives, the *devised prototype* used in the tests, the *switched beam antenna radiation pattern characterization*, the *performance measurement and comparison* tests and the *workplan* that was followed since the beginning of this dissertation until its end.

3.1 Objectives

Previous work done in performance evaluation of wireless mesh networks with directional antennas is mostly done on simulation platforms, and moreover, the parameter measured is the aggregate throughput of established connections [2, 4, 5, 12]. In the related work research, we see that end-to-end delay is also considered [1, 3]. We must not deny that throughput is the parameter, in terms of importance when evaluating the performance of a network, which we should pay particular attention, but there are also other parameters that should be considered for a complete characterization of the network itself. The objectives of this dissertation are the construction of a prototyped hardware based solution of integration of directional antennas and its control logic in several nodes to deploy a static wireless mesh network to allow evaluation of the impact of these antennas in the performance of the network in terms of throughput, delay, and fairness, in comparison to the same network based on regular IEEE 802.11 omni-directional communicating equipment. After a comparison is established, it is possible to conclude if directional antennas contribute for a positive or negative outcome of the measured performance parameters.

3.2 Research methodology

Defining a research methodology is a good practice, in order to help us plan its execution, and also to know which direction should be followed at each stage of its development. Most of the times the process is cyclic, particularly if experimental research is being done.

In this case, the research methodology defined for this thesis is depicted in the following flowchart:

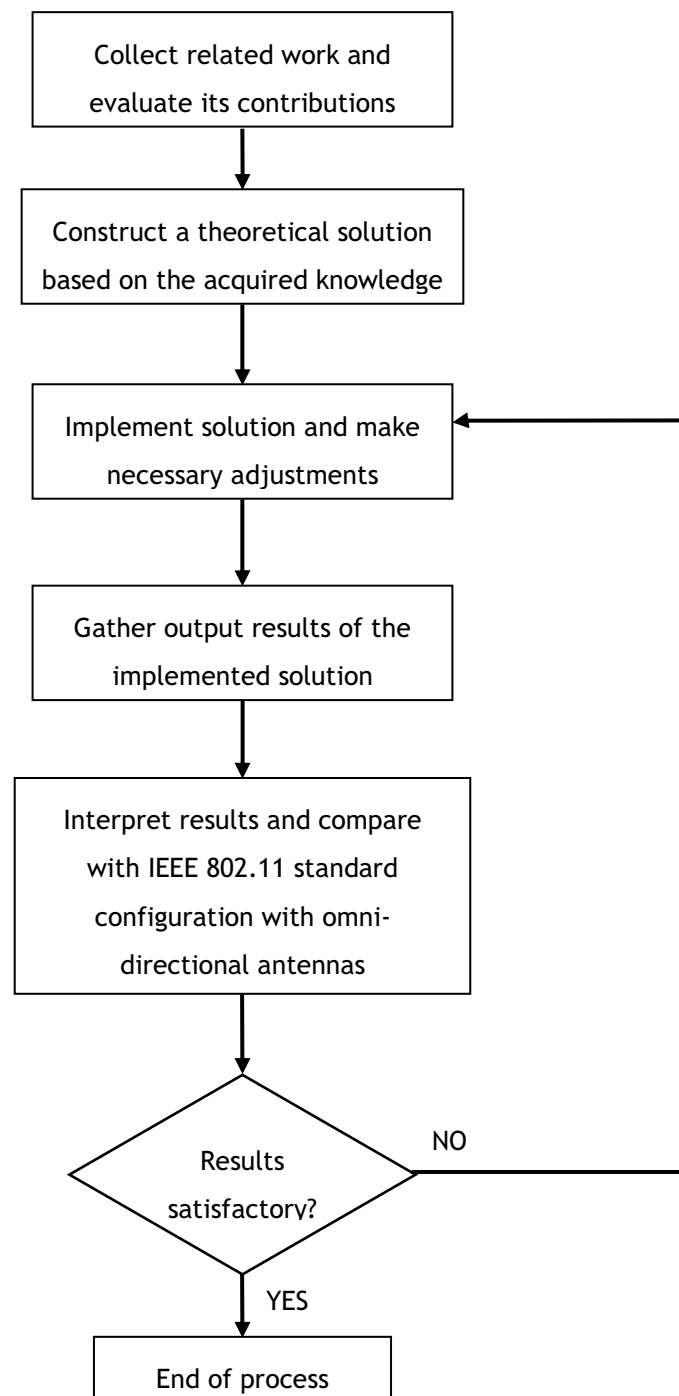


Figure 3.1 - Research Methodology Flowchart

3.3 Possible models

Resulting from the evaluation the objective of this thesis, two possible solutions for our node configuration have been identified.

3.3.1 First solution

The first identified solution consists in including N MAC interfaces, where N is the number of desired directions of communication, each with a single beam antenna associated used to communicate in only one direction. With this, each set of MAC interface and antenna would be used to communicate with only one neighbor node. Each packet coming from the upper layers is placed on the respective Interface Queue (IFq) by the information provided by the TCP/IP layer. This way, the MAC interface only concerns about establishing the connection when the channel is available.

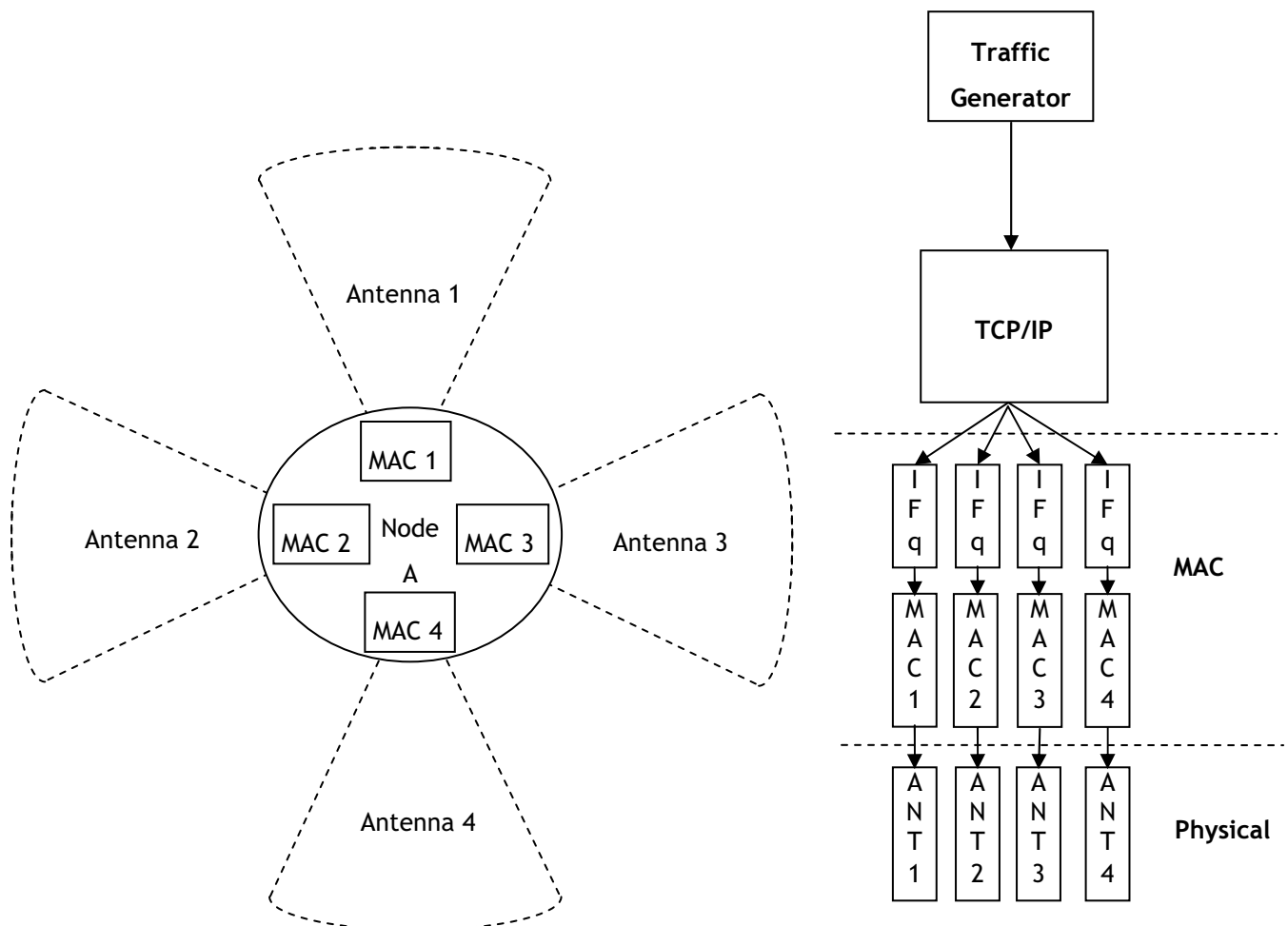


Figure 3.2 - Node Configuration - 1st Solution

3.3.2 Second solution

The second identified solution consists in having only one MAC interface controlling a switched beam antenna with N beams, where N is the number of desired directions of communication. It is assumed that the MAC interface has access to the information of which beam must be activated to establish communication with the desired neighbor through its MAC address. When the upper layers generate packets, these contain information of which neighbor to be sent and, based on that information, the MAC interface is able to activate the beam correspondent to the respective neighbor node.

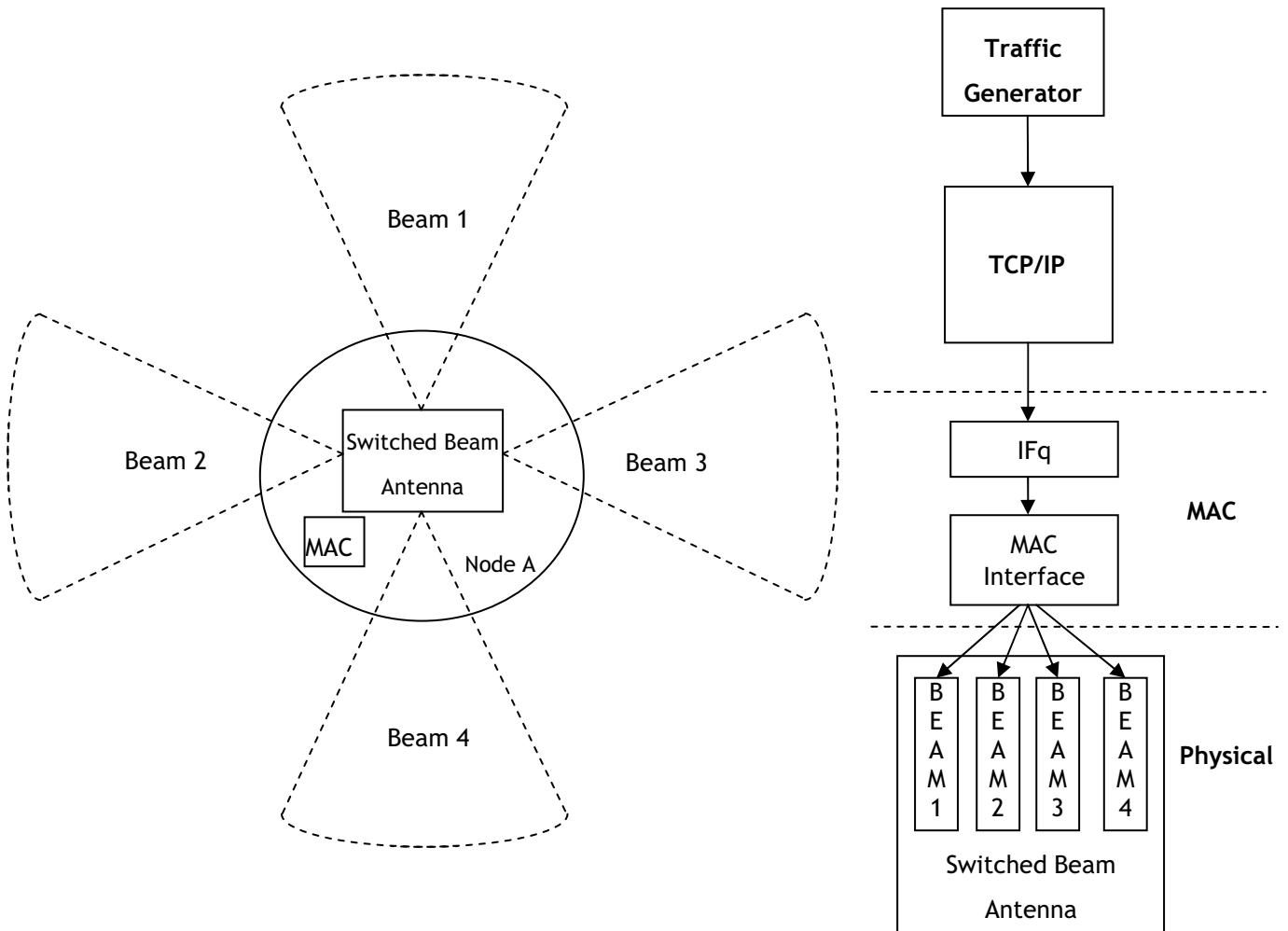


Figure 3.3 - Node Configuration - 2nd Solution

Our choice went for the second solution since it was possible to purchase switched beam antennas, and this way we end up saving funds in extra MAC interfaces and also the trouble of coordination between them in each node.

3.4 Devised prototype

In this section we present all the details regarding the hardware and software used in the construction and development of our prototype. To provide a general overview of our prototype the following diagram is presented:

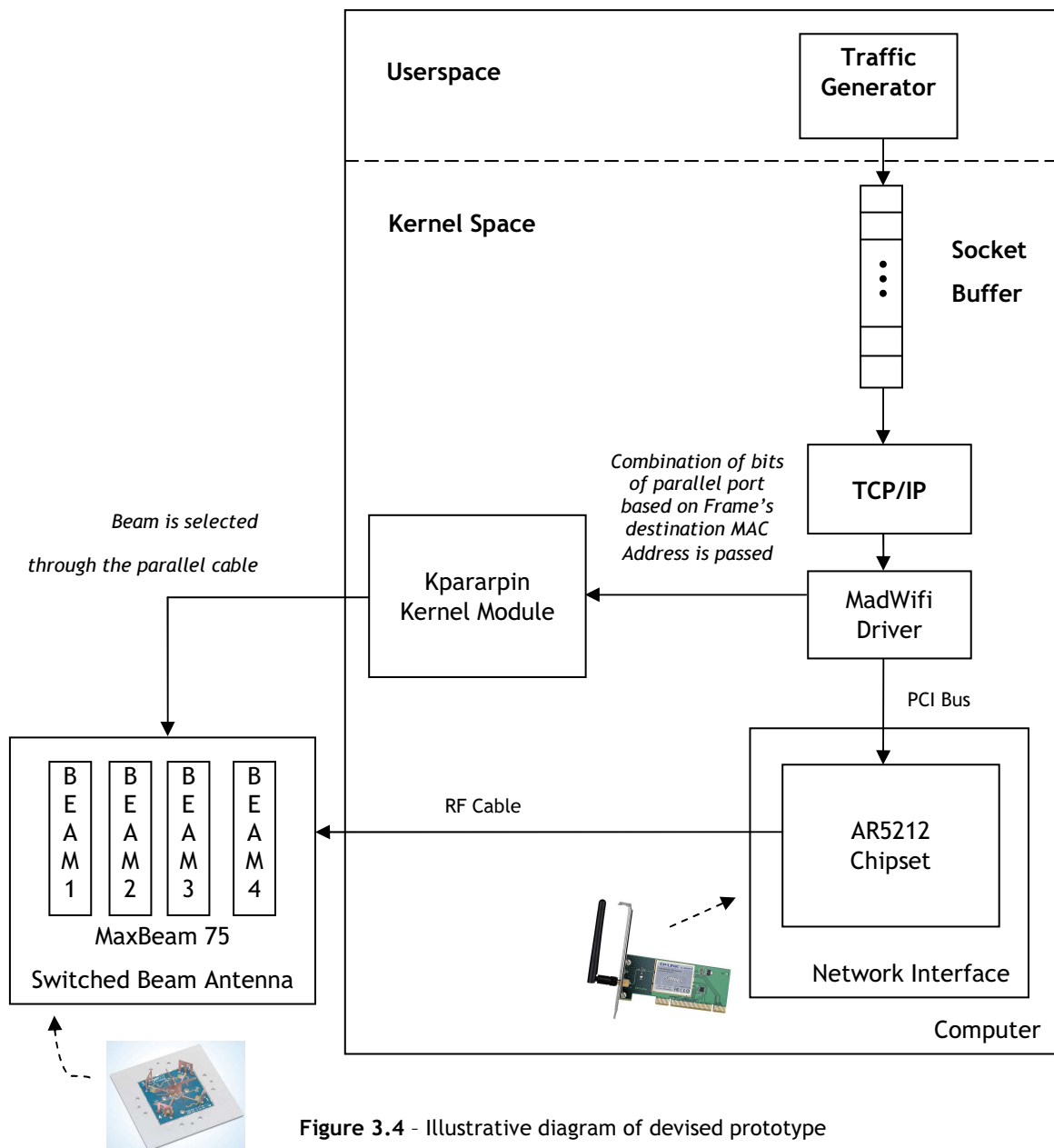


Figure 3.4 - Illustrative diagram of devised prototype

Starting with the computers' description, Intel Pentium III based desktop computers were used, with 512 Mbytes of RAM, a CD/DVD-ROM disc drive and at least 10 Gbytes of hard disk space. Each computer was also equipped with an Ethernet network card, to allow remote access, in case the computer is placed far away from where the user is taking the performance parameters and also to allow Internet access.

The requisites that the wireless interface card had to fulfill, so that it could be integrated in the WMN nodes were: detachable antenna, to enable disconnection of the regular IEEE 802.11 omni-directional antenna and connection of our switched beam antenna; market availability and reduced cost; PCI interface card and Atheros chipset based card (AR5212), which are demands of the chosen driver - MadWifi. The wireless interface card to integrate in the WMN nodes chosen, which fulfilled all these requisites, was the TP-Link TP-WN551G Wireless PCI Card.



Figure 3.5 - TP-Link TP-WN551G Wireless PCI Card [wireless_card_datasheet]

The directional antenna chosen to figure in the integration of each WMN node was the Airgain MaxBeam 75 Smart Antenna (Figure 3.6). The reasons which justified our choice were mainly the suitability for your project, the availability of the product and the reduced cost.

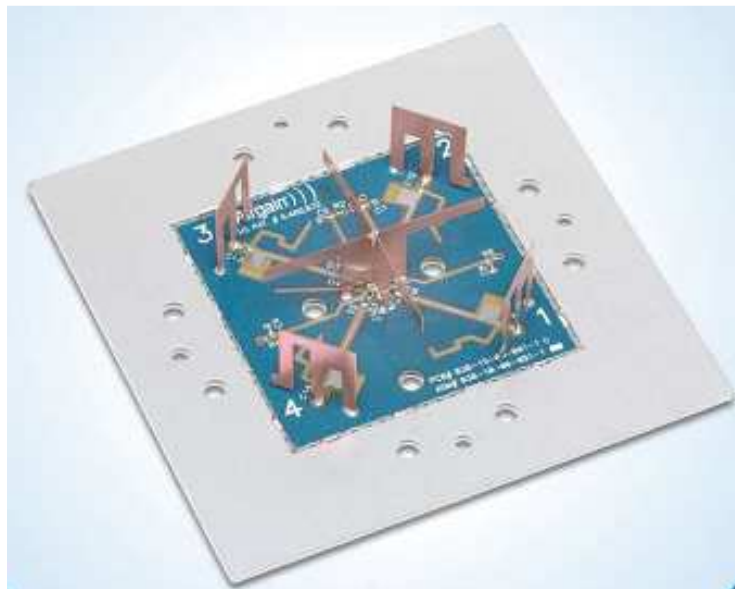


Figure 3.6 - Airgain MaxBeam 75 Smart Antenna [18]

To integrate this antenna into each node, some problems had to be overcome. As opposed to regular IEEE 802.11 omni-directional antennas which only have the RF connector, this switched beam antenna has two interfaces: one RF connector (U.FL plug) and a 6-pin connector which controls the beam switching, i.e., the radiation pattern the antenna forms. To control the 6-pin connector (Figure 3.7), it was decided the IBM-PC IEEE 1284 standard parallel port [17] of the computer would be used, as it meets the requirements stated in the product specification sheet of the switched beam antenna, which is printed in annex. The parallel port is fast enough to enable pattern-per-packet, i.e., formation of a different radiation pattern for each packet which needs to be sent.

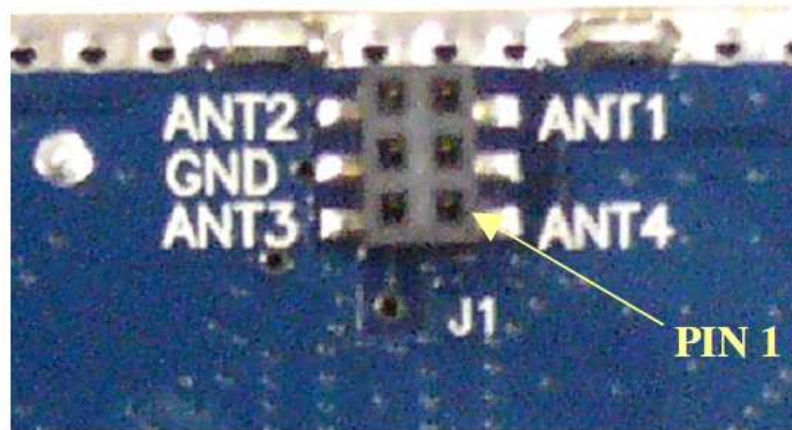


Figure 3.7 - 6-pin connector to control switching

To connect the U.FL plug of the switched beam antenna to the RP-SMA female connector of the wireless interface card (see Figure 3.8), some extra components had to be purchased.

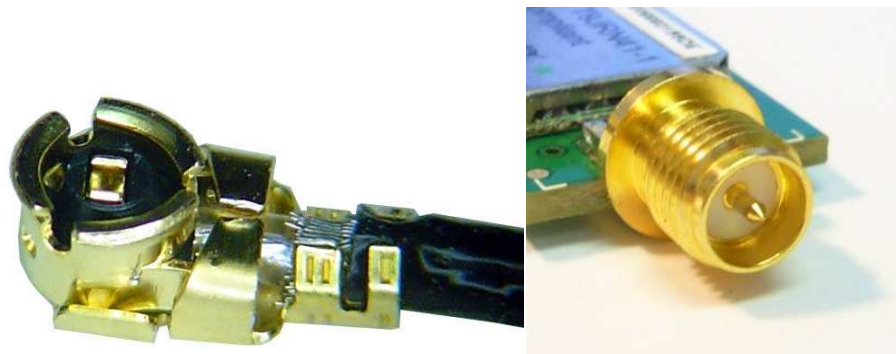


Figure 3.8 - U.FL plug [21] and RP-SMA female [22]

A vast variety of international shops were contacted, such as: Mouser Electronics, Gradconn, Wellshow Technology, SparkFun Electronics, DigiKey Corp., Farnell and others. The only international shops which provided a valid solution were DigiKey Corp. and Farnell, by presenting the products in Figure 3.9.

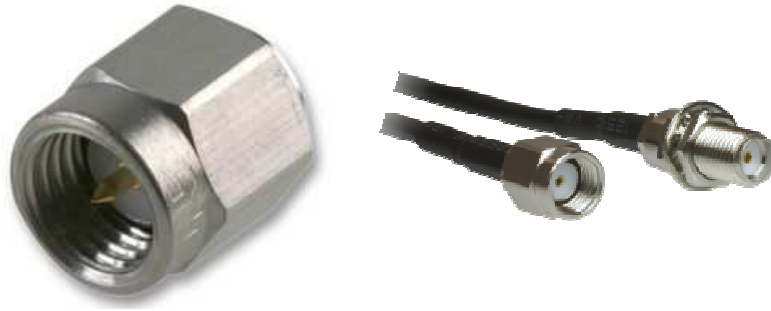


Figure 3.9 - U.FL jack to SMA plug adapter [23] and RP-SMA male to SMA female [24]

With these two components it was possible to interconnect our switched beam antenna with the wireless interface card. It was chosen to purchase these components from DigiKey Corp. as it offered lower price rates for the quantities we needed.

Another issue needed to be attended was the fragility of the structure of the antenna. To overcome this, a set of plastic boxes was bought from a local shop - Aquário-Comércio de Electrónica Lda - to protect the switched beam antenna from weather conditions and structural impacts (see Figure 3.10).

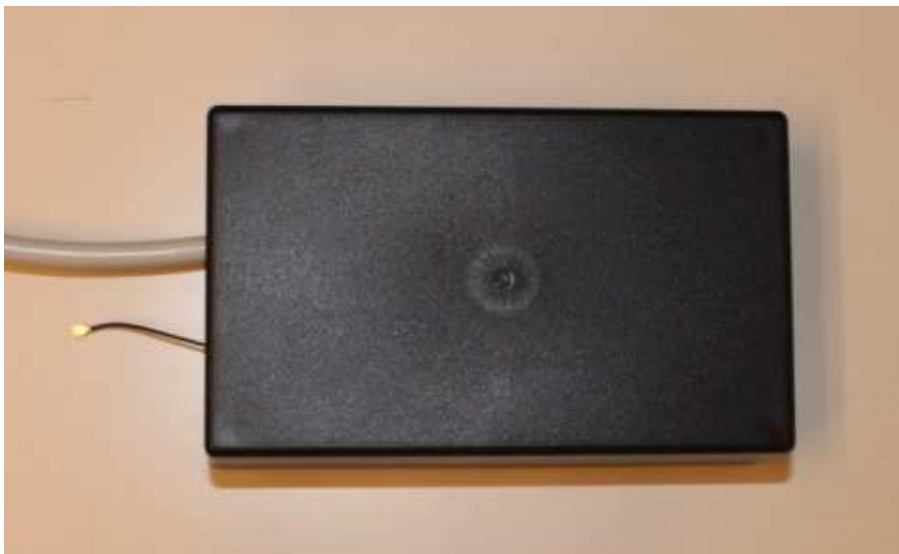


Figure 3.10 - Switched beam antenna inside plastic box

The software tools used allowed the fulfillment of the objectives of this thesis, by enabling the control of the switched beam antenna and collecting the necessary performance parameters to establish a comparison between the performance of a WMN with regular IEEE 802.11 omni-directional antennas and the same WMN with our switched beam antenna. This was accomplished by modifying the source code of the wireless interface card driver and integrating it with a parallel port Linux kernel module controller.

As for the operating system, all nodes run Debian Lenny v.5.0 kernel 2.6.26-2-686 [25], which is a GNU/Linux based operating system.

The wireless interface card driver used was MadWifi [26], and the main reasons for choosing it were that it enabled our modifications in the source code under the GNU GPL v.2.0 license and also allowed transmit power control.

To control the parallel port of the computer, we concluded the best way to do it was by installing a dedicated Linux kernel module to carry out this functionality. We chose Kparapin, which is a Linux kernel module built by Parapin Software [27] that allows setting and clearing individual pins of the parallel port, to establish the desired radiation pattern of the switched beam antenna, at each instant of time.

The traffic generator and measurement tool used was the Linux version of Iperf [28], which established TCP/IP connections between pairs of nodes and provided the maximum throughput over those links. The TCP version used was TCP Reno, which adds fast retransmit phase, slow start and the algorithm of fast recovery to standard TCP [29].

Only with all this information and resources was it possible to develop our prototype to initiate a new phase of this dissertation, which consisted in the radiation pattern characterization and the performance measurement and comparison tests.

3.5 Switched beam antenna radiation patterns

By consulting the datasheet [18] and the product specification sheet, which is printed in annex, of the switched beam antenna, it was not possible for us to correlate the different radiation patterns the antenna can form with the combinations to be inputted in the 6-pin connector of the antenna. The information that could be extracted regarding the 6-pin connector is that one pin is Ground, four pins are enablers of each sector of the switched beam antenna and the remaining pin is not connected. If we have four pins that control the sectors of the switched beam antenna, it means we can have up to $2^4 = 16$ different combinations of radiation patterns.

To overcome this situation, a series of tests were conducted at the anechoic chamber. The intention of these tests was to determine which radiation pattern was formed for each of the 16 different possible combinations of the 6-pin connector. During the first session of tests, we could conclude by the results we were collecting, that there should be a problem with the power supply of the switched beam antenna. Soon, we realized that the pin that is referred as not connected in the product specification sheet is in fact the power supply of the SMD integrated circuit that computes the beam switching of the antenna. Having solved this, we were ready to start the test procedure.

Before starting the tests and collecting measurement values, we had to calibrate the two port network analyzer (Figure 3.11). The calibration done was respectively: open circuit, short circuit and match (normalized 50 Ω) on each port. Then, a through calibration was done with the two ports connected one to the other. The computer which controls the rotating platform (Figure 3.11) runs a MATLAB application where we can define the value in degrees that we want the platform to rotate.



Figure 3.11 - Network analyzer and computer which controls rotating platform

The transmitter antenna of the anechoic chamber (Figure 3.12) was connected to port 1 of the network analyzer.



Figure 3.12 - Transmitter antenna of the anechoic chamber

The switched antenna to be analyzed was placed over the rotating platform of the anechoic chamber (Figure 3.13) and the RF cable was connected to the port 2 of the network analyzer.



Figure 3.13 - Switched beam antenna to be tested over the rotating platform

The switched beam antenna was oriented over the rotating platform as show in Figure 3.14, where 0° is the reference of the initial position, and it is pointing towards the transmitter antenna of the anechoic chamber.

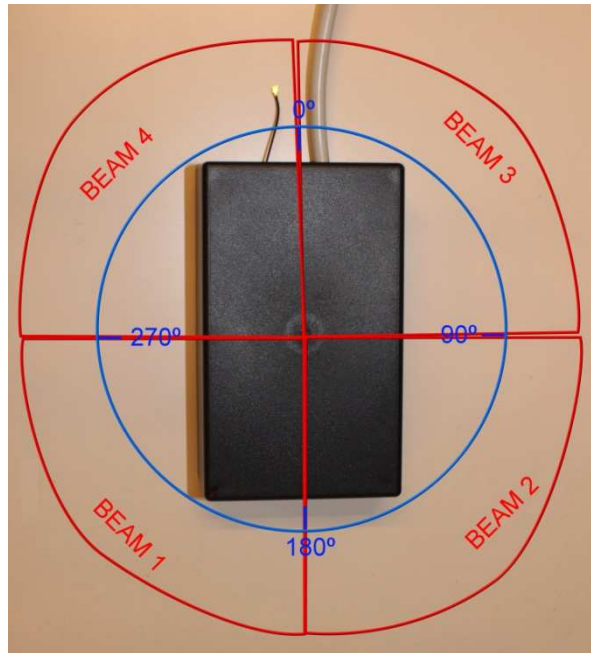


Figure 3.14 - Orientation of switched beam antenna over the rotating platform

The final test done was using a switched beam antenna without the plastic box over the rotating platform. The intuit of this test was to quantify an approximate value of the losses introduced by the box.



Figure 3.15 - Switched beam antenna without plastic box over the rotating platform

To draw the various radiation patterns of the switched beam antenna, we measured the parameter S_{21} at the frequency 2,45 GHz, which is the central frequency of the band of the antenna specified in the datasheet [18], using the network analyzer in steps of 10 degrees for all the different combinations of the four control pins. A program written in C language to apply all the different possible combinations through the parallel port was compiled and executed on the computer which was connected to the switched beam antenna. The sequence that was inputted is shown in the following table:

Table 3.1 – Sequence of parallel port combinations

<i>Combination</i>	<i>PIN1</i>	<i>PIN2</i>	<i>PIN3</i>	<i>PIN4</i>
1st	0	0	0	0
2nd	1	0	0	0
3rd	0	1	0	0
4th	0	0	1	0
5th	0	0	0	1
6th	1	1	0	0
7th	0	1	1	0
8th	0	0	1	1
9th	1	0	0	1
10th	1	0	1	0
11th	0	1	0	1
12th	1	1	1	0
13th	0	1	1	1
14th	1	1	0	1
15th	1	0	1	1
16th	1	1	1	1

While the tests were progressing, we could conclude that the sector was active when a zero was inputted. This way, it was unnecessary to draw the radiation pattern of the 16th combination, since all the sectors would be deactivated. We could also conclude that to activate a single sector we must input only one zero in the 4 pins, which corresponds to combinations 12, 13, 14 and 15. To activate the omni-directional mode we had to input zeros in all 4 pins, which corresponds to the 1st combination. The results we obtained for all the combinations can be observed in the radar charts underneath (Figure 3.16), which are oriented in the same way as Figure 3.14:

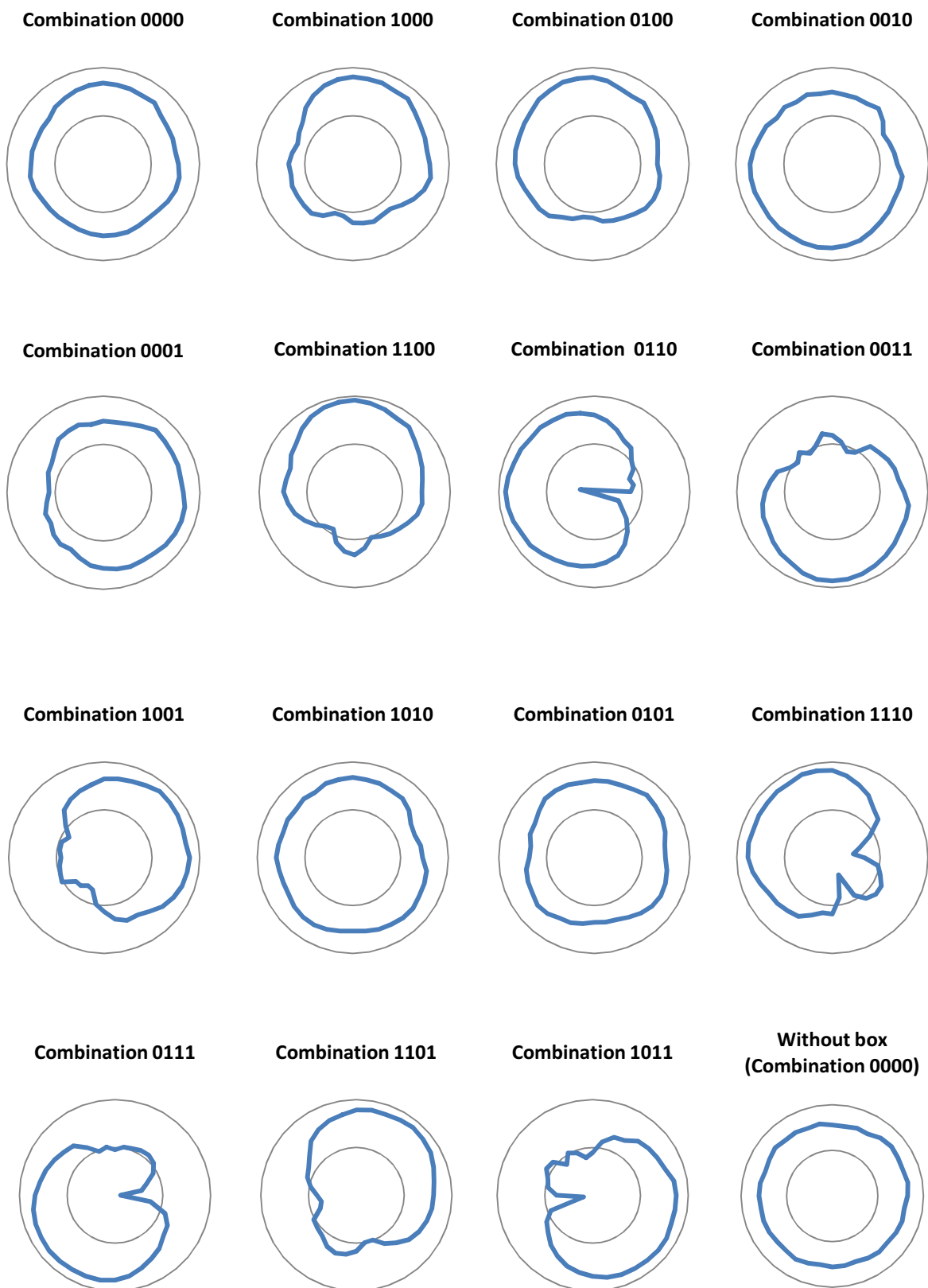


Figure 3.16 - Radiation patterns for all the possible combinations of pins and without box

The full table with all the values which were used to plot the previous radar charts is printed in annex. The only table we present here refers to the values used in the estimation of the losses introduced by the box.

Table 3.2 – Estimation of losses introduced by the box

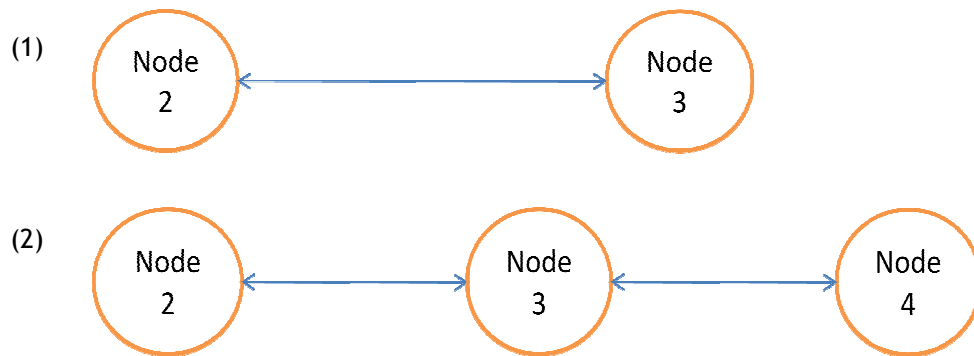
	<i>With box (dB)</i>	<i>Without box (dB)</i>	<i>Losses (dB)</i>
0°	-46,44	-48,95	-2,51
10°	-46,69	-49,12	-2,43
20°	-46,88	-48,40	-1,52
30°	-47,28	-48,70	-1,42
40°	-46,83	-46,95	-0,12
50°	-48,75	-46,24	2,51
60°	-49,28	-46,75	2,53
70°	-49,20	-47,01	2,19
80°	-49,57	-46,35	3,22
90°	-48,73	-47,01	1,72
100°	-47,91	-48,00	-0,09
110°	-48,02	-47,45	0,57
120°	-48,94	-47,73	1,21
130°	-50,20	-48,42	1,78
140°	-50,70	-48,05	2,65
150°	-50,45	-48,60	1,85
160°	-50,00	-49,42	0,58
170°	-50,13	-48,93	1,20
180°	-50,22	-48,90	1,32
190°	-50,62	-49,40	1,22
200°	-51,06	-48,65	2,41
210°	-51,44	-47,95	3,49
220°	-51,30	-48,59	2,71
230°	-51,06	-48,62	2,44
240°	-50,80	-48,15	2,65
250°	-49,66	-48,00	1,66
260°	-49,34	-48,30	1,04
270°	-50,09	-47,83	2,26
280°	-50,14	-47,95	2,19
290°	-50,63	-48,75	1,88
300°	-50,64	-48,17	2,47
310°	-50,80	-47,24	3,56
320°	-49,06	-48,14	0,92
330°	-48,39	-47,90	0,49
340°	-47,56	-48,55	-0,99
350°	-46,87	-48,00	-1,13

There are some positions of the box which have negative losses, these coincide with the positions which the RF connector of the box is facing the antenna of the anechoic chamber. Since the RF connector also irradiates electromagnetic energy, we can conclude that the negative values for the losses are caused by this fact. The average value for the losses introduced by the box is 1,24 dB.

3.6 Performance characterization

The last tests executed, to fulfill the objectives of this thesis, were the performance measurement tests. The computers used in these tests were numbered from 1 to 4. Since we only needed three computers, and computer number 1 was used for several initial experiments, we end up using computers 2, 3 and 4 for these tests. The performance tests were conducted with the establishment of two different scenarios and three different configurations for the physical layer of nodes.

The tested scenarios were:



Each node was composed of a computer with a wireless interface card. Every computer used in our tests was configured with the following steps:

- Install Debian GNU/Linux, kernel 2.6.26-2-686;
- Blacklist ath5k (pre-installed driver);
- Install packages “build-essential” and “linux headers” to allow compiling;
- Compile MadWifi driver and make install;
- Compile Parapin and make install;
- Load Kparapin module into Linux Kernel;
- Load MadWifi driver into Linux Kernel;

The main objective of using three different node configurations for the performance tests, was to enable the establishment of a comparison between them. Each configuration required a different version of the MadWifi driver to be loaded when the tests were being executed. The physical layer configurations used on each node were:

- (a) SOA - Standard IEEE 802.11 2dBi omni-directional antennas;
- (b) OA - Switched beam antenna in omni-directional mode;
- (c) DA - Switched beam antenna in directional mode.

By looking into the product specification sheet of the switched beam antenna, it is possible to conclude that when it is operating in omni-directional mode it has a peak gain of 4 dBi, whereas in directional mode it has a peak gain of 7 dBi.

The implemented finite state machine at driver level of the DA configuration, which is the more complex in the perspective of the driver, is depicted in the following diagram that, for simplicity is only represented the transmission phase. For reception, the mode the antenna is, at all times, is in omni mode.

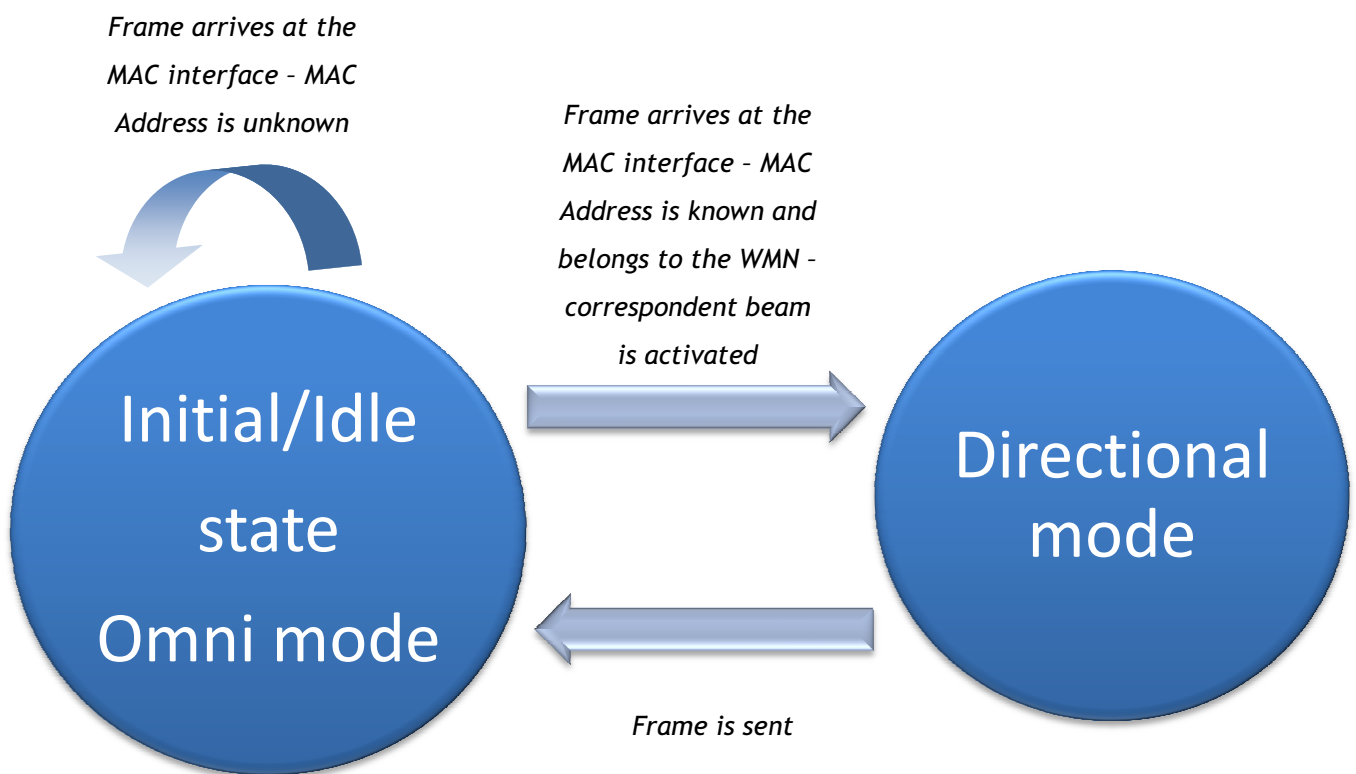


Figure 3.17 - Finite state machine implemented in the driver of DA configuration

Having defined the scenarios to be tested and the different physical layer configurations for the nodes, we were ready to start the test procedure. These tests were done outdoors at the entrance of INESC building and in the end of the day, so that the wireless medium was as unoccupied as possible. The performance parameters collected in all the test scenarios and node configurations were throughput and delay. We also measured RSSI and link quality which are provided just for reference. For the second scenario, fairness was calculated using the values of the throughput of the two flows (2<->3 and 3<->4) according to Jain's fairness index, which is calculated with the following formula:

$$f(x_1, x_2, \dots, x_n) = \frac{(\sum_{i=1}^n x_i)^2}{n \sum_{i=1}^n x_i^2} \quad (2.2)$$

where x_i is the throughput of flow i and n is the number of competing flows.

3.6.1 Test procedure - first scenario

To test the first scenario, two computers were placed with their backs facing each other, so that the antennas could have pure line-of-sight (Figure 3.18). The main objective of this test was to evaluate our devised solution in terms of connectivity using the three configurations, by measuring throughput and average delay. The switching capability is not explored in this scenario, since only one way of communication is used in each antenna when working in directional mode.

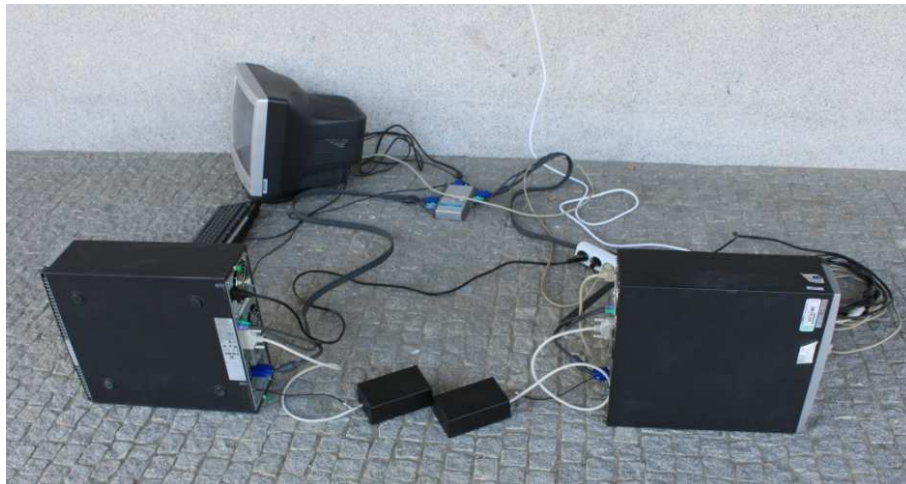
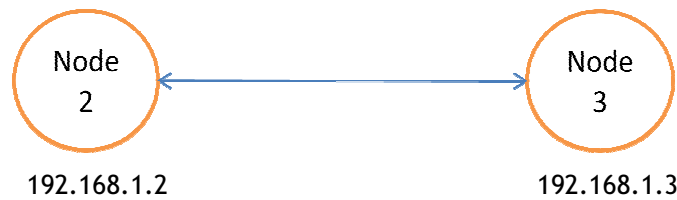


Figure 3.18 - First tested scenario

The first node configuration used was SOA and the computers were configured using the commands `iwconfig` and `ifconfig`. The configuration scripts and the outputs of the `iwconfig` and `ifconfig` commands are printed in annex. To computer 2 was attributed the IP 192.168.1.2 and to computer 3 was attributed the IP 192.168.1.3 so that it was possible to establish the TCP/IP link with Iperf. The RSSI, which stands for received signal strength indication, and link quality values are directly obtained through the command `iwconfig` of the driver. To measure the throughput, Iperf establishes a TCP/IP link and tries to exchange as much data as possible for a pre-determined period of time. This value determines the throughput performance value of the connection. Three samples were taken for each configuration and each distance between nodes and the average was calculated to be used to draw the charts. To measure the average delay, a ping test was executed to measure de RTT - Round Trip Time. 10 pings were executed and the average was the registered value for the performance parameter.

Initially, the computers were next to each other and the performance parameters were collected. Afterwards, the distance between them was incremented in 5 meters and a new collection of performance parameters was registered. When the distance between the nodes reached 50 meters, it was not increased any further and another node configuration was tested. The next node configuration used was OA and the computers were configured using the commands `iwconfig` and `ifconfig`, similarly to the previous configuration. The same test procedure was carried out as in the SOA node configuration. The last node configuration tested in this scenario was DA. The results that were obtained are presented in the following charts. The tables with all the collected values that were used to draw the charts and the effective gains in throughput and average delay charts are printed in annex.

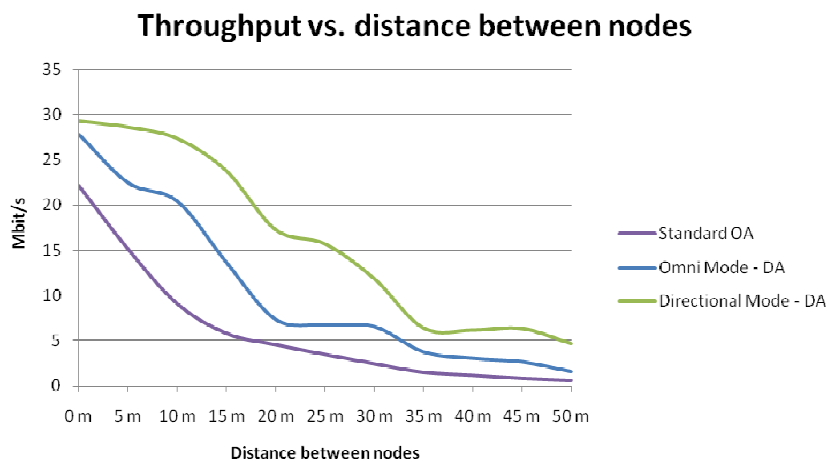


Figure 3.19 - Throughput results chart - 1st scenario

By inspection of Figure 3.19, if we look at the tendencies of the curves, we can conclude that there is a clear relation between the throughput performance parameter and the distance between nodes, that is common to all three curves, i.e., as the distance between nodes increases the throughput decreases at a rate that, an experienced and trained eye could foresee that it can be approximated by a negative exponential. If we compare our solution to the one which is implemented by the standard IEEE 802.11b, that

can achieve maximum throughputs of 11Mbit/s, we can conclude that our solution performs better under 7-8 meters using standard IEEE 802.11 2dBi omni-directional antennas. For that distance, our tests show that the effective gain of our solution using the switched beam antenna in omni mode in comparison to the standard configuration we tested is about 100%, i.e., the throughput doubles, whereas in directional mode the effective gain rises to about 150%. If we make a direct comparison of the standard IEEE 802.11b and our devised solution using the switched beam antenna in directional mode, we can conclude our solution always performs better, in this test scenario, for distances between nodes less than 30 meters. These results are all a direct consequence of the high gain of the switched beam antenna, that can reach peaks of 7dBi in directional mode, minus the attenuation of the box, which is around 1,24 dB. In this test scenario the switching capability of our antenna was not tested.

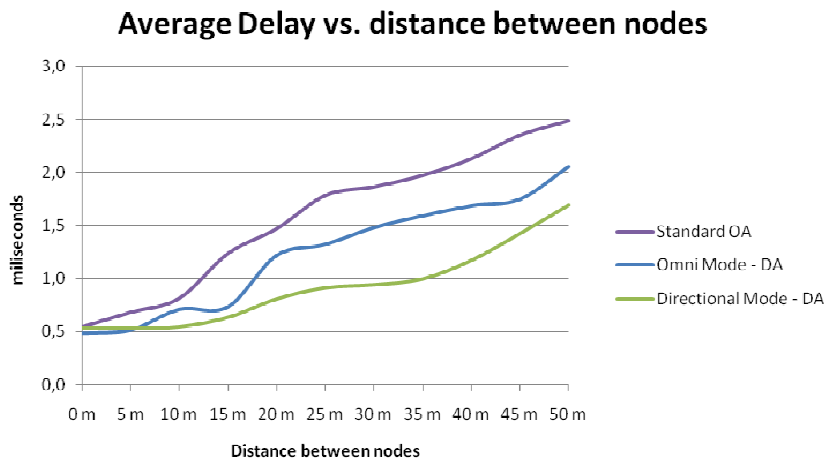
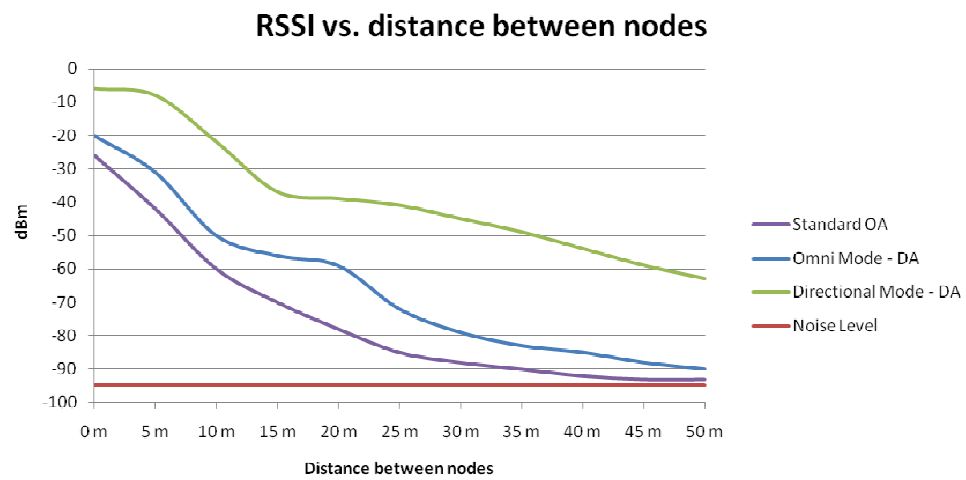
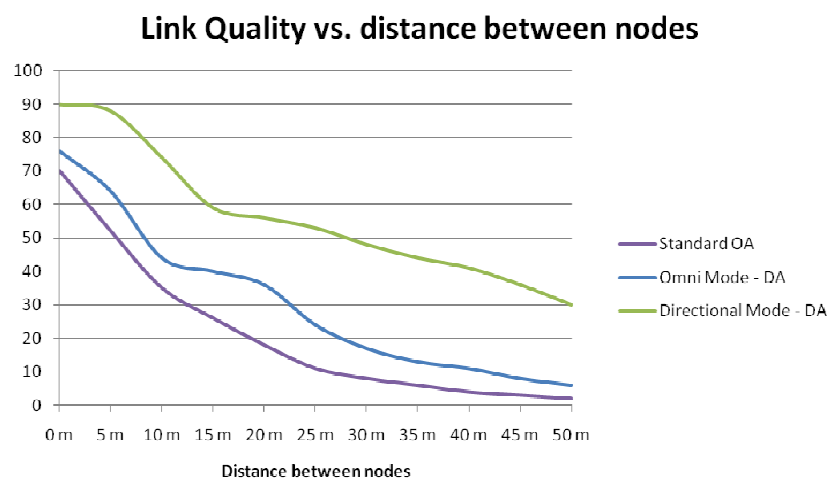


Figure 3.20 - Average delay results chart - 1st scenario

In opposition to the previous analyzed performance parameter - throughput, the curves of average delay, as seen in Figure 3.20, could be approximated by a linear interpolation. Also, another difference is the positive tendency as the distance between nodes increases, i.e., for higher distances the delay is higher too. We can also conclude that our switched beam antenna performs better in omni mode in comparison to the SOA configuration, which uses standard IEEE 802.11 2dBi omni-directional antennas. The best performance is, in fact, achieved by our devised solution using the switched beam antenna in directional mode, that is, the average delay is always lower than the other two configurations, with the exception of the value in the origin, which could be explained by the high reflections the high gain antenna can suffer when they are next to each other. The maximum effective gain of the OA configuration in comparison to the SOA configuration is 40% at 15 meters, whereas the DA configuration reveals an effective gain of around 50% from 15 meters to 35 meters.

As aforementioned, the RSSI and link quality charts are presented just for reference.

Figure 3.21 - RSSI results chart - 1st scenarioFigure 3.22 - Link quality results chart - 1st scenario

3.6.2 Test procedure - second scenario

To test the second scenario the three computers were placed in line with their backs facing a central point, as seen in Figure 3.23. The main objectives of this test were, not only to evaluate our devised solution in terms of connectivity using the three configurations, by measuring throughput and average delay, as in the first scenario, but also to test the switching capability of our antenna, when working in directional mode, and conclude if it affects or improves the performance of the network. In this scenario, it was also possible to calculate the fairness performance parameter using the previously stated Jain's fairness index, as two distinct links were established (2<->3 and 3<->4) and the throughputs were quantified independently.

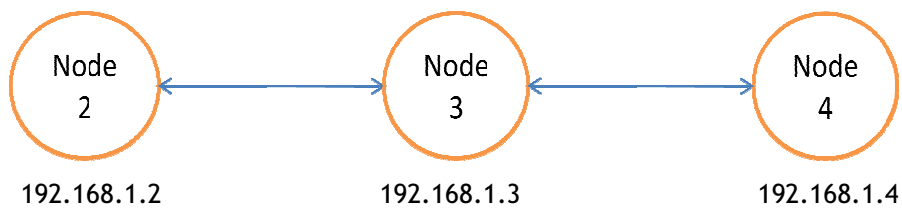


Figure 3.23 - Second tested scenario

Similarly to the first scenario, the first node configuration used was SOA and the computers were configured using the commands `iwconfig` and `ifconfig`. The configuration scripts and the outputs of the `iwconfig` and `ifconfig` commands are also printed in annex. To computer 2 was attributed the IP 192.168.1.2, to computer 3 was attributed the IP 192.168.1.3 and to computer 4 was attributed the IP 192.168.1.4 so that it was possible to

establish the two TCP/IP links with Iperf. The performance parameters were measured using the same methods as in the first scenario, the only differences were that Iperf established two links, instead of one, and the maximum throughput values of each link were collected. These two different values were useful to quantify the fairness performance parameter. To measure the average delay 10 pings were executed simultaneously over the two links, and the averages were collected.

Initially, the computers were next to each other and the performance parameters were collected. Afterwards, the distance between the two extreme computers was incremented in 5 meters relatively to the central computer and a new collection of performance parameters was registered. Differently to the first scenario where we kept increasing the distance between nodes until it reached 50 meters, we only increased the distance until 25 meters, so that the distance between the extreme computers was 50 meters. In the first scenario we could also conclude that it was pointless to increase the distance more than 25 meters between nodes as the bitrates were very low, that is, much worse than the standard IEEE 802.11b, which can reach bitrates of 11 Mbit/s. The other two node configurations - OA and DA - were used and the performance parameters were collected using the same test procedure. The results that were obtained are presented in the following charts. The tables with all the collected values that were used to draw the charts are printed in annex and also the charts with the effective gains in aggregate throughput and average delay.

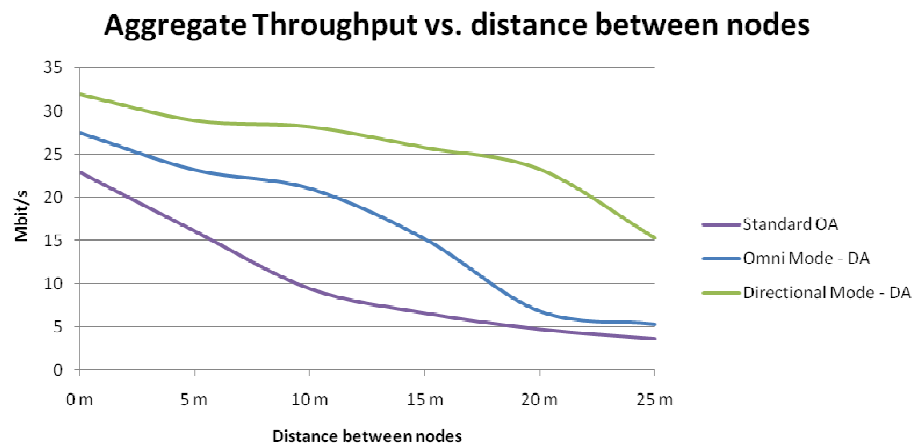


Figure 3.24 - Aggregate throughput results chart - 2nd scenario

In Figure 3.24, if we look at the tendencies of the curves, we can conclude that there is a clear relation between the throughput performance parameter and the distance between nodes, that is common to all three curves, i.e., as the distance between nodes increases the throughput decreases similarly to the first scenario. If we compare our solution to the one which is implemented by the standard IEEE 802.11b, that can achieve maximum throughputs of 11Mbit/s, we can conclude that our solution performs better under 7-8 meters using standard IEEE 802.11 2dBi omni-directional antennas. For that distance, our tests show that the effective gain of our solution using the switched beam antenna in omni mode in comparison to the standard configuration we tested is about 100%, i.e., the throughput doubles, whereas in directional mode the effective gain rises to

about 150%, very similar to the 1st tested scenario. The maximum effective gain of the OA mode is verified at 12 meters and it is about 150%. On the other hand, the maximum effective gain of the DA mode is verified at 20 meters and it is about 400%. If we make a direct comparison of the standard IEEE 802.11b and our devised solution using the switched beam antenna in directional mode, we can conclude our solution always performs better, in this test scenario. In omni mode, our implementation of the switched beam antenna performs better than the maximum throughput of the standard IEEE 802.11b, which is 11 Mbit/s, for distances less than 17 meters. These results are all a direct consequence of the high gain of the switched beam antenna, similarly to the first tested scenario. Another important conclusion we could extract from this test scenario is that the switching capability of our antenna does not have a negative impact on the performance of the network since the measurements are very similar to the first scenario.

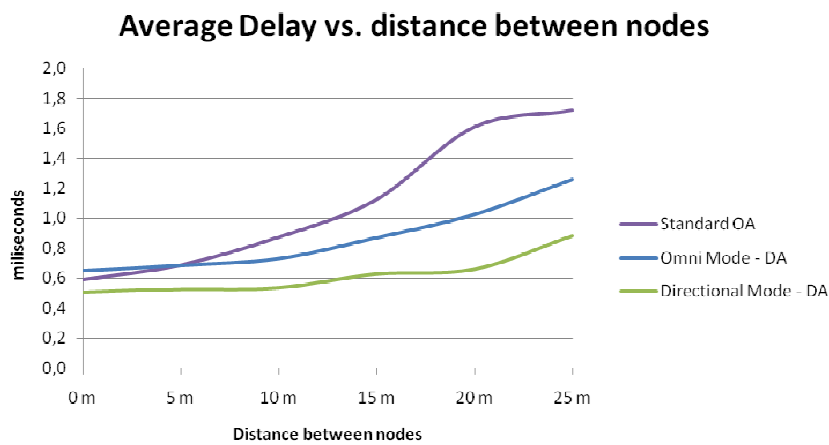


Figure 3.25 - Average delay results chart - 2nd scenario

If we analyze Figure 3.25, we can see a similar tendency in comparison to the first scenario, as it could be anticipated: for higher distances the delay is higher too for all the three configurations. We can also conclude that our switched beam antenna performs better in omni mode in comparison to the SOA configuration, which uses standard IEEE 802.11 2dBi omni-directional antennas with the exception of the value in the origin, which could be explained by the high reflections the antenna can suffer when they are next to each other. The best performance is, in fact, achieved by our devised solution using the switched beam antenna in directional mode, that is, the average delay is always lower than the other two configurations. The maximum effective gain of the OA configuration in comparison to the SOA configuration is 35% at 20 meters, whereas the DA configuration reveals an effective gain of around 60% at 20 meters.

Relatively to this test scenario, we also present charts with the individual information of throughput per flow represented and also average delay per flow, for a more detailed analysis of our test results and their validation.

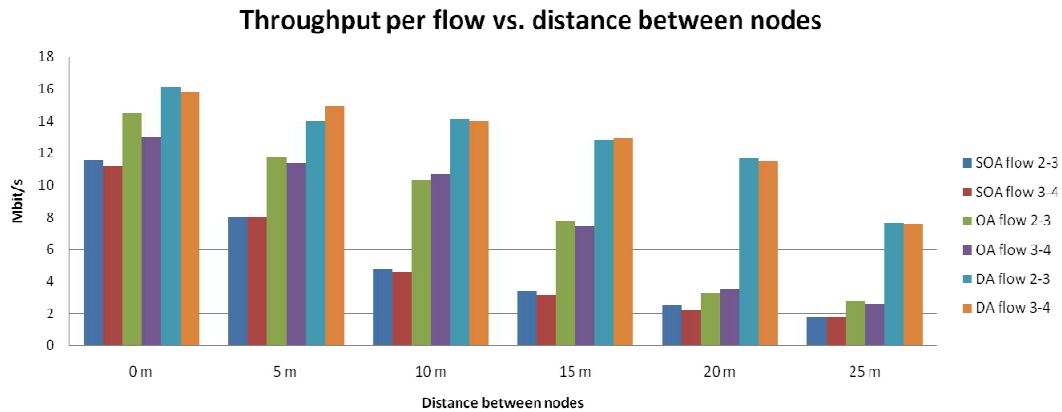


Figure 3.26 - Throughput per flow results chart - 2nd scenario

By inspecting Figure 3.26, we can confirm that there are some differences, in the order of fractions of Mbit/s, when comparing two flows of the same configuration and at the same distance. This could be justified by the fact that TCP was used and, in our test scenario more specifically, TCP Reno was used, which adds fast retransmit phase, slow start and the algorithm of fast recovery to standard TCP. One of the phases of TCP is bitrate negotiation, and probably what happened in all cases was that the negotiation was not exactly equal for the two flows. Afterwards, we will see that these differences do not affect the fairness performance parameter.

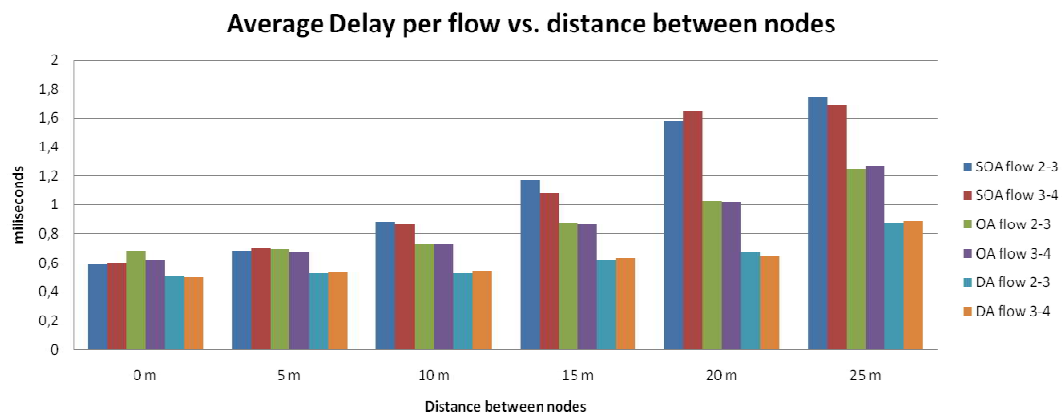


Figure 3.27 - Average delay per flow results chart - 2nd scenario

As for the average delay parameter we can conclude, by analyzing Figure 3.27, that there are also differences when comparing values of the two flows of the same configuration and at the same distance. This could be caused by the same reasons that we given in previous chart, since we believe that throuput and delay have a relation of inverse proporcionality, i.e., if we have high throughputs, we will have low average delays. Both these results, throuput and average delay can register differences if the different flows, due to the probability of imprecise manual aligment of the antennas. We believe that, if the antennas were perfectly aligned, which in practice is not acheivable, these differences could be smaller or inexistant.

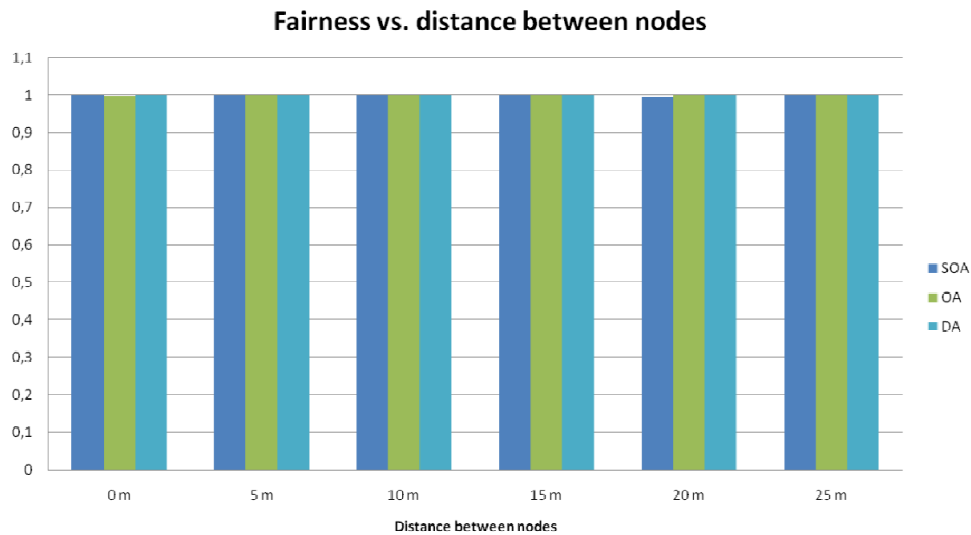
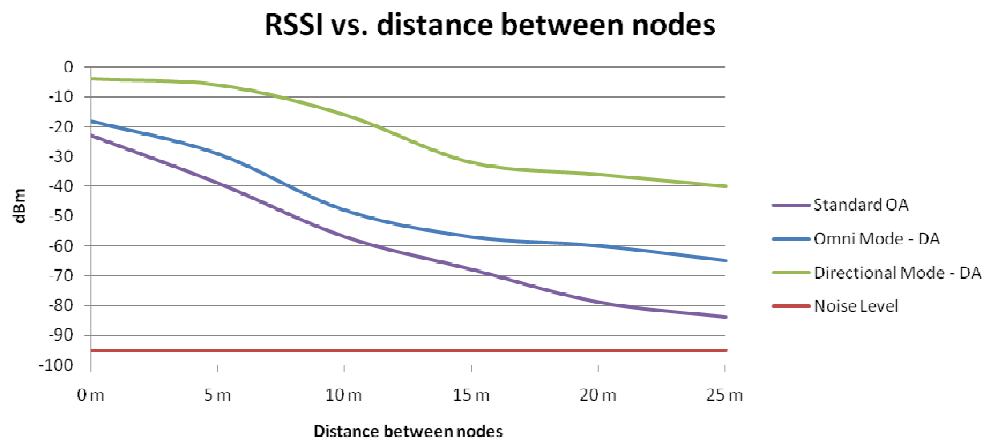
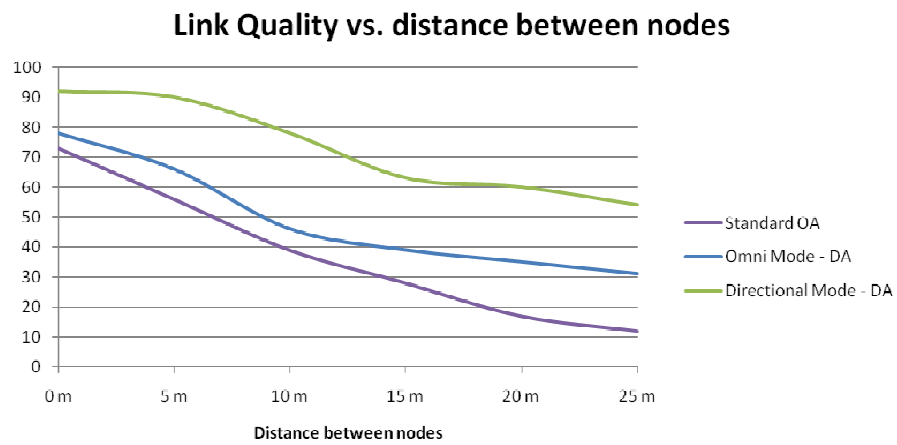


Figure 3.28 - Fairness results chart - 2nd scenario

Finally, we present in Figure 3.28 the results of our calculations of the fairness performance parameter using Jain's fairness index formula. We can conclude that all configurations present values of fairness extremely close to 100% for all distances. This happens because our static WMN is composed of only 3 nodes and, as a result, it is not prone to occur unfairness. If we increased the number of nodes and the directions of communication of each node, we would probably start to verify unfairness in our network.

The RSSI and link quality charts are also presented just for reference.

Figure 3.29 - RSSI results chart - 2nd scenarioFigure 3.30 - Link quality results chart - 2nd scenario

Chapter 4

Conclusion

This chapter presents an overview of the developed work during this dissertation in the *review of the developed work* section, and the main conclusions withdrawn from the results obtained and discussion of these in the *results and relevant contributions* section.

4.1 Review of developed work

This report describes all the work progress developed during this dissertation. Considering the objectives proposed two solutions were devised to construct the prototype to integrate in the testbed. Both solutions were evaluated and one was chosen depending on the constraints that each solution implied. After one of the solutions being chosen, we were able to start the construction of our prototype, dealing with all the difficulties that came up along the process. By solving these difficulties and having the prototype ready, we could start the test phase. Firstly, a set of tests were carried out to conclude which radiation patterns were obtained for each combination of the 4 control pins of the switched beam antenna. Finally, the last tests executed were the performance tests, in which two scenarios, one with two computers and the other with three computers, were tested and the performance in terms of RSSI, link quality, throughput and average delay of three different node configurations were compared. These configurations were defined as the objectives of this dissertation demanded: the first configuration integrated standard IEEE 802.11 2 dBi omni-directional antennas, whereas the second and third configuration integrated our switched beam antenna in different modes, which were, respectively, omni-directional mode and directional mode.

4.2 Results and relevant contributions

The main results and relevant contributions of this dissertation were the following:

4.2.1. Development of prototype integrating a switched beam antenna

By developing a prototype which integrated a switched beam antenna, it was possible to use that prototype on several nodes and establish a static WMN. This allowed us to carry out radiation pattern evaluation tests and performance characterization tests to fulfill the objectives of this dissertation.

4.2.2. Identification of radiation patterns of switched beam antenna

By developing a prototype which integrated a switched beam antenna, it was possible to execute a series of test in the anechoic chamber at FEUP. These tests were very important since they allowed the establishment of a direct relation between the possible combinations of the 6-pin connector, of the switched beam antenna, with the different radiation patterns the antenna forms. No information was provided regarding this issue, neither in the datasheet of the switched beam antenna [18], nor in the product specification datasheet which is printed in annex.

4.2.3. Improvement in performance of network

It has been shown in the performance characterization section of the previous chapter that, with the integration of our prototype of a switched beam antenna, we can achieve considerable gains in throughput when comparing to the same network configuration using IEEE standard 802.11 2dBi omni-directional antennas. It has also been proved that lower average delays are verified when using our prototype.

Annexes

Annex A - Table of switched beam antenna radiation pattern characterization

Table A.1 – Full table with values of S21 parameter in dBm for all possible combinations in steps of 10°

$f=2,45\text{ GHz}$	Beam Combinations															Without casing (1st)	
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th	13th	14th	15th		
0°	-46,44	-43,87	-43,99	-50,13	-50,33	-41,60	-47,83	-56,35	-47,04	-46,42	-47,73	-43,53	-61,00	-44,32	-62,11	-48,95	
10°	-46,69	-44,18	-45,03	-50,75	-50,41	-42,40	-49,92	-58,81	-46,50	-46,92	-47,64	-45,25	-59,54	-43,84	-57,36	-49,12	
20°	-46,88	-44,29	-46,70	-50,80	-49,64	-43,33	-52,52	-62,15	-46,05	-46,97	-47,70	-47,60	-59,17	-44,10	-54,17	-48,40	
30°	-47,28	-45,07	-47,51	-51,06	-48,18	-44,62	-55,30	-61,05	-45,12	-47,65	-47,07	-49,87	-58,32	-43,63	-53,54	-48,70	
40°	-46,83	-44,62	-46,99	-49,89	-46,27	-44,63	-56,11	-55,21	-43,77	-47,66	-45,85	-53,20	-58,04	-43,04	-50,40	-46,95	
50°	-48,75	-46,50	-48,86	-52,39	-46,84	-47,05	-59,73	-54,49	-44,14	-49,25	-46,62	-54,99	-58,90	-43,56	-49,48	-46,24	
60°	-49,28	-47,70	-50,16	-55,43	-47,10	-48,72	-61,10	-53,11	-44,48	-51,92	-47,16	-62,00	-61,60	-44,14	-48,74	-46,75	
70°	-49,20	-48,23	-51,33	-54,68	-47,13	-49,96	-64,40	-52,24	-45,00	-52,43	-48,41	-67,78	-66,05	-45,60	-47,78	-47,01	
80°	-49,57	-48,73	-52,50	-53,80	-47,44	-51,22	-63,30	-51,88	-45,36	-51,12	-50,06	-71,10	-68,70	-46,96	-45,52	-46,35	
90°	-48,73	-48,06	-53,08	-52,94	-46,89	-51,85	-64,80	-49,96	-44,24	-50,76	-50,27	-66,73	-77,70	-47,67	-45,08	-47,01	
100°	-47,91	-47,29	-51,60	-50,39	-45,72	-51,37	-86,00	-47,55	-44,70	-48,62	-49,17	-60,67	-64,91	-47,93	-45,01	-48,00	
110°	-48,02	-48,58	-50,84	-50,40	-45,55	-52,19	-69,20	-47,19	-45,32	-48,18	-48,37	-58,69	-57,70	-48,64	-45,04	-47,45	
120°	-48,94	-50,87	-50,75	-50,38	-45,77	-54,18	-66,90	-47,13	-46,59	-47,87	-47,91	-56,30	-54,73	-49,64	-44,28	-47,73	
130°	-50,20	-53,57	-51,34	-49,35	-46,30	-55,89	-62,50	-46,10	-48,13	-47,07	-48,44	-56,24	-53,55	-51,25	-44,18	-48,42	
140°	-50,70	-55,77	-52,93	-48,66	-47,20	-57,11	-58,40	-45,11	-50,65	-47,18	-49,70	-57,85	-51,15	-54,07	-44,56	-48,05	
150°	-50,45	-55,63	-54,29	-47,60	-47,51	-58,55	-54,58	-44,33	-52,25	-47,77	-51,19	-61,80	-49,48	-56,63	-44,70	-48,60	
160°	-50,00	-54,57	-55,07	-46,28	-47,35	-59,77	-51,50	-43,45	-52,07	-48,06	-52,41	-72,40	-47,64	-60,14	-44,72	-49,42	
170°	-50,13	-55,10	-55,98	-45,65	-47,90	-56,15	-50,08	-42,91	-53,93	-48,82	-52,61	-63,02	-45,70	-59,96	-45,18	-48,93	
180°	-50,22	-55,60	-57,76	-45,24	-48,67	-53,59	-49,08	-42,75	-57,43	-49,32	-53,00	-56,44	-44,52	-56,56	-46,18	-48,90	
190°	-50,62	-58,11	-57,72	-44,93	-49,33	-54,76	-48,41	-42,80	-60,20	-48,86	-51,96	-56,63	-44,05	-54,95	-47,24	-49,40	
200°	-51,06	-58,34	-55,79	-45,19	-51,18	-57,40	-47,73	-43,85	-65,80	-48,10	-51,00	-54,50	-44,06	-54,25	-48,56	-48,65	
210°	-51,44	-55,25	-54,54	-45,64	-52,93	-62,10	-47,17	-45,58	-66,50	-47,59	-50,87	-51,70	-44,22	-55,37	-50,62	-47,95	
220°	-51,30	-53,30	-51,90	-45,57	-52,20	-61,15	-46,21	-46,33	-64,75	-47,64	-49,50	-51,00	-44,08	-57,75	-52,81	-48,59	
230°	-51,06	-53,45	-51,10	-45,88	-53,00	-58,60	-45,10	-47,55	-64,62	-48,09	-48,98	-50,15	-44,02	-58,75	-55,68	-48,62	
240°	-50,80	-53,38	-51,00	-46,30	-54,84	-55,95	-45,02	-49,00	-59,68	-49,10	-50,15	-49,69	-44,50	-59,45	-57,83	-48,15	
250°	-49,66	-53,15	-50,00	-45,90	-54,44	-53,40	-43,94	-49,20	-60,52	-49,13	-50,50	-47,96	-44,70	-63,93	-61,41	-48,00	
260°	-49,34	-53,95	-48,57	-45,82	-56,12	-51,76	-43,25	-50,38	-61,12	-48,75	-51,11	-46,15	-45,33	-65,13	-76,10	-48,30	
270°	-50,09	-53,34	-47,81	-45,98	-57,53	-50,16	-42,80	-51,91	-61,90	-48,03	-52,82	-44,74	-46,55	-63,53	-64,88	-47,83	
280°	-50,14	-54,38	-47,53	-46,93	-57,00	-50,88	-43,45	-53,76	-61,10	-48,45	-53,00	-44,44	-48,13	-60,64	-61,13	-47,95	
290°	-50,63	-55,59	-47,55	-48,05	-55,71	-51,38	-44,33	-55,56	-61,06	-49,08	-51,43	-44,97	-49,23	-58,23	-60,08	-48,75	
300°	-50,64	-54,20	-47,12	-48,53	-55,30	-49,29	-44,53	-59,67	-63,01	-48,45	-51,29	-44,52	-50,65	-56,98	-57,70	-48,17	
310°	-50,80	-52,80	-46,59	-50,18	-53,65	-48,22	-45,30	-61,09	-58,97	-48,87	-49,78	-44,50	-52,00	-54,45	-58,38	-47,24	
320°	-49,06	-49,58	-45,16	-49,25	-51,08	-45,70	-44,83	-58,53	-54,00	-48,00	-47,84	-43,95	-52,95	-50,45	-63,11	-48,14	
330°	-48,39	-47,16	-44,79	-50,34	-50,62	-43,65	-45,40	-61,41	-51,87	-48,49	-47,63	-44,08	-57,00	-48,31	-59,52	-47,90	
340°	-47,56	-45,40	-43,84	-49,38	-50,13	-42,44	-45,54	-59,65	-50,30	-46,98	-47,54	-42,92	-60,47	-46,73	-61,13	-48,55	
350°	-46,87	-44,36	-44,00	-50,41	-51,30	-41,96	-46,62	-55,37	-49,08	-46,85	-48,18	-43,10	-59,53	-45,78	-64,01	-48,00	

Annex B - Configuration scripts, iwconfig and ifconfig outputs of performance measurement and comparison tests

First scenario - SOA configuration

Computer 2

Configuration script:

```
madwifi-unload;           //Remove driver from Linux kernel
make all install;         //Compile and install driver (SOA version)
modprobe ath_pci;         //Insert driver into Linux kernel
ifconfig ath0 down;       //Deactivate VAP ath0
ifconfig wifi0 down;      //Deactivate wireless interface card
ifconfig ath0 192.168.1.2; //Attribute IP
iwconfig ath0 channel 9;  //Set channel(9) and frequency (2,452GHz)
iwconfig ath0 essid SOA;  //Set network ESSID
iwconfig ath0 txpower 14dBm; //Set transmit power at 14dBm
ifconfig wifi0 up;        //Activate wireless interface card
ifconfig ath0 up;         //Activate VAP ath0
```

iwconfig output:

```
ath0      IEEE 802.11g  ESSID:"SOA"  Nickname:""
Mode:Ad-Hoc  Frequency:2.452 GHz  Cell: 02:22:57:EA:27:70
Bit Rate:0 kb/s  Tx-Power=14 dBm  Sensitivity=1/1
Retry:off  RTS thr:off  Fragment thr:off
Encryption key:off
Power Management:off
```

Figure B.1 - Computer 2 iwconfig output - first scenario - SOA configuration

ifconfig output:

```
ath0      Link encap:Ethernet  HWaddr 00:22:57:ea:27:70
inet addr:192.168.1.2  Bcast:192.168.1.255  Mask:255.255.255.0
inet6 addr: fe80::222:57ff:feea:2770/64  Scope:Link
UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
```

Figure B.2 - Computer 2 ifconfig output - first scenario - SOA configuration

Computer 3:**Configuration script:**

```

madwifi-unload;           //Remove driver from Linux kernel
make all install;         //Compile and install driver (SOA version)
modprobe ath_pci;         //Insert driver into Linux kernel
ifconfig ath0 down;       //Deactivate VAP ath0
ifconfig wifi0 down;      //Deactivate wireless interface card
ifconfig ath0 192.168.1.3; //Attribute IP
iwconfig ath0 channel 9;   //Set channel(9) and frequency (2,452GHz)
iwconfig ath0 essid SOA;   //Set network ESSID
iwconfig ath0 txpower 14dBm; //Set transmit power at 14dBm
ifconfig wifi0 up;        //Activate wireless interface card
ifconfig ath0 up;         //Activate VAP ath0

```

iwconfig output:

```

ath0      IEEE 802.11g  ESSID:"SOA"  Nickname:""
          Mode:Ad-Hoc  Frequency:2.452 GHz  Cell: 02:22:57:EA:27:70
          Bit Rate:0 kb/s  Tx-Power=14 dBm  Sensitivity=1/1
          Retry:off  RTS thr:off  Fragment thr:off
          Encryption key:off
          Power Management:off

```

Figure B.3 - Computer 3 iwconfig output - first scenario - SOA configuration**Ifconfig output:**

```

ath0      Link encap:Ethernet  HWaddr 00:19:e0:0f:da:4a
          inet addr:192.168.1.3  Bcast:192.168.1.255  Mask:255.255.255.0
          inet6 addr: fe80::219:e0ff:fe0f:da4a/64  Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1

```

Figure B.4 - Computer 3 ifconfig output - first scenario - SOA configuration

First scenario - OA configuration

Computer 2

Configuration script:

```
madwifi-unload;           //Remove driver from Linux kernel
make all install;         //Compile and install driver (OA version)
modprobe ath_pci;         //Insert driver into Linux kernel
ifconfig ath0 down;       //Deactivate VAP ath0
ifconfig wifi0 down;      //Deactivate wireless interface card
ifconfig ath0 192.168.1.2; //Attribute IP
iwconfig ath0 channel 9;   //Set channel(9) and frequency (2,452GHz)
iwconfig ath0 essid OA;    //Set network ESSID
iwconfig ath0 txpower 14dBm; //Set transmit power at 14dBm
ifconfig wifi0 up;        //Activate wireless interface card
ifconfig ath0 up;         //Activate VAP ath0
```

iwconfig output:

```
ath0      IEEE 802.11g  ESSID:"OA"  Nickname:""
Mode:Ad-Hoc  Frequency:2.452 GHz  Cell: 02:22:57:EA:27:70
Bit Rate:0 kb/s  Tx-Power=14 dBm  Sensitivity=1/1
Retry:off  RTS thr:off  Fragment thr:off
Encryption key:off
Power Management:off
```

Figure B.5 - Computer 2 iwconfig output - first scenario - OA configuration

Ifconfig output:

```
ath0      Link encap:Ethernet  HWaddr 00:22:57:ea:27:70
inet addr:192.168.1.2  Bcast:192.168.1.255  Mask:255.255.255.0
inet6 addr: fe80::222:57ff:feea:2770/64  Scope:Link
UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
```

Figure B.6 - Computer 2 ifconfig output - first scenario - OA configuration

Computer 3:**Configuration script:**

```

madwifi-unload;           //Remove driver from Linux kernel
make all install;         //Compile and install driver (OA version)
modprobe ath_pci;         //Insert driver into Linux kernel
ifconfig ath0 down;       //Deactivate VAP ath0
ifconfig wifi0 down;      //Deactivate wireless interface card
ifconfig ath0 192.168.1.3; //Attribute IP
iwconfig ath0 channel 9;   //Set channel(9) and frequency (2,452GHz)
iwconfig ath0 essid OA;    //Set network ESSID
iwconfig ath0 txpower 14dBm; //Set transmit power at 14dBm
ifconfig wifi0 up;        //Activate wireless interface card
ifconfig ath0 up;         //Activate VAP ath0

```

iwconfig output:

```

ath0      IEEE 802.11g  ESSID:"OA"  Nickname:""
          Mode:Ad-Hoc  Frequency:2.452 GHz  Cell: 02:22:57:EA:27:70
          Bit Rate:0 kb/s  Tx-Power=14 dBm  Sensitivity=1/1
          Retry:off  RTS thr:off  Fragment thr:off
          Encryption key:off
          Power Management:off

```

Figure B.7 - Computer 3 iwconfig output - first scenario - OA configuration**Ifconfig output:**

```

ath0      Link encap:Ethernet  HWaddr 00:19:e0:0f:da:4a
          inet addr:192.168.1.3  Bcast:192.168.1.255  Mask:255.255.255.0
          inet6 addr: fe80::219:e0ff:fe0f:da4a/64  Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1

```

Figure B.8 - Computer 3 ifconfig output - first scenario - OA configuration

First scenario - DA configuration

Computer 2

Configuration script:

```
madwifi-unload;           //Remove driver from Linux kernel
make all install;         //Compile and install driver (DA version)
modprobe ath_pci;         //Insert driver into Linux kernel
ifconfig ath0 down;       //Deactivate VAP ath0
ifconfig wifi0 down;      //Deactivate wireless interface card
ifconfig ath0 192.168.1.2; //Attribute IP
iwconfig ath0 channel 9;   //Set channel(9) and frequency (2,452GHz)
iwconfig ath0 essid DA;    //Set network ESSID
iwconfig ath0 txpower 14dBm; //Set transmit power at 14dBm
ifconfig wifi0 up;        //Activate wireless interface card
ifconfig ath0 up;         //Activate VAP ath0
```

iwconfig output:

```
ath0      IEEE 802.11g  ESSID:"DA"  Nickname:""
Mode:Ad-Hoc  Frequency:2.452 GHz  Cell: 02:22:57:EA:27:70
Bit Rate:0 kb/s  Tx-Power=14 dBm  Sensitivity=1/1
Retry:off  RTS thr:off  Fragment thr:off
Encryption key:off
Power Management:off
```

Figure B.9 - Computer 2 iwconfig output - first scenario - DA configuration

ifconfig output:

```
ath0      Link encap:Ethernet  HWaddr 00:22:57:ea:27:70
inet addr:192.168.1.2  Bcast:192.168.1.255  Mask:255.255.255.0
inet6 addr: fe80::222:57ff:feea:2770/64  Scope:Link
UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
```

Figure B.10 - Computer 2 ifconfig output - first scenario - DA configuration

Computer 3:

Configuration script:

```

madwifi-unload;           //Remove driver from Linux kernel
make all install;         //Compile and install driver (DA version)
modprobe ath_pci;         //Insert driver into Linux kernel
ifconfig ath0 down;       //Deactivate VAP ath0
ifconfig wifi0 down;      //Deactivate wireless interface card
ifconfig ath0 192.168.1.3; //Attribute IP
iwconfig ath0 channel 9;   //Set channel(9) and frequency (2,452GHz)
iwconfig ath0 essid DA;    //Set network ESSID
iwconfig ath0 txpower 14dBm; //Set transmit power at 14dBm
ifconfig wifi0 up;        //Activate wireless interface card
ifconfig ath0 up;         //Activate VAP ath0

```

iwconfig output:

```

ath0      IEEE 802.11g  ESSID:"DA"  Nickname:""
          Mode:Ad-Hoc  Frequency:2.452 GHz  Cell: 02:22:57:EA:27:70
          Bit Rate:0 kb/s  Tx-Power=14 dBm  Sensitivity=1/1
          Retry:off  RTS thr:off  Fragment thr:off
          Encryption key:off
          Power Management:off

```

Figure B.11 - Computer 3 iwconfig output - first scenario - DA configuration

ifconfig output:

```

ath0      Link encap:Ethernet  HWaddr 00:19:e0:0f:da:4a
          inet addr:192.168.1.3  Bcast:192.168.1.255  Mask:255.255.255.0
          inet6 addr: fe80::219:e0ff:fe0f:da4a/64  Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1

```

Figure B.12 - Computer 3 ifconfig output - first scenario - DA configuration

Second scenario - SOA configuration

Computer 2

Configuration script:

```
madwifi-unload;           //Remove driver from Linux kernel
make all install;         //Compile and install driver (SOA version)
modprobe ath_pci;         //Insert driver into Linux kernel
ifconfig ath0 down;       //Deactivate VAP ath0
ifconfig wifi0 down;      //Deactivate wireless interface card
ifconfig ath0 192.168.1.2; //Attribute IP
iwconfig ath0 channel 9;   //Set channel(9) and frequency (2,452GHz)
iwconfig ath0 essid SOA;   //Set network ESSID
iwconfig ath0 txpower 14dBm; //Set transmit power at 14dBm
ifconfig wifi0 up;        //Activate wireless interface card
ifconfig ath0 up;         //Activate VAP ath0
```

iwconfig output:

```
ath0      IEEE 802.11g  ESSID:"SOA"  Nickname:""
Mode:Ad-Hoc  Frequency:2.452 GHz  Cell: 02:22:57:EA:27:70
Bit Rate:0 kb/s  Tx-Power=14 dBm  Sensitivity=1/1
Retry:off  RTS thr:off  Fragment thr:off
Encryption key:off
Power Management:off
```

Figure B.13 - Computer 2 iwconfig output - second scenario - SOA configuration

ifconfig output:

```
ath0      Link encap:Ethernet  HWaddr 00:22:57:ea:27:70
inet addr:192.168.1.2  Bcast:192.168.1.255  Mask:255.255.255.0
inet6 addr: fe80::222:57ff:feea:2770/64  Scope:Link
UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
```

Figure B.14 - Computer 2 ifconfig output - second scenario - SOA configuration

Computer 3:

Configuration script:

```

madwifi-unload;           //Remove driver from Linux kernel
make all install;         //Compile and install driver (SOA version)
modprobe ath_pci;         //Insert driver into Linux kernel
ifconfig ath0 down;       //Deactivate VAP ath0
ifconfig wifi0 down;      //Deactivate wireless interface card
ifconfig ath0 192.168.1.3; //Attribute IP
iwconfig ath0 channel 9;  //Set channel(9) and frequency (2,452GHz)
iwconfig ath0 essid SOA;  //Set network ESSID
iwconfig ath0 txpower 14dBm; //Set transmit power at 14dBm
ifconfig wifi0 up;        //Activate wireless interface card
ifconfig ath0 up;         //Activate VAP ath0

```

iwconfig output:

```

ath0      IEEE 802.11g  ESSID:"SOA"  Nickname:""
          Mode:Ad-Hoc  Frequency:2.452 GHz  Cell: 02:22:57:EA:27:70
          Bit Rate:0 kb/s  Tx-Power=14 dBm  Sensitivity=1/1
          Retry:off  RTS thr:off  Fragment thr:off
          Encryption key:off
          Power Management:off

```

Figure B.15 - Computer 3 iwconfig output - second scenario - SOA configuration

Ifconfig output:

```

ath0      Link encap:Ethernet  HWaddr 00:19:e0:0f:da:4a
          inet addr:192.168.1.3  Bcast:192.168.1.255  Mask:255.255.255.0
          inet6 addr: fe80::219:e0ff:fe0f:da4a/64  Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1

```

Figure B.16 - Computer 3 ifconfig output - second scenario - SOA configuration

Computer 4:

Configuration script:

```
madwifi-unload;           //Remove driver from Linux kernel
make all install;         //Compile and install driver (SOA version)
modprobe ath_pci;         //Insert driver into Linux kernel
ifconfig ath0 down;       //Deactivate VAP ath0
ifconfig wifi0 down;      //Deactivate wireless interface card
ifconfig ath0 192.168.1.4; //Attribute IP
iwconfig ath0 channel 9;  //Set channel(9) and frequency (2,452GHz)
iwconfig ath0 essid SOA;  //Set network ESSID
iwconfig ath0 txpower 14dBm; //Set transmit power at 14dBm
ifconfig wifi0 up;        //Activate wireless interface card
ifconfig ath0 up;         //Activate VAP ath0
```

iwconfig output:

```
ath0      IEEE 802.11g  ESSID:"SOA"  Nickname:""
Mode:Ad-Hoc  Frequency:2.452 GHz  Cell: 02:22:57:EA:27:70
Bit Rate:0 kb/s  Tx-Power=14 dBm  Sensitivity=1/1
Retry:off  RTS thr:off  Fragment thr:off
Encryption key:off
Power Management:off
```

Figure B.17 - Computer 4 iwconfig output - second scenario - SOA configuration

Ifconfig output:

```
ath0      Link encap:Ethernet  HWaddr 00:19:e0:0f:da:9b
inet addr:192.168.1.4  Bcast:192.168.1.255  Mask:255.255.255.0
inet6 addr: fe80::219:e0ff:fe0f:da4a/64  Scope:Link
UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
```

Figure B.18 - Computer 4 ifconfig output - second scenario - SOA configuration

Second scenario - OA configuration

Computer 2

Configuration script:

```
madwifi-unload;           //Remove driver from Linux kernel
make all install;         //Compile and install driver (OA version)
modprobe ath_pci;         //Insert driver into Linux kernel
ifconfig ath0 down;       //Deactivate VAP ath0
ifconfig wifi0 down;       //Deactivate wireless interface card
ifconfig ath0 192.168.1.2; //Attribute IP
iwconfig ath0 channel 9;   //Set channel(9) and frequency (2,452GHz)
iwconfig ath0 essid OA;    //Set network ESSID
iwconfig ath0 txpower 14dBm; //Set transmit power at 14dBm
ifconfig wifi0 up;        //Activate wireless interface card
ifconfig ath0 up;         //Activate VAP ath0
```

iwconfig output:

```
ath0      IEEE 802.11g  ESSID:"OA"  Nickname:""
          Mode:Ad-Hoc  Frequency:2.452 GHz  Cell: 02:22:57:EA:27:70
          Bit Rate:0 kb/s  Tx-Power=14 dBm  Sensitivity=1/1
          Retry:off  RTS thr:off  Fragment thr:off
          Encryption key:off
          Power Management:off
```

Figure B.19 - Computer 2 iwconfig output - second scenario - OA configuration

Ifconfig output:

```
ath0      Link encap:Ethernet  HWaddr 00:22:57:ea:27:70
          inet addr:192.168.1.2  Bcast:192.168.1.255  Mask:255.255.255.0
          inet6 addr: fe80::222:57ff:feea:2770/64  Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
```

Figure B.20 - Computer 2 ifconfig output - second scenario - OA configuration

Computer 3:

Configuration script:

```
madwifi-unload;           //Remove driver from Linux kernel
make all install;         //Compile and install driver (OA version)
modprobe ath_pci;         //Insert driver into Linux kernel
ifconfig ath0 down;       //Deactivate VAP ath0
ifconfig wifi0 down;      //Deactivate wireless interface card
ifconfig ath0 192.168.1.3; //Attribute IP
iwconfig ath0 channel 9;  //Set channel(9) and frequency (2,452GHz)
iwconfig ath0 essid OA;   //Set network ESSID
iwconfig ath0 txpower 14dBm; //Set transmit power at 14dBm
ifconfig wifi0 up;        //Activate wireless interface card
ifconfig ath0 up;         //Activate VAP ath0
```

iwconfig output:

```
ath0      IEEE 802.11g  ESSID:"OA"  Nickname:""
Mode:Ad-Hoc  Frequency:2.452 GHz  Cell: 02:22:57:EA:27:70
Bit Rate:0 kb/s  Tx-Power=14 dBm  Sensitivity=1/1
Retry:off  RTS thr:off  Fragment thr:off
Encryption key:off
Power Management:off
```

Figure B.21 - Computer 3 iwconfig output - second scenario - OA configuration

Ifconfig output:

```
ath0      Link encap:Ethernet  HWaddr 00:19:e0:0f:da:4a
inet addr:192.168.1.3  Bcast:192.168.1.255  Mask:255.255.255.0
inet6 addr: fe80::219:e0ff:fe0f:da4a/64  Scope:Link
UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
```

Figure B.22 - Computer 3 ifconfig output - second scenario - OA configuration

Computer 4:

Configuration script:

```

madwifi-unload;           //Remove driver from Linux kernel
make all install;         //Compile and install driver (OA version)
modprobe ath_pci;         //Insert driver into Linux kernel
ifconfig ath0 down;       //Deactivate VAP ath0
ifconfig wifi0 down;      //Deactivate wireless interface card
ifconfig ath0 192.168.1.4; //Attribute IP
iwconfig ath0 channel 9;   //Set channel(9) and frequency (2,452GHz)
iwconfig ath0 essid OA;    //Set network ESSID
iwconfig ath0 txpower 14dBm; //Set transmit power at 14dBm
ifconfig wifi0 up;        //Activate wireless interface card
ifconfig ath0 up;         //Activate VAP ath0

```

iwconfig output:

```

ath0      IEEE 802.11g  ESSID:"OA"  Nickname:""
          Mode:Ad-Hoc  Frequency:2.452 GHz  Cell: 02:22:57:EA:27:70
          Bit Rate:0 kb/s  Tx-Power=14 dBm  Sensitivity=1/1
          Retry:off  RTS thr:off  Fragment thr:off
          Encryption key:off
          Power Management:off

```

Figure B.23 - Computer 4 iwconfig output - second scenario - OA configuration

Ifconfig output:

```

ath0      Link encap:Ethernet  HWaddr 00:19:e0:0f:da:9b
          inet addr:192.168.1.4  Bcast:192.168.1.255  Mask:255.255.255.0
          inet6 addr: fe80::219:e0ff:fe0f:da4a/64  Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1

```

Figure B.24 - Computer 4 ifconfig output - second scenario - OA configuration

Second scenario - DA configuration

Computer 2

Configuration script:

```
madwifi-unload;           //Remove driver from Linux kernel
make all install;         //Compile and install driver (DA version)
modprobe ath_pci;         //Insert driver into Linux kernel
ifconfig ath0 down;       //Deactivate VAP ath0
ifconfig wifi0 down;      //Deactivate wireless interface card
ifconfig ath0 192.168.1.2; //Attribute IP
iwconfig ath0 channel 9;  //Set channel(9) and frequency (2,452GHz)
iwconfig ath0 essid DA;   //Set network ESSID
iwconfig ath0 txpower 14dBm; //Set transmit power at 14dBm
ifconfig wifi0 up;        //Activate wireless interface card
ifconfig ath0 up;         //Activate VAP ath0
```

iwconfig output:

```
ath0      IEEE 802.11g  ESSID:"DA"  Nickname:""
Mode:Ad-Hoc  Frequency:2.452 GHz  Cell: 02:22:57:EA:27:70
Bit Rate:0 kb/s  Tx-Power=14 dBm  Sensitivity=1/1
Retry:off  RTS thr:off  Fragment thr:off
Encryption key:off
Power Management:off
```

Figure B.25 - Computer 2 iwconfig output - second scenario - DA configuration

ifconfig output:

```
ath0      Link encap:Ethernet  HWaddr 00:22:57:ea:27:70
inet addr:192.168.1.2  Bcast:192.168.1.255  Mask:255.255.255.0
inet6 addr: fe80::222:57ff:feea:2770/64  Scope:Link
UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
```

Figure B.26 - Computer 2 ifconfig output - second scenario - DA configuration

Computer 3:

Configuration script:

```

madwifi-unload;           //Remove driver from Linux kernel
make all install;         //Compile and install driver (DA version)
modprobe ath_pci;         //Insert driver into Linux kernel
ifconfig ath0 down;       //Deactivate VAP ath0
ifconfig wifi0 down;      //Deactivate wireless interface card
ifconfig ath0 192.168.1.3; //Attribute IP
iwconfig ath0 channel 9;  //Set channel(9) and frequency (2,452GHz)
iwconfig ath0 essid DA;   //Set network ESSID
iwconfig ath0 txpower 14dBm; //Set transmit power at 14dBm
ifconfig wifi0 up;        //Activate wireless interface card
ifconfig ath0 up;         //Activate VAP ath0

```

iwconfig output:

```

ath0      IEEE 802.11g  ESSID:"DA"  Nickname:""
          Mode:Ad-Hoc  Frequency:2.452 GHz  Cell: 02:22:57:EA:27:70
          Bit Rate:0 kb/s  Tx-Power=14 dBm  Sensitivity=1/1
          Retry:off  RTS thr:off  Fragment thr:off
          Encryption key:off
          Power Management:off

```

Figure B.27 - Computer 3 iwconfig output - second scenario - DA configuration

ifconfig output:

```

ath0      Link encap:Ethernet  HWaddr 00:19:e0:0f:da:4a
          inet addr:192.168.1.3  Bcast:192.168.1.255  Mask:255.255.255.0
          inet6 addr: fe80::219:e0ff:fe0f:da4a/64  Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1

```

Figure B.28 - Computer 3 ifconfig output - second scenario - DA configuration

Computer 4:

Configuration script:

```
madwifi-unload;           //Remove driver from Linux kernel
make all install;         //Compile and install driver (DA version)
modprobe ath_pci;         //Insert driver into Linux kernel
ifconfig ath0 down;       //Deactivate VAP ath0
ifconfig wifi0 down;      //Deactivate wireless interface card
ifconfig ath0 192.168.1.4; //Attribute IP
iwconfig ath0 channel 9;  //Set channel(9) and frequency (2,452GHz)
iwconfig ath0 essid DA;   //Set network ESSID
iwconfig ath0 txpower 14dBm; //Set transmit power at 14dBm
ifconfig wifi0 up;        //Activate wireless interface card
ifconfig ath0 up;         //Activate VAP ath0
```

iwconfig output:

```
ath0      IEEE 802.11g  ESSID:"DA"  Nickname:""
Mode:Ad-Hoc  Frequency:2.452 GHz  Cell: 02:22:57:EA:27:70
Bit Rate:0 kb/s  Tx-Power=14 dBm  Sensitivity=1/1
Retry:off  RTS thr:off  Fragment thr:off
Encryption key:off
Power Management:off
```

Figure B.29 - Computer 4 iwconfig output - second scenario - DA configuration

Ifconfig output:

```
ath0      Link encap:Ethernet  HWaddr 00:19:e0:0f:da:9b
inet addr:192.168.1.4  Bcast:192.168.1.255  Mask:255.255.255.0
inet6 addr: fe80::219:e0ff:fe0f:da4a/64  Scope:Link
UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
```

Figure B.30 - Computer 4 ifconfig output - second scenario - DA configuration

Annex C - Tables of performance characterization tests and effective gains charts

First scenario:**Table C.1 – Performance measurements - SOA configuration**

	Received Signal Strength Indication (RSSI - dBm)	Link Quality	Throughput (Mbit/s)	Average Delay (ms)
0 m	-26	70	22,14	0,542
5 m	-42	52	15,11	0,679
10 m	-60	35	9,09	0,811
15 m	-70	26	5,81	1,235
20 m	-78	18	4,57	1,469
25 m	-85	11	3,49	1,784
30 m	-88	8	2,48	1,865
35 m	-90	6	1,53	1,974
40 m	-92	4	1,19	2,132
45 m	-93	3	0,85	2,354
50 m	-93	2	0,62	2,489

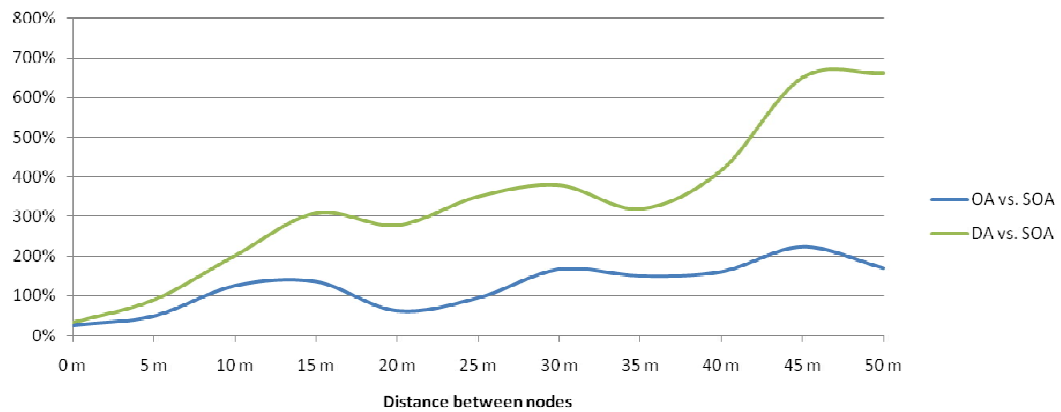
Table C.2 – Performance measurements - OA configuration

	Received Signal Strength Indication (RSSI - dBm)	Link Quality	Throughput (Mbit/s)	Average Delay (ms)
0 m	-20	76	27,80	0,484
5 m	-31	64	22,47	0,515
10 m	-50	44	20,43	0,709
15 m	-56	40	13,67	0,733
20 m	-59	36	7,38	1,220
25 m	-72	24	6,78	1,324
30 m	-79	17	6,60	1,483
35 m	-83	13	3,82	1,595
40 m	-85	11	3,10	1,689
45 m	-88	8	2,73	1,752
50 m	-90	6	1,66	2,060

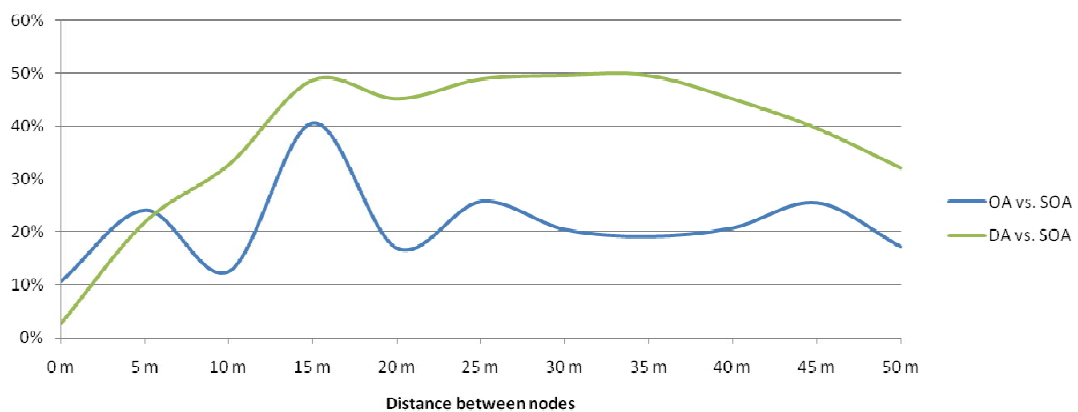
Table C.3 – Performance measurements - DA configuration

	Received Signal Strength Indication (RSSI - dBm)	Link Quality	Throughput (Mbit/s)	Average Delay (ms)
0 m	-6	90	29,27	0,527
5 m	-8	88	28,60	0,530
10 m	-22	74	27,33	0,545
15 m	-37	59	23,73	0,633
20 m	-39	56	17,27	0,805
25 m	-41	53	15,70	0,911
30 m	-45	48	11,87	0,939
35 m	-49	44	6,41	0,995
40 m	-54	41	6,16	1,169
45 m	-59	36	6,35	1,421
50 m	-63	30	4,70	1,689

Effective Gains in Throughput vs. distance between nodes

Figure C.31 - Effective gains in throughput results chart - 1st scenario

Effective Gains in Average Delay vs. distance between nodes

Figure C.32 - Effective gains in average delay results chart - 1st scenario

Second scenario:**Table C.4 – Performance measurements - SOA configuration**

	Received Signal Strength Indication (RSSI - dBm)	Link Quality	Aggregate Throughput (Mbit/s)	Average Delay (ms)
0 m	-23	73	22,81	0,592
5 m	-39	56	16,00	0,690
10 m	-57	39	9,39	0,876
15 m	-68	28	6,59	1,126
20 m	-79	17	4,71	1,610
25 m	-84	12	3,60	1,720

Table C.5 – Performance measurements - OA configuration

	Received Signal Strength Indication (RSSI - dBm)	Link Quality	Aggregate Throughput (Mbit/s)	Average Delay (ms)
0 m	-18	78	27,47	0,650
5 m	-29	66	23,17	0,686
10 m	-48	46	21,02	0,731
15 m	-57	39	15,18	0,870
20 m	-60	35	6,84	1,024
25 m	-65	31	5,32	1,256

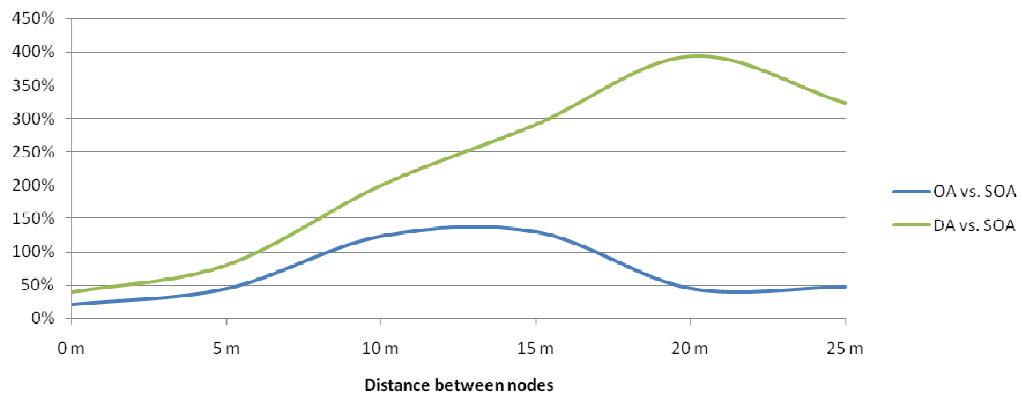
Table C.6 – Performance measurements - DA configuration

	Received Signal Strength Indication (RSSI - dBm)	Link Quality	Aggregate Throughput (Mbit/s)	Average Delay (ms)
0 m	-4	92	31,95	0,508
5 m	-6	90	28,90	0,529
10 m	-16	78	28,17	0,538
15 m	-32	63	25,76	0,630
20 m	-36	60	23,24	0,661
25 m	-40	54	15,26	0,883

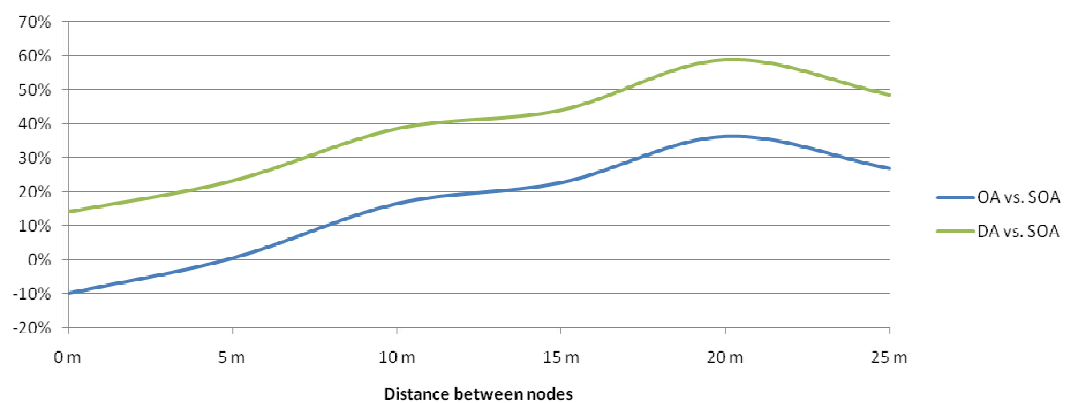
Table C.7 – Performance measurements - Fairness

	SOA	OA	DA
0 m	0,999717655	0,997040314	0,999897597
5 m	0,999996486	0,999776257	0,998935435
10 m	0,999604689	0,99976352	0,999991937
15 m	0,998817149	0,999651895	0,999981771
20 m	0,995686753	0,998869487	0,999952603
25 m	0,999978607	0,999307958	0,999996133

Effective Gains in Throughput vs. distance between nodes

Figure C.33 - Effective gains in throughput results chart - 2nd scenario

Effective Gains in Average Delay vs. distance between nodes

Figure C.34 - Effective gains in average delay results chart - 2nd scenario

Annex D - Airgain MaxBeam75 Product Specification Sheet

Product Specification

Airgain “Copperhead” Antenna Product Specification Model B2475SC000

Document Number: 038-02-00-100-1 Rev B



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Revision history

Revision	Date	Note
038-02-00-100-1 Rev A	25 APR 07	Drafted from 038-02-00-001-1 Rev B Copperhead Specification 23APR07. Update Sec. 5 for 2.6mm tall connector, J1.
038-02-00-100-1 Rev B	09 MAY 07	Add updates from design review

Disclaimers

The information in this document is provided in connection with Airgain Antenna products and is proprietary and confidential. Airgain may make changes to at anytime, without notice. *Please verify with Airgain before finalizing a product design.*

Product Specification**Table of Contents**

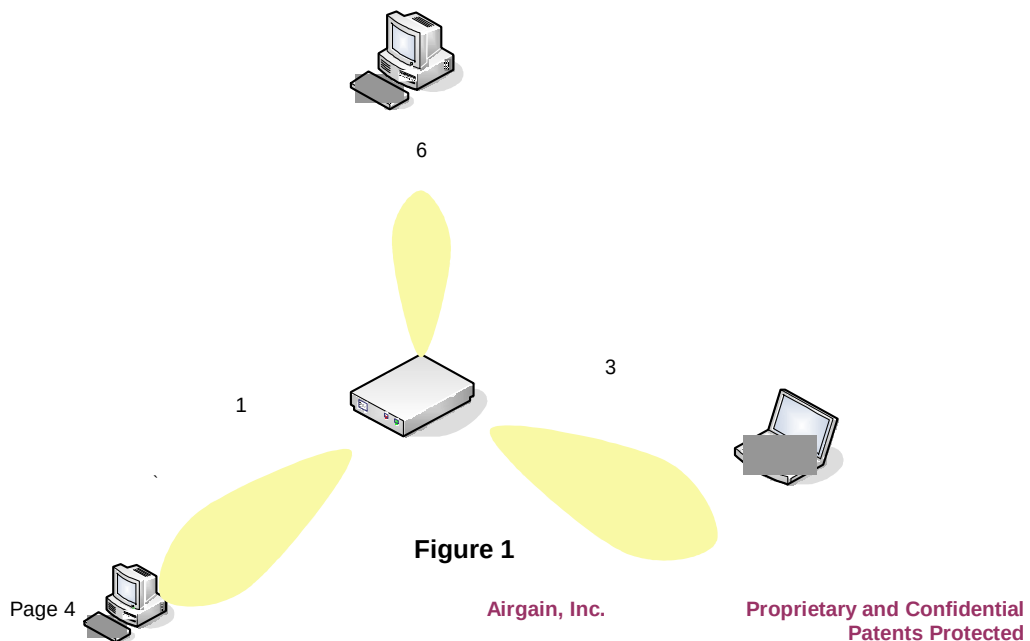
1.....Introduction.....	4
2.....Features.....	5
3.....Product Description	6
4.....Interface	7
5.....Control Connector Specifications	8
6.....RF Specification	9
7.....Firmware	9
8.....General Specification.....	9
9.....Environmental Specification.....	10
10. ..Fire Rating	10
11. ..ROHS	10
12. ..J1, Datasheet	11

1. Introduction

Performance has become the most important issue when evaluating products in the Wireless LAN industry. Data-Throughput and Range are the primary metrics used to gage the performance of a WLAN connection. Many factors impact WLAN performance. They are categorized as, either **Environmental-Influences** or **System-Constraints**. The Environment-Influences include; Interference, Multi-path (scattering), Range and Orientation. The System-Constraints include; System-Design (Transmitting Power, Receiver Sensitivity, Overhead), and **Antenna Gain**.

The Airgain Copperhead Smart Antenna provides excellent solutions to minimize the negative effects of Environment-Influences. In addition, the Copperhead further enhances performance with superior Antenna-Gain specifications. Using leading design and engineering, the Copperhead Antenna provides 15 unique “smart” beams covering 360 degrees. The “smart” beam formation is controlled by Airgain proprietary firmware to maximize Signal-to-Noise Ratio (SNR) by minimizing interference, and multi-path, while boosting signal at the same time. It has been demonstrated that WLAN devices, equipped with Airgain Smart Antennas, have shown significantly higher Data Throughput, compared to other antenna products on the market.

The following picture illustrates an Airgain Copperhead Antenna connecting three clients by switching No.1, No.3 and No.6 beam respectively. The optimized directivity of the antenna beams reject scattering and multipath wave going into the receiver of AP. The high gain of the narrow directional beam formed by the Copperhead Antenna also extends the range.



Product Specification

2. Features

- IEEE 802.11 b/g
- 15 antenna beams covering 360 degrees
- Software controlled beams to achieve highest optimal performance by eliminating interference and multipath
- Higher throughput and better reliability
- Peak antenna gain (4 to 7 dBi) extending the range
- Fast switching network to guarantee lowest overhead
- Independent sub-system can be easily integrated, which shortens the lead-time for product development
- Low cost

3. Product Description

The Copperhead Antenna is a sub-system with controlling firmware as shown in figure 2 and figure 3. The printed-circuit-board of the Copperhead Antenna assembly contains components on the top and bottom surfaces of the board. The Antenna Copper Radiating Elements, Metal Grounding frame, and passive Electronics Components are on the top side of the Copperhead Assembly. The, Control Connector (6 pin), and the RF Cable are mounted to the bottom side of the assembly.

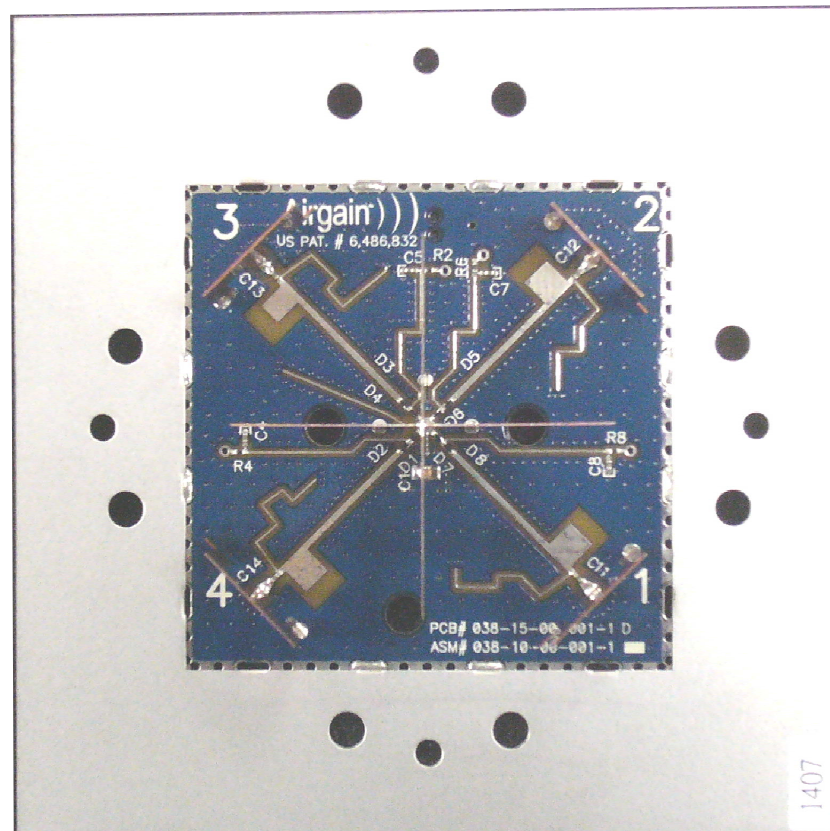


Figure 2
Top Side of Copperhead Antenna

Product Specification

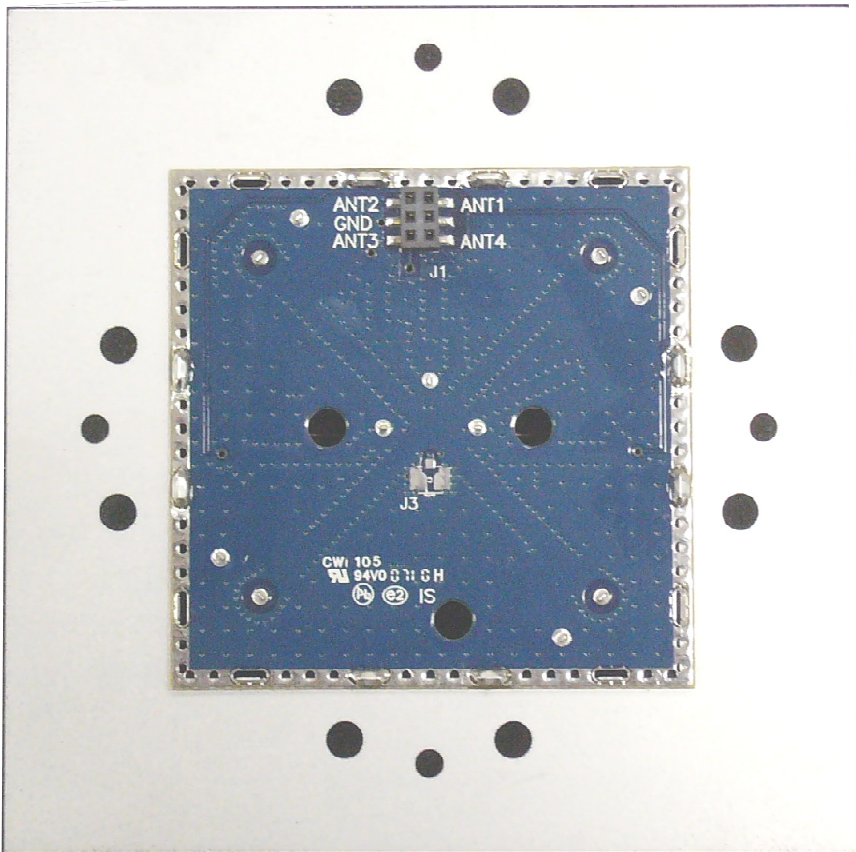


Figure 3
Bottom Side of Copperhead Antenna

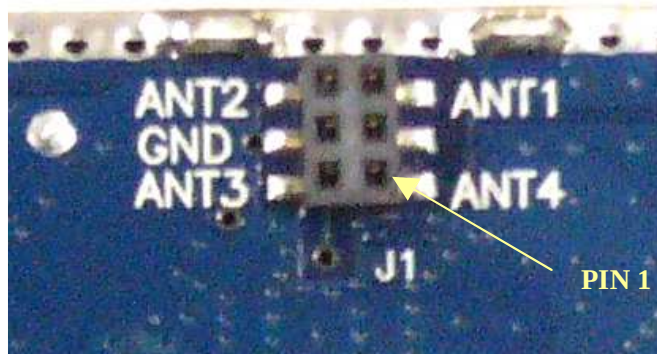
This Control Connector is used to provide connection for signal ground and four Digital Control signals to activate the Copperhead Antenna Elements.

4. Interface

- | | | |
|--------|-------------------|--|
| 4.1.1. | Control Connector | 6-pin connector (female receptacle) |
| 4.1.2. | RF Connector | One set of soldering pads for 50 Ohm, 1.13mm diameter, micro coax cable. |

5. Control Connector Specifications

- 5.1.1. Source Current requirements to signal inputs are 5.6mA at 2.4Vdc to 14.8mA at 5.25Vdc with less than +/- 5% ripple. Sink Current requirements to signal inputs are 0mA.
- 5.1.2. Control signal inputs have 300 Ohm impedance into diode input circuits.
- 5.1.3. J1, the control and ground connector is a 2mm x 2mm, dual row, 6 pin female receptacle.
- 5.1.4. J1 is 2.6mm tall, accommodating board to board mating with a minimum 4.5mm board separation. See the included datasheet for detail.
- 5.1.5. J1, pin 1 is ANT 4 enable; pin 2 is ANT 3 enable; pin 3 is not connected, input pin 4 is Ground; pin 5 is ANT 1 enable; pin 6 is ANT 2 enable.
- 5.1.6. Control signal input logic “1” is 2.4 to 5.25Vdc. Selected antenna is “ON”.
- 5.1.7. Control signal input logic “0” is 0.4 to 0Vdc. Selected antenna is “OFF”.



Shown from bottom side of
Copperhead Antenna

Figure 4

Product Specification

6. RF Specification

6.1.1.	Frequency Range	2.4 to 2.497 GHz
6.1.2.	Antenna Type	Four Monopoles with reflectors
6.1.3.	Antenna Patterns	15 switch-able beams covering 360 Degrees
6.1.4.	Antenna Peak Gain	4 to 7 dBi
6.1.5.	Maximum Transmit Power	26 dBm (400 mW)

7. Firmware

The objective of the firmware is to utilize eight primary beams of the Copperhead Antenna to optimize the signal-to-noise ratio (SNR) by pointing the antenna beam in an optimum direction, thereby minimizing data errors and increasing data throughput and range.

In general, the software “finds” best path for connection by sending packets through the different directions of the antenna to its clients. The clients respond to these packets, and the SNR of each beam is then retrieved. The beam with the best SNR is utilized as the optimal direction to send and receive data.

Since Copperhead Antenna can have up to 15 beams, it may take some amount of time to scan the SNR ratio for each direction. Therefore we actually like to optimize more frequently without causing a significant impact on data traffic, using a shorter optimization procedure.

8. General Specification

8.1.1.	Standards	IEEE 802.11 b/g
8.1.2.	PCB Dimension	55.5 X 55.5 (mm)
8.1.3.	Physical Dimension	90 X 90 X 19.5 (mm)
8.1.4.	Weight	19.1g (0.67 oz)

9. Environmental Specification

9.1.1.	Temperature	Operating temperature: 0 to 60°C Storage temperature: -20 to 70°C
9.1.2.	Humidity	Operating: 0% to 70% Storage: 0% to 95% non-condensing
9.1.3.	Drop Test	Vertical drop of 100 cm to each face of Airgain shipping carton
9.1.4.	Vibration Test	5 to 500 Hz for one hour per axis in Airgain shipping carton
9.1.5.	ESD Test	Airgain will support customer for specification, test, and certification, in customer’s case
9.1.6.	FCC Test	Airgain will support customer for certification of FCC part 15 in customer’s case

10. Fire Rating

10.1.1.	Fire rating	FR4 material rated UL94-V0
---------	-------------	----------------------------

11. ROHS

11.1.1.	Airgain Copperhead Antennas are RoHS compliant.	
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Technical drawing of a 2.0x6.2mm 3P SMT component. The drawing includes three views: a top view showing a rectangular body with six pins (3.6mm pitch, 0.7mm width, 0.6mm spacing), a side view showing a height of 2.0mm and a width of 2.6mm, and a cross-sectional view showing a thickness of 0.3mm and a total width of 6.4mm. Dimensions are in millimeters. The drawing is labeled with 'A', 'B', 'C', and 'D' at the top and '1', '2', '3', '4', '5', '6', '7', '8' along the sides.

Annex E - Public Defence Presentation

Performance Evaluation of Directional Antennas on Static Wireless Mesh Networks

Francisco Ribeiro Fernandes

Supervisor: Prof. Manuel Ricardo
Co-Supervisor: Saravanan Kandasamy

22nd July 2010



Performance Evaluation of Directional Antennas on Static Wireless Mesh Networks

2

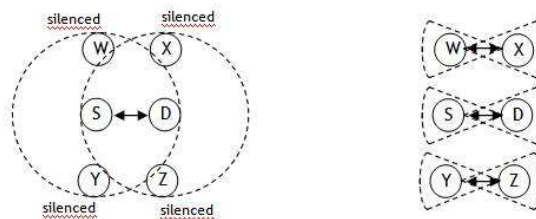
Outline

- Introduction
- Objectives
- Possible models
- Devised prototype
- Switched beam antenna radiation patterns
- Performance characterization
- Conclusion



Introduction

- Static wireless mesh networks
 - Fully distributed networks
 - IEEE 802.11 MAC protocol (assumes omni antennas are used)
- Omni-directional vs. directional antennas



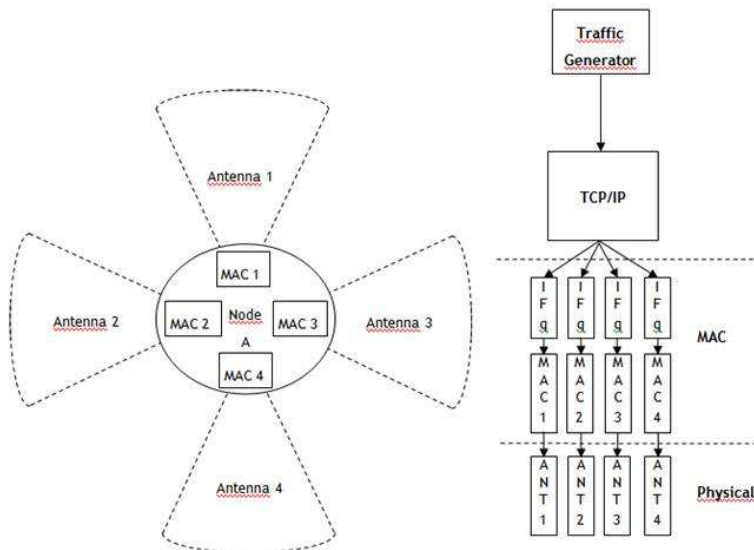
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Objectives

- Construction of a hardware prototype integrating a directional antenna and its control logic
- Evaluation of the impact of the directional antennas in the performance of the network in terms of **throughput, delay, and fairness**
- Comparison of the previous results with the performance results using regular IEEE 802.11 omni-directional antennas

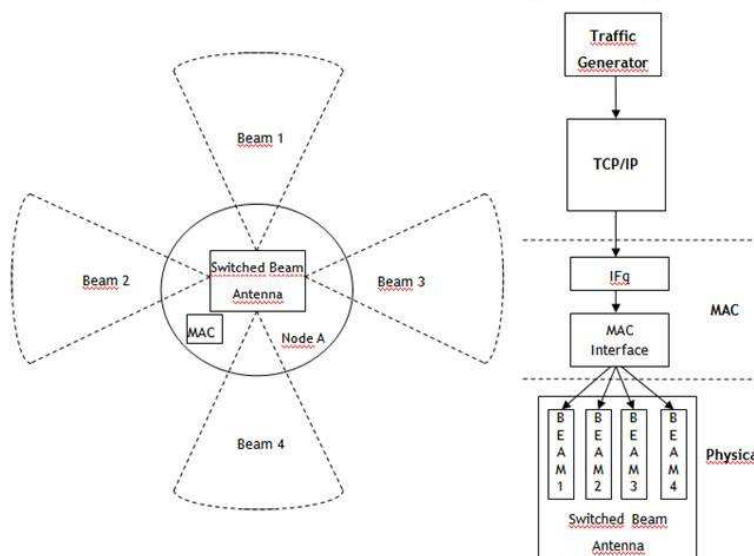
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Possible models (1/2)



- N MAC interfaces
- N single beam antennas (Example N=4)

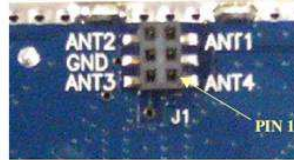
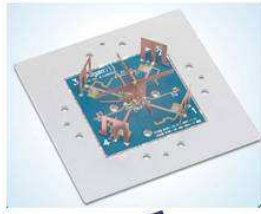
Possible models (2/2)



- 1 MAC interface
- 1 switched beam antenna with N beams (Example N=4)

- Availability of switched beam antenna

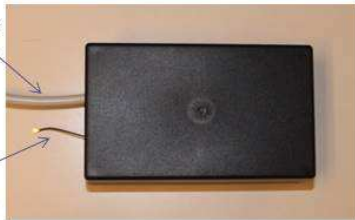
Devised prototype (1/2)



- 4 control pins
- 1 ground pin
- 1 power supply pin

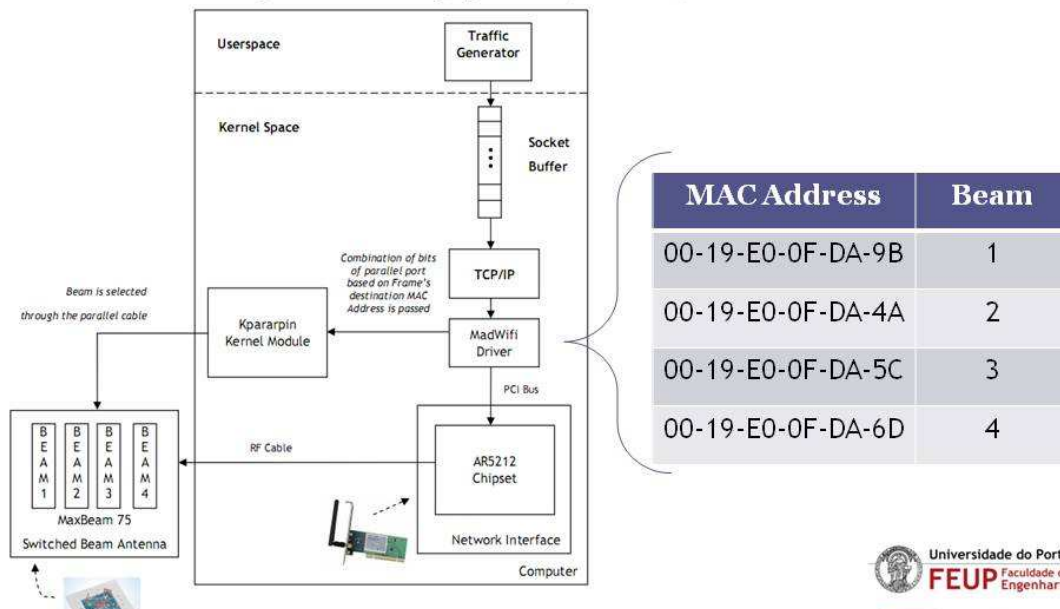
Parallel cable

RF cable

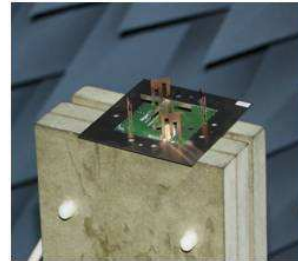
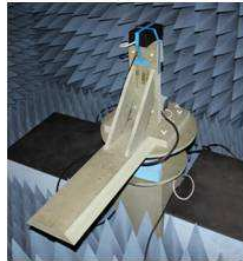


- IBM-PC IEEE 1284 standard parallel port to control the 6-pin connector
- RF components had to be purchased to convert from U.FL RF connector of the antenna to RP-SMA connector of the wireless interface card

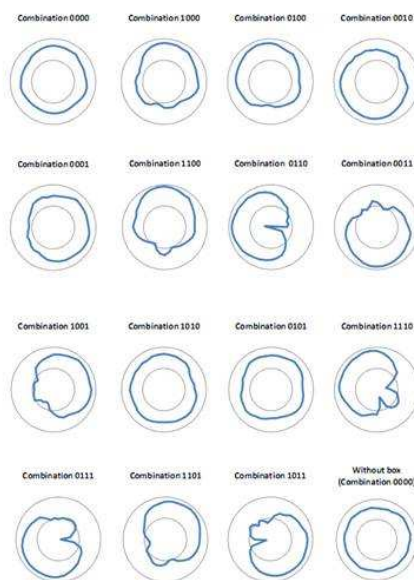
Devised prototype (2/2)



Switched beam antenna radiation patterns (1/2)



Switched beam antenna radiation patterns (2/2)



- Sectors are active when a zero is inputted in the correspondent pin
- Omni mode is set when we input zeros on all control pins
- All sectors are off when we input ones on all control pins
- Losses of the box were estimated in 1,24 dB

Radiation pattern
without box

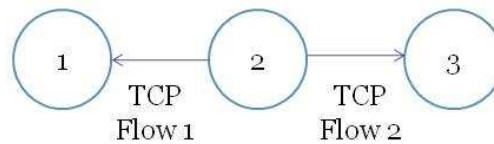
Performance characterization (1/8)



First tested scenario



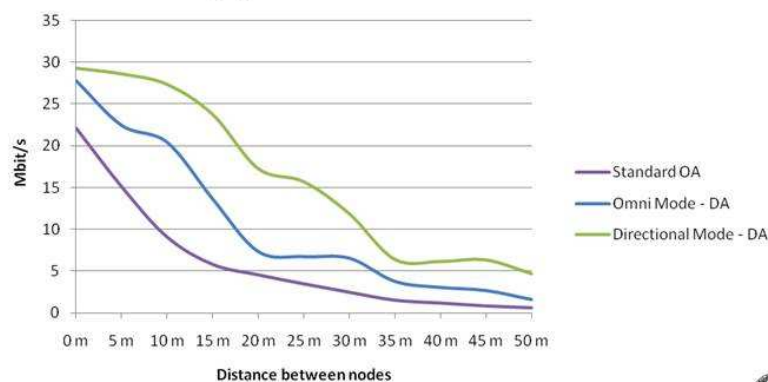
Second tested scenario



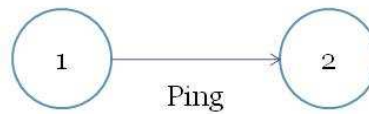
Performance characterization (2/8)



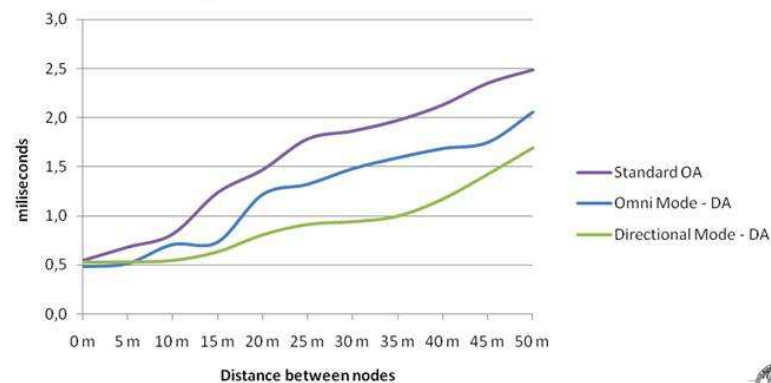
Throughput vs. distance between nodes

Throughput results chart – 1st scenario

Performance characterization (3/8)



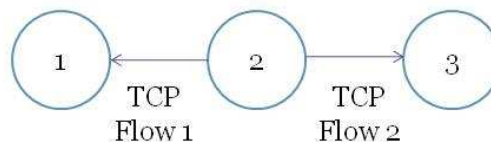
Average RTT vs. distance between nodes



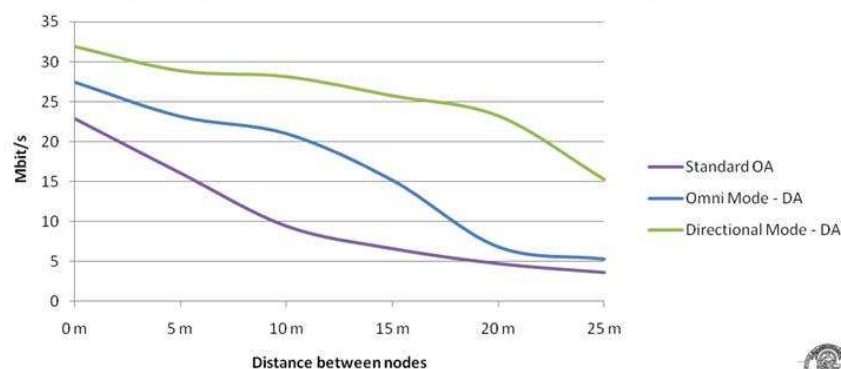
Average RTT results chart – 1st scenario

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Performance characterization (4/8)



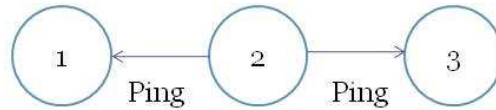
Aggregate Throughput vs. distance between nodes



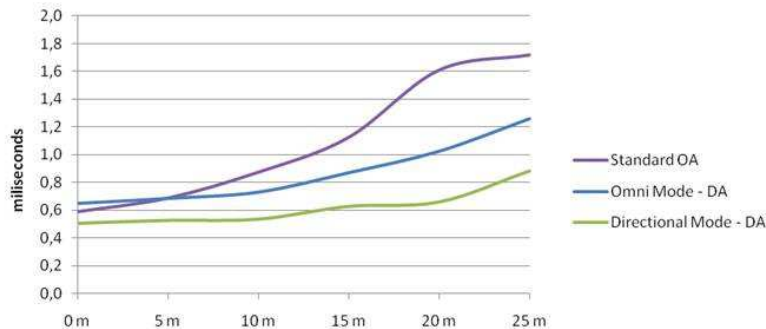
Aggregate throughput results chart – 2nd scenario

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Performance characterization (5/8)



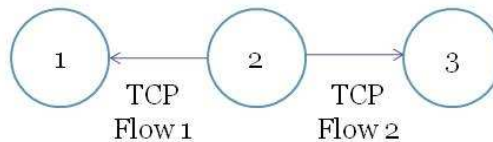
Average RTT vs. distance between nodes



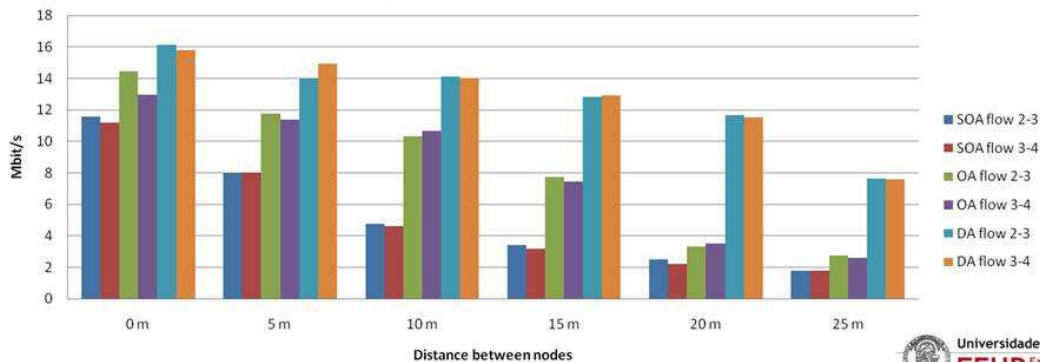
Average RTT results chart – 2nd scenario

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Performance characterization (6/8)



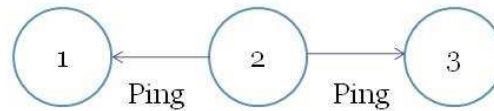
Throughput per flow vs. distance between nodes



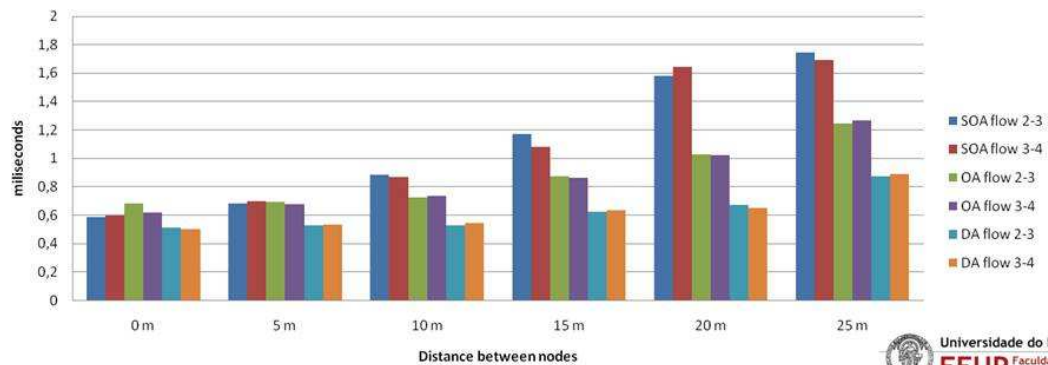
Throughput per flow results chart – 2nd scenario

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Performance characterization (7/8)



Average RTT per flow vs. distance between nodes

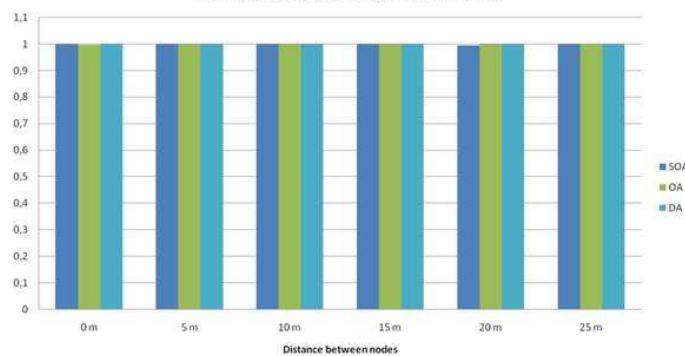


Average RTT per flow results chart – 2nd scenario

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Performance characterization (8/8)

Fairness vs. distance between nodes



Fairness results chart – 2nd scenario

$$f(x_1, x_2, \dots, x_n) = \frac{(\sum_{i=1}^n x_i)^2}{n \sum_{i=1}^n x_i^2}$$

Jain's fairness index formula

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Conclusion

Relevant results and contributions

- Development of prototype integrating a switched beam antenna
 - Enabling implementation of **pattern-per-packet**
- Improvement in the performance of SOA vs. OA and DA
 - First scenario (Maximum effective gains) $EG_i = \frac{S_i - S_{SOA}}{S_{SOA}}, i \in \{OA, DA\}$
 - Throughput: + 100% (OA mode) and + 150% (DA mode)
 - Average delay: - 40% (OA mode) and - 50% (DA mode)
 - Second scenario (Maximum effective gains)
 - Throughput: + 100% (OA mode) and + 150% (DA mode)
 - Average delay: - 35% (OA mode) and - 60% (DA mode)
 - Fairness – All results very close to 100%

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Future Work

- Performance evaluation of larger networks
 - 3x3 topology and others with inclusion of multi-hop
- Modify the system to enable mobility of nodes
- Construct the MAC address table in real time
 - Neighbor discovery and RSSI measurements

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Annex F - Scientific Article

Performance Evaluation of Directional Antennas on Static Wireless Mesh Networks

Francisco Fernandes¹, Manuel Ricardo¹, Saravanan Kandasamy¹

Abstract — Previous research done in wireless mesh networks, typically assumes omni-directional antennas are used, which has the implication of when two nodes are communicating, all nodes in the vicinity must stay silent. With the use of directional antennas, two nodes can communicate without affecting communications of other nodes in the vicinity. One of the primary objectives of this dissertation is to exploit these opportunities that directional antennas can provide, and translate that into improvements of the performance of the mesh network.

Keywords — Directional Antennas, MAC, Testbed, Wireless Mesh Networks

I. INTRODUCTION

Wireless Mesh Networks (WMNs) are fully distributed networks which are constructed based on several nodes with wireless communicating equipment. These networks communicate according to the IEEE 802.11 MAC protocol, which has been designed assuming only omni-directional antennas are used. The majority of WMNs established nowadays make use of omni-directional antennas, which are antennas that communicate in all directions (360 degrees) of the horizontal plane. The implication on this is that nodes placed in the vicinity of communicating nodes are silenced. By including antennas with directional beamforming, known as directional antennas, two pairs of communicating nodes in each other's vicinity may communicate simultaneously, as long as their lines of sight do not intersect (Fig.1).

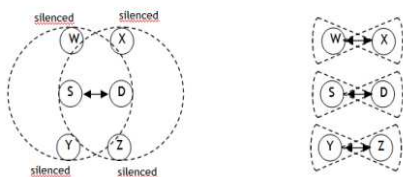


Fig. 1. Using omni-directional antennas versus directional antennas.

The main objectives of the study which this article describes were to develop a prototype integrating a directional antenna, deploy a static WMN testbed integrating the developed

prototype, evaluated the performance parameters of this configuration in terms of throughput, delay and fairness and compare those parameters with performance results of the same network using standard IEEE 802.11 omni-directional antennas.

This article is divided as follows. In Section I, a brief introduction about the topic under discussion on this article is given and also the organization of this article is presented. In Section II, we present the researched and analyzed hardware implementations proposed in the related work. In Section III, we present the work which was developed during the dissertation that this article is related. In Section IV, we conclude the article.

II. RELATED WORK

Subramanian et al. [1] deploys a 6 node testbed in an office environment. Each node is equipped with Atheros IEEE a/b/g mini-PCI wireless card slotted to a laptop computer, which a four-sector Vivaldi antenna is connected. The main conclusion obtained by this study is if a correct sector combination is achieved, an improvement of the relative aggregate throughput up to 200% in comparison to omni-mode configuration can be obtained, due to the reduction of the directional hidden terminal problem and benefiting from the greater spatial reuse from the sectorized antenna.

Buettner et al. [2] has as most important information for our concern, the transmission and reception chains architecture. The hardware used is a Senao 5345MP MiniPCI wireless adapter connected to a phased array 8-dipole antenna from Fidelity Comtech. There is no information about the setup of the topology used to set the testbed.

Lai et al. [3] describe the design of an antenna which could be used in our hardware configuration. It consists in a switched beam antenna employing a four-element slot antenna array. It provides 10 configuration modes – 8 beamforming modes and 2 omni-directional modes.

Dunlop et al. [4] analyze the impact of a switched beam antenna in a sensor network. The only provided information relative to hardware setup is the antenna used, which is a MaxBeam smart antenna. The main conclusion of this study is that using the switched beam antenna and evaluating its performance, a positive impact is verified, with main improvements in throughput, delay and power consumption.

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III. DEVELOPED WORK

A. Developed prototype

The prototype which was developed to accomplish the objectives of proposed is depicted in the following diagram:

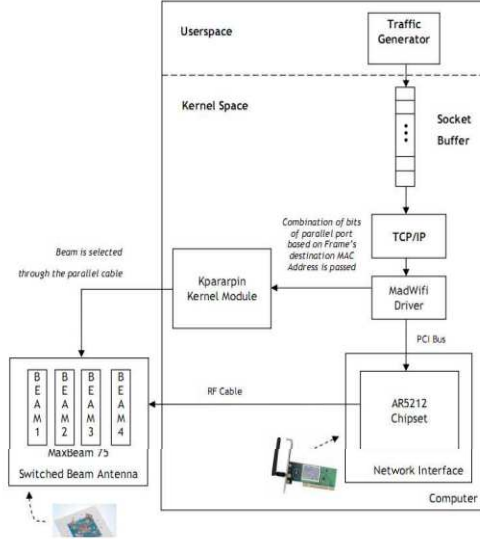


Fig. 2. Developed prototype.

To control the switched beam antenna, the MADWIFI driver [5] was modified to communicate with the parallel port kernel module controller Kparapin [6], in order to form a certain radiation pattern of the switched beam antenna depending on the destination MAC address contained in the packet which was generated on the upper layers. If the MAC address is known and belongs to a node which is part of our WMN, the driver knows which beam to activate, since it also knows the relative position of the destination node in relation to the source node. On the other hand, if the MAC address is unknown, the omni mode is activated and the frame is sent.

B. Switched beam antenna radiation patterns

Tests at the anechoic chamber were carried out to determine the radiation patterns that our prototype could provide. All the 16 possible combinations of the control connector of the antenna were tested, except one, which corresponds to having all the sectors deactivated. Also, a test with an antenna without box was done to estimate the losses introduced by the box that our antenna were placed in (Fig. 3).

The conclusions which we extracted from these tests were that the sectors of the antenna are active when a zero is inputted in the correspondent control pin and, as a consequence the omni mode corresponds to having zeros on all control pins.

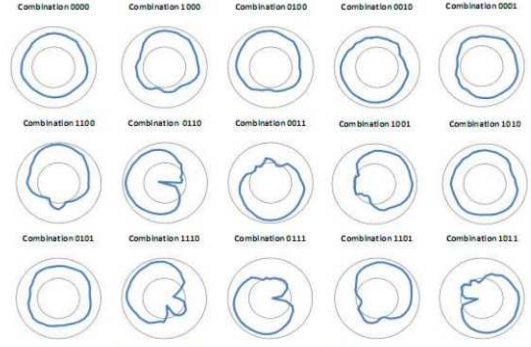


Fig. 3. Switched beam antenna radiation patterns.

C. Performance characterization

On the performance characterization tests two scenarios were tested, the first with two nodes (two upper charts) and the second with three nodes (all the other charts). The results we obtained in terms of throughput, delay (the real measured parameter was RTT – Round Trip Time, which can be approximated to $2 \times \text{delay}$) and fairness are presented in the following charts:

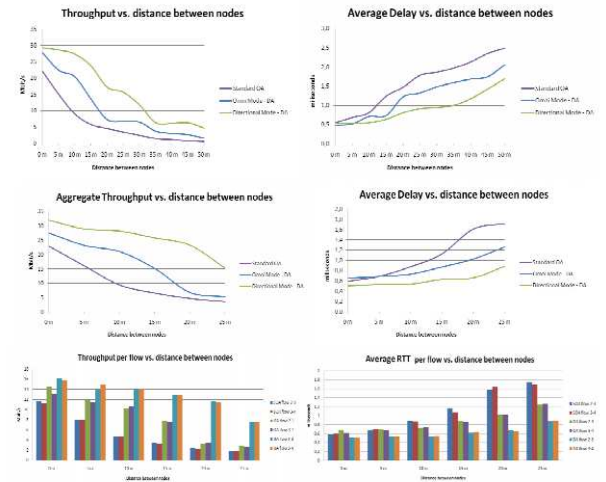


Fig. 4. Performance characterization results.

IV. CONCLUSION

A prototype was developed and the performance of the network was evaluated. With this solution it was possible to implement “pattern-per-packet”, and the performance gains that our solution provides are considerable.

V. REFERENCES

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