Improving the resource utilization in Wireless Mesh Networks based on Spatial -TDMA

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Abstract

Wireless Mesh Networks are expected to gain significant importance in the telecommunications market in the near future. Nevertheless, some critical factors menace them not to achieve their expected features. In this thesis we focus our research on the improvement of their performance. To face the multiple access issue we consider the utilization of Spatial Time Division Multiple Access (STDMA). STDMA benefits from the spatial distribution of nodes allowing the reuse of timeslots by users sufficiently far apart. This feature permits a better utilization of the spectrum, but arises an NP-complete optimization problem consisting in distributing efficiently links into timeslots. In the first part of the thesis, we will address the link scheduling problem and we will propose two heuristics to try to improve the overall performance of the system. In the second part of the thesis, we will deal with directional antennas, and in particular, with switched beam antennas. Several works have demonstrated the significant benefits of switched beam antennas applied to WMNs. This kind of antennas are formed by several fixed beam patterns that are switched according to the communications requirements. Switching among patterns cause, though, a consumption of energy and a lose of time to stabilize the patterns. A set of algorithms to reduce the switchings without deteriorating the frame length achieved with the scheduling algorithms will be presented.
Introduction

Over the last few years, wireless communications have become one of the most vibrant areas of research in the telecommunications field. This research is revolutionizing some traditional concepts of wireless communications. Wireless Mesh Networks (WMNs) have naturally emerged as a result of this momentum and quickly become an intensive research topic. The leading exponents of this increased interest in WMNs are the provision of a low cost and a rapid deployable network able to fulfil a diverse set of applications [1]. The envisioned applications for WMNs range from being a viable alternative to wire line last mile broadband Internet service delivery at home or offices to backhaul support for 3G and IEEE 802.11 'x' hot spots to even support transient networking.

Despite recent advances in WMNs, there is still a wide range of different open research issues. One of the most important building blocks of wireless mesh networks consists in designing an efficient medium access control (MAC) scheme. A well-designed MAC protocol is essential to maximize the performance and the efficiency of the network. One approach for multiple access is to employ contention based schemes where nodes compete for accessing the channel. In this category, the most frequently MAC used protocols are based on Carrier Sense Multiple Access (CSMA). However, contention-based medium access methods are inherently inappropriate for providing QoS guarantees [2], which is becoming a basic premise for lots of communications i.e. in VoIP. Thereafter, contention-based medium access protocols are not appropriate for WMNs. Collision-free access techniques are another kind of MAC schemes more suitable for WMNs, since it is possible to guarantee QoS. These protocols ensure that transmissions are always successful. Within this category we have Time Division Multiple Access (TDMA), where time is divided into time intervals called slots and each node receives its own timeslot. Nevertheless, a more interesting solution in
terms of efficiency can be found if we allow reusing timeslots when it is possible, in other words, allowing the use of the same timeslot to nodes that are sufficiently far apart. This approach is called Spatial Time Division Multiple Acces (STDMA) and was introduced in the seminal work of Nelson and Kleinrock [3].

However, STDMA arises the issue of resource allocation and, in particular, the scheduling problem. Designing an efficient scheduling algorithm for STDMA wireless mesh networks is one of the most challenging research topics. The main goal is to minimize the time span for all links to transmit, that is, minimize the frame length. Thereby, high levels of throughput can be attained and the spectral efficiency can be increased as well. Finding the optimal reuse of timeslots (the shortest frame length) has been shown to be an NP-complete optimization problem [4]. In order to provide a feasible STDMA timeslot allocation a number of sub-optimal algorithms with polynomial time complexity have been previously proposed [5], [6], [7]. In the first part of the thesis we will try to achieve deep knowledge of some of these sub-optimal algorithms, to afterwards try to implement efficient new scheduling algorithms for STDMA wireless mesh networks.

The enhancement of the spatial reuse of resources in WMNs may also be achieved through the application of radio techniques. Some of these techniques such as cognitive radios or MIMO systems, belonging to advanced radio techniques, are not a practical solution for real WMNs due to their high complexity and cost. However, other radio techniques such as directional antennas are a relatively cheap and simple technology that has been proposed and widely studied for WMNs [8][9] over the last few years. Directional antennas concentrate the transmitted energy into a limited region avoiding the inefficiencies of omnidirectional antennas caused by spreading the energy in all directions, and therefore, increasing significantly the interference power level to other concurrent transmitting links. Undoubtedly, the interference reduction that can be achieved by directional antennas permits a higher spatial reuse with respect to omnidirectional antennas, leading in that respect to better resource exploitation and potentially better overall performance of the network [10].

The application of directional antennas in conjunction with collision free scheduling algorithms has shown to significantly reduce the overall frame length in STDMA, compared to case where nodes are equipped with omnidirectional antennas [11]. In addition, the deployment of switched beam antennas has been previously studied in
conjunction with routing decisions to minimize the energy consumption in wireless multi hop networks [12]. Switched beam systems are formed by several available fixed beam patterns. An antenna uses different patterns depending on the direction towards a communication need to be established. The change of radiation pattern in an antenna is commonly called in the literature as a switch [13]. To perform a switch on the antenna it is consumed energy ($\approx 40\mu W$) and required an amount of fixed time (between $5\mu s$ to $0.25ms$) to stabilize the new radiation pattern [14][15][16][17], while at the same time very frequent beam switchings can affect frame acquisition and overall reliability of the deployed mesh network.

The key objective of the second part of the thesis is to provide efficient algorithms for reducing the number of beam switchings without deteriorating the timeslot allocation. Thereby, it is minimized the total time required for altering the transmission antenna patterns in all nodes in the network and it is also reduced the energy consumed by the antennas improving the overall performance of the system. To the best of our knowledge this is the first work that analyzes this cross issue between link scheduling and beam switching in directional antennas and develops polynomial time algorithms to minimize unnecessary beam switchings without penalizing the spatial reuse of timeslots.

The rest of the thesis is organized as follows. In chapter 1 it is presented a theoretical overview of the major concepts involved in this thesis. Hence, the chapter is divided in three main sections: a description of WMNs, a discussion of different MAC schemes for WMNs to present STDMA and the scheduling problem, and finally, a brief introduction to directional antennas and their usage in WMNs. Before starting with a detailed study of the different scheduling algorithms for WMNs based on STDMA and the implementation of new algorithms to reduce the switching effects, in chapter 2 is presented the models and the numerical parameters considered in all numerical investigations. It is very important to set up a defined environment to simulate all algorithms in identical conditions to perform fair comparisons. In chapter 3 it is described two of the most well known scheduling techniques for WMNs based on STDMA as well as it is presented a new scheduling algorithm based on graph colouring techniques. Chapter 4 is entirely focused on the presentation of a new algorithm, result of this research, that outperform the previous scheduling algorithms presented in chapter 3. This algorithm can extend some greedy scheduling algorithms
ameliorating significantly their results. The last chapter of this thesis, as mentioned above, presents the switching problem and a set of algorithms that in polynomial time and without deteriorating the frame length suppress unnecessary switchings. Finally, we state the conclusions from our work and we also suggest some lines for further research.
Chapter 1

Background and Related Work

The purpose of this chapter is to provide a better understanding of the main concepts involved in this thesis. For that reason this chapter will be centered on three topics: Wireless Mesh Networks, Medium Access Control schemes and directional antennas.

In the first section we will introduce Wireless Mesh Networks. We will briefly explain the main characteristics and some of its applications. Afterwards, we will describe the network architecture and we will point out the main advantages of WMNs. Finally, we will outline the critical factors influencing network performance. Section 1.2 will revise different solutions for the Medium Access Control in WMNs, putting emphasis in the STDMA technique. We want to stress the STDMA scheme because it satisfies the requirements of WMNs and it will be the baseline for the work presented in this thesis. Finally, in section 1.3 we will discuss the employment of directional antennas and smart antennas on WMNs.

1.1 Wireless Mesh Networks

1.1.1 Overview

Wireless Mesh Networks (WMNs) are a relative novel technology that is gaining significant attention. In contrast to traditional wireless networks, a WMN is dynamically self-organized and self-configured. In other words, the nodes in the mesh
network automatically establish and maintain network connectivity. Additionally, all
nodes have the capability to rely packets to other nodes on behalf of their neighbors,
that is, every node of the network can act as a router. These features bring many
advantages such as low up-front cost, easy network maintenance, robustness, and
reliable service coverage. Moreover, the gateway functionality contained in some of
the WMNs nodes enables the integration of this kind of networks with various ex-
isting technologies like Internet, cellular, IEEE 802.11, WiMax, etc. Consequently,
through an integrated wireless mesh network, the end-users can take advantage of
multiple wireless networks.

WMNs are emerging as a possible solution for numerous applications. The most
remarkable applications are the substitution of the wire line last mile broadband
Internet service delivery, the backhaul of 3G and IEEE 802.11 ‘x’ hot spots and
transient networking.

1.1.2 Network Architecture

Wireless Mesh Networks consist of mesh routers and mesh clients connected through
wireless links. As mentioned before, both kind of nodes act as routers, forwarding
packets on behalf of other nodes that may not be within direct wireless transmission
range of their destinations. Mesh routers have minimal mobility (or no mobility at
all) and form the backbone of WMNs. They are also the nodes that provide network
access to mesh and conventional clients. Gateway and bridging functions also rely on
this kind of nodes. Consequently, mesh routers are usually equipped with multiple
interfaces.

On the other hand, mesh clients can be mobile and they only have one interface.
Also, mesh clients usually suffer from power consumption constraints.

The architecture of WMNs can be classified into three main groups based on the
functionality of the nodes [1]:

- **Infrastructure/Backbone meshing**: this type of infrastructure is only com-
  prised of mesh routers, which form an infrastructure for clients that connect to
  them. The gateway functionality of the routers permits to integrate thewire-
  less mesh network with clients employing existing technologies such as Ethernet
or WiMax among others. This architecture is shown in figure 1.1.

![Figure 1.1: Infrastructure/Backbone meshing.](image1)

- **Client meshing:** only mesh clients are contained in this type of architecture, as shown in figure 1.2. Client meshing provides peer-to-peer networks among client devices. This architecture is very similar to the ad-hoc network architecture.

![Figure 1.2: Client meshing.](image2)

- **Hybrid meshing:** the combination of the backbone architecture with the client meshing results in the hybrid architecture. Mesh clients can access the
network either through the mesh routers or directly meshing with other mesh clients. Furthermore, mesh routers can provide connectivity to networks with different technologies such as Wi-Fi, WiMax, cellular. See figure 1.3

Figure 1.3: Hybrid meshing.

### 1.1.3 Advantages

WMNs offer numerous benefits compared to other technologies. Some of the most remarkable ones are highlighted as follows:

- **Increased reliability**: the existence of more than one path from the sender to the receiver eliminates single point failures and potential bottlenecks links, resulting in significantly increased communications reliability.

- **Large coverage area**: the multi-hop feature of WMNs provides non line of sight (NLOS) connectivity among users. Furthermore, multi-hop joint to other techniques such as spatial reuse or multi-channel communications allow long distance communications.

- **Automatic network connectivity**: WMNs are characterized by being dy-
namically self-organized and self-configured. In other words, the mesh clients and routers automatically establish and maintain network connectivity. For instance, when new nodes are added to the network, there is a reorganization of the network considering the new available routes and hence, the scalability is assured.

- **Low installation costs**: two main reasons make this kind of technology cheaper compared with others. On the one hand, the self-organization and self-configuration of nodes make the set up and the operation of the network cheaper, since it eliminates or at least reduces the need for manual intervention. On the other hand, the provision of, for instance, broadband Internet service to a large zone is assured just connecting a few nodes to the wired network. This contrasts with the deployment of Wi-Fi Access Points (APs), where due to the limited range of transmission it is needed a large number of APs, and thus, a large number of expensive wired connections.

### 1.1.4 Critical factors influencing network performance

The unique characteristics of WMNs bring many open research issues to the network architecture design and the communication protocols. Although there exist recent advances in wireless mesh networking, many research challenges remain open. Next, we summarize the critical factors that have to be taken into account in order to assure good performance:

- **Radio techniques**: Currently, many solutions have been proposed to increase capacity and flexibility of wireless systems. Typical examples include directional and smart antennas, multiple input multiple output (MIMO) systems and multi-radio/multi-channel systems. In addition, more advanced radio techniques have appeared recently such as reconfigurable radios, cognitive radios, and even software radios. However, the current costs and complexity of these advanced radio technologies are still too high to be widely accepted.

- **Scalability**: WMNs must be able to deal with large network topologies, without incrementing exponentially the number of operations performed as the
number of nodes increases. Furthermore, the degradation of the throughput as the number of hops augment should be resolved.

- **Mesh connectivity:** Many advantages of WMNs originate from the redundancy of paths among nodes. Nevertheless, this becomes a critical design factor for MAC protocols and routing algorithms.

- **Broadband and QoS:** WMNs must be able to support real time applications, and thus, their QoS requirements. New performance metrics based on packet loss ratio, delay jitter, aggregate and per-node throughput are being considered by communications protocols.

- **Compatibility and Inter-Operability:** It is desired that WMNs can integrate existing technologies, otherwise the motivation of deploying WMNs will be compromised.

- **Security:** The new characteristics brought by WMNs demands novel security protocols. The success of WMNs is strongly related to the capability of provide a real secure network. Customers would not subscribe services if they are not reliable.

- **Ease of use:** It is fundamental to design protocols that enable the network to be as autonomous as possible. Rapid deployment and relatively low costs greatly depends on the consecution of this characteristic.

### 1.2 Medium access control

Due to the nature of the wireless communication medium, where the channel is shared by multiple users, when a transmission occurs multiple nodes receive the information that may be destined to a specific node, and in turn, multiple transmissions may result in mutually interfering at a given node. In order to deal with these problems a Medium Access Control (MAC) protocol must be used at the bottom level of the link layer. The Medium Access Control (MAC) moderates access to the shared radio channel by defining a set of rules that allow nodes to communicate to each other in relatively efficient, fair, and dependable manner. Wireless MAC protocols have been studied intensively since the 1970s and there exist different ways to classify them.
As it is shown in figure 1.4, we are going to differentiate between contention based schemes, collision-free schemes and hybrid schemes.

![Medium access control diagram]

**Figure 1.4:** MAC protocols diagram.

Traditionally, MAC protocols for wireless networks are based on contention based methods, where users compete for accessing the channel. The user has no specific reservation of the channel and only tries to contend for the channel when it has packets to transmit. This has clear advantages when the traffic is unpredictable. Prime examples of this methods are ALOHA and CSMA with their different flavours. These kinds of schemes resolve collisions through randomized retransmissions. The contention protocols are simple and tend to perform well at low traffic loads [18]. However, the performance tends to degrade as the traffic loads are increased. This can result in exponentially packet delay. Hence, contention based MAC protocols do not offer QoS guarantees, which have become basic in order to support real-time communications.

On the other hand, collision-free schemes ensure that transmissions are always successful. The strategy is to distribute the channel resources among the users. The most relevant MAC protocols within this category are:

- **Time Division Multiple Access (TDMA)**, where time is divided into time intervals called timeslots and each user can transmit only on its own timeslot.

- **Frequency Division Multiple Access (FDMA)**, where the available spectrum is divided into orthogonal bands and each user is assigned a unique frequency band.
• **Code Division Multiple Access (CDMA)**, the strategy followed by this technique is the employment of different spreading codes by each user. The spreading codes reduce the amplitude of the interference emitted by each user in exchange of occupy a wider portion of the spectrum.

• **Orthogonal Frequency Division Multiple Access (OFDMA)**, this technique can be understood as a mix of TDMA and FDMA. The spectrum is divided into several sub-carriers which are assigned dynamically to users.

All MAC protocols presented above tend to perform well at moderate and heavy loads of traffic. Furthermore, they can assure a minimum QoS. Due to the good performance, reasonable simplicity and low cost, in this thesis we are going to base our work in the Spatial Time Division Multiple Access scheme, an extension of TDMA.

1.2.1 **Spatial Time Division Multiple Access**

Despite TDMA is simple to implement, the resource utilization is poor, since each user of the network has assigned its own timeslot [19]. In order to improve the resource utilization of TDMA schemes, Spatial Time Division Multiple Access (STDMA) was proposed in the seminal work of Kleinrock and Nelson [3]. STDMA takes advantage of the spatially distribution of the nodes, allowing concurrent transmissions from nodes that are sufficiently far apart. This can be done as long as the interference added by the transmitters of a specific timeslot is below a SINR threshold in every receiver node of that timeslot. This constraint, which is related with the bit error rate (BER), allows the users to successful decode the packets received.

The employment of STDMA entails the management of the resources, since depending on how we organize the links or nodes in the timeslots we obtain more or less efficient schedules. The problem can be seen under two different perspectives; either the goal is to maximize the transmission opportunities of a set of links or nodes for a given frame length or the goal is to minimize the time span for all links or nodes, in other words, minimize the frame length. In this thesis we will attack the problem under the perspective of minimizing the number of timeslots used.

As mentioned above, it is possible to schedule links or nodes. In link schedul-
ing, the transmission right in every slot is assigned to certain source-destination pairs (links), defined before the scheduling decisions. In node scheduling, the transmission right in every slot is assigned to certain nodes. This implies that we only know the transmitters but not the receiver/s, thus, each node of a given timeslot must be able to communicate with all its neighbours (node $i$ and $j$ are neighbours if there exist a $link(i, j)$). In other words, we are assuring that nodes can successfully broadcast packets to its neighbours when employing node based schedulers, whereas link based schedulers only assure successful transmission among certain source-destination pairs. Hence, node based schedulers are more suitable for multicast communications, while link based schedulers are used for unicast communications.

In order to clarify these two different approaches figure 2.5 presents two identical networks with different schedules depending on whether it has been considered link or node scheduling. Note that we consider unidirectional links in the download scenario. Node 1 is the gateway and all nodes have been rooted from node 1. Taking as starting point node 6, we can clearly state the differences between the two schedulers. In link scheduling all links have a defined time interval to transmit. For example, link $(6, 7)$ has assigned timeslot 2 and link $(6, 8)$ has assigned timeslot 3. In constrast, node scheduling only assigns timeslots to nodes. In this case, links $(6, 7)$ and $(6, 8)$ have assigned the same timeslot, since node 6 is the owner of the timeslot but not the links. This implies that when node 6 transmits, nodes 7 and 8 receive the same packet. To transmit different packets to nodes 7 and 8 we would have to employ two cycles of the schedule. Therefore, it is clear that for unicast communications is more efficient to use link scheduling, whereas for multicast communications is better to use node scheduling.
1.3 Employing directional antennas in WMNs

The improvement of the spectral efficiency in WMNs may also be achieved through the application of other techniques such as directional antennas. The employment of directional antennas have demonstrated to greatly improve the performance of WMNs [8][9][10]. This enhancement is because directional antennas concentrate the power into limited regions, and consequently, they considerably diminish the interference caused to users that are not within these regions.

However, directional antennas lack of the required flexibility that WMNs demand. The employment of this kind of antennas require the manual intervention each time, for instance, the routing is changed. For example, the introduction of a new node in the network may vary the routing, and consequently, some antennas should be manually redirected to point to the new receivers established by the new routing. Therefore, a key feature as the automatical re-configuration of the network is violated by the employment of directional antennas.
A more appropriate kind of antennas that have the advantages of directional antennas and offer a major flexibility are the so-called smart antennas. Smart antennas generally combine multiple antenna elements with a signal processing capability to optimize its radiation and/or reception pattern automatically in response to the signal environment. Basically, there are two major categories of smart antennas:

- **Switched beam antennas**: comprised of multiple fixed beams that are formed by shifting the phase of each antenna element of an antenna array by a predetermined amount, or simply by switching between several fixed directional antennas. The transceiver can select one or more beams to transmit or receive. Figure 1.6 shows an example of the possible beams that can be selected.

- **Adaptive arrays**: these antennas are theoretically able to form an infinite number of radiation patterns. The patterns are created taking into account the desired signal and the interferers. In other words, they have the capability of direct the main beam toward the desired signal while suppressing the antenna pattern in the direction of the interferers. Figure 1.7 shows an example of an adaptive array where the main beam points to the desired signal and the interference is suppressed with a null in the pattern.

![Figure 1.6: Example of a switched beam antenna with 8 beams.](image)

![Figure 1.7: Pattern of an adaptive array rejecting interference.](image)

Adaptive arrays tend to perform better than switched beam antennas, since they place the desired signal at the maximum of the main lobe and reject the interfer-
ers. Nevertheless, adaptive arrays are not convenient for WMNs due to their high complexity and cost. Switched beam antennas, although not performing at the same level of adaptive arrays, offer the advantages of directional antennas joint to a major flexibility, and a lower cost and complexity compared to adaptive arrays. The employment of switched beam antennas avoid the necessity of manual intervention in the network, since each time we need to point to a new user the system only needs to reconfigure the active beams.

The change of pattern in a switched beam antenna is commonly called in the literature as a switch [13]. In STDMA, switched beam antennas generally need to perform a certain number of switches during each cycle of the schedule in order to transmit/receive to/from different users. These switches require a certain amount of energy (≈ 40µW) and time (5µs to 0.25ms) to stabilize the pattern [14][15][16][17]. In the last part of the thesis we will try to correct these inefficiencies by minimizing the number of switches without deteriorating the spatial reuse of timeslots (the frame length).
Chapter 2

System model

In this chapter we present the assumptions and the models considered in all numerical investigations. These models provide a certain level of abstraction in order to reproduce reality in such a way that afterwards we can analyze the results obtained. The models proposed cover both parts of the thesis. Note that when introducing directional antennas the models become more complex due to the singular aspects of directional antennas and their effects on the interference.

The chapter is organized as follows. First, we provide a brief overview of the network model. Then, section 2.2 focuses on the antenna models, and in particular, on the modelling of switching beam antennas. Next, we show how we have modelled interference. Finally, we describe the setting of the network, including the simulation parameters employed in all numerical investigations.

2.1 Network model

We consider a WMN, which can be modelled by a network graph \( G = (V, E) \), where \( V \) is the set of nodes (mesh routers) and \( E \) expresses the set of wireless links. Note that we consider a network comprised only by mesh routers, hence no mobility is assumed nor power constraints are specifically taken into account. Each node is equipped with one wireless interface card. We further assume that all nodes in the mesh network operate at the same frequency band (frequency reuse factor is one).
and we do not consider spurious or other inter channel interference. A special node in the topology acts as the gateway node for providing Internet working; throughout the numerical investigations and without loss of generality a single gateway node is considered. The packet length is normalized and occupies a single timeslot.

2.2 Antenna model

In the last chapter, where directional antennas are employed, we assume that each node in the WMN is equipped with a switched beam by using phase array antennas forming a radiation pattern with $K$ identical and selectable beams. The radiation pattern of a beam is approximated by a main lobe of constant gain $g_m$ and beamwidth $\theta_m$ and a side lobe of constant gain $g_s$ and beamwidth $(2\pi - \theta_m)$, as it is illustrated in 2.1. For the rest of the thesis, omnidirectional antennas with unitary gain are considered.

![Figure 2.1: The Keyhole radiation pattern used to model a beam of a switched beam antenna.](image)

Without loss of generality, we assume that the direction of each beam is fixed and the boresights of the first sector are always directed towards the $0^\circ$ and $\theta_m$ on a polar plane. When a link needs to be established for communication between nodes $i$ and $j$, then node $i$ calculates the relative angle, $\phi_{ij}$, between the $0^\circ$ in the polar plane and link $(i,j)$ to determine the employed antenna beam. Based on the above assumptions, the selected beam $\xi_{ij}$ that node $i$ would use to communicate with node $j$ via link $(i,j)$ is given by equation 2.1 below,

$$\xi_{ij} = \left\lfloor \frac{\phi_{ij}}{\theta_m} \right\rfloor$$

(2.1)
Note that node $j$ will apply the exact same procedure to determine the beam $\phi_{ji}$. Figure 2.2 shows the distribution of the antenna beams and the beam selected by node $i$ to establish link $(i,j)$.

![Figure 2.2: An example of a node with a switched beam antenna with 8 beams, where the angle of each beam ($\theta_m$) is 45°. The selection of the beam that is used for link $(i,j)$ is based on angle $\phi_{ij}$ which depicts which beam will be used for this communication link.](image)

Observe that each switched beam antenna can have a number of different patterns depending on which beams are active at the same time. The number $N_p$ of different possible patterns for a switched beam antenna is given by equation 2.2 below,

$$N_p = \sum_{K=1}^{B} \left( \begin{array}{c} B \\ k \end{array} \right), \quad \text{where } B = \frac{2\pi}{\theta_m}$$

(2.2)

In fact, the above expression is an absolute upper bound; the different beam patterns will be limited by the number of active links that belong in different beams. Therefore, the actual number of possible beam patterns for node $i$ can be calculated using expression 2.2 if we substitute $B$ with $B_i$, where $B_i \leq B$ is the number of beams that contain at least one active link. An example on the different beam forming patterns is shown in figure 2.3 for a node with a degree 3.
Figure 2.3: Different possible beam forming patterns for a node with degree 3. For this example $N_p = 7$.

Directional antennas focus a significant amount of the transmitted energy in a specific direction. In order to model directional antennas it is necessary to find an expression that relates the gains and beamwidth with the total amount of energy transmitted by an omnidirectional antenna with unit gain. Several models have been considered in the literature, and in this work we adopt a model similar to the one proposed in [13]. The model assumes a 2 dimensional radiation pattern to calculate the parameters of a directional antenna. Equation 2.3 relates the parameters of the directional antenna.

\[
g_m \frac{P}{2\pi} \theta_m + g_s \frac{P}{2\pi} (2\pi - \theta_m) = P
\]

Equation 2.3 expresses how the total amount of transmitted power $P$ is spread between the main and side lobes. This same equation is also valid when $N_b > 1$ beams are activated simultaneously. In that case, to model the antenna gains it is considered an antenna that has a main lobe with beamwidth $N_b \cdot \theta_m$ and a side lobe with beamwidth $(2\pi - N_b \cdot \theta_m)$. 

20
2.3 Interference model

For a single transmission bit-rate, each link \((i,j) \in E\) needs to satisfy a signal to interference noise ratio (SINR) threshold \((\gamma)\) for successful packet decoding. More specifically, the SINR inequality that needs to be satisfied can be written as follows,

\[
g_{ij}A_{ij}^{ab}p_{ij} \sum_{(m,n) \in E',\{i,j\}} g_{mj}A_{mj}^{cd}p_{mn} + W \geq \gamma
\]

where \(p_{ij}\) denotes the transmission power for link \((i,j)\), \(g_{ij}\) is the link gain for link \((i,j)\), \(E'\) is the subset of links in \(E\) that are transmitting simultaneously to link \((i,j)\), \(A_{ij}^{ab}\) is the antenna gain of the transmission node \(i\) when using beam pattern \(a\) multiplied with the antenna gain of the receiver node \(j\) with pattern \(b\) and \(W\) expresses the power of background and thermal noise. When omnidirectional antennas are employed the antenna gains are normalized to unitary value and so the terms \(A_{ij}^{ab}\) and \(A_{mj}^{cd}\) are always 1. It is important to remark that this inequality is only valid for unidirectional links, since this thesis only considers unidirectional links. In case bidirectional links were considered the inequality should be rewritten as follows,

\[
g_{ij}A_{ij}^{ab}p_{ij} \sum_{(m,n) \in E',\{i,j\}} \max\{g_{mj}A_{mj}^{cd}p_{mn}, g_{nj}A_{nj}^{ef}p_{nm}\} + W \geq \gamma
\]

and

\[
g_{ji}A_{ji}^{ba}p_{ji} \sum_{(m,n) \in E',\{i,j\}} \max\{g_{mi}A_{mi}^{gh}p_{mn}, g_{ni}A_{ni}^{op}p_{nm}\} + W \geq \gamma
\]

where the maximum interference provoked by each link is considered.

2.3.1 Performing fast SINR calculations

As it will become evident in the sequel, a large number of SINR operations need to be performed. In that respect, we would like to provide a fast procedure to perform all these operations. The method proposed avoids unnecessary calculations, and hence, it improves the computational efficiency of the algorithms. The idea behind the method is to prevent the re-calculation of some parameters that have already
been calculated in previous checkings by updating iteratively the SINR of all the scheduled links.

According to the interference model stated above, each time we allocate a link in a timeslot, all the receiver nodes of that timeslot, including the receiver of the new link, must accomplish the SINR threshold. The SINR calculated in the links already scheduled in the timeslot only vary from the previous SINR because of the aggregate interference brought by the new link. On the other hand, the SINR in the receiver of the link that we try to allocate must be calculated with the entire inequality.

Next, we develop the SINR inequality presented above to show how we can save some operations by only saving a parameter for each link scheduled.

\[
\frac{g_{ij}A_{ij}^{ab}p_{ij}}{g_{mj}A_{mj}^{cd}p_{mn} + W} \geq \gamma \quad \text{(2.6)}
\]

\[
g_{ij}A_{ij}^{ab}p_{ij} \geq \gamma \left( \sum_{(m,n) \in E' \setminus \{(i,j)\}} g_{mj}A_{mj}^{cd}p_{mn} + W \right)
\]

At this point, depending on which node is checked the expressions are different. If we want to check the SINR of the link \((u,v)\) that we want to allocate, the inequality that needs to be satisfied is

\[
g_{uv}A_{uv}^{ab}p_{uv} \geq \gamma \left( \sum_{(m,n) \in E' \setminus \{(u,v)\}} g_{mv}A_{mv}^{cd}p_{mn} + W \right) \quad \text{(2.7)}
\]

To check the SINR of the links already scheduled in the timeslot we must accomplish inequality 2.8

\[
g_{ij}A_{ij}^{ab}p_{ij} \geq \gamma \left( \sum_{(m,n) \in E' \setminus \{(i,j)\}} g_{mj}A_{mj}^{cd}p_{mn} + g_{uj}A_{uj}^{gh}p_{uv} + W \right)
\]

\[
g_{uj}A_{uj}^{gh}p_{uv} \leq \frac{g_{ij}A_{ij}^{ab}p_{ij}}{\gamma} - \sum_{(m,n) \in E' \setminus \{(i,j)\}} g_{mj}A_{mj}^{cd}p_{mn} - W = \beta_{ij} \quad \text{(2.8)}
\]

where \(\beta_{ij}\) is the maximum aggregated interference that link \((i,j)\) can support if a new link is scheduled. Observe that all parameters of \(\beta_{ij}\) are independent of the link that we are trying to allocate. For the SINR calculation for the links already allocated in the timeslot, instead of using inequality 2.6, we only have to compare their respective \(\beta\)s with the interference produced by the new link. Note that \(\beta_{ij}\)
has been already calculated in previous SINR calculations. In case the new link results to be feasible, we must update all $\beta$s and calculate the $\beta$ corresponding to the new scheduled link. This updating only requires to substract to the previous $\beta$s the aggregated interference by the new link. For instance, if link $(u,v)$ is feasible we update $\beta_{ij}$ as follows

$$\beta'_{ij} = \beta_{ij} - g_{uj}A_{uj}^{gh}p_{uv}$$ (2.9)

With regard to the new $\beta$ we only have to isolate inequality 2.7.

$$\beta_{uv} = g_{uv}A_{uv}^{ab}p_{uv} - \gamma\left( \sum_{(m,n) \in E \setminus \{(u,v)\}} g_{mv}A_{mv}^{cd}p_{mn} + W \right)$$ (2.10)

Note that not only the number of operations performed are reduced when links are not feasible, but also the number of operations are reduced when the link is feasible as the updates are much more simple than the calculation of the entire SINR.

### 2.4 Setting of the WMN

The Wireless Mesh Network is deployed in a square area $A \times A \ Km^2$ containing $N$ wireless nodes that are random uniformly distributed. Two nodes in the mesh network can establish a link if the receiving node satisfies the Signal to Interference Noise Ratio threshold ($\gamma$) criterion, defined in 2.4.

Based on all feasible links that can be constructed when no co-channel interference is considered (figure 2.4), a shortest path spanning tree is constructed rooted at the gateway node, spanning all other nodes in the network (figure 2.5). The spanning tree is based on the Minimum Power Routing (MPR) scheme, as described and analyzed in [20]. The MPR scheme is based on Dijkstra’s algorithm and uses the required transmitted power to combat the path loss as the cost of the link. Given that the transmitted power for link $(i,j)$ is related with the distance between nodes $i$ and $j$ the cost is defined as follows,

$$w_{ij} = d(i,j)^{\alpha}$$ (2.11)

where $d(i,j)$ is the Euclidian distance between nodes $i$ and $j$, and $\alpha$ is the path loss exponent.
The power transmitted by a node in the network is determined by the minimum power required to establish a communication with a receiver node in absence of interference as long as it does not exceed the maximum power transmitted ($P_{max}$), in other words, it is the minimum power to accomplish a Signal to Noise Ratio threshold ($SNR$). It is important to remark that independently the use of directional or omnidirectional antennas, the power required by a node $i$ to establish a link with node $j$ is calculated considering omnidirectional antennas, where the antenna gain is 1. The aim of not using directional antennas to calculate the power requirements for establishing a link is to ensure that if the antenna patterns of nodes change, their SNR thresholds will still be accomplished. In other words, the power emitted by a directional and a omnidirectional antenna is the same. Note that this fact refers to the last chapter where directional antennas are employed. To calculate the required transmission power level for link ($i, j$) the following simple path loss model has been considered hereafter,

$$ PL(d(i, j)) = PL(d_0) + 10\alpha\log\left(\frac{d(i, j)}{d_0}\right) \quad (2.12) $$

where $d(i, j)$ expresses the Euclidean distance of link ($i, j$), $PL(d_0)$ is the close-in reference distance loss, which is assumed to be equal to 78 dB for distance $d_0$ equal to 50 meters, and finally $\alpha$ denotes the path loss exponent, which in general take values between 2 (free-space path loss) to 6 depending on the environment under consideration [21].

It should be noted that only unidirectional links in the downlink scenario (from the gateway to the nodes) are considered. Similar results are expected to hold also
for the uplink scenario. Since a shortest path spanning tree is created, rooted from the designated gateway node, the links that need to be scheduled are \( N - 1 \) in all numerical investigations. Furthermore, scheduling is taking place under the assumption that at the same timeslot a node cannot transmit and receive, transmit to more than one node or receive from more than a node. These assumptions are called in [22] as the degree, outdegree and indegree constraints. In practice, these constraints imply that links that have one node in common must be allocated in different timeslots.

Finally, we consider the often-used scenario where each link requires to be scheduled in only one timeslot. Therefore, the frame length computed by the scheduling algorithm expresses the minimum possible number of timeslots so that each link transmits at least once.

In the second part of the thesis the Greedy Physical algorithm, which will be explained in detail in chapter 3, will be employed to schedule links, since the proposed techniques for reducing the number of beam switchings presented are actually independent of the scheduling algorithm.

At last, note that all numerical investigations have been conducted over 200 randomly generated wireless mesh network topologies.

The complete set of simulation parameters used in the numerical investigations are summarized in Table 2.1 below.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Explanation</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Length of the Square Area</td>
<td>850 meters</td>
</tr>
<tr>
<td>N</td>
<td>Number of Nodes</td>
<td>5-200</td>
</tr>
<tr>
<td>L</td>
<td>Number of Links</td>
<td>4-199</td>
</tr>
<tr>
<td>( d_0 )</td>
<td>Close-in reference distance</td>
<td>50 meters</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
<td>15 dB</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>SINR threshold</td>
<td>8 dB</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Path loss exponent</td>
<td>3.5</td>
</tr>
<tr>
<td>( P_{\max} )</td>
<td>Maximum transmitted power</td>
<td>20 Watt</td>
</tr>
<tr>
<td>( f_c )</td>
<td>Carrier frequency</td>
<td>3800 GHz</td>
</tr>
<tr>
<td>W</td>
<td>Thermal and background noise</td>
<td>-132 dBW</td>
</tr>
</tbody>
</table>

Table 2.1: Simulation parameters
Chapter 3

Scheduling techniques

The level of resource utilization in STDMA greatly depends on the scheduling algorithm. Ideally, the algorithm should be able to compute an optimal schedule, i.e. the minimum frame length, and recalculate the schedule whenever a change occurs in the network topology. However, finding the optimal reuse of timeslots has been shown to be an NP-complete optimization problem [4]. Instead, a number of sub-optimal algorithms with polynomial time complexity have been proposed in order to find feasible schedules for STDMA.

In this chapter, we will detail some of the most important heuristics that have been proposed in the literature in order to efficiently solve the resource allocation problem in STDMA schemes. Furthermore, we will propose a new scheduling algorithm based on graph colouring techniques, in particular, it will be based on the Recursive Largest First. All algorithms presented are link based schedulers as we are interested in unicast communications.

The scheduling algorithms presented will be classified according to the main interference models that have been proposed in the literature [23]: the protocol and the physical interference models. Interference is the main factor that limits capacity in mesh networks and in wireless networks in general, which is a consequence of using a shared communication medium. Hence, an accurate modeling of interference is fundamental in order to derive theoretical and/or simulation-based results of some practical relevance.

The rest of the chapter is organized as follows. First, we will present the heuristics
according to the interference model followed. Next, we will study and analyze the performance of these heuristics. Finally, we will draw the conclusions.

3.1 Physical interference model

The physical interference model uses the Signal to Interference Noise Ratio (SINR) to describe the aggregate interference in the network. In this model, a transmission from node $i$ to node $j$ is successful if and only if the SINR at the receiver is at least the minimum SINR threshold ($\gamma$) required. The necessary condition for successful transmission can be written as,

$$SINR_{ij} \geq \gamma \quad (3.1)$$

where $SINR_{ij}$ is the SINR at node $j$ when a transmission from node $i$ to node $j$ is taking place and $\gamma$ is the SINR threshold.

The physical interference model is widely considered as a reference model for physical layer behaviour. However, this model implies a higher complexity with respect to the protocol interference model.

3.1.1 Greedy physical

The first scheduling algorithm presented under the physical interference model is the Greedy Physical (GP) algorithm, which was defined in [24]. This algorithm starts by ordering the links to be scheduled according to the interference number. The interference number of a link $(i,j) \in E$ is the number of links $(m,n) \in E \setminus (i,j)$ that cannot establish a communication at the same time, excluding those that have a common node with link $(i,j)$. A set of two links is considered infeasible when the receiver nodes do not satisfy the SINR constraint described in 2.4. Based on the interference number, a sorted list is created with the higher interference number first, and then, links are packed according to the scheduling algorithm stated in 1.
Algorithm 1 Greedy Physical

| Input:    | $L$, List containing all links sorted by its interference number |
| Output:   | $S$, A feasible schedule                                           |
|           | $TS$, Frame length found for $S$                                   |

1: $TS \leftarrow 0$
2: for $i=1:L$ do
3: Schedule link $L_i$ in the first available slot such that the resulting set of scheduled transmission is feasible with the physical interference model.
4: if currently available slots are not sufficient to schedule $L_i$ then
5: Let $TS \leftarrow TS + 1$ \{add a new slot at the end of the schedule $S$\}
6: Schedule $L_i$ in the new slot
7: end if
8: end for

3.1.2 Packing heuristic

The Packing Heuristic (PH) presented below is the algorithm that has been detailed in [20], which is also a variation of the heuristic algorithm used in [25] and [26], where different weights are utilized to sort the links. This algorithm tries to pack as many links as possible in each timeslot, having as a starting point a list, where links with higher transmitted power are sorted first. The pseudo-code of the algorithm is shown in 2.
Algorithm 2 Packing Heuristic

Input: $A$, List containing all links sorted by its power levels (highest power first)

Output: $B$, A feasible schedule $TS$, Frame length found for $S$

1: $t \leftarrow 1$
2: $B \leftarrow \emptyset$
3: At timeslot $t$ schedule the first link in list $A$ for transmission and shift it from list $A$ to list $B$.
4: repeat
5: Proceed down the current list $A$ scheduling links for transmission in timeslot $t$, if feasible, and shifting them to list $B$ if they transmit.
6: Let $t \leftarrow t + 1$
7: until $A$ is empty
8: Let $TS \leftarrow t - 1$

3.1.3 Comparison between GP and PH

GP and PH apply the same two-step procedure:

1. Create a list of links sorted in decreasing order following some criterion
2. Pack links following the sorted list

The first step is actually what differentiates both algorithms. On the other hand, the second step, although performed differently by the two algorithms, does not provide any variation to the final schedule.

In fact, this two-step procedure followed by both algorithms is based on a bin packing heuristic named First Fit Decreasing (FFD) algorithm. The bin packing problem involves the packing of a set of weighted items into the minimum number of bins of unit capacity. The problem can be formulated as follows:

Instance: A list of nonnegative numbers $a_1, \ldots, a_n \leq 1$

Task: $\sum_{i: f(i) = j} a_i \leq 1$ for all $j \in \{1, \ldots, k\}$ such $k$ is minimum (3.2)
This problem is strongly related to the scheduling problem. Items are analogous to links and bins to timeslots. The goal is to minimize the number of bins used, in our case, the number of timeslots. However, due to the nature of the interference the scheduling problem becomes more complex and differs from the bin packing problem at some points. For instance, it is difficult to model the capacity of a bin (timeslot) as it cannot be understood as a fixed value because it depends on the interference of the allocated links and varies each time a new link is introduced. Furthermore, it is critical to find good criteria to size items (links). Despite the differences, the heuristics applied to the bin packing problem can help to find good solutions in the link scheduling problem. In particular, we have mentioned that PH and GP adopt the ideas of a simple heuristic that works reasonably well called FFD algorithm. This algorithm first arranges the items in decreasing order of size and then following the list created puts each item into the first bin into which it fits, or in a new bin if none of the existing ones can accommodate it.

The way items are put into bins in the FFD algorithm is the same procedure GP uses to allocate links into timeslots. However, PH follows a different strategy to allocate links, but that reaches the same schedule given the same list. In other words, if GP and PH sorted links in the same order, the schedule found by them would be identical. The strategy employed by PH does not consist in trying to allocate links in the first timeslot available, instead it fixes a timeslot and tries to pack in it all links that have not yet transmitted. To illustrate both methods and demonstrate that given the same list they reach the same solution figure 3.1 is presented.
As we can see from figure 3.1, to allocate the first link both schedulers create the first timeslot. From this point, they start behaving differently. For instance, to allocate the second link in the schedule, GP first checks the feasibility of timeslot 1 when link 2 is in it. As this set is not feasible and there are no more timeslots, link number 2 is allocated in a new timeslot. In the PH the strategy followed is different. We do not try to allocate a specific link, instead we fix a timeslot and we try to
pack all the remaining links of the list. As in the previous case, we try to pack link number 2 in timeslot 1, but as mentioned before this is not possible. Then we try to pack the next link of the list, link number 3. In this case, the timeslot is feasible, thus, link number 3 is allocated in timeslot 1. Note that although at the end of each step the schedules are different, at the end of the whole process they are equal.

Once both allocation strategies have been verified to reach the same solution for a given list, it would be interesting to analyze the efficiency of these strategies. To do so we present in figure 3.2 the cumulative distribution of SINR operations performed to build a schedule of 60 nodes. Note that we are reporting an empirical study as the theoretic development of the problem is complex and is not the goal of this study. It is important to remark that the feasibility of timeslots is always checked following the same steps in order to fairly compare the number of operations performed by both schedulers. Each time a new link is tried to be allocated in a timeslot, we first check the SINR in the receiver of the new link, and then, the SINR of the receivers of the current timeslot, starting from the receiver of the first link allocated. Proceeding in an ordered manner is required when a link cannot be scheduled in a timeslot. The reason is that depending on the order receivers are checked, before the first one that does not support the aggregate interference brought by the new link, the number of operations performed may vary.

![Figure 3.2: Distribution of the number of SINR operations needed to schedule 60 links with GP and PH. Note that the horizontal axis represents the number of links already scheduled.](image)

Figure 3.2: Distribution of the number of SINR operations needed to schedule 60 links with GP and PH. Note that the horizontal axis represents the number of links already scheduled.
Figure 3.2 reveals that the total number of SINR operations calculated by both methods is the same. However, the distribution of these operations is different. In the PH a major number of operations are performed to schedule the firsts links compared to GP, while for the last links the situation is reversed. The reason is that PH at the beginning checks more SINR as it tries to pack all the contained links of the list in a specific timeslot, not creating a new timeslot until all links have been checked. As the process advances, the number of links contained in the list reduces, and therefore, the number of SINR calculations reduces as well. In contrast, GP performs less calculations at the beginning, as this method picks the first link of the list and packs it in the first timeslot available. Due to the few number of scheduled links at the beginning, there are not many calculations neither.

In conclusion, after this detailed discussion comparing GP and PH we have seen that the differences between the two algorithms are: the selected criterion to sort links in the creation of the list and the distribution of the SINR operations required to schedule links due to the different allocation strategies followed. The relevance of this study will become evident in the next chapter, in particular, in section 4.3.

3.2 Protocol interference model

In the protocol interference model, a transmission between nodes is successful if the receiver node falls inside the transmission range of its intended transmitter and falls outside the interference ranges of other non-intended transmitters. Thus we can write these conditions as follows,

\[ d_{ij} \leq R_i \]  \hspace{1cm} (3.3)
\[ d_{jk} \geq R'_k \]  \hspace{1cm} (3.4)

where \( d_{ij} \) is the Euclidean distance between node \( i \) and \( j \), \( R_i \) represents the transmission range of node \( i \) and \( R'_k \) represents the interference range of any node \( k \) that is transmitting. The setting of the transmission range is based on a Signal to Noise Ratio (SNR) threshold, while the setting of the interference range is rather heuristic and remains and open problem.

Figure 3.3 shows an example where link \((u,v)\) is interfering with link \((i,j)\) because node \( j \) is within the interference range of node \( u \).
Figure 3.3: Interfering links according to protocol interference model.

This model is simple as we do not need to calculate the SINR, and we just need to know the distances among nodes. Due to its simplicity and to the fact that this model can be used to mimic the behaviour of CSMA/CA networks such as IEEE 802.11, the protocol interference model has been widely used in literature. Nevertheless, there have been doubts on its validity as it does not accurately capture physical layer characteristics, and thus, solutions obtained under the protocol model may be infeasible in practice. The problem lies in the interference range. For the case when a node falls in the interference range of a non intended transmitter, the protocol model assumes that this node cannot receive correctly from its transmitter. But this can be overly conservative if the interference range is oversized. On the other hand, for the case when a node falls outside the interference range of all the non intended transmitters, the protocol model assumes that there is no interference. But this is somewhat optimistic, as small interference from different transmitters can aggregate and may not be negligible. This is the result of undersized interference ranges. A compromise in the size of the interference range is needed. However, this compromise is not straightforward and still remains as an unsolved problem.
3.2.1 Recursive largest first (RLF)

Next, we propose in this thesis a new scheduling technique that formulates the scheduling problem in terms of graph-theoretic colouring problem. Classical graph colouring consists in colouring the edges or vertices of a graph \((G = (V, E))\) such adjacent vertices or adjacent edges respectively, do not share the same colour. Recall that vertices \(u, v \in V\) are called adjacent or neighbours if \(u, v \in E\) and nonadjacent if \(u, v \notin E\). Edges \(o, m \in E\) are said to be adjacent if \(o \cap m \neq \emptyset\) and nonadjacent if \(o \cap m = \emptyset\). Figure 3.4 shows an example of edge colouring and vertex colouring.

![Classical colouring](image)

**Figure 3.4:** Classical colouring.

Graph colouring serves for the resolution of a large variety of problems such as timetable scheduling, register allocation or pattern matching among others. We will center our research on vertex colouring, as we will describe the STDMA link scheduling problem, as a vertex colouring problem. The vertex colouring problem is equivalent to find a partition of \(V\) into a minimal number of subsets of mutually compatible elements. The situation is described by a graph \(G = (V, E)\) with vertex set \(V\) and edge set \(E\) formed by all pairs of incompatible elements. Partitioning of \(V\) into \(k\) subsets is equivalent to colouring the vertices of \(G\) with \(k\) colours. This problem is an NP-hard problem.

The high computational complexity of the graph colouring problem necessitates the use of approximation heuristics methods. Several methods have been proposed in the literature, but in this work we will focus on a simple method which has demonstrated to perform reasonably well. This method is the Recursive Largest First (RLF), a graph colouring technique proposed by Leighton [27]. RLF incrementally
constructs an independent set $V_i \subseteq V$ of vertices that are coloured with the first colour, then, considering only vertices in $V \setminus V_1$, constructs the next independent set $V_2$ as a second colour class and so on. The first vertex placed in $V_i$, $i \in 1, 2, \ldots$, is a vertex of maximum degree in the subgraph induced by $V \setminus \bigcup_{j=1}^{i-1} V_j$. At each other step, the algorithm selects a vertex with the maximum number of adjacent vertices that are uncoloured but already inadmissible for the $i$th colour. Formally, the algorithm can be stated as follows,

**Algorithm 3** Recursive largest first

<table>
<thead>
<tr>
<th>Input:</th>
<th>$G = (V, E)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output:</td>
<td>$C$, list of coloured vertices</td>
</tr>
</tbody>
</table>

1: $C \leftarrow \emptyset$
2: $U \leftarrow \emptyset$
3: $V_{aux} \leftarrow V$
4: $q \leftarrow 0$
5: Choose a vertex $k$ of maximum degree in the subgraph induced by $V_{aux}$. Increment $q$ by 1 and proceed to 6.
6: Assign colour $q$ to $k$. Move $k$ from $V_{aux}$ to $C$ and all $i \in V_{aux}$ that are adjacent to $k$ from $V_{aux}$ to $U$. If $V_{aux}$ remains nonempty, then proceed to 7. Otherwise check whether $C = V$. If so, then stop with $G$ coloured with $q$ colours. If not, then set $V_{aux} := U$, $U := \emptyset$ and return to 5.
7: Choose a vertex $k \in V_{aux}$ that has the maximum number of edges to vertices in $U$. Go to 6.

In order to apply this technique to the STDMA link scheduling problem it is needed to construct an interference graph. The interference graph is a graph where elements that are incompatible are connected through edges. In particular, for the link scheduling problem we construct a graph $G_{int} = (V', E')$ comprised of a set of vertices $V'$ representing the links or edges of the communication graph ($G = (V, E) \mid V' \subseteq E$) and a set of edges $E'$, connecting the links that are interfering to each other. This means that the network links, now represented by nodes in the interference graph, are connected through edges among them if they cannot be scheduled into the same timeslot. Link $v'_1$ is interfering link $v'_2$ if the interference range, with centre in the transmitter of link $v'_1$, contains the receiver of link $v'_2$. Note that, although,
\(v'_1\) could not be interfering \(v'_2\), \(v'_2\) could interfere \(v'_1\) and the result is that \(v'_1\) and \(v'_2\) interfere each other. Furthermore, as it has been stated in chapter 2, we consider that adjacent links are not able to communicate simultaneously. Therefore, in the interference graph links that are adjacent in the communication graph are interfering to each other. Figure 3.5 shows the communication graph with the interference ranges and the resulting interference graph. In this example, the interference graph shows that link 1 cannot transmit at the same time link 2 and link 3 do (they are connected through edges). Link 1 and link 2 are adjacent in the communication graph (they have a node in common), whereas link 1 and link 3 cannot be scheduled in the same timeslot as the receiver of link 3 is within the interference range of link 1.

![Communication graph](image1)

![Interference graph](image2)

**Figure 3.5:** Communication graph with the interference ranges and the resulting interference graph.

Next, we describe the algorithm that we have implemented to apply the RLF. The first step consists in setting up the interference range of each transmitter. Initially, the interference ranges are set up with the transmission range of each transmitter (Euclidian distance between the two nodes involved in the communication). Observe that a node has as many interference ranges as outgoing links. Then, we construct the interference graph according to the interference ranges and the indegree, outdegree and degree constraints stated in chapter 2. After that, we apply the RLF to the interference graph to obtain a schedule of length \(TS\). Once the schedule has been obtained, we check its feasibility. A schedule is feasible only if all receivers of every timeslot have a SINR higher than a certain threshold. In case the schedule is not
feasible we increment the interference range of all nodes in order to have a new interference graph more restrictive toward a feasible schedule. Incrementing the interference range of all nodes is a simple way to obtain a new interference graph, although other strategies such as selective increments could lead to better solutions.

The outer loop of the algorithm, where the feasibility of the schedule is checked, could lead to think that we are presenting an algorithm more likely to be within the physical interference model than within the protocol interference model. However, we would like to remark that in contrast to the algorithms within the physical model this algorithm does not decide the allocation of a link into a timeslot according to the SINR calculated, instead it uses the interference ranges. Furthermore, this outer loop is presented here in order to fairly compare RLF with the other two algorithms, though we may eliminate this outer loop and specify a criterion to establish the interference ranges to create the interference graph.

The pseudo-code of the algorithm is shown next

Algorithm 4 RLF applied to STDMA link scheduling on WMNs

| Input: | $G = (V, E)$ |
| Output: | $S$, Schedule found |
| 1: | Interference ranges ← Transmission ranges |
| 2: | repeat {outer loop} |
| 3: | Obtain $G_{int} = (V', E')$ from $G = (V, E)$ and the interference ranges |
| 4: | Apply RLF to the $G_{int}$ |
| 5: | Interference ranges ← Interference ranges · Increment of range |
| 6: | until $S$ is feasible |

### 3.3 Numerical results

In this section we will analyze the performance of the algorithms presented above.

#### 3.3.1 General behaviour of the algorithms

Figure 3.6 shows the number of timeslots in average obtained with GP, PH and RLF depending on the number of nodes in the network. Observe that for few nodes
the number of timeslots increases fast when adding a new node, however, this rapid increase in timeslots is slowed down as the number of nodes augments, to the point that from a certain number of nodes the increases remain constant. This implies that at the beginning the number of links allocated per timeslot increases as the number of nodes does, indicating an amelioration on the reuse of timeslots. Two factors are responsible of this behaviour.

For few nodes the average degree \(d(G)\) and maximum degree \(\Delta(G)\) (where degree is the number of incoming and outgoing links of a node) of the network, presented in figures 3.7 and 3.8 respectively, have a big impact on the number of timeslots required. As the number of links augments, the interference becomes the main limiting factor on the reuse. It is worth noting that the maximum degree of a network \(\Delta(G)\) represents a strict minimum bound on the possible number of timeslots in a free interference network. There are at least \(\Delta(G)\) links that have to be scheduled in different timeslots as they have a node in common. In fact, and referring this problem again with the colouring problem, and more specifically with the edge colouring, we know that according to Vizing’s theorem the minimum
number of timeslots required if the optimal solution is found is,

\[ \Delta(G) \leq G(\chi) \leq \Delta(G) + 1 \]  \hspace{1cm} (3.5)

where \( G(\chi) \) is the chromatic number, in other words, the minimum number of colours required to colour all edges such no adjacent edges share the same colour. In our case, the chromatic number represents the minimum number of timeslots required, since links sharing the same node cannot have the same colour, that is, they must be allocated in different timeslots.

![Figure 3.7: Average degree of the network depending on the number of nodes.](image)

![Figure 3.8: Maximum degree of the network depending on the number of nodes.](image)

The second factor influencing the better reuse of timeslots is due to a decrement on the interference generated by each user. This decrement responds to the fact that nodes are always distributed in the same area, and therefore, an increment on the number of nodes joint to the utilization of MPR implies shorter links, what at the same time means a reduction on the transmitted power by users. This reduction of power permits a higher reuse of timeslots.

### 3.3.2 Performance comparison among algorithms

As we can see in figure 3.6, the best scheduling technique found for most of the simulation, in terms of number of timeslots, is the Greedy Physical. Figure 3.9 shows more clearly the difference in percentage between RLF and PH compared to GP. The maximum difference reached between the GP and the RLF is around 10%. However, from this point GP becomes less efficient to the point that for large topologies the best scheduling algorithm is the RLF (negative values of the gain). PH
behaves in the same way RLF does compared to GP, although it never outperforms the GP algorithm.

![Graphs](image)

(a) Difference in percentage between GP and RLF
(b) Difference in percentage between GP and PH

**Figure 3.9:** Gain in percentage of GP compared to RLF and PH.

### 3.3.3 RLF analysis

A critical parameter of the RLF algorithm presented in section 3.2.1 is the interference range assigned to each transmitter. In the literature different values are applied, although most of the works take as interference range 2 or 3 times the transmission range [28][29]. These values are approximated and their success depends on lots of factors of the scenario. Remind that undersized values of the interference ranges result in not practical schedules, and oversized interference ranges will lead to inefficient schedules. Because of that, and to fairly compare the RLF with two algorithms within the physical interference model, we check the feasibility of each schedule obtained with the RLF algorithm through an outer loop. The outer loop increases the interference ranges of all transmitters until a feasible schedule, in terms of SINR, is found. The number of iterations performed by the outer loop depends on two parameters: the initial interference ranges assigned and their increments on distance per iteration. Next, we study the number of iterations performed, as they are related with the computational efficiency of the algorithm. In figure 3.10 it is presented the cumulative distribution of iterations depending on the distance increments.
This figure reveals an undersized initial interference range as well as a significant increment on the number of iterations when the distance increments are small. Setting the initial interference range to higher values, instead of the current transmission range assigned, would lead to a reduction on the number of iterations performed by the outer loop. Nevertheless, finding an adequate initial interference range is hard because of the many parameters involved in the correct initialization of this parameter, such as the number of nodes or the SINR required. With regard to the distance increments, we would like to note that besides affecting on the number of iterations they also impact on the quality of the solution achieved. Large distance increments mean less iterations, and so obtaining worse solutions in terms of timeslots. In order to discern the impact of the distance increments in the timeslot allocation we present table 4.1. Remind that we have defined the increments as a percentage of the transmission range of each transmitter. For instance, if the transmission range of a certain transmitter is 200 meters and the increments are set up to a 5%, the increment value for this transmitter is 10 meters.
### Table 3.1: Number of timeslots for a network with 40 nodes depending on the distance increments

<table>
<thead>
<tr>
<th>Distance increments (%)</th>
<th>Number of timeslots</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.74</td>
</tr>
<tr>
<td>2.5</td>
<td>9.76</td>
</tr>
<tr>
<td>5</td>
<td>9.88</td>
</tr>
<tr>
<td>10</td>
<td>10.05</td>
</tr>
</tbody>
</table>

From table 4.1, we observe the deterioration of the timeslot allocation as the distance increments are larger. In our simulations we have chosen distance increments of 2.5% of the transmission range, which permits to obtain good results in terms of number of timeslots without requiring an excessive number of iterations, as can be seen in figure 3.10.

### 3.4 Concluding remarks

In this chapter, we described two of the most accepted scheduling techniques for WMNs based on STDMA. Furthermore, we evaluated their performance using the models and parameters explained in chapter 2. Thereby, we obtained a quality benchmark that we used in this same chapter to evaluate a new scheduling algorithm proposed in this thesis. This algorithm, based on graph colouring techniques, demonstrated to perform reasonably well for large topologies, but poor results were obtained for small topologies. However, applying a better criterion to set and increase the interferences ranges may lead to significant improvements on their performance.

Furthermore, we stated the similarities between the Greedy Physical and the Packing Heuristic with a bin packing heuristic called First Fit Decreasing algorithm. In that respect, we would like to note that other simple bin packing heuristics such as the Best Fit algorithm can open new lines in the research of the maximization of the reuse of timeslots.
Chapter 4

Ameliorating some greedy scheduling techniques

In this chapter a fast randomized parallel link swap based packing (RSP) algorithm for timeslot allocation in a Spatial Time Division Multiple Access (STDMA) wireless mesh network is presented. The proposed randomized algorithm extends greedy scheduling algorithms that utilize sorted lists of links to create the schedules by applying a local search that leads to a substantial improvement in the spatial timeslot reuse. In particular, we will apply RSP to the previously explained GP and PH algorithms, though it could be applied to other algorithms. As will become evident in the numerical investigations, the proposed scheme can significantly decrease the frame length by up to 11%, providing in that respect better spatial reuse of timeslots in the mesh network compared to previous well known greedy scheduling algorithms. Another key benefit of the proposed scheduling scheme is that the computations can be parallelized. Clearly, among the applications that can significantly gain from multi-core and multi-CPU enabled network elements are the scheduling algorithms. To this end, the proposed fast scheduling algorithm falls within the family of the so-called ”embarrassingly” parallel problems [17] since different iterations of the algorithm can be executed without requiring any communication between them.

The rest of the chapter is organized as follows. In section 4.1 we study the gains achieved by sorting links following GP and PH criteria compared to a random sorting and we propose new approaches to attack the scheduling problem. In the
next section we present RSP algorithm which as mentioned before is based on a local search. A simple method to save calculations in the RSP, and hence, to increase the computational efficiency will be presented in section 4.2. Finally we will present the numerical investigations in section 4.4 and the concluding remarks in section 4.5.

4.1 Different approaches to the link scheduling problem

The strategy followed by several scheduling algorithms consists in firstly sorting the links based on a pre-defined criterion and then greedily packing the links into timeslots to generate feasible schedules. Both steps have an important role in the consecution of an efficient spatial reuse of the timeslots. In this section, though, we are only going to focus on the influence of the first step. In the previous chapter we have described two different criteria based on the interference number and the transmitted power. At this point, it is interesting to quantify the contribution gain of these criteria with respect to a random sorting of the links. Table 1 presents the gains in percentage of timeslots between sorting the links according to the GP and the PH criteria with a random order. The way links are packed into timeslots, once the sorted list has been created, is performed in the same manner FFD does. We can appreciate significant gains for the GP criterion and moderate gains for the PH one. Clearly the way links are sorted has a clear relevance on the resultant schedule.

<table>
<thead>
<tr>
<th>Nodes</th>
<th>PH (%)</th>
<th>GP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>3.5</td>
<td>6.5</td>
</tr>
<tr>
<td>40</td>
<td>3</td>
<td>8.4</td>
</tr>
<tr>
<td>60</td>
<td>3.3</td>
<td>9.8</td>
</tr>
</tbody>
</table>

Table 4.1: Percentage gain of GP and PH criteria with respect to a random sorting of the links.

Finding the best order in a brute force enumeration is not possible as there are $(N - 1)!$ possible ways to sort links. Because of that, it is important to find good
criteria to sort links. There are other possibilities such as optimization heuristics that can help to improve the reuse of timeslots. Generally, these heuristics are feed with an initial solution that serves as starting point. Examples of these techniques are tabu search, simulated annealing or genetic algorithms among others. Nevertheless, all these techniques present different sets of parameters difficult to configure, since they are very dependable on the scenario, as well as they require a cost function not easy to construct. Furthermore, they usually require a large number of iterations to find good solutions.

Another possible approach to find good solutions is to perform a local search. The idea is to start exploring the neighborhood of a solution given by some greedy algorithm. This is the basis of the RSP, which is going to be explained in detail in next section.

4.2 Randomized Link Swap Packing (RSP)

The RSP algorithm is based on altering those sorted lists by swapping $N_s$ (number of swaps) times the order of two elements selected randomly from the list $L$. The number of swaps applied to the list characterizes the degree to which the original list is distorted. After the swapped list is generated, links are scheduled according to the GP or PH algorithms as described in the previous chapter. Hence, a new feasible schedule is obtained. Different criteria can be applied in order to determine the best schedule when schedules with the same frame length as the best one found so far are generated. For instance, to improve the interference robustness of the network, possible criteria are (i) to choose the schedule with the best averaged SINR or (ii) the schedule with the maximum average min-SINR across all timeslots. This process is repeated for a pre-defined number of iterations ($M_{ITER}$). The pseudo-code of the proposed RSP algorithm is shown in 5 below.
Algorithm 5 Randomized Link Swap Packing

**Input:**
- $L$, list containing all links sorted by its interference number, or power levels
- $N_s$, number of swaps
- $M_{ITER}$, maximum number of iterations
- $P$, number of processors

**Output:**
- $S_{BEST,p}$, a feasible schedule found so far at processor $p$
- $T_{BEST,p}$, the minimum frame length found so far at processor $p$

1: $S_{BEST,p}$, $T_{BEST,p} \leftarrow \text{Schedule}(L)$
2: for each processor do
3:  for $i=1:M_{ITER}$ do
4:   $L_{SWAP} \leftarrow L$
5:   for $j=1:N_s$ do
6:    $L_{SWAP} \leftarrow \text{Swap two elements from } L_{SWAP}$
7:  end for
8:  $S, T_S \leftarrow \text{Schedule } L_{SWAP}$
9:  if $T_S \leq T_{BEST}$ then
10:     $T_{BEST,p} \leftarrow T_S$
11:     $S_{BEST,p} \leftarrow \text{BestSchedule}(S, S_{BEST,p})$
12:  end if
13: end for
14: $T_{BEST} \leftarrow \min(T_{BEST,p})$
15: $S_{BEST} \leftarrow \text{BestSchedule}(S_{BEST,p})$
16: end for

As it can be observed from algorithm 5, the proposed RSP algorithm can be easily parallelized and run in $P$ processors. In fact, the RSP algorithm can run without requiring any communication between the different processors, therefore there is no communication cost or delay for exchanging information between the different processors. Hence, the RSP algorithm enables embarrassingly parallel computations since different schedules can be calculated independently, offering a convenient way to use multiple processors concurrently to solve the problem.
4.3 Savings

As mentioned above, the RSP algorithm modifies a given list by swapping $N_s$ elements and then proceeds to obtain a new feasible schedule. Remind that each time a schedule is calculated a large number of operations need to be performed. Hence, reducing the number of operations becomes a priority to improve the computational efficiency of the algorithm. Nevertheless, note that RSP does not need to re-schedule all links each time the list is modified. All links placed before the first swapped link do not need to be re-scheduled, as they will remain in the same timeslots of the original schedule, the schedule calculated with the original list ($L$).

In fact, this is straightforward for the GP algorithm where links are scheduled sequentially from the created list. On the other hand, PH fills timeslots until no more links can be packed, and therefore, the initial list is emptied none sequentially. Consequently, when applying the savings strategy to PH we need to save the order on which links are inserted into the timeslots from the initial list ($L$), and then, we can either apply the swaps to this new list or we can apply the swaps to the original list and use this mapping to know which links do not need to be re-scheduled.

In section 3.1.3 we concluded that GP and PH only differ on the resultant schedule because of the different criterion when sorting the links. However, we have shown that, although the number of calculations performed to construct a schedule given the same initial list is the same for both algorithms, the distribution of the SINR operations is different. In particular, we have seen that PH calculates more SINR for the first links, whereas GP does more calculations to schedule the last links. Then, if RSP adopt the strategy followed by PH to schedule links, we can benefit from a major reduction in the number of SINR operations, since we avoid the allocation of the first links, that are the ones that need more operations to be scheduled.

Mathematically, the average number of links that does not have to be re-scheduled is determined by 4.4. It is necessary to previously calculate the probability density function (pdf) shown in 4.1. In order to obtain the pdf, we calculate in 4.2 the probability of saving at least $k$ links after applying $N_s$ swaps and in 4.3 the probability of saving at least more than $k$ links after applying $N_s$ swaps. Each swap is an independent event, hence the probability of saving at least $k$ links after applying $N_s$ swaps is the probability of saving at least $k$ links for one swap and raise it to the
power of the $N_s$ swaps applied. The probability of saving at least $k$ links for one swap is the probability of selecting a link from the set $L - k$ (as shown on the left side of figure 4.1) and then selecting another different link from the same set (as shown on the right side of figure 4.1).

![Diagram](image)

Figure 4.1: Packing list.

\[ P(S = k) = P(S \geq k) - P(S > k), \quad \text{with } 0 \leq k < L - 2 \]  \hspace{1cm} (4.1)

\[ P(S \geq k) = \left( \frac{L - k}{L} \cdot \frac{L - 1 - k}{L - 1} \right)^{N_s} \]  \hspace{1cm} (4.2)

\[ P(S > k) = \left( \frac{L - k - 1}{L} \cdot \frac{L - 1 - k - 1}{L - 1} \right)^{N_s} \]  \hspace{1cm} (4.3)

\[ \overline{S} = \sum_{k=0}^{L-2} k \cdot P(S = k) \]  \hspace{1cm} (4.4)

### 4.4 Numerical investigations

We evaluate the performance of the RSP by comparing it with the two well known and tested greedy STDMA scheduling schemes that utilize the physical interference

The quality of the solution provided by the RSP algorithm scheme ($T_{RSP}$) is compared to the corresponding solutions from the GP ($T_{GP}$) and the improvement, denoted as $I(\%)$ is measured as follows,

$$I(\%) = \frac{T_{GP} - T_{RSP}}{T_{GP}}$$  (4.5)

The same measure is used to compare the solution quality of the proposed RSP algorithm with the PH ($T_{PH}$) algorithm.

Figure 4.2 shows the performance gains on the minimum frame length using the proposed randomized scheduling scheme compared to the Greedy Physical algorithm with respect to the number of iterations. Observe that the gains with the number of iterations follow a concave like function, which means that the net benefit of performing higher number of iterations diminishes with the number of iterations. Substantial improvements are achieved with a reduced number of iterations, for instance, with just 15 iterations the schedule allocation is ameliorated above 5 % for topologies with 40 and 60 nodes.

![Figure 4.2: Performance gains on the minimum frame length using the RSP algorithm compared to the GP algorithm with respect to the number of iterations for topologies with 40 and 60 nodes. These results have been calculated using 3 swaps.](image)
The same behaviour holds when the RSP is applied to the Packing Heuristic, as figure 4.3 shows.

![Graph showing performance gains on the minimum frame length using RSP algorithm compared to PH algorithm for topologies with 40 and 60 nodes (3 swaps are assumed).](image)

**Figure 4.3**: Performance gains on the minimum frame length using the RSP algorithm compared to the PH algorithm for topologies with 40 and 60 nodes (3 swaps are assumed).

In this case, the gain obtained is slightly higher and, in consequence, with less than 10 iterations we achieve an improvement above 5%. Figure 4.4 describes the performance improvement on the minimum frame length using RSP (with different number of link swaps) compared to the GP and PH for different number of nodes in the network. As mentioned above, the number of swaps applied to the list influences the degree to which the original list is distorted. Observe from figure 4.4 that after a small number of swaps the performance stops increasing.

We should note that the iterations of the algorithm can be parallelized and therefore to optimally utilize multi core processor units. This is a crucially important feature of the proposed scheme since it is now widely accepted that number of cores to even double every two years creating in that respect a need to design scheduling algorithms that can be easily parallelized.
Figure 4.4: Performance gains on the minimum frame length using the RSP algorithm (with different number of link swaps) compared to the GP and PH. These results have been calculated with 200 iterations.

Finally, table 4.2 shows the average number of links that do not need to be rescheduled after one iteration of the RSP algorithm for a different number of swaps and different number of nodes. The number of links saved increases as the number of nodes in the network increases, and decreases as the number of swaps increases.

<table>
<thead>
<tr>
<th>Number of swaps</th>
<th>N=20</th>
<th>N=40</th>
<th>N=60</th>
<th>N=80</th>
<th>N=100</th>
<th>N=120</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.0</td>
<td>12.7</td>
<td>19.3</td>
<td>26.0</td>
<td>32.7</td>
<td>39.3</td>
</tr>
<tr>
<td>3</td>
<td>2.3</td>
<td>5.2</td>
<td>8.0</td>
<td>10.9</td>
<td>13.7</td>
<td>16.6</td>
</tr>
<tr>
<td>5</td>
<td>1.3</td>
<td>3.1</td>
<td>4.9</td>
<td>6.7</td>
<td>8.6</td>
<td>10.4</td>
</tr>
</tbody>
</table>

Table 4.2: Average number of links saved

4.5 Conclusions

In this chapter a fast randomized link scheduling algorithm for STDMA enabled wireless mesh networks was detailed. The randomization is based on swapping links on
a list that is created by well known greedy scheduling algorithms such as the Greedy Physical and the Packing Heuristic. Extensive numerical investigations reveal that the proposed fast scheduling scheme can improve by up to 11% the timeslot reuse compared to the previous mentioned link scheduling algorithms. Another important characteristic of the proposed scheme is that its structure is amenable for parallel processing and therefore, emerging multi-core and multi-CPU enabled network elements can be fully utilized. The simplicity of the algorithm, the achieved gains and the potential of parallel computation clearly demonstrate the potential benefits of the proposed scheme.

Future avenues of research include a theoretical characterization of the proposed randomized scheduling scheme. In addition, it would be worthwhile to investigate the potential of integrating the proposed scheme with routing, so that a joint randomized scheduling and routing scheme can be implemented.
Chapter 5

Directional antennas in WMNs

In previous chapters we discussed different scheduling algorithms to try to efficiently allocate links into timeslots, and hence, to increase the spectral efficiency of the system. In this chapter, we will focus on the employment of selectable multi-beam directional antennas, such as beam switched phase array antennas, which have been proved to significantly enhance the overall reuse of timeslots by reducing interference levels across the network, and thereby, increasing the spectral efficiency of the system. To perform though a switch on the antenna beam it may require up to 0.25 msec in practical deployed networks [15], while at the same time very frequent beam switchings can affect frame acquisition and overall reliability of the deployed mesh network.

To face all these problems and benefit from switched beam antennas we present a set of algorithms that try to minimize the overall number of required beam switchings in the mesh network without penalizing the spatial reuse of timeslots, i.e., keeping the same overall frame length in the network. Numerical investigations reveal that the proposed set of algorithms can reduce the number of beam switchings by almost 90% without affecting the spatial reuse of timeslots.
5.1 The effect of link scheduling on antenna beam switching

The pattern and order of the beam switchings for a specific node in the network depends on the link scheduling algorithm. For every beam switch, the antenna consumes energy and requires an amount of time to stabilize the new radiation pattern. Therefore, reducing the number of beam switchings increases the performance and robustness of the network. To illustrate how the order of the link scheduling algorithm itself affects the number of beam switchings in a node we proceed with an example.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{beam_switching.png}
\caption{Sequences of radiation patterns with 2 and 4 switches. Note that the links in bold represent the links that are active (transmitting or receiving) each time.}
\end{figure}

Figure 5.1 shows a node equipped with an antenna that can form 4 different beams (each of 90°) and has 4 incoming or outgoing links. The number of beam switches varies depending on the timeslot allocation, i.e., the link scheduling. Since there are four links, these need to be scheduled in different timeslots. In this scenario, it is assumed that links $e_1$ and $e_2$ use a common beam to establish a communication and
the other two links, i.e., $e_3$ and $e_4$ utilize another (common) beam to communicate. In the upper part of figure 5.1, links are activated following the sequence $e_1 - e_2 - e_3 - e_4$. As links $e_1$ and $e_2$ use the same antenna beam and are activated consecutively, there is no antenna beam switching between these transmissions. The same argument applies for links $e_3$ and $e_4$. On the other hand, the antenna must always apply a beam switch between links $e_2$ and $e_3$ as they utilize different radiation patterns and are activated consecutively; the same applies for links $e_4$ and $e_1$ taking into account that after link $e_4$ is activated, link $e_1$ will be the next link to be activated. Therefore, in this case the antenna will need to apply two beam switchings. The same links as described above, but activated in different order $e_1 - e_3 - e_2 - e_4$ are presented at the bottom part of figure 5.1. In this case, in each timeslot the antenna needs to change the previous radiation pattern. Hence, the antenna applies a switch between each pair of links, even between links $e_4$ and $e_1$, as it was explained in the previous example. As a consequence, in this case four beam switches are required by the node.

The above example shows how an antenna with just two different active radiation patterns can have a different number of beam switchings depending on the order the links have been scheduled by the scheduling algorithm in the mesh network. On the other hand observe that, for a given timeslot allocation, the number of switches might decrease as the number of different patterns in an antenna does. In addition, despite the fact that in this example the antenna utilize a single beam for every link activation, the same procedure of counting the number of switches applies for antennas where simultaneous beams are activated at the same time. In the next sections the proposed algorithms consider more generalized cases compared to the above example for reducing the number of beam switchings by joining different beams without though affecting the feasibility of each link transmission.

The result below provides an upper bound in the worst-case scenario regarding the interaction between link scheduling and beam switching.

**Lemma 1** For a node $i$ with active beams $B_i > 1$ and degree $D_i > 2$, the number of beam switch reductions is bounded by $D_i - 2$.

**Proof** Using figure 5.2 it can be seen that in the worst case scenario where the scheduling order of links is as follows $1 \rightarrow 2 \rightarrow 3 \rightarrow ... \rightarrow D_i - 1 \rightarrow D_i$ the number of beam switchings is equal to $D_i$ (or $D_i - 1$ if $D_i$ is an odd number). The minimum
number of beam switchings is 2; this is the case when the scheduling order is as follows, $2 \rightarrow 4 \rightarrow 6 \rightarrow \ldots \rightarrow D_i \rightarrow 1 \rightarrow 3 \rightarrow \ldots \rightarrow D_i - 1$.

Using the above result, the upper bound on the number of beam switch reductions in a WMN with $N$ nodes is

$$\sum_{i=1|D_i>2}^{N} (D_i - 2)$$

(5.1)

**Figure 5.2:** Upper bound on the number of beam switchings when scheduling is agnostic on the pattern of the beam switchings at the antenna.

### 5.1.1 Complexity of finding the minimum number of beam switchings in the network

Finding in a brute force manner the minimum number of beam switchings that can still produce a feasible STDMA scheduling can only take place for small wireless mesh network topologies since the complexity increases exponentially with the number of nodes in the network. Table 5.1 shows the different possible antenna configurations for a node with 3 and 4 beams. In the table, the horizontal axis represents the timeslots and the beam configuration is encoded as a binary string, where binary 1 and 0 denotes if the beam at the specific timeslot is active or not respectively. The bold binary strings denote the case where a node has 3 beams.
Table 5.1: Binary Encoded Antenna Beam Configurations for 3 (in bold) and 4 Beams.

<table>
<thead>
<tr>
<th>Configurations</th>
<th>Timeslots</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
</tr>
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<td>100</td>
</tr>
<tr>
<td>3</td>
<td>010</td>
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<tr>
<td>4</td>
<td>001</td>
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<td>0100</td>
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<td>14</td>
<td>0110</td>
</tr>
<tr>
<td>15</td>
<td>0101</td>
</tr>
</tbody>
</table>

Figure 5.3 gives an example of the combinatorial explosion of searching possible different antenna pattern for perfect binary trees. The average degree of a perfect binary tree is $2 - 2/N$, where $N$ is the number of nodes in the network. This closely resembles the average degree of the randomly generated shortest path tree topologies showed in chapter 3. Clearly, a brute force enumeration of all possible beam configurations to find a configuration with the minimum number of beam switchings can only take place for topologies with small number of nodes. In the following sections we detail algorithms which their complexity increases polynomially with the number of nodes in the network.
Figure 5.3: Number of antenna configurations for perfect binary tree topologies with different number of nodes. In the notation $A(B)$, $A$ express the number of nodes in that binary tree level and $B$ is the number of antenna configuration for these nodes. For the topology with 7 nodes the number of possible antenna configurations are $C_7 = 2 \cdot 5^2$, for the network with 15 nodes are $C_{15} = 2 \cdot 5^6$, while for the case of 31 nodes are $C_{31} = 2 \cdot 5^{14}$.

5.2 Antenna Beam Joining Strategies

It is well known in the literature ([13],[30],[31]) and as it will also be demonstrated in section 5.3, that the performance of a multi hop wireless network increases when
the antenna beam width is decreasing. This improvement is due to the fact that directional antennas improve the spatial reuse of the network. As the beam width of the antennas decreases it is expected that the number of beam switchings increases. Therefore, reducing the number of beam switchings becomes more important in the cases where the spatial timeslot reuse in the network is high. Initially, each link in the network is assigned to one radiation pattern for the receiving antenna and one for the transmitting antenna and each pattern is initially formed by only one beam. The intuitive rational is that when the number of different beam patterns in an antenna decreases, it is expected that the number of beam switches is likely to decrease too. Hence, minimizing the number of different patterns of an antenna, or in other words, allowing multiple beams per node to be activated at the same time, is the main strategy for reducing the number of beam switchings. We further assume that the timeslot allocation is not feasible when all nodes operate in an omnidirectional mode (that case would negate the need to decrease the number of beam-switchings). An absolute upper bound on the number of beam-switchings, \( b_s \), can be derived from the degree, \( D_i \), of the nodes in the network. It can be easily shown that the following inequality holds,

\[
1 \leq b_s \leq \sum_{i=1}^{N} D_i I(D_i) \quad (5.2)
\]

where \( I(x) \) is the indicator function defined as follows,

\[
I(x) = \begin{cases} 
1 & \text{if } x > 1 \\
0 & \text{otherwise}
\end{cases}
\]

Case Study: For \( N = 50 \) nodes in a wireless mesh network and assuming an average degree in the network equal to 2 then \( b_s = 100 \). To put this into perspective, if we further assume the links are packed by the STDMA scheduling algorithm in 10 timeslots and that each timeslot has a duration of 2.5msec\(^1\) then in this wireless mesh network we would have 4000 beam switchings per second.

To reduce the number of beam switchings in the network suitable beam joining should be performed at each node. The consequence of joining different beams implies that when a node \( i \) wants to transmit to a neighbour node \( j \), its power will be spread along several beams of the antenna instead of just along one beam, i.e., the beam

\(^1\)Frame length based on IEEE 802.16e transmission characteristics
that link \((i, j)\) belongs to. As a result, there will be an increase of the interference in the regions where there was not any active beam before the joining. Increasing levels of interference across the network caused by joining different beams of an antenna may create infeasibility on the timeslot allocation.

Two different approaches are presented with the aim of reducing the aggregate number of beam switchings in the network, while at the same time ensuring that the scheduling remains feasible. In the first strategy, beams belonging to the antennas with lower number of different radiation patterns are selected to be joint first, as will be detailed in 5.2.1. In the second strategy, beams are sorted in increasing order by their interference number (IN), which was explained in chapter 3. Another important criterion is how to validate if the requirements of the network are still satisfied in case that two different radiation patterns are activated at the same time. Two different approaches can be applied whether a fixed scheduling of the links is considered or whether a rescheduling of them is allowed.

Sections 5.2.1 and 5.2.2 detail the proposed beam joining algorithms based on the interference number and pattern order strategies, when both of them employing a fixed schedule. Finally, section 5.2.3 describes how to modify the previous algorithms to allow rescheduling of the links.

### 5.2.1 Beam Joining algorithm with Pattern Order

The first algorithm presented in the sequel tries to join firstly the patterns of those antennas that initially have less active beams (number of antenna beams that contain at least one link). The rational is to first join the beams of those antennas that once joined their emitted power will be spread in less directions. Thereby, we favour that more antennas can join their beams afterwards, since the aggregate interference brought by the previous joining affected the minimum directions possible. In case two antennas have the same number of active beams, the antenna with lower degree (number of incoming and outgoing links of an antenna) is sorted first. The purpose of this distinction is to initiate merging firstly the patterns of those antennas that affect less timeslots, as they are more likely to interfere with less links. The pseudocode of the proposed scheme is shown below,
Algorithm 6 Beam Joining with Pattern order

**Input:** $G = (V, E)$, communication graph of the network $N_p$, List containing all nodes (antennas) sorted by the number of different patterns in increasing order and if they are equal by degree.
$L_s$, List containing the incoming and outgoing links of a node $S$, Schedule $Gains$, gains of all patterns

**Output:** $Patterns$, List of all patterns and their respective associated patterns that are activated at the same time.

1: for $i = 1$ to $|N_p|$ do
2: $L_s \leftarrow E(N_p[i]) \{E(v)$ denotes the set of all edges in $E$ at a vertex $v$, as defined in [32]\}
3: $a \leftarrow 1$
4: for $j = 1$ to $|L_s|$ do
5: $a \leftarrow a + 1$
6: for $k = a$ to $|L_s|$ do
7: if $Different_Patterns(Ls[j], Ls[k])$ then
8: $Temp\_Patterns \leftarrow Join(Ls[j], Ls[k])$
9: $Temp\_Gains \leftarrow Update\_gains(Ls[j], Ls[k])$
10: if $Feasible(S)$ then
11: $Patterns \leftarrow Temp\_Patterns$
12: $Gains \leftarrow Temp\_Gains$
13: end if
14: end if
15: end for
16: end for
17: end for

The algorithm starts by selecting a node from the list $N_p$, in which nodes are sorted in increasing order according to the number of different patterns they have; in case they have the same number of patterns they are sorted by the degree of the nodes. Thereafter, a list $L_s$ is created with the incoming and outgoing links of the selected antenna. At this point, two links are select from list $L_s$ and it is checked
if the associated patterns of these links are suitable to be joined, i.e., if they are different.

Once two patterns are suitable candidates the Pattern list is updated. Note that originally each link in the network uses only one beam (or a pattern with a single beam) to transmit and one beam to receive. The Pattern list initially contains the beam associated to each link, where from the first element until $|E|$ identifies the beam of the transmitter of each link and from $|E| + 1$ until $2|E|$ contains the beam that links utilize to receive. Furthermore, initially we add to each link the pattern of those links that uses the same radiation pattern in a common antenna, since links that uses equal patterns in the same antenna are initially considered merged. Then as the patterns of two links are merged, the Pattern list is updated adding to each beam that is associated to these two links, the rest of beams that are associated to these links. For instance, we want to join the transmitter pattern of link $m$, formed only by beam $m$, with the receiver pattern of link $n$, formed only by beam $n + |E|$. That means that link $m$ will use to transmit the beams $m$ and $n + |E|$ and so $n$ will use $n + |E|$ and $m$ to receive. Therefore, the set of beams merged together, forms a new pattern. Assume for instance that we want to join the transmitter pattern of a link $o$ (link $o$ uses the beam $o$) with the transmitter pattern of link $m$. As a design criterion of the algorithm, if we want to join the pattern of link $o$ with the pattern of link $m$ which is already joined with the pattern of link $n$, link $o$ has to be also joined with $n$. Therefore, links $m, n$ and $o$ will use to communicate the initial patterns $m$, $n + |E|$ and $o$ activated at the same time.

After a new Pattern list is found the gains are updated. All patterns that have been modified, whose number of active beams has been changed, need to recalculate their gains, as it has been explained in chapter 2. The last step consists in checking whether the link schedule is still feasible with the modified radiation patterns. It is only necessary to check the feasibility of the set of links scheduled in those timeslots that contain a link whose patterns has been changed. If the schedule is feasible, the new radiation patterns and gains of the network are preserved. Thereupon, the algorithm tries to join the associated patterns of another pair of links from list $L_s$. When all the possible combinations have been explored, the same procedure is repeated for a different antenna.
5.2.2 Beam Joining algorithm with Interference Number

The idea behind this algorithm is to iteratively find the beam that is causing less interference to the network and try to join this beam (taking into account that this beam might be already joined with other beams) with the next beam from the same antenna (which might be also joined with others) that causes less interference. In order to do that a metric that measures the interference caused by a transmitting link need to be used. The interference number (IN), in chapter 3, is a good approximation for finding the pair of patterns that are causing less interference to the network. Due to calculating the IN each time a new pattern is formed is not computationally efficient, we only calculate the IN with the initial radiation patterns (initially all patterns are formed by a single beam) and create a list of links sorted in increasing order of IN. Following this list we join patterns as will be explained later. Clearly, not updating this list each time a pattern changes implies that we might be joining patterns that are not the ones causing less interference, however we defer from calculating the IN each time a change of pattern occurs since that would substantially increase the computational complexity. The pseudo code of the proposed scheme is shown in Algorithm 7.

Algorithm 7 Beam joining with Interference Number

| Input: | $G = (V, E)$, communication graph of the network  
|        | $r$, uniformly distributed $[0, 1]$ random variable.  
|        | $L$, List containing all links sorted in increasing order by  
|        | its interference number (IN)  
|        | $Ls ← ∅$, List containing the incoming and outgoing links of a node  
|        | $S$, Schedule  
|        | $Gains$, gains of all patterns  
| Output: | $Patterns$, List of all patterns and their respective associated patterns  
|         | that are activated at the same time.  
| 1: | $p ← 0.5$  
| 2: | for $i = 1$ to $|L|$ do  
| 3: | $[u, v] ← L(i)$  
|    | {where (u,v) are the nodes of link i}
if $r > p$ then
5. else
7. end if
8. for $k = 1$ to 2 do
9. $Ls \leftarrow E(A[k]) \setminus L(i)$ \{$E(v)$ denotes the set of all edges in $E$ at a vertex $v$, as defined in [32]$\}$
10. $Ls \leftarrow \text{OrderbyIN}(Ls)$
11. $\text{jointSuccess} \leftarrow 0$
12. $j \leftarrow 0$
13. while $j < |Ls|$ and $\text{jointSuccess} = 0$ do
14. $j \leftarrow j + 1$
15. if $\text{Candidates}(L[i], Ls[j])$ then
16. $\text{Temp\_Patterns} \leftarrow \text{Join}(L[i], Ls[j])$
17. $\text{Temp\_Gains} \leftarrow \text{Update\_gains}(L[i], Ls[j])$
18. if $\text{Feasible}(S)$ then
19. $\text{jointSuccess} \leftarrow 1$
20. $\text{Patterns} \leftarrow \text{Temp\_Patterns}$
21. $\text{Gains} \leftarrow \text{Temp\_Gains}$
22. end if
23. end if
24. end if
25. end while
26. end for
27. end for

The Beam Joining algorithm based on the interference number initiates by sorting the links in increasing order of their IN. Thereafter, the algorithm selects link $e1 = (u, v)$ from list $L$ and decides equiprobably from which antenna $u$ or $v$ to start joining beam patterns. Then, it is created a sorted list by IN ($L_s$) with the incoming and the outgoing links of the antenna selected without including link $e1$. Based on that, the first candidate to perform the beam joining from list $L_s$ is selected. Note that the antenna selected has associated a radiation pattern for each incoming and outgoing link, where each pattern can be compound for a different number of beams. Once
both links are selected, it is checked if these patterns are suitable to be joined.

Patterns are suitable to be joined whether they are different or even being equal and the links that use these patterns are different. The first situation is very reasonable since the goal of the algorithm is to join different patterns in order to reduce the number of switches. The second case could be more confusing as joining equal patterns does not lead to a reduction of the switches. However, in this algorithm, patterns are not considered merged initially in order to give more flexibility to the joining procedure. For instance, suppose that patterns of links $e_1$ and $e_2$ are initially considered merged. Following the order established in the IN list we want to join the patterns associated to links $e_3$ and $e_2$. However, due to requirements of the system, the pattern corresponding to link $e_3$ can not be joined with the original pattern of link $e_1$ (without merging it with pattern of link $e_2$), but it can be joined with the original pattern of link $e_2$ (without considering it merged with $e_1$). Hence, patterns of link $e_3$ and $e_2$ cannot be joined because of having merged initially patterns of links $e_1$ and $e_2$. Figure 5.4 shows how one switch would have been saved if links $e_1$ and $e_2$ had not been merged initially and patterns would have been joined following the interference number.
As previously explained in 5.2.1, when two patterns are suitable candidates the Pattern List and the antenna gains are updated. After that, if the schedule is feasible we keep the new radiation patterns and gains of the antenna, whereas if it is not feasible, we select another candidate from list $L_s$. Thereupon, whether we are in the first antenna and we managed to join the pattern of link $e_1$ with another pattern or whether the pattern of link $e_1$ cannot be joined with any pattern from list $L_s$, we change of antenna and apply the same procedure as above. In case we have checked both antennas, we select another link from list $L$ to perform the joining. The same process is followed until all links from list $L$ have been selected.

Once the algorithm is terminated, it is checked for each antenna if the number of beam switchings are lower with the initial patterns than with the current beam forming patterns. In each antenna that this situation occurs, it is tried to be corrected restoring the initial patterns of that antenna. However, it is not always possible to restore the initial patterns of an antenna, because that modification might not
accomplish the feasibility of the timeslot allocation. The pseudocode to perform the switch correction is shown in 8.

Algorithm 8 Switch Correction

1: \( Sw_{\text{initial}} \leftarrow \text{Count\_switches}(\text{Initial\_Patterns}, S) \) \{by Initial Patterns we refer the patterns formed by single beams at each transmitter, before joining any beam\}
2: \( Sw \leftarrow \text{Count\_switches}(\text{Patterns}, S) \) \{Patterns, refer to the patterns after the joining procedure\}
3: for \( i = 1 \) to \( |V| \) do
4: \( \text{if } Sw[i] > Sw_{\text{initial}}[i] \text{ then} \)
5: \( \text{Temp\_Patterns} \leftarrow \text{Restore\_beams}(i), \text{disjoint beams of antenna } i \)
6: \( \text{Temp\_Gains} \leftarrow \text{Restore\_gains}(i), \text{set up initial gains of antenna } i \)
7: \( \text{if Feasible}(S) \text{ then} \)
8: \( \text{Patterns} \leftarrow \text{Temp\_Patterns} \)
9: \( \text{Gains} \leftarrow \text{Temp\_Gains} \)
10: \( Sw[i] \leftarrow Sw_{\text{initial}}[i] \)
11: \( \text{end if} \)
12: \( \text{end if} \)
13: \( \text{end for} \)

5.2.3 Beam Joining by allowing STDMA re-scheduling

Up to this point, a fixed link schedule was assumed and joining antenna beams was accepted if the link schedule remained feasible. Joining beams causes a change of the antenna patterns, and so in its gains, which implies a redistribution of the interference. Consequently, re-allocating the links each time a beam joint is performed, might take profit of this redistribution allowing more simultaneous beams to be activated at the same time. Hence, each time a pattern is modified, instead of checking the feasibility of the set of links scheduled in those timeslots that contain a link whose patterns have been changed, we may re-schedule all links in order to redistribute more efficiently the interference. Thereby, a beam joint is successful if the new schedule has the same or less number of timeslots than the initial schedule, since the purpose of this work is not the reduction of switches at the expense of
a deterioration in the timeslot allocation, in other words, increasing the number of timeslots. In terms of number of switches, the re-scheduling might permit a higher reduction of switches, however this approach is less computationally efficient since requires a complete re-allocation of all links each time beams are joined. Algorithm 9 shows how to modify algorithms 6 and 7 to apply this strategy.

Algorithm 9 Re-scheduling in Beam Joining algorithms
1: % New input parameters
2: TS, Number of timeslots of S
3: S_{current} ← S, Current Schedule
4: % Modification in the Beam Joining algorithms, replacing lines from 10 to 13 in algorithm 6 and lines from 19 to 23 in algorithm 7
5: TS_{new}, Schedule_{new} ← Calculate_Schedule(), with the updated Patterns
6: if TS_{new} ≤ TS then
7:   Patterns ← Temp_Patterns
8:   Gains ← Temp_Gains
9:   S_{current} ← Schedule_{new}
10: jointSuccess ← 1 % Only for algorithm 6
11: end if

5.3 Numerical investigations

In this section we present the computational results obtained based on the set of algorithms proposed in section 5.2.

Figure 5.5 illustrates the improvement achieved in terms of spatial reuse of timeslots employing switched beam forming antennas compared to omnidirectional antennas. Despite the fact that demonstrating the performance improvement of directional antennas in WMNs is not the main goal of this work, it is important to state this fact in order to justify the rational of deploying directional antennas. As expected, the spatial reuse decreases as the beam width of the antenna is increasing. This expected behavior occurs since directional antennas focus most of their transmitted power in an area controlled by the beamwidth of the main lobe; as the beamwidth increases larger areas are interfered and, as a consequence, this affects the spatial reuse of
timeslots. Finally, observe that the improvement is becoming more significant as the number of nodes of the network increases.

Figure 5.5: Reduction of timeslots employing directional antennas compared to employing omnidirectional antennas.

A similar behavior for the spatial reuse with directional antennas can be observed for the reduction of the number of beam switchings. The reduction of switches increases as the directionality of the antenna beam increases, as can be noted from figure 5.6. Observe from the figure that as the number of nodes increases the percentage of switches reduced after applying algorithm 7 decreases. However, this does not mean that the absolute value of beam switchings saved has diminished, as it is shown in table 5.2. From the table it can be noted that as the number of nodes increases the initial number of switches augments. The same behavior holds for algorithm 6, except for a slightly reduction in the percentage of improvement in terms of how much the number of beam switches have been reduced. Hence, in these scenarios algorithm 7 achieves better performance than algorithm 6.
Figure 5.6: Number of switches reduced (in percentage) using algorithm 7 compared to the initial switches with directional antennas depending on their beamwidth.

<table>
<thead>
<tr>
<th>Nodes</th>
<th>$\theta_m$</th>
<th>Initial Switches</th>
<th>Final Switches</th>
<th>Final Reduction</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>IN</td>
<td>PO</td>
<td>IN (%)</td>
<td>PO (%)</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>31.7</td>
<td>13.1</td>
<td>58.8</td>
<td>55.6</td>
</tr>
<tr>
<td>20</td>
<td>60</td>
<td>31.6</td>
<td>15.6</td>
<td>50.7</td>
<td>47.5</td>
</tr>
<tr>
<td>40</td>
<td>30</td>
<td>66.1</td>
<td>28.4</td>
<td>57.0</td>
<td>53.6</td>
</tr>
<tr>
<td>40</td>
<td>60</td>
<td>65.7</td>
<td>36.6</td>
<td>44.4</td>
<td>40.6</td>
</tr>
<tr>
<td>60</td>
<td>30</td>
<td>99.9</td>
<td>42.9</td>
<td>57.1</td>
<td>53.6</td>
</tr>
<tr>
<td>60</td>
<td>60</td>
<td>99.6</td>
<td>56.5</td>
<td>43.2</td>
<td>39.5</td>
</tr>
</tbody>
</table>

Table 5.2: Comparison between beam joining algorithms that use the Interference Number (IN) and Pattern Order (PO) metrics.

In figure 5.6 we also evaluate the reduction in the number of beam switches in the case where a fixed scheduling is considered or when link rescheduling is allowed. When rescheduling the links is permitted, the scheduling algorithm is able to gain from the redistribution of the interference, entailing in an increased reduction of the number of beam switchings. Therefore, by rescheduling the links in the WMN can...
considerably decrease the number of switches, although the computational complexity increases compared to the case where there is a fixed schedule.

Figures 5.7 and 5.8 illustrate the performance of directional beam switched antennas when varying the Side Lobe Level (SLL). Increasing the SLL results in a more directional antenna and, as a consequence, link scheduling can be performed with less required timeslots. Observe from figure 5.7 the convex structure of the curve regarding the percentage of reduction in beam switchings as a function of SLL. This result reveals that there is an optimal SLL value for which the total aggregate number of beam switchings in the network is minimized. Figure 5.8 shows in percentage the reduction of the frame length (in terms of timeslots) for different values of SLL. As it can be seen from the figure, initially the timeslots decrease fast, since overall interference is decreasing and therefore links can be packed more efficiently in each timeslot. Note that each additional increase in the value of SLL yields smaller and smaller improvements in the number of timeslots and also that beyond some point the reduction of timeslots reaches a plateau where no more improvement can be achieved.

![Figure 5.7: Number of switches reduced (in percentage) using algorithm 7 compared to the initial switches with directional antennas depending on the SLL.](image-url)
Figure 5.8: Reduction of timeslots employing directional antennas compared to employing omnidirectional antennas depending on the SLL.

Despite the fact that figure 5.8 has been obtained when considering a fixed schedule, the same behavior holds also when rescheduling is allowed. The reason is that, even if rescheduling is allowed, the scheduling algorithm will still reach a limit on how many links can allocate in each timeslot due to the SINR constraint.

5.4 Concluding remarks

Directional antennas significantly improve the spatial reuse of resources in WMNs due to the increased directivity of the antenna beam, which allows the nodes to avoid inferring signals arriving at the receiver from other concurrent transmissions. A switch beam antenna system generates a pre-defined number of beams and can select and switch between the beams depending on which link is activated, i.e., which link is scheduled for transmission. In this chapter we have shown that link scheduling and beam switching are closely intertwined and, in fact, the number of beam switchings can unnecessarily increase depending on the order in which the links are scheduled for transmission. We have illustrated how by jointly considering beam switching and link scheduling the number of beam switchings can be dramatically decreased. To this end, a set of algorithms are proposed to jointly optimize scheduling and antenna
beam switching. A wide set of numerical investigations reveal that the number of beam switchings can be reduced by almost 90% without affecting the frame length (the spatial reuse of timeslots in the network).
Conclusions and future perspectives

In this thesis we have contributed to enhance the performance of WMNs. We have centered our attention in WMNs based on STDMA, although all algorithms presented can easily be applied to WMNs based on other MAC schemes such as FDMA. Two different approaches have been developed to ameliorate the resource utilization of this kind of networks.

In the first part of the thesis we conducted our research on the link scheduling problem, where we tried to minimize the time span for all links to transmit. We provided a description of the problem as well as the study and analysis of two well known scheduling heuristics named Greedy Physical and Packing Heuristic. Furthermore, two different algorithms have been proposed. We presented a new scheduling algorithm based on a graph colouring technique called Recursive Largest First. It has demonstrated to be highly competitive for large topologies compared to the two previous heuristics described. The second algorithm proposed in this thesis was the RSP, which is based on a local search. The RSP significantly improves existing scheduling techniques, as it became evident in the numerical investigations. In addition, its design permits to compute different iterations of the algorithm in multiple CPUs or cores without requiring any communication between them, gaining therefore, in computational efficiency.

In the second part of the thesis, we have centered our attention in the employment of directional antennas on WMNs, since several works pointed significant gains using directional antennas compared to omnidirectional antennas. We have considered switched beam antennas, since the common directional antennas were not able to
offer the features required by WMNs. However, switching patterns provokes a waste of time and energy. We faced these inefficiencies by proposing a set of algorithms to minimize the number of switches without deteriorating the frame length of the schedule. The numerical results reported that the set of algorithms were able to reduce by almost a 90% the number of switches performed, ameliorating substantially the overall performance of the network. To the best of our knowledge this was the first work that dealt with the switching pattern problems.

In conclusion, we have improved the resource management of WMNs by two different approaches. However, there are still lots of open research lines that could lead to further improvements. For instance, we could go one step further and investigate the potential of integrating the STDMA link scheduling schemes proposed with routing, so that a joint scheduling and routing scheme can be implemented. Furthermore, future avenues of research can include the application of new bin packing heuristics to the STDMA link scheduling problem, or more general heuristics as tabu search, genetic algorithms or simulated annealing among others. The application of new radio advanced techniques or the development of new algorithms based on multiple-channels or multiple-radios also have a promising future. There is a wide variety of techniques or algorithms that will permit further enhancements in the performance of WMNs.
References


Appendix A

Switched beam antenna

The FCi-3100X Phocus Array System is a "Full Power" intelligent wireless access point with a patented dynamic electronically focused circular phased array antenna system for standards-based IEEE 802.11 bi g and custom network deployments. Many wireless access point deployment configurations can be dramatically simplified or "tuned" for the best coverage at a significantly reduced capital infrastructure expense using dynamic antenna technology.

The Phocus Array 3100X is a feature rich IEEE 802.11 compliant access point or client bridge/gateway. It is a small (approximately ½ cubic foot) lightweight rugged weatherproof package.

Based on Fidelity Comtech's patented Flexible Vector Modulator Technology™ (FlexVMT™), the 8-element uniform circular phased array used in the FCi-3100X's beam has a variable target footprint from a standard 360° "super" omnidirectional pattern (4 times larger than normal) to an extended long reach focused 43° co-phased pattern. The FlexVMT can electronically switch between steered or shaped patterns in less than 100 μSec on a packet-by-packet basis or be statically administered.

Because the Phocus Array System selectively directs its signal, security and privacy are dramatically improved by reducing eavesdropping possibilities and interference. This also capability permits "good neighbor" behavior.

The beam pattern can also avoid other radiation patterns and sources, avoiding interference and with its ultra sensitive receiver improves signal reach and quality for better throughput performance due to fewer packet retransmissions, increasing capacity and the speed of your wireless applications. Normal Wi-Fi devices typically have four (4) times their normal range.

The Phocus Array System combines signals from all eight antenna elements to form each directional or super omnidirectional pattern. This "spatial integration" provides up to 6.1 dB better performance than traditional antenna diversity systems.

Phocus Array Systems are targeted for use in wireless solutions for ship-to-shore, harbor, intermodal container yards, train yards, auto yards, warehouses, and tactical government security and defense applications.

Since 2001, Fidelity Comtech has provided premier RF components, antennas, and interfaces to commercial and government customers. Our products implementing the G.R.I.P.S. feature set and FlexVMT technologies are changing and improving the way the world uses wireless communications.
### Geo-Location
- Geo-l—Dynamic Beam Steering and Shaping included

### Reach Improvement
- Phased array’s ‘Super-Omni’ signal using spatial integration provides up to 6.1 dBi better performance than traditional antenna diversity systems, thereby doubling reach in free space and balancing coverage.
- Focused signal’s range can increase up to 4 times over the “super” Omni-directional pattern’s reach or 16 times the coverage area.
- Bi-directional link reliability also dramatically improves with a focused beam and receiver antenna gain

### Interference Improvement
- Focused directed or shaped beam reduces interference by up to 88%

### Privacy / Security
- Focused directed or shaped beam keeps signal away from threats and permits “Good Neighbor” behavior
- WEP, WPA, WPA2 (PSK and EAP: TLS/EAP-FAST/PREAP/TTLS/LDAP, TKIP/CCMP
- White list (MAC) and tables firewall (IP)
- Multiple:
  - Radius server support w/ certificates
  - VLANs (16) + FlexSecure
  - SSIDs

### Modes Supported
- Only AP Bridge mode is supported in the security software release
- Customers that need AP Router, AP Client and Ad Hoc modes need to purchase v2.1

### Management and Software Interface
- Remote software/firmware UpGradability using secure browser-based administration (HTTPS/SSL w/ certificate), configuration, monitoring and pattern selection; SNMP (Ethernet MIB-2), HTTP redirect
- Admin device identification, model number, serial number, unique naming

### Power Consumption
- Low power requirements simplify installation and increase usage in mobile or remote applications

### Ruggedized Package
- Optimal for outdoor and mobile vehicle applications

### Compact Size
- Ideal for portable / vehicle systems and those that require a small “wind sail” profile

### Specifications

#### Physical Characteristics
- **Antenna Type** (s): Eight (8) element uniform circular phased array Each with an associated FlexiVMT T/R module
- **Dimensions** (½ cubic foot): 9.5” width x 9.5” depth x 11” height (.24m x .24m x .28m)
- **Weight**: 9.0 lbs (4.1 Kgs)
- **Input Connection**: 10/100 Ethernet via industrial RJ-45 connector

#### Electrical
- **EIRP - Effective Isotropic Radiated Power**: Regular Power Version — 42 dBi, meets FCC requirements 500 Milli-Watts conducted power
- **Coverage Patterns**: Standard 360º horizontal by 35º vertical, focused to 43º Horizontal
- **Radiation Patterns**: Omni-directional or sector, 16 high-gain presets, and custom available
- **Dynamic Pattern Reconfiguration**: <100_uSecs
- **Frequency Bandwidth**: 2.401 GHz–2.484 GHz supporting IEEE 802.11 b/g
- **Data Rates—802.11 b and g**: 1, 2, 5.5, 6’, 9’, 11’, 12’, 18’, 24’, 36’, 48’, 54’ Mbps/sec
- **Antenna Gain**: 15 dBi maximum (43º HPBW azimuth)
- **Array Control**: Single Intel XScale 425 processor w/128M Byte of RAM
- **Input Power**: Power over Ethernet (POE), 23 watts maximum at 48VDC
- **Power Consumption**: 9.0—12.1 Watts average, 20 Watts peak.
- **Multipath reception**: Multiphase power envelope via 8 element Uniform Circular Array
- **Operating Temperature**: -40º Celsius (-40º F) to +65º Celsius (185º)

#### Certifications
- **Radio / Vibration / Environmental**: FCC - Part 15, IC - CoC

#### Warranty
- **System**: One year limited warranty (Extended warranty available)

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Since 2001, Fidelity Comtech, Inc. (FCI) has been the premier provider of RF amplifiers and antennas to commercial and government end customers, system integrators, and original equipment manufacturers (OEMs). Our customers use our products in security, ultra-high mobility, mobile network, mobile asset tracking and management, and data wireless local area network (WLAN) applications. Located at the base of the Rocky Mountains in Longmont, Colorado, Fidelity Comtech designs, manufactures, and supports products for our customers from amplifiers and antennas to complete system products like the Phoous Array System family of wireless access points and routers.

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