

Scheduling in a Multi-Sector Wireless Cell

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

In this thesis, we propose a scheduling problem for the downlink of a single cell system with multiple sectors. We formulate an optimization problem based on a generalized round robin scheme that aims at minimizing the cycle length necessary to provide one timeslot to each user, while avoiding harmful interference. Since this problem is under-constrained and might have multiple solutions, we propose a second optimization problem for which we try to find a scheduling that minimizes the cycle length while being as efficient as possible in resource utilization. Both of these problems are large integer programming problems that can be solved numerically using a commercial solver, but for real time use, efficient heuristics need to be developed. We design heuristics for these two problems and validate them by comparing their performances to the optimal solutions.

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Chapter 1

Introduction

The developments in wireless communication networks over the past couple of decades have been enormous and have become ubiquitous in modern days. It is commonly assumed that the next generation of wireless communication networks will be heterogeneous, with different types of wireless network and technologies coexisting. There are currently many different types of wireless networks. Wireless local area networks and cellular networks are by far the most dominant wireless networks of our generation and have still sparked numerous research studies. There are also many other emerging wireless networks, such as mesh networks and sensor networks, which have great future potential. In the next section, we will briefly describe cellular network, which is the focus of this thesis.

1.1 Cellular Communication System

Although the first two generations of wireless communication focused primarily on voice transmission and do not require high data rate or bandwidth, with the growing demands for multimedia-rich contents, current and future generations require a much higher rate and better quality of service.

In wireless communication, resources like spectrum are limited and have to be shared by everyone. The idea of cellular network goes back as early as 1947, and it was thought that instead of using just one high-powered antenna to cover an entire metropolitan area, we should employ several lower powered antenna base stations scattered throughout the city, thereby breaking a macro-cell into several smaller micro-cells. The spectrum is then divided such that the base stations of each of these micro-cells would be able to use a certain frequency band or channel without being affected too much by neighbouring cells (i.e., to avoid inter-cell interference).

The biggest advantage to breaking a macro-cell into smaller micro-cells is that the frequency band can be reused by other micro-cells as long as they do not interfere with each other; this means that more users can be supported and hence the network has higher capacity. The term “frequency reuse” indicates how often a frequency band can be reused. A frequency reuse of 2 would mean that we reuse the same frequency every 2 cells. This would be best if it could be done. Hence a small reuse factor is preferable. In order to minimize the reuse factor, proper frequency planning is required so that interference does not

become a major problem to each micro-cell. Figure 1-1 is a cellular network with frequency reuse factor 4.

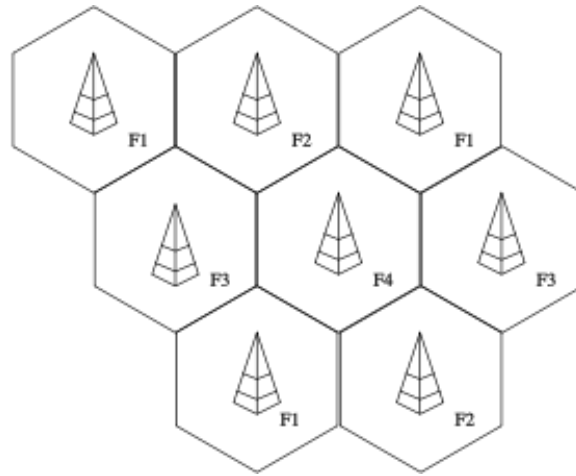


Figure 1-1: Cellular Network with Frequency Reuse, courtesy of [22]

In each of these micro-cells, the bandwidth resources can be allocated to users using several methods; frequency-division-multiple-access (FDMA), time-division-multiple-access (TDMA), or code-division-multiple-access (CDMA). In FDMA, frequency is again divided into smaller bands with each user occupying one band. In this scenario, users can only use a portion of the network bandwidth, but would always be able to access it. This was used in the first generation cellular system. TDMA, on the other hand, divides time into timeslots. Users in a TDMA scheme can only access the network for a portion of the time, but would be able to use the entire cell's resource. CDMA is very different in that it uses a digital modulation technique known as spread-spectrum which spreads the signal bandwidth into a much larger frequency band and requires a special decoding method to recover the message. Both TDMA and CDMA systems have been employed extensively in the second generation network system and are still quite often used in the third-generation network. Each of these multiplexing schemes has its advantages and disadvantages, depending on what the network operator requires.

In order to know where improvements can be made, we must first understand where the limitations are. Unlike a wired network, where capacity can be increased by adding more physical resources, and throughput can be improved by using faster a medium, the main problem facing wireless networks is that the wireless channel has to be shared by everyone.

We also need to be aware that not only does the channel have to be shared, its characteristics are quite different from the traditional wired network. First of all, compared with a wired transmission, the signal strength of a wireless transmission decreases with distance quite rapidly which causes it to be more prone to errors. The change in wireless signal strength can be attributed to path loss, shadowing, and multi-path fading. Path loss means that a signal loses power as it propagates through space and is distance dependent. We usually represent path loss by a loss exponent, which varies depending on the type of medium in which the signal is propagating, typically ranging from 2 to 4. Shadowing refers to the phenomenon where wireless signal is hindered by an obstacle which causes a significant drop in power and is often modeled with a log-normal distribution. Multi-path fading refers to the fact that the wireless signal may reach its destination through many paths (by bouncing off different objects). There are many different multi-path fading models, such as Rayleigh fading and Rician fading. In Rayleigh fading, there is no line-of-sight signal which dominates over all other received signals, this model is more applicable in a dense urban or indoor environment where a signal scatters several times before it reaches its destination. Rician fading on the other hand, contains a dominant line-of-sight component, and may be more suitable for an outdoor environment such as satellite communication. For a mobile user, these factors will change whenever the user moves around, which causes the user to perceive the channel condition differently as time goes by. Channel conditions can also be affected if the user notices other node transmissions (to or from) on the channel. Since different nodes may be using the channel at different times, interference caused by other node transmissions also changes with time. All of these factors contribute to the time varying channel condition.

The channel condition is often quantified with the notion of a signal-to-interference-noise ratio. This ratio compares the signal strength with the combined power of both noise and interference from other nodes, where a higher ratio indicates a better channel condition. The signal-to-interference-noise ratio is very important in decoding the wireless signal. A packet with a poor signal-to-interference-ratio would be very hard or even impossible to decode and could be regarded as an erroneous packet. It is clear that we can easily control this ratio by either increasing the transmit power or reducing interference.

Because different nodes will perceive channels differently, by giving the same resource to different users, it is not necessary that they would receive the same type of performance. In fact, the user who sees a good channel condition will generally receive much better throughput (and most likely more frequently) than the user who sees a bad channel condition.

In the next couple of sections, we will briefly describe some of common terminologies in cellular networking.

1.2 Centralized versus Distributed

The classical wireless network can be divided into two categories: centralized and distributed. In a centralized network, things are managed by a single network component, in most cases, the base station. In general, this means that the base station will need to handle a lot more processing and all of the coordination efforts, which requires it to be much more intelligent. For cellular network systems, a centralized network is natural because of the existence of the base stations. There are many advantages to this type of network design; first of all, it is simple and can be easily set up. Secondly, since the base station has all the information regarding the network, it makes optimization a simpler task. Furthermore, since all of the major processing is done by the base station, nodes can have a much simpler design. However, one of the biggest disadvantages to a centralized network is the idea of a single point of failure (at the base station) which would bring down the entire network without a chance for recovery. Also, a centralized network is much less scalable.

On the other hand, in a distributed network, every node knows some information about the network by sharing what they know with their neighbouring nodes. There is no single point of failure and the network is more robust in terms of failure recovery. Distributed networks are also more scalable in general. However, a distributed network suffers from time synchronization issues where not all nodes in the network will share a common time scale. Also, each node is responsible to perform a certain amount of information processing which requires a more complex node design, and more power to run.

1.3 Single Hop versus Multi-Hop

In every cellular network, there is at least one base station which serves every node in the cell. A network where every node can communicate directly with the base station is called a single-hop network. On the other hand, if a node must rely on hopping through other nodes to get to the base station, it is known as a multi-hop network, this is illustrated in Figure 1-2.

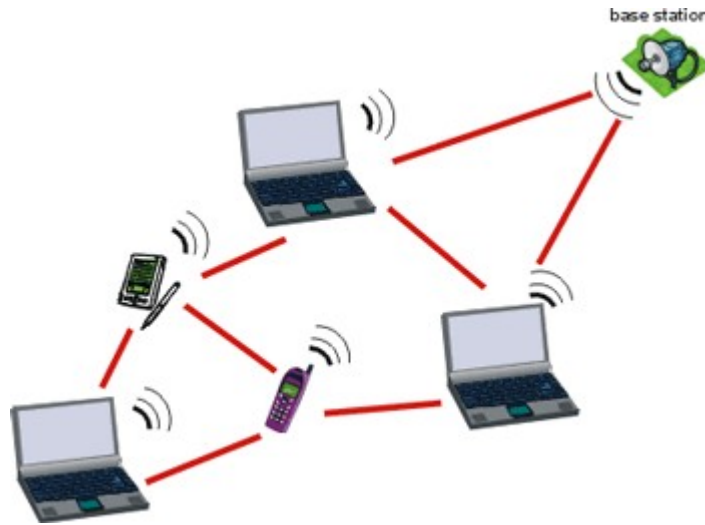


Figure 1-2: Multi-Hop Network, courtesy of [23]

In a single-hop network, since all nodes must communicate with the base station directly, a higher transmit power is necessary from the base station for downlink transmission and for each node for uplink transmission. Multi-hop networks on the other hand, allow the same cell coverage at a much lower transmit power.

However, hopping through other nodes to get to the base station has certain disadvantages. As we have discussed earlier, the wireless channel is prone to errors, therefore, the more hops it takes to reach the base station, the more chance there is for a packet error. When an error occurs, a packet has to be retransmitted, which degrades the throughput. Also, in multi-hop networks, intra-cell interference is an issue which must be dealt with carefully. In general, single-hop networks provide better throughput than multi-hop networks.

1.4 Scheduling versus Random Access

As we have mentioned earlier, resources in the cellular network are shared by everyone, the logical question becomes, how can we access the resources? There are two approaches in general: random access and scheduling.

Random access, as the name suggests, means that nodes will access the resource randomly. In the ALOHA protocol, for example, when a node has a data packet to send, it will send it out immediately. In the event of a collision, the nodes whose transmission collided will simply try to resend the packets at a later time. A more sophisticated protocol was developed later known as carrier sense multiple access

(CSMA) in which nodes will listen to the channel and make sure it is free before trying to transmit. Carrier sense multiple access with collision avoidance (CSMA/CA) is a modified version of CSMA which is used by the 802.11 based wireless local area networks.

Scheduling on the other hand, handles things differently. Instead of having each node randomly accessing the network resources, they are scheduled and have to wait until their turn to access the medium. There are many different types of scheduling algorithms. The simplest scheme of all is the round robin approach, where by each node takes turns in accessing the channel for a period of time. In this approach, every node would get an equal access to the network and no nodes would be starved. Other types of scheduling algorithms, such as max-min fair scheduling, proportional fair scheduling, and weighted fair queueing scheduling algorithms, are all commonly used depending on the needs of the overall network. Some of the research done on these scheduling algorithms can be found in [11-13,19, 21]. Opportunistic scheduling is another popular scheduling technique which has been vigorously researched in the past few years. This type of scheduling technique exploits the time-varying channel condition to try to schedule the user which has the best channel condition to improve the system throughput. It has been shown in many papers that opportunistic scheduling can improve the throughput significantly compared with more basic scheduling algorithms, such as round robin.

If we were to compare between random access and scheduling, it would appear that random access has a simpler overall structure. In a scheduled network, nodes will need to know when they should transmit, whether through a centralized server or by a distributed method, whereas for a random access network, nodes will only need to worry about whether someone else is already using the channel or not. However, in a random access network scheme, collisions are unavoidable which triggers packet retransmission in many scenarios, which in turn reduces the overall throughput. On the other hand, by scheduling node transmissions efficiently, throughput of the network can be dramatically improved. The cost of using a scheduling scheme is a more complex network structure, more intelligence at the base station and overhead, since each node needs to send information to the base station (for centralized scheduling), or in each node (for distributed scheduling), and time to run the scheduling algorithms.

1.5 Sectoring and Directional Antenna

In the beginning of this chapter, we discussed the advantage of splitting cells into smaller micro-cells in that more users can now be supported by the system. However, increasing capacity by making cells smaller is very costly in terms of infrastructure costs (installing tower, base station, etc); therefore, we need another method of increasing network capacity without having to resort to cell splitting every time.

With the development of directional antennas, sectorization became the most commonly used method of increasing cell capacity. Sectorization is similar to cell splitting in that the cell network is now divided into smaller sectors, with each sector receiving from its corresponding directional antenna at the base station. One main difference between cell splitting and sectorization is that in cell splitting, the frequency bands have to be divided and allocated to different micro-cells, whereas in sectoring, the same frequency channels are still used by every sector in the cell. One of the main advantages of sectorization is to decrease the infrastructure cost, which is extremely expensive with cell splitting. Other advantages to sectorization can be found in [2, 10].

A directional antenna just as its name suggests, is an antenna that directs its energy in a particular direction, as illustrated in the Figure 1-3. Unlike conventional omni-directional antennas where power radiates quite evenly in all directions, a directional antenna can focus its energy towards a particular direction like a beam. There are many benefits in using a directional antenna. First of all, by focusing its energy towards a certain direction, it can cover a greater distance than an omni-directional antenna using the same power level. Secondly, using directional antenna can reduce interference to other sectors or cells, which means that the system would be able to achieve better throughput.

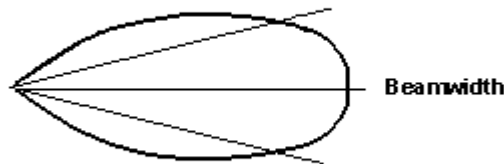


Figure 1-3: Radiation Pattern of Directional Antenna

In Figure 1-3, the beamwidth in general is measured as the angle at which the relative power of the transmit antenna is still above 50% (this is also known commonly as the -3dB beamwidth). Modeling the antenna radiation pattern is not an easy task, since there is no sharp cut-off point where the radiation power drops immediately. In [4], the authors note that perfect sectorization is not possible due to the non-ideal radiation pattern of the directional antenna. If perfect sectorization were possible, network capacity would have been proportional to the number of sectors since all sectors could be on at the same time. The

authors therefore propose a new sector beam synthesis technique to reduce inter-sector interference using antenna arrays. Although this can provide better precision in sectorization, and hence improve overall system capacity, the larger array size for each sector would indicate higher cost in implementation.

The authors in [20] considered two models for defining the antenna radiation pattern. In the first model, the sidelobe interference outside the beamwidth is constant, and the same directional gain is seen by users inside the beamwidth. Directional gain is generally normalized to the centre of the beam and represents how much signal strength can still be observed. Although this model simplifies some of the analysis, it is not as realistic as it can be. The second antenna radiation model looked at in [20] considered using a First Order Bessel Function of the First Kind. In this model, nodes both inside and outside the beamwidth will observe different directional gain depending on how far of an angle it deviates from the center of the signal beam. The directional gains for this antenna model within 3 dB beamwidth for different numbers of sectors are demonstrated in the Figure 1-4.

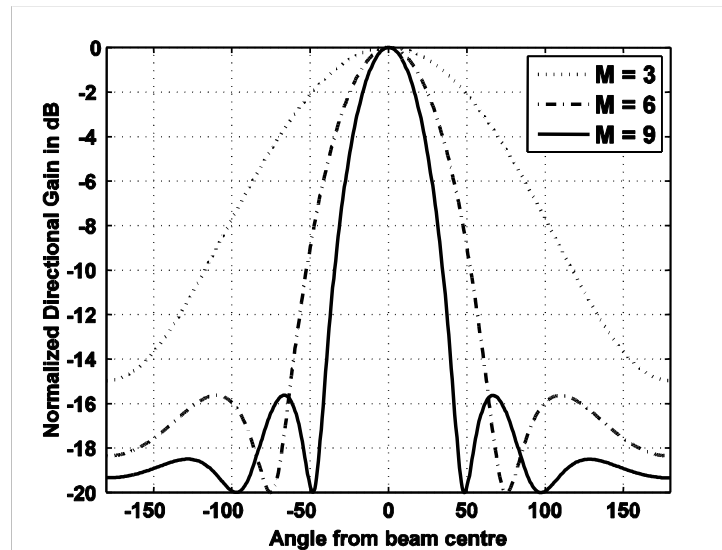


Figure 1-4: Normalized Directional Gain for Antenna Pattern based on First order Bessel Function

In Figure 1-4, the first thing that we observe is that as we increase the angle from the beam centre, the directional gain decreases. For a cell with 9 sectors, each sector covers a 40 degree area with the edge of the sector being 20 degrees from the beam centre, exactly half of the sector coverage. Since the beamwidth gain is defined as -3 dB, it means at the edge of the sector, or 20 degrees from the beam

centre, the signal would have a directional gain of -3 dB, which can be observed in the figure above. We can still observe some signal power from the directional antenna even when we go beyond 20 degrees from the beam centre, which then is observed by other sectors as simply interference. The same can be said for a cell with 3 and 6 sectors, but because of the larger sector coverage, the drop in directional gain is not as severe.

We focus in this thesis on the downlink wireless cell with one base station and N nodes located randomly in range of the base station. In order to provide equal rights to every node in terms of access time (which is one form of fairness), each frame will have to be divided into N timeslots with each node getting one timeslot per frame. Every node would then receive different rate depending on its signal-to-interference-noise ratio. However, this network is clearly not scalable, since if we increase the number of nodes in the system, the size of the frame will increase and nodes will have to wait a very long time to be served. This is because the base station is the bottleneck of the system since it can deal with only one transmission (sent or received at a given time).

One way to alleviate this problem is to divide the cell into multiple sectors by using directional antennas at the base station. With the network divided into M sectors, nodes in one sector now communicate with the directional antenna directed at their sector. This would allow multiple nodes to be serviced at the same time. However, not all sectors can be scheduled at the same time since each sector now creates interference to other sectors. The question then becomes, what is the best way to schedule nodes together so that we can minimize the cycle length?

However, solving the scheduling problem optimally for the above network is extremely time-consuming, and can take several hours even for a small number of nodes (less than 100). This is compounded by the fact that the channel conditions and the number of users present in the system may vary rapidly. Therefore, for a scheduling policy to be feasible in real life, it has to be fast and use all the resources wisely.

The purpose of this thesis is to formulate the above scheduling problem which aims at minimizing the number of timeslots required to provide equal access to every node in a multi-sector cell while being as efficient as possible. We also propose heuristics that can solve the problems sub-optimally but quickly.

This thesis is organized as follows: chapter 2 provides some background information and looks at some of the related works in scheduling in multi-sector cells.

In chapter 3, we present our overall system model. We start with some variable definitions, network parameters, antenna pattern, and also the interference model. We then discuss our objectives and formulate them into two optimization problems.

Numerical results for the exact solution are presented in chapter 4 for these two problems. We start by introducing the parameters used for the test cases and present the results for the two problems. In order to gain some useful insights to build our heuristics, we study the impact of limiting the concurrent transmission on the two problems.

In chapter 5, we propose two heuristics to solve our first optimization problem. A modified version of one of our heuristic is presented to achieve better result in our second optimization problem. We end the chapter by looking at the complexity of the heuristics as well as their runtime results.

Chapter 6 is the concluding chapter of this thesis. We reiterate some of the findings in the thesis and suggest possible future work.

Chapter 2

Background and Related Work

Wireless network optimization research has always been a hot and challenging field. Researchers always try to optimize the wireless network based on a given set of performance indicators, where throughput is the most commonly used. In many of the problems, finding the optimal solution is either NP-hard or NP-complete. Therefore, many researchers resort to simplifying the problem by making certain assumptions, or by solving the problem sub-optimally through the use of heuristics.

In the following section, we will discuss some of the work done in the past on multi-sector scheduling.

2.1 Past Work on Multi-Sector Scheduling

For fixed wireless networks, the authors in [5] proposed several methods for dynamic resource allocation. In this paper, each cell is divided into 6 sectors and TDMA is used. The authors attempt to dynamically allocate timeslots to different sectors such that the signal-to-interference ratio is high enough for successful reception. The authors first show that the problem of optimizing resource allocation under signal-to-interference ratio is indeed NP-complete. Two heuristics with reuse factor of 2 and 6 are then proposed. For a cell with reuse factor of 2, sectors are labeled 1 or 2 such that no neighbouring sectors have the same label. Timeslots are grouped into sub-frames and labeled 1 and 2 alternately. Sectors can only transmit in their corresponding sub-frame. Similarly, for a cell with reuse factor of 6, sectors are labeled from 1 to 6 counter-clockwise and timeslots are grouped into 6 sub-frames.

The heuristic with reuse factor of 2 allows a sector to use up a capacity of at most 50% of the channel capacity whereas with a reuse factor of 6, the bandwidth utilization is limited to $\frac{1}{6}$. It is clear that for better performance, we would want as high capacity as possible; therefore, lower reuse factor is more desirable. However, with lower reuse factor, the effect of inter-sector and even inter-cell interference may be quite severe, which may result in many packets becoming corrupted and needing retransmission. It then becomes a tradeoff between maximum achievable capacity and transmission reliability.

This is followed by a new and much more flexible approach called the staggered resource allocation (SRA) method. In the SRA method, a cell is still divided into 6 sectors and timeslots grouped into 6 sub-

frames, but the way timeslots are allocated is quite different. The sub-frame assignment for the major interferers are always staggered by one unit, this is done not only to take advantage of the characteristics of the directional antennas, but also to help avoid major sources of interference from adjacent cells. If all the timeslots in a sub-frame have been used, the sector can utilize the timeslot of the sub-frame for the opposite sector in the cell. Under the assumption of moderate traffic load (less than one third of the channel capacity), sectors will not significantly interfere with each other. The authors also considered limiting concurrent transmissions to improve the signal to interference ratio for different quality-of-service grades. In simulating the SRA method, they consider a simple path-loss interference model and independent traffic process and studied the effects of varying traffic load on throughput and the probability of packet success. The authors found that not only was a higher throughput was achieved, by utilizing a simple control mechanism to limit concurrent transmissions of major interferers, the probability of a successful transmission under a bad channel or antenna environment can be significantly improved. This paper is mainly focused on improving the throughput and decreasing the packet error rate for different traffic loads. In our work, instead of focusing on throughput, we look at minimizing delay experienced by the nodes assuming that base station antennas always have packets to send to them. Instead of varying the traffic load, we consider varying the number of sectors in the system, the beamwidth gain factor, and signal-to-interference-noise ratio to see how it affects our minimum cycle length.

The authors in [6] proposed a scheme called quasi-static resource allocation with interference avoidance (QRA-IA) aimed at combating both inter-cellular and intra-cellular interference. The idea behind this scheme is that by periodically turning off some sector's antennas for a certain amount of time, other terminals may experience an improvement in performance, and therefore identify the time durations which they would prefer to transmit. This information can then be used to come up with an effective scheduling to turn off different antenna beams. In simulating the methods above, the authors show that both the throughput and coverage are significantly improved. The authors note that this method can also be applied to a multi-cell system in a decentralized manner and can still achieve good results. The idea of turning off certain antenna beams is similar to one of our proposed heuristics based on forming antenna sets. By turning on a sector antenna, interference seen by other nodes will increase and likewise, if an antenna is turned off, the interference seen by other nodes will decrease. If we know our target signal-to-interference ratio, the base station can calculate every antenna combinations for which the node would still be able to receive information correctly from the directional antenna. We develop our second

heuristic based on forming this kind of antenna sets, and show through simulation that it is indeed an effective heuristic algorithm to minimize the cycle length defined in our optimization problem.

In [8], the authors suggest that frame scheduling be done in a centralized manner. Since the optimal scheduling problem is NP-complete, the authors proposed a sub-optimal solution based on first-fit algorithm. In this paper, the cell is divided into different sectors each equipped with an antenna. However, the cell only has a number of available ports, which also correspond to the number of antennas that can be simultaneously on. The author assumes that packets arrive and are queued at the base station while waiting to be transmitted. The authors describe the concept of compatibility as the condition where concurrent communications to or from different nodes are possible using the capture threshold. In this framework, if the signal power exceeds interference by at least the capture threshold for every node in a set, the set is considered compatible. The effect of power control was briefly mentioned and the authors explained that by using it, higher signal to interference ratio can be tolerated. The first fit algorithm proposed by the authors works by assigning the current packet to the first timeslot that does not violate the compatibility requirement. This can be considered a very greedy type of algorithm in which one tries to fit a node in the first opportunity that it sees available. Our greedy algorithm differs in that instead of looping through timeslots to find the timeslot to schedule a node, we loop through nodes to see which node we can schedule in this timeslot. The authors also included the notion of restricting concurrent transmission by limiting the number of available ports for transmission. In our work, we further expand on this notion and try to draw a relationship between restricting ISET size and the sub-optimal solution that we can achieve.

The authors in [7] proposed the use of dynamic slot allocation for packet-switched space-division-multiple-access and compare the performance of random allocation against heuristic-based allocation algorithms. In this paper, the system proposed by the author utilizes eight smart directional antennas which are capable of beam forming to increase the signal-to-interference-noise ratio. The number of nodes in the system ranges from 1 to 50. Three different heuristic algorithms were proposed and their overall complexities were analyzed. The first-fit algorithm is quite similar to the one proposed in [8], but differs in that in this paper, the algorithm goes from one slot to another, whereas in the previous paper, the authors traverse user by user. The best-fit algorithm is much more complicated. It attempts to add a node to the timeslot such that the resulting signal-to-interference-noise ratio is minimized among all the timeslots. It also makes sure that by scheduling the node into this timeslot, the signal-to-interference ratio constraint is still satisfied. The authors then analyze the capacity of different heuristics under three different propagation models, which are Rayleigh, Rician, and line-of-sight only (LOS-only). An

interesting observation is that for the first fit algorithm, LOS-only has the best performance with Rayleigh being the worst, and the order is reversed in the best fit algorithm scenario. Both algorithms, however, far exceed the capacity reached by random allocation. As the experiments performed were under the assumption of a certain amount of channel coherence time, the authors then analyze the effects when channel variations are introduced and conclude that this variation has significant impact in degrading the system performance. Part of the work in this paper is very similar to the first optimization problem that this thesis focuses on, which is to minimize the cycle length required to provide time fairness to every node in the cell. The best-fit algorithm proposed by the authors' shares some similarities with our modified greedy algorithm in that both of the heuristics consider the importance of signal-to-interference-noise ratio in scheduling different nodes. This paper also analyze the average number of packets per timeslot while varying the number of nodes in the system, which is different from our second optimization problem where we seek to maximize the average packets per timeslot while minimizing the cycle length.

Chapter 3

System Model & Problem Formulations

3.1 Introduction

In this section, we start by presenting our overall system model and gradually work towards defining our optimization problems. We define N as the number of users or nodes located randomly in the cell (i.e., within a fixed radius of the base station), and M as the number of sectors into which the cell is equally divided. M also represents the number of antennas located at the gateway or base station placed in the centre of the network. Each sector has its own directional antenna to transmit to every node in its sector. This is illustrated in the figure below.

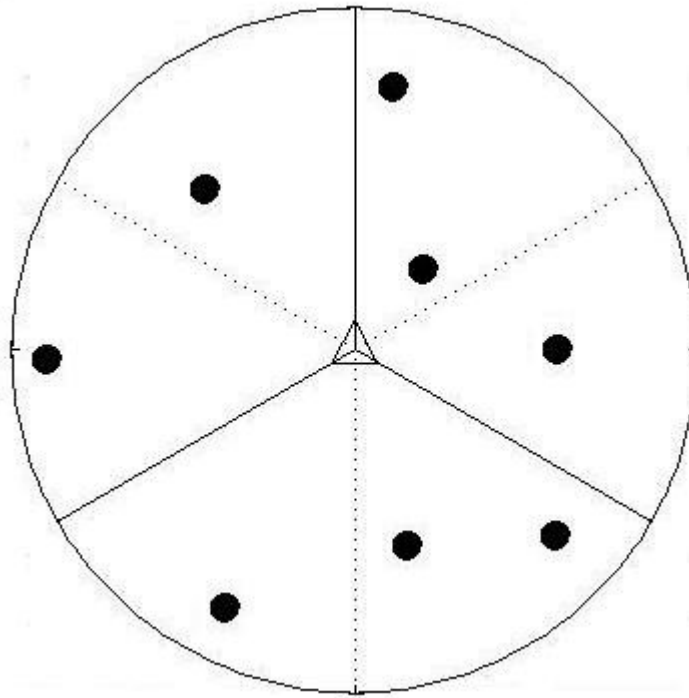


Figure 3-5: 3-sector system with 8 nodes

In the figure above, the base station is represented by the triangle at the centre, and nodes are represented by solid black circles. The three dotted lines represent the centre of the beam (i.e., the line of

symmetry) for each of the directional antenna located at the base station. In our model, we consider downlink transmissions only and that the nodes are associated with the antenna corresponding to the sector which it resides in. The directional antennas at the base station can at most communicate with one node within its sector at any given time.

As we have discussed earlier, directional antennas are used at the base station, therefore, there is a directional gain associated with it. We consider the antenna model used in [20], where the direction gain $f(\theta, M)$ is defined as:

$$f(\theta, M) = C_1 + (1 - C_1) | 2J_1(\alpha(\theta)) / \alpha(\theta) |^2$$

$$\alpha(\theta) = 4\pi C_2 \sin(\frac{\theta}{2})$$

where θ is the angle between the line connecting the node and the antenna and the line of symmetry of the sector, C_1 and C_2 are parameters that controls the side lobe interference. The value of C_2 is computed such that the directional gain, $f(\theta, M)$, at the edge of the sector is equal to the beamwidth gain denoted as A . $J_1(\cdot)$ is the First Order Bessel Function of the First Kind.

We further define the transmit power of each directional antenna as P , and β as the signal-to-interference-and-noise ratio (SINR) threshold value for the modulation scheme being used. Next, we define d_0 and d_{\max} as the reference distance and maximum distance respectively, and η as the path loss exponent. N_0 is defined as the average thermal noise power.

We define a link l between node x and the base station antenna to be feasible if the received power exceeds the β threshold ($P'_x > \beta$). This value can either be measured in real life or calculated using a certain interference model. There are many different kinds of interference models out there, such as additive interference model, capture threshold model, and interference range model. In our thesis, we will only consider the additive interference model. In this model, the sum of interference caused by other node transmissions is simply considered as noise. With this model, in the absence of interference, a link is feasible if

$$\frac{P \cdot f(\theta_x, M) \cdot G_x}{N_0} \geq \beta \quad (1)$$

where G_x is the channel gain seen by node x . The channel gain, G_x in our model is calculated as

$\left(\frac{d_x}{d_0}\right)^{-\eta} \cdot g_x$, where d_x is the distance from the base station to node x , and g_x is the coefficient due to

Rayleigh fading. Although it is entirely possible that a node can form feasible links with other directional antennas not corresponding to its sector, we consider them as interference coming from outside sectors rather than links since we have stated that nodes will only receive from the directional antenna corresponding to the sector it is in.

As we have stated earlier, having different sectors allows us to transmit simultaneously to different nodes situated in different sectors of the cell. If the directional antenna i is transmitting to node x_i and at the same time directional antenna j is transmitting to node x_j , not only is node x_i possibly affected by the harmful interference it receives from j , node x_j which also observes destructive interference due to directional antenna i being on, can also be affected. The interference is added to the noise seen in the previous equation, and similarly, transmission to either node x_i or x_j would only be considered successful if it exceeds the SINR requirement. In the case above, if both x_i and x_j satisfy the SINR requirement, we say that these two nodes can receive concurrently from their corresponding directional antennas. We now present a more general case:

A set of s links is considered feasible, only if

$$\frac{P \cdot f(\theta_{x,x}, M) \cdot G_{x,x}}{N_0 + \sum_{y \in s: y \neq x} P \cdot f(\theta_{x,y}, M) \cdot G_{x,y}} \geq \beta, \forall x, y \in s \quad (2)$$

where $f(\theta_{x,y}, M)$ and $G_{x,y}$ are the directional gain and channel gain perceived by node x from the directional antenna transmitting to node y respectively. For all sets s where the above condition holds true, any node in s can receive with its corresponding antenna at the same time as every other nodes in the set s . We would from now on refer to the sets that satisfy equation (2) as an independent set (ISET). One thing we can observe about the ISET is that as we increase the number of sectors in our system, the number of ISETs increases dramatically.

Having described all of the above, we can now begin to describe the problems which we are trying to solve. The first problem which we look at is a generalized round robin in case of multi-sector where we try to minimize the cycle length. We define cycle length as the number of timeslots required to give each

node access to c timeslots. One thing to note is that the length of a cycle is an integer value. The optimization problem is as follows.

Define:

- S - The set of all ISETs
- ω_s - The number of timeslots in which ISET s is used
- k_i - The number of timeslots node i is scheduled.
- C - The required number of timeslots.

Note that

$$\sum_{s \in S} 1_{i \in s} \omega_s = k_i, \quad \forall i \in N$$

Whenever an ISET s is used, every node in this ISET is given a timeslot. This means that nodes are not bound to a particular ISET. Node i can receive a timeslot from every ISET which contains node i that has been scheduled.

3.2 Problem One

$$\text{minimize } \sum_{s \in S} \omega_s$$

$$\text{subject to } k_i \geq c, \quad \forall i \in N$$

$$\omega_s \geq 0, \omega_s \in \mathbb{Z}, \forall s \in S,$$

This is an integer linear programming problem. Let us start with a very simple case with a single sector cell. With only one antenna at the base station and no chance for concurrent transmission, the total number of ISETs in this cell configuration would be the number of nodes in the system, where each node on its own forms an ISET. To satisfy the above constraint, we can see that the number of timeslots that we would require would simply be $c \cdot N$. Now suppose that the cell is divided into two sectors with equal number of nodes on each sector and let us further assume that every node in the first sector can form

an ISET with any node in the second sector. The number of ISETs in this case would be $N + \left(\frac{N}{2}\right)^2$.

This is a significant jump in terms of the number of ISET in the system, even for a small number of nodes.

We can see from this simple example that by increasing the number of sectors in the cell, we dramatically increase the number of ISETs, which makes this a potentially very large integer programming problem. Also, since we are not limited at how we choose the ISETs to satisfy the timeslot requirement for each node, there could be multiple solutions to our problem. This leads to the formulation of our second problem as follows.

3.3 Problem Two

$$\begin{aligned} & \text{maximize } \sum_i k_i, \quad \forall i \in N \\ & \text{subject to } \sum_{s \in S} \omega_s = T^* \text{ and } k_i \geq c, \forall i \in N \\ & \omega_s \geq 0, \omega_s \in \mathbb{Z}, \forall s \in S \end{aligned}$$

where T^* is the solution to the first problem.

The second problem is a logical extension to our first problem. By knowing the minimum number of timeslots required to give every node c timeslots, we would like to solve for the maximum number of packets that can be transmitted as a measure of how well the network is being utilized.

One of the main issues in solving the above optimization problems is that these are very large integer programming problems because the number of ISETs can be extremely large, especially with higher numbers of nodes or sectors. This makes computing the optimal solution a difficult task. In a real life situation, no network operator would want to wait for hours or days to come up with an optimal scheduling policy, especially if the network topology or the number of users in the network changes frequently. In the next chapter, we will analyze the exact solutions for the above problems for several test cases so as to get benchmark results for our heuristics and gain some insights.

Chapter 4

Numerical Results

4.1 Introduction and Parameters for the Test Cases

In this chapter, we will present and discuss some of the numerical results from the simulations of the optimal problems described in chapter 3. The optimal problems were solved using the CPLEX software developed by ILOG. The parameters used for constructing the test cases are presented in the table below.

Table 4-1: Test Case Parameters

N	90
M	3 to 9
P	9.5 dBm
β	6.4 dB, 10.0 dB
d_0	10 (metres)
d_{\max}	1000 (metres)
N_0	-100 dBm
η	3
C_1	-20 dB
A	-1 dB to -6 dB
c	1

The value for the transmit power was chosen so that in the absence of interference, every nodes would be able to form a link with the directional antenna at the base station. By varying the number of sectors in the system, SINR threshold value, and beamwidth gain, we hope to see the effect of these parameters on the performance. As we have mentioned earlier, this is an extremely large integer programming problem due to the sheer number of ISETs. Therefore, in our test cases, we stop at 9 sectors which is already very challenging to solve. Although we have fixed the value of c to 1, the problems can be easily adapted for

other values of c . We also model the Rayleigh fading model as an exponentially distributed variable with unit mean. We run 20 different realizations of the test parameters and the resulting average was taken. In each realization, different node locations and Rayleigh fading coefficients are generated.

4.2 Analysis on Problem One

In our first optimization problem, we are looking to minimize the number of timeslots to give everyone equally fair time access. The optimal results are given in the figures below. We should first note that these results also apply for the second optimization problem.

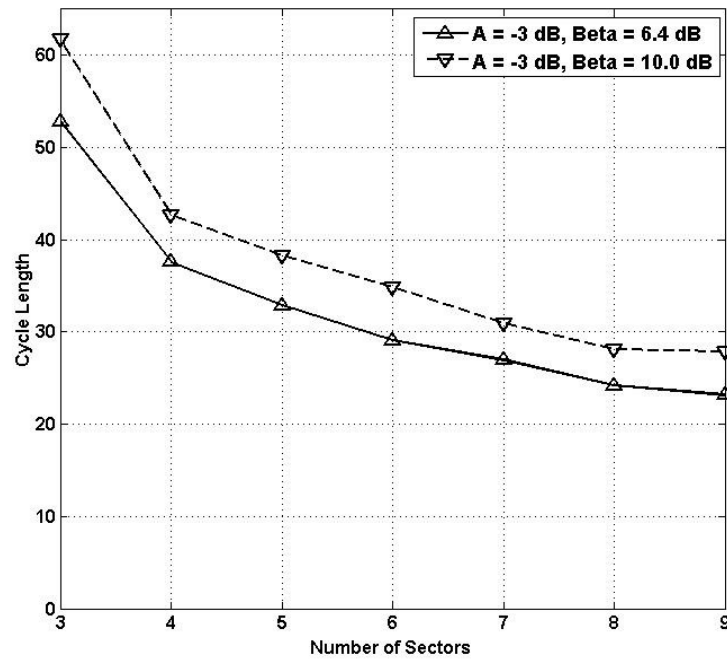


Figure 4-6: (Optimal) Minimum Cycle Length for $A = -3$ dB

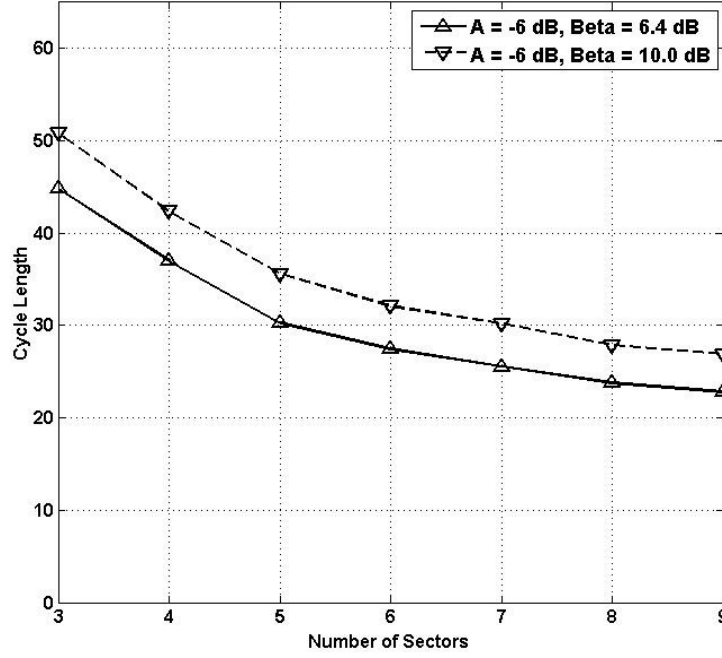


Figure 4-7: (Optimal) Minimum Cycle Length for $A = -6$ dB

By looking at the figures we validate our previous statement that as we increase the number of sectors in the system, we decrease the cycle length to provide access to everyone. We observe the sharpest drop by increasing the number of sectors from 3 to 4, after which, the decreasing trend seems to slow down which seems to indicate that continuing to increase the number of sectors in the cell will not result in significant improvement in minimizing the cycle length.

In both Figure 4-1 and 4-2, by increasing the value of β , it is not surprising to see that cycle length increases. By increasing the SINR threshold, we limit the cell's capability to form larger ISETs, therefore, it is logical that more timeslots would be required to satisfy everyone in the cell. We should note that in Figure 4-2, for $\beta = -6.4$ dB the cycle length obtained for $M = 8$ and 9 is an upper bound since we were unable to solve it completely due to the size of the number of ISET, which means the optimal value should be even lower.

In order to compare the effect of beamwidth gain A , we present the following figures (Figure 4-3, 4-4).

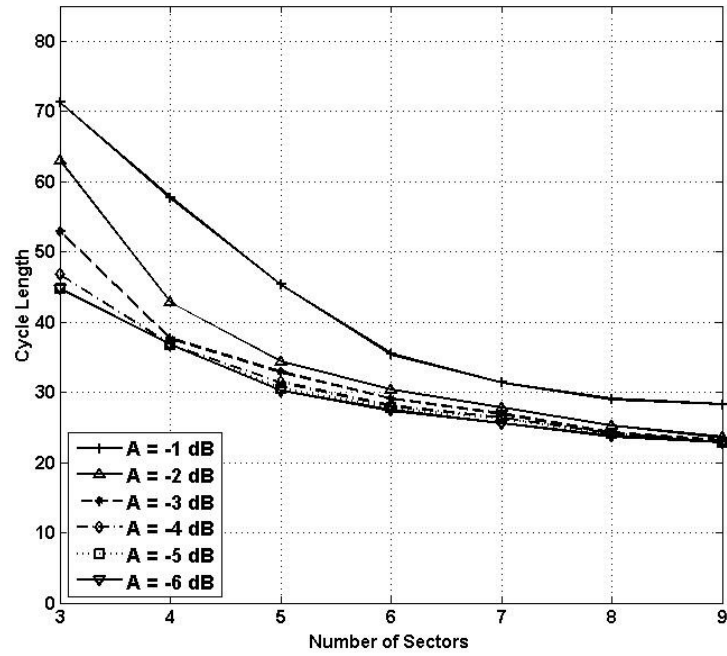


Figure 4-8: (Optimal) Minimum Cycle Length while varying Beamwidth Gain for $\beta = 6.4$ dB

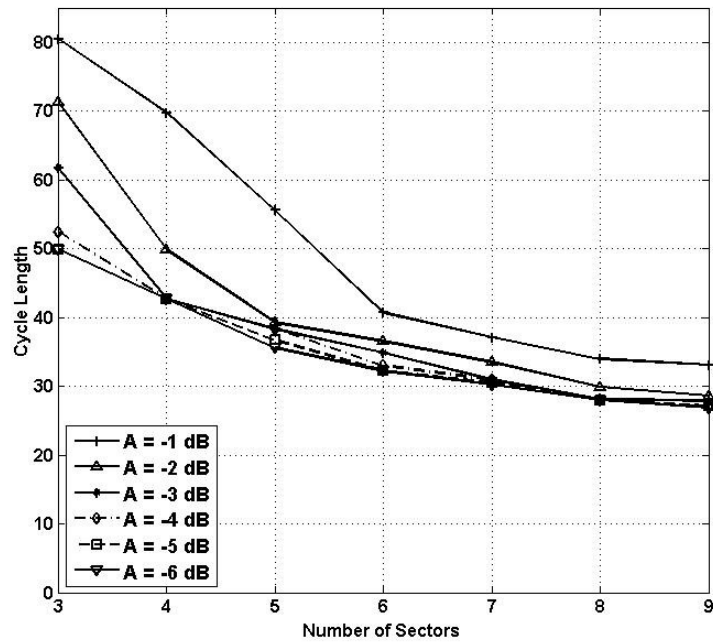


Figure 4-9: (Optimal) Minimum Cycle Length while varying Beamwidth Gain for $\beta = 10.0$ dB

In the figures above, we observe that as we decrease the beamwidth gain value, A , from -1 dB to -6 dB, the cycle length decreases. The beamwidth gain value indicates how fast the directional gain drops, which also shows how well the directional beam can control its radiation pattern, where a lower beamwidth gain value indicates a better and more focused directional antenna. A beamwidth gain value of -3 dB means that the power at the edge of the sector would have dropped by -3 dB, or in another word, lost 50% power with respect to the centre of the beam. The same trend was observed for higher SINR threshold value as well. This is not a surprising trend. By decreasing the beamwidth gain value, the interference caused by other sectors transmitting also decreases. However, as we can observe from the figure, the trend does not continue forever, as the optimal results for beamwidth gain of -5 dB lies very close with the results for -6 dB beamwidth gain. The optimal beamwidth gain value for different number of sectors is shown in Figure 4-5 below which suggest that lower beamwidth gain value is better. However, if we continue to decrease the beamwidth gain, we may start to lose performance since the effect of noise may limit the size of ISET which we can form for nodes located near the edge of the sectors.

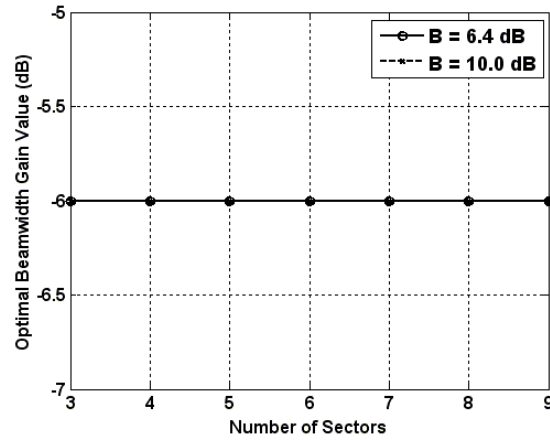


Figure 4-10: Optimal Beamwidth Value (Problem One)

4.3 Analysis on Problem Two

As we have discussed in earlier chapter, there could be several solutions to the first optimization problem. Therefore, in order to best utilize the network capability the second optimization problem was proposed. We want to see what is the maximum number of packets we can send out while minimizing the cycle length. Since we know that for a different number of sectors, we get a different minimum cycle length, in

order to be fair, we look at the average number of packets per timeslot by dividing the total number of packets sent by the cycle length. The results are presented in the figures below.

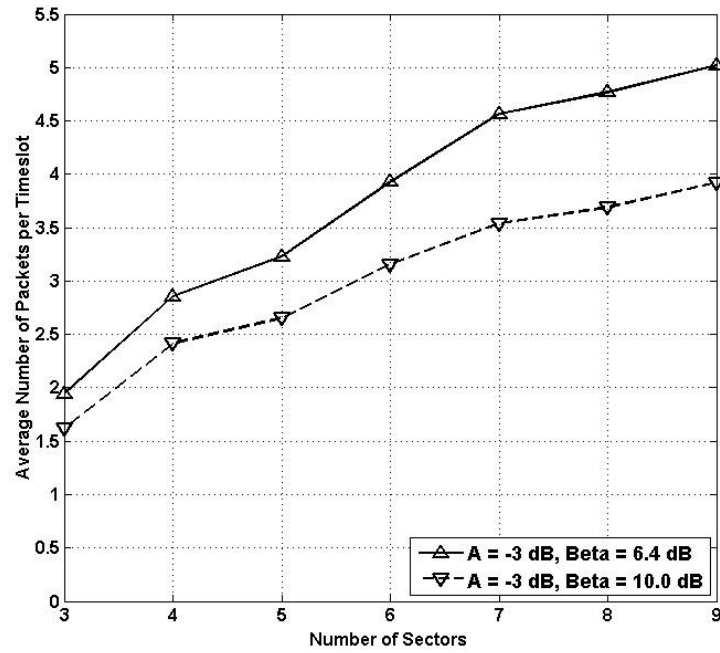


Figure 4-11: (Optimal) Number of Packets/Timeslot for A = -3 dB

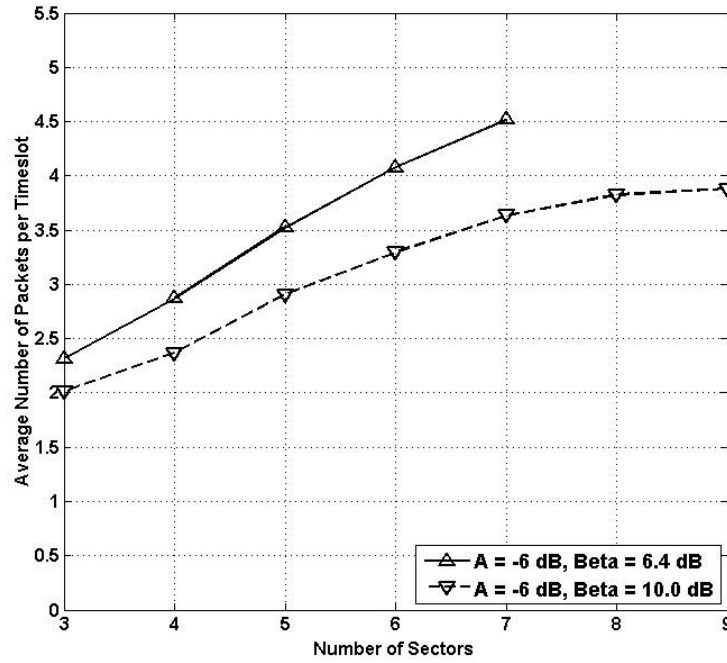


Figure 4-12: (Optimal) Number of Packets/Timeslot for A = -6 dB

Analyzing the two figures above (Figure 4-6 and 4-7), we can observe first of all that as the number of sectors increases, the average number of packets being transmitted per timeslot also increases. This holds true for both beamwidth gain of -3 dB and -6 dB. Also, as we increase the SINR threshold value, the average number of packets sent is also reduced, and the gap between the two threshold values appears to increase as the number of sectors in the cell increases. This is logical since as we increase the number of sectors, for higher SINR threshold value, it becomes harder and harder to pack more nodes into a single timeslot. The reason why Figure 4-6 stops at 7 sectors is because we were unable to completely solve the first optimization problem optimally due to extremely large number of ISETs and therefore could not proceed to solving the second optimization problem.

We will conclude this section by looking at trends as we vary the beamwidth values. This is demonstrated in the next set of figures.

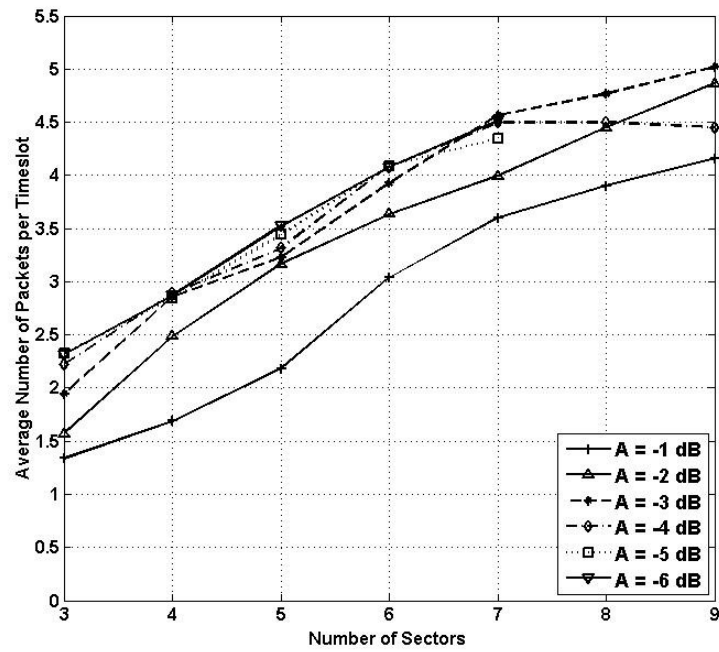


Figure 4-13: (Optimal) Number of Packets/Timeslot while varying Beamwidth Gain for $\beta = 6.4$ dB

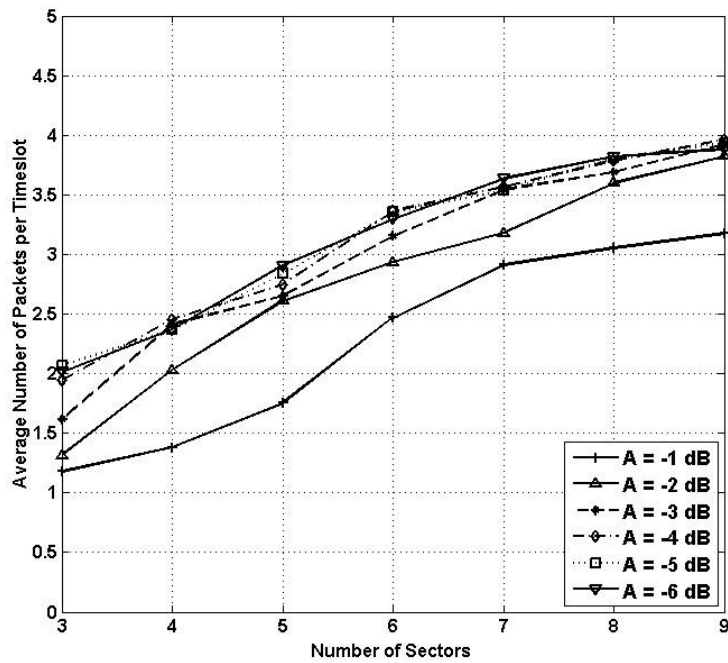


Figure 4-14: (Optimal) Number of Packets/Timeslot while varying Beamwidth Gain for $\beta = 10.0$ dB

In the figures above (Figure 4-8 and 4-9), we observe that in the beginning, by decreasing the beamwidth gain from -1 dB to -3 dB, we increase the average number of packets we are transmitting in each timeslot for different sector values. However, as we go from -4 dB to -6 dB beamwidth gain, the results are very close, but the overall trend of increasing average number of packets per timeslots with increasing number of sectors remains the same. For a 3-sector cell, we see that on average, we can transmit 2.5 or 2 packets per timeslot for $\beta = 6.4$ dB and 10.0 dB, respectively, but for a cell with 9 sectors, we get an average reuse of 5 or 4 instead. Unlike the first optimization problem where there is no crossing points, Figure 4-8 and Figure 4-9 above definitely have several crossings. This indicates that lower beamwidth gain does not guarantee a better result, and that for different number of sectors, the best beamwidth gain value varies. Figure 4-10 below shows the optimal beamwidth gain value for different number of sectors.

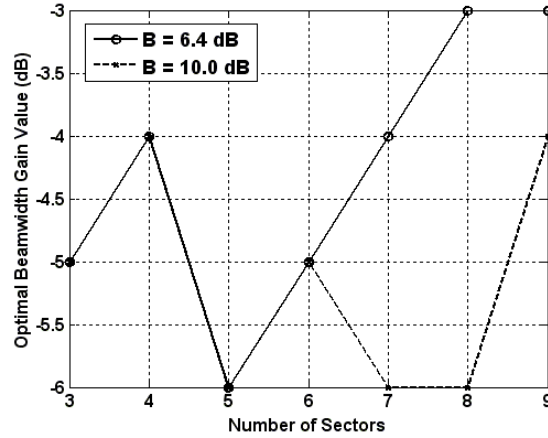


Figure 4-15: Optimal Beamwidth Value (Problem Two)

4.4 Reducing the Problem Complexity

As we have stated in the previous chapter, one of the main issues in obtaining the optimal solutions to both integer programming problems is that with increasing number of sectors, the number of ISETs significantly increases. From an engineering point of view, it would be interesting to see the impact of limiting the ISET size. The first thing that we can do to reduce the number of ISETs is to reduce the maximum size of a single ISET.

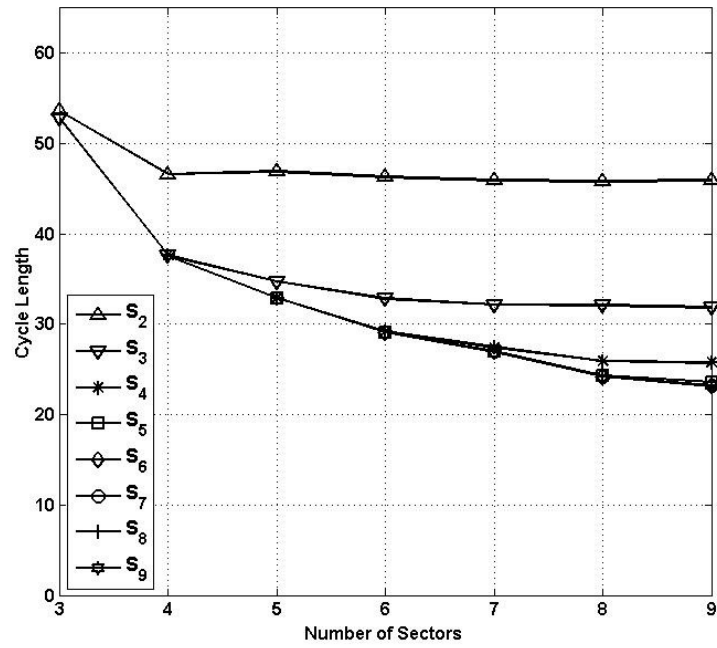


Figure 4-16: (Optimal) Minimum Cycle Length with ISET Size Limit, $A = -3$ dB, $\beta = 6.4$ dB

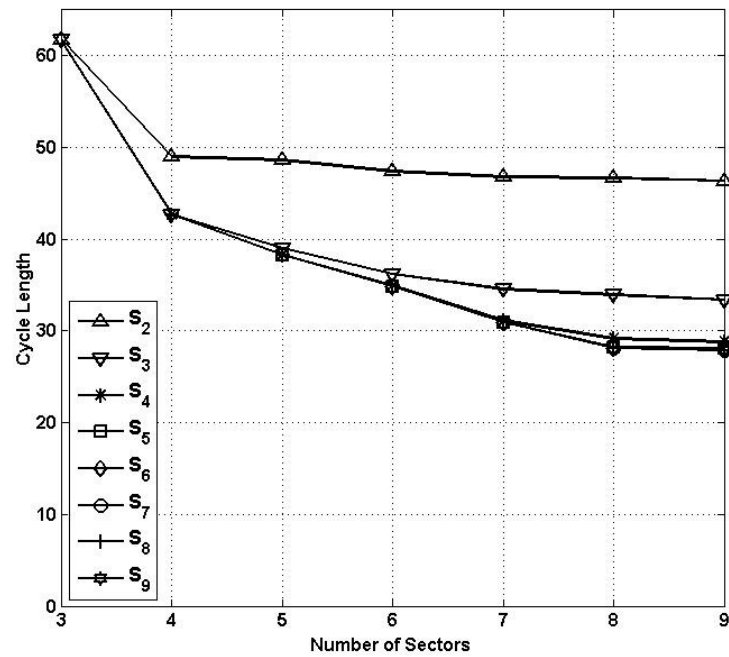


Figure 4-17: (Optimal) Minimum Cycle Length with ISET Size Limit, $A = -3$ dB, $\beta = 10.0$ dB

In Figure 4-11 and 4-12, $S_{\mathcal{C}}$ means that we limit our search to ISET of size no greater than \mathcal{C} . By limiting the maximum ISET size, we are reducing the number of total ISETs, which would allow us obtain a solution more quickly, but a suboptimal one. The suboptimal solution can give us an upper bound as to where the actual optimal solution lies.

In these two figures, we can observe that as we increase the maximum ISET size limit, the cycle length decreases. As we increase the number of sectors, the maximum ISET size that we need to achieve result close to optimal also increases. In fact, looking at the figures above, it seems that the value of \mathcal{C}

required would be close to $\left\lceil \frac{M}{2} \right\rceil + 1$. This is true for both $\beta = 6.4$ dB and 10.0 dB.

We will now look at the effect of restricting ISET size in our second problem.

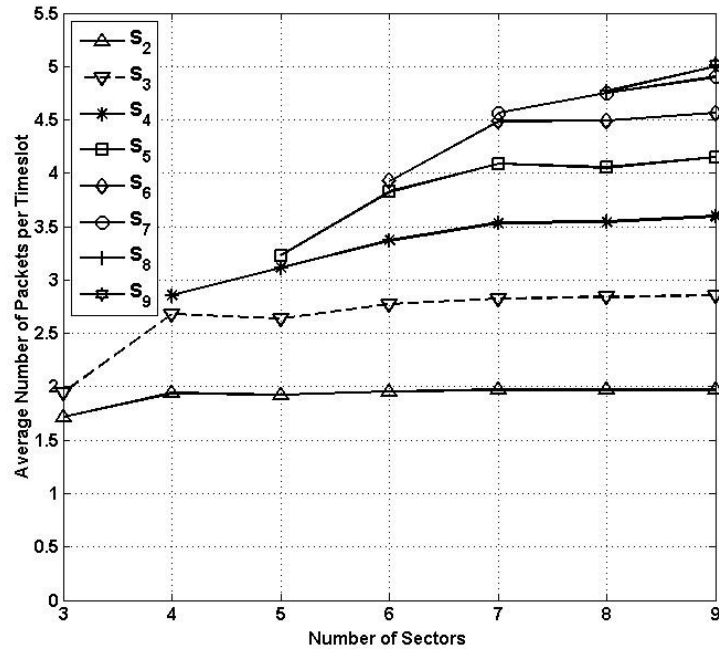


Figure 4-18: (Optimal) Number of Packets/Timeslot with ISET Size Limit, $A = -3$ dB, $\beta = 6.4$ dB

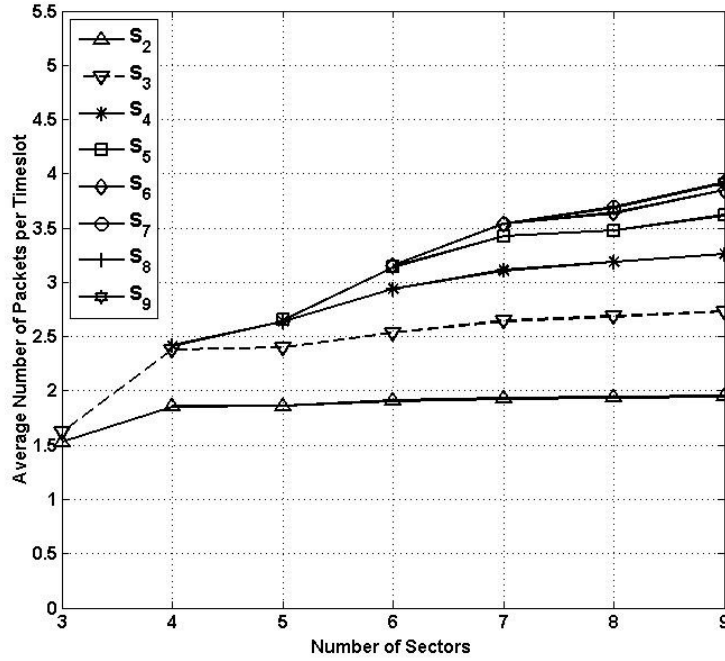


Figure 4-19: (Optimal) Number of Packets/Timeslot with ISET Size Limit, $A = -3$ dB, $\beta = 10.0$ dB

In Figure 4-13 and 4-14, the expression we found for the suitable value of \mathcal{L} does not hold for the second problem. Since we are trying to maximize the number of packets that we are trying to send, we should try to allow maximum size to be as large as possible. In these two figures, in order to achieve a good approximate of the optimal value, the value of \mathcal{L} required would be closer to $M - 1$.

In the first problem, we found that by restricting the ISET size to $\left\lfloor \frac{M}{2} \right\rfloor + 1$, we can achieve close to the optimal solution. This means that for a large number of sectors, we would on average only require half of the sectors to be turned on. Let us consider a naïve approach of doing this, and separate all the sectors in the cell into two groups. In each timeslot, we will only schedule nodes from either group but not together, we will refer to this as the alternating sector approach. To compare our results, we will

consider only an even number of sectors in the system and compare it with limiting the size of \mathcal{L} to $\frac{M}{2}$.

The results are illustrated in Figure 4-15 and Figure 4-16 below.

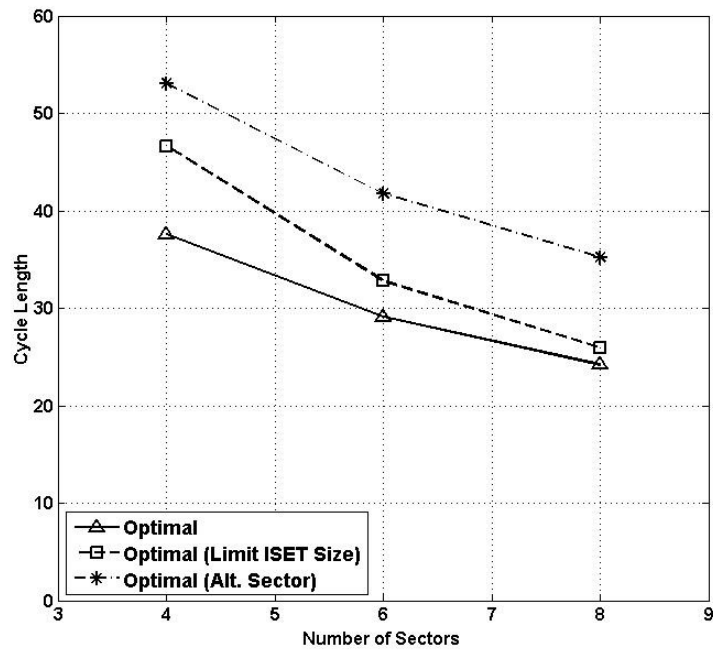


Figure 4-20: Minimizing Cycle Length: Optimal vs Alternating vs ISET Limit, $A = -3$ dB $\beta = 6.4$ dB

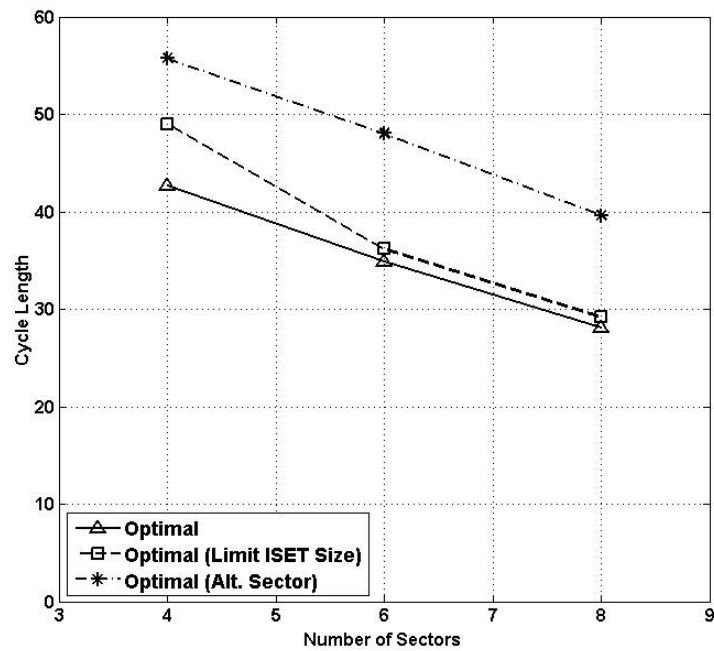


Figure 4-21: Minimizing Cycle Length: Optimal vs Alternating vs ISET Limit, $A = -3$ dB $\beta = 10.0$ dB

We should first note that all the ISETs formed in the alternating sector method would be included in the ISET size restriction approach, and therefore we would expect limiting ISET size would perform better than separating the cell into two groups of sectors. In the figure above, both methods perform poorly against the optimal solution. The ISET restriction method performs better than alternating sector approach, and as the number of sectors increases, this method gradually perform closer to the optimal solution.

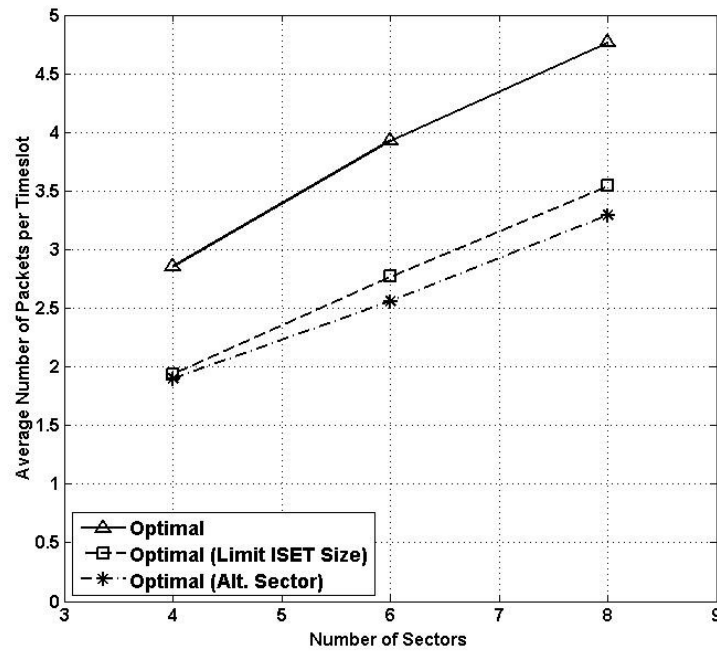


Figure 4-22: Number of Packets/Timeslot: Optimal vs Alternating vs ISET Limit, $A = -3$ dB $\beta = 6.4$ dB

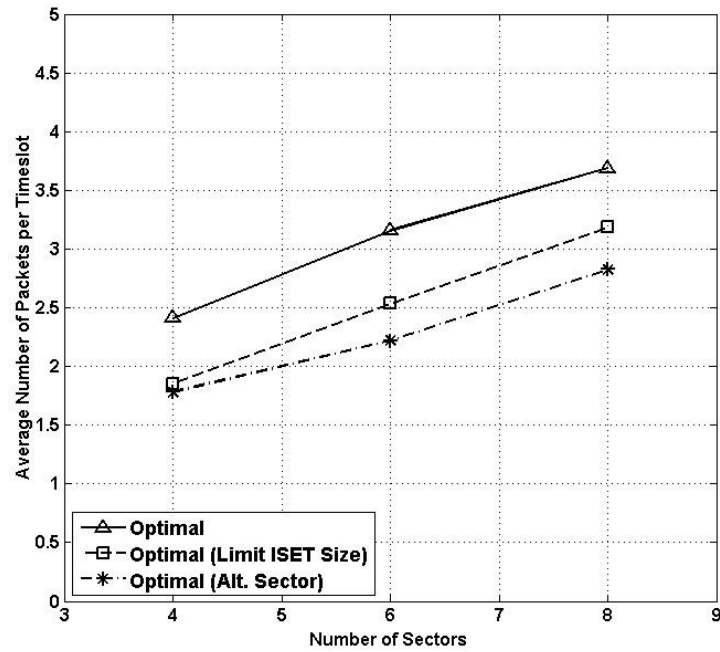


Figure 4-23: Number of Packets/Timeslot: Optimal vs Alternating vs ISET Limit, $A = -3$ dB $\beta = 10.0$ dB

In these figures again, limiting the maximum ISET size outperforms alternating sector approach. The difference between the two methods increases as the number of sectors grows, and holds true for both value of β . Similar to the first optimization problem, both methods perform poorly against the optimal solution.

Having observed the optimal results we now look at some heuristic algorithms, and expect that they can achieve good performance while being sufficiently fast.

Chapter 5

Heuristics

5.1 Heuristics based on Greedy Algorithm for Problem One

Our first approach in designing the heuristics is based on the greedy algorithm, which is very straight forward. We will always pick the sectors with the most number of nodes which have not yet been given a timeslot, and then try to find the first node in this sector that can form a set with the nodes that we are currently scheduling by looking at the SINR constraints. We will continue this process until we have looked through every sector in the cell. The detailed procedure for this algorithm is described below.

Define:

- c – The number of timeslots required to satisfy a node, usually kept to 1.
- u – Set of nodes which are not yet satisfied. This is initially the set of all nodes in the system.
- S_j – Set of nodes in sector j still not satisfied.
- W_i – Number of timeslots allocated to node i .
- B – Set of node(s) to be scheduled in the next timeslot. It will be referred to as the next node set.
- T_B – The set of sectors corresponding to B .
- T_N – The set of sectors which do not have nodes that can be scheduled in the next timeslot.
- T^* – The set of sectors which might have nodes that can be scheduled in the next timeslot.
- V_j – The set of nodes in sector j which can form an ISET with B .

Algorithm Procedure:

1. u is initially set to all nodes in the system.
2. While there are still nodes that needs to be satisfied ($u \neq \emptyset$), do the following:
 - (a) B, T_B, T_N, T^* are set to the empty set.
 - (b) Find the first sector j where S_j is largest, and pick the first node i in sector j .
 - (c) Add node i to B , and j to T_B .
 - (d) Increment W_i , if $W_i = c$, remove i from S_j and u .

- (e) For every sector j' that is not in T_B or T_N , such that every node in B can withstand the sector j' being active and still satisfies the SINR constraint, add j' to T^* .
- (f) Order the sector in T^* by S_j .
- (g) While T^* is not empty, start from the first sector j' in T^* do the following.
 - i. If there are no nodes in j' which satisfy the SINR constraint, remove j' from T^* , add j' to T_N , and restart from step (g).
 - ii. Otherwise, find the first node n' in j' which satisfy the SINR constraint, and add node n' to B and j' to T_B .
 - iii. Increment $W_{n'}$, if $W_{n'} = c$, remove n' from $S_{j'}$ and u .
 - iv. Repeat from (e).
- (h) All nodes in B will be scheduled together.
- (i) Restart algorithm from (a).

The greatest advantage of this heuristic algorithm is its simplicity. As long as the base station is aware of the channel conditions for every node, it can run the algorithm on the fly to come up with the scheduling table.

5.2 Heuristic based on Forming Antenna Set for Problem One

The second approach is slightly more complicated. Instead of forming the ISET like in the optimal solution, we look at a new concept of forming antenna sets. What we notice is that if a node x_i in sector i can withstand the antenna in sector j to be turned on, it actually does not matter which node antenna j is actually transmitting to. Therefore, instead of forming actual ISETs, we can simply form antenna sets, which inform us of all possible combinations of sectors that can be turned on and still allow the node to receive correctly from its corresponding base station. Unlike the number of ISETs which is huge, the number of antenna sets is much more limited, and hence more desirable. The procedure for this algorithm is described below starting with a few more variable definitions.

Define:

- $S(i)$ – The sector in which node i is in.
- C_i – a set of all antenna sets which can be on at the same time as $S(i)$ without disturbing transmission to node i .
- X_i – The cardinality of the largest set in C_i .
- $A_B = \bigcap_{i \in B} C_i$. This will be referred to as the common sets.

- $V_j(B)$ – the set of nodes in sector j which can form an ISET with B

Algorithm Procedure:

1. u is initially set to all nodes in the system.
2. While there are still nodes that needs to be satisfied ($u \neq \emptyset$), do the following:
 - (a) B, T_B, T_N, T^* are set to the empty set.
 - (b) Find the sector j where S_j is largest.
 - (c) Find the node i in j where X_i is the smallest.
 - (d) Add node i to B , and j to T_B .
 - (e) Increment W_i , if $W_i = c$, remove i from S_j and u .
 - (f) Find A_B , and sort the sets based on the size of antenna set.
 - (g) For all sector j' in A_B that is not already in T^* , nor in T_B nor T_N , add to T^* .
 - (h) While T^* is not empty, do the following.
 - i. Order sector j' in T^* first by the largest set it can form with A_B , and in case of a tie, order by $|S_j|$.
 - ii. For all j' in T^* , find $V_{j'}(B)$ and order node i' in $V_{j'}(B)$ by $C_{i'}$ in increasing order. If $V_{j'}(B)$ is empty, add j' to T_N .
 - iii. Find the first sector j^* in T^* where $V_{j^*}(B)$ is not empty, pick the first node n^* in $V_{j^*}(B)$.
 - iv. Add node n^* to B and j^* to T_B .
 - v. Increment W_{n^*} , if $W_{n^*} = TS$, remove n^* from S_{j^*} and u .
 - vi. Repeat from (f).
 - (i) All nodes in B will be scheduled together.
 - (j) Restart algorithm from (a).

The biggest difference between this heuristic and the previous one based on greedy algorithm is that in this heuristic, antenna sets will need to be generated for every node before going through the algorithm. In a cell with M sectors, there are $2^M - 1$ sector combinations. In order to reduce complexity, we can reduce the number of antenna sets formed at each node by limiting the antenna generation procedure to only form the maximal antenna set. In this case, we would at most generate $N * (M - 1)$ antenna sets in total, which should not consume too much time.

We will now look at some of the simulation results for the two heuristics described earlier. To compare the performances, we will use the optimal solutions from the previous chapter as the benchmark value.

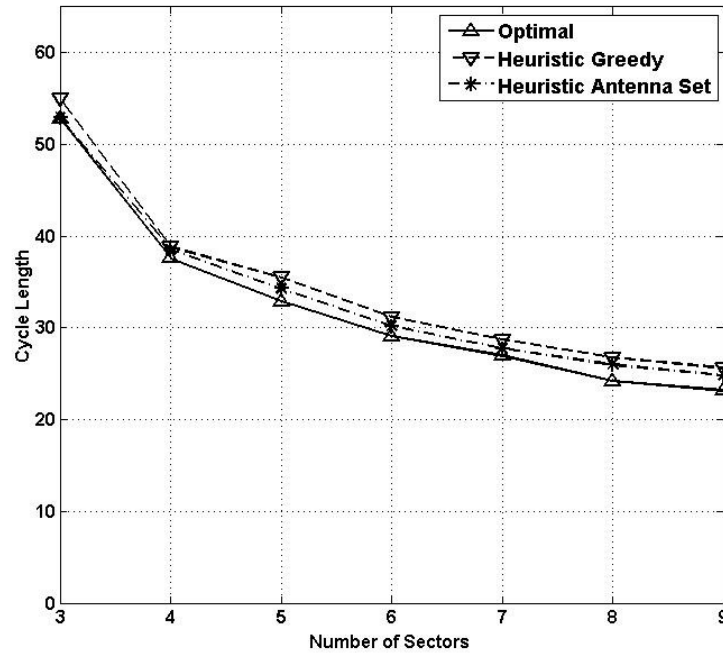


Figure 5-24: Minimum Cycle Length Comparison, $A = -3$ dB, $\beta = 6.4$ dB

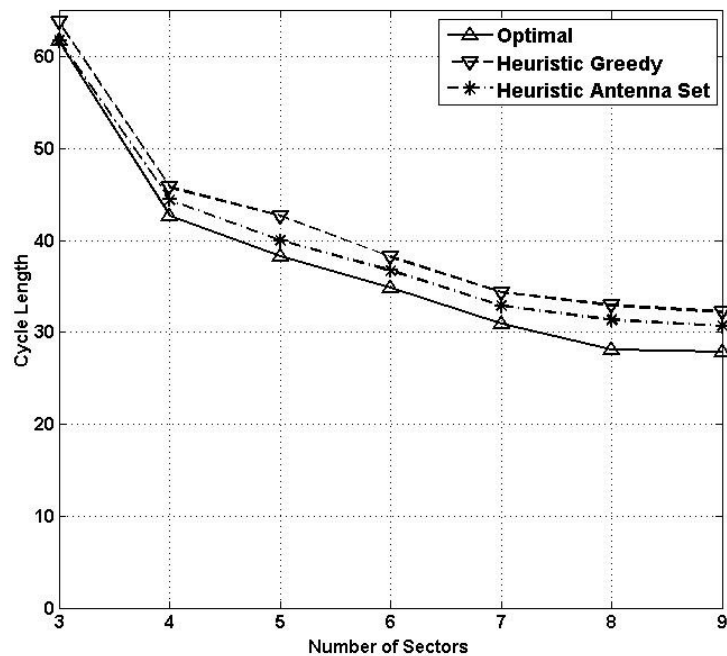


Figure 5-25: Minimum Cycle Length Comparison, $A = -3$ dB, $\beta = 10.0$ dB

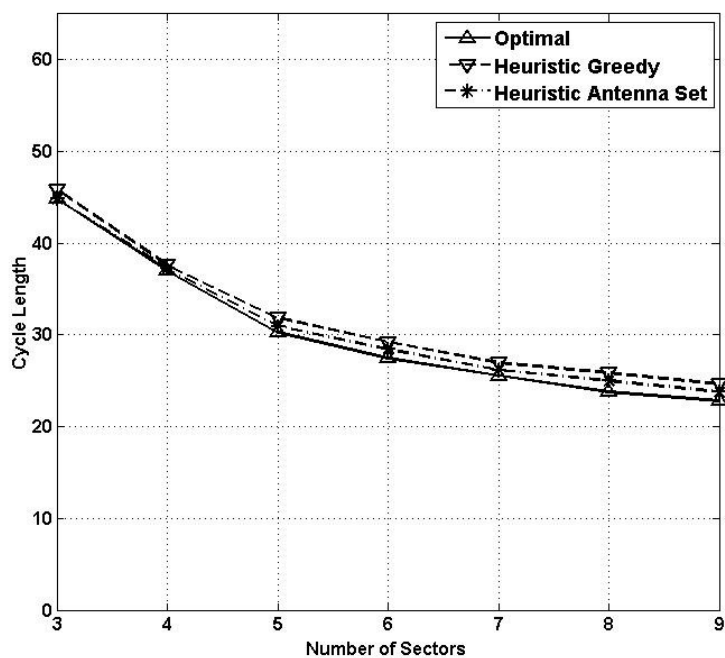


Figure 5-26: Minimum Cycle Length Comparison, $A = -6$ dB, $\beta = 6.4$ dB

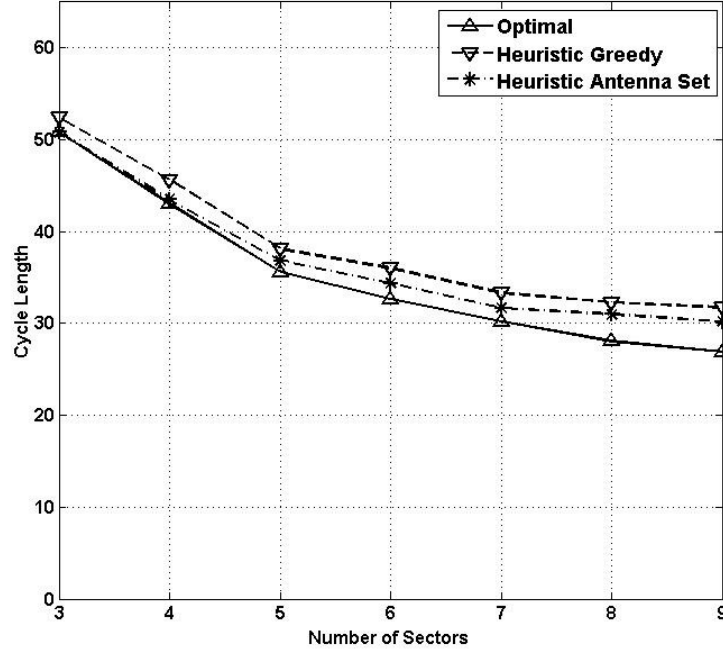


Figure 5-27: Minimum Cycle Length Comparison, $A = -6$ dB, $\beta = 10.0$ dB

In Figures 5-1 to 5-4, we can observe that both heuristics follow a trend similar to the optimal solution. Both heuristics require a few extra timeslots in order to provide time fairness to every node in the cell. In both heuristics, as the number of sectors increases, their performance decreases. For a 9 sector cell, for beamwidth gain value $A = -3$ dB and $\beta = 6.4$ dB, the heuristics based on greedy and forming antenna sets are 7% and 10% less efficient in allocating timeslots compared with the optimal solution. The effect of increasing the SINR threshold saw a small decrease in the heuristics performance, where the greedy heuristic is 15% less efficient and 10% less for the antenna-set heuristic. By decreasing the beamwidth gain value from -3 dB to -6 dB, for lower value of $\beta = 6.4$ dB, the heuristics perform slightly better than before, however, at higher SINR value, the heuristics again loses roughly 15% in performance. Overall, the performance of the two heuristics in solving our first problem is satisfactory and the second heuristic is slightly better.

5.3 Heuristics for Problem Two

For our second problem, we are looking to maximize the number of packets we can send out while meeting the minimum cycle length requirement from the first problem. Both the heuristics described earlier need to be changed. In order to maximize the number of packets that we can send out, nodes that

have already been served should be eligible to be served again. Therefore, the only step which we would require to do is after finding the set of nodes B , we will try to add nodes which have already been satisfied previously. For simplicity, the process of adding used node will be the same as nodes that have not yet been served. We will now present the figures showing the results from the simulation for the two adapted heuristics.

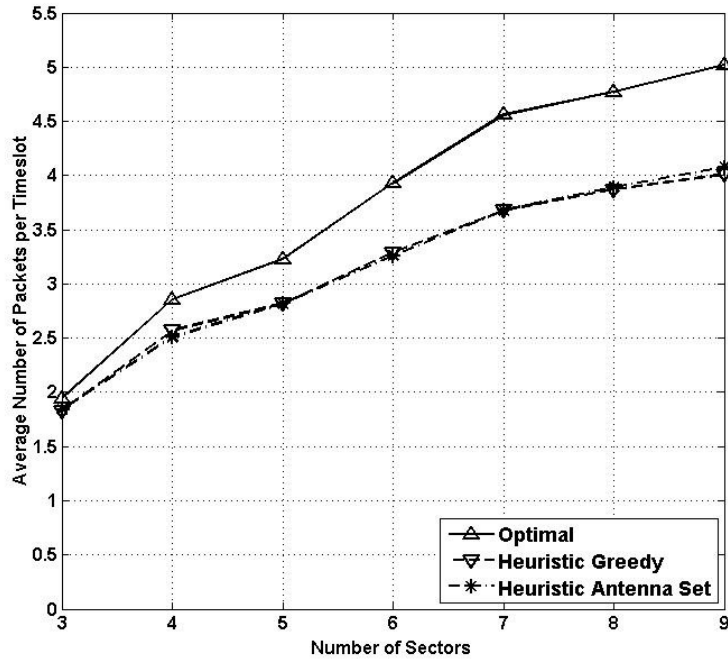


Figure 5-28: Number of Packets/Timeslot Comparison, $A = -3$ dB, $\beta = 6.4$ dB

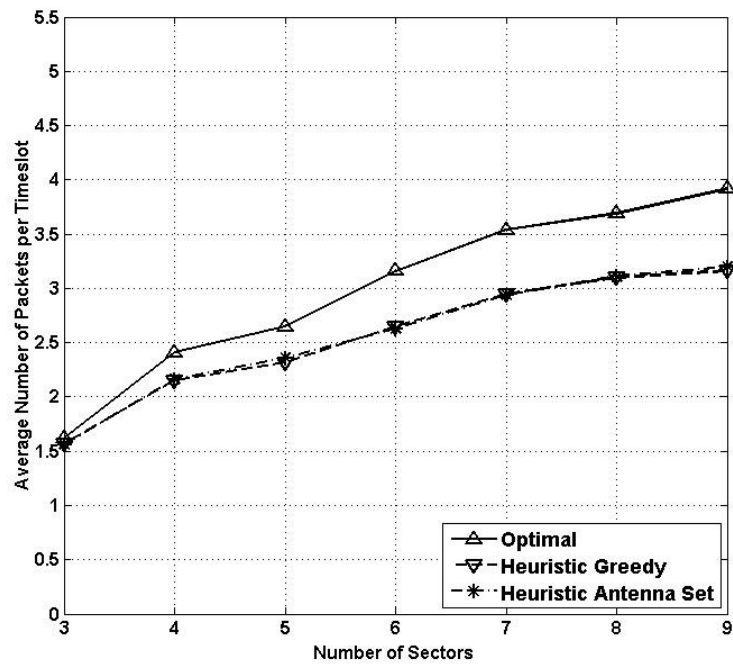


Figure 5-29: Number of Packets/Timeslot Comparison, $A = -3$ dB, $\beta = 10.0$ dB

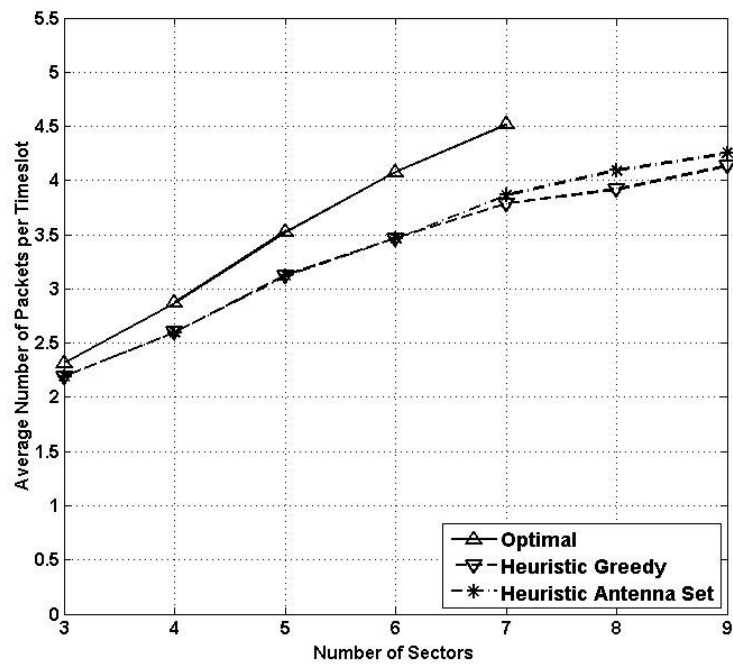


Figure 5-30: Number of Packets/Timeslot Comparison, $A = -6$ dB, $\beta = 6.4$ dB

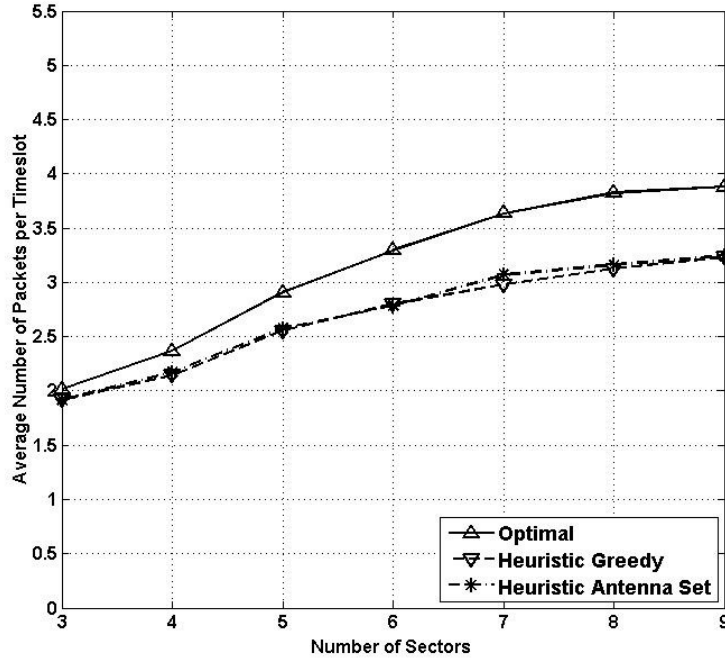


Figure 5-31: Number of Packets/Timeslot Comparison, $A = -6$ dB, $\beta = 10.0$ dB

By analyzing Figures 5-5 to 5-8, we observe that as the number of sectors increase, the performance of the two heuristics with respect to the second problem of maximizing the average number of packets per timeslot, are nearly identical and equally poor. For different values of A and β , as we increase the number of sectors in the cell, the heuristics become less efficient in packing as many packets into a timeslot as possible. For a cell with 9 sectors, the performance drops by as much as 20% compared with the optimal solution. It is therefore essential to either modify the existing algorithms to improve the second objective function, or to come up with a whole new heuristic algorithm.

After reviewing the procedure for the first heuristic based on the greedy algorithm, we notice that the method by which the next sector or the next node are chosen can probably be improved. In the original scheme, the next possible sector choice is ordered based on the number of nodes which have yet to be satisfied with the highest being chosen as the next sector. The sector picked by the previous procedure then chooses the first node which satisfies the SINR requirement as the next node to be added to the current node set. These procedures do not take the amount of interference the new sector might bring to the current node set into consideration. For example, sector 1 and sector 2 both have the highest number of unsatisfied nodes; however, due to their location, the sector 1 antenna produces the most amount of

interference on nodes inside sector 2, and vice versa. It is therefore worth the effort to try to come up with a new scheme of choosing the next sector and the next node which take interference into consideration.

One possible method of doing this is for every node to rank each sector in terms of the interference that it observes. The nodes in the current node set will choose the sector with the lowest rank sum as the next sector. When choosing the next node, each node will observe the sectors that will be scheduled and sum up the corresponding rank, with the node with the lowest rank sum being picked as the next node. The new modified heuristic is now the following where the changes made to the original heuristic is indicated in bold.

Algorithm Procedure:

1. u is initially set to all nodes in the system.
2. **Each node in u will rank sectors other than its own from 1 to $M-1$ based on the interference with rank 1 given to sectors with the lowest perceived interference and rank $M-1$ to sectors with the highest interference.**
3. While there are still nodes that needs to be satisfied ($u \neq \emptyset$), do the following
 - (a) B, T_B, T_N, T^* are set to the empty set.
 - (b) Find the sector j where S_j is largest, and pick any node i in sector j .
 - (c) Add node i to B , and j to T_B .
 - (d) Increment W_i , if $W_i = c$, remove i from S_j and u .
 - (e) For every sectors neither in T_B nor T_N , and satisfies the SINR constraint for every node in B , add to T^* .
 - (f) **Sum up the sector rank among nodes in B , and sort T^* based on lowest sum.**
 - (g) While T^* is not empty, start from the first sector j' in T^* do the following.
 - i. If there are no nodes in j' which satisfy the SINR constraint, remove j' from T^* , add j' to T_N , and restart from step (g).
 - ii. **For every node n' in j' which satisfy the SINR constraint, sum up the rank of the sectors in T_B , and choose the node n^* with the lowest rank sum.**
 - iii. Increment W_{n^*} , if $W_{n^*} = c$, remove n^* from $S_{j'}$ and u .
 - iv. Repeat from (e).
 - (h) All nodes in B will be scheduled together. Nodes that have already been satisfied can be added to this set following similar procedure from step (e) to (g). Restart algorithm from (a).

The only difference in this modified greedy algorithm is that we are being more careful in how we pick the next sector as well as next node. There is a small processing overhead before running the algorithm where each node has to rank the sectors in terms of interference factor, but the processing time involved is actually negligible. Now we will present the simulation result for the modified greedy algorithm.

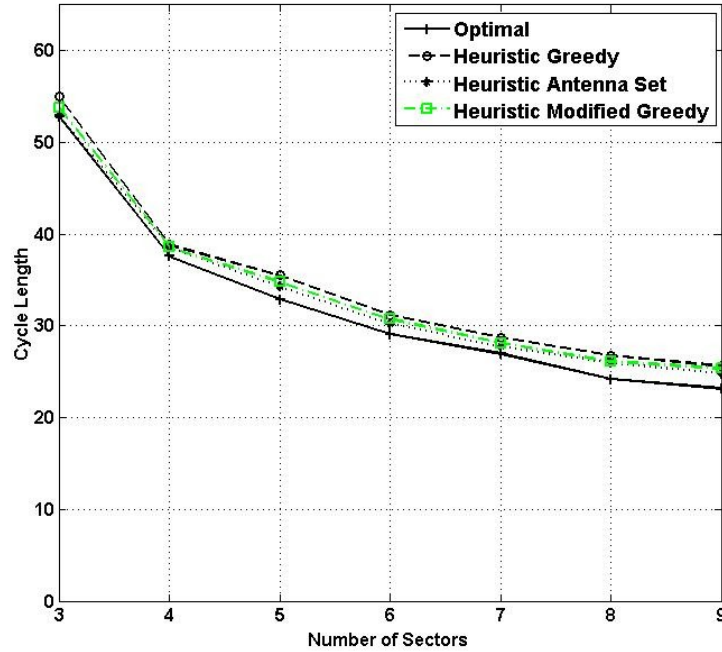


Figure 5-32: Minimum Cycle Length with Modified Greedy, $A = -3$ dB, $\beta = 6.4$ dB

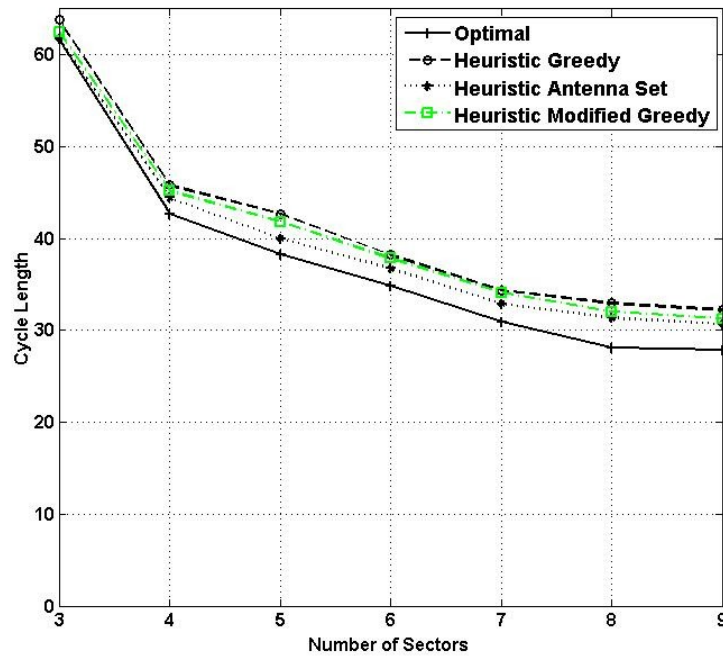


Figure 5-33: Minimum Cycle Length with Modified Greedy, $A = -3$ dB, $\beta = 10.0$ dB

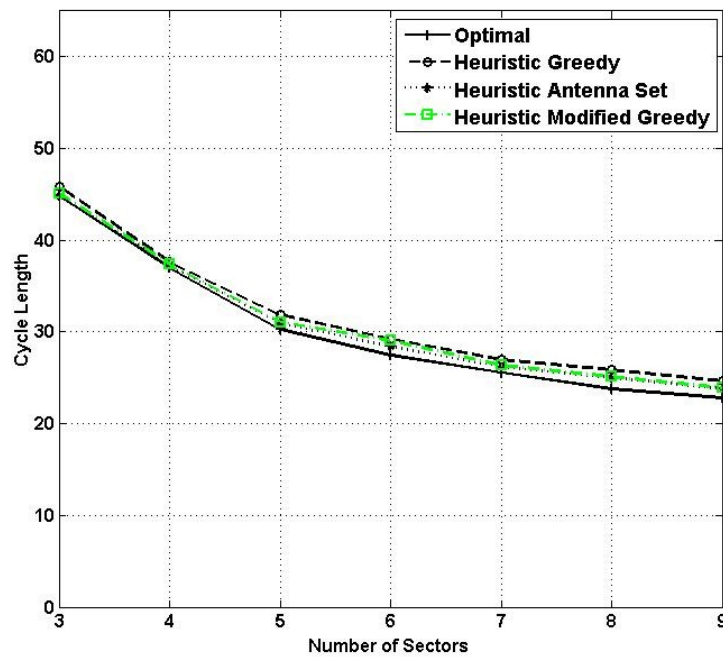


Figure 5-34: Minimum Cycle Length with Modified Greedy, $A = -6$ dB, $\beta = 6.4$ dB

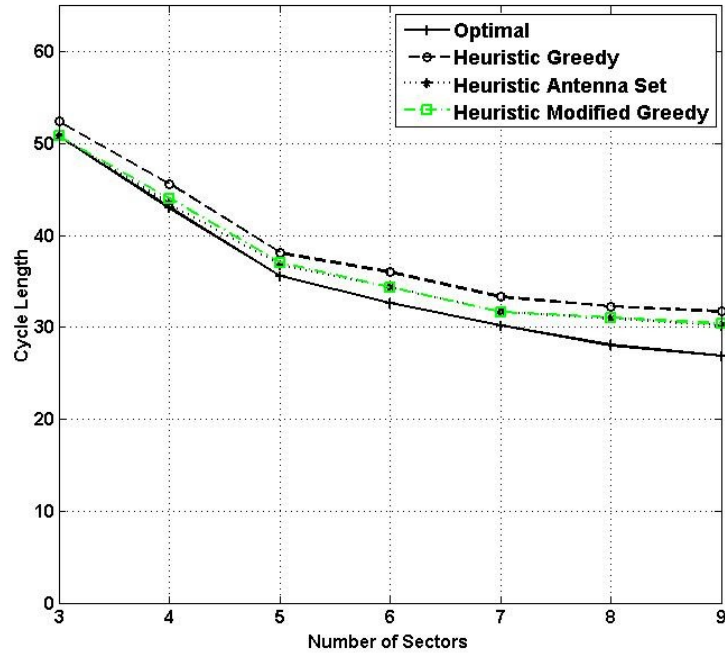


Figure 5-35: Minimum Cycle Length with Modified Greedy, $A = -6$ dB, $\beta = 10.0$ dB

In Figure 5-9 to 5-12, the modified greedy heuristic actually improved the performance of the original heuristic for the first problem. In fact, the modified algorithm performed almost as well as the heuristic based on forming the antenna set for some combinations of A and β . What we are more interested in is how well this modified heuristic performs in the second problem where we maximize the number of packets per timeslot. The results are illustrated in Figures 5-13 to 5-16.

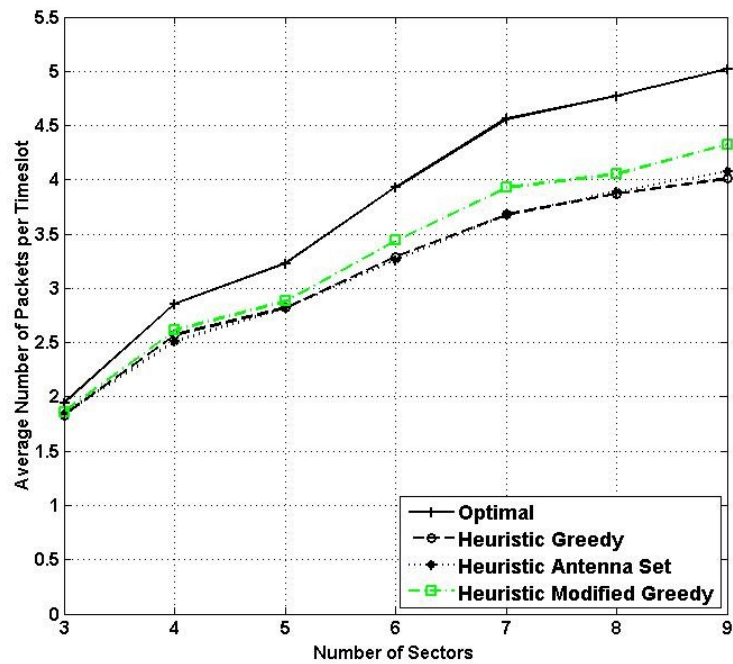


Figure 5-36: Number of Packets/Timeslot with Modified Greedy, $A = -3$ dB, $\beta = 6.4$ dB

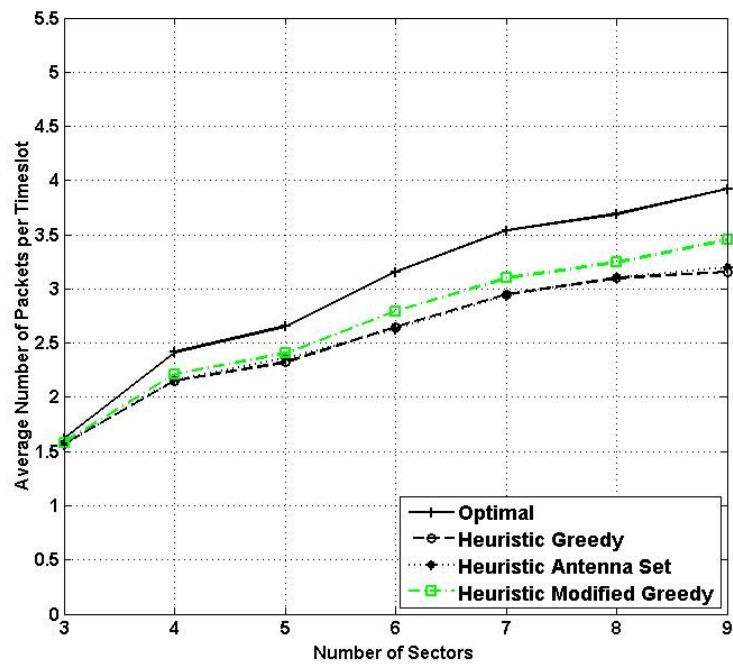


Figure 5-37: Number of Packets/Timeslot with Modified Greedy, $A = -3$ dB, $\beta = 10.0$ dB

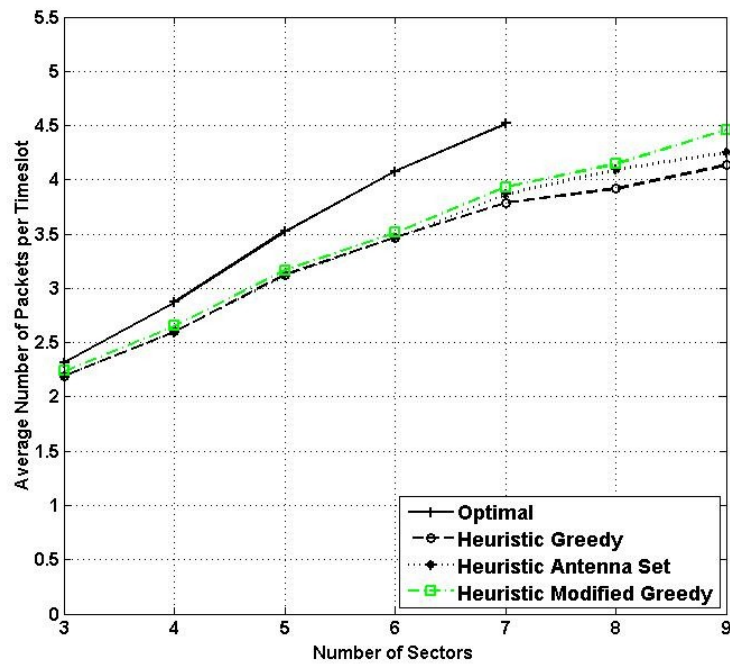


Figure 5-38: Number of Packets/Timeslot with Modified Greedy, $A = -6$ dB, $\beta = 6.4$ dB

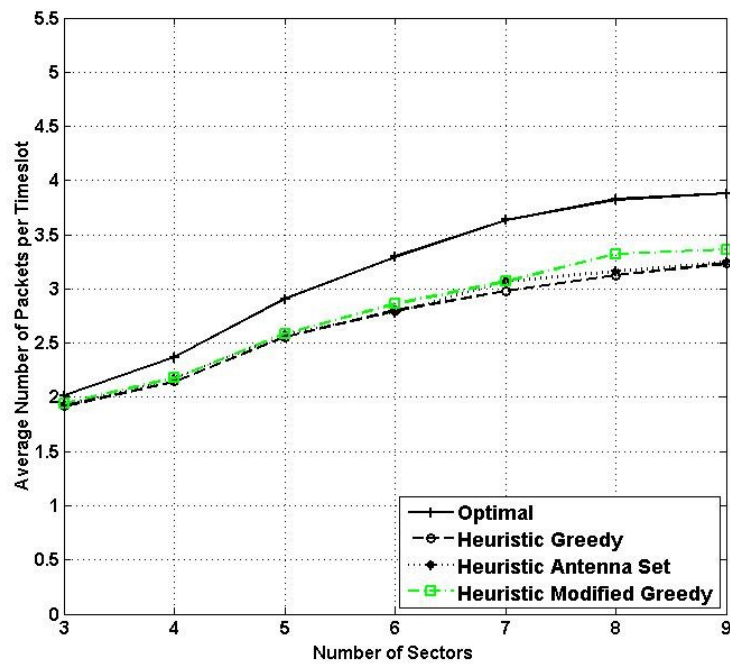


Figure 5-39: Number of Packets/Timeslot with Modified Greedy, $A = -6$ dB, $\beta = 10.0$ dB

In Figure 5-13 to 5-16, the modified greedy algorithm improves the performance of the original algorithm and reduces the gap between the heuristic and the optimal solution by roughly 25-30%. The result indicates that ordering the next sector list based on the number of unsatisfied nodes is not the best choice, and that interference should be at least considered for better performance. It is important to note that in our simulation, a very crude integer ranking system was used by each node. This can most likely be further fine-tuned to achieve even better result.

5.4 Complexity Analysis of the Two Heuristics

In this section, we will briefly analyze the complexity of the heuristics proposed in section 5-1 and 5-2. In both heuristics, the procedure must loop until every node is satisfied. In the worst-case scenario, where every node must each occupy a timeslot on its own, this loop will run N times, and hence this part of the procedure is of the order $O(N)$.

Inside the outer loop, the first step is to choose a sector from which we will be choosing a node to add to the current set. It is quite clear that not every sector can be necessarily turned on without violating the SINR constraints of the nodes in the current set nor is it guaranteed that the sector has nodes that can be added successfully. In the worse case scenario, it may take up to M tries to find a suitable next sector, and in each sector attempt, up to N nodes if no nodes can satisfy the SINR constraint. Therefore this step has a complexity of order $O(MN)$ for the greedy algorithm.

In the second heuristic, before the next sectors can be picked, one of the procedures is to generate the common antenna sets from the current set of chosen nodes. Since each node has a maximum of M antenna set, generating the common sets with N nodes has a complexity of the order $O(MN)$. Having found the common sets, choosing the next sector has complexity of $O(M)$.

After picking a sector, we must finally find a node to add to the current set. This step involves checking if a node in this sector satisfies the SINR value. In the first heuristic using the greedy algorithm, the first node which satisfies the requirements is chosen, which might require the algorithm to go through every node in the sector. Similarly for the second heuristic, every node in the sector is first verified to see if it satisfied the SINR constraints, and then sorted accordingly. This step, however, is essentially incorporated by the previous step in picking the next possible sectors, and hence really have a complexity of $O(1)$.

Since the procedure for adding nodes that have already been satisfied to the current node set is exactly the same as choosing the next sector or node in the algorithm, the complexity of this step is the same. It is therefore expected to have a complexity in the order of $O(MN)$.

The overall complexity is computed to be $O(N^2M)$, and is summarized in Table 5-1 below.

Table 5-2: Summary of the complexity analysis

Procedure	Complexity of 1 st Heuristic	Complexity of 2 nd Heuristic
Outer loop	$O(N)$	$O(N)$
Generating common sets	N/A	$O(MN)$
Picking next sector	$O(MN)$	$O(M)$
Adding used node	$O(MN)$	$O(MN)$
Overall	$O(N * (2MN + I)) = O(N^2M)$	$O(N * (2MN + M + I)) = O(N^2M)$

We will conclude this section by looking at the runtime analysis of the proposed heuristic algorithms. The results in the following figure is obtained by programming the heuristics in C++ and run under a Pentium 4 2.4 GHz machine using the Ubuntu operating system.

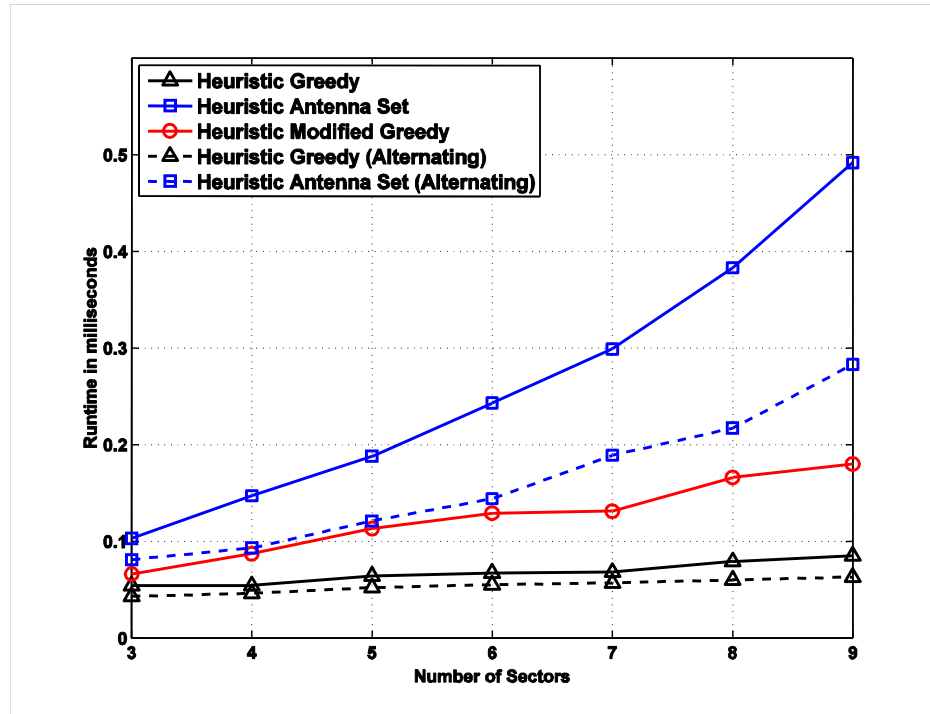


Figure 5-40: Runtime Comparison

From Figure 5-17, we can note that both heuristics have a very fast runtime. The runtime for the two heuristics are not dependent on the value of A or β . For the first heuristic based on the greedy algorithm, increasing the number of sectors appears to have only a slight effect on the runtime. The second proposed heuristic based on forming antenna sets, has a much more complicated structure, and has been demonstrated in earlier section, to slightly outperform the greedy heuristic in minimizing the cycle length. However, the more complex algorithm requires a much longer runtime, and it can be seen in this figure that the effect of increasing the number of sectors is much more visible.

Second, limiting the ISET formation to only alternating sectors has marginal effect in decreasing the runtime for the first heuristic. As we have described earlier, the alternating-sector approach is similar to dividing the single cell into two smaller cells with half the number of sectors. Since the greedy heuristic runtime does not depend much on the number of sectors in the cell, the alternating-sector approach will only make very little difference in reducing the overall runtime. On the other hand, the second heuristic based on forming antenna set clearly shows a dependence on the number of sectors in the cell; therefore, breaking the cell to form smaller cells with lesser number of sectors would help decrease the runtime more significantly. Also, as we have stated earlier for the second heuristic, the antenna set combinations must first be calculated prior to running the algorithm. However, since the time this process takes is much less than 1% of the total simulation runtime, which is negligible compared to the other steps in the procedure, and therefore, we will simply consider the total runtime instead of looking at the runtime of this process and the algorithm separately.

Analyzing the complexity of the newly modified algorithm, since the only changes were how the next sector and next node list are arranged, we believe the overall complexity will remain the same. In the above figure, although the modified greedy algorithm requires longer runtime compared with the original algorithm due to the added complexity, its runtime is much shorter compared with the second heuristic based on forming antenna sets. As we have seen in earlier figures, the modified greedy algorithm performs almost equally well with the second heuristic in terms of minimizing the cycle length, and outperforms it by being more efficient in network utilization.

Chapter 6

Conclusion

In this thesis, we have analyzed many issues. We considered a scheduling problem derived from a generalized round robin which aimed at minimizing the number of timeslots required to provide time fairness to everyone in the cell. We proposed a second problem which maximizes the network utilization while minimizing the round robin cycle length.

While analyzing the exact solution using the commercial optimization tool, CPLEX, we found that increasing the number of sectors in the system helps decrease the minimum cycle length. For smaller number of sectors, increasing the number of sectors has a larger effect in reducing cycle length than for higher number of sectors, which suggest that increasing the number of sectors in the system beyond a critical value will not improve our first problem. Second, lowering the beamwidth gain value also helps reduces the minimum cycle length, although after the beamwidth gain goes below -4 dB, the improvement becomes marginal.

We also observed the effect of restricting the ISET size. We saw that by allowing a maximum ISET size of $\left\lfloor \frac{M}{2} \right\rfloor + 1$, we can achieve very close to optimal results for the first optimization problem.

However, for the second optimization problem, we should allow a maximum ISET size to be as large as possible to achieve the best result. We note that the second approach in reducing ISET size based on splitting the sectors in the cell into two groups and solving them independently, is not an efficient way to schedule nodes to minimize cycle length or to maximize the average number of packets per timeslot.

The two heuristics that we proposed in this paper performed quite well in the first optimization problem, with the second heuristic based on forming antenna sets being slightly more efficient in allocating timeslots. However, both heuristics performed poorly in maximizing network utilization when compared against the optimal results.

To solve the second optimization problem more efficiently, we modified the existing heuristic based on a greedy algorithm. When we analyzed the way sectors and nodes were chosen in the greedy algorithm, we decided that it was necessary to take interference into consideration and modified the original greedy algorithm. The results from the simulations were promising. Not only did we marginally improve the

performance for the first problem, we see a modest improvement in the second problem where the gap between the optimal solution and heuristic result was decreased by roughly 25-30%. We noted that this result can probably be further improved by fine-tuning how we prioritize the sectors or the nodes.

Although this paper only examines downlink transmission from the base station, if we make the assumption that each node can control its transmit power such that the received power at the base station is the same for every node, the heuristics proposed in this paper can also be applied towards the uplink channel case.

This paper will now conclude by stating some possible future works. The two heuristics studied in this paper are not the only possible approach to this problem. There are definitely many more ways this problem can be solved, which may produce yet faster results or results closer to the optimal solution.

It was observed in an earlier section that the rate in which the minimum cycle length drops decreases as the number of sectors increases. We noted that there probably exists a sector number where having more sector would not necessarily decrease the cycle length. A possible research area would be to find this optimal number of sectors and relate it with the number of nodes in the network. By knowing how many sectors to divide the network into, we can avoid the cost of installing more antennas at the base station than what we really need.

Furthermore, the framework provided in this paper is based on round-robin scheduling scheme. In this framework, by providing time fairness, we are in fact optimizing the network from the worst node's perspective. Suppose that there is one node that cannot share a timeslot with any other nodes in the system due to poor channel conditions, the heuristic would allocate a relatively large portion of the system resources, which in our case is a timeslot in a frame, in order to satisfy this particular node. This type of time fairness, however, is not appropriate for a network in practice. Therefore, reformulating the problem to provide proportional fairness while restricting the maximum starvation period, would be another interesting area for future research.

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