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Mimo Communication for Ad Hoc Networks: A Cross Layer Approach

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MIMO COMMUNICATION FOR AD HOC NETWORKS: A CROSS LAYER APPROACH

A Thesis Presented

by

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DEDICATION

To,

My parents

and

in loving memory of my sister Ritu

ACKNOWLEDGMENTS

I would like to express my deep appreciation and gratitude to my advisor, Prof. Aura Ganz, for her guidance, suggestion and support throughout my graduate studies. Without her valuable support, I would never have been able to bring my ideas and research to realization. I believe experiences gained under her guidance will be a guiding force in my professional career as well as my personal life.

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Finally, and most importantly, I would like to thank the almighty God, for it is under his grace that we live, learn and flourish.

ABSTRACT

MIMO COMMUNICATION FOR AD HOC NETWORKS: A CROSS LAYER APPROACH

May 2008

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New technologies such as pervasive computing, ambient environment, and communication avid applications such as multimedia streaming are expected to impact the way people live and communicate in the wireless networks of the future. The introduction of these new technologies and applications is, however, a challenging task in wireless networks because of their high bandwidth requirements and Quality of Service (QoS) demands.

A significant recent advance in wireless communication technology, known as Multiple-Input Multiple-Output (**MIMO)** provides unprecedented increase in link capacity, link reliability and network capacity. The main features of MIMO communication are spatial multiplexing, point-to-multipoint and multipoint-to-point transmission as well as interference suppression in contrast to the conventional single antenna (Single-In Single-Output, **SISO**) networks.

In this thesis, we investigate the problem of scheduling flows for fair stream allocation (or, stream scheduling) in ad hoc networks utilizing MIMO antenna technology. Our main contributions include: i) the concept of stream allocation to flows

based on their *traffic demands* or *class*, ii) stream allocation to flows in the network utilizing single user or multiuser MIMO communication, iii) achieving the proportional fairness of the stream allocation in the minimum possible schedule length, and iv) performance comparison of the stream scheduling in the network for single user and multiuser communication and the tradeoff involved therein. We first formulate demand-based fair stream allocation as an integer linear programming (ILP) problem whose solution is a schedule that is guaranteed to be contention-free. We then solve this ILP in conjunction with binary search to find a minimum length contention-free schedule that achieves the fairness goals. Performance comparison results show the benefit of multiuser MIMO links over single user links which is predominant at higher traffic workloads in the network. We also implement a greedy heuristic for stream scheduling and compare its performance with the ILP-based algorithm in terms of the fairness goals achieved in a given schedule length. OPNET-based stochastic simulation confirms the benefits of MIMO-based stream scheduling over single antenna links, as shown by our theoretical analysis.

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CHAPTER 1

INTRODUCTION

New technologies such as pervasive computing, ambient environment, and communication avid applications such as video conferencing and multimedia streaming are expected to impact the way people live and communicate in the wireless networks of the future. The delivery of multimedia information significantly increases the amount of traffic transmitted over the wireless channels as well as introduces the need to provide quality of service (QoS) support to the diverse media streams.

The realization of a wireless network, with unprecedented transport capacity required to support such applications, requires innovation at all the layers of the network stack-jointly. The use of multiple antennas at transmitter and receiver, popularly known as Multiple-Input Multiple-Output (*MIMO*) wireless is an emerging physical layer technology that has the potential to make wireless links, with 1 *Gbps* capacity, a reality due to its unprecedented spectral efficiency [3,4,5,6]. The capability of MIMO links to operate in non-line-of-sight (NLOS) harsh fading and multipath environments and their ability to suppress interference is a paradigm shift from the existing wireless link technologies. These characteristics enable MIMO based wireless network the ability to offer QoS to multimedia traffic in wireless links, extended range for better connectivity and highly reliable wireless links in harsh environments. MIMO wireless link technology offers a rich scope for research in ad hoc networks owing to its various characteristics. Some of the unorthodox properties of MIMO links, arising due to the multiple antennas (also referred to as spatial degrees-of-freedom, **DoF**) at the transmitter and receiver side, include interference suppression, high link reliability, capacity scaling, interference avoidance, co-operative transmission, multi-packet reception, and point-to-multipoint transmission. Proper management of the above mentioned MIMO induced resources will lead to efficient resource utilization which results in high network throughput and QoS support.

In this thesis we propose *demand-based fair MIMO stream allocation* to the traffic flows in the network for medium access control (MAC). This approach is flexible and adaptive to varying traffic demands and network topology. To achieve this, we develop a theoretical framework for guiding the development of demand-based resource allocation and media access control algorithms that can exploit MIMO's capabilities in multihop wireless networks that provide QoS support to multimedia applications. To achieve this task we carry out the following tasks:

1. Theoretical framework for algorithm development: We have defined an abstract network model for MIMO communication (both single user and multiuser). We develop a centralized algorithm in this framework for MIMO stream scheduling that make use of MIMO's single user and multiuser spatial multiplexing and interference suppression capabilities in the contention-free setting. The proposed centralized algorithm efficiently and fairly schedules the required traffic demands. We study the interplay between schedule length and fairness, and identify the mutual tradeoffs. For contention free scheduling, we formulate the problem of stream scheduling in a MIMO ad hoc network as an integer linear programming (ILP) problem. For a given network topology, set of flow demands, and schedule length, the solution to the ILP formulation yields a schedule of a given length that satisfies the demands optimally. Furthermore, we show that even we can identify the optimal schedule length, that is, the shortest schedule required to achieve *strict fairness*.

2. Contention-free scheduling algorithms: While our formulation and approach guarantees a schedule that has optimal length and satisfies strict fairness, it is not necessarily a viable algorithm in practice, since we do not have efficient algorithms to find solutions to the ILP formulation. Therefore, we develop practical centralized algorithm that gives near-optimal performance in terms of fairness.

3. OPNET Simulations: We developed simulation model in OPNET for MIMO links to evaluate the proposed algorithm under different conditions such as: varying traffic patterns, varying degree of freedom available at the network nodes, etc.

The remainder of the thesis is organized as follows. In Chapter 2, we introduce the basics of MIMO wireless communication and in Chapter 3 we present the related work. Chapter 4 introduces the system model for MIMO stream scheduling. Chapter 5 presents the theoretical framework for MIMO stream scheduling utilizing single user spatial multiplexing. Chapter 6 presents the theoretical framework for MIMO stream scheduling utilizing multiuser spatial multiplexing. Chapter 7 presents the theoretical framework for stream scheduling in networks using SISO links. Chapter 8 presents the greedy algorithm for MIMO stream scheduling. Chapter 9 and chapter 10 present the theoretical results and OPNET simulation results, respectively. Chapter 11 outlines the contributions and concludes the thesis.

CHAPTER 2

MIMO BACKGROUND

In recent years, considerable research has been done to exploit the benefits of directional antennas, switched-beam antennas, and smart antennas in ad hoc wireless networks. However, these antenna technologies provide good performance in line-of-sight environments but results in degraded performance in non-line-of-sight (NLOS) environments (indoor environments, urban outdoor environments, forested terrain, etc.). MIMO [3,4,5,6,14,15,16] is one of the recently emerging smart antenna technology, where adverse wireless channel characteristics and conditions are exploited rather than mitigated. The MIMO physical link exploits multi-path propagation in scattering environments through the use of multiple-antennas and sophisticated signal processing techniques at both the transmitter/receiver side (see Figure 2.1, a MIMO link system with four transmit and four receive antennas). MIMO generally operates in two modes: diversity mode and spatial multiplexing mode.

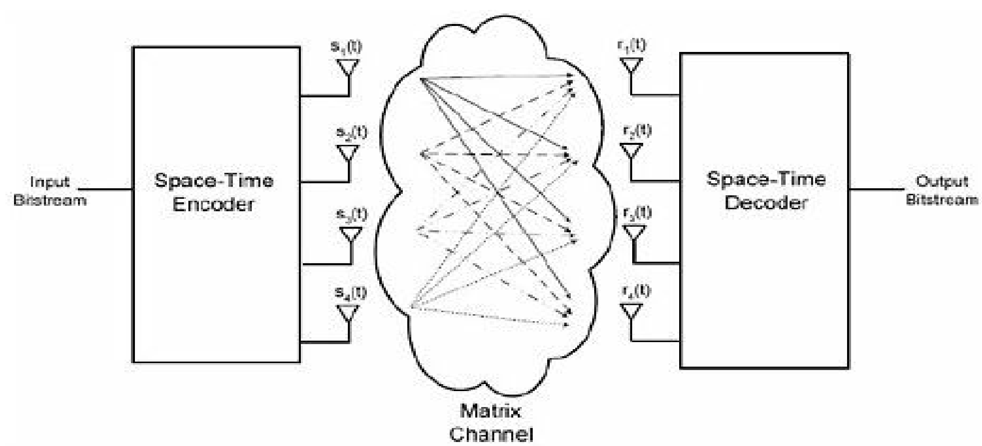

Figure 2.1: A 4X4 MIMO link

2.1 MIMO Single User Communication

Single user MIMO communication pertains to the fact that a transmitter (receiver) is engaged into meaningful communication with only one receiver (transmitter) at a time.

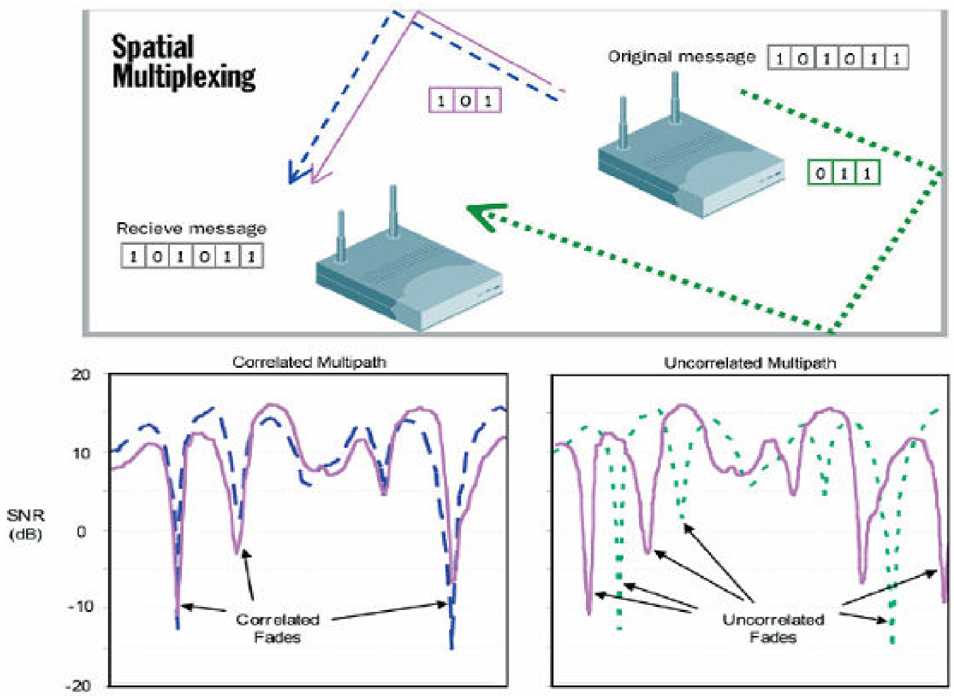

Figure 2.2: Spatial multiplexing over uncorrelated multipaths

2.1.1 MIMO Single User Spatial Multiplexing

The MIMO link (utilizing M transmit and N receive antennas) in spatial multiplexing mode, de-multiplexes an incoming data stream over M transmit antennas. This transmission results into M independent streams [5,6] transmitted over the *same frequency*, using the *same modulation* and the *same signal constellation*. The receiver side must have a minimum of M receive antennas so as to be able to successfully recover the transmitted data. Such MIMO systems increase communication data rates drastically above current systems and as they operate by creating parallel channels in the same frequency band, thereby increasing spectral efficiency. This mode relies on the availability of rich scattering and multi-path environment so that the transmitted streams at the receiver are uncorrelated (see Figure 2.2). The average capacity (i.e. *bandwidth normalized capacity*) increases linearly with M:

$$C_a \approx M \log(1 + SNR)$$

In general the capacity will grow proportional to the smallest number of antennas $k = \min(M, N)$ where M is the number of transmitter side and N the receiver side antennas. This is a tremendous capacity increase, especially given the scarce spectral resources below 10 GHz frequency range and achieving this capacity is infeasible using traditional techniques with single antenna radios. Therefore in theory and in the case of idealized random channels (rich scattering between the transmitter and the receiver), limitless capacities can be realized provided we can afford the cost and space of many antennas and RF chains. In reality the performance will be dictated by the practical transmission algorithms selected and by the physical channel characteristics (scattering in the propagation environment, etc).

2.1.2 MIMO Spatial Diversity

In spatial diversity [14,15,16] mode, MIMO systems use multiple antenna arrays to maximize range or reliability between the transmitter and receiver by choosing the best signal path between them. The diversity helps in achieving a very low BER (bit error ratio) and thus increases the reliability of the link thus enhancing the throughput. The basic principle of diversity is to use different "channels" (signal path) to convey the same information unit from the transmitter to the receiver (see Figure 2.3). This means that, at the end, only one information stream is exchanged, but with better signal quality. The application of diversity is especially useful when the different channels that are used fade in a statistically independent fashion, or, in other words, when the probability that all channels are bad at the same time is low. In this way, the information can be recovered from the channel(s) where the signal-to-noise ratio is the best. Hence, spatial diversity is useful when the link budget must be improved in order to increase the communication range or in order to reduce the transmit power or boost link reliability.

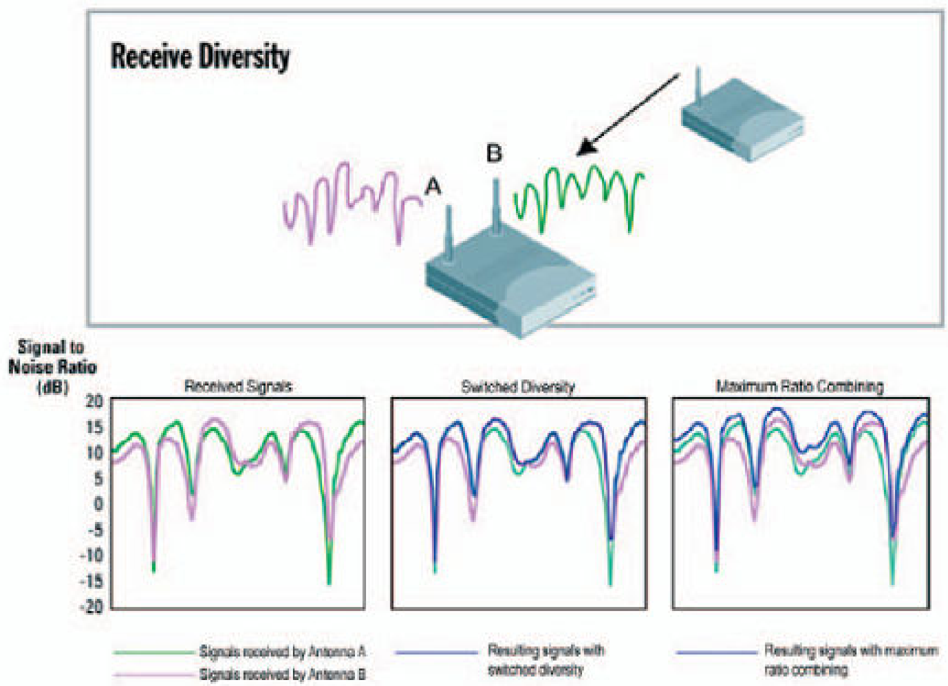

Figure 2.3: Receive-side diversity and diversity techniques like maximal ratio combining, switched diversity

2.2 MIMO Multiuser Communication

Multiuser MIMO can exploit multiple users as well as multiple antennas as spatial resources using suitable transmit or receive side signal processing techniques compared to single user MIMO which uses only multiple antennas as spatial resource. Multiuser MIMO addresses two communication problems: MIMO broadcast channels and MIMO multiple access channels for downlink and uplink (in cellular network terminology), respectively [17]. In the uplink multiuser scenario, multiple users all transmit data to the same node and in the downlink scenario one node transmits to multiple nodes. While single user MIMO can be represented as point-to-point communication between a transmitter and receiver pair.

2.2.1 MIMO Multiuser Spatial Multiplexing

Downlink multiuser spatial multiplexing (MUSM) [15, 16] is an example of MIMO broadcast communication. The basic idea behind downlink MIMO multiuser spatial multiplexing is to multiplex data streams to multiple users at the same time and precancel inter-user interference at the transmitter itself.

MUSM orthogonalizes the signal meant for different users (i.e. the data streams) and thus eliminates co-channel interference. One such technique is precoding. Using the precoder [18,19,20], *the multiuser MIMO channel is decoupled into K parallel non-interfering single-user MIMO links. Each user operates in its corresponding single-user link independently without affecting other links*. The number of antennas at the receiver upper bounds the number of streams that can be detected (e.g. *using a linear Zero Forcing receiver, ZF*) while the number of antennas at the transmitter upper bounds the total number of independent data streams that can be transmitted.

MIMO multiuser reception is an example of the MIMO multiple access communication. Multiple users equipped with multiple antennas can transmit to the same user with multiple antennas. Again, the number of antennas at the receiver side determines the upper bound on the number of streams detected. Some of the receivers used for detecting the multiple data streams of the multiple users are those based on a decorrelator utilizing spreading codes [21], and those based on conventional linear and non-linear receivers used for decoding multiplexed data streams [20,22].

Thus, multiuser spatial multiplexing allows a transmitting node to transmit multiple independent data streams to multiple users such that none of the users experiences interference due to other users' streams. Also, a receiver utilizing multiuser detection can receive multiple independent data streams transmitted by multiple users. Henceforth, we will refer to ***m***ulti***u***ser spatial ***m***ultiplexing as MUM.

2.3 MIMO Interference Suppression

Interference cancellation mitigates network interference, providing network with the ability to offer higher data rates, increased capacity and improved coverage. This ultimately leads to a superior user experience.

From a receiver's perspective, MIMO transmission results in the superposition of signals on each Rx antenna. Mathematically, this can be seen as an equation with a number of unknowns (the transmitted signals). If every equation represents a unique combination of the unknown variables (each transmitted signal experiences independent channel fading) and the number of equations is equal to the number of unknowns, then their exits a unique solution to the problem. If the number of equations is larger than the number of unknowns, a solution can be found by performing a projection using the *least squares* method ([6]), also known as the *Zero Forcing* (ZF) method. For the symmetric case, the ZF solution results in the unique solution. Thus, for the receiver equipped with N antennas to differentiate M data streams successfully, $M \leq N$ must be satisfied. However, if the number of streams at the receiver exceeds its DoF then it can still successfully decode the M data streams if the excess streams do not degrade the SNR of the desired streams below the receive threshold. This can happen when the excess interfering stream's transmitters are far from the receiver than its desired transmitters.

In general, in a multiuser environment with K users and each user utilizing N antennas there will be $K \times N$ interfering signals arriving at the user. The classical interference suppression techniques with multiple antennas at the receiver will require $N*(K-1)+1$ antennas at the receiver for suppressing co-channel interference from $K-1$ users and receiving the desired signal with a diversity order of N [38].

In [23] an approach based on array signal processing combined with channel coding is presented. Multi-layered space-time architecture is proposed for group interference suppression using space-time coding. This layered receiver detection architecture is a generic form of that proposed by the seminal BLAST (Bell Labs Space Time) work [5]. The set of transmitter side antennas are partitioned into a set and each of the set uses individual space-time codes to transmit information from each group of antennas. At the receiver, the individual codes are decoded by treating signals from other groups of transmitters as noise. This technique can be applied in a K-multiuser scenario with the condition that the number of receiver side antennas is M such that $M \geq N*(K-1)+1$ utilizing product codes [39]. Also, receiver requires perfect channel state information.

The seminal work in [24] presents a MMSE (Maximum Mean Square Error) interference suppression technique and maximum likelihood decoder for space-time block coded transmissions. In a multiuser environment with synchronous K-users the receiver using $M \geq K$ will perfectly suppress the interference from $K-1$ co-channel users by exploiting the temporal and spatial structures of the codes. In [25], it is proved that the above result cannot be generalized for the case when each user has more than two transmit antennas. This work also shows that utilizing quasi-Orthogonal Space Time Block codes the interference from K user can be cancelled by using $K-1$ antennas only. Note in these two works, the users are not exploiting spatial multiplexing (Both utilize full rate space-time codes i.e. effectively the transmission rate is one symbol/per symbol period across all the antennas).

In [26], the authors propose receiver architecture, termed CDMA-BLAST, based on decorrelating detector for multiuser detection for the cellular multiple access interference (uplink) communication. The transmitters are assumed to have multiple antennas. Through the use of spreading codes the inter-user interference is separated at the receiver and then layered space-time detection is applied to separate data streams of the user. The authors show that high spectral efficiency can be achieved through the use of multi-code transmission in the multiuser scenario.

In [21] authors investigate the use of layered space-time, also known as Vertical-Bell Laboratories Layered Space-Time (V-BLAST) scheme, for multiuser detection in fading channels. The multiple transmit antennas in V-BLAST are treated as individual mobile station transmitters while the base station consists of multiple receive antennas. Users are organized in groups and allocated a unique spreading code within the same group. Using these orthogonal codes, the different groups are separated (a combined space code matched filtering), and layered space-time algorithm is then invoked to further remove the remaining interference between users.

2.4 Stream Control in Spatial Multiplexing

In [28], the authors introduce the term *stream control* in MIMO's spatial multiplexing mode and show the gains obtained by using stream control with interference suppression compared to TDMA-based approaches without interference suppression. It is shown that based on distance between interfering links a single DoF can counter more than one interfering streams and hence *in a given collision region (all links in this region interfere with each other)* more streams can be accommodated than the number of DoFs at the receiver. In general, if the distance between interfering links in a given collision region is below a certain threshold then each interfering stream requires the sacrifice of one DoF. Otherwise, if mutually interfering links are farther apart, then multiple interfering streams can be suppressed by fewer DoFs at the interfered receiver [28]. We note that stream control algorithms cannot exploit the full capacity of MIMO links due to conflicting demands on the spatial DoFs (or, number of antennas) for interference suppression.

CHAPTER 3

RELATED WORK

The problem of user scheduling has been well explored in the cellular MIMO broadcast (downlink) and multi-access channels (uplink) [27]. These studies focus on maximizing the sum rate capacity of the MIMO broadcast and multi-access channel based on bit error ratio constraints, transmit power constraints, etc.

While there has been considerable focus on point-to-point MIMO physical links, cellular broadcast and multi-access channel, very little research effort has focused on the benefits of MIMO for interference-limited multi-hop ad hoc networks. In [7] the authors proposed a derivative of 802.11 medium access control protocol, MIMA-MAC, to exploit the interference suppression capability of the MIMO-OFDM transceiver. It employs multiple antennas to mitigate interference from neighboring nodes, and to increase the number of simultaneous traffic flows, resulting in an increase in the total network throughput. In MIMA-MAC, the transmitters use a single fixed antenna and the receiver uses multiple antennas allowing the receiver to suppress interference using space-time processing. In [29], a similar approach based on RTS/CTS mechanism is suggested to exploit MIMO's interference suppression capability for accommodating multiple transmissions in the same collision region. The beamforming technique is used to transmit the ***same*** stream (same symbol across all antennas) weighted differently across the transmit antennas. It enables multiple interfering streams to co-exist through beam coordination. That is, effectively each node transmits one stream at a time. Also, one DoF sacrifice is assumed to null out an interfering node.

It has been shown that pure contention-based approaches agnostic of MIMO physical layer [9,13], are not suitable in ad hoc networks since they do not exploit MIMO's interference suppression capability. Such approaches abstract MIMO links as a "*fat pipe*" and thus are only able to view it as a high capacity link.

Demirkol and Ingram [28] introduced the concept of *stream control*-determining the number of transmit antennas for each link that maximizes the throughput of MIMO ad hoc network. They show that *optimal stream control* corresponds to (k/l) streams allocated to each of the l mutually interfering links equipped with k adaptive arrays. Appropriate power allocation is needed for each of these mutually interfering links to achieve optimal stream control.

Sundaresan and Sivakumar [9,13] were the first to study the problem of stream allocation in MIMO ad hoc networks exploiting optimal stream control to achieve proportional fairness. In their proposed centralized and distributed scheduling algorithms, the bottleneck links (belonging to multiple contention regions) are allowed to transmit with all possible streams while other links use optimal stream control. That is stream allocation is determined by the number of mutually interfering links. The algorithms achieve proportional fairness by allocating at least k-streams (k is the number of antennas at each node) at the end of every l (size of the largest maximal clique in the flow contention graph) slots. Also, they do not explore the problem of optimizing the schedule length for achieving fairness goals.

Zorzi et al. [12] proposed a frame synchronous distributed stream scheduling approach to exploit multiuser detection capability, based on LAST-MUD [21], of the MIMO receivers. The nodes probabilistically alternate roles between transmitter and receivers to allow a fair share of the channel to other nodes as transmitter. In [10], random medium access algorithm is proposed to exploit the multi-user detection capability of the receivers based on LAST-MUD. The media access arbitrates the admission of different number of streams in a collision region based on different policies (e.g. policy of disregarding the interfering streams and allowing transmission of all requested streams; policy of considering DoF sacrifice to suppress interfering streams).

The use of LAST-MUD based receivers in ad hoc networks will require the allocation of spreading codes to the nodes in a coordinated manner. In ad hoc networks, new nodes may not have this prior knowledge of the spreading code matrix (codes in use in the network) and each node must keep track of the spreading codes in use in its neighborhood [2].

In [30] the problem of user-QoS enhancement is explored via rate adaptation in MIMO ad hoc networks. QoS is defined in terms of goodput (number of intact bits delivered to the destination) which in turn is quantified by the diversity gain of the flow on a link. The goal is to find paths which maximize the minimum QoS-requirement given a set of fixed input data traffic rates. In terms of MIMO terminology, it tries to maximize the minimum spatial diversity gain in the network for a set of given multiplexing gain (link transmission rate) associated with each user traffic. The solution assigns minimum values of multiplexing gains to satisfy the input rates and utilizes the left degree of freedom to enhance diversity gain. This work assumes channel capture by the nodes i.e. only one link is active in a collision region at any given time.

Multiplexing gain is traded-off for diversity gain rather than interference suppression. Also, it assumes that the network operates at a high signal-to-noise ratio.

In [31], 802.11 RTS/CTS mechanism is modified to exploit the benefits of Multiuser MIMO in wireless LAN settings. The access point transmits MU-RTS (multiuser RTS) to poll multiple receivers for reception. The central access point uses a priority assignment scheme for the different traffic classes and a delay-sensitive scheduler to schedule transmission of multiple data frames (from different traffic classes based on the priority) to multiple destinations at the same time. The scheme doesn't provide any fairness guarantees to the traffic flows.

CHAPTER 4

SYSTEM MODEL

The increasing demand of wireless services associated with the scarcity of the radio spectrum and the trend to provide end-to-end QoS in emerging and future communication avid applications calls for the design of spectrally efficient systems with QoS support. To fulfill these two requirements of spectral efficiency and QoS provision in the highly dynamic environment of wireless network requires the collaboration of several layers in the system as well as the use of multiple transmit and receive antennas. In an interference-limited ad hoc network, one important component to achieve the aforementioned efficiency goals is a properly designed scheduling algorithm. Using a theoretical framework, we capture the issues associated with the design of scheduling algorithms for MIMO ad hoc network and present a centralized algorithm which achieves fair resource allocation in optimal schedule length. The thesis proposal focuses on cross-layer architecture to the MIMO resource allocation problem and will identify the trade-offs associated with the contention-free and contention-based scheduling approaches.

We assume users (nodes equipped with MIMO radio) employ single user detection in presence of multiple interfering users. This means users treat transmissions from undesired users as interference and cancels out their contribution even though it can successfully decode the transmitted packets of the interfering users.

In our system model, each node is equipped with a *k*-antenna array. The environment in which the network is operating is assumed to be rich-scattering (e.g. home networks) where the signal at the receiver's antenna elements are not correlated.

4.1 Network Model

Node Graph: The node graph is the communication graph on which the traffic flows are routed. Given the *physical* network topology, we define a *node graph* $G_N = (V_N, E_N)$, where V_N represents the set of nodes in the network, and E_N represents the set of edges between all those pairs of nodes that are within transmission/reception range of each other. Let the *node distance* $d_N(a,b)$ between nodes *a* and *b* in the network to be the Euclidean distance between the physical locations of *a* and *b*. We denote the transmission, reception, and interference range by D_{Tx}, D_{Rx} and D_I respectively. We assume in our work that these ranges are all equal, that is, $D_{Tx} = D_{Rx} = D_I$. The topology of the node graph is then defined as follows:

$$E_N = \{(x, y) \mid x, y \in V_N ; d_N(x, y) \le D_{Rx}\}$$

The edge set E_N captures two unidirectional links between every pair of two nodes, since each node can be a transmitter or receiver respectively depending on the direction of the traffic flow.

Definition of a Flow: A *flow* $u = (a,b)$ is defined as the directional flow of the traffic in the network between a pair of nodes *a* and *b* in V_N. In our model, we only consider traffic on *per-hop flows*. More formally, a flow $u = (a,b)$ is a *per-hop flows* if $\{a,b\} \in E_N$. Note that for each edge $\{a,b\} \in E_N$, there are exactly two flows (a,b) and (b,a), representing communication from *a* to *b*, and from *b* to *a*. Furthermore, for each flow $u = (a,b)$, we let $Tx(u) = a$ represent the transmitter of flow *u*, and $Rx(u) = b$ represent the receiver of flow *u*.

Flow Contention Graph: Two flows are within contention region of each other if either of their transmissions can cause interference to the other due to actual physical proximity, or the flows require a node to be a common transmitter/receiver, or a node is required to be a transmitter and receiver at the same time. The contention between two flows depends on the capability of the physical layer of the links. For example, two flows sharing a common receiver may perform simultaneous reception if the links utilize MUM capability. Thus, the definition of flow contention is different for networks utilizing SISO, SUM and MUM. To capture the contention between two traffic flows, we define the *distance between two flows u* and *v* as $d_F(u,v)$. If the flow distance is less than the interference distance then we say that the flows interfere.

We now define the flow contention graph $G_F = (V_F, E_F)$. Let V_F be the set of all traffic flows between nodes in V_N (i.e., there are two vertices for each edge $\{x, y\}$ in E_N, indicating the possibility of communication from *x* to *y* and from *y* to *x*), and let $E_F = \{(u,v) \mid d_F(u,v) \leq D_I\}$ (E_F represents the set of edges between those pairs of nodes in G_F that are within the contention region of each other, see Figure. 4.1.).

Demands in the Flow Contention Graph: The traffic demand or class of a flow can be represented by a weight on the associated vertex in the flow contention graph; for convenience we will write the demands as a function $W_F : V_F \to Z^+$. We will assume that these demands are given as input, along with the node graph G_N (we note that the flow contention graph G_F can easily be computed from G_N).

We assume per hop traffic flow demands and not the traffic demand for flows between any arbitrary source- destination pairs in the network (e.g. it is common in traffic engineered networks to route traffic along predetermined paths when the traffic demand for flows between source-destination pairs are known). Also, considering per hop traffic allow paths to be selected by the routing algorithm and thus allows intermediate links on a given path to change.

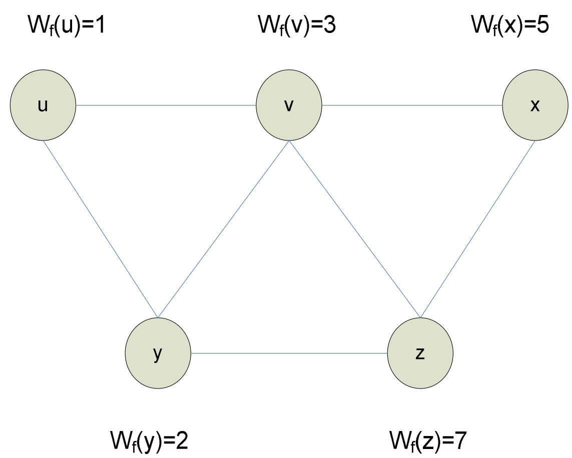

Figure 4.1: A flow contention graph, in which the nodes represent flows and edges represent mutual interference between flows

Resource Contention Regions in the Flow Contention Graphs: We refer to the set of all maximal cliques in the flow contention graph G_F as the *resource contention regions* of G_F. Let $R_1(G_F) \cup R_2(G_F) \cup ... \cup R_l(G_F) = V_F$ be the set of all maximal cliques of G_F (see Fig. 4.2). For notational convenience, since we will consider a single node graph and a single flow contention graph in this paper, we will write the maximal cliques as $R_1, R_2, \ldots, R_l$. The flows in each resource contention region are those flows that mutually interfere with one other. For an arbitrary flow graph, the problem of even identifying these contention regions is NP-hard; however, we follow the standard assumption that contention regions can be identified efficiently, since ad hoc network topologies generally tend to be chordal graphs, for which the problem of finding maximal cliques can be solved in polynomial time [28,40,41]. Each contention region can accommodate only a fixed number of independent streams based on our assumptions. That is, the capacity of the contention region is fixed and determined by the number of antennas at the receiver.

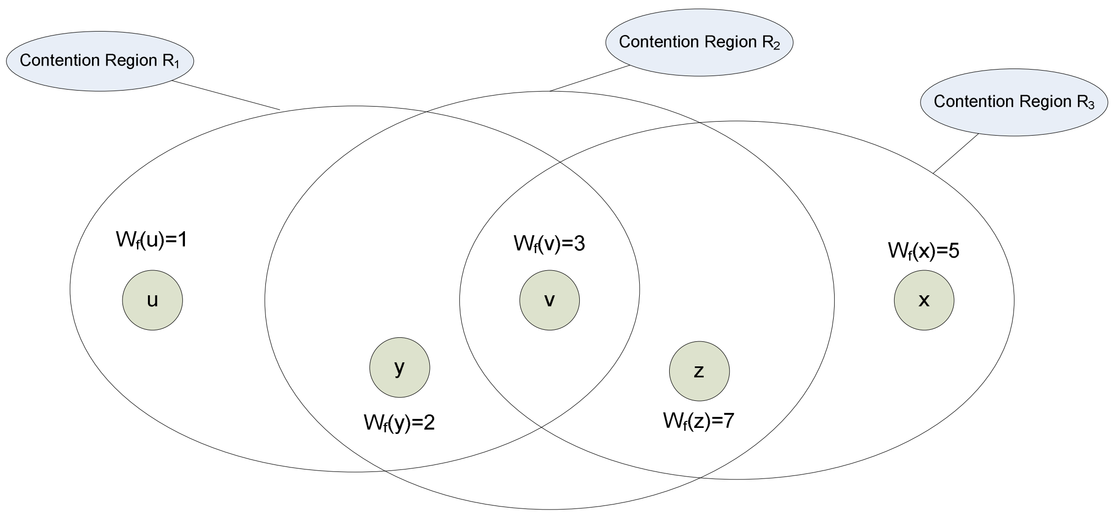

Figure 4.2: Resource contention regions corresponding to the flow contention graph of Figure 4.1

Mutually Exclusive Flows in MIMO Ad Hoc Networks: In conventional wireless networks, all the flows in the same contention region are mutually exclusive. Only one of them can transmit at a given time without causing contention. In traditional ad hoc networks, multiple flows in the same contention region can be accommodated by using multiple non-overlapping frequency channels and multiple radios. In the case of MIMO, all the flows in a given contention region may not be mutually exclusive because of the interference suppression, or multiuser reception or point-to-multipoint transmission capabilities of the MIMO nodes.

Fairness Model: To provide consistent proportional sharing of the MAC layer resources, we use the number of MIMO streams communicated by a flow for data transmission, over the course of a given schedule, as the quantitative metric for each flow in the network. We make the distinction between streams that are allocated versus streams that are communicated, because if the given schedule forces flows to contend for resources in a given time slot, the actual amount of data transmitted may be less than what is possible. While it may be possible to consider contention in the schedule, the resulting throughput is a complex function of the flow contention graph G_F. Thus, we focus on contention-free stream scheduling. For a given schedule, let S_u be the total number of streams communicated on flow *u*. Then proportional fairness is achieved if, for all flows $u, v \in E_F$:

$$\frac{S_u}{S_v} = \frac{W_F(u)}{W_F(v)}$$

holds. Strict fairness is achieved when, in addition to proportional fairness, for all flows $u \in E_F$ we have $S_u = W_F(u)$ i.e. the flow communicates the number of streams as allocated to it based on its demand/class.

We call a schedule optimal for a set of demands if it is a minimum length schedule that achieves contention-free strict fairness. Henceforth, we will refer to this minimum schedule length as the *optimal schedule length*.

CHAPTER 5

PROBLEM FORMULATION FOR SINGLE USER MIMO SPATIAL MULTIPLEXING

The increasing demand of wireless services associated with the scarcity of the radio spectrum and the trend to provide end-to-end QoS in emerging and future communication avid applications calls for the design of spectrally efficient systems with QoS support. To fulfill these two requirements of spectral efficiency and QoS provision in the highly dynamic environment of wireless network requires the collaboration of several layers in the system as well as the use of multiple transmit and receive antennas. In an interference-limited ad hoc network, one important component to achieve the aforementioned efficiency goals is a properly designed scheduling algorithm. Using a theoretical framework, we capture the issues associated with the design of scheduling algorithms for MIMO ad hoc network and present a centralized algorithm which achieves fair resource allocation in optimal schedule length. This thesis focuses on cross-layer architecture to the MIMO resource allocation problem and will identify the trade-offs associated with the contention-free scheduling approaches for single user and multiuser communication.

In this chapter, we present the stream scheduling framework for a network where the MIMO links utilize SUM capability. We first present the MIMO physical layer model and the network model used and then the proposed framework for the stream scheduling.

5.1 Physical Layer Model

The fading between each transmit and receive antenna pair is assumed to be independent (because of rich scattering.) We assume a quasi-static flat Rayleigh fading wireless channel (so that channel is invariant during one slot of a stream transmission and changes independently between slots). Uniform power allocation is assumed across the transmit antenna array (each active antenna gets P/k of the total available power P for the transmission of an independent data stream [5,6]).

The single-user detection at the receiver treats all unintended transmissions as pure interference. The number of streams falling on a receiver is no more than the number of antennas (or, DoF) k at the receiver. This allows the streams falling on a receiver to be decoded successfully with high probability as the excessive interfering streams would have to be treated as enhanced noise at the receiver thereby affecting the successful decoding probability.

Channel state information (CSI) is critical to minimize inter-user interference under all channel conditions in a single user MIMO link. We assume the channel transfer matrix is known to a receiver of its own channel (desired streams) and the interfering streams. The CSI can be obtained at the start of the transmission slot through training symbols and feedback packets [34]. CSI varies independently over slots as the channel experiences flat fading during each time slot.

5.2 Network Model

The network model for stream scheduling in networks utilizing SUM has the same definitions for the node graph, flows, flow demands and fairness as described in chapter

4. We, now, define the flow contention graph and mutual exclusivities of the flows due to the use of the single user detection.

5.2.1 Flow Contention Graph

To capture the contention between two traffic flows (on links utilizing SUM), we define the distance between two flows u and v as:

$$d_F(u,v) = \begin{cases} 0, \quad if & \begin{matrix} Tx(u) = Tx(v), Rx(u) = Rx(v), \\ Tx(u) = Rx(v), Tx(v) = Rx(u) \end{matrix} \\ \min\{d_N(Tx(u), Rx(v)), d_N(Tx(v), Rx(u))\} & \end{cases}$$

Note that two interfering flows u and v (with $d_F(u,v) > 0$) can be scheduled in the same time slot because MIMO receivers can perform interference suppression.

5.2.2 Mutually Exclusive Flows

When the nodes in the network utilize single user detection, two flows u and v are *mutually exclusive* only when $d_F(u,v) = 0$. This means that two flows are mutually exclusive if the common node is required to be a transmitter and receiver at the same time or, the common node is required to be the transmitter (receiver) for multiple flows for point-to-multipoint transmission (for multipoint-to-point reception).

5.3 MIMO Stream Scheduling Algorithm for Single User Spatial Multiplexing

In our proposed network model, MIMO ad hoc networks employing SUM can accommodate k streams in a single contention region compared to a single stream in conventional SISO wireless ad hoc networks. In addition, MIMO receivers are capable of suppressing interference thereby allowing multiple streams of multiple flows to coexist in a contention region. The number of interfering streams they can suppress is limited to the DoF the receiver has to spare from the reception of desired streams. For example, if a receiver has DoF as five and it is engaged in receiving two streams from a transmitter then it can successfully counter three interfering streams.

When a link is scheduled for transmission in conventional wireless networks, transmit and receive side antennas are allocated for one particular flow transmission and reception. In contrast, in a MIMO link a subset of the antennas can be allocated to flows (e.g., when stream control is used). The stream scheduling algorithm determines the number of antennas allocated at the transmitter for transmission, number of antennas allocated at the receiver side for reception and number of antennas dedicated for interference suppression. Stream scheduling can lead to resource sharing between nodes in the wireless network, leading to a better utilization of the available resources (DoF and the channel).

5.3.1 Contention-free MIMO Stream Scheduling

Our aim is to provide proportional service differentiation to the different traffic classes in the given MIMO multi-hop ad hoc network. To enable service differentiation, we adopt a contention free TDMA-based approach for stream scheduling. In each slot, traffic flows are scheduled to be transmitted with a specific number of streams which is determined a) to maximize the total number of streams schedulable, b) based on the traffic flow demands/class. We consider this problem for MIMO communication, and capture SUM and interference suppression capabilities by formulating the problem of stream scheduling in a MIMO multi-hop ad hoc network as an ILP problem. For a given network topology, set of flow demands, and schedule length, the solution to the ILP formulation yields a schedule of the given length that satisfies the demands optimally.

Furthermore, we show that even we can identify the optimal schedule length required to achieve contention-free strict fairness.

At the high level, our aim is to maximize the number of flows at any given time in the network under certain constraints. First, we cannot schedule more streams in a given contention region than the number of antennas on a node in that region and the number of streams communicated by the flow should not exceed its demand. Second, we must ensure the mutual exclusivity of certain flows; that is, we cannot schedule two mutually exclusive flows in the same slot in a schedule. Finally, a flow node's receiver must not be overloaded with more than *k* streams when it is active and can be overloaded with arbitrary number of streams when the flow is inactive.

Recall that $R_1, R_2, ..., R_l$ was the set of all maximal cliques in the flow contention graph, as discussed above. Also, recall that we assumed that each node in our MIMO network have *k* DoF, thus each flow has a maximum of *k* communication streams at any given time. For interference suppression, we assume that each flow has to use as many antennas for interference suppression as interfering streams falling on it, so the capacity of each resource contention region is simply *k*. For each of the flows in the set E_F, let S_{ut} denote the number of streams allocated to flow *u* in time slot *t* and let $x_{ut} \in \{0,1\}$ be an indicator variable that denotes whether a flow is active during time slot *t*; x_{ut} will allow us to enforce the mutual exclusivity among the flows.

We now present our ILP formulation for contention-free MIMO stream scheduling.

Input: The node graph G_N , the contention graph G_F , the contention regions $R_1, R_2, ..., R_l$, the demands to be satisfied W_F , the DoF k at each node and the desired schedule length L .

ILP Formulation

Minimize $\sum_{u \in V_F} \left(W_F(u) - \sum_{t=1}^{L} S_{ut} \right)$

Subject to:

a. Capacity constraints and flow demands:

$$S_{ut} \geq 0 \tag{1}$$

$$\forall R_i, t : \sum_{u \in R_i} S_{ut} \leq k \tag{2}$$

$$\forall u : \sum_{t=1}^{L} S_{ut} \leq W_F(u) \tag{3}$$

b. Receiver overloading:

$$\forall u : S_{ut} + \left(\sum_{v \in V_F : (Tx(v), Rx(u)) \in E_N \wedge u \neq v} S_{vt} \right) \leq x_{ut} k + k(1 - x_{ut})(|E_F| - 1) \tag{4}$$

c. Mutual exclusivity:

$$\forall t, \forall a \in V_N : \sum_{u \in V_F : Tx(u) = a \vee Rx(u) = a} x_{ut} \leq 1 \tag{5}$$

$$\forall u, t : 0 \leq S_{ut} \leq x_{ut} W_F(u) \tag{6}$$

It is evident that capacity and receiver overloading constraints, (2) and (4) captures the MIMO interference suppression capability. At any given time an active receiver will not be overloaded beyond *k* streams. Henceforth, it can successfully decode the desired streams and reject the interfering streams. An inactive receiver can be overloaded, in the worst case, by as many streams as k times the number of flows (minus one for the inactive flow with this node as a receiver) in the contention graph. Equation (5) captures the mutual exclusivity constraint of the flows for at any given time a single flow is active when multiple flows share a transmitter or/and receiver. In a given contention region multiple flows can transmit streams, but the total number of streams is limited by the number of antennas. There is *no net gain* in the number of total streams that can be scheduled for a single slot for a given contention region. However, it should be clear that the ability to schedule multiple flows per slot, rather than a single flow, provides flexibility in our ability to provide proportional fairness.

An integral solution to the variables of this ILP problem gives a contention-free schedule of length L. Furthermore this schedule minimizes the amount of demand that is not satisfied. We will now show that a simple binary search can be used to find the optimal schedule length. For convenience, in the remainder of the paper, we will refer to the optimization criterion for the ILP above as the contention-free fairness measure.

5.3.2 Computing Optimal Schedule Length

In this section, we will present a simple algorithm for finding the optimal schedule length, given a method for solving the ILP formulation for SUM above. First, we note that any contention-free schedule that achieves strict fairness satisfies the following bounds for its length:

Lemma 1. The length of any contention-free schedule for SUM satisfies:

$$L \geq \max_{R_i} \left\lceil \frac{\sum_{u \in R_i} W_F(u)}{k} \right\rceil$$

Proof. First, observe that flows in different contention regions can be scheduled in the same slot, and thus we need only to identify a lower bound on the number of slots needed to schedule demands for any contention region. We can assume that there are no mutual exclusivity constraints (see Fig. 5.1), since such constraints would only require a longer schedule. Then, we observe that for any region R_i, a given slot can accommodate number of streams equal to the capacity of the region. The lemma follows since the number of slots required to fulfill the demand in a region is at least the total demand in the region divided by its capacity.

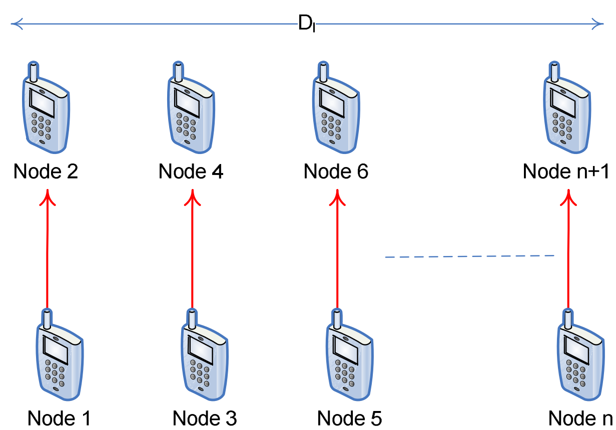

Figure 5.1: The best case scenario for stream scheduling for SUM links. None of the flows in the dominant contention region are mutually exclusive with any other flow.

Lemma 2. The length of any contention-free schedule for SUM satisfies:

$$L \leq \max_{R_i}\left(\sum_{u \in R_i}\left\lceil \frac{W_F(u)}{k} \right\rceil\right)$$

Proof. Although each contention region can be scheduled concurrently, in the worst case all the flows in each contention region can be mutually exclusive with each other (e.g. all the flows share a common transmitter, see Fig. 5.2). In this worst case, each flow must be scheduled independently, since, for example, every flow can be made to share a transmitter. Thus, the lemma follows since in any other scenario more than one flow can be scheduled simultaneously[1].

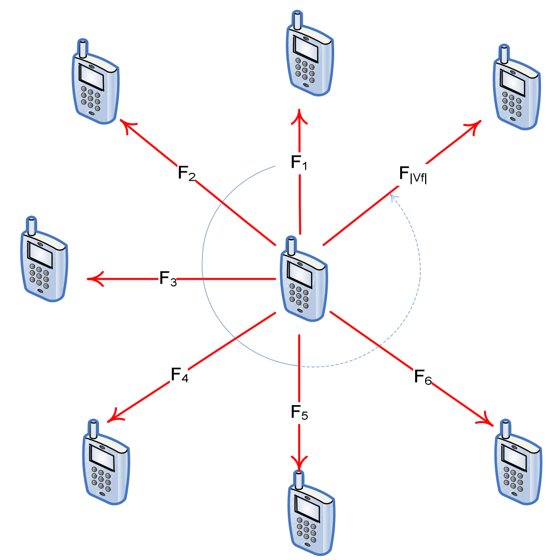

Figure 5.2: Worst case scenario for stream scheduling for SUM links. All the flows in the dominant contention region are mutually exclusive because they share a common transmitter.

Informally, Lemma 1 states that the set of mutually contending flows with largest total traffic demand essentially dominates the schedule length. However, the schedule length is also affected by the mutual exclusivity of flows, which we must ensure in order to have a valid schedule.

In order to compute the optimal schedule length, we can solve the ILP formulation repeatedly, using a binary-search algorithm to determine the best schedule length. In the algorithm (see Fig. 5.3 for the pseudo code), the lower bound on L serves as the lower index and the upper bound on L as the upper index for the binary search algorithm. If

---

[1] When all the flows in the network are mutually contending and $\forall\, u \in V_F, k$ is a factor of $W_F(u)$ then the lower bound holds even when none of the flow is mutually exclusive with any other flow. In this case, exactly k streams will be scheduled in any contention region at a given time slot.

we ever obtain a schedule with an objective function value of 0, we halve the schedule length. This process is repeated until we find the minimum value of L for which we have an objective function value of 0. The solution to the ILP is then a contention-free schedule that achieves strict fairness with a minimum schedule length. Note that the number of times we must solve the ILP is logarithmic in the length of the optimal schedule.

```
BinarySearch( L_lb, L_ub, G_F, G_N, R_1,R_2...R_l, W_F ) {
        low = L_lb          // lowerbound on L
        high = L_ub         // upperbound on L
        L = floor((low+high)/2)     //Initial probe schedule length
        while ( low ≤ high ) {
           obj_fn = SolveILP_SUM(L, G_F, G_N, R_1,R_2...R_l, W_F)
           if ( obj_fn > 0 )
              low = L+1
           else if ( obj_fn == 0 ){
              high = L-1
              previous_L = L   //Remember this schedule length L
           }
           L = floor((low+high)/2)   //Next probe schedule length
        }
        return previous_L
}
```

Figure 5.3: Pseudo code for the centralized algorithm to determine the schedule and optimal schedule length for contention-free strict fairness (floor refers to the greatest integer function)

CHAPTER 6

PROBLEM FORMULATION FOR MULTIUSER MIMO SPATIAL MULTIPLEXING

In this chapter, we present the stream scheduling framework for a network where the MIMO links utilize multiuser MIMO communication i.e. MUM for point-to-multipoint transmission and multipoint-to-point reception. We first present the MIMO physical layer model and the network model used and then the proposed framework for the stream scheduling.

6.1 Physical Layer Model

As in the SUM case, the fading between each transmit and receive antenna pair is assumed to be independent. We assume a quasi-static flat Rayleigh fading wireless channel. Uniform power allocation is assumed across independent data streams. We assume closed-loop systems for the multiuser communication where the CSI is available at the transmitter of the receiver side of the link as well.

The transmitter-side CSI is used to design precoders for pre-canceling inter-user interference at the receiver. We assume the linear precoders which require accurate downlink CSI at the transmitter. Other precoders such as those using unitary precoding require pairing of orthogonal users through SDMA. When the transmitter isn't transmitting data streams to multiple users than the signals are not precoded. Note, that the precoder only cancels interference at the receivers of the users to whom data streams are transmitted. Other receivers would experience interference from these transmitted streams. Effectively, the receivers which are not the destinations for the transmited streams need to have CSI from the transmitter to cancel out these interfering streams. (*A simple linear receiver such as the zero-forcing can cancel out interference from other users.*)

The assumption of perfect CSI has been widely used in many existing literature in MIMO precoding and multiuser MIMO system. It can be fulfilled by channel estimation in time-division-duplex systems or feedback in frequency division-duplex systems.

6.2 Network Model

The network model for stream scheduling in networks utilizing MUM has the same definitions for the node graph, flows, flow demands and fairness as described in the previous chapter 4. We, now, define the flow contention graph and mutual exclusivities of the flows.

6.2.1 Flow Contention Graph

To capture the contention between two traffic flows (on links utilizing MUM), we define the distance between two flows *u* and *v* as:

$$d_F(u,v) = \begin{cases} 0, & if \quad (Tx(u) = Rx(v)) \vee (Tx(v) = Rx(u)) \\ \infty, & if \quad (Tx(u) = Tx(v)) \vee (Rx(u) = Rx(v)) \\ \min\{d_N(Tx(u), Rx(v)), d_N(Tx(v), Rx(u))\} & \end{cases}$$

Recall that, in the case of multiuser communication utilizing precoding at the transmitter the resulting flows are independent non-interfering links.

6.2.2 Mutually Exclusive Flows

When the nodes in the network utilize MUM, two flows *u* and *v* are mutually exclusive only when $d_F(u,v)=0$. This means that two flows are mutually exclusive if the common node is required to be a transmitter and receiver at the same time.

6.3 MIMO Stream Scheduling Algorithm for Multiuser Spatial Multiplexing

We now present our ILP formulation for contention-free MIMO stream scheduling.

Input: The node graph G_N, the contention graph G_F, the contention regions $R_1, R_2, ..., R_l$, the demands to be satisfied W_F, the DoF k at each node and the desired schedule length L.

ILP Formulation

Minimize $\sum_{u \in V_F} \left(W_F(u) - \sum_{t=1}^{L} S_{ut} \right)$

Subject to:

a. Capacity constraints and flow demands:

$$S_{ut} \geq 0 \tag{7}$$

$$\forall R_i, t : \sum_{u \in R_i} S_{ut} \leq k \tag{8}$$

$$\forall u : \sum_{t=1}^{L} S_{ut} \leq W_F(u) \tag{9}$$

b. Receiver overloading:

$$\forall u : S_{ut} + \left(\sum_{v \in V_F : (Tx(v), Rx(u)) \in E_N \wedge u \neq v} S_{vt} \right) \leq kx_{ut} + k(1 - x_{ut})(|E_F| - 1) \tag{10}$$

c. Mutual exclusivity:

$$\forall t, \forall u, v \in V_F : (Tx(u) = Rx(v))(x_{vt} + x_{ut}) \leq 1 \tag{11}$$

$$\forall t, \forall a \in V_N : \sum_{u \in V_F : Tx(u) = a} x_{ut} \leq k \tag{12}$$

$$\forall t, \forall a \in V_N : \sum_{u \in V_F : Rx(u) = a} x_{ut} \leq k \tag{13}$$

$$\forall u, t : 0 \leq S_{ut} \leq x_{ut} W_F(u) \tag{14}$$

Equation (8), (9) and (10) captures the capacity, traffic demand and interference suppression constraints similar to the case for SUM. For multiuser communication, (12) and (13) captures the point-to-multipoint transmission and multipoint-to-point reception, respectively. Now, a transmitter can communicate upto *k* streams across multiple flows and a receiver can receive upto *k* streams from multiple flows.

An integral solution to the variables of this ILP problem gives a contention-free schedule of length *L*.

6.4 Computing Optimal Schedule Length

In this section, we will use the binary search algorithm (as defined for the SUM case except that it will invoke the ILP for MUM) for finding the optimal schedule length, given a method for solving the ILP formulation above. First, we note that any contention-free schedule that achieves strict fairness satisfies the following bounds for its length:

Lemma 3. *The length of any contention-free schedule for MUM satisfies:*

$$L \geq \max_{R_i} \left\lceil \frac{\sum_{u \in R_i} W_F(u)}{k} \right\rceil$$

Proof. First, observe that flows in different contention regions can be scheduled in the same slot, and thus we need only to identify a lower bound on the number of slots needed to schedule demands for any contention region. The best case corresponds to the scenario when flows have any configuration except that two flows share a node as a source and sink (node is a transmitter for one flow and receiver for the other flow). This is equivalent to the single user detection case when none of the flows are mutually exclusive because flows which are sharing the receiver or transmitter can be decomposed into non-interfering flows. These flows can be scheduled simultaneously due to multiuser precoding/detection.

Then, we observe that for any contention region R_i, a given slot can accommodate a number of streams equal to the capacity of the region. The lemma follows since the number of slots required to fulfill the demand in a region is at least the total demand in the region divided by its capacity.

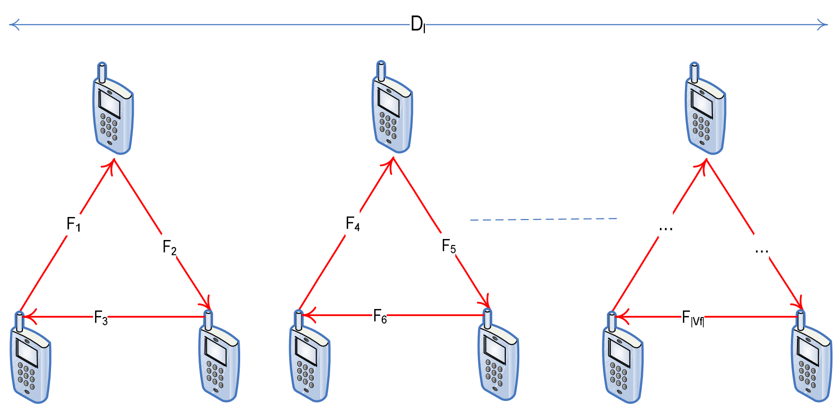

Figure 6.1: Worst case scenario for stream scheduling for MUM links. All the flows are in the same contention region and each flow is mutually exclusive to two other flows.

Lemma 4. *The length of any contention-free schedule for MUM satisfies:*

$$L \leq \max_{R_i} \left(\sum_{u \in R_i} \left\lceil \frac{W_F(u)}{k} \right\rceil \right)$$

Proof. First, observe that the worst case scenario for MUM is when no two flows share a common transmitter or receiver in the dominant contention region. This happens when the flows form triangular configurations as shown in Fig. 6.1. It can be observed from the scenario shown in the figure that any fourth flow cannot be simultaneously mutually exclusive to three other flows as it will result in two flows sharing a common transmitter or receiver. This is due to the fact that a node can either be in transmit or receive state, thus any third edge incident on the node implies any two flows (out of the three incident on the node) as sharing a common transmitter or receiver. This would allow MUM to exploit the configuration to simultaneously schedule the flows.

Now, for this worst case configuration we can see that the optimal schedule length will be a complex expression of the actual flow weights in the contention region. But we show that upper bound given in the lemma is the worst case upper bound for MUM. Observe that for the given configuration, if all the flow weights are multiples of k then only one flow will be scheduled for stream transmission (there can not be any gain by partially scheduling the streams of the flows). Thus, the lemma follows as each scheduled flow consumes all the capacity of the contention region.

We observe that the lower/upper bound for the MUM case is exactly the same as that for SUM. Thus, it is the cumulative traffic demand in the dominant contention region and the available DoF at each node that determines the lower/upper bound on the schedule length.

In order to compute the optimal schedule length, as before we can repeatedly solve the ILP formulation for MUM, using binary search. The algorithm is as described for SUM (see Fig. 5.3 for the pseudo code) except that we invoke the ILP formulation for MUM.

CHAPTER 7

PROBLEM FORMULATION FOR SISO LINKS

In this chapter we describe the ILP formulation for stream scheduling when the links utilize SISO communication. Though the ILP formulation for SUM and MUM includes the SISO case for $k=1$ in the formulation, we describe here a simpler formulation to capture the SISO stream scheduling for the sake of completeness. We formulate for the two cases when SISO communication link has the capacity equivalent to a single DoF available to MIMO links as well as the capacity equivalent of the MIMO link with k DoF. We formulate for these two cases to evaluate and compare the performance of SISO links with equivalent capacity as MIMO links as well as when SISO links do not have the MIMO equivalent capacity.

7.1 Physical Layer and Network Model

We assume for the single antenna case the same MIMO physical layer but with the exception that each node employs only single antenna (thereby no multiplexing or diversity gain). We do not consider coding gain either.

The network model remains unchanged except for the definition of the mutually exclusive flows. For the network equipped with a single antenna (a single radio), all the flows are mutually exclusive since the radios are incapable of interference suppression (due to another interfering radio in the same frequency channel) compared to MIMO link radios (neither these single antenna radios are capable of multiuser communication).

7.1.1 Stream Scheduling Algorithm for SISO Links with Capacity Equivalent to a MIMO Link with Single DoF

We now present our ILP formulation for contention-free stream scheduling in networks utilizing single antenna radios with link capacity equivalent to a MIMO link with a single active DoF.

Input: The node graph G_N, the contention graph G_F, the contention regions $R_1, R_2, \ldots, R_l$, the demands to be satisfied W_F, the DoF *1* at each node and the desired schedule length L.

ILP Formulation

Minimize $\sum_{u \in V_F} \left(W_F(u) - \sum_{t=1}^{L} S_{ut} \right)$

Subject to:

a. Capacity constraints and flow demands:

$$S_{ut} \geq 0 \quad (14)$$

$$\forall R_i, t : \sum_{u \in R_i} S_{ut} \in \{0,1\} \quad (15)$$

$$\forall u : \sum_{t=1}^{L} S_{ut} \leq W_F(u) \quad (16)$$

Compared to the contention-free SUM and MUM stream scheduling, we do not require any *receiver overloading* or *mutual exclusivity* constraints for strict fairness. Since the capacity constraint allows *only one flow* to be active in any contention region at any time *all the flows are mutually exclusive*. So, mutual exclusivity is captured by the capacity constraint, (15), of the ILP formulation. In a MIMO-based network, an active receiver can receive streams from other interfering transmitters because of interference suppression and hence must be assured that the number of interfering streams do not exceed the available DoF. But for a SISO-based network, if a receiver is active then it implies that the corresponding flow is active and hence it will be mutually exclusive to all the flows which are in the common contention region of this active flow. All the other flows remain inactive in the common contention regions. Therefore, capacity constraint guarantees that receivers never get overloaded.

1) Optimal Schedule Length

In this section, we will present a simple proof for finding the optimal schedule length.

Lemma 5: The length of the optimal contention-free schedule satisfies:

$$L = \max_{R_i} \left\lceil \sum_{u \in R_i} W_F(u) \right\rceil$$

Proof: Note that in each contention region only one flow can be scheduled at any given time. Thus, the optimal schedule length will be determined by the contention region with the most traffic demand. The lemma follows since only a unit traffic demand is satisfied for any contention region at any given time slot.

7.1.2 Stream Scheduling for SISO Links with Capacity Equivalent to a MIMO Link with *k active* DoF

We now present our ILP formulation for contention-free stream scheduling in networks utilizing single antenna radios equivalent to a MIMO link with ***k active*** DoF.

.***Input***: The node graph G_N, the contention graph G_F, the contention regions $R_1, R_2,..., R_l$, the demands to be satisfied W_F, the DoF k at each node and the desired schedule length L.

ILP Formulation

Minimize $\sum_{u \in V_F} \left(W_F(u) - \sum_{t=1}^{L} S_{ut} \right)$

Subject to:

a. Mutual exclusivity:

$$\forall R_i, t : \sum_{u \in R_i} x_{ut} \leq 1 \tag{17}$$

b. Capacity constraints and flow demands:

$$S_{ut} \geq 0 \tag{18}$$

$$\forall R_i, t : \sum_{u \in R_i} S_{ut} \leq k \tag{19}$$

$$\forall u : S_{ut} \leq k x_{ut} \tag{20}$$

$$\forall u : S_{ut} \leq x_{ut} W_F(u) \tag{21}$$

$$\forall u : \sum_{t=1}^{L} S_{ut} \leq W_F(u) \tag{22}$$

Compared to the contention-free SUM and MUM stream scheduling, we do not require any *receiver overloading* for strict fairness. The *mutual exclusivity* constraint is required since compared to the SISO case for *k=1* the flows can communicate the minimum of $\{k, W_F(u)\}$ streams when scheduled (so mutual exclusivity is not implicit) as captured by (19) and (20). The capacity and flow demand constraints, (19) and (20) respectively, coupled with the mutually exclusivity constraint makes ***a scheduled flow to communicate the minimum of*** $\{k, W_F(u)\}$ ***streams*** (minimum of link capacity and the demand). That is, either a schedule flow communicates as much data in a time slot as the SISO link can accommodate (when $W_F(u) > k$) or as much as its traffic demands (when $k > W_F(u)$). Note that to achieve strict fairness the flows would communicate exactly $W_F(u)$ data streams. So, even if the SISO link has a capacity equivalent to MIMO link with DoF *k* but when the flow is allocated stream transmission in any slot such that $S_{ut} < k$ the SISO link will use modulation techniques to reduce the link data rate to the unit of S_{ut}.

1) Optimal Schedule Length

In this section, we will present a simple proof for finding the optimal schedule length.

Lemma 6: The length of the optimal contention-free schedule satisfies:

$$L = \max_{R_i} \left[\sum_{u \in R_i} \left\lceil \frac{W_F(u)}{k} \right\rceil \right]$$

Proof: Note that in each contention region only one flow can be scheduled at any given time. Thus, the optimal schedule length will be determined by the contention region with the most traffic demand. The lemma follows since only *k* units of traffic demand is satisfied for any contention region at any given time slot.

CHAPTER 8

CENTRALIZED GREEDY ALGORITHM FOR MIMO STREAM SCHEDULING

While our ILP-based algorithm guarantees a schedule that has optimal length for achieving strict fairness, it relies on a number of potentially costly invocations to an ILP solver. Therefore, we propose a greedy heuristic for stream scheduling in networks utilizing SUM and MUM communication. The results from the greedy heuristic-based scheduler are presented in chapter 9 and also compared to the optimal results from the binary search algorithm.

The heuristic greedily selects the dominant contention regions (based on their rank which is determined by the cumulative traffic demand/workload in the contention regions) for scheduling stream transmission. The approach is motivated by the fact that the bounds on the schedule length are determined by the dominant contention region. The heuristic proceeds in two phases where in the first phase contention regions are identified and ranked in ascending order of the traffic workload in the contention region. The actual scheduling takes place in the second phase in two stages. In the first stage, non-overlapping dominant contention regions are scheduled (greedily for the contention region with highest traffic workload first) for up to *k* stream transmissions. If there are non-overlapping contention regions that are not scheduled, each is greedily scheduled to transmit as many streams as possible without overloading any active receiver. Each flow is selected in a manner such that it is not mutually exclusive to the scheduled flows. Note that any set of flows selected *across non-overlapping contention* regions in the first stage of the second phase, may still belong to a lower ranked contention region. Hence such set of flows are scheduled to communicate not more than *k* streams by virtue of their membership in the same contention region. Also, when scheduling non-overlapping contention regions *k* streams may not be scheduled in the region because of the mutual exclusivity of the flows. This approach makes sure that no active flow scheduled in the contention region gets overloaded beyond *k* streams.

In the second stage of the second phase, the heuristic attempts to squeeze as many streams as possible in the regions between non-overlapping contentions such that no active flows scheduled in the first stage gets overloaded beyond *k* streams. The heuristic greedily selects a contention region which has not been scheduled yet (and is not any scheduled in the first stage) and finds a flow which is not a member of any of the already scheduled contention region. If this contention region has any capacity left (after flows scheduled in the first stage) the flow is scheduled for stream transmission.

The greedy scheduler can be easily modified to incorporate the multiuser spatial multiplexing capability of the MIMO nodes in the network. When scheduling flows in any contention region, pair of flows which share a transmitter/receiver are now eligible to be scheduled in the same time slot.

Phase I
Input: G_F W_F K (Degree of Freedom at each node)
1. Indentify all the contention regions
2. Rank the contention regions weighted by the cumulativeW_F
Output: CR_1, CR_2…CR_l
Rank(CR_1),Rank(CR_2)…Rank(CR_l)

Phase II
*Input: **CR** = {CR_1, CR_2…. CR_l}*
Rank(CR_1),Rank(CR_2)…Rank(CR_l)
Output:
Stream schedule $\forall f \in G_F$
*T := 0; Capacity(CR_j)=K $\forall$ $CR_j \in$ **CR***
While there is non-zero traffic workload in CR
Sort CR in decreasing order of cumulativeW_F
***Scheduled_CR** = {}*
/ Stage 1 Stream Scheduling */*
*1. Choose the next highest ranked contention region, CR_i, which doesn't overlaps with CR_j, $\forall$ $CR_j \in$ **Scheduled_CR***
*a.. Schedule non-mutually exclusive flow/flows **f** $\in CR_i$, for up to min{K,min{Capacity(CR_j) } $\forall$ CR_j such that **f** $\in CR_j$}*
*b. Update the flow demands of the scheduled flows **f** $\in CR_i$*
*c. Reduce the capacity of CR_j by the number of streams communicated by **f**, $\forall$ CR_j such that **f** $\in CR_j$*
*d. Add CR_i to **Scheduled_CR***
*2. If more contention regions available in **CR** which doesn't overlaps with CR_j, $\forall$ $CR_j \in$ **Scheduled_CR** then goto step 1*
/ End of Stage 1 */*
/ Stage 2 Stream Scheduling */*
*3 .Choose the next dominant contention region CR_i such that $CR_i \in$ **CR** $\wedge$ $CR_i \notin$ **Scheduled_CR**; if no such CR_i then goto step 8*
4. Find the flow/flows which are scheduled for stream transmission and $\in CR_i$
*5. If the flows above transmit total x streams such that x < K, then find flow/flows **f'** $\in CR_i$ $\wedge$ **f'** $\notin CR_j$ $\forall$ $CR_j \in$ **Scheduled_CR** and schedule **f'** for upto K-x streams*
*6. Reduce the capacity of CR_j by the number of streams communicated by **f'**, $\forall$ CR_i such that **f'** $\in CR_i$*
*7. Add CR_i in **Scheduled_CR**; goto step 3*
/ End of Stage 2 */*
8. T := T+1

Figure 8.1: Pseudo code for the centralized greedy stream scheduling algorithm for single user MIMO communication

CHAPTER 9

RESULTS

9.1 ILP Formulation Verification

The ILP formulation has been rigorously tested on large ad hoc network topologies with traffic flow demands superposed on the links. We used the publicly available mixed integer linear programming solvers [35,36,37] for solving our formulation in the binary search algorithm. Some results from the algorithm for simple topologies (each node is equipped with four antennas) have been illustrated here.

The solver output, scheduled stream transmissions, is displayed in tables for the various schedule lengths. For topology in Figure 9.1, we see (ref. Table 9.1) that for schedule length of one slot the flow *y* is not scheduled as such its demand remains unsatisfied. Also we see that the receiver of flow *y* is overloaded with eight streams since it is inactive in 1st slot. While schedule length of two slots assures contention-free strict fairness; for all the flows have their traffic demands satisfied hence it is the optimal schedule length. In both schedule, none of the active receivers receive more than four streams in any of the slots. For topology in Figure 9.2, the optimal schedule length that achieves contention-free strict fairness corresponds to three slots.

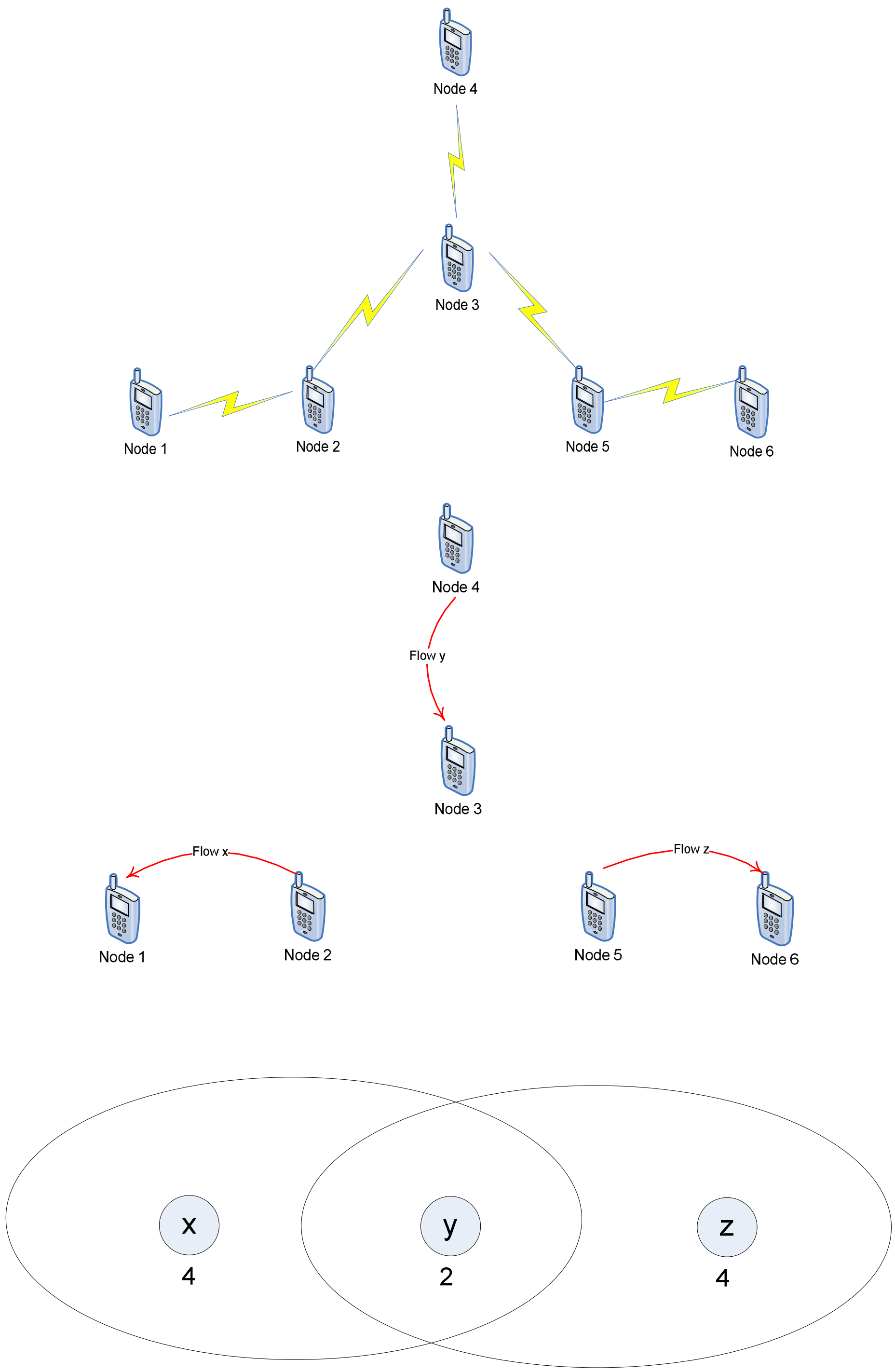

Figure 9.1: Node graph, corresponding flow graph and contention regions (with traffic flow demands)

Table 9.1: Stream allocation with scheduled transmissions for topology in Figure 9.1

Schedule Length	Slot No.	No. of Streams Scheduled
L=1		
X	1	4
Y	1	0
Z	1	4
L=2		
x	1	2
y	1	2
z	1	0
x	2	2
y	2	0
z	2	4

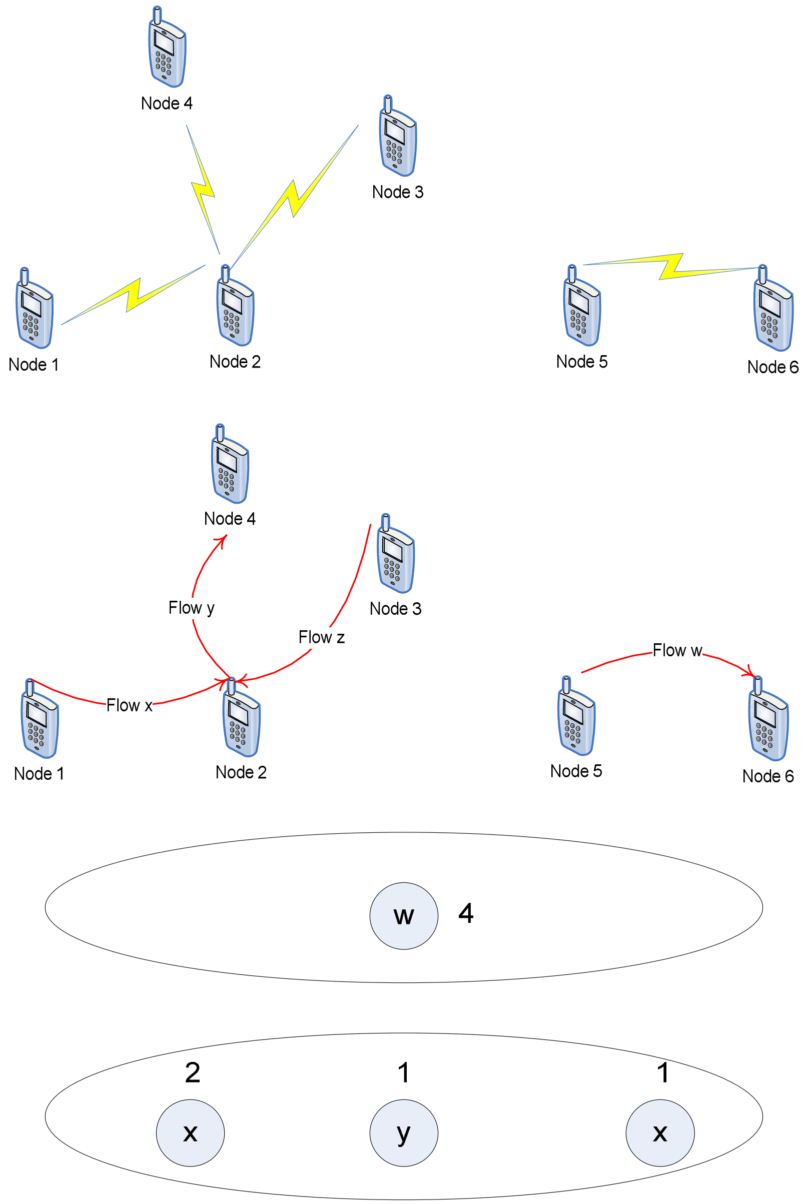

Figure 9.2: Node graph, corresponding flow graph and non-overlapping contention regions (with traffic flow demands)

Table 9.2: Stream allocation and scheduled transmissions for topology in Figure 9.2

Schedule Length	**Slot No.**	**No. of Streams Scheduled**
L=1		
w	1	4
x	1	2
y	1	0
z	1	0
L=2		
w	1	4
x	1	2
y	1	0
z	1	0
w	2	0
x	2	0
y	2	1
z	2	0
L=3		
W	1	4
X	1	2
Y	1	0
Z	1	0
W	2	0
X	2	0
Y	2	1
Z	2	0
W	3	0
X	3	0
Y	3	0
Z	3	1

9.2 Performance Comparison of Stream Scheduling for Single User and Multiuser Communication

In this section, we study the performance of stream scheduling utilizing SISO, SUM and MUM communication. We use optimal schedule length, traffic workload (demand) in the network and the available DoF at each node as parameters for the performance study. The stream scheduling is performed for a random ad hoc network topology generated in a 4X4 unit square area with two nodes per unit area. The topology has a total twenty six flows in the network as shown in Fig. 9.3. The topology has ten contention regions for SUM and twenty nine contention regions for MUM representing a dense network scenario. Also, for the SISO case we assume the capacity of the link to be equivalent to that of MIMO link with a *single active stream* (or, a MIMO link with *a single active DoF*). Compared to SISO case, stream scheduling for SUM as well as MUM (see Fig. 9.4 and Fig. 9.5), clearly provide better performance in terms of schedule length (this in turn translates into higher network throughput compared). The benefit of MIMO is more pronounced for heavier traffic workload in the network since it can schedule more traffic streams compared to SISO. As the DoF at each node in the network is increased, the optimal schedule length is reduced for a given traffic workload. We see diminishing returns in terms of schedule length for increased DoF at nodes for a given traffic workload. This will happen because either the DoF made available would sufficiently satisfy the traffic demands or the schedule length will hit saturation (as explained next).

We also observe that increasing the DoF freedom causes saturation in the schedule length. The saturation of the schedule length happens because of mutually exclusive flows in the network. SUM and MUM cannot schedule mutually exclusive flows at the same time and hence must schedule them independently in different slots causing saturation in the schedule length irrespective of the available DoF at the nodes. Also, because MUM can schedule flows which are mutually exclusive for SUM (flows sharing a common transmitter or those sharing receiver) we find that the saturation limit in the schedule length for MUM is lower than that for SUM (see Fig. 9.4, Fig. 9.5 and Fig. 9.6).

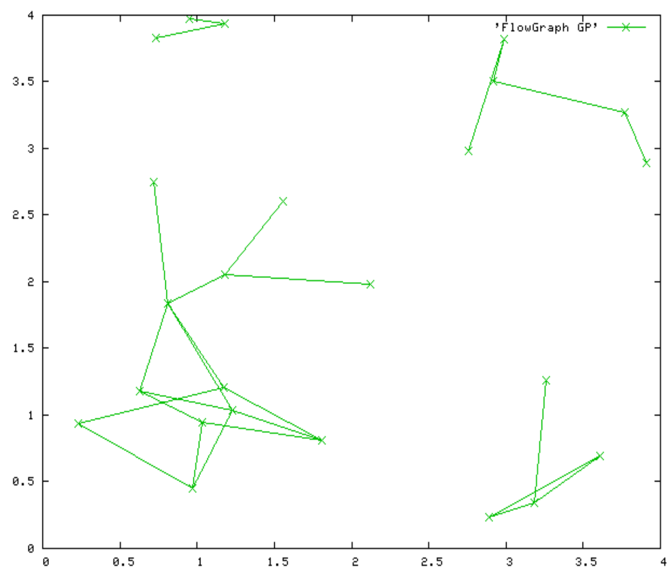

Fig. 9.3: The flow graph of a randomly generated topology in a 4X4 unit area with two nodes per unit area (the edges represent the traffic flow between two nodes)

We see that the advantage of multiuser communication is more pronounced at higher traffic workload on the links. MUM nearly halves the schedule length compared to SUM (see Fig. 9.5) case for heavy traffic workload on the links in the network. SUM requires more DoF to achieve the same optimal schedule length. Also, MUM reduces the lower bound on the schedule length because now the mutually exclusive flows which shared a transmitter or receiver can be scheduled at the same time slot. It can be deduced that for denser network topologies MUM will far outweigh the performance of SUM. But increasing DoF also introduces double the overhead for MUM. Since CSI estimation requires only few bits [34], MUM will overall give a drastic improvement in performance. Therefore, we can say that for light traffic workloads SUM can give the same performance of MUM with more DoF but without the complexity of closed loop CSI (channel information at both uplink and downlink) and multiuser transmitter/receivers. For heavier traffic workloads, though SUM can give the same performance as MUM but the number of DoFs required can be much higher than achievable using practical implementations (typically 8X8 single user MIMO systems are practical). For such heavier workloads, MUM can give higher performance amortizing the channel estimation costs when compared to SUM.

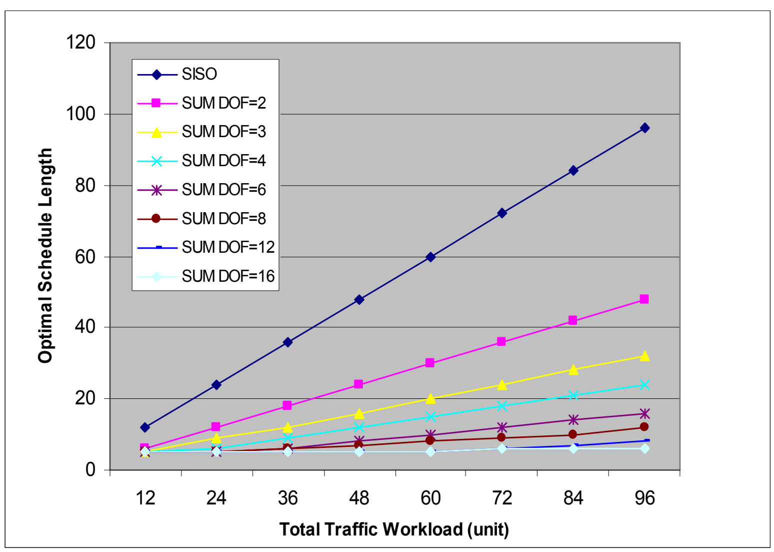

Figure 9.4: A comparison of the optimal schedule length for varying DoF for a random topology shown in Figure 9.3 (SUM is Single User MIMO).

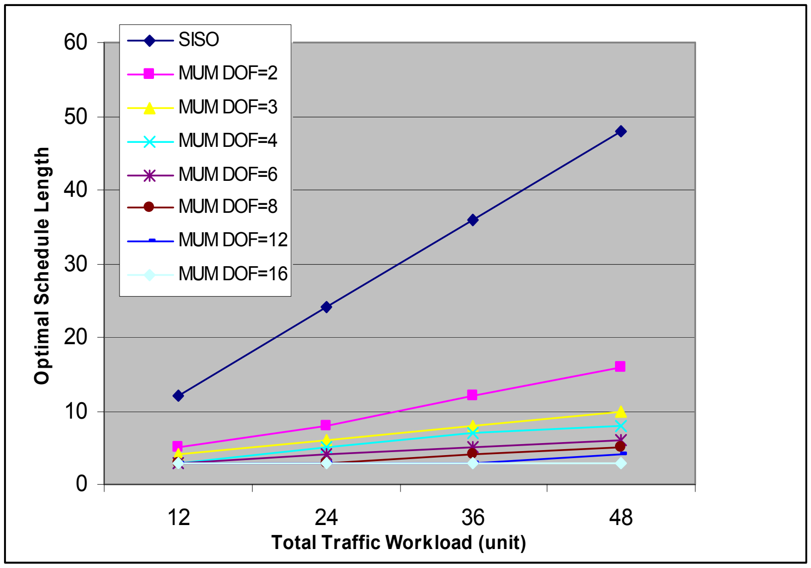

Figure 9.5: A comparison of the optimal schedule length for varying DoF for a random topology shown in Figure 9.3 (MUM is Single User MIMO).

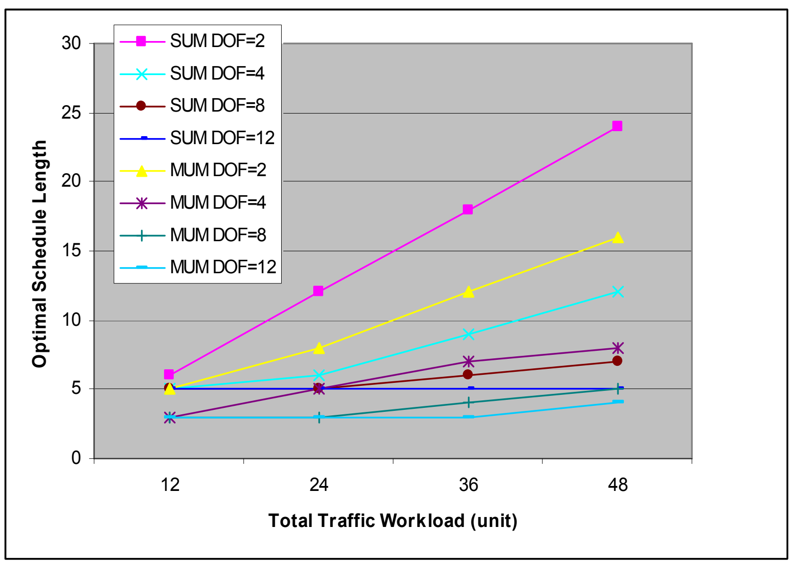

Figure 9.6: Optimal schedule lengths for varying DoF when the nodes utilize SUM and MUM.

9.3 Performance Comparison of Stream Scheduling for SISO with Single User and Multiuser MIMO Stream Scheduling

For SISO, we see that higher link capacity doesn't necessarily translate into shorter schedule length. This is because SISO doesn't allow concurrent stream transmission which is possible for MIMO single user and multiuser communication. While SISO with link capacity equivalent to MIMO link capacity with DoF *k*, gives better performance compared to SISO link capacity equivalent to MIMO link with a single DoF it never performs better than MIMO. Further, SISO schedule length is bounded by the size of the dominant contention region while SUM lower bound on the schedule length is also determined by the number of mutually exclusive flows in the contention region.

While SISO with higher link capacity can give better performance, as a side effect, it leads to inefficient use of bandwidth as it cannot utilize the available bandwidth at the links for concurrent stream transmission due to lack of spatial degree of freedom. As we can see from Fig 9.7 and Fig. 9.8, SISO with higher link capacity follows a staircase curve for the optimal schedule length as it cannot utilize all the bandwidth when the traffic demand is low. When the traffic demand of the flows is such that it is a factor of the link capacity the optimal schedule length is same as that for SUM because there is no gain in partially scheduling flows for stream transmission. And, when the demand exceeds the link capacity SISO wastes bandwidth by allowing a flow to communicate as much data stream as the capacity even if it doesn't has that much traffic demand. But MIMO links in such scenarios will concurrently schedule multiple interfering links such that as much capacity of the contention regions are utilized as possible without overloading any active receivers.

Also, though we assume that SISO links can have as much link capacity as MIMO links its well established that conventional techniques like modulation and coding cannot help SISO links achieve the same link capacity as MIMO links. From our analysis, we conclude that simply high link capacity, as with SISO links, cannot result in better performance in terms of throughput and proportional fairness of the wireless channel resources for different traffic flows in the network. It is the additional degrees of freedom available to MIMO links (spatial DoF with SUM, and multiuser as well as spatial DoF with MUM) that results in better performance of the network.

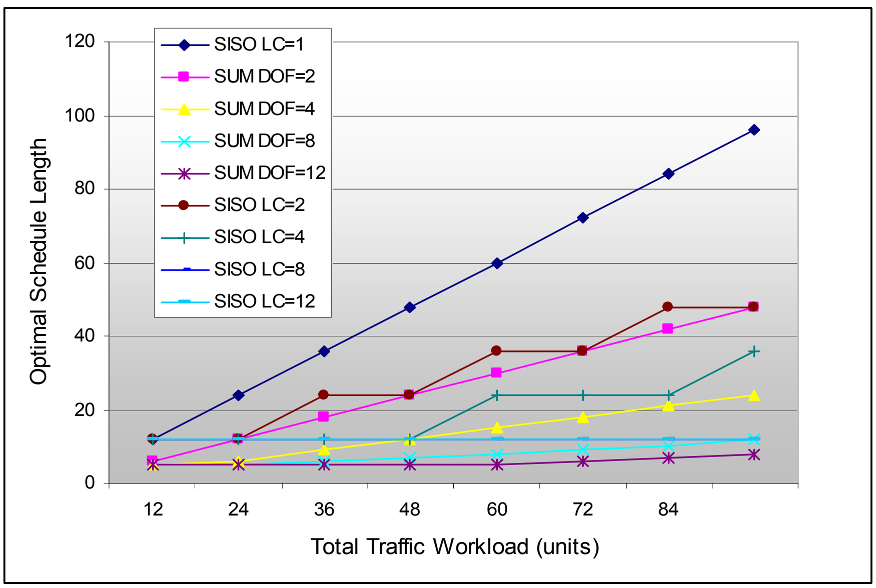

Figure 9.7: Optimal schedule length for SISO with link capacity *k* (equivalent to MIMO links with *k* DoF) compared to SUM

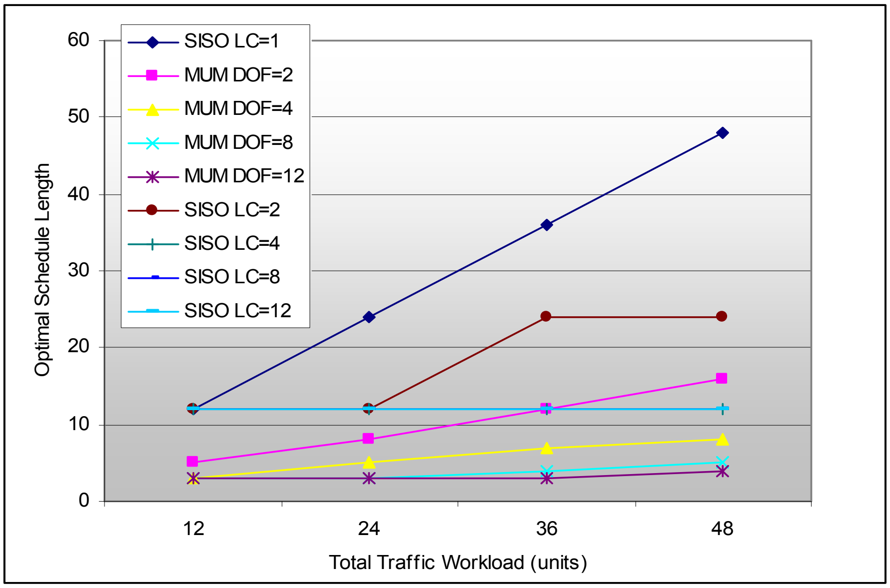

Figure 9.8: Optimal schedule length for SISO with link capacity k (equivalent to MIMO links with k DoF) compared to MUM

9.4 Performance Comparison of the Greedy Heuristic and Optimal Scheduler

We proposed a simple greedy heuristic for stream scheduling in networks utilizing SUM and MUM. Our results show that greedy heuristic closely approximates the optimal schedule length. For the topology in Fig. 9.3, we see from the plot in Fig. 9.9 that the greedy heuristic almost matches the performance of the optimal scheduler for low and high traffic workloads.

The plot in Fig. 9.10 shows the divergence in the schedule length (of the greedy scheduler) from the optimal schedule length. We can see that the divergence is upper bounded for all traffic workloads and also that the divergence is very small compared to the optimal schedule length (for the given traffic workload and the DoF).

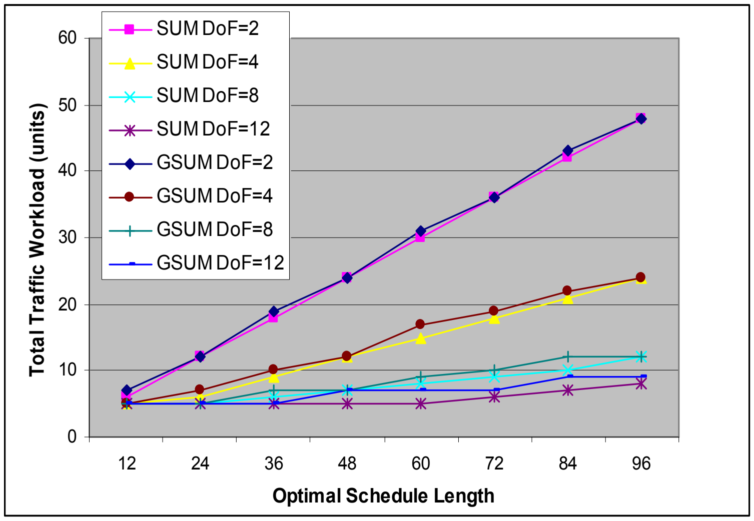

Figure 9.9: Performance comparison of the greedy scheduler with the optimal scheduler (SUM represents optimal scheduler and GSUM represents greedy scheduler for Single User MIMO)

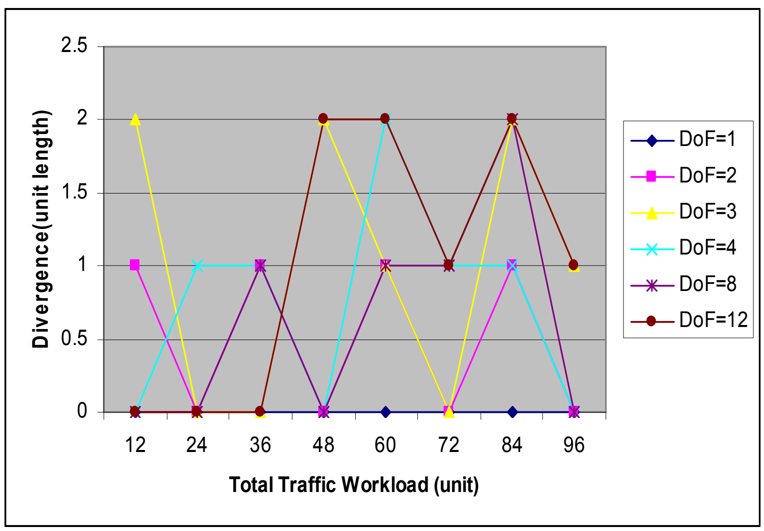

Figure 9.10: Divergence of the greedy scheduler from the optimal schedule length for varying DoFs

CHAPTER 10

SIMULATION

Owing to the ease and flexibility of simulation, it is the preferred mode for network performance evaluation. OPNET is the de facto standard for evaluation of the protocol performance in the networking research community.

Therefore, we will use OPNET simulations to evaluate the performance of MIMO stream scheduling (the optimal binary search algorithms for contention free scheduling) utilizing SUM (single user spatial multiplexing) in OPNET. The performance is evaluated using network ***goodput*** as a metric to characterize the gain of using MIMO in ad hoc networks. Our simulation results show that stream scheduling using SUM outperforms that based on SISO communication.

10.1 OPNET Modeler

OPNET Modeler [5] is object-oriented discrete-event network simulation software that supports many network types and technologies. It is based on a series of hierarchical models such as *network models*, *node models* and *process models* that directly parallel the structure of real networks and protocols. The behavior of the network is simulated usually in process models, which comprises of Finite State Machines (FSM). These states are constructed using C/C++ codes and OPNET kernel functions. Transition between states is done using a wide variety of interrupts.

Wireless Module is one of the several add-on modules available from OPNET. It is used in conjunction with the Modeler software to simulate wireless networks. Fixed or mobile wireless nodes can be simulated using wireless module. Transmission of packets is done through fourteen built-in radio transceiver pipeline stages that depict different aspects of transmission in wireless medium.

Using the graphical editor interface and APIs (application level interfaces), one can design and build models for various network entities from physical layer modulator to application processes and study the behavior of these entities.

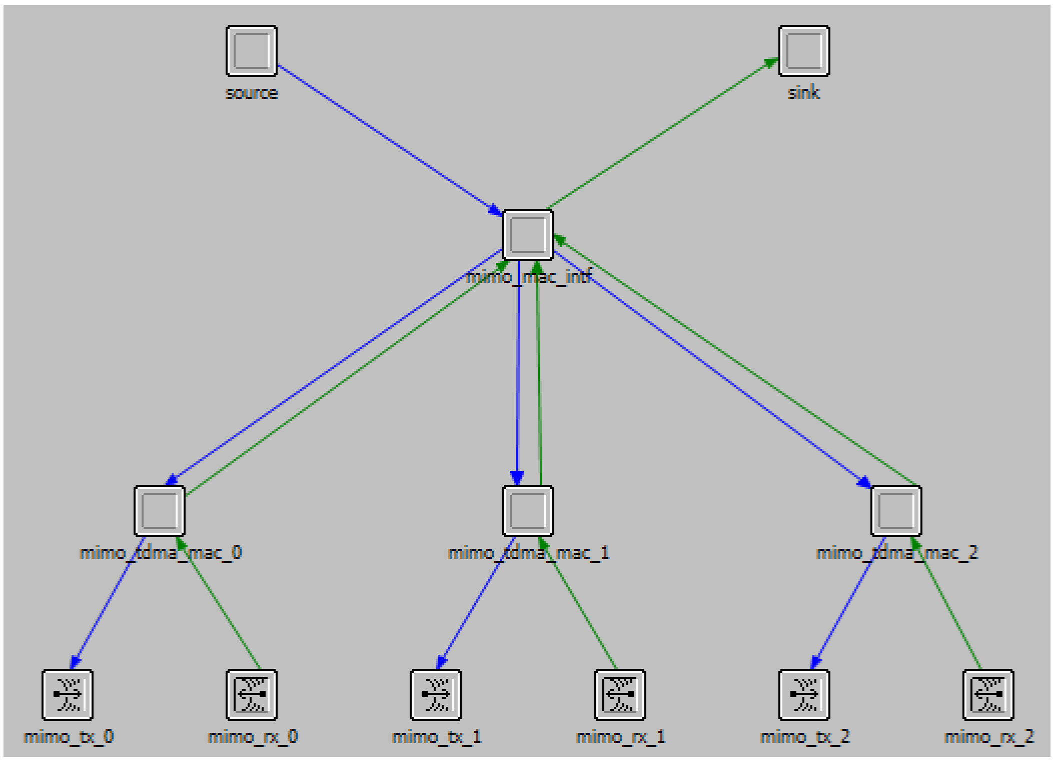

Figure 10.1: A MIMO node model in OPNET with three antennas (or, DoF)

10.2 MIMO OPNET Model

We developed a synchronous time slotted medium access (TDMA) protocol in OPNET for MIMO stream transmission. The wireless 802.11a node model in OPNET is modified with multiple radios at the physical layer to accommodate the multiple MIMO antennas, or DoF. Also, we modify the 802.11a MAC to allow for contention-free slotted transmission in the network. The stream transmission schedule produced by the binary search algorithm, using the ILP solver, serves as input to the simulation. A node reads the input at the start of the TDMA superframe and schedules itself to transmit/receive at its next active time slot. The scheduled node wakes up at the active time slot and reads the input to find the number of data streams it has to transmit/receive. Only those radios at nodes that are involved in transmission/reception are active in a time slot while other radios (at the active and inactive node) are tuned to very high frequency (at which current active receivers cannot receive the signals) to emulate radio sleep state.

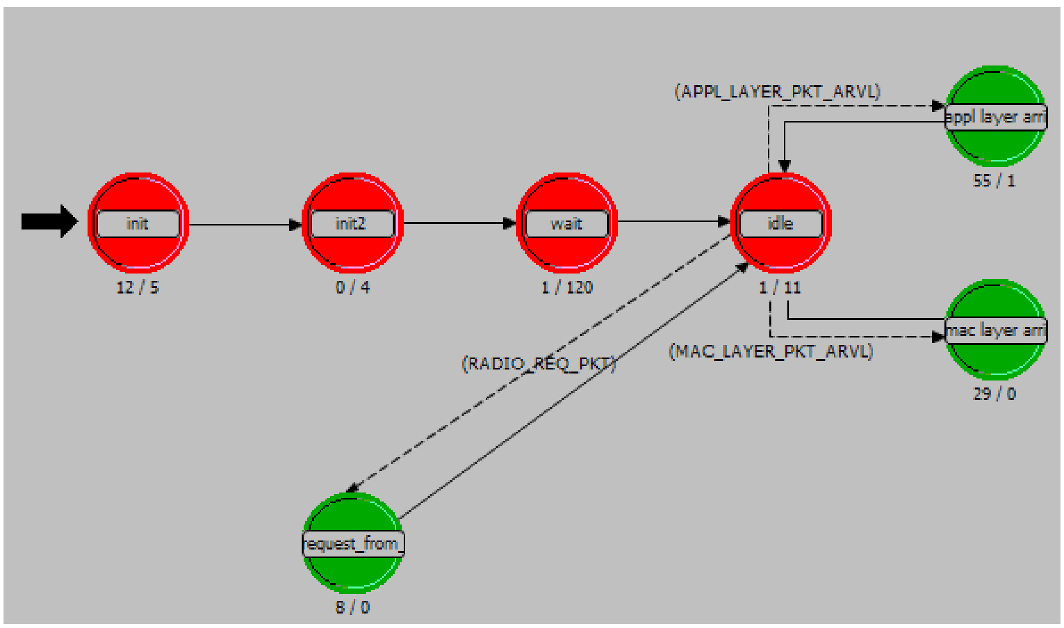

Figure 10.2: The OPNET process model for MIMO TDMA MAC interface

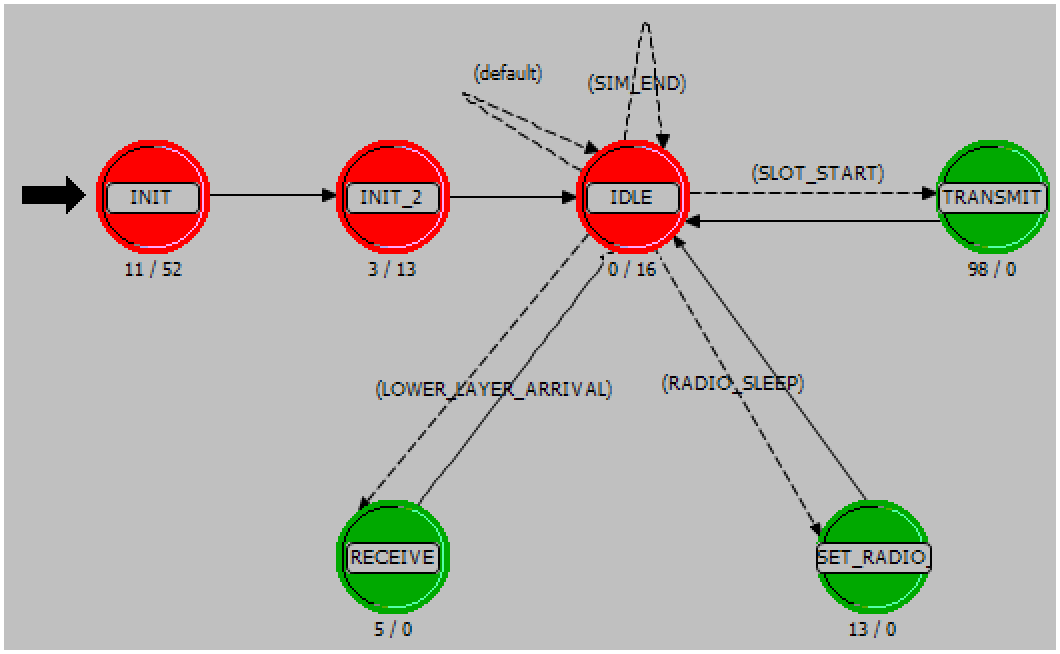

Figure 10.3: The OPNET process model for MIMO TDMA MAC

Fig. 10.1 shows a MIMO node model in OPNET with DoF 3. Fig. 10.2 and 10.3 shows states and transitions for process model in OPNET for the MIMO MAC interface and the TDMA MAC respectively. The source module generates packets to be sent to the destination node. The mimo_mac_intf module buffers the packets arriving from the upper application layer and sends to a radio whenever that particular radio interrupts the mac interface process (through a packet request interrupt) during its active transmission slot. On the successful reception of packet at a destination receiver, it is forwarded up the layer, where the packet is sent to the sink (for destruction to free up the allocated memory in the simulation for the packet). The mimo_tdma_mac at a particular radio wakes up only at its active time slot where it is involved in a transmission or reception while it sleeps at other time slots. When it is scheduled for a transmission it requests for a packet from the mac interface through an interrupt and upon receiving the packet transmits it immediately.

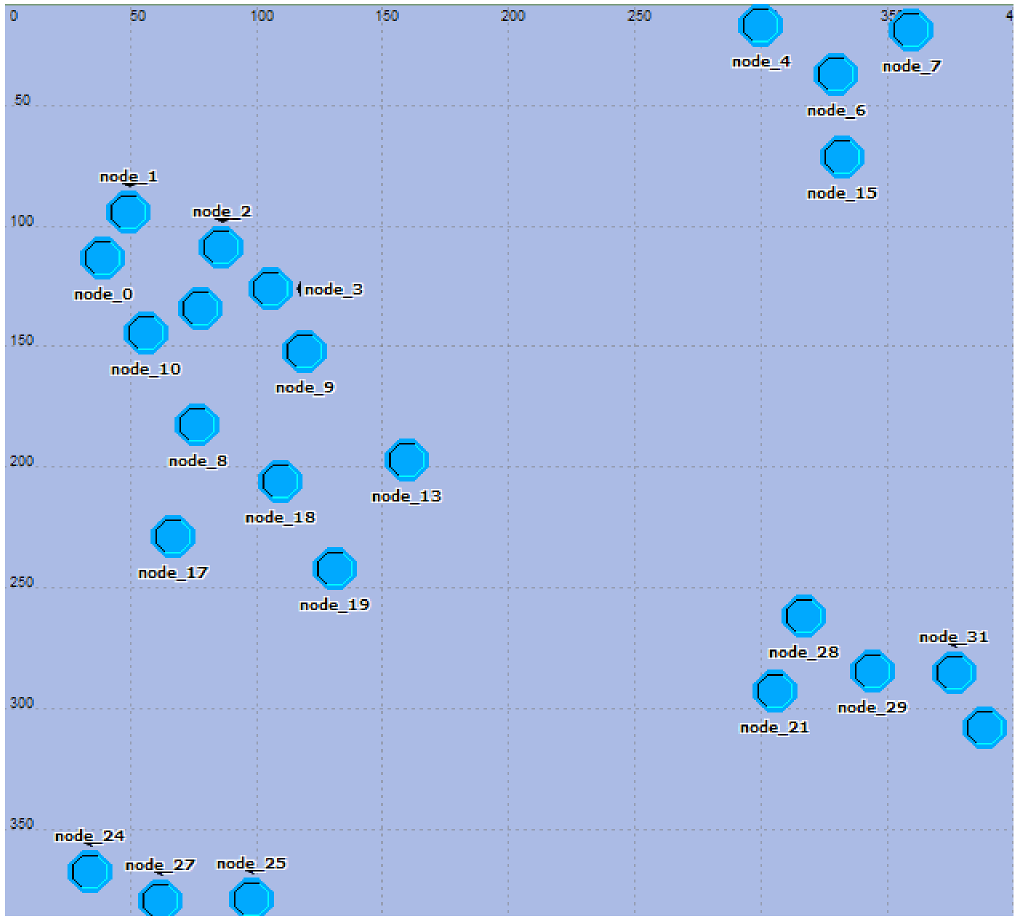

Figure 10.4: Simulation scenarios with 32 nodes placed randomly in 400X400 square meter area

10.3 Simulation Results

We evaluated our model for a dense network scenario where nodes are randomly placed over an area of 400 x 400 square meters (shown in Fig. 10.4). There are 26 traffic flows in the network. Each node is equipped with either one, two or three radios depending on the SISO or SUM scenarios. Each DoF has a data rate support for 54 Mbps. Data packets of 1024 bytes were generated. The time slot length for TDMA was set to 152µs, which is equal to the sum of transmission and propagation delay. *Also, the SISO links have a capacity of 54 Mbps i.e. equivalent to MIMO link capacity with single DoF.*

The traffic load is varied from by uniformly increasing the application data rate at each of the flow node involved in a transmission. *It is to be noted that by traffic load we mean the peak traffic workload such that transmission schedule is fully utilized i.e. if a flow is scheduled for transmission it successfully communicates as many streams as per the schedule (packets are guaranteed to be available at the mac interface queue for transmission).* The metric used for performance comparison of the stream scheduling for SUM and SISO is *network goodput* - defined as the total number of successful packet receptions at the receivers in the network in a given time interval. Also, it is to be noted that in our simulations we have an overhead of a slot for each TDMA superframe which is implemented to reflect the real world scenario where all network setup and negotiations are performed at the beginning of the TDMA superframe. This slot will be called ***setup slot***, henceforth.

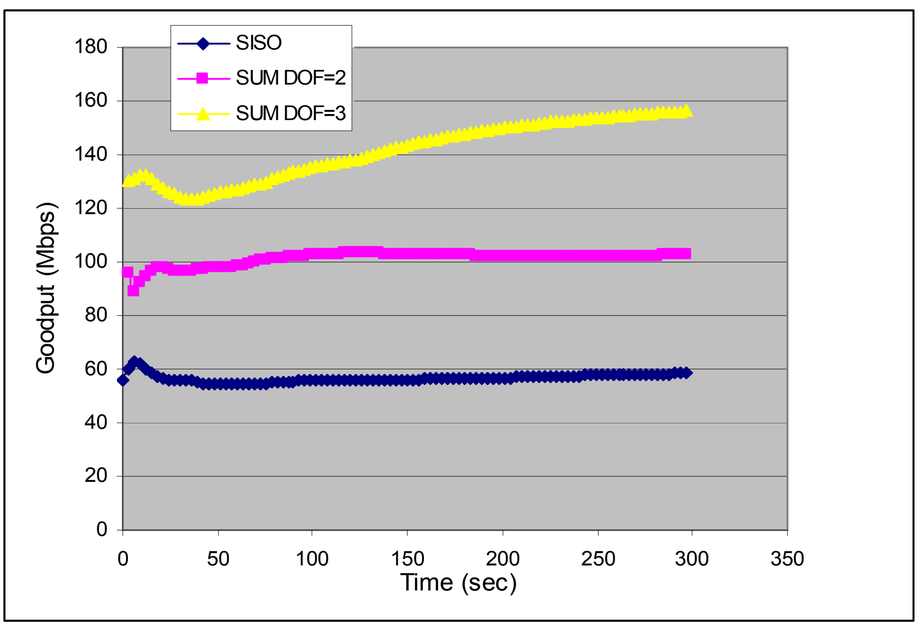

Figure 10.5: Time averaged network goodput for the network scenario in Figure 10.4 for varying DoF and a given traffic load on the flows

From Fig. 10.5, we see that SISO goodput is almost constant while that for SUM with DoF=2 is almost double that of SISO while for SUM with DoF=3 is 2.4 times the goodput of the SISO case. It is to be noted that the theoretical slot length for contention free schedule for this scenario was as follows: SISO: 12 slots, 6 slots for SUM DoF=2 and 5 slots for SUM DoF=3.

The simulated goodput for SUM cases almost mirrors the theoretical result which was in terms of slot length. Since the schedule length for SUM cases is almost half that of SISO case, the number of *overhead slot* is also almost double that for SISO case as a result the goodput for SUM case is not exactly in the ratio as conveyed by the theoretical results.

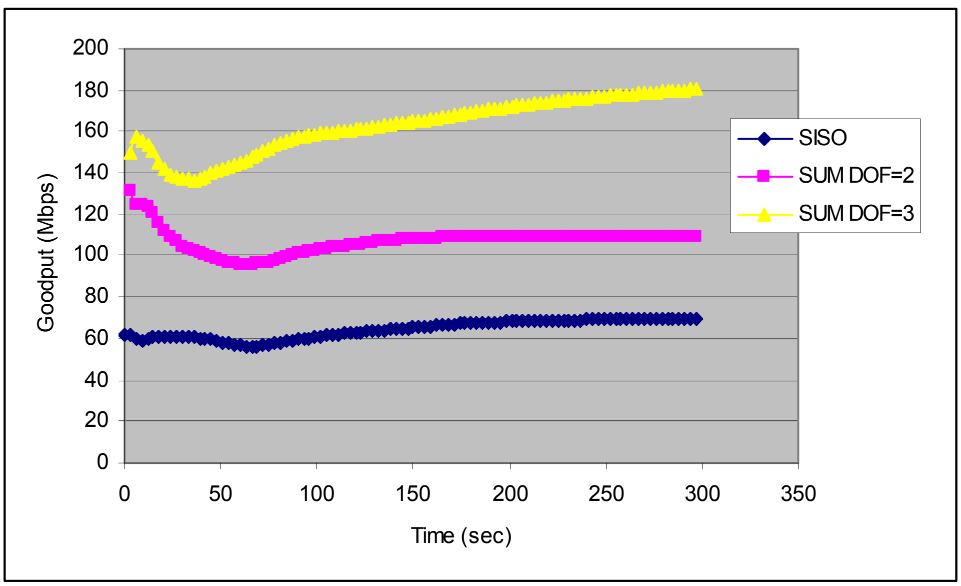

Figure 10.6: Time averaged network goodput for the network scenario in Figure 10.4 for varying DoF when traffic load on the flows is tripled compared to previous case

From Fig. 10.6, the traffic load on the flows is tripled compared for the case in Fig. 10.5. It is to be noted that the theoretical slot length for contention free schedule for this scenario was as follows: SISO: 36 slots, 18 slots for SUM DoF=2 and 12 slots for SUM DoF=3.

The simulated goodput for SUM cases almost mirrors the theoretical result which was in terms of slot length. Since the schedule length for SUM cases is half and a third, respectively, of the SISO case, the numbers of overhead slot is also almost double and triple for the two SUM cases; as a result the goodput for SUM case is not exactly in the ratio as conveyed by the theoretical results.

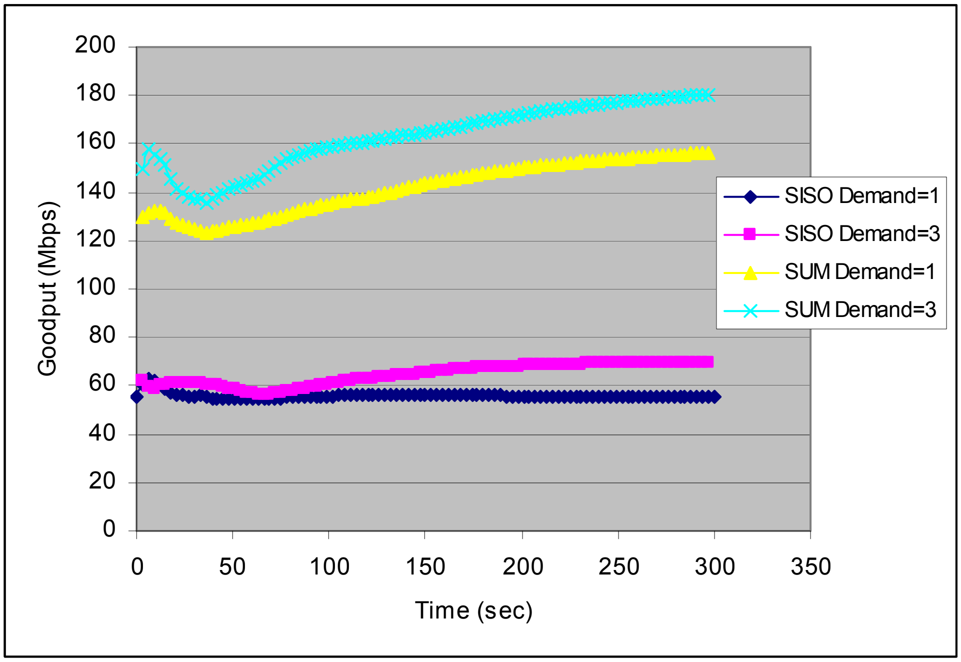

Figure 10.7: Performance comparison of SUM (DoF 3) and SISO for varying traffic load in the network (Demand units represents the relative load on the links for the different scenarios)

In Fig 10.7, we compare the performance of SISO and SUM for varying traffic demands of the flows. We see that SISO gives almost same goodput even when the traffic demand of the flows is tripled. This is because SISO links do not have additional DoFs which can accommodate multiple flows when traffic load on the flow increases as such SISO goodput in the network remains constant even when load increases. The slight difference in the goodput is attributed to the more number of overhead slots for SISO schedule for lower traffic demand on the flow (the scheduled length is 3 times for higher traffic demand compared to that for lower traffic demand).

We see that SUM gives better performance when the traffic demand of the flows is tripled. This is because SUM links utilize the additional resources (DoFs) to concurrently schedule transmission of mutually interfering flows and hence the goodput increase when the load increases. But as our theoretical analysis has shown, SUM goodput will also saturate at a point when additional DoF cannot concurrently schedule mutually exclusive flows.

While for the stream transmission schedule produced by the optimal binary search algorithm, we evaluated the performance of SUM and SISO for peak traffic workload, we are also interested in comparing their respective performance when the traffic load is not at the peak for full utilization of transmission slots. From Figure 10.8, we can see that the loss in network goodput is more for SUM compared to SISO and the loss becomes more pronounced as DoF increases. This is because when traffic workload is not at the peak SUM's lose in link utilization is more compared to SISO and the lose increases as the DoF increases (the network has more capacity when DoF at SUM links increase). Also, it can be observed from the simulation results in Figure 10.8 that at even when traffic load is not at its peak, SUM gives much better performance compared to SISO. *In this case, we note that if the traffic workload is at the peak then strict fairness in terms of traffic transmission may not be met.*

Figure 10.9 shows the per-hop average delay for the packets when the traffic load in the network is varied upto the peak traffic load for SUM and SISO. When the traffic load is upto 40% of the peak, the per-hop delay is almost the same for SUM and SISO indicating that the queuing delay is almost nil for the packets. But, as the traffic load increases the per-hop delay for both SISO and SUM increases indicating that the packets are getting queued. For the case of SUM DoF=3, the per-hop delay is almost $1/3^{rd}$ of that for SISO as it is transmitting three streams (or, packets) compared to SISO in a given time slot there by lowering the average queuing delay of the packets (for SISO, for the same traffic workload these packets would have to wait for the duration of three TDMA superframe in the queue for transmission). Similar argument holds for SUM DoF=2 case when compared to SISO.

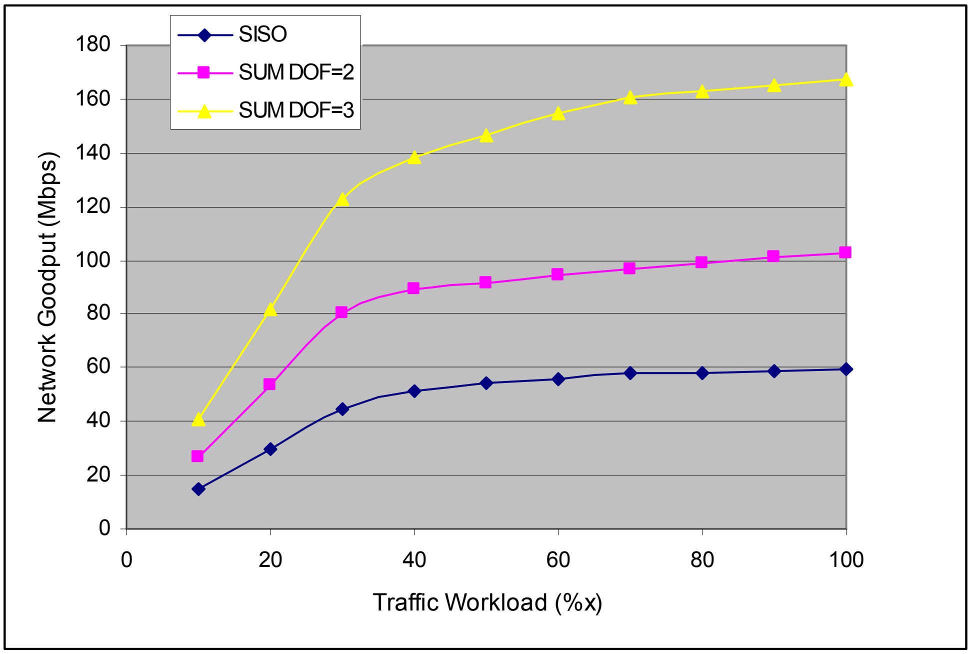

Figure 10.8: Network goodput for varying traffic workload in the network (traffic load is percentage of x, where x represent traffic load where transmission slots are fully utilized by the scheduled flows)

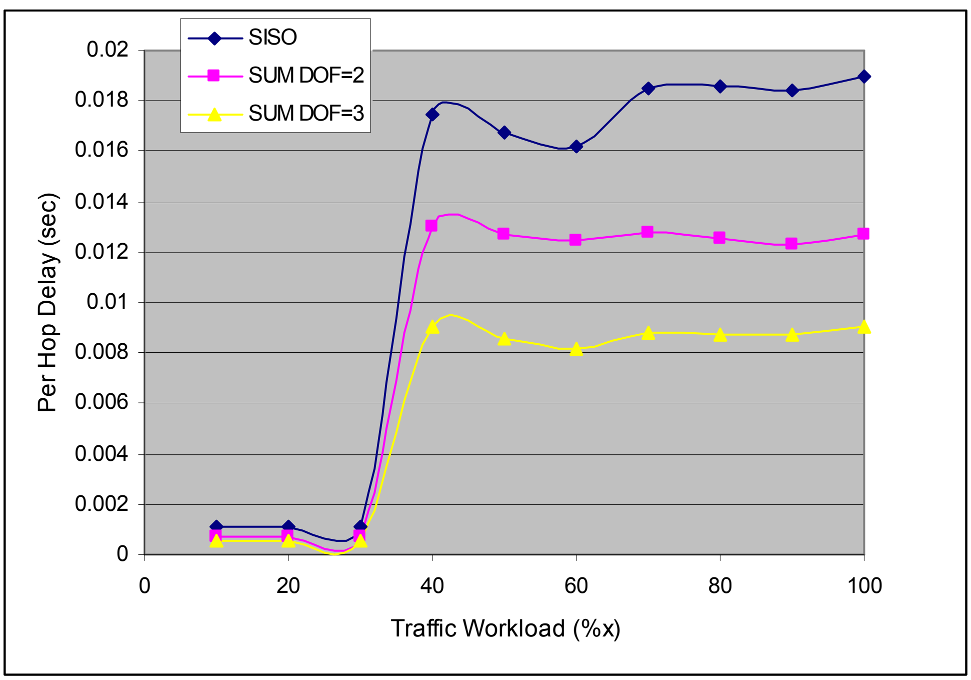

Figure 10.9: Per hop delay for varying traffic load in the network (traffic load is percentage of x, where x represent traffic load where transmission slots are fully utilized by the scheduled flows)

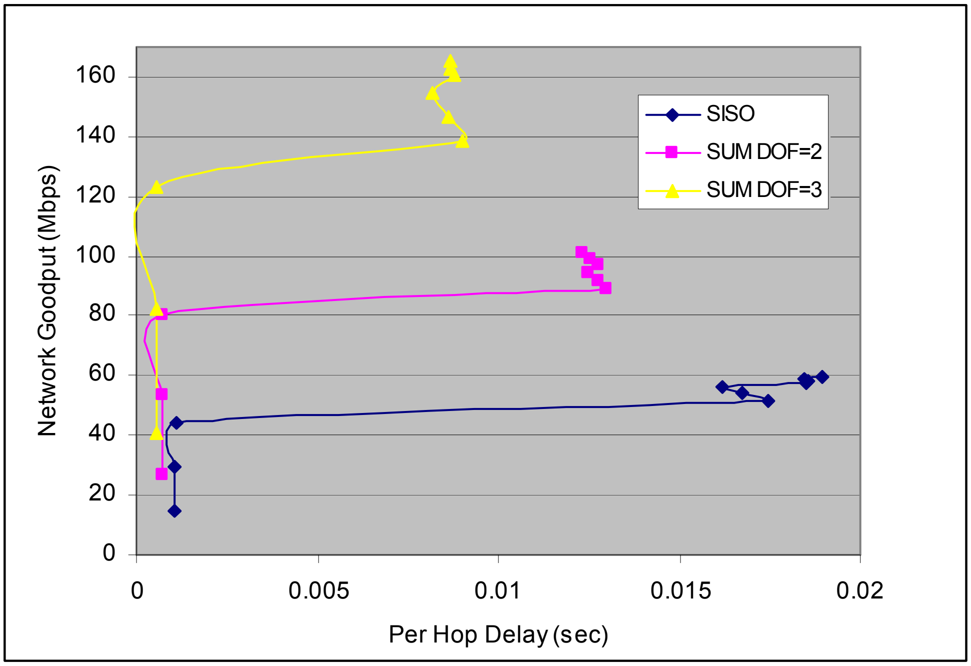

Figure 10.10: Network goodput for varying per-hop delay (where per hop delay for each DoF is for varying traffic workload as shown in Figure 10.9)

CHAPTER 11

CONCLUSION

In this thesis, we formulated the problem of fair stream allocation in MIMO ad hoc networks based on traffic demands, for single user and multiuser MIMO communication. We developed a scheduling strategy to achieve fair allocation of the streams to the traffic flows in minimum schedule length and maximizing the network throughput in each slot; previous work did not focus on traffic demands for stream allocation, providing guarantees on schedule length for fairness and utilizing multiuser aspect of MIMO communication. For this scheduling strategy, we formulated an ILP problem for both the MIMO single user and multiuser communication. We solve the ILP in conjunction with a binary-search algorithm to compute the optimal schedule length to achieve strict fairness goals. The performance of single user and multiuser stream scheduling, using the optimal binary search algorithm, for varying traffic workloads and DoF was studied on a random ad hoc network topology. We show that the benefits of multiuser communication are more pronounced over single user communication in heavily loaded network. Further, at light-to-medium traffic workload, using single user MIMO with more DoF rather than multiuser MIMO can give the same performance but without the complexity of closed loop CSI and multiuser transceivers.

While our ILP-based algorithm guarantees a schedule that has optimal length for achieving strict fairness, it relies on a number of potentially costly invocations to an ILP solver. Therefore, we developed a centralized greedy heuristic for the stream scheduling. The greedy heuristic closely approximates the performance in terms of fairness goals and the schedule length compared to the optimal ILP-based algorithm. Also, our OPNET-based stochastic simulation confirms our theoretical results and reinforces the benefits of MIMO compared to SISO communication.

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