CHARACTERIZATION AND ANALYSIS OF MULTI-HOP WIRELESS MIMO NETWORK THROUGHPUT

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Overview

- Introduction
- MIMO Basics
- Problem Statement
  - Protocol descriptions
- Packet-level Constraints
- Test Setup
- Results
- Conclusions

Introduction

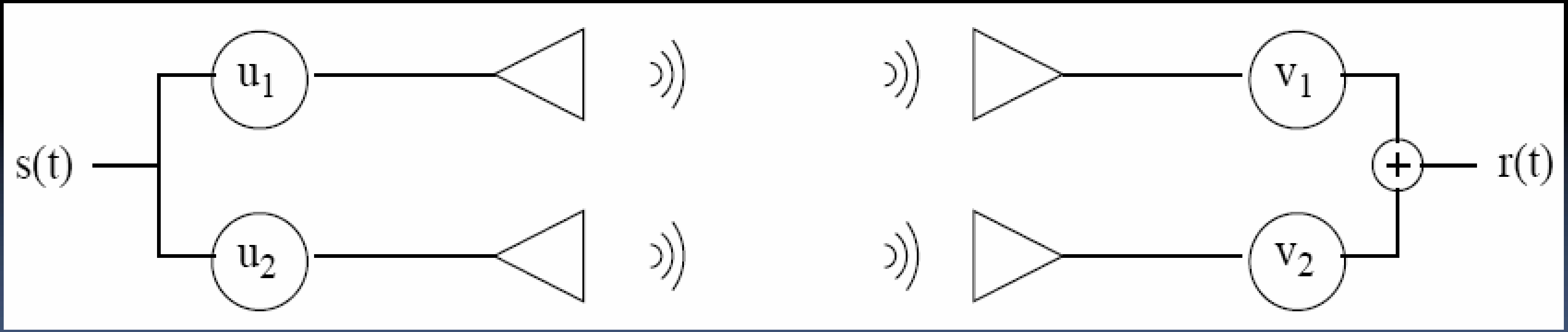
- MIMO: Multiple-input, multiple-output
  - Array of antennas at transmitter and receiver
- Two potential benefits
  - Spatial reuse: allow multiple simultaneous transmissions within a physical space
  - Spatial division multiplexing: transmit multiple data streams simultaneously to increase data rate

Introduction

- Paper goals
  - Model the constraints under which a multi-hop MIMO network must operate
    - Compare constraints of three protocols and two avoidance models
  - Find the maximum throughput of MIMO networks using these protocols
  - Evaluate the effect of network parameters on achievable throughput

MIMO Basics

- Transmitter and receiver both have multiple physical antennas

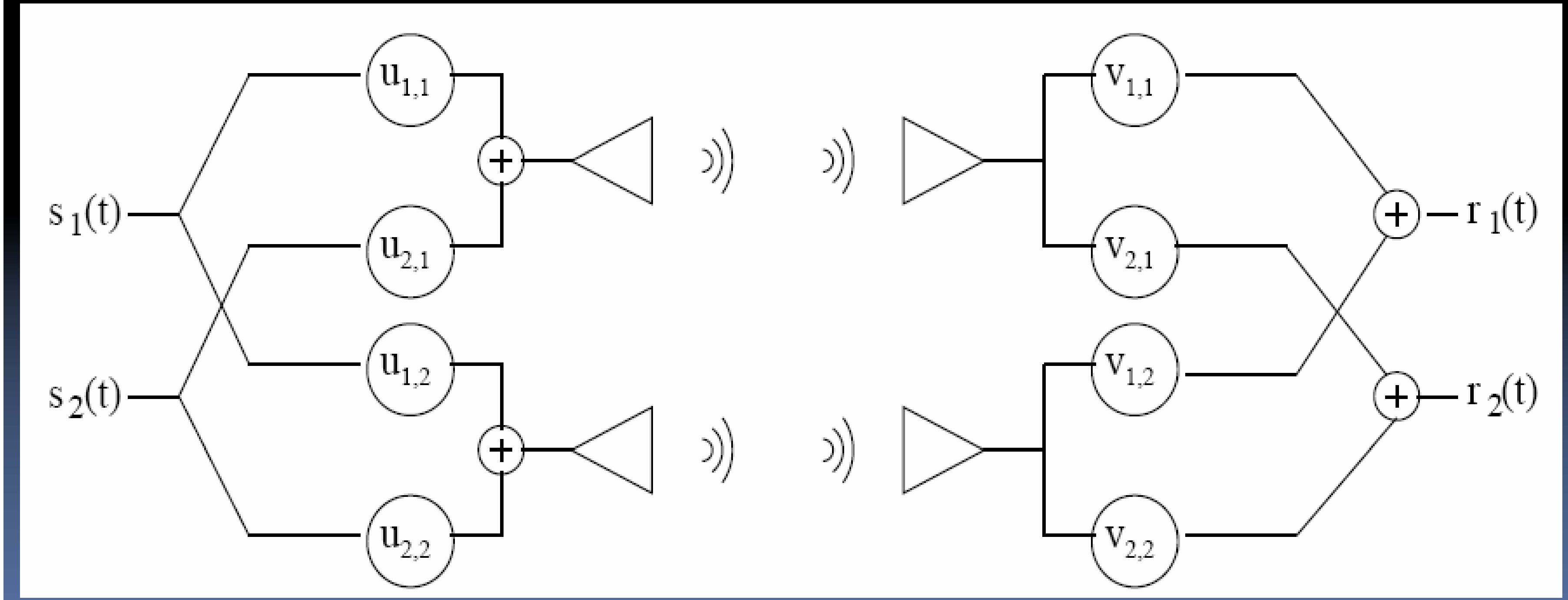


MIMO Basics

- Transmitter uses a weighting vector $\mathbf{u} = [u_1, u_2]$ while receiver uses a weighting vector $\mathbf{v} = [v_1, v_2]$
- Channel coefficient matrix H (??)
- s(t) = transmitting signal, r(t) = received signal
- r(t) = (uHv) * s(t)
- We can find values for u and v such that uHv at target = 1 and at other nodes = 0

MIMO Basics

- Multiple-stream signals



MIMO Basics

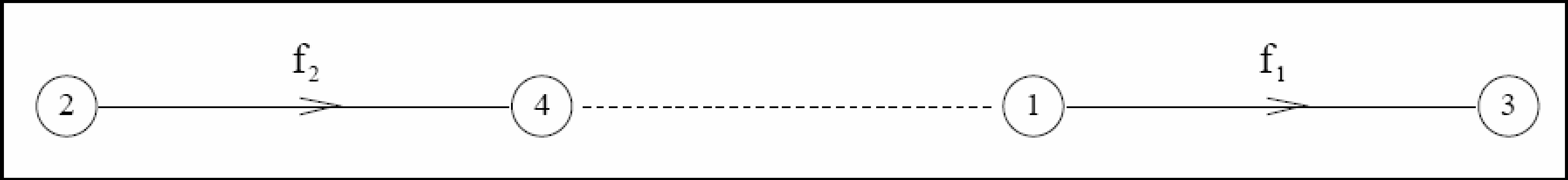
- Two weight vectors at each end: e.g. u_1, u_2 at transmitter
- Create vectors such that:
  - $u_1 H v_1 = 1$
  - $u_2 H v_1 = 0$
  - $u_1 H v_2 = 0$
  - $u_2 H v_2 = 1$

MIMO Basics: Spatial Reuse

- A transmitter-receiver pair with multiple antennas can transmit signals without interference from other streams

- Given a node with an incoming transmission and an interfering transmission, we can solve for v given:
  - H for each link
  - Weight vector u for each transmitter

MIMO Basics: Spatial Reuse



- Node 4 can receive transmission from 3 with spatial reuse
- Find v = [v_1, v_2] such that $(u_2 H_{2,4})v = 1$ and $(u_1 H_{1,4})v = 0$

MIMO Basics: Multiplexing

- Node 4 could instead use its antennas to receive two streams from node 2

- Constraints outlined before: use two weight vectors such that
  - $r(t)_1$ gets $s(t)_1$ at full strength
  - $r(t)_2$ gets $s(t)_1$ at zero strength
  - $r(t)_1$ gets $s(t)_2$ at zero strength
  - $r(t)_2$ gets $s(t)_2$ at full strength

Interference Avoidance Models

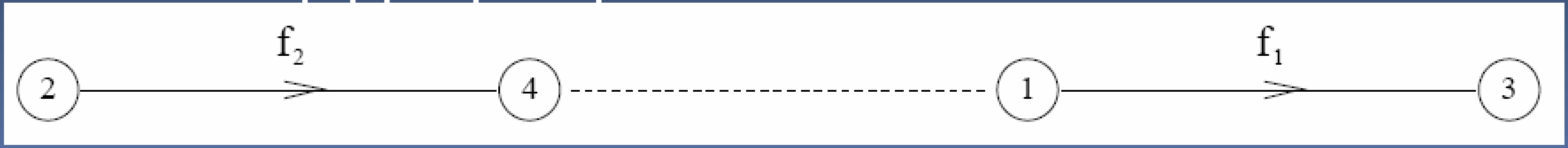
- Ways to ensure that the constraints outlined so far can be followed
- Non-cooperative Interference Avoidance (NiM)
  - Transmitters find weight vectors to null their signal at all receivers before transmitting
  - Receivers find weight vectors to null their signal from all nearby transmitters before receiving
- Cooperative Interference Avoidance (CiM)
  - Either the transmitter OR the receiver ensures that no interference takes place (solve system

Degrees of Freedom

- Each additional antenna at a node offers it another degree of freedom
- Each available degree of freedom can be used to either:
  - Prevent interference from a stream, or
  - Transmit/receive an additional stream
- Three possible situations: all DoFs used for spatial reuse, all DoFs used for multiplexing, or a mix of both

Degrees of Freedom

- m is transmitting to n
- α_m = transmit degrees of freedom
  - Number of streams m is transmitting + number of streams being received within m's neighborhood
- β_n = receive degrees of freedom
  - Number of streams n is receiving + number of streams being transmitted within n's

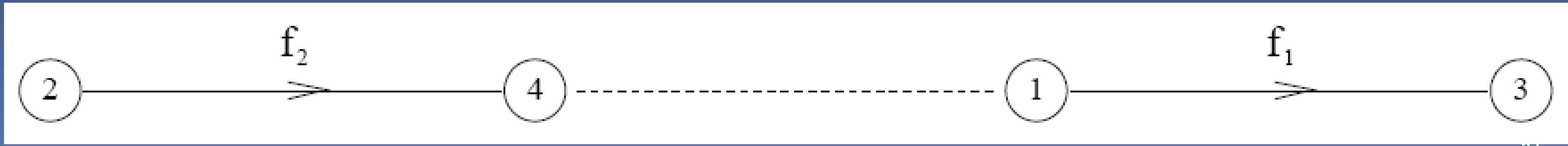


Problem Statement

- Network Model
- L = set of all node pairs (m,n) such that m can transmit to n (individual links referred to as i)
- L_m^+ : set of all links whose transmitter is m
- L_m^- : set of all links whose receiver is m
- L_m : $L_m^+ \cup L_m^-$

Problem Statement

- C = set of all link pairs (i,j) such that a transmission on i will interfere with a transmission on j
- C_i^+ : set of all links whose receivers interfere with i's transmission
- C_i^- : set of all links whose transmitters interfere with i's reception



Protocols

- Spatial Reuse Only MIMO Protocol (SRP)
  - All of a node's degrees of freedom are dedicated to preventing interference and increasing spatial reuse
- Spatial Multiplexing Only MIMO Protocol (SMP)
  - All of a node's degrees of freedom are dedicated to transmitting and receiving additional simultaneous streams
  - No spatial reuse, so for every (i,j) pair in C, only

Protocols

- Spatial Reuse & Multiplexing MIMO Protocol (SRMP)
  - A node’s degrees of freedom may be assigned to spatial reuse or spatial multiplexing, whichever results in higher throughput
- Use TDMA for collision avoidance
- Set of flows Q where each q has a source, destination, and flow rate

Constraints

- Examine the constraints of the system under the different MIMO protocols and interference avoidance models
- During simulation, maximize Σf_q for the system while maintaining the integrity of the constraints

Constraints: SRP

- Only one link per node may be active at a time

$$\sum_{i \in L_m} y_i^t \leq 1, \quad \forall m \in N, \forall t \in T$$

- Under NiM, every sender or receiver must ensure it has enough degrees of freedom

$$(\omega - \beta_{r(i)} + 1) y_i^t + \sum_{j \in C_i^-} y_j^t \leq \omega$$

$$(\omega - \alpha_{t(i)} + 1) y_i^t + \sum_{j \in C_i^+} y_j^t \leq \omega$$

- When attempting to transmit, the above simplifies to $\Sigma\, y_j + 1 \leq \beta$ (or α)

Constraints: SRP

- Under CiM, only one of the transmitter or receiver needs to null the signal

$$1 + \sum_{l \in C_i^+} \lambda_{il}^t \le \alpha_{t(i)}$$
$$1 + \sum_{l \in C_j^-} \mu_{lj}^t \le \beta_{r(j)}$$
$$y_i^t + y_j^t \le \lambda_{ij}^t + \mu_{ij}^t + 1$$

- Constraint defined by sum of nulled signals rather than individual degrees of freedom

Constraints: SMP

- z_i : number of active streams over link i

$$z_i^t \leq \alpha_{t(i)} y_i^t \text{ and } z_i^t \leq \beta_{r(i)} y_i^t$$

- Still only one active link at a time

$$\sum_{i \in L_m} y_i^t \leq 1, \quad \forall m \in N, \forall t \in T$$

- No spatial reuse, so only one active link for every contending pair

$$y_i^t + y_j^t \leq 1, \forall (i,j) \in C, \forall t \in T$$

Constraints: SRMP

- Similar interference constraints to SRP, but we must now be aware of the number of streams at each link. Under NiM:

$$(\Omega - \beta_{r(i)})y_i^t + \sum_{j \in C_i^- \cup L_{r(i)}^-} z_j^t \leq \Omega$$

$$(\Omega - \alpha_{t(i)})y_i^t + \sum_{j \in C_i^+ \cup L_{t(i)}^+} z_j^t \leq \Omega$$

- When simplified, shows that in order for a node to be active, its degrees of freedom must exceed the number of active streams on nearby nodes plus its own active streams

Constraints: SRMP

- Under CiM:

$$\sum_{l\in L^+_{t(i)}} z^t_l + \sum_{l\in C^+_i} \theta^t_{il} \le \alpha_{t(i)},$$
$$\sum_{l\in L^-_{r(j)}} z^t_l + \sum_{l\in C^-_j} \vartheta^t_{lj} \le \beta_{r(j)},$$
$$z^t_i \le \vartheta^t_{ij} + \alpha_{t(i)}(1-y^t_i),$$
$$z^t_j \le \theta^t_{ij} + \beta_{r(j)}(1-y^t_j).$$

- α used to either send streams or null streams for receivers, β used to receive streams or suppress interference, and active streams on a link are constrained by nulling/suppression

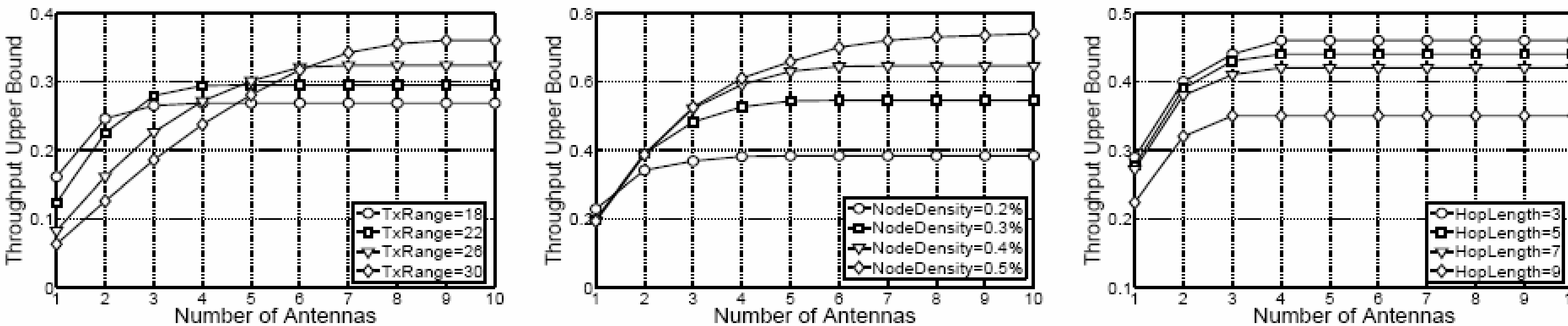
LP Relaxation

- Relax constraints from instantaneous to average
- $y_i = \frac{1}{\tau} \sum_{t \in S} y_i^t$
- Same for λ, μ, z, θ, υ.
- Relaxed constraints same format as instantaneous, but use the average over a time slot set S

Test Setup

- Network Parameters
  - Link capacity set to 1 unit/second
  - Degrees of freedom strictly equal to antennas
  - 100mx100m space with random distribution
  - Q total source-destination pairs (active flows)
- Transmission Range
  - Controls degree of nodes and interference
- Node Density
  - Increases node degree, but not interference
- Hop Length
  - Increases chances for interference

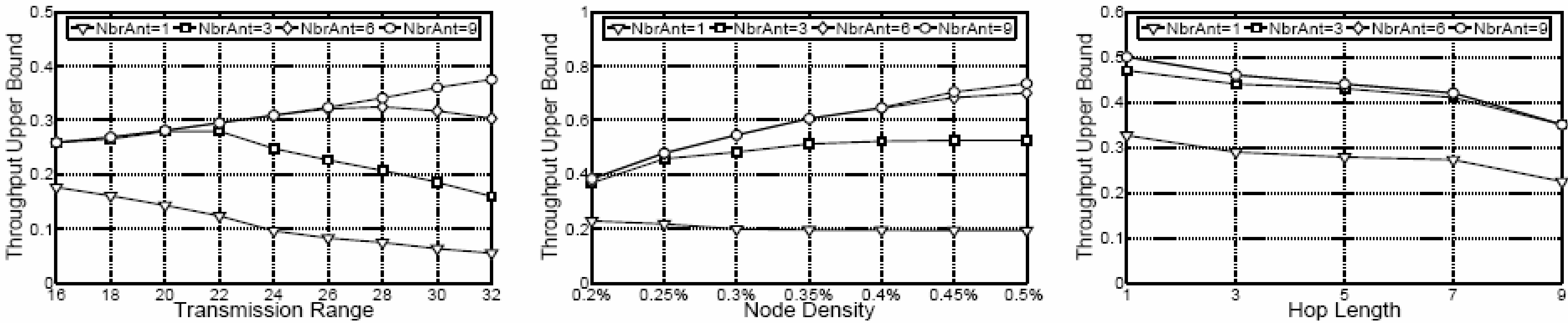
Results: SRP



(a) Effect of transmission range (b) Effect of node density (c) Effect of hop length

- Asymptotic bound
  - Once all medium contention has been resolved, no further improvement can be made
- High transmission ranges suffer too much interference at low antenna numbers, but when more antennas are added, the benefits of increased node degree help it

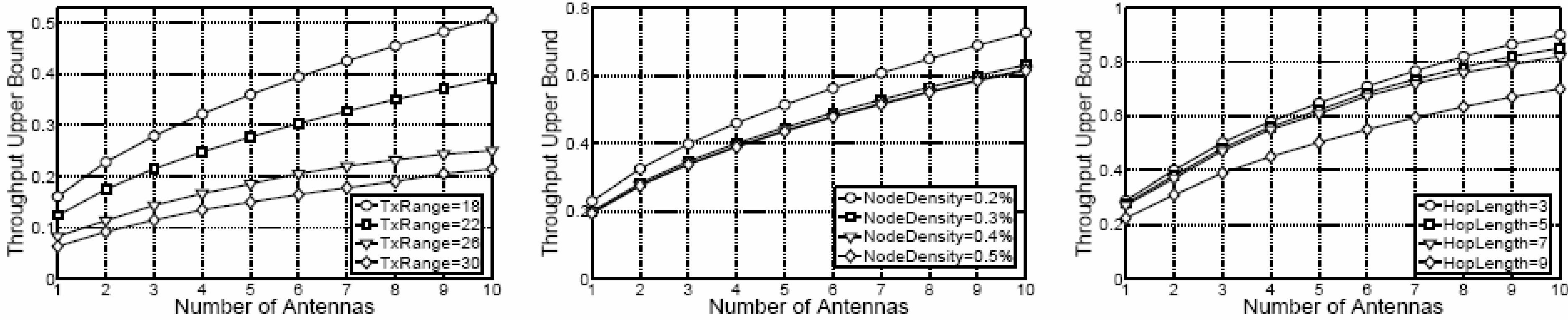
Results: SRP



(d) Effect of transmission range (e) Effect of node density (f) Effect of hop length

- Transmission Range
  - Tradeoff of node degree and interference
- Node Density
  - Better with enough antennas, asymptotic
- Hop Length
  - Worse (increased contention/interference)

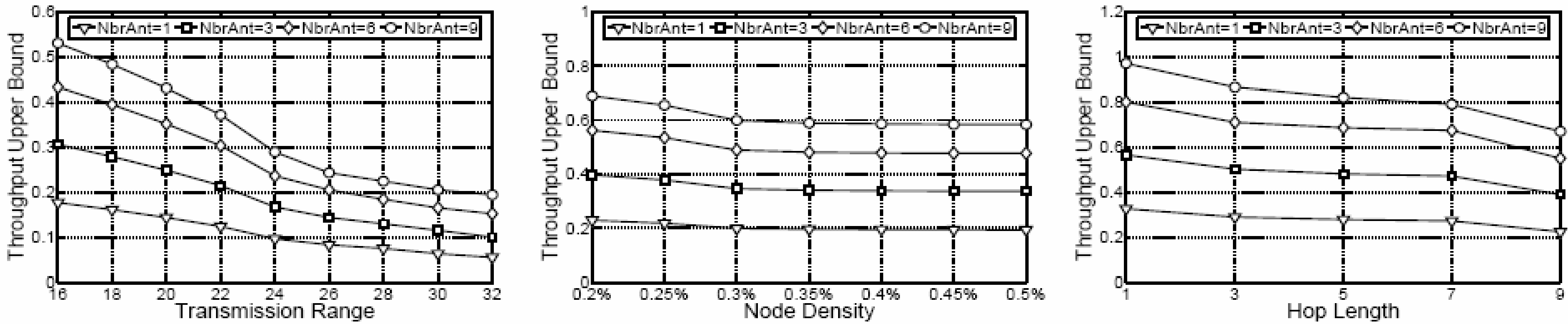
Results: SMP



(a) Effect of transmission range (b) Effect of node density (c) Effect of hop length

- Linear increase
  - Every new antenna provides additional streams and thus additional throughput
- Any increase in interference has a negative impact

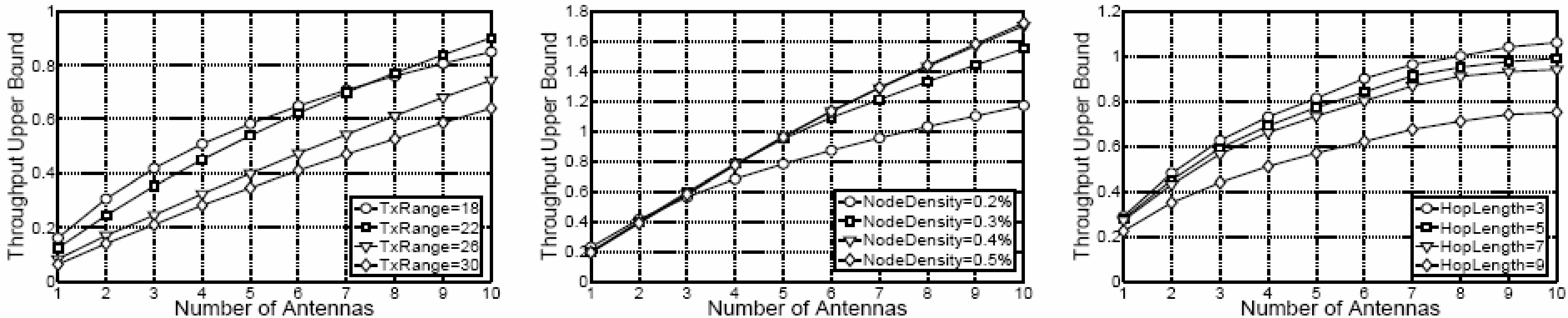
Results: SMP



(d) Effect of transmission range (e) Effect of node density (f) Effect of hop length

- Transmission Range
  - Increasing interference hurts throughput
- Node Density
  - Not explained – slight interference issues?
- Hop Length
  - Worse (increased contention/interference)

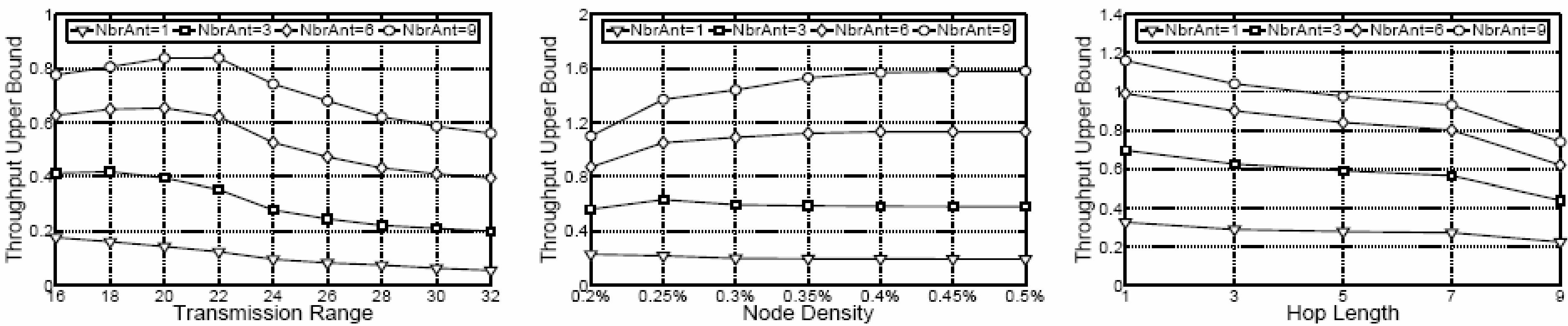
Results: SRMP



(a) Effect of transmission range (b) Effect of node density (c) Effect of hop length

- No asymptotic bound
  - SRMP resolves medium conflicts, but because extra degrees of freedom can be used for multiplexing, additional antennas continue to increase throughput

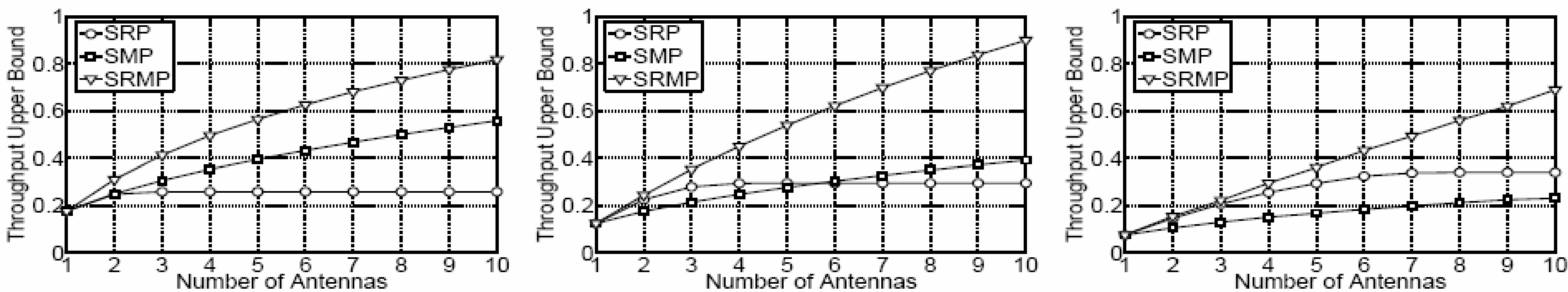
Results: SRMP



(d) Effect of transmission range (e) Effect of node density (f) Effect of hop length

- Transmission Range
  - Unique maximums for each antenna setup
- Node Density
  - Increasing node degree increases throughput
- Hop Length
  - Worse (increased contention/interference)

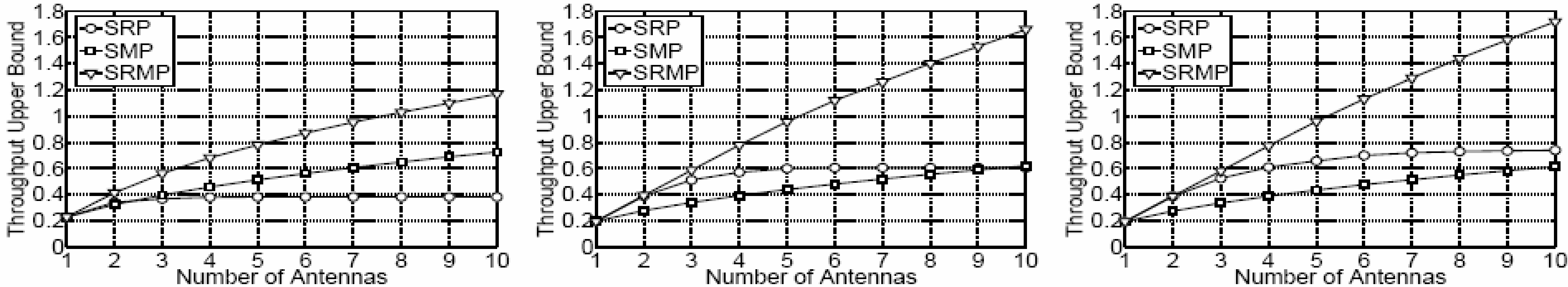
Results: SRP v. SMP



(a) TxRange = 16 (b) TxRange = 22 (c) TxRange = 28

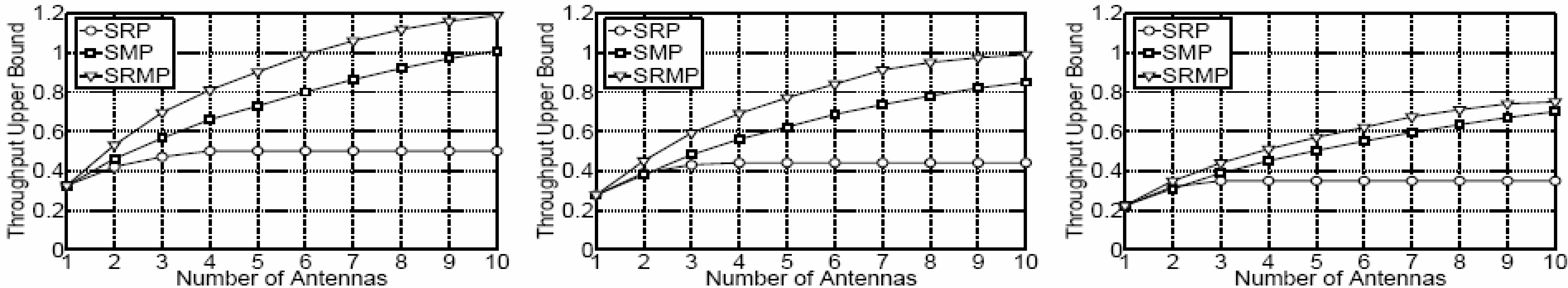
- Low TxRange
  - SRP tops out early, SMP experiences little interference
- Mid TxRange
  - SRP increases faster, SMP better with more antennas
- High TxRange
  - Too much interference for SMP to perform well

Results: SRP v. SMP



(a) NodeDensity = 0.20%   (b) NodeDensity = 0.35%   (c) NodeDensity = 0.50%

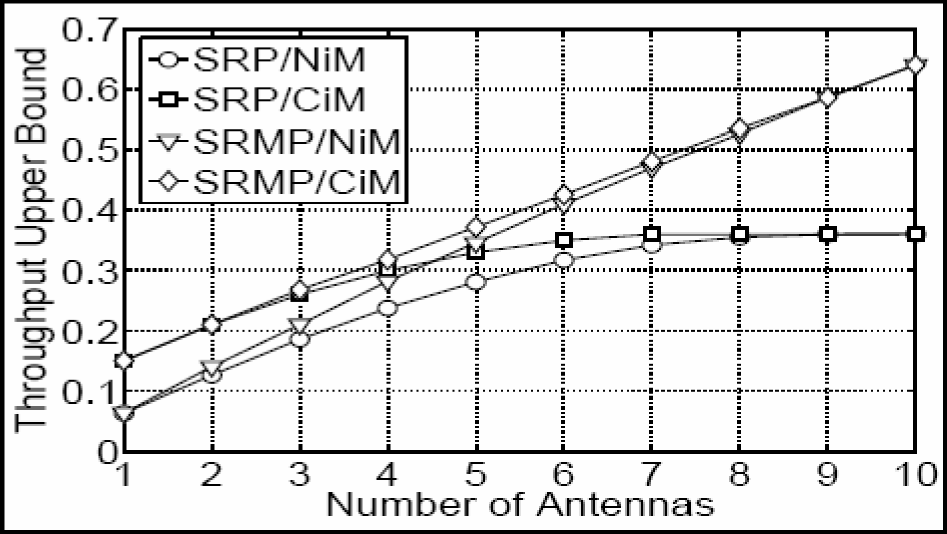
- Same effect as transmission range



(a) HopLength = 1   (b) HopLength = 5   (c) HopLength = 9

- No change in trend with more hops

Results: NiM v. CiM



- CiM always outperforms
  - Additional degrees of freedom available for more reuse or multiplexing

Conclusions

- LP problem of optimal throughput over a MIMO network solved under various configurations
- MIMO protocols and interference models can be used by network designers

Conclusions

- **A lot** of future research to be done
- Many actual implementation decisions and problems are left to future work or not even mentioned
  - Discovery of u, v, H
  - Heterogeneous networks
  - Cooperation mechanism for CiM