Diversity Routing for Multi-hop Wireless Networks With Cooperative Transmissions

Sriram Lakshmanan and Raghupathy Sivakumar

GNAN Research Group
Georgia Institute of Technology

Introduction

Guest commentary: what went wrong with muni Wi-Fi, what cities can do now

May 20, 2008 at 12:36 AM by Karl Edwards

It is too easy in light of the recent news that MetroFi is selling their networks to begin to say that the municipal WiFi (note that I said Wi-Fi and not wireless) downturn is all because of EarthLink and MetroFi. Easy to pick on the companies that have come out and said, "This isn't working and we are closing shop".

nging

caling law in

uire receive

with small

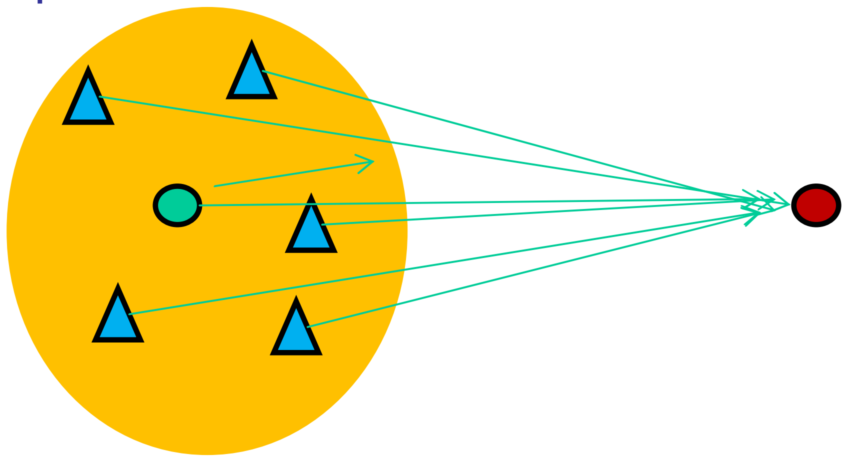
mple

extensions to conventional routing

- Focus of this work: Routing in networks with VMISO links
  - Considerations and tradeoffs
  - Design and evaluation of routing protocol

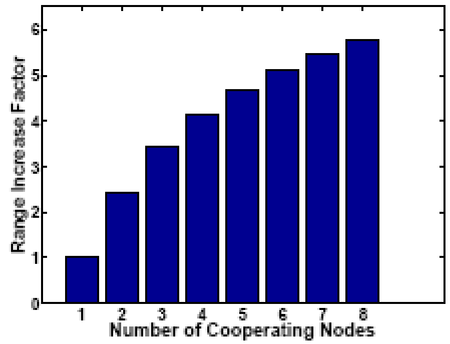
Background

- Diversity: For a given Signal to Noise Ratio (SNR), the error probability in an uncoded Rayleigh fading channel
    - without diversity - $P_b \propto SNR^{-1}$
    - with k fold diversity - $P_b \propto SNR^{-k}$
- Approach: Distributed Space Time Codes
    - Nodes transmit encoded versions of symbols ($\pm s_i$, $\pm s_i^*$)
    - Receiver processes with channel knowledge to obtain a smaller error rate
    - Nodes transmit at the fixed (maximum) power
    - Local broadcast precedes CT

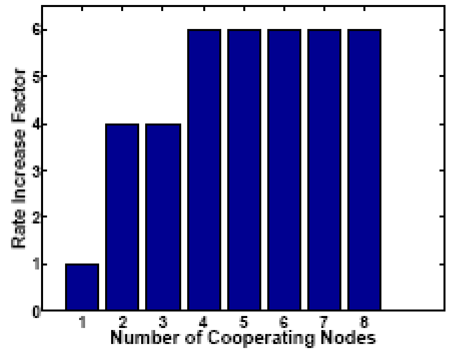


Background

- Benefits
  - For a fixed BER, cooperation lowers SNR requirement.
    - E.g. BPSK in Rayleigh fading – 25dB versus 10 dB for BER 10^{-3}
  - Benefits depend on ***strategy*** i.e rate or range of the link and ***number of cooperating nodes*** n_c.
- Feasibility
  - Asynchronous reception leads to ISI/Doppler spread like effect [1]
  - Relative delay differences small compared to symbol duration in 802.11 [2].

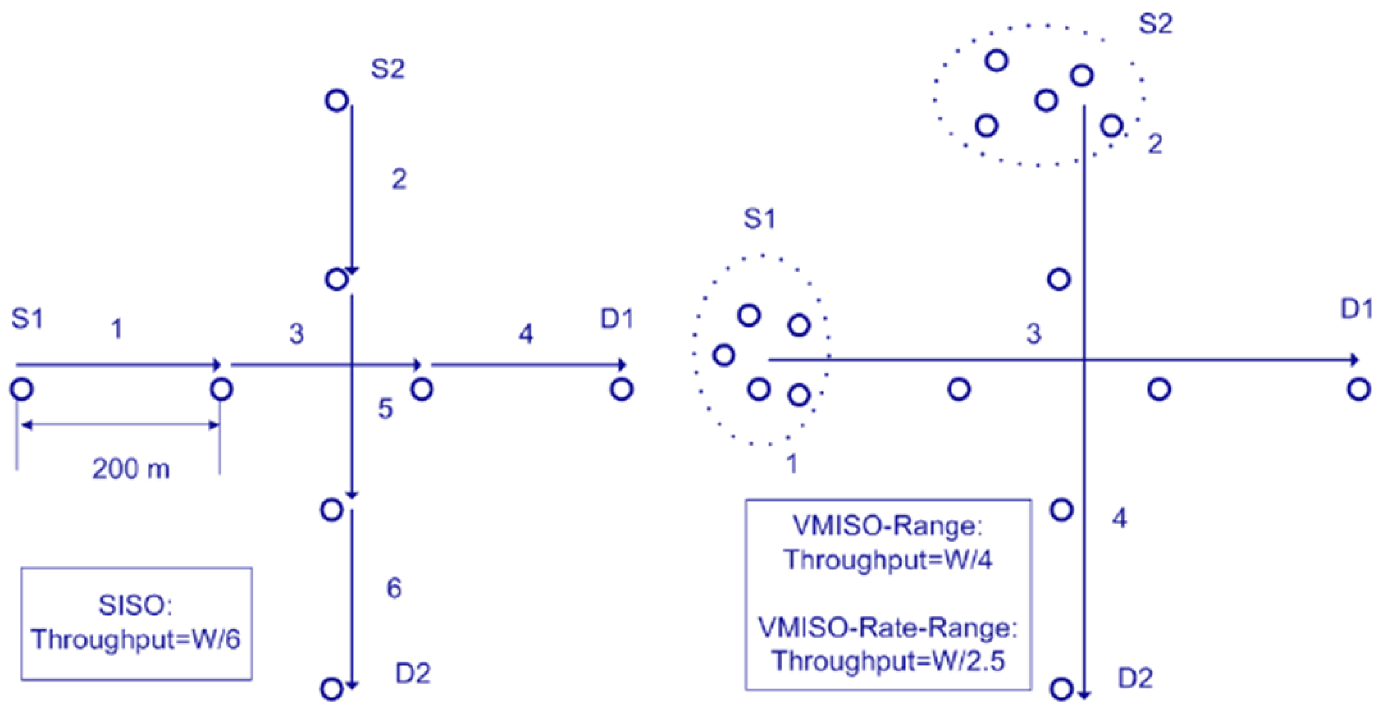


a) Range Increase



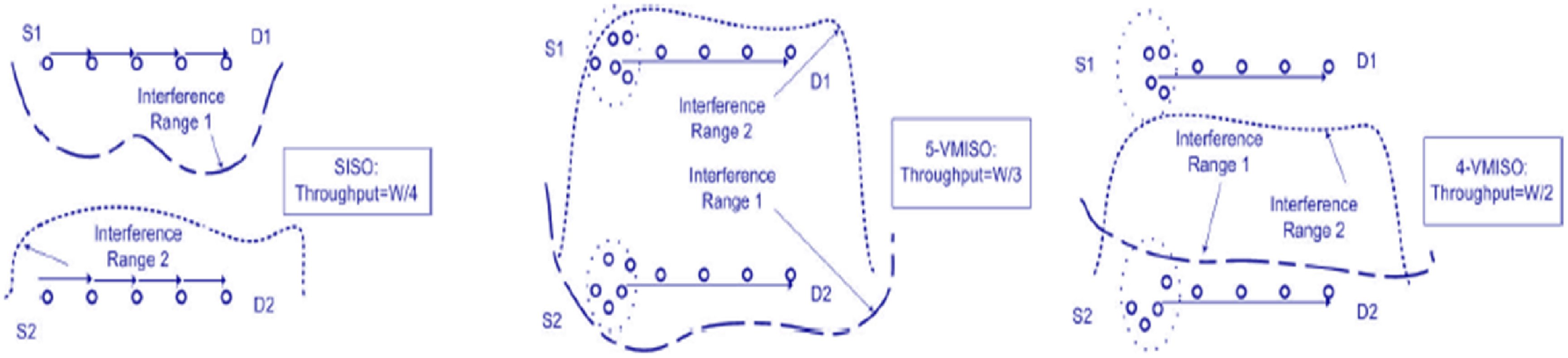
b) Rate Increase

Motivation - Strategy



The strategy used changes the throughput from 1.5 to 2.4
i.e by a factor of 1.6

Motivation- Cluster Size



(a) SISO (b) VMISO with cluster size 5 (c) VMISO with cluster size 4

Cluster size changes the throughput from 1.3 to 2
i.e by a factor of 1.5

Analysis of benefits

- Unit Disk Graph model [Gupta2001]
- Communication and Interference range of VMISO links with cluster size of n_c, path loss exponent α, modulation order m.
  - Communication range changes with n_c and m to $R_f(n_c,m)$.

$$R_f(n_c) = \left(\frac{n_c * {P_b}^{\frac{1}{n_c}} - 1}{\binom{2n_c - 1}{n_c}^{\frac{1}{n_c}}}\right)^{\frac{1}{\alpha}}$$

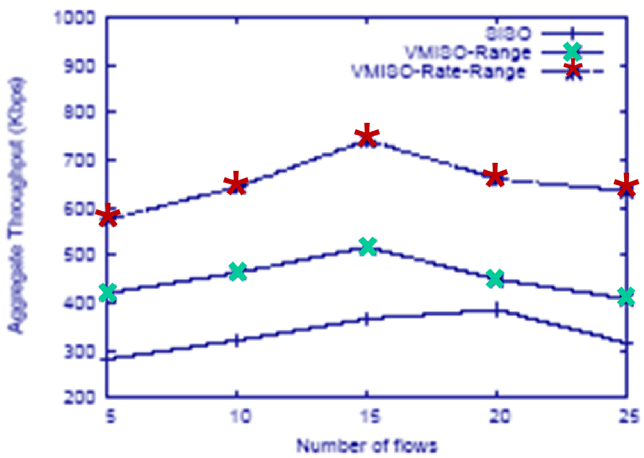
  - Time for VMISO transmissions is given by an increase of (nc)^(2/α) /m

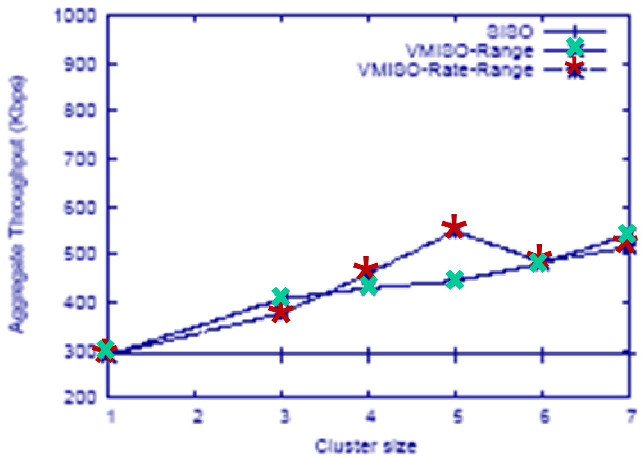
$$\frac{T_{HYBRID}(n_c, m)}{T_{SISO}} = \frac{R_f(n_c, m)}{1 + \frac{{n_c}^{\frac{2}{\alpha}}}{m}}$$

Strategy	Rate	Range	Hybrid (α=4)
Capacity ratio to SISO	$O(1)$	$O({n_c}^{\frac{1}{\alpha}})$	$O\left(\frac{m * n_c}{2^{\frac{m}{2}} * (m + {n_c}^{\frac{1}{2}})}\right)$

- With network level adaptation, best improvement depends on pair of n_c,m

Motivation - Simulation





- 2500m by 2500m grid
- 200 nodes deployed uniformly
- VMISO - Range: Basic rate modulation
- VMISO - Rate-Range: Fixed High rate modulation
- Randomly chosen S-D pairs in a network
- DSR with VMISO links
- 802.11 based MAC [Jakllari2007]
- CBR flows using UDP transport
- Averaged over 10 seeds
- Strategy and Cluster size important even in random scenarios

Summary of observations

- *Observation 1*: Joint rate - range optimization offers the best possible performance when compared to optimizing one factor in isolation.
  - e.g. 2X over SISO and 1.6X over range
- *Observation 2*: The optimal cluster size is not a fixed value (e.g. maximum) and varies with the strategy of operation.
  - e.g. The throughput optimal cluster size is 5 as opposed to a maximum cluster size of 8 for random scenarios.
- Summary
  - Valid for random and arbitrary scenarios
  - High gains for arbitrary scenarios
  - Important to carefully choose pair of cluster size and strategy at the granularity of network and more so for flows and links.

Problem formulation

- Problem: Given a set of Source - Destination Pairs, how to construct routes that optimally use VMISO links to maximize aggregate flow throughput

- Relaxations:
  - Routes built on top of SISO Shortest paths
  - Flow level assignment

- Problem is NP Hard!
  - Even for Single hop flows.
  - Interference and notion of link

- Can we design a feasible algorithm using the insights about the tradeoffs?

Design Considerations

- Cluster Size – Many or Few
  - Inter flow Interference vs single flow improvements
  - Unlike SISO, relation between interference range and communication range depends on cluster size

$$S_I(P_j, n_c, m) = \frac{2 * R_i * n_c^{\frac{2}{\alpha}}}{R(n_c, m)}$$

- Strategy – Farther or Faster
  - Number of Hops vs average per-hop rate
  - End-to-end throughput is a function of both the above

$$D = \frac{T(n_c) * 2^{m-1}}{T(n_c) * 2^{m-1} + 1}$$

- Isolated or sequential optimizations are feasible but limited in improvements
  - Joint optimization required to truly benefit from VMISO

Proteus - Adaptive diversity algorithm

- Overview
  - Models the tradeoffs and incorporates it in an appropriate path metric
  - Incorporates interference from existing flows on the SISO route
  - Performs assignment for each flow in a greedy manner subject to the maximum node degree on the path

- Input: Network with nodes, flows (sources and destinations),
- Output: path Pi, cluster size nc, strategy index m for all flows in the network.
- Use Path Metric :

$$M(P_i, k, m) = \frac{1}{max(F(P_i,n_c,m), min(\frac{nhop(P_i)*S}{R(n_c,m)))}, \frac{2*R_i(n_c)}{R(n_c,m)})} * \frac{CR(n_c)*2^{m-1}}{CR(n_c)*2^{m-1}+L(n_c)}$$

  - Where F(Pi,nc,m) is the maximum (previously assigned) flow interference (bottleneck contention) experienced for the path Pi, using nc and m, CR the code rate and Ri is the interference range
- Compute the path metric for each flow , one after the another choosing Pi, nc and m that maximizes the throughput

Protocol Realization

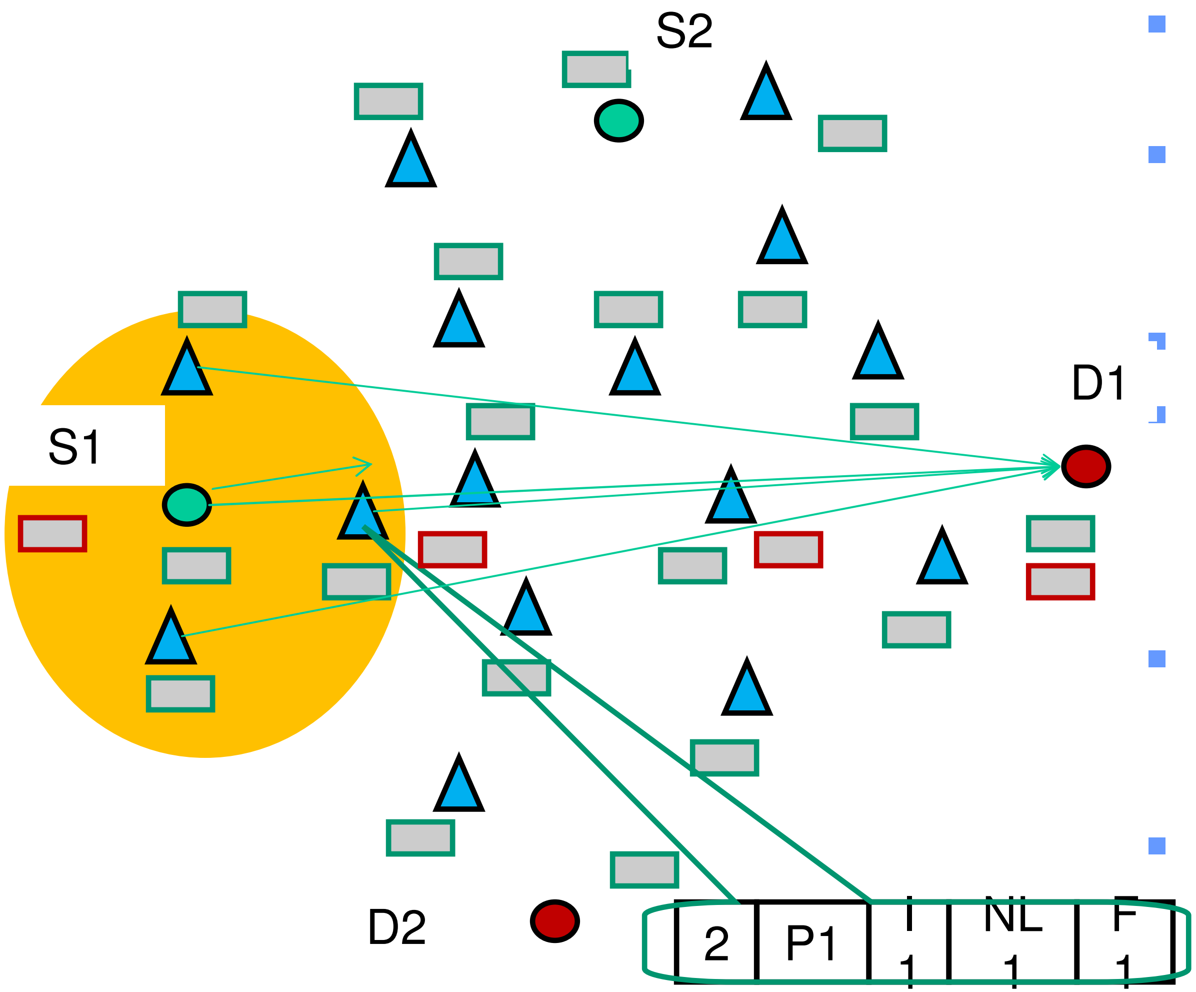
- Conventional route discovery augmented with additional information
- Such as number and interference activity of neighbors

1. Route Request: Additional 4-Tuple stamped on route request, (Pj ; Ij ;NLj ; Fj)
   - where Pj is the received signal strength from the previous hop,
   - Ij is the ambient interference level (the fraction of time, the channel is busy) ,
   - NLj , the neighbor list consisting of the number of links (unique source addresses) that each neighboring node has overheard and
   - Fj , the number of flows already served by this node.
2. Route Response
   - Intermediate nodes update statistics if any
   - Source computes path metric based on the 4-tuples
   - Contention levels estimated using the interference information (Carrier sense threshold crossing) and the pilot tones
3. Route Failures and Maintenance
   - Route re-computation

Protocol Realization – MAC support

- Receiver needs nc, m and channel state information
- Local Transmission at each hop
  - Source transmits local packet with an order of neighbors
  - Available neighbors transmit pilots in the order indicated
  - Transmission suspended if nc pilots not heard
- Pilot Tone transmission
  - Receiver waits for a preset time to hear pilot tone
  - collects CSI from the pilots
  - Returns to idle state if no transmission heard until a timeout
- VMISO Transmission
  - Preamble at the basic rate indicating the payload rate and nc
  - With the knowledge, receiver decodes using the appropriate space Time decoding procedure
  - Preambles and pilots are few μs and small compared to Data symbol durations

Illustration of Proteus



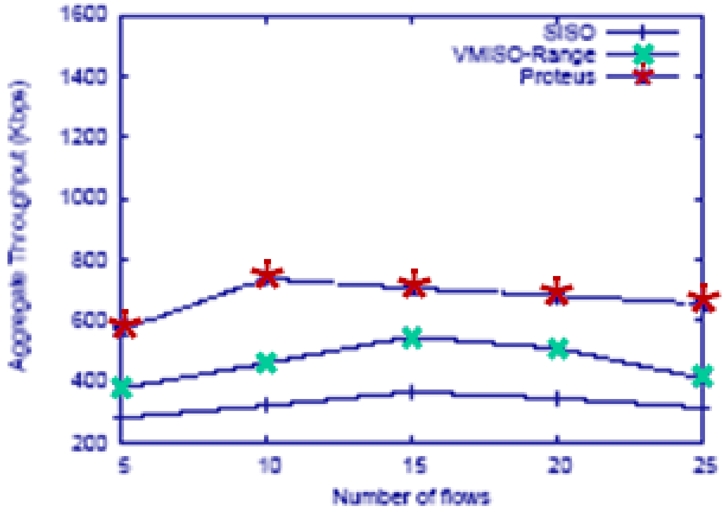
- S1 Starts DSR route discovery broadcast
- Nodes add neighbor summary with interference information
- D1 responds with reply
- Source picks shortest SISO path, computes expected rate of different nc,m and picks the best
- Source initiates VMISO with preamble giving information to nodes
- Nodes update interference statistics

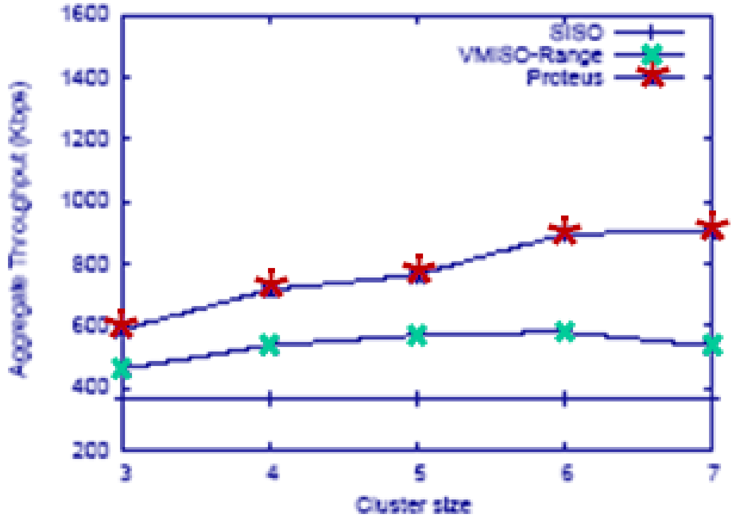
S2 computes similarly

Evaluation Setup

- Modified NS2.28 simulator
- Receiver calculates Pt $\Sigma\ \alpha_i^2 / d_i^4$ for each cooperative transmitter i and computes cumulative SINR.
- Compares SINR with a threshold depending on the modulation. (e.g 25 dB for BPSK)
- Modulations- BPSK, QPSK, 16-QAM and 64-QAM
- 200 nodes in a 2500m by 2500m grid
- Random Constant Bit Rate (CBR) flows over User Datagram Protocol (UDP)
- Modified DSR and 802.11[2]
- 10 random seeds with 100s runs
- Comparison with SISO and VMISO-Range

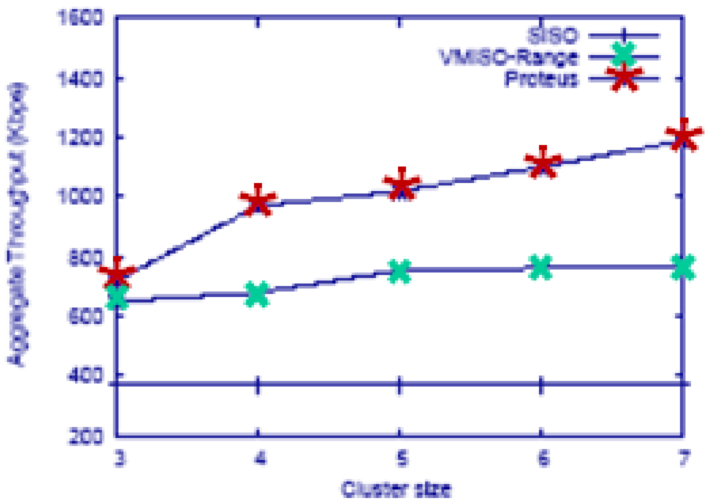
Results



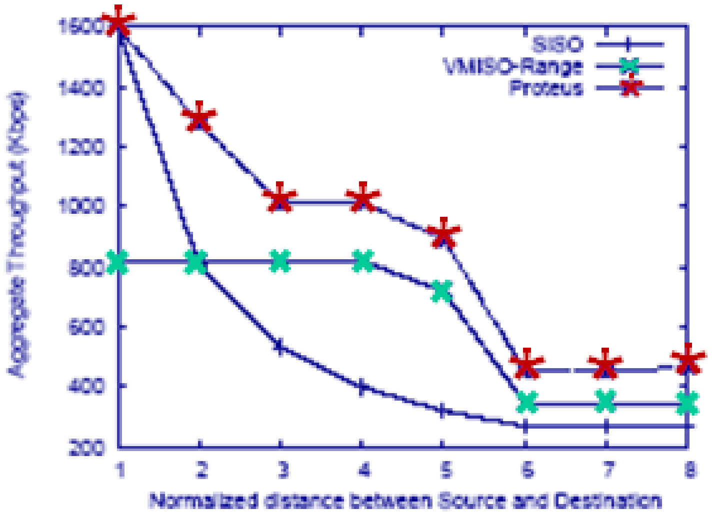


- With flows
  - Proteus improves over SISO and VMISO-Range by about 2.6X and 1.8X for 10 flows
  - As the number of flows increases, Proteus retains throughput
- Cluster Size
  - With increasing cluster size upto 7, Proteus causes increased throughput
  - The throughput is improved over 2.2X and 1.5X over SISO and VMISO-range for 15 flows.
  - Higher gain over VMISO Range at higher cluster size about 2X.

Results



- Grid size
  - Smaller grid size leads to higher improvement
  - since the reduction in spatial reuse is not significant
  - Improvements around 2X over VMISO Range and 3X over SISO.



- S-D separation
  - For strategically picked S-D pairs, with bounded hops between them
  - Gains over SISO large for hops > 1 and hops < 6
  - Improvements over VMISO range high for hops between 1 and 4.

Summary

- Identified two key trade-offs for routing in networks with VMISO links
  - Inter-flow Interference vs. single flow performance gains (Cluster size)
  - End-to-end gains vs. link level gains (Strategy)
  - Optimal choice that balances trade-offs is not fixed
- Designed Proteus, a routing protocol which identifies routes and per-flow strategies to improve network throughput
- Hybrid VMISO shows promise in multi-hop networks
  - gains from 15% to 300% over conventional routing achievable
- Future work
  - Optimized Neighbor selection
  - Prototype Implementation
  - Opportunistic variants and VMIMO

References

[Barriac2004] G.Barriac et al,"Distributed beamforming for information transfer in sensor networks" IPSN 2004

[Jakllari2007] G. Jakllari and et al, "A cross layer framework for exploiting virtual miso links in mobile ad hoc networks," IEEE Transactions on Mobile Computing, 2007

[Lakshmanan2008] S.Lakshmanan and R.Sivakumar, "Diversity routing for multi-hop wireless networks using cooperative transmissions", GNAN Technical report, 2008

[Gupta2001]The capacity of wireless networks, Transactions on Information theory, 2001.

[Ozgur2008] Ozgur, A.; Leveque, O.; Tse, D.N.C. "Hierarchical Cooperation Achieves Optimal Capacity Scaling in Ad Hoc Networks", IEEE Transactions on Information Theory, Vol. 53, Issue 10, Oct. 2007.

Questions

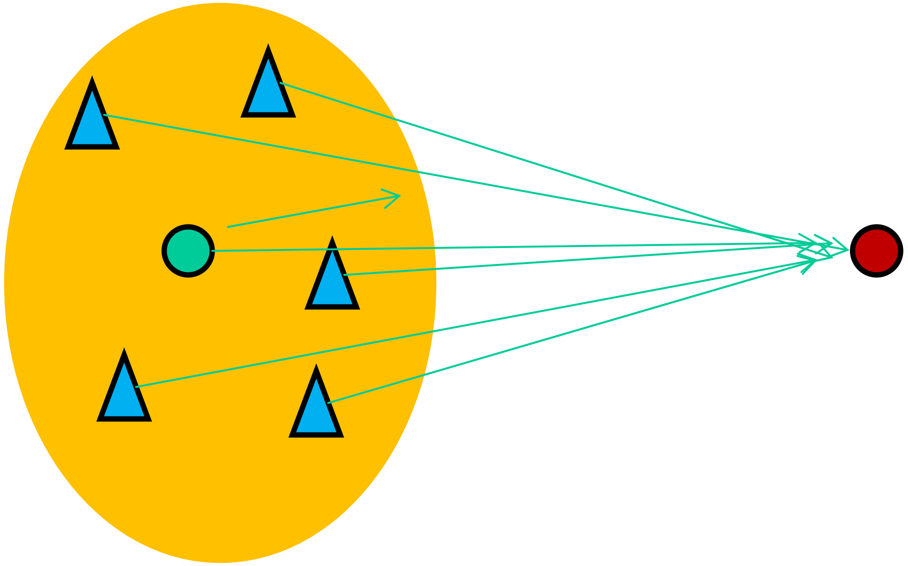
- Why VMISO as opposed to VMIMO?
  - Higher coordination costs
- Why VMISO as opposed to MISO ?
  - Lack of hardware support, VMISO can be built over MISO networks, richer spatial diversity, better scalability properties
- Optimality of algorithm
- These are the two fundamental properties of VMISO relevant to routing. There are many more..
- DSTC as opposed to other strategies – simplicity of implementation without receiver processing changes

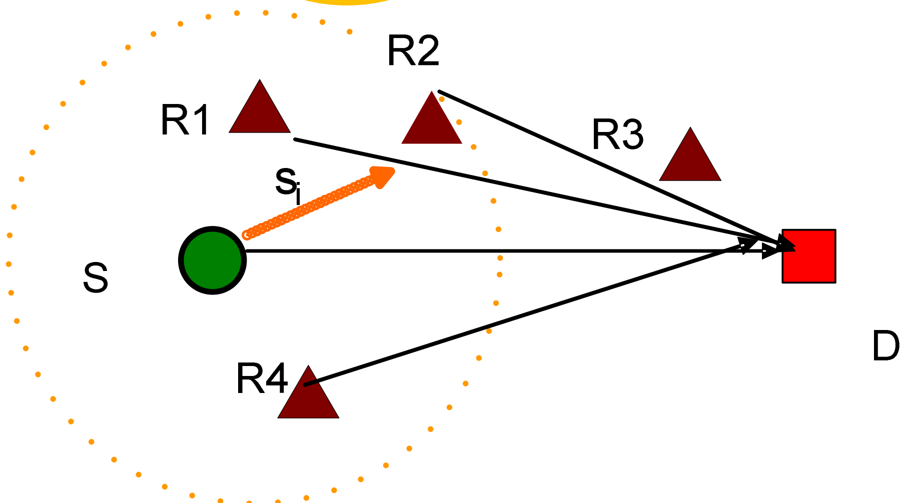
1. Title
2. Intro, conetx and goal
3. Outline
4. Cooperation model and baseline benefits
5. Motivation 1
6. Motivation 2
7. Algorithm considerations
8. Considerations and tradeoff
9. Algorithm overview
10. Overview
11. Distributed realization
12. Evaluation setup
13. Evaluatio nResult
14. Evaluation Result
15. Conclusions
16. Backup: Distributed algo animation
17. Other considerations like sync
18. More results
19. Modeling cooperative

Lessons from practical deployments

nd

- A high density of 30 - 40 APs per square mile required for even baseline performance
- Less than 1 out of 12 deployments successful!




R2
R1
R3
s_i
S
D
R4

$$O(\frac{m * n_c}{2^{\frac{m}{2}} * (m + {n_c}^{\frac{1}{2}})})$$

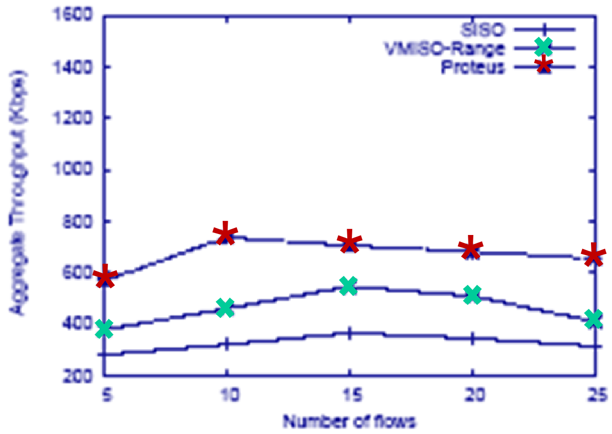
$$O({n_c}^{\frac{1}{\alpha}})$$

$$\frac{T_{RANGE}}{T_{SISO}} = O({n_c}^{\frac{1}{\alpha}})$$

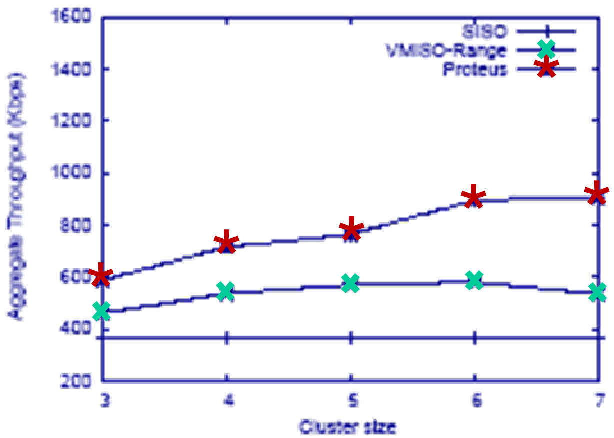
Design

- Design considerations
  - Cluster Size – Many or Few
    - Inter flow Interference vs single flow improvements
  - Strategy – Farther or Faster
    - Number of Hops vs average per-hop rate
  - Order – Joint or sequential
    - Range maximization followed by rate increase
    - Rate maximization followed by range increase
    - Joint rate-range optimization
- Isolated or sequential optimizations are feasible but limited in improvements
- Joint optimization is needed

Results



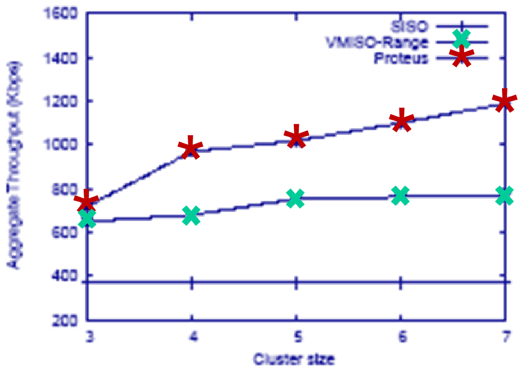
(a) Throughput with 150 nodes



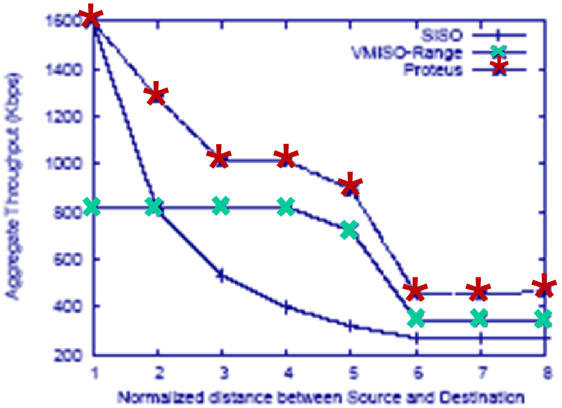
(d) Throughput with 15 flows

- With flows
  - Proteus improves over SISO and VMISO-Range by about 2.6X and 1.8X for 10 flows
  - As the number of flows increases, Proteus retains throughput
- Cluster Size
  - With increasing cluster size upto 7, Proteus causes increased throughput
  - The throughput is improved over 2.2X and 1.5X over SISO and VMISO-range for 15 flows.
  - Higher gain over VMISO Range at higher cluster size about 2X.

Results



(a) Throughput vs cluster size with small grid size



(c) Throughput with S-D distance

- Grid size
  - Smaller grid size leads to higher improvement
  - since the reduction in spatial reuse is not significant
  - Improvements around 2X over VMISO Range and 3X over SISO.
- S-D separation
  - For strategically picked S-D pairs, with bounded hops between them
  - Gains over SISO large for hops > 1 and hops < 6
  - Improvements over VMISO range high for hops between 1 and 4.

Outline

- Context and Background
- Motivation
- Design elements
- Protocol
- Evaluation
- Summary