Routing in Ad-Hoc Networks with MIMO Links

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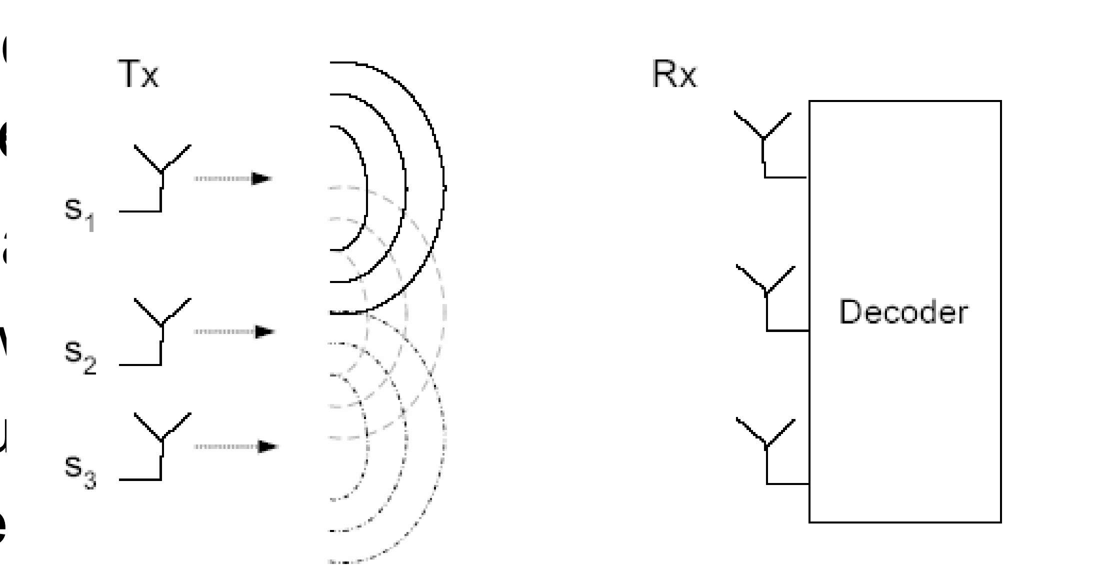
November 7th, 2005.

MIMO in Ad-hoc Networks

- Ad-h ... multi-hop wirel
- Limit
  - Lo ... applications
  - Flu ... of service
  - Ne



  - Power efficiency is critical for mobile applications
- Multiple Input Multiple Output is a smart antenna technology
- MIMO provides high spectral efficiencies and reliability at the cost of no extra bandwidth and power - especially efficient in multipath and interference-limited environments

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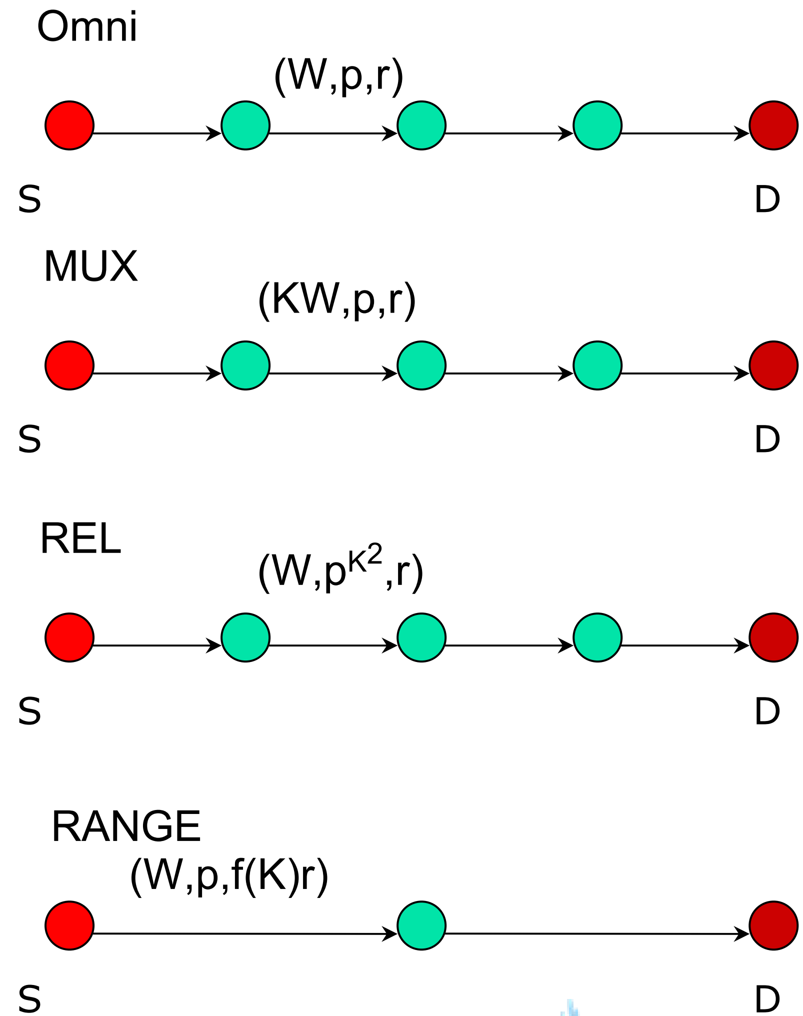
Strategies of Operation

- Spatial Multiplexing
  - Independent data streams transmitted (eg. VBLAST); multipath exploited for decoding
  - ☞ MUX: Linear increase in link capacity/rate, $W \to KW$
- Diversity
  - Dependent data streams transmitted (eg. STBC); redundancy provides robustness to multipath fading
  - ☞ REL: Increased link reliability (reduced error rates), $p \to p^{K^2}$
  - ☞ RANGE: Diversity used for increased communication range, $r \to f(K)r$
- Tradeoff in exploiting rate, range and reliability simultaneously



The Problem and Contributions

- The Problem
  - Different MIMO strategies contribute in different ways
    - Rate increases the throughput on the link
    - Range helps bridge network partitions
    - Reliability alleviates packet errors during channel fading
  - How does one efficiently exploit the different strategies to improve network performance using effective routing?
- Contributions
  - What are “good” routes?
  - How to compute such good routes most effectively?
  - How to maintain routes efficiently during network dynamics?

Analysis of Strategies (1)

- Compare strategies based on throughput capacities
- MUX: 'W' scales to 'KW'
  - Hop length remains same
- REL: lower loss probability reduces effective number of hops traveled
- RANGE: smaller hop length reduces effective number of hops traveled
- Lower multi-hop burden in diversity improves throughput

$$\lambda \le \frac{16AW}{\pi\Delta^2 n r^2 \bar{h}}$$

$\bar{h}$ average lossy hop length

$$\bar{h} = f(h,p) \ge h$$

$$\lambda_{mux} \le \frac{16AKW}{\pi\Delta^2 n r^2 \bar{h}_{mux}} \qquad \bar{h}_{mux} = \bar{h}$$

$$\lambda_{rel} \le \frac{16AW}{\pi\Delta^2 n r^2 \bar{h}_{rel}} \qquad \bar{h}_{rel} = f(h, p^{K^2}) \le \bar{h}_{mux}$$

$$\lambda_{ran} \le \frac{16AW}{\pi\Delta^2 n (rf)^2 \bar{h}_{ran}} \qquad \bar{h}_{range} = f(h/f_r, p) \le \bar{h}_{mux}$$

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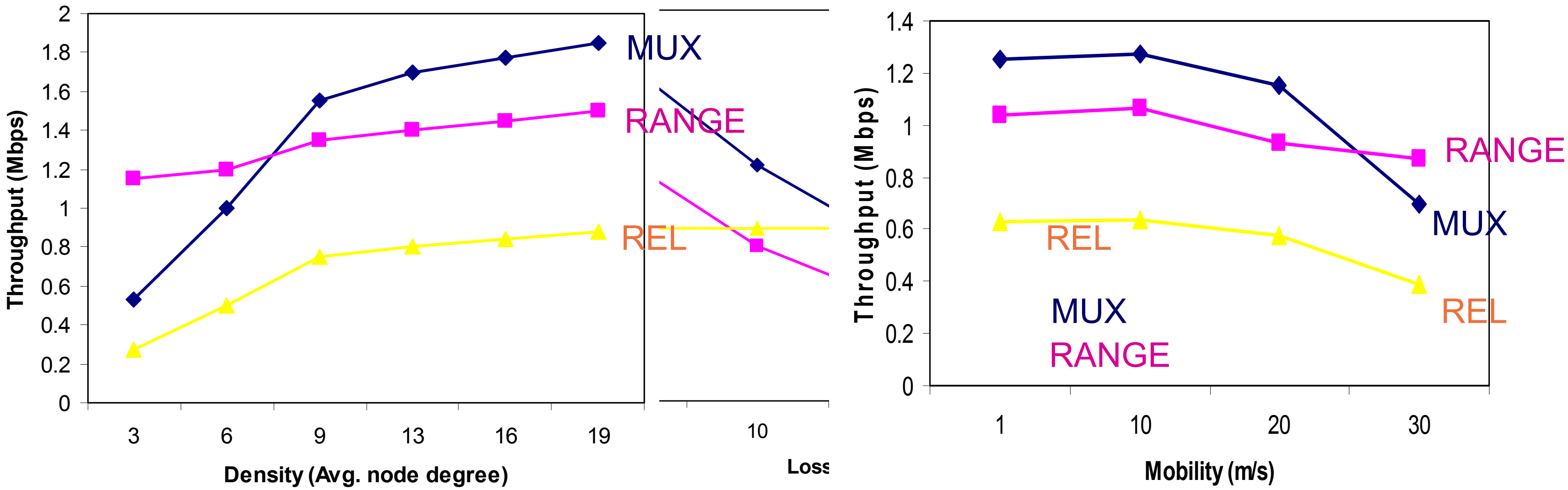
Analysis of Strategies (2)

- Inferences
  - MUX performs the best under most conditions
  - REL outperforms MUX for moderate-high loss rates due to increased reliability
  - RANGE outperforms MUX only at large loss rates due to the reduction in spatial reuse
  - REL outperforms RANGE under all conditions
  - Analysis favors MUX to REL, and REL to RANGE strategies
- Analysis captures connected, static and lossy networks
- NS2 simulations with realistic PHY models used to evaluate strategies under practical conditions [1]

[1] "Linear and non-linear receiver processings in MIMO ad-hoc networks," H. Shekar, K. Sundaresan, M.A. Ingram, in IEEE WPMC 2005.

Analysis of Strategies (3)



- MUX – best in connected network conditions with low mobility and loss rates
- REL -best under fading conditions with moderate to large packet loss rates
- RANGE - best in sparse network conditions by bridging network partitions
- RANGE -robust to mobility losses due to increased communication range

☞ What are "good" routes?

- Routes with rate links for high throughput; range links for bridging partitions and during mobility; reliability links during channel fading

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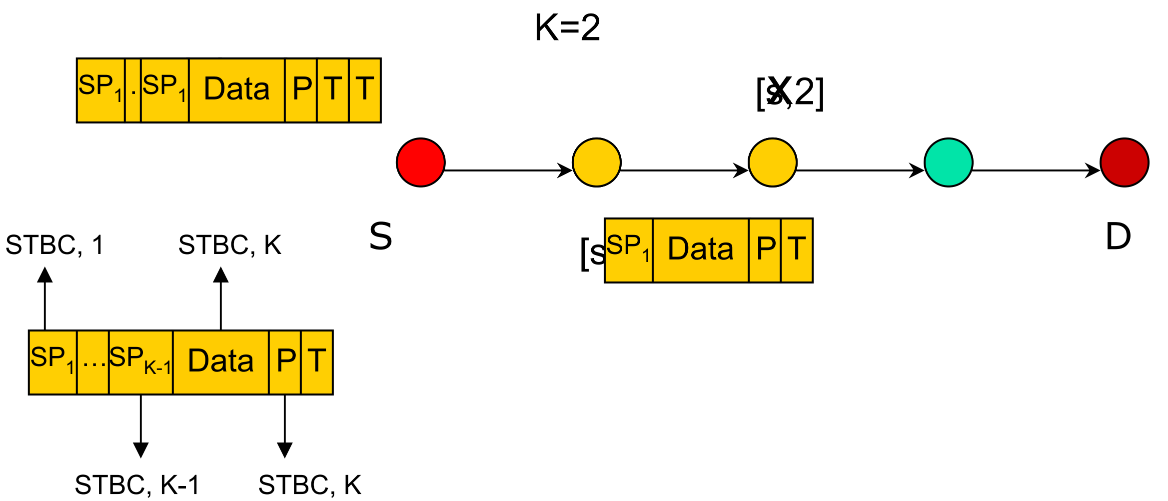
MIR Solution Framework (1/2)

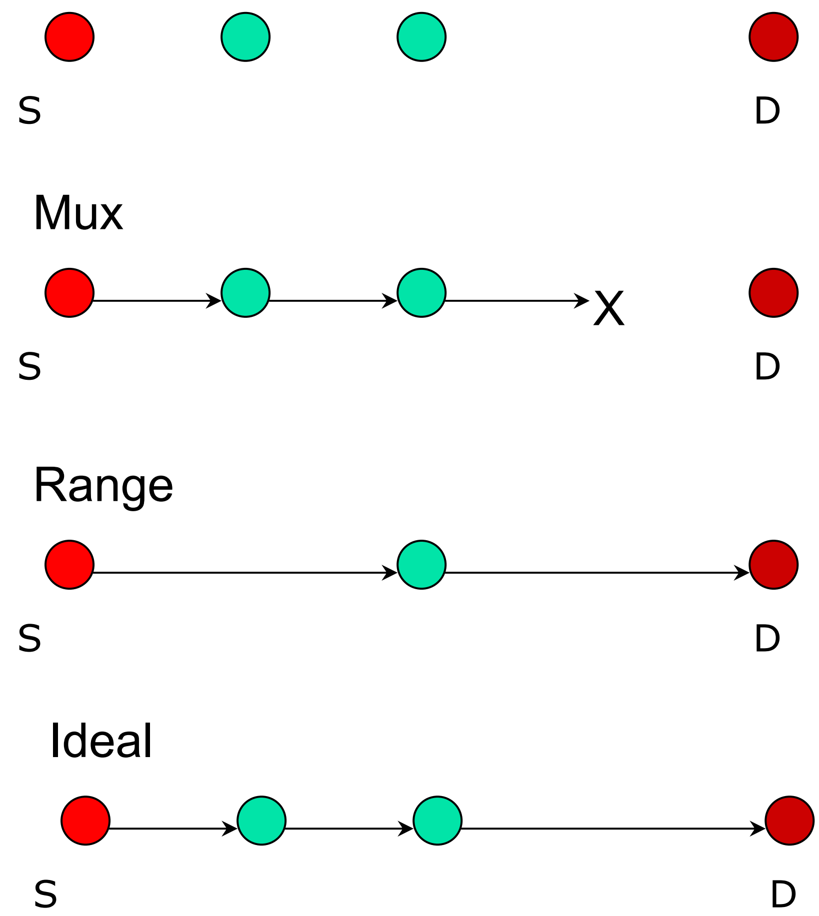
- Routing Layer Support
  - MIMO Routing - reactive source routing protocol
  - Source discovers routes on demand – flooding of route request (RREQ), intermediate nodes stamp id, route reply (RREP) carrying route sent back from destination
  - During link failures intermediate nodes send route error (RRER) notification; source discovers another route
  - Extensions to proactive routing protocols
- MAC Layer Support
  - STBC used as invariant strategy for preamble
    - Contains the strategy to be used for actual packet
    - Provides better reliability to the preamble
  - Range extension detection during use of RANGE
    - K-1 short preambles follow data to help nodes identify hop distance from source

MIR Solution Framework (2/2)



Route Discovery (1)

- Rate links provide high throughput but cannot bridge partitions
  - If rate unsuccessful then use range – large delay
- Range links bridge partitions but reduce spatial reuse
- What is the optimal combination of the two strategies?
  - Need routes with maximal rate links and minimal range links so as to only bridge partitions
  - Time required for discovering optimal routes must be close to the best case delay incurred in a MUX scheme



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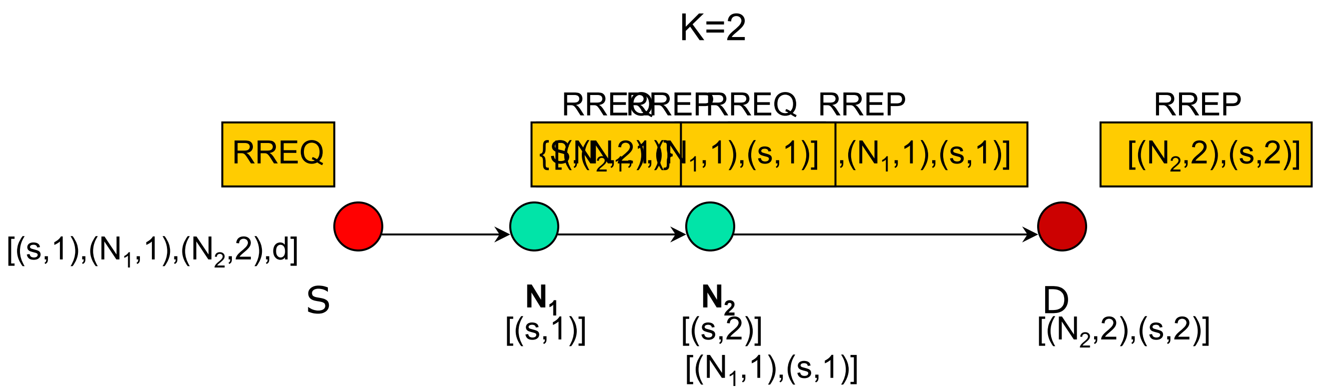
Route Discovery (2)

- Route metric
  - Maximum rate links with minimal range links required to bridge partitions
- Route request (RREQ) propagation happens using diversity (RANGE)
- Range links initially formed are patched with rate links in parallel with the RREQ propagation
- Route reply (RREP) propagation exploits nature of discovered links

Route Discovery (3)



- MIR achieves a route discovery latency that is close to that of MUX
  - Best-case latency (MUX) is $T_{MUX} = (T/K)h = T(h/K)$
  - RANGE with synchronous bridging takes $T_{RAN} = Th = T(h/k) + T(h/k)(K-1)$; $T_{RAN} = T_{MUX} + f(h,K)$
  - MIR takes $T(h/k) + T(K-1)$; $T_{MIR} = T_{MUX} + f(K)$

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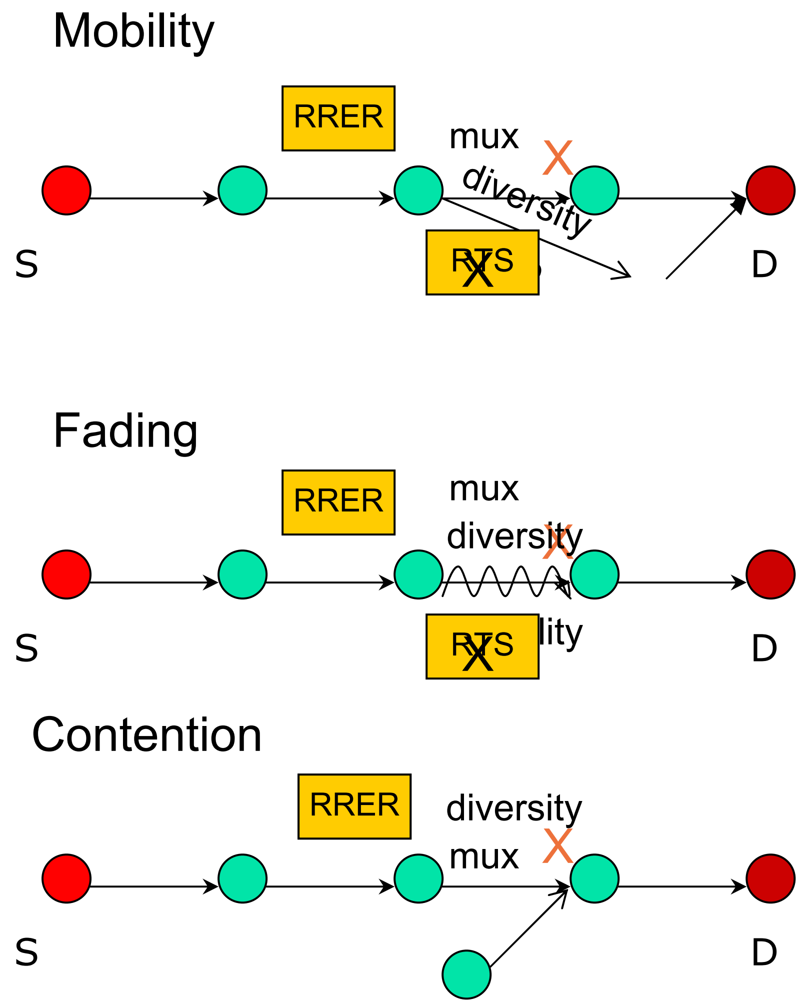
Route Maintenance (2)

- Identify mobility and fading channel errors from contention losses
- Ensure discovery of an alternate route before the current link/route breaks
  - Prevent reacting to transients like “temporary” mobility and channel fading
- Determine the minimal number of elements required for diversity to overcome the loss
  - Excessive use of diversity gain only reduces rate

Route Maintenance (2)

- CSMA/CA's retransmission mechanism exploited to proactively detect mobility and fading losses
- Switch from MUX to diversity made to provide increased range and reliability during mobility and fading
- After switching to diversity, proactive RRER issued
- Contention and transient link changes identified by receiver's ability to receive short preambles
  - "RRER cancel notification" (RCN) message sent to source



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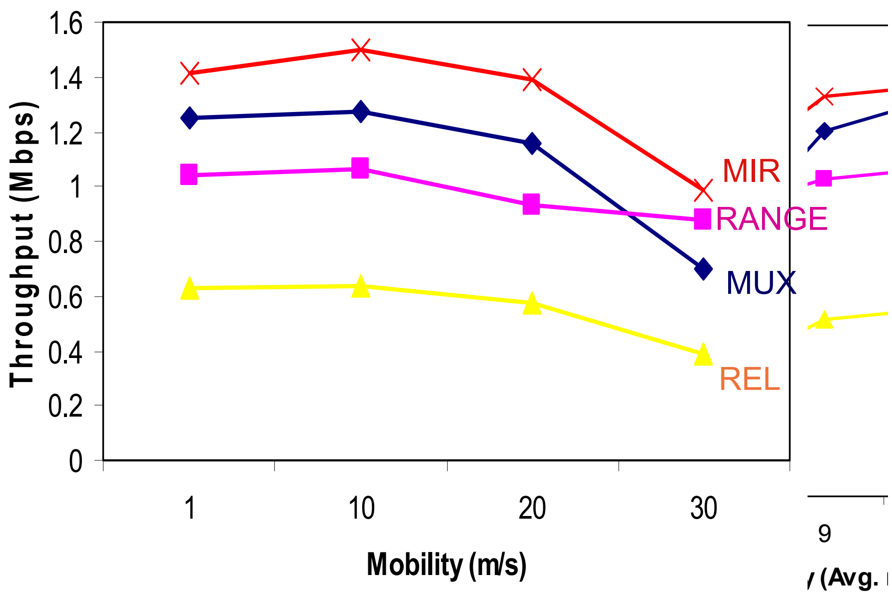
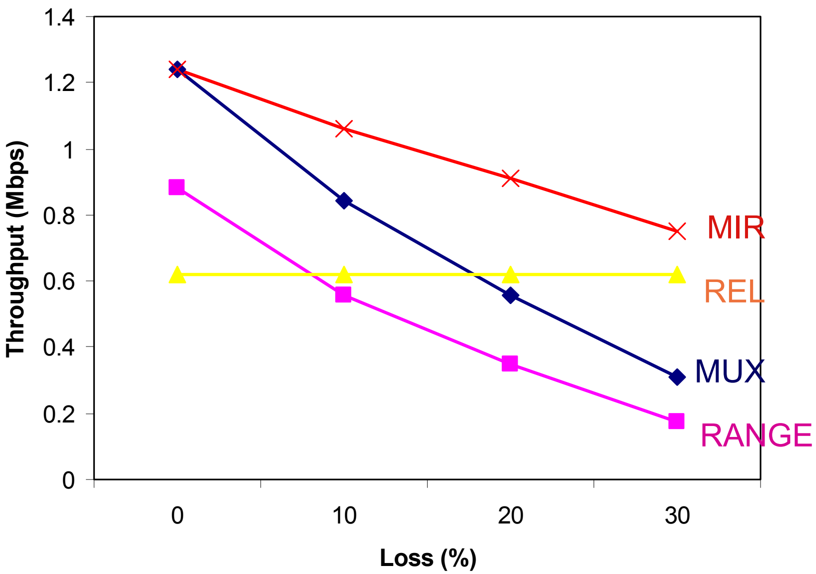
Performance Evaluation

- NS2 network simulator
- Realistic physical layer model incorporating packet drop probabilities for different MIMO receiver processings based on received SINR
- 100 nodes placed in a 2-D grid
  - Network size varied to vary density
- Network parameters: density, mobility, loss rate, load (# flows), antenna elements
- UDP with CBR used as traffic application
- Aggregate throughput used as metric of comparison
- Strategies compared: MUX, BER, RANGE, MIR

Results (1)





- MIR adapts between the multiplexing and diversity strategies transparently based on perceived network conditions to provide optimal performance

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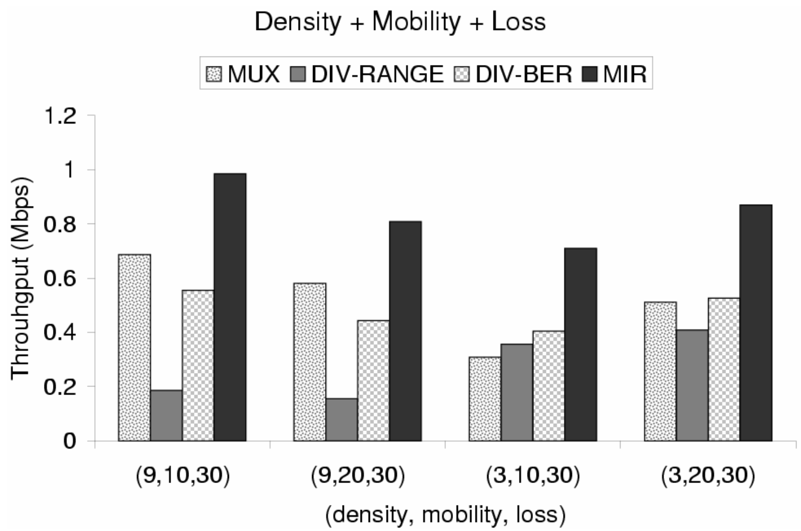
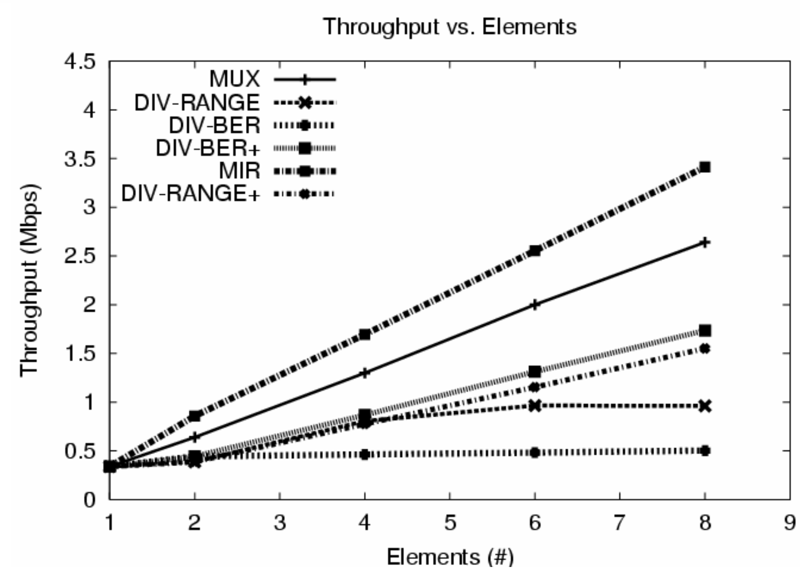
Results (2)





- MIR exhibits significant gains under combined impact of varying density, loss and mobility conditions
- MIR exhibits good scalability with elements by appropriate combination of multiplexing and diversity

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Conclusions

- Exploitation of MIMO antenna technology in ad-hoc routing protocol operation
  - Relevance of MIMO gains to routing protocol operations
  - Design rules for operation of strategies based on varying network conditions
  - Protocol mechanisms transparently adapt between strategies to provide improved network performance
- Application to proactive routing protocols
- Security issues in MIR needs to be addressed
- http://ece.gatech.edu/research/GNAN/projects