Energy-aware and Link-adaptive Routing Metrics for Ultra Wideband Sensor Networks

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Outline

- Motivation
- Related work
- System model
- Routing metrics
- Simulation results
- Conclusions

Motivation

- Considered scenario
  - Ultra wideband (UWB) sensor network
  - Multi-hop capability
  - Energy constrained
  - Primarily non-mobile applications
- Routing is an open problem
- Goal
  - Exploit spatial diversity in order to increase throughput while extending network lifetime
- Proposed solution
  - Integrate link quality and energy level measures in the next hop routing decision

Related work (1)

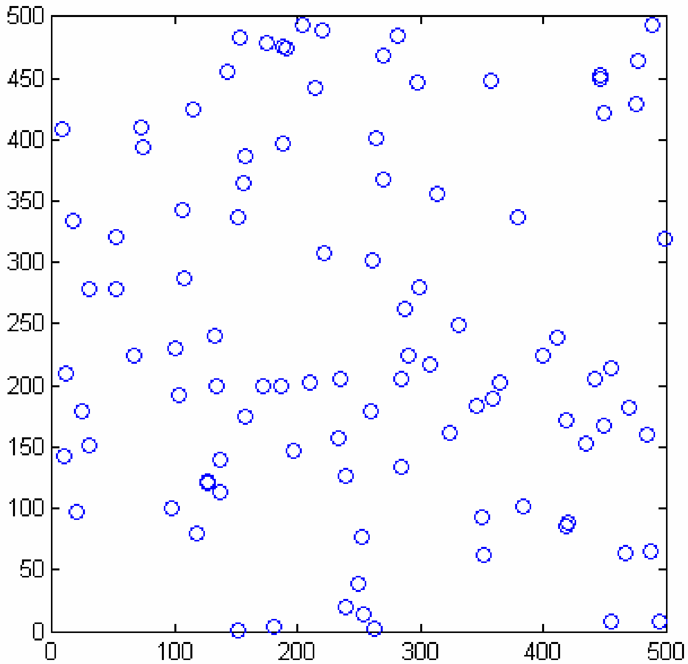
- Energy aware routing protocols
  - Some energy aware routing protocols focused on finding the minimum energy path from the source to the destination node [Singh98] [Michail00]
    - Only the summation of the consumed energy on the route is minimized
    - Chosen routes may contain nodes with little remaining battery capacity leading to quicker network partition
  - Max-min battery capacity based routing strategies were proposed [Toh01] [Chang 04] [Senouci04]
    - The minimum total energy along the route and the residual battery capacity of each node are combined together in the route decision
  - Deficiency
    - Did not take into account other network performance metrics such as throughput and end-to-end delay

Related work (2)

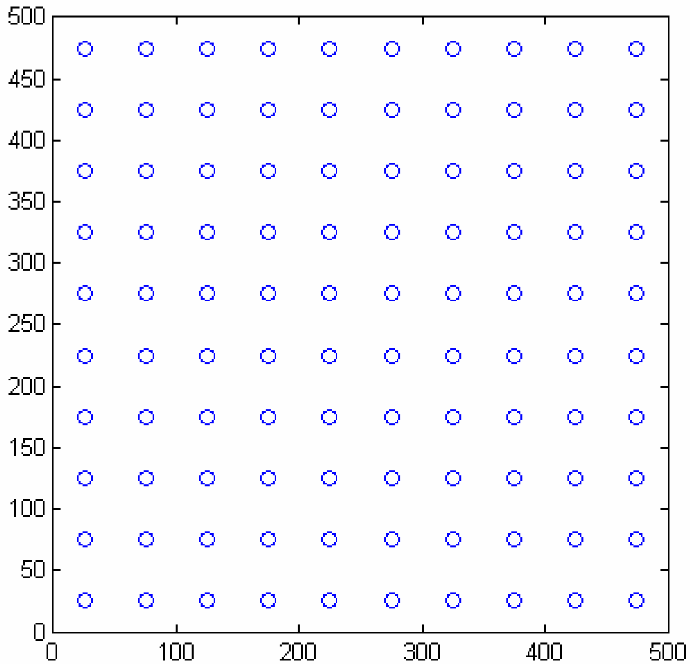
- Measure of network performance
  - Total throughput
    - Example: transport capacity, which is the bit-distance product that can be transported by the entire network [Gupta00]
  - Local throughput
    - The rate at which a node successfully transmits packets
      - Most Forward within radius R (MFR) [Takagi84]
      - Expected Forward Progress [Sousa90]
      - Information Efficiency [Subbarao00]

Network topology model

- Random or grid topology
- *N* nodes uniformly distributed in a square area with edge *R*



Random Topology



Grid Topology

Traffic model

- Assume a time slotted system
- Each node generates a fixed length packet with probability p in a given time slot
- Packet is destined to a randomly chosen destination node other than itself
- Nodes will not generate, transmit, relay nor receive any packets when they are out of energy

Channel model

- Pathloss:
  - Measurement-based UWB low altitude outdoor channel model [Buehrer04], where $PL \propto d^{2.61}$
- Shadowing and multipath fading are not considered
- Assume that rake combing scheme is used in the receiver that minimizes the impact of multipath fading

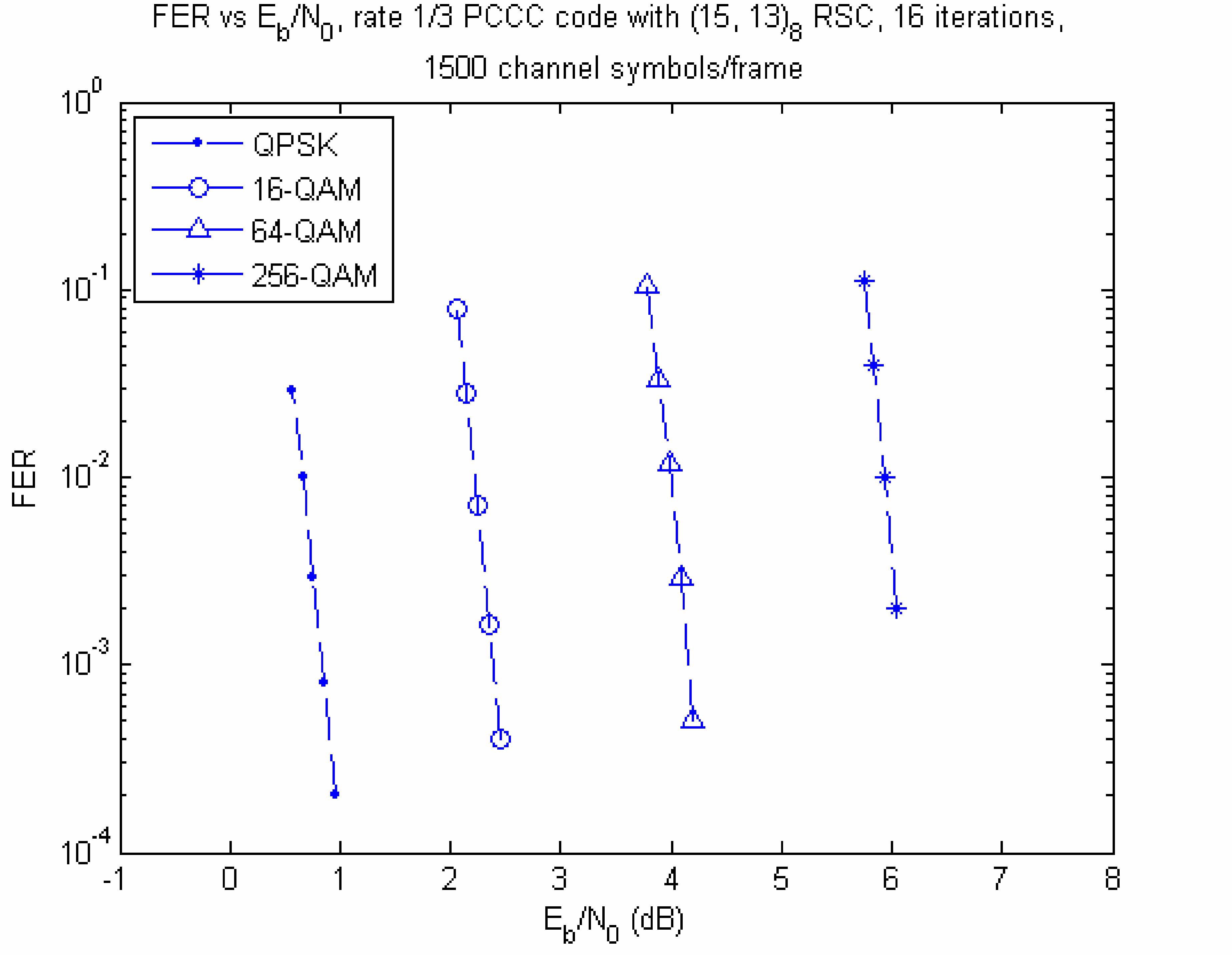
Multiple access scheme

- DS-CDMA
  - Conventional single user receiver
  - Low implementation cost and low signal-to-noise ratio (SNR) requirements
- Given that node *i* transmits to node *k*, the received *SNIR* at node *k* is

$$SNIR_{i,k} = \frac{Pt_i / (d_{i,k}^{\alpha})}{\frac{1}{PG}\sum_{j \neq i} Pt_j / (d_{j,k}^{\alpha}) + N}$$

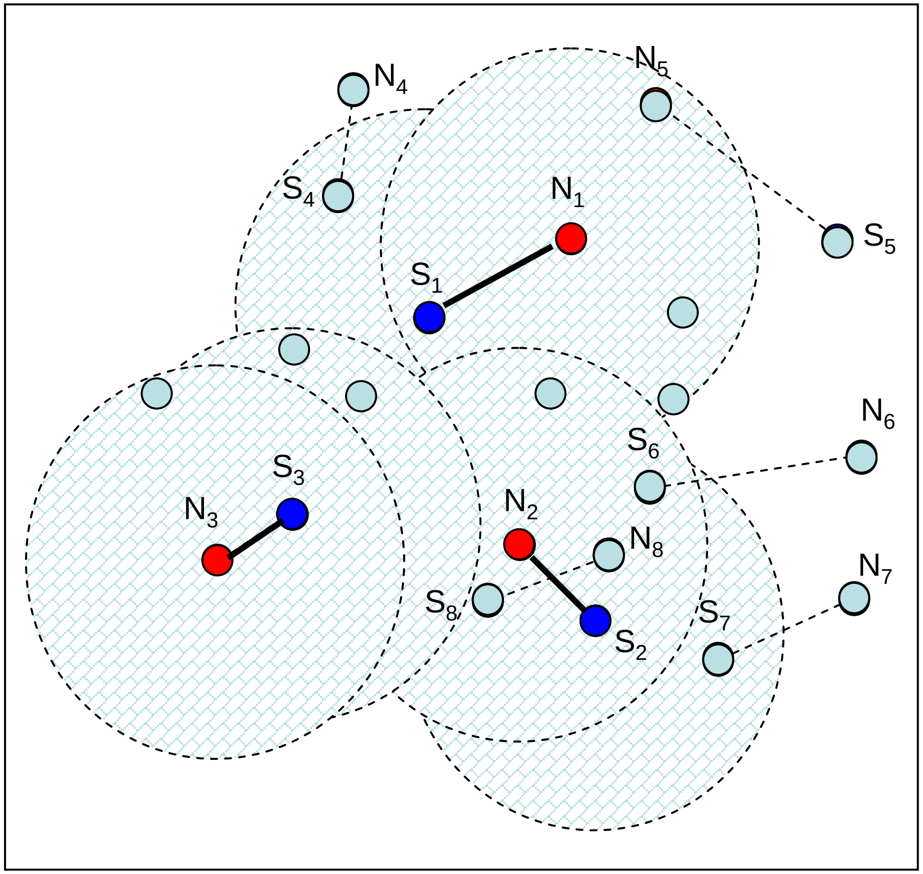
Modulation and coding schemes

- Fixed modulation
  - QPSK
- Adaptive modulation
  - QPSK, 16-QAM, 64-QAM and 256-QAM
  - Higher order modulation schemes support multiple packet transmission
- Turbo coding
  - 1/3 rate PCCC code with generator polynomials $(15,13)_8$


FER vs E_b/N_0, rate 1/3 PCCC code with $(15, 13)_8$ RSC, 16 iterations,
1500 channel symbols/frame
QPSK
16-QAM
64-QAM
256-QAM
FER
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
-1
0
1
2
3
4
5
6
7
8
E_b/N_0 (dB)

Medium access control

- Idealized version of CSMA/CA (Carrier Sensing Medium Access/Collision Avoidance) with RTS/CTS (Ready to Send/Clear to Send) based handshaking scheme
  - The random selection of active links can be considered similar to the channel sensing procedure in CSMA/CA
  - An exclusion zone with a radius equal to the transmission range is used at both the transmitter and receiver
    - Emulates effect of RTS/CTS
    - Resolves collisions
    - Alleviates the near-far effect of the spread spectrum system



1. Randomly select active links from all links which are accessing the medium channel
2. Other links within the transmitter's RTS and receiver's CTS area will be excluded

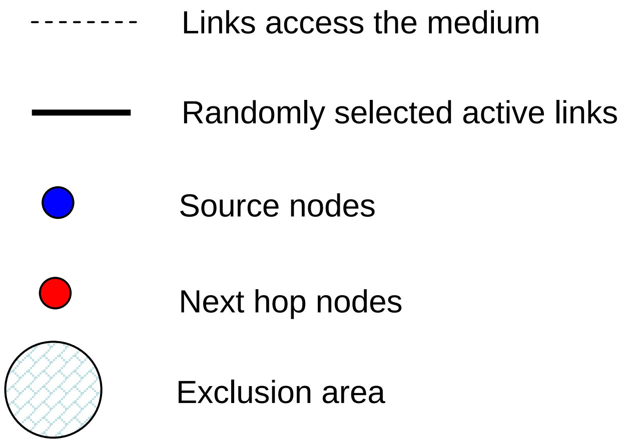


Illustration of the medium access scheme

Queue management

- Queue management depends on the modulation scheme (fixed or adaptive)
- Packets adjacent to each other in the buffer may have different destinations and therefore might not be routed to the same next hop node

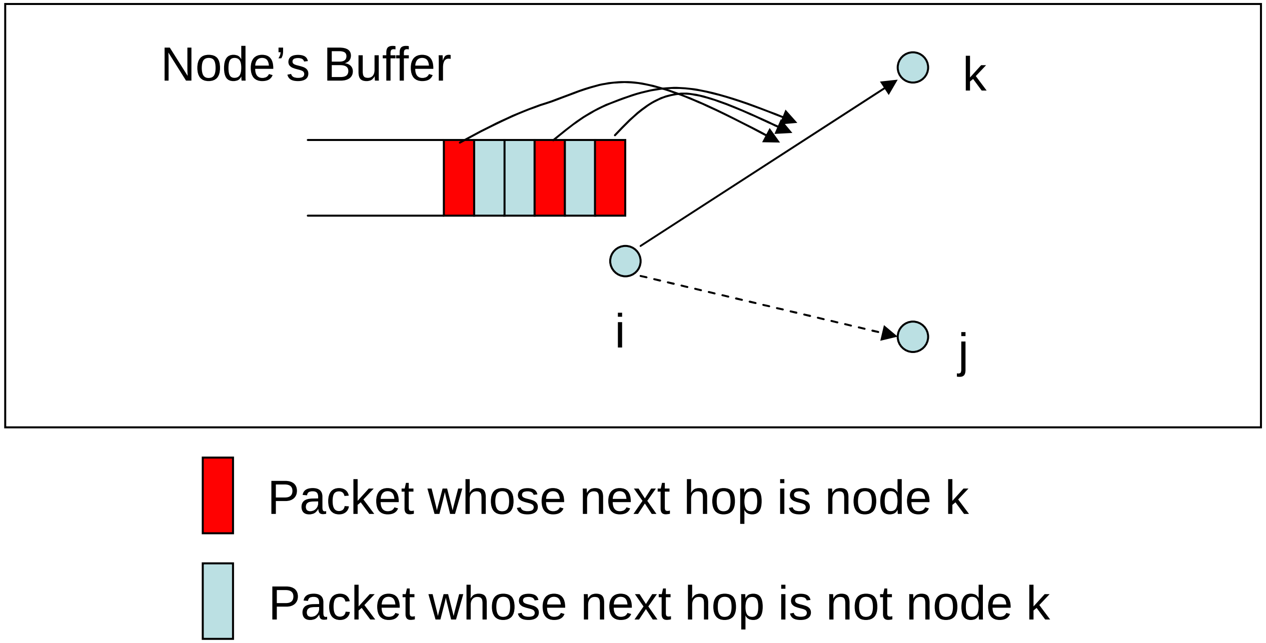


Illustration of the queue management

Energy consumption model

- A homogeneous scenario is considered where all nodes have the same transmission power and initial battery capacity (E_i)

$$E_{Tx} = E_{tx\_elec} + E_{amp} \approx P_{ti} \cdot T$$

$$E_{Rx} = E_{tx\_elec} = \tau \cdot E_r$$

- At a given time slot *n*, the remaining battery capacity (E_B^n) of a given node will be

$$\begin{cases} E_B^n = E_i, \ \ when \quad n = 0 \\ E_B^n = E_B^{n-1} - \Delta E^n, \ \ if \quad n \in 1,2,3\ldots \end{cases}$$

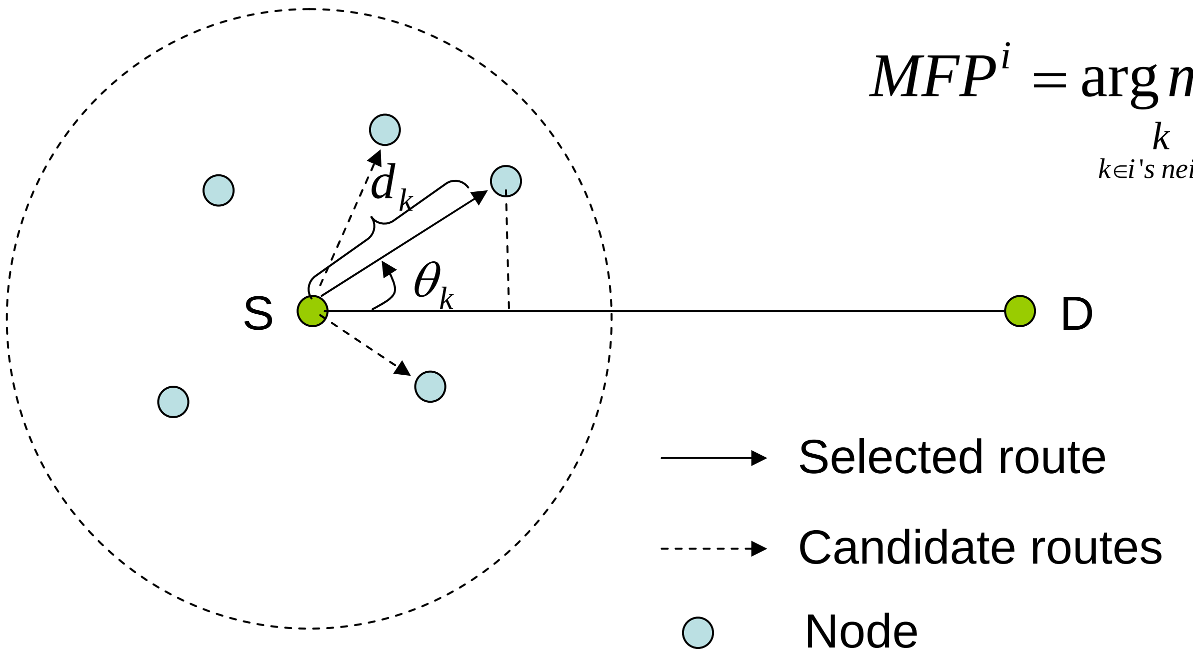
$$where \quad \Delta E^n = \delta_t^n \cdot E_{Tx} + \delta_r^n \cdot E_{Rx}$$

Overview of proposed routing metrics

- Maximum Forward Progress (MFP)
  - Motivated by Most Forward within radius R (MFR) [Takagi84]
  - Maximizes forward progress toward the destination
- Energy-aware Maximum Forward Progress (MFP_{energy})
  - Extension of MFP that considers battery capacity
- Maximum Information Progress (MIP)
  - Motivated by Information Efficiency [Subbarao00]
  - Considers link quality
- Energy-aware Maximum Information Progress (MIP_{energy})
  - Extension of MIP that considers battery capacity
  - Both energy-aware and link-adaptive

Routing metric - MFP

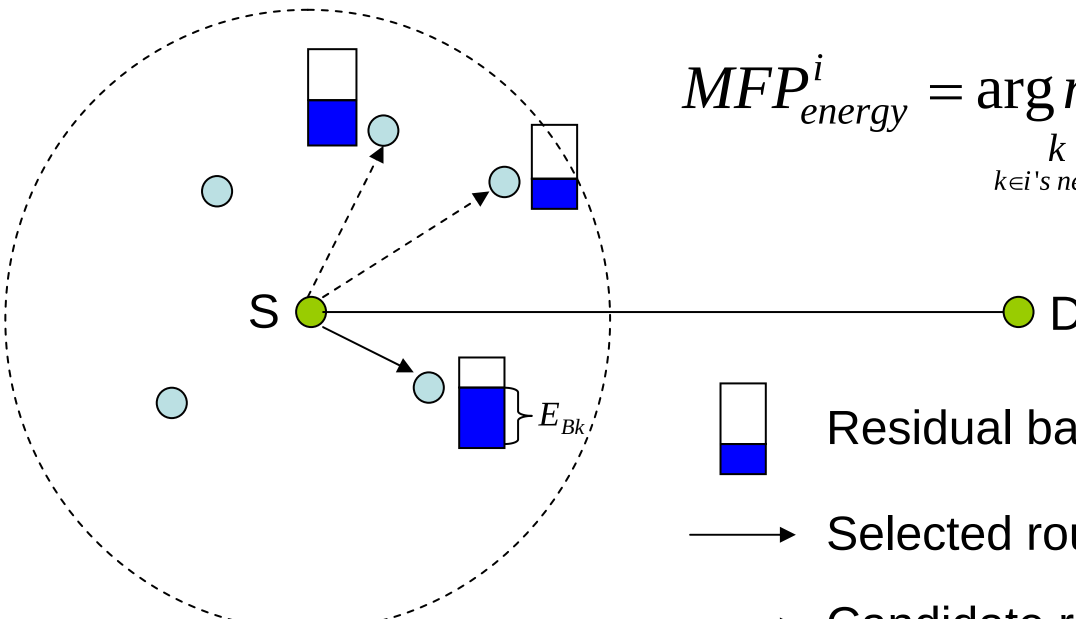
- Maximum Forward Progress (MFP)
  - Measures the one hop throughput in terms of forward progress in the direction to the final destination
  - Aims to minimize the total number of hops to the destination



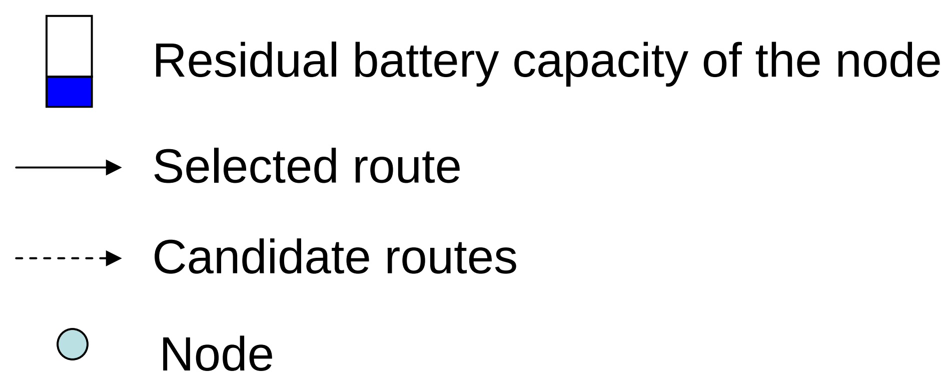
$$MFP^i = \underset{\substack{k \\ k \in i\text{'s neighbor}}}{\arg\max}\,(d_k \cdot \cos\theta_k)$$

Routing metric - MFP_{energy}

- Energy-aware Maximum Forward Progress (MFP_{energy})
  - Combine the neighbor node's remaining battery capacity with the forward progress of that node
  - Aims to extend the network lifetime while minimizing the total number of hops toward the destination



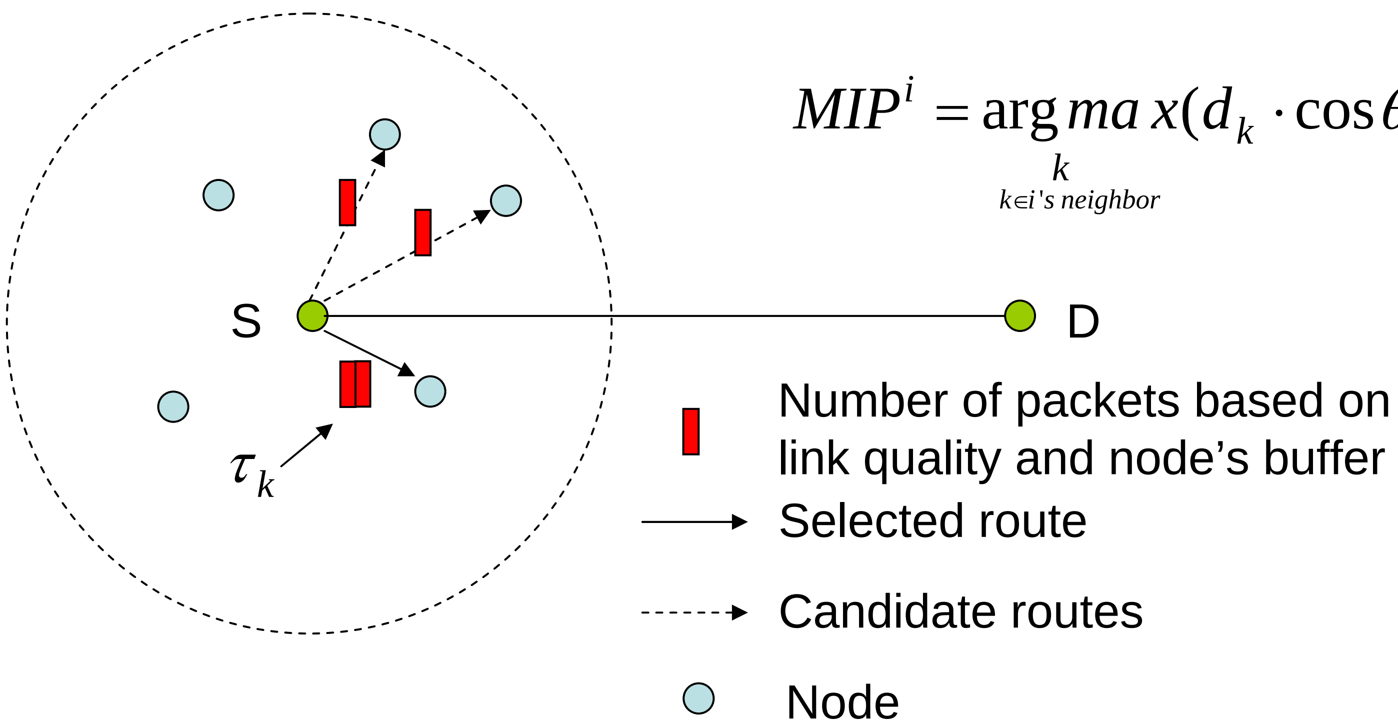
$$MFP^{i}_{energy} = \underset{k \in i\text{'s neighbor}}{\arg\max_{k}} (d_k \cdot \cos\theta_k \cdot E_{Bk})$$



Routing metric - MIP

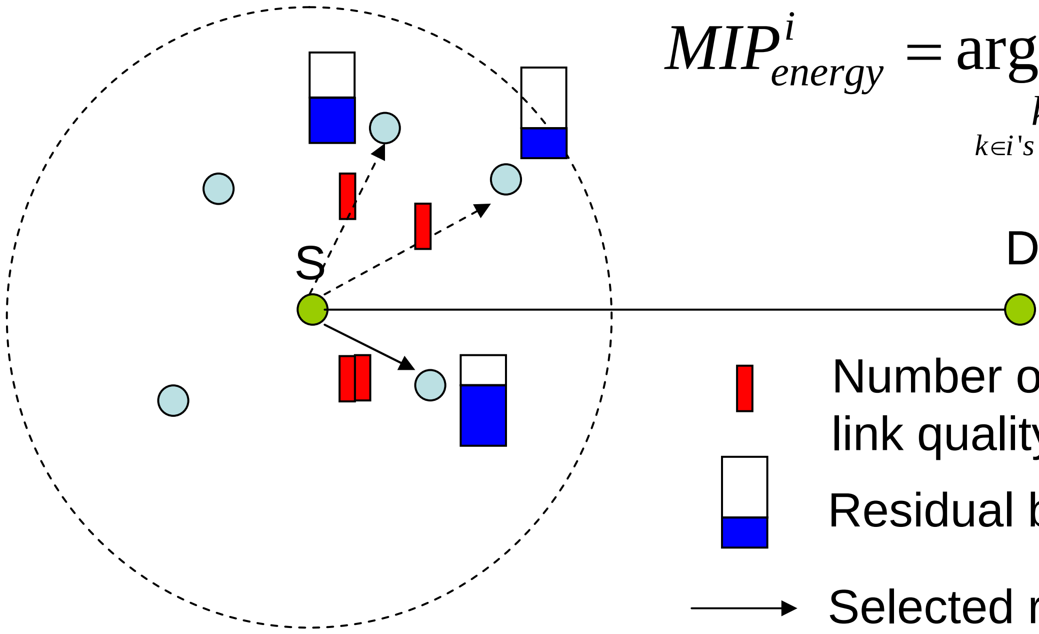
- Maximum Information Progress (MIP)
  - Adapts the number of transmitted packets to the link quality
  - Accelerates the delivery of the queued packets and provides increased system throughput and decreased end-to-end delay compared to MFP
  - Balance the achievable next hop transmission distance and spectral efficiency

$$MIP^i = \arg\max_{\substack{k \\ k \in i\text{'s neighbor}}} (d_k \cdot \cos\theta_k \cdot \tau_k)$$

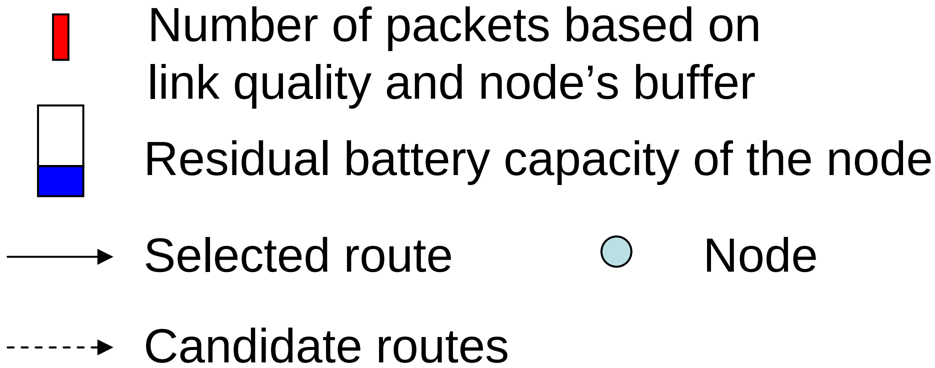


Routing metric - MIP_{energy}

- Energy-aware Maximum Information Progress (MIP_{energy})
  - Considers both the next hop remaining battery capacity and link quality in the routing decision
  - Energy-aware and link-adaptive



$$MIP^{i}_{energy} = \underset{k \in i\text{'s neighbor}}{\arg\max_k} (d_k \cdot \cos\theta_k \cdot \tau_k \cdot E_{Bk})$$



Routing schemes

- MFP metrics can apply fixed or adaptive modulation schemes
  - Nodes first select the next hop node based on the routing metrics
  - Then they apply fixed or adaptive modulation according to the availability of the link quality information before actual transmission
- MIP metrics must use adaptive modulation
  - Already take into account the link quality in the next hop route decision
- Six possible routing schemes

Routing scheme	Description
MFP-FM	Apply MFP metric with fixed modulation
MFP_{energy}-FM	Apply MFP_{energy} metric with fixed modulation
MFP-AM	Apply MFP metric with adaptive modulation
MFP_{energy}-AM	Apply MFP_{energy} metric with adaptive modulation
MIP-AM	Apply MIP metric with adaptive modulation
MIP_{energy}-AM	Apply MIP_{energy} metric with adaptive modulation

Simulation

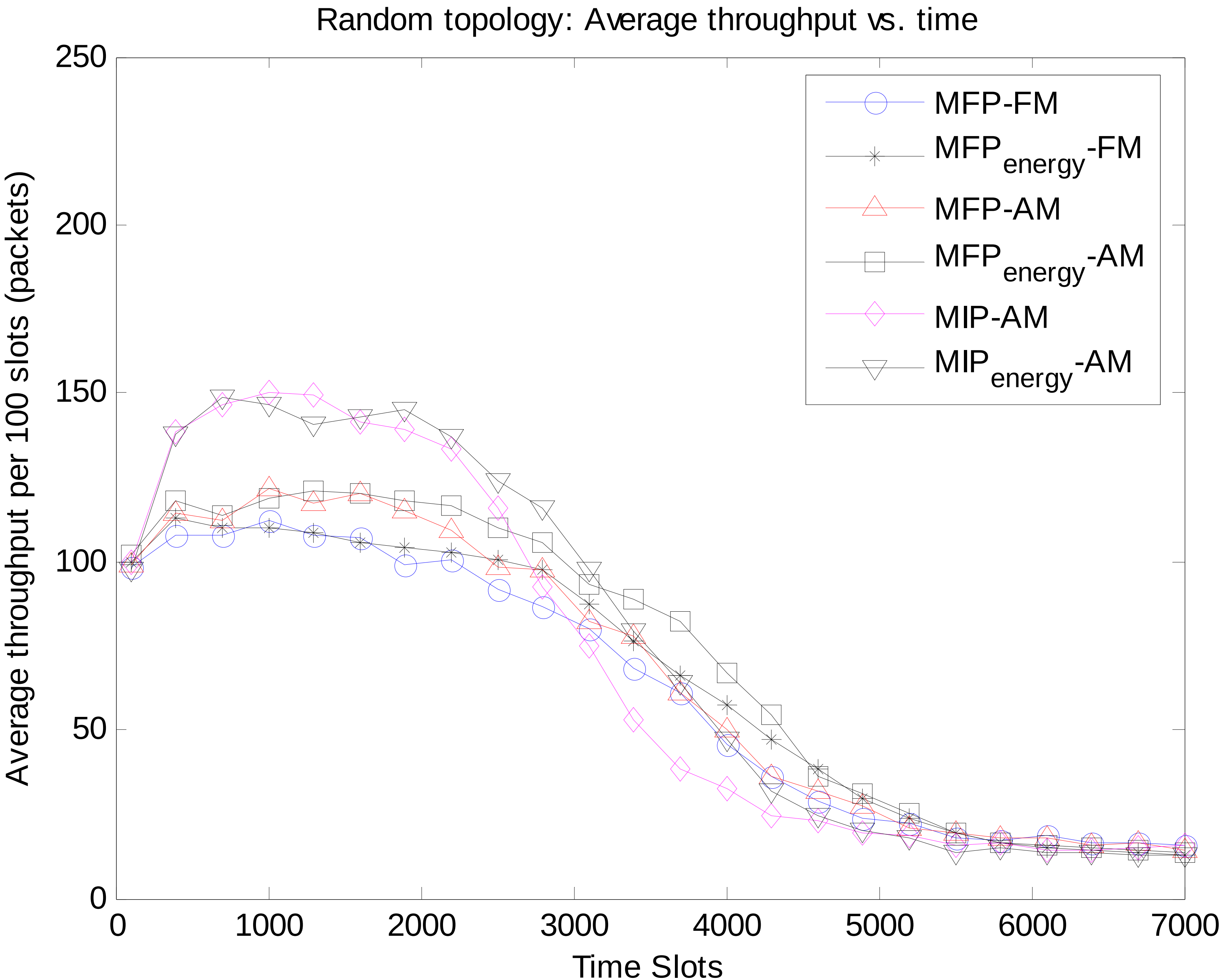
- A simulator based on the following parameters is designed to evaluate the performance of different routing metrics

TABLE II: Simulation Parameters

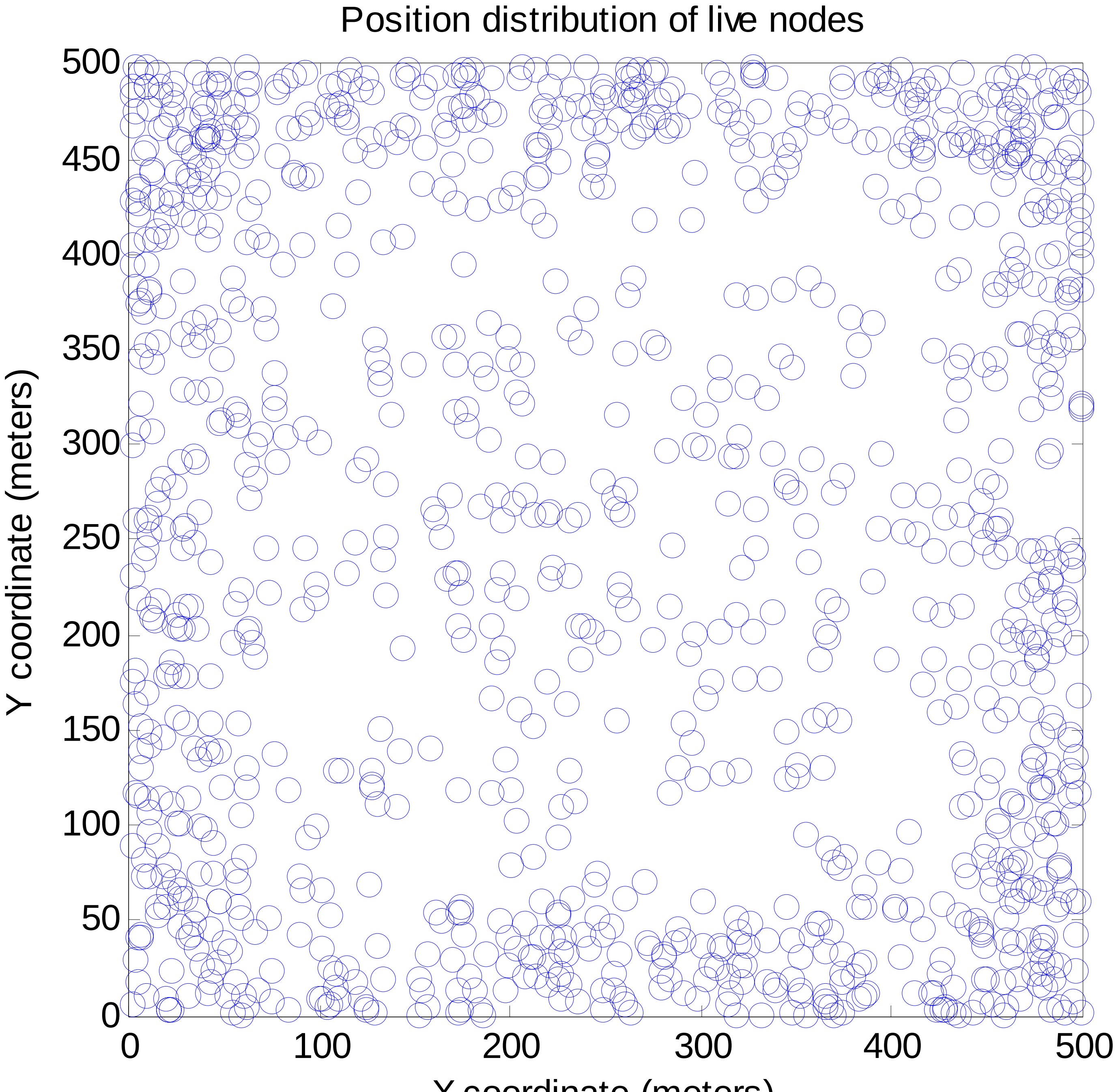
Parameter	**Value**
Area	$500 \times 500m^2$
Number of nodes	100
Pathloss exponent	2.61
Processing gain	750
Data rate	10 Mbps
E_b/N_o thresholds	[0.67, 2.25, 3.99, 5.94] dB for $[QPSK, 16QAM, 64QAM, 256QAM]$
Traffic generation rate	0.02 packets/slot/node
Simulation time	7000 time slots
Simulation realizations	20

Performance evaluation

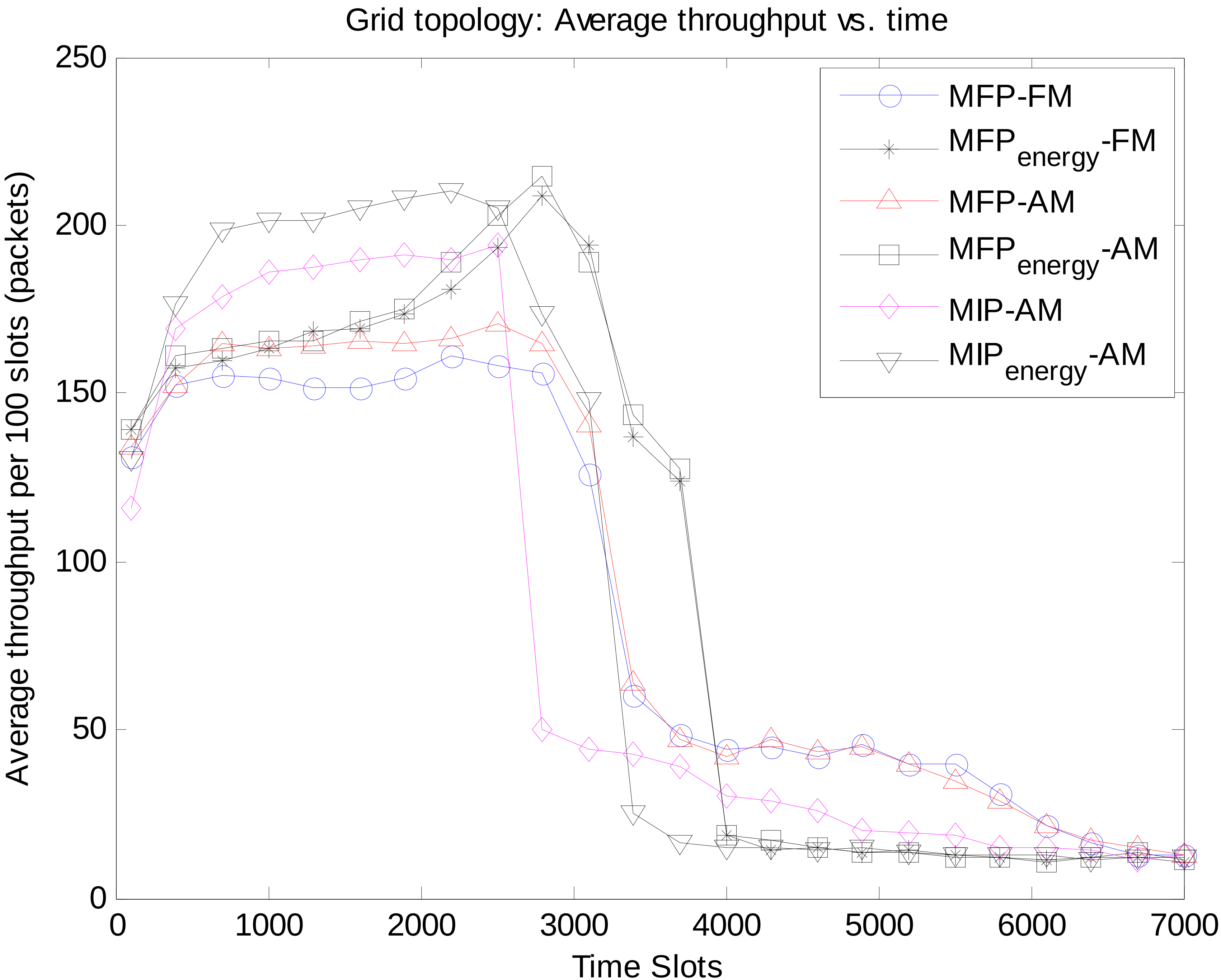
- The performance of the routing metrics is evaluated in terms of
  - Average throughput (averaged over a certain time interval, in our case 100 time slots)
  - Cumulative throughput
  - Average delay of received packets
  - Fraction of live nodes
- Additional scenarios considered
  - Mobility
  - Power control
  - Varying transmission range

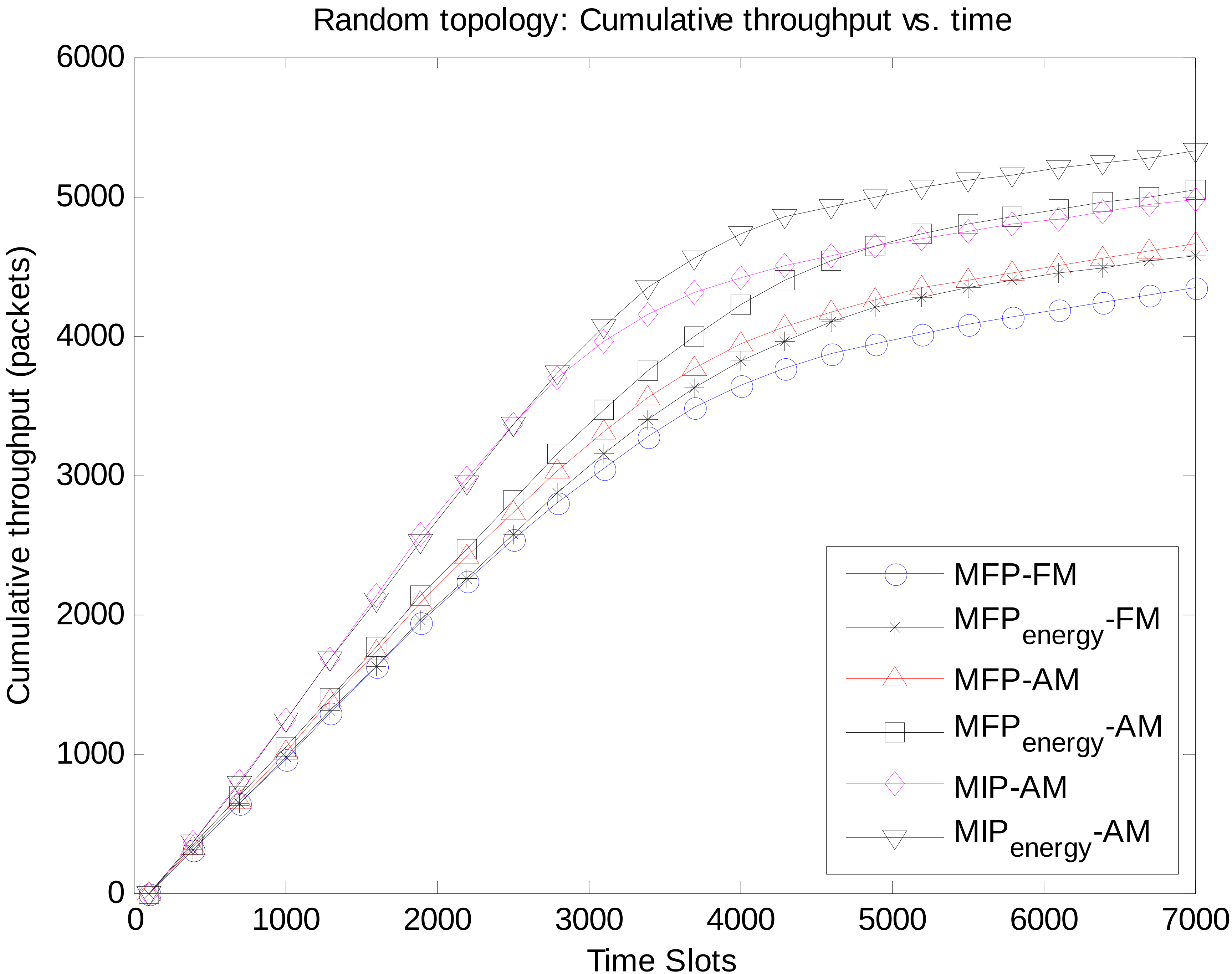


Random topology: Average throughput vs. time
Average throughput per 100 slots (packets)
Time Slots
0
50
100
150
200
250
0
1000
2000
3000
4000
5000
6000
7000
MFP-FM
MFP$_{energy}$-FM
MFP-AM
MFP$_{energy}$-AM
MIP-AM
MIP$_{energy}$-AM



Position distribution of live nodes
Y coordinate (meters)
X coordinate (meters)
0
50
100
150
200
250
300
350
400
450
500
0
100
200
300
400
500

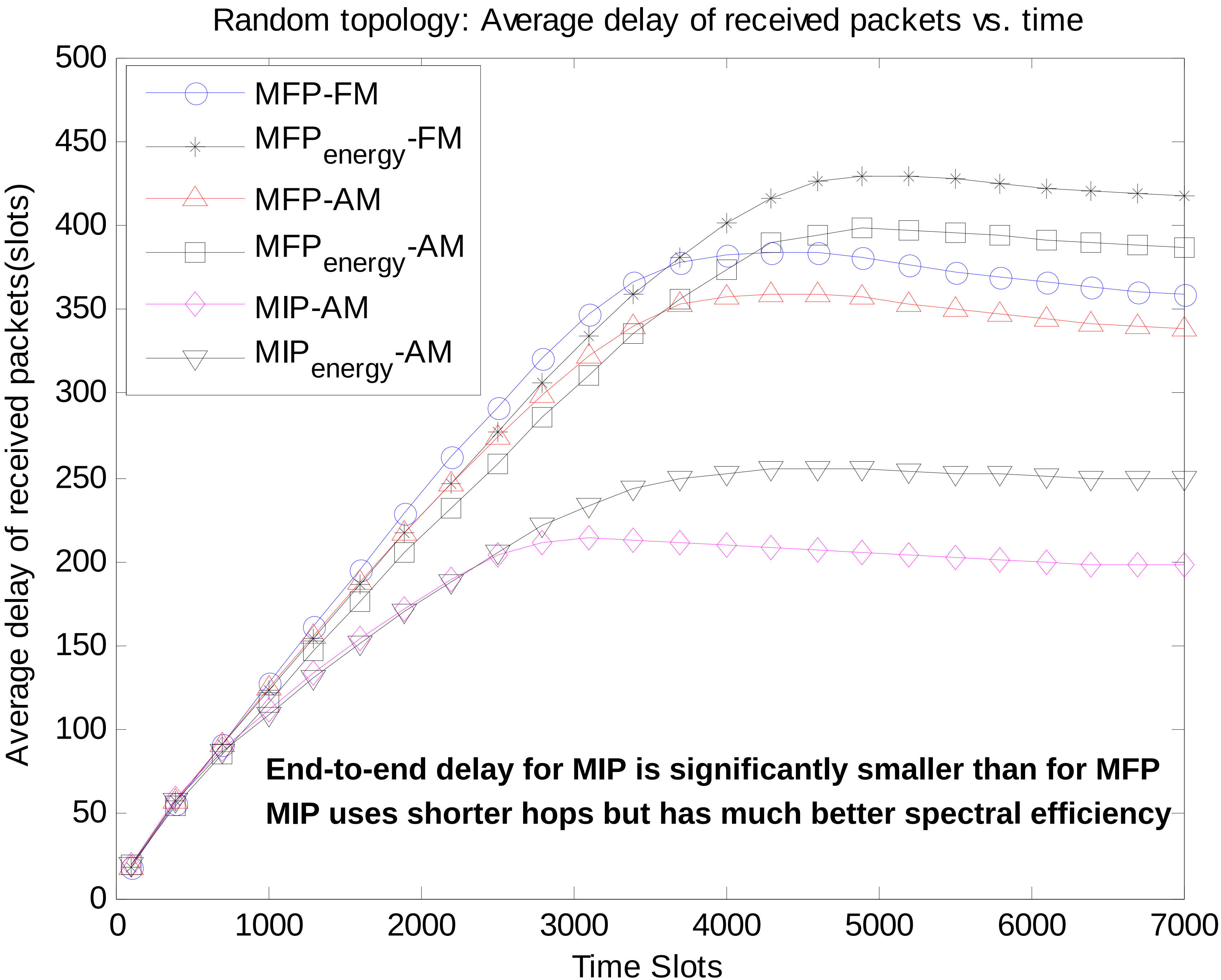

Grid topology: Average throughput vs. time
250
200
150
100
50
0
0
1000
2000
3000
4000
5000
6000
7000
Time Slots
Average throughput per 100 slots (packets)
MFP-FM
MFPenergy-FM
MFP-AM
MFPenergy-AM
MIP-AM
MIPenergy-AM



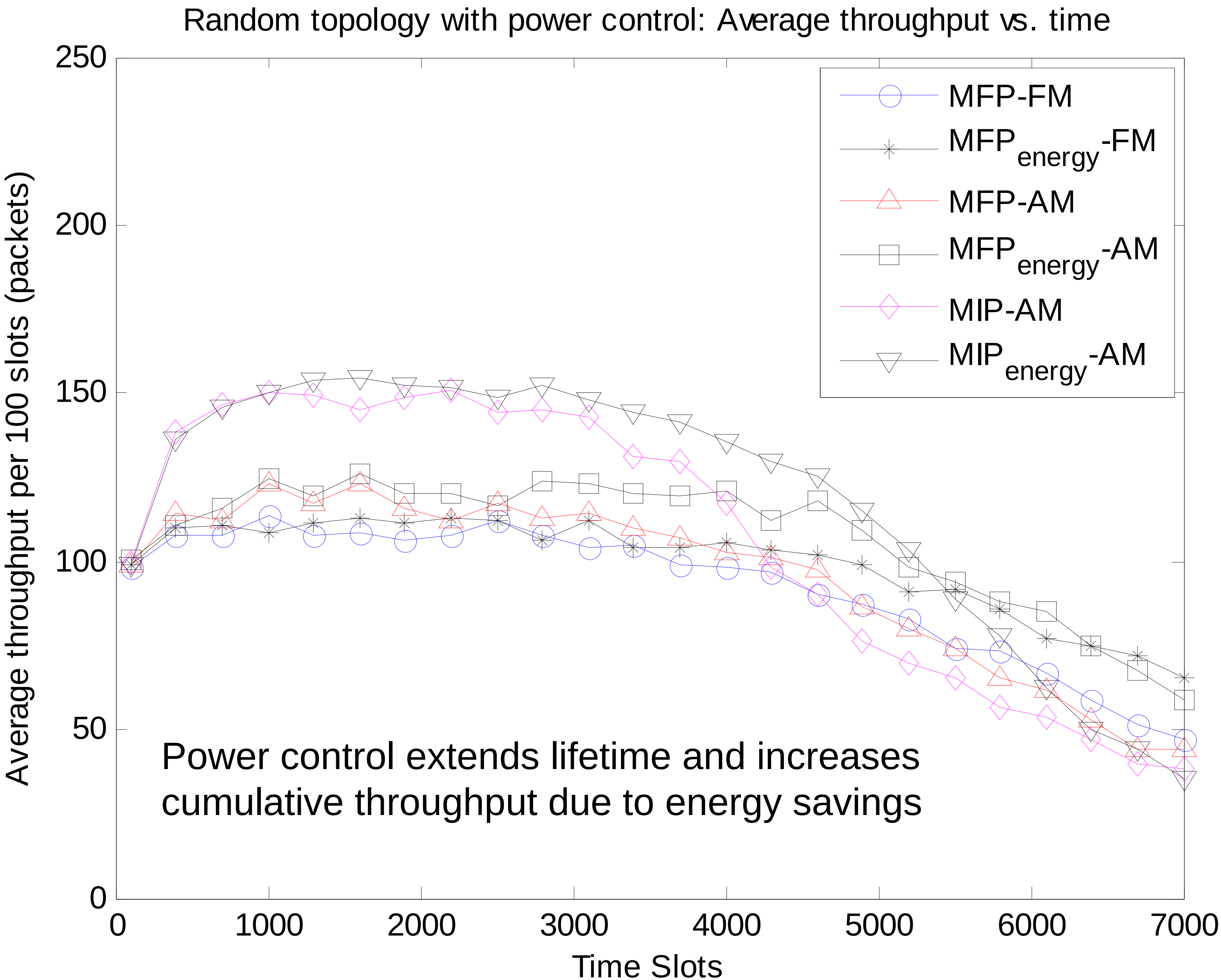
Random topology: Cumulative throughput vs. time
Cumulative throughput (packets)
Time Slots
0
1000
2000
3000
4000
5000
6000
7000
MFP-FM
MFP$_{energy}$-FM
MFP-AM
MFP$_{energy}$-AM
MIP-AM
MIP$_{energy}$-AM

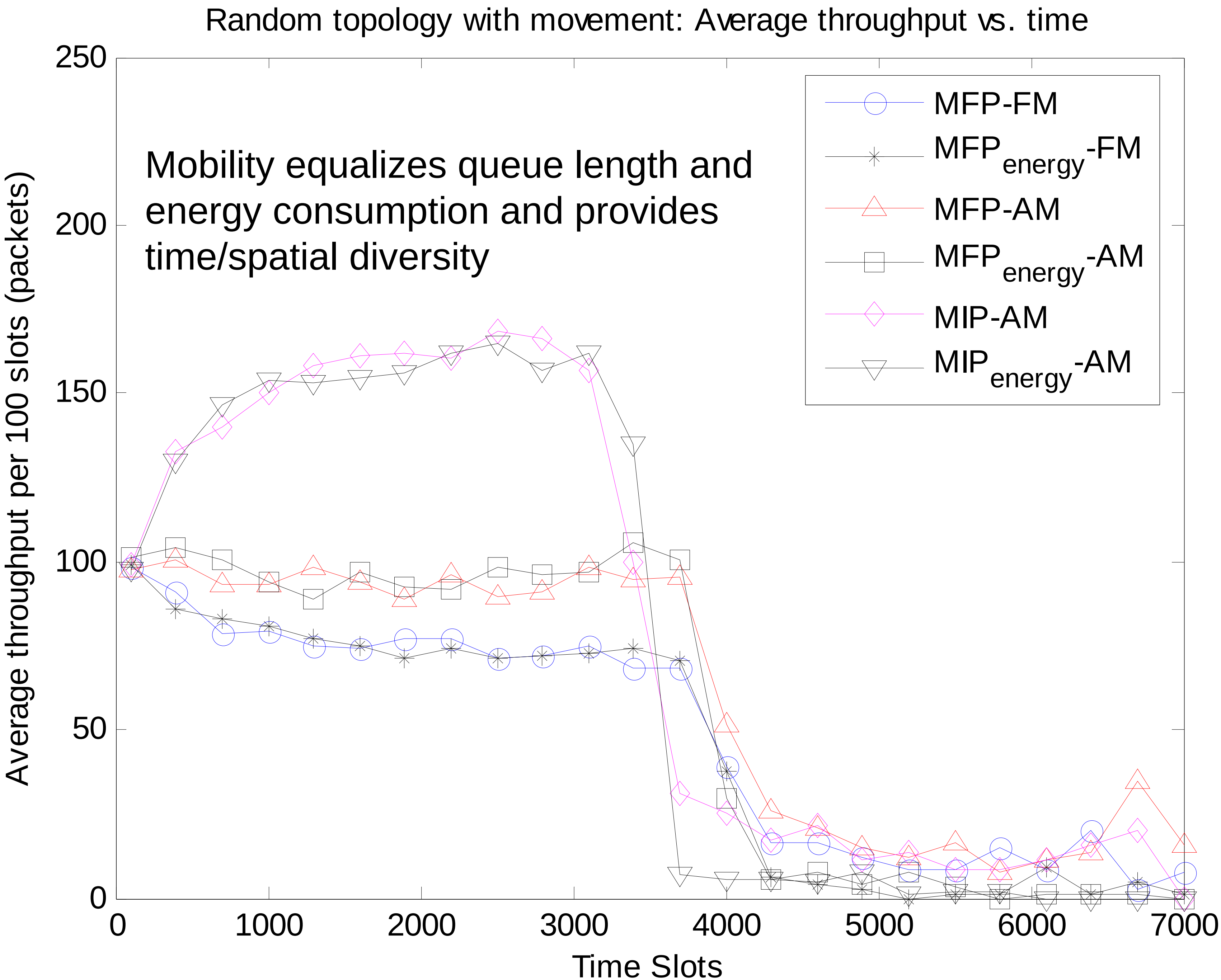
Observations

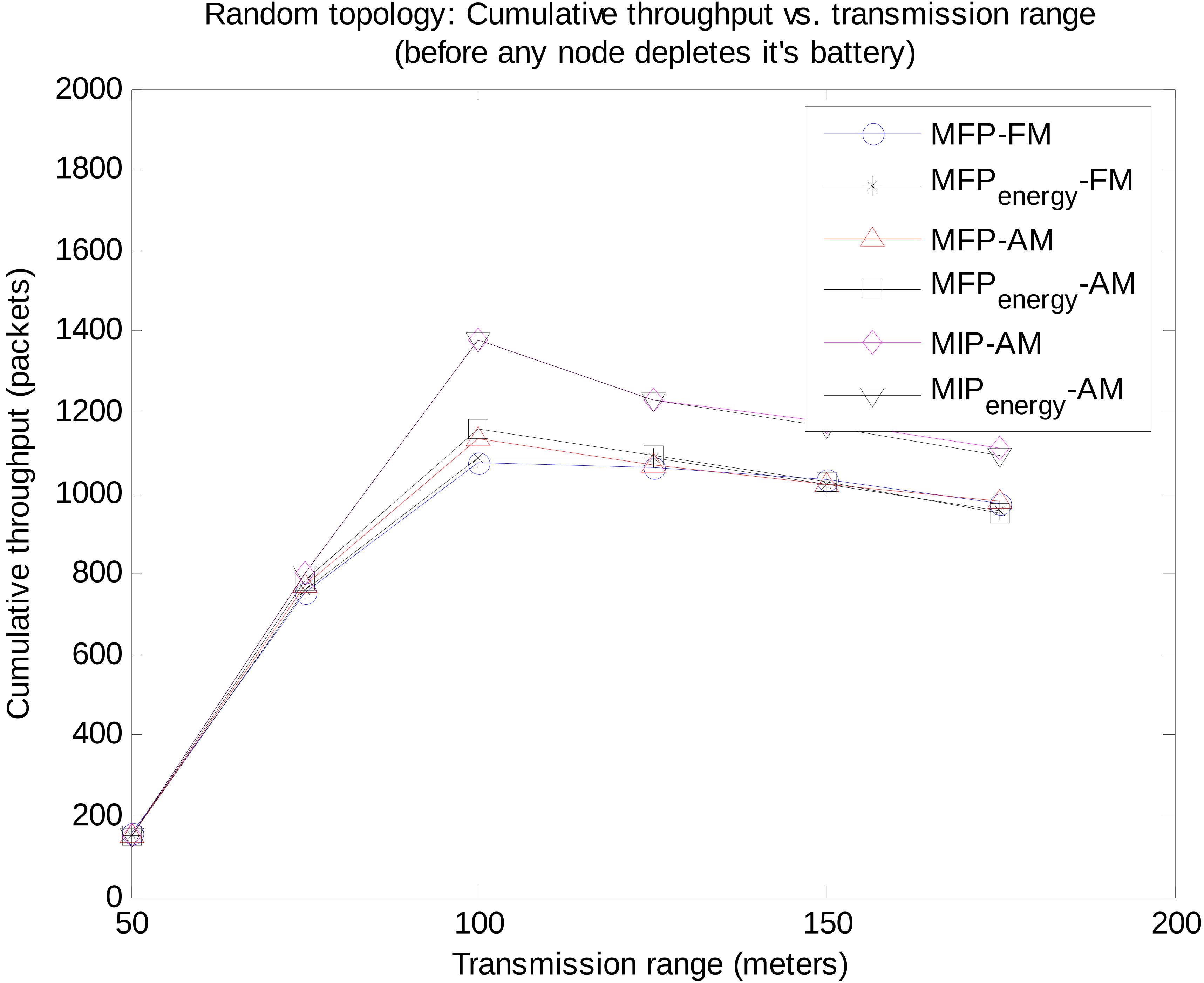
- Both random and grid topologies
  - MIP outperforms MFP considerably (30-50%) in terms of throughput, before network begins to deteriorate
  - Energy-aware metrics slightly improve throughput
  - Energy-aware routing metrics postpone the point of network deterioration
- Grid topology
  - 30-50% higher throughput than random topology due to better network connectivity
  - Steeper throughput deterioration than random topology due to abrupt loss of connectivity



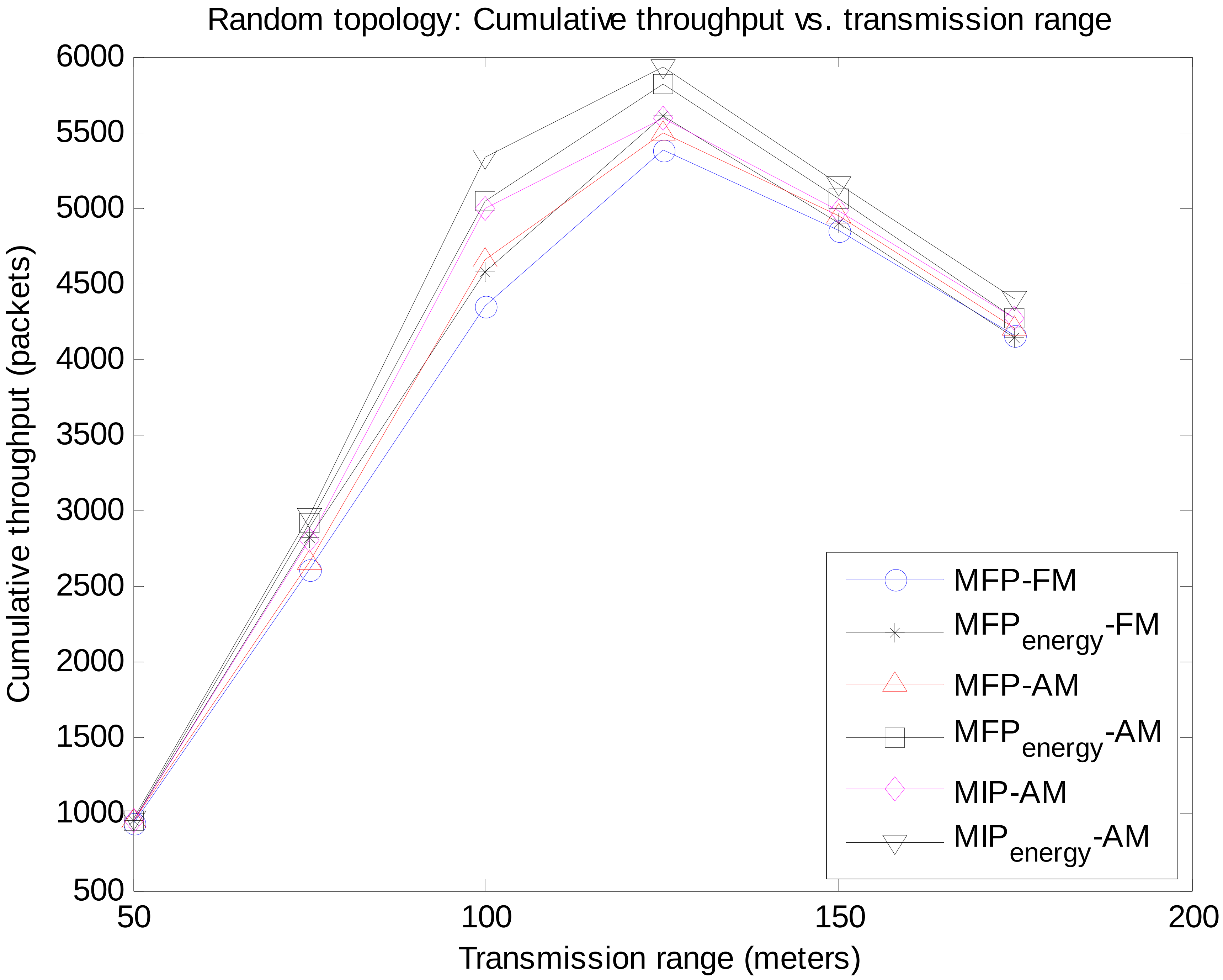
Random topology: Average delay of received packets vs. time
MFP-FM
MFP energy -FM
MFP-AM
MFP energy -AM
MIP-AM
MIP energy -AM
End-to-end delay for MIP is significantly smaller than for MFP
MIP uses shorter hops but has much better spectral efficiency
Average delay of received packets(slots)
Time Slots
0
50
100
150
200
250
300
350
400
450
500
0
1000
2000
3000
4000
5000
6000
7000


Random topology with power control: Average throughput vs. time
Average throughput per 100 slots (packets)
Time Slots
0
50
100
150
200
250
0
1000
2000
3000
4000
5000
6000
7000
MFP-FM
MFP$_{energy}$-FM
MFP-AM
MFP$_{energy}$-AM
MIP-AM
MIP$_{energy}$-AM
Power control extends lifetime and increases cumulative throughput due to energy savings


Random topology with movement: Average throughput vs. time
Mobility equalizes queue length and energy consumption and provides time/spatial diversity
MFP-FM
MFP$_{energy}$-FM
MFP-AM
MFP$_{energy}$-AM
MIP-AM
MIP$_{energy}$-AM
Average throughput per 100 slots (packets)
Time Slots
0
50
100
150
200
250
1000
2000
3000
4000
5000
6000
7000



Random topology: Cumulative throughput vs. transmission range
(before any node depletes it's battery)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
50
100
150
200
Cumulative throughput (packets)
Transmission range (meters)
MFP-FM
MFP$_{energy}$-FM
MFP-AM
MFP$_{energy}$-AM
MIP-AM
MIP$_{energy}$-AM


Random topology: Cumulative throughput vs. transmission range
Cumulative throughput (packets)
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
50
100
150
200
Transmission range (meters)
MFP-FM
MFPenergy-FM
MFP-AM
MFPenergy-AM
MIP-AM
MIPenergy-AM

Conclusions

- By considering the link quality in the corresponding routing metrics, the inherent spatial diversity of the multi-hop network is efficiently exploited
- Additionally, taking into account the nodes residual battery capacity results in extended network lifetime
- The grid topology has better throughput performance than the random topology due to better network connectivity
- End-to-end delay for MIP is significantly improved over MFP because MIP has much better spectral efficiency
- Power control extends lifetime and increases cumulative throughput due to energy savings
- Mobility equalizes node's queue length and energy consumption, and provides time-spatial diversity
- There exists an optimal transmission range for nodes in terms of network performance which corresponds to10-12 neighbor nodes

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