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Analysis, Comparison, and Optimization of Routing Protocols for Energy Harvesting WSNs

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joint work with

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NCCR MICS
National Competence Center in Research
Mobile Information and Communication Systems

FNSNF
Fonds national suisse
Schweizerischer Nationalfonds
Fondo nazionale svizzero
Swiss National Science Foundation

What is energy harvesting?

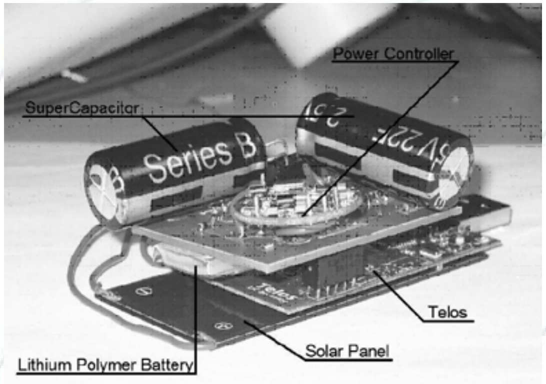
Hydro-electric power

Solar power

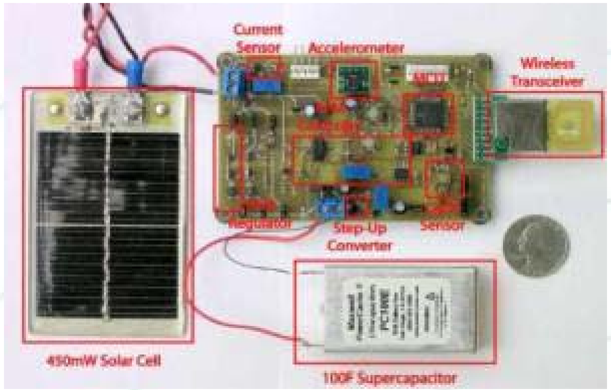
Wind power

Energy harvesting wireless sensor platforms

[Prometheus: Culler]

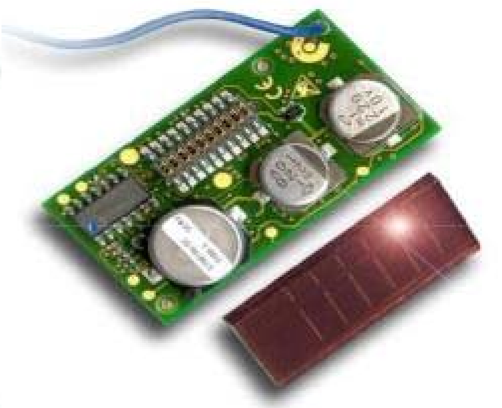


[Everlast: Simjee, Chou]

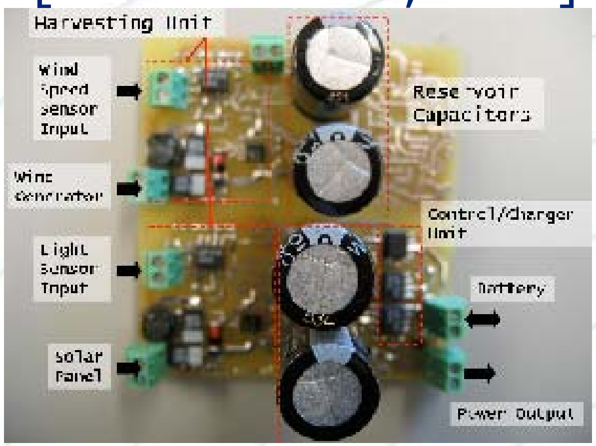


[Heliomote: Srivastava]

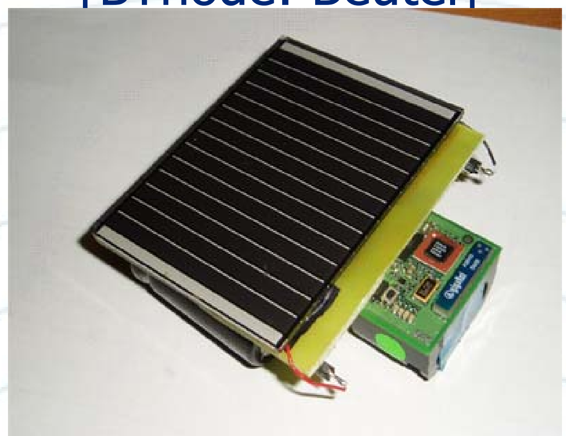
[STM100: enocean.com]



[AmbiMax: Park, Chou]

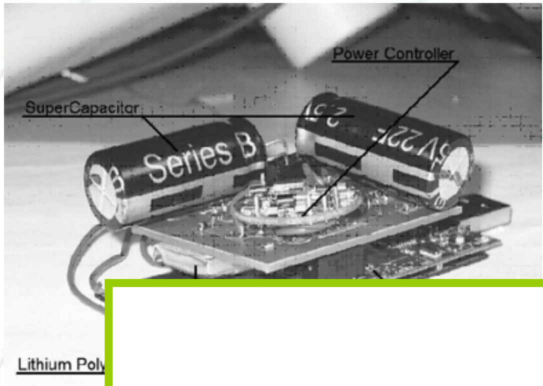


[BTnode: Beutel]



Energy harvesting wireless sensor platforms

[Prometheus: Culler]



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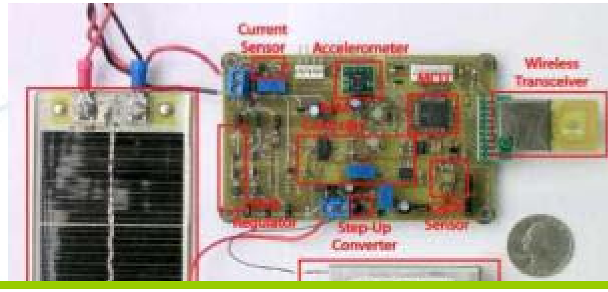
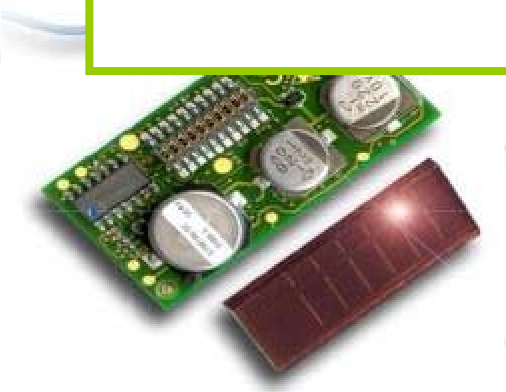
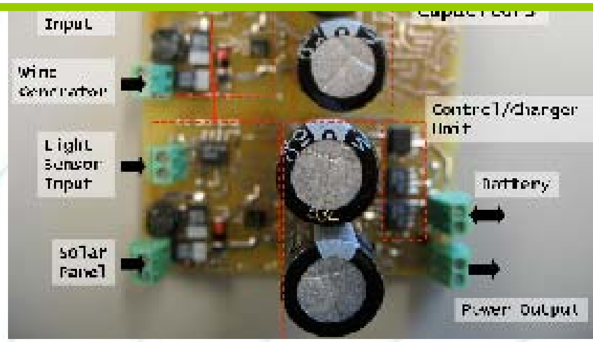


[Heliomote: Srivastava]

What is the challenge when routing with energy-harvesting systems?

[STM





eutel]

Energy-aware routing in sensor networks

- Energy-aware routing in battery-operated networks
  - Maximize network lifetime under given workload
  - Distribute the workload as uniform as possible

- Energy-aware routing in energy-harvesting networks
  - Maximize workload under environmental constraints
  - Favor nodes that harvest the most environmental power

Routing algorithms for energy-harvesting WSNs

- Random Max-Flow (R-MF)
  - A. Bogliolo, E. Lattanzi, and A. Acquaviva. Energetic sustainability of environmentally powered wireless sensor networks. In PE-WASUN ’06.
- Energy-opportunistic Weighted Minimum Energy (E-WME)
  - L. Lin, N. B. Shroff, and R. Srikant. *Asymptotically optimal energy-aware routing for multihop wireless networks with renewable energy sources. IEEE/ACM Trans.* Netw., 15(5):1021–1034, 2007.
- Randomized Minimum Path Recovery Time (R-MPRT)
  - E. Lattanzi, E. Regini, A. Acquaviva, and A. Bogliolo. Energetic sustainability of routing algorithms for energy-harvesting wireless sensor networks. Comput. Commun., 30(14-15):2976–2986, 2007.

Motivation

- Existing routing algorithms for energy-harvesting networks make idealized assumptions:
  - Ideal Medium Access Control (MAC)
  - Lossless wireless channel
  - Global knowledge

- What is the impact of realistic assumptions?
  - Real low-power duty-cycling MAC protocol
  - Random packet loss due to interference (internal and external)
  - Knowledge is not for free

Random max-flow (R-MF)

- Every edge is assigned a capacity

$$\text{capacity} = \frac{\text{harvesting rate of the transmitter}}{\text{packet energy}}$$

- Extended Ford-Fulkerson algorithm is used to calculate the node-constrained maximum flow
  - Probability of selecting an edge is proportional to the flow through that edge
- The algorithm requires global knowledge of the network
  - Network topology and harvesting rate of all nodes
  - Static routing tables at each node represent the optimal flow distribution

Energy-opportunistic weighted minimum energy (E-WME)

- Shortest path routing with respect to the node cost
  - Path recalculated at each node
- Each node is annotated with a cost depending on
  - Available energy
  - Battery capacity
  - Harvesting rate
  - Reception and transmission energy
- The algorithm requires local knowledge of the network
  - Path costs (shortest path) of all neighboring nodes
  - Dynamic routing tables

Randomized minimum path recovery time (R-MPRT)

- Similar to E-WME but with a much simpler cost metric
- Every edge has a cost (inverse to R-MF's capacity)

$$\text{cost} = \frac{\text{packet energy}}{\text{harvesting rate of the transmitter}}$$

- Sensor calculates shortest path through all its edges
  - Probability of sending packet on a path is inverse proportional to the path cost
- The algorithm requires local knowledge of the network
  - Path cost to the sink for all neighboring nodes (equal to R-MRT)
  - Routing tables are dynamic

We modified R-MPRT using another cost metric

- Original version: R-MPRT-orig

$$\text{cost} = \frac{\text{packet energy}}{\text{harvesting rate of the transmitter}}$$

- Modified version: R-MPRT-mod

$$\text{cost} = \frac{\text{packet energy}}{\text{available energy at the transmitter}}$$

- Note: our modified metric does not directly consider the harvesting rate

Evaluation: Simulation in Castalia 2.2

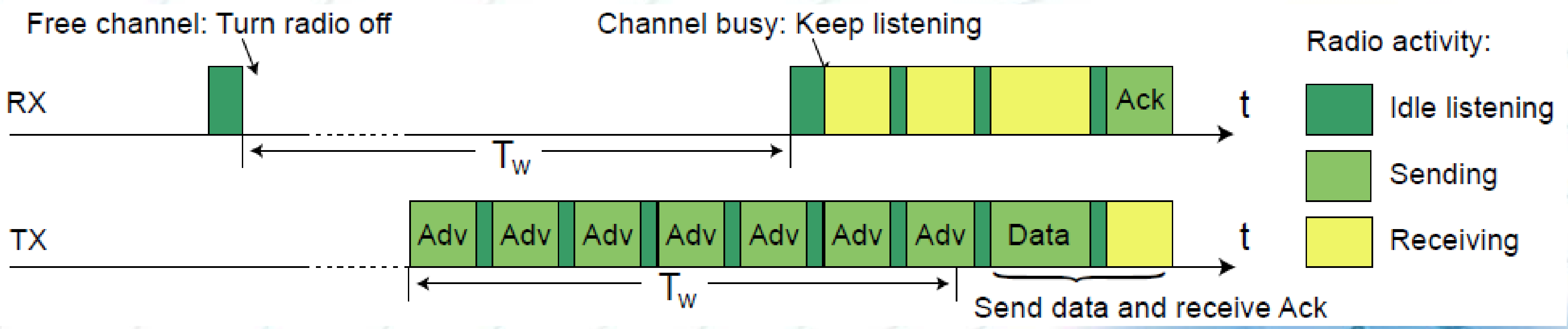
- Castalia: State of the art WSN simulator
  - Based on OMNet++
  - Advanced channel model based on empirically measured data
  - Radio model based on real low-power radios (timing, energy)
  - Node clock drift, CPU power consumption
- Simulation in a 100-node network
  - One sink node with unlimited power supply
  - Nodes have a 100 joule battery
  - 1 joule initial charge for sending the first few packets
  - Average harvesting rate: 0.95 mW
- Sensor nodes vs. routing nodes
  - 81 nodes inject (sample) data: injection rate ψ = [50, 1000] s
  - 18 routers forward data only

Metrics

- Packets can only be forwarded if the sender and receiver have sufficient energy to operate the radio
  - The packet loss is therefore well suited as a performance metric
- Average packet loss
  - Total number of lost packets divided by the total number of generated packets by all sensors
- Worst-case packet loss
  - Highest number of lost packets originating from a single sensor divided by the number of generated packets of the sensor
  - The worst-case packet loss reflects fairness
- Sustainable rate: less than 1% packet loss

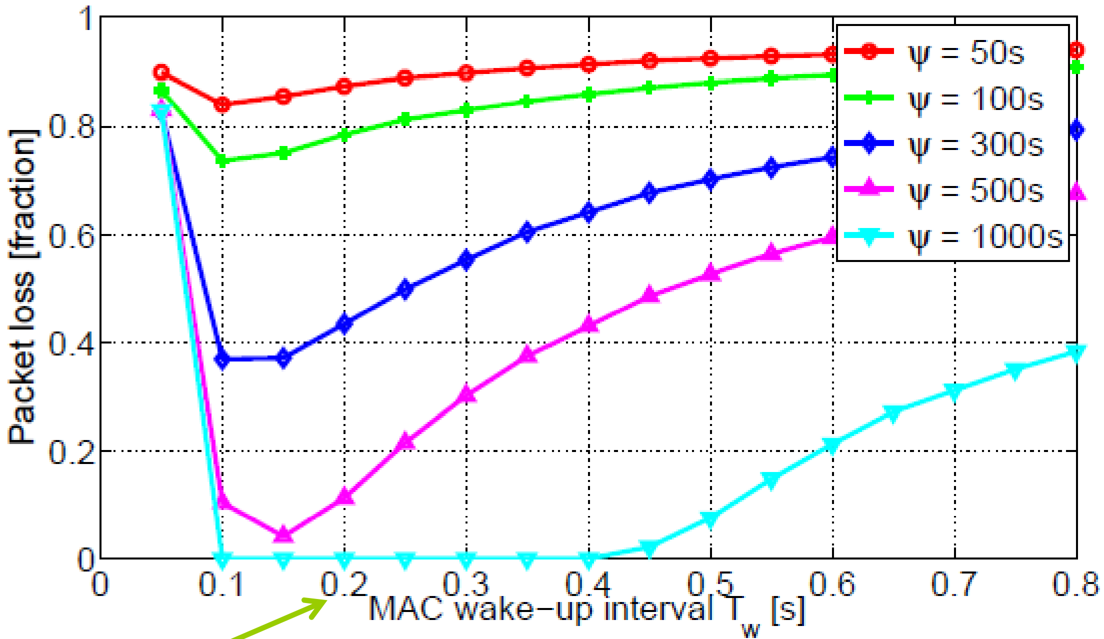
Influence of MAC protocol

- Random-access protocols are well suited
  - No expensive arbitration (and initialization) is required
  - SpeckMAC sends a packet-based preamble (minimizes overhearing)
- SpeckMAC:
  - The sender sends a long stream (length T_W) of advertisement packets followed by the data packet
  - Receiver wakes-up every T_{W}. The node keeps listening if the channel is busy and the advertisement indicate a packet for it



Evaluation: Influence of MAC parameter setting

- SpeckMAC main parameter is the wake-up interval T_w
- Depending on the data rate ψ an optimal parameter setting can be determined



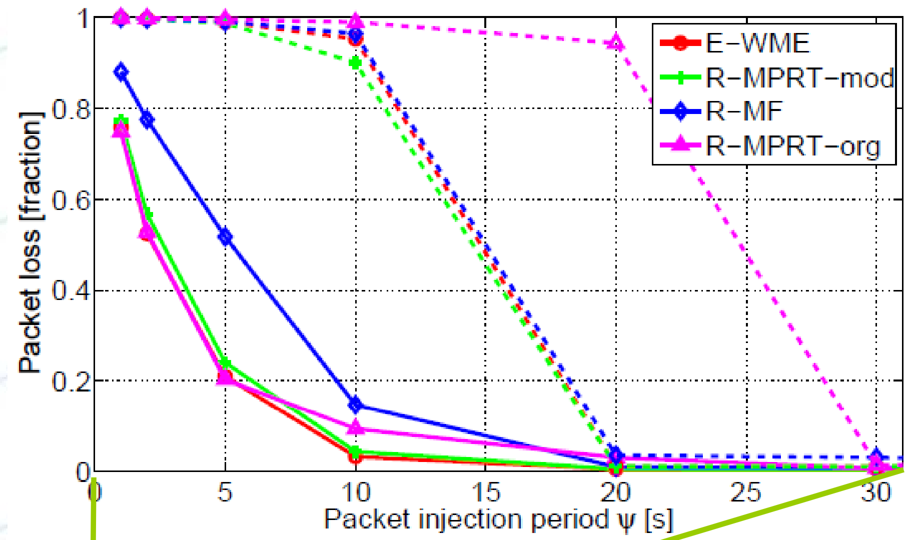
E-WME

A T_w = 0.2 s is well suited for a large range of data rates

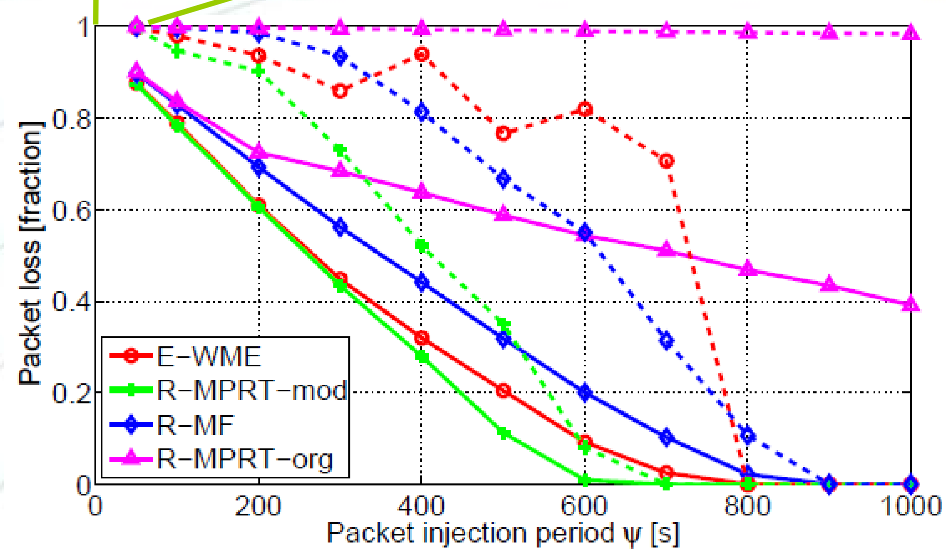
Ideal MAC vs. real MAC

- Ideal MAC protocol
  - Sustainable rate: ψ = 20 s
- SpeckMAC
  - Sustainable rate: ψ ≈ 800 s
- Idealistic MAC is 40 times more efficient
  - Potentially misleading

Ideal MAC protocol



SpeckMAC protocol



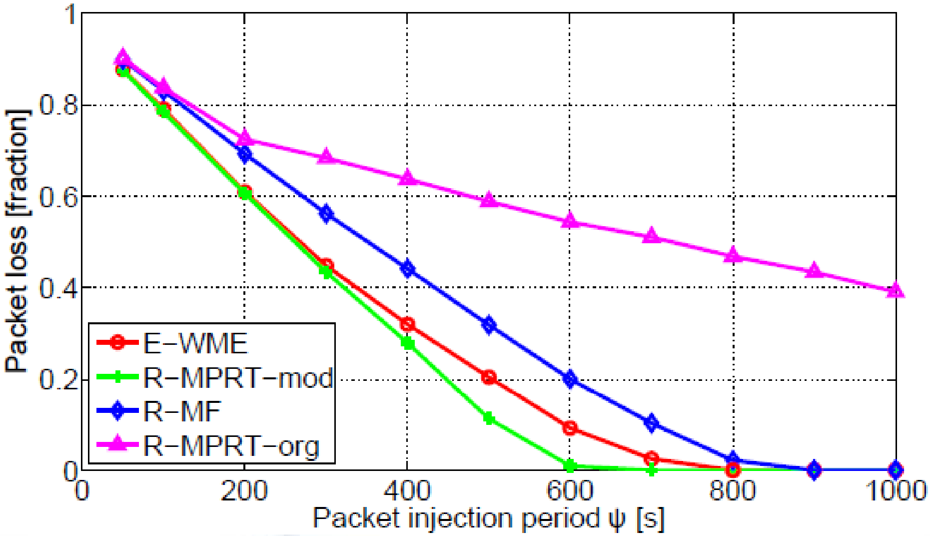
———	Average packet loss
- - - -	Worst-case packet loss

Comparing protocols using real MAC protocol

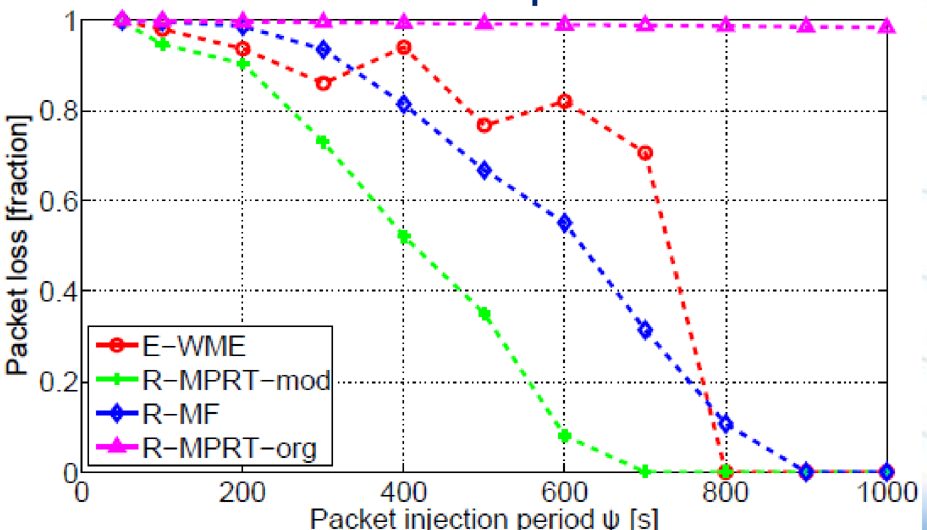
- Our R-MPRT outperforms remaining protocols
  - For both average and worst-case packet loss
  - For data rates ψ=[600,800]s: The worst-case packet loss of R-MPRT-mod is less than the average for the other protocols

- The original R-MPRT has a very high packet loss
  - R-MPRT-org is not further considered

Average packet loss



Worst-case packet loss



Routing protocol overhead

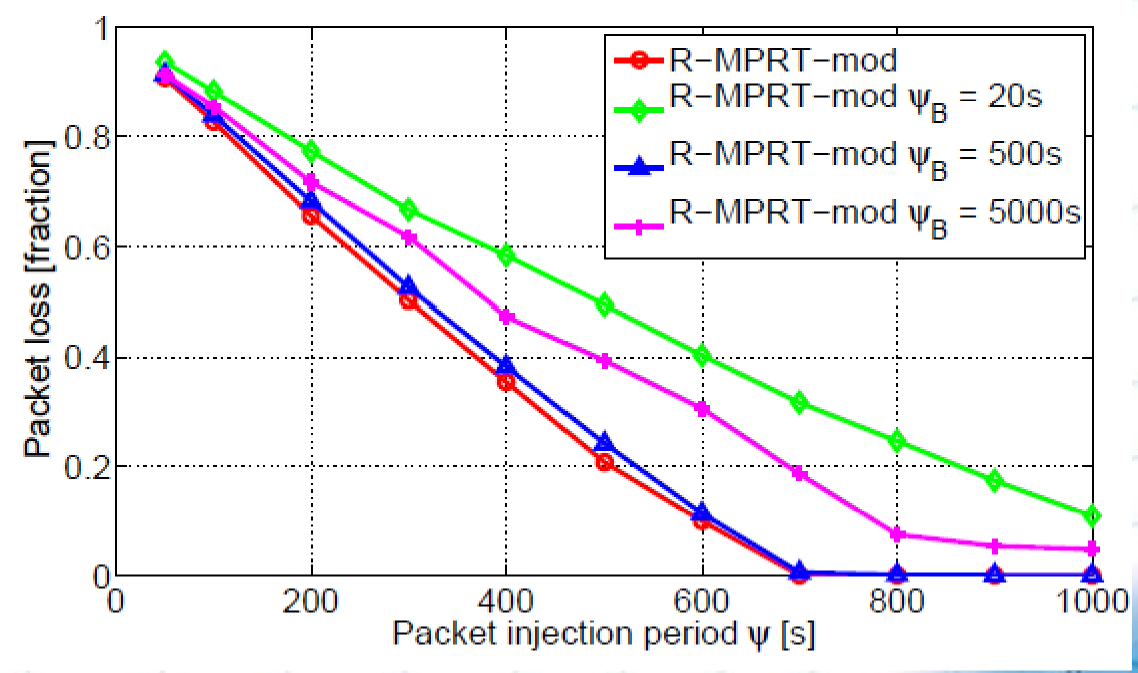
- Protocols are often evaluated making the idealistic assumption that global or local knowledge is available
- R-MF: Network topology and harvesting rate of all nodes
  - This information is almost impossible to get
  - R-MF is therefore not further considered
- E-WME/R-MPRT: Path costs of all neighboring nodes
  - This information can be obtained sending regular beacons

What is the impact if regular beacons are necessary for obtaining the routing information?

Routing protocol overhead for R-MPRT-mod

- The optimal beacon period shows a similar packet loss than having local knowledge for free

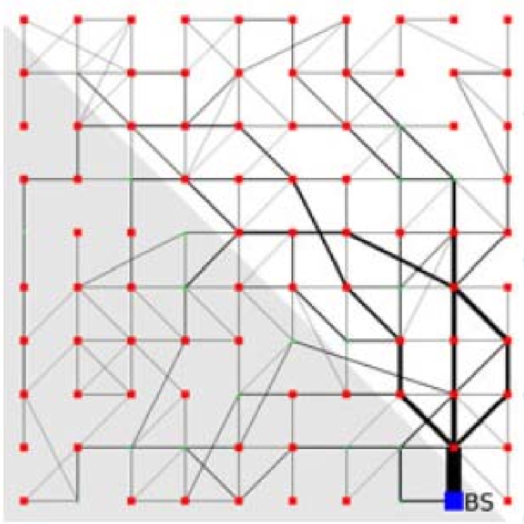
- Misconfiguration of the beacons interval ψ_B
  - Too few beacons: neighbor information gets outdated
  - Too many beacons: beacons hardly provide updated information



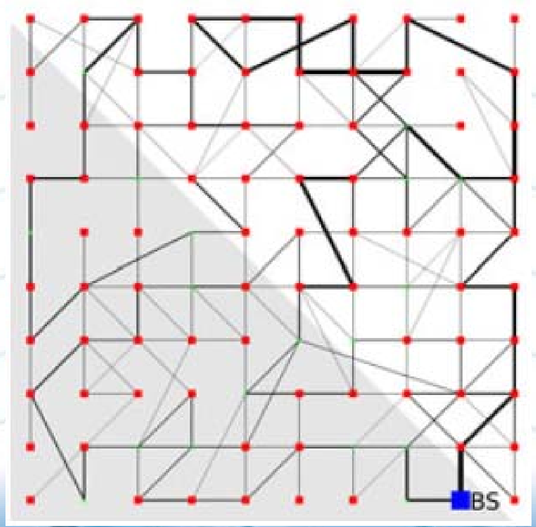
Non-uniform harvesting rates

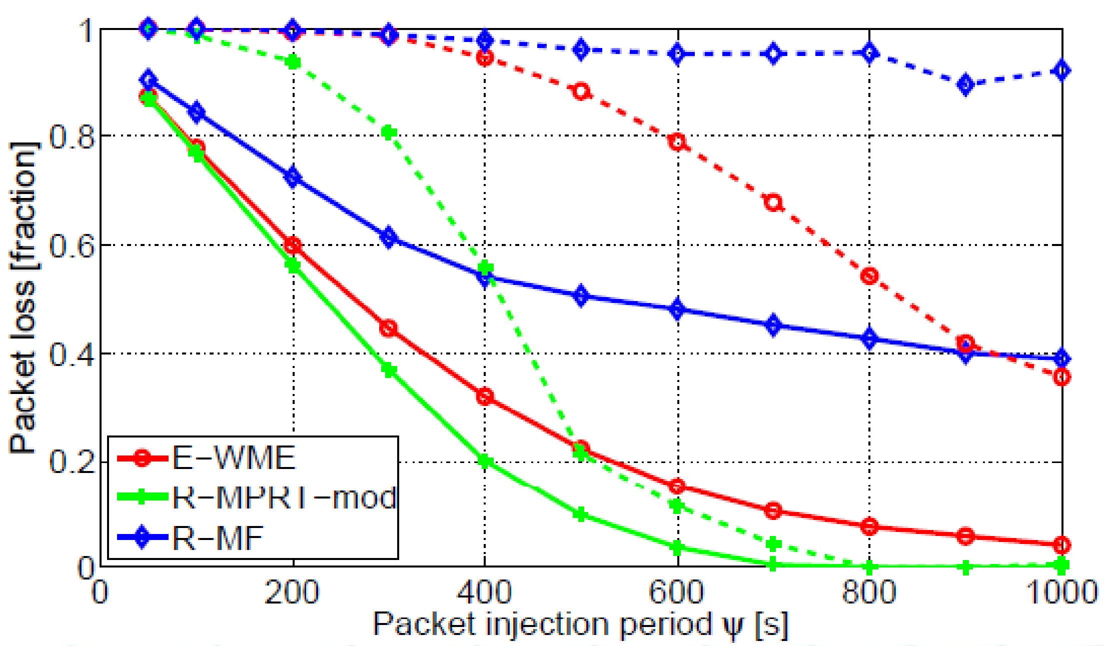
- Half of the nodes have a lower harvesting rate (dark shade)
- R-MPRT-mod prefers routes in the bright triangle (similar for E-WME)
- The static routing tree of R-MF shows is rather erratic

R-MPRT-mod



R-MF

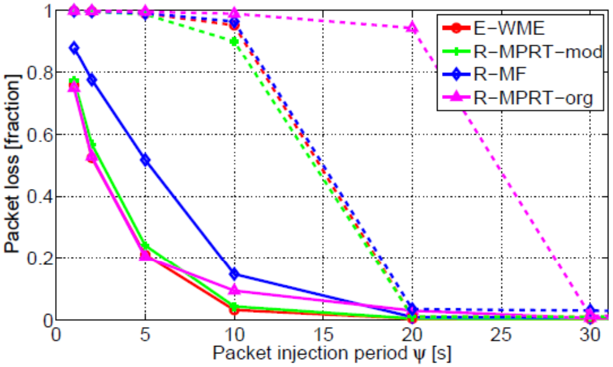




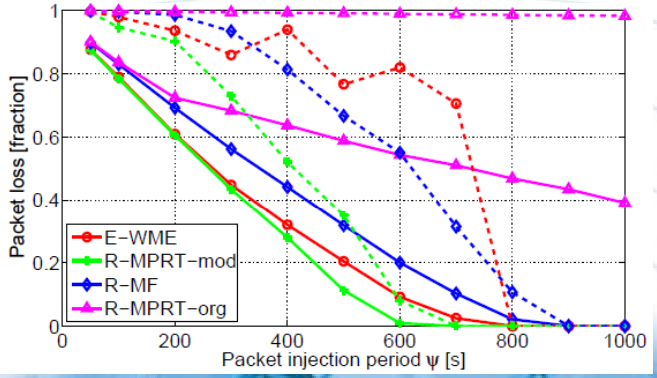
Conclusion

- Energy-harvesting systems:
  - Target to maximize workload under environmental constraints
- Make realistic assumption
  - Overhead of real MAC protocol
  - Routing information is not for free
- Our modified algorithm outperforms the discussed algorithms
  - Harvesting rate is not considered
  - Only use the stored energy for the cost metric

Idealistic



Real world



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