Opportunistic Routing in Multi-Sink Mobile Ad Hoc Wireless Sensor Networks (ORMMA-WSN)

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Artūras Lukošius

Supervised by:
Prof. Dr. rer. nat. habil. C. Görg
Dr.-Ing. Andreas Timm-Giel
Dipl.-Ing. Bernd-Ludwig Wenning

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- Objectives
- Introduction
- Opportunistic Routing in WSN
  - Introduction
  - Protocols
  - Spatial Diversity
- Simulation Model of ORMMA-WSN
  - Theoretical Model
  - Multi-Sink Scenario
  - Programming Model
  - Communication Model
- Evaluation of Simulation Results
- Summary and Outlook

Objectives

- Development of an opportunistic routing method for WSN
- Intermittent connectivity and knowledge about the nodes' relative movement in order to achieve an efficient, reliable routing
- Simulation of models and algorithms of the designed routing algorithm in OPNET
- The major part - network layer using the opportunistic routing algorithm on top of existing layer 1 and layer 2 models
- Multi-Sink scenario for opportunistic routing

Introduction

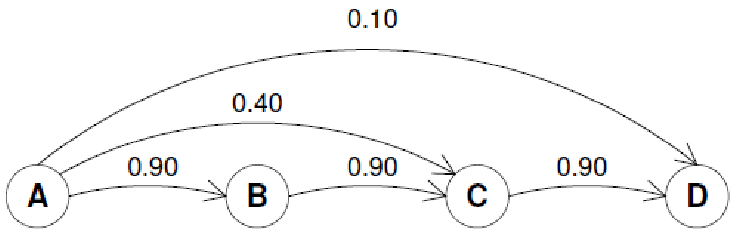
- Wireless Sensor Network (WSN) – large scale network of sensor nodes
- Deployment of nodes changes frequently in mobile WSN
- Mobile nodes - opportunistic elements for packet relay
- Limitations of many existing routing protocols:
  - single sink structure
  - no or only limited mobility
- Routing in WSN with Multiple Sinks requires new approach
- Intermittent connectivity, mobility and power consumption are the main challenges for many routing protocols

Opportunistic Routing
Introduction

- Unicast routing technique for multi-hop wireless networks
- Optimal transmission only when conditions are favorable
- Based on geographic routing
  - awareness of surrounding neighbors and their specific locations
  - awareness of channel quality
  - not a single candidate, but a set of candidates is used
  - election of next hop according to node availability
  - Network Layer (NET) selects furthest node which is closest to the destination
- NET + MAC. Final decision in MAC by candidate connectivity
- Challenge: nodes must agree which of them is forwarder
- Overhead is expected in denser networks (high neighborhood cardinality)
- Powerful and well-suited for sensor networks (intermittent connectivity)

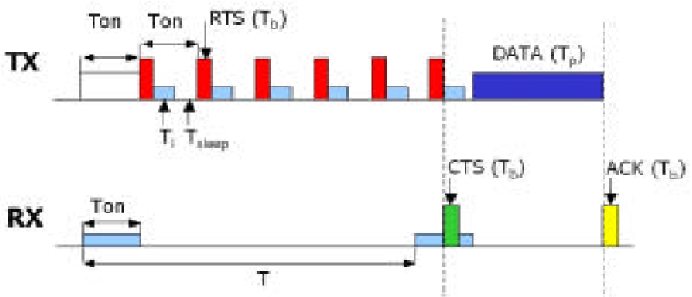
Opportunistic Routing Protocols

- Extremely Opportunistic Routing (ExOR)
  - ranking of forwarding nodes by number of hops
  - sender specifies priorities of receiving nodes
  - path is determined during packet propagation
  - prediction of most useful forwarder



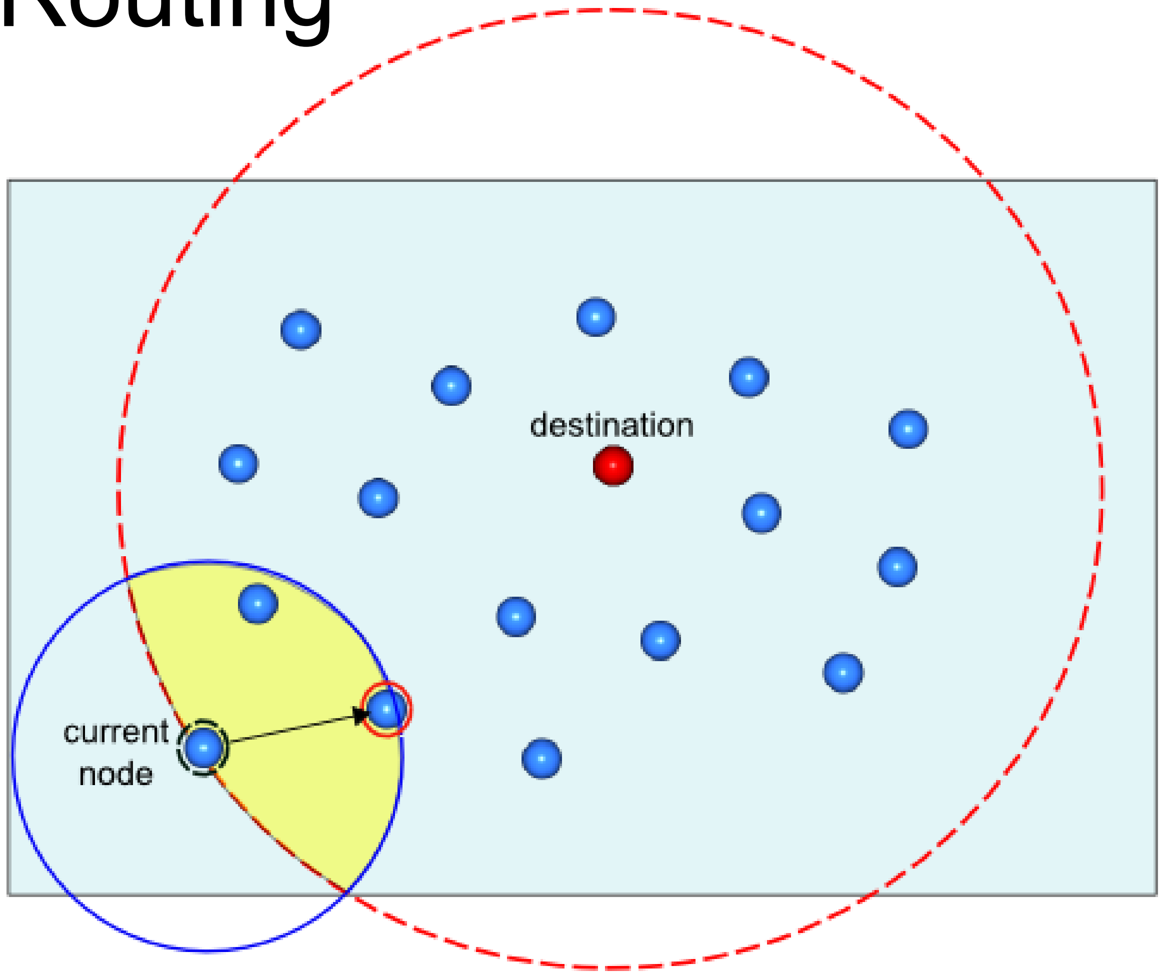
- Opportunistic Routing in Ad Hoc Networks (OPRAH)
  - uses promiscuity of air interface to find more optimal path
  - uses AODV to fill specific route data
  - less suitable for WSN (high power consumption)

- Region-Based Opportunistic Routing
  - selection of forwarding region (spatial diversity)
  - Transceiver Initiated Cycled Receiver. RTS/CTS
  - sensing slots to back-off for multiple forwarding nodes
  - next hop: first node responding to the RTS



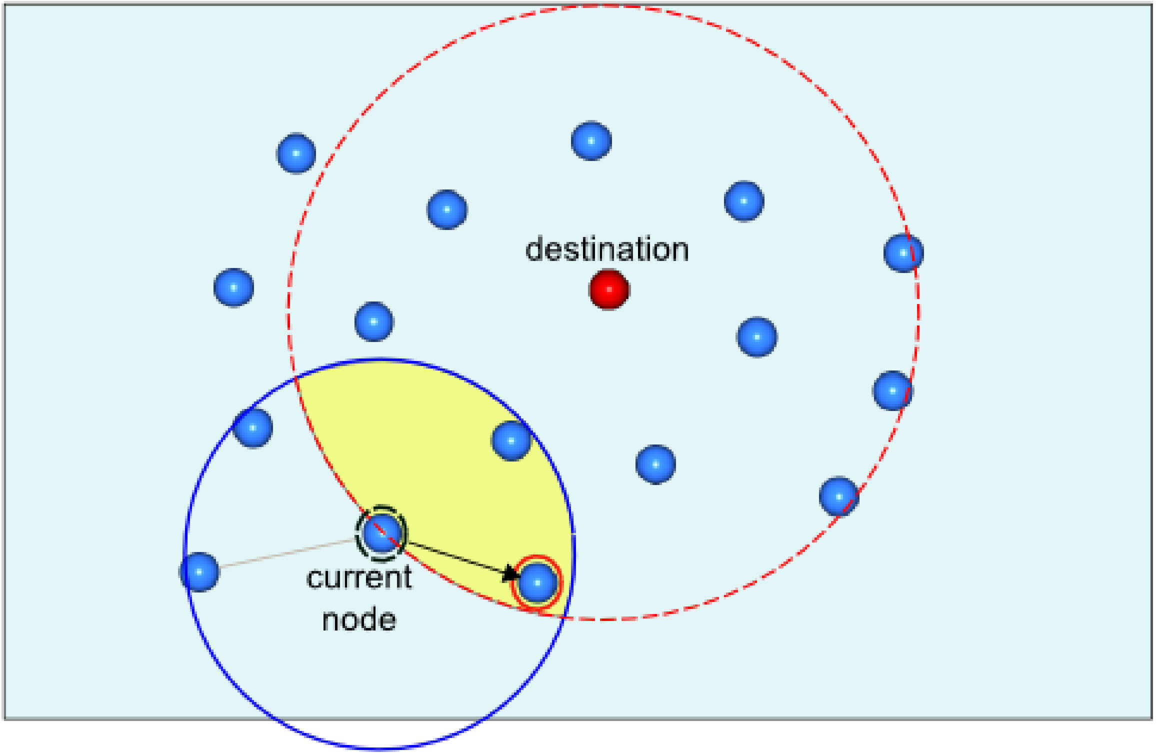
Opportunistic Routing
Spatial diversity

- Nodes know their own and destination location
- MAC specifies forwarding region
  - optimal: lens of nodes closer to the destination
- Next hop is based on connectivity



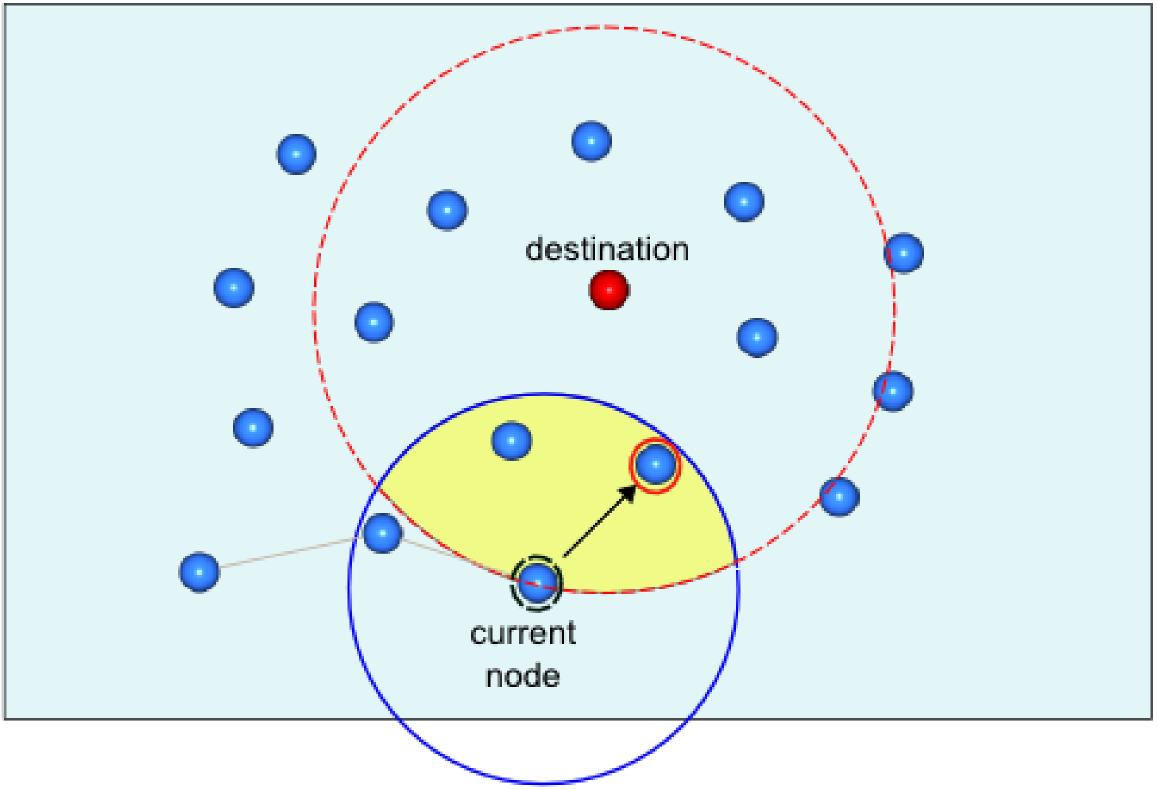
Opportunistic Routing
Spatial diversity (2)

- Nodes know their own and destination location
- MAC specifies forwarding region
  - optimal: lens of nodes closer to the destination
- Next hop is based on connectivity



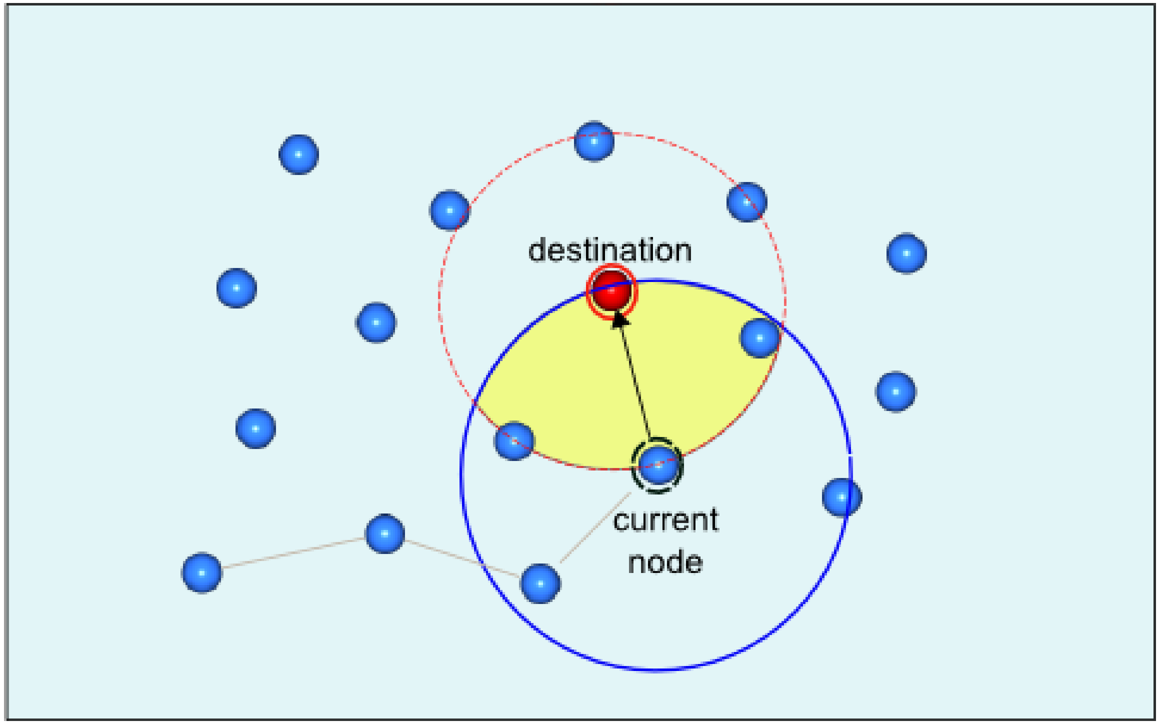
Opportunistic Routing
Spatial diversity (3)

- Nodes know their own and destination location
- MAC specifies forwarding region
  - optimal: lens of nodes closer to the destination
- Next hop is based on connectivity



Opportunistic Routing
Spatial diversity (4)

- Nodes know their own and destination location
- MAC specifies forwarding region
  - optimal: lens of nodes closer to the destination
- Next hop is based on connectivity

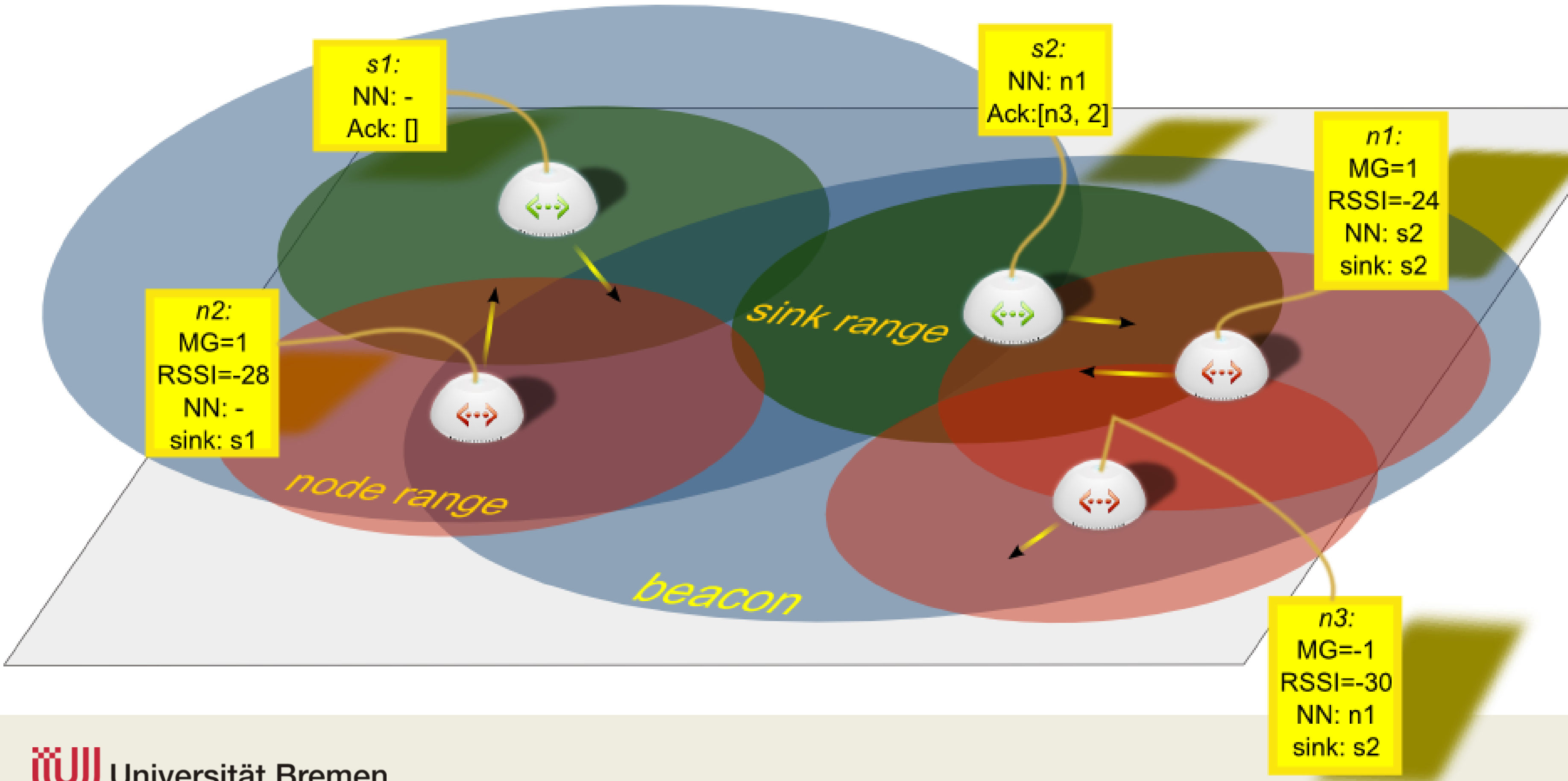


Simulation Model of ORMMA-WSN
Multi-Sink scenario

- Sensor nodes and multi-sinks are mobile, $N_{sensor\ nodes} > N_{sinks}$
- Limited communication range (no full connectivity inside a scenario)
- Sinks send higher power periodic beacons (covering larger area):
  - Neighbor Node (NN) list of nodes that appear in the comm. range
  - ACK list to data packets received during beacon interval
- Nodes forward beacons with normal TX power
- Data transmission only in the communication range
- Each sensor node obtains its mobility information:
  - Mobility Gradient (MG) is calculated from sink beacon RSSI
  - BNN and Best Sink
- Packets are relayed to the BNN according to the mobility information
- Each next hop node makes own decision about routing direction

Simulation Model of ORMMA-WSN

Example of Multi-Sink scenario



Simulation Model of ORMMA-WSN

Theoretical model

- Idea: If a mobile node moves away from the sink, it must give all pending packets to the most successful neighbor node
- Received Signal Strength Indicator (RSSI) is the measured average power of the incoming packet
- Mobility Gradient (MG) is the information about mobile node's movement direction relative to the sink:

$$MG = sign(RSSI_2 - RSSI_1) = sign(\Delta RSSI)$$

- MG values:

$$\begin{cases} MG = -1, \text{ from sink}, \\ MG = \;\; 0, \text{ constant}, \\ MG = +1, \text{ to sink}. \end{cases}$$

- MG is expired when Sink Expiration Time is exceeded
- MG and RSSI define node's mobility information which is shared with neighbor nodes by beacon forwarding

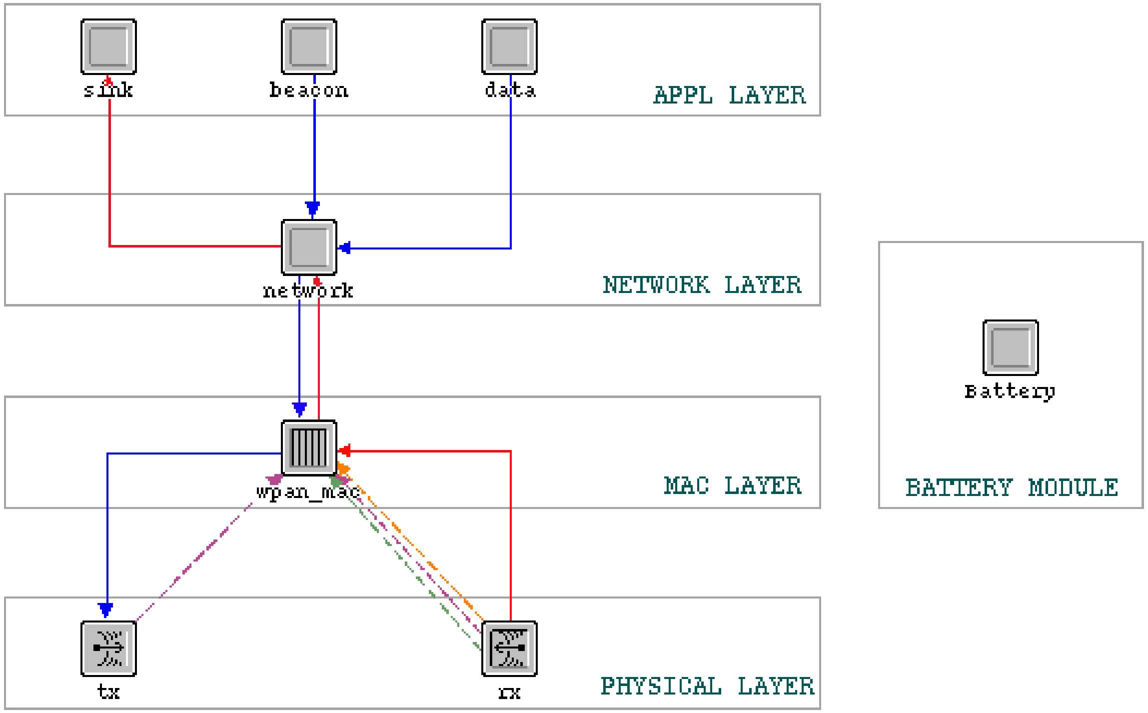
Simulation Model of ORMMA-WSN

Theoretical model (2)

- Neighborhood information is extracted from forwarded beacons
- Best Neighbor Node (BNN) is elected according to MG and RSSI values:
  - source MG=1 or no neighbors: keep packet
  - source MG=0 or MG=-1, neighbor MG=1: best NN, route packet
  - source MG=-1, neighbor MG=0, RSSI_nn > RSSI_src: best NN, route packet
  - source MG=-1, neighbor MG=-1, neighbor is in sink range: best NN, route packet
- Source and NN in sink range:
  - RSSI_nn > RSSI_src: route packet
  - RSSI_src > RSSI_nn, send packet to the sink
- Neighborhood information is expired when Neighbor Node Expiration Time is exceeded
- Neighbor Node is accepted if RSSI_nn > RSSI_threshold

Simulation Model of ORMMA-WSN
Node model

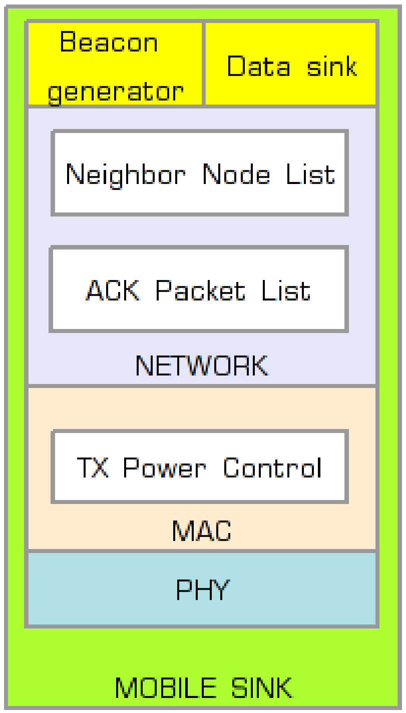
- Sink/Sensor node elements
- Ad-hoc Mode
- Unslotted CSMA/CA, non-beacon-enabled MAC protocol
  - modified OpenZB model
- IEEE 802.15.4 PHY characteristics
- ORMMA-WSN at NET layer
- Computation of the power consumption
  - MICAz model supported
- Frame formats
  - Data, ACK, NET

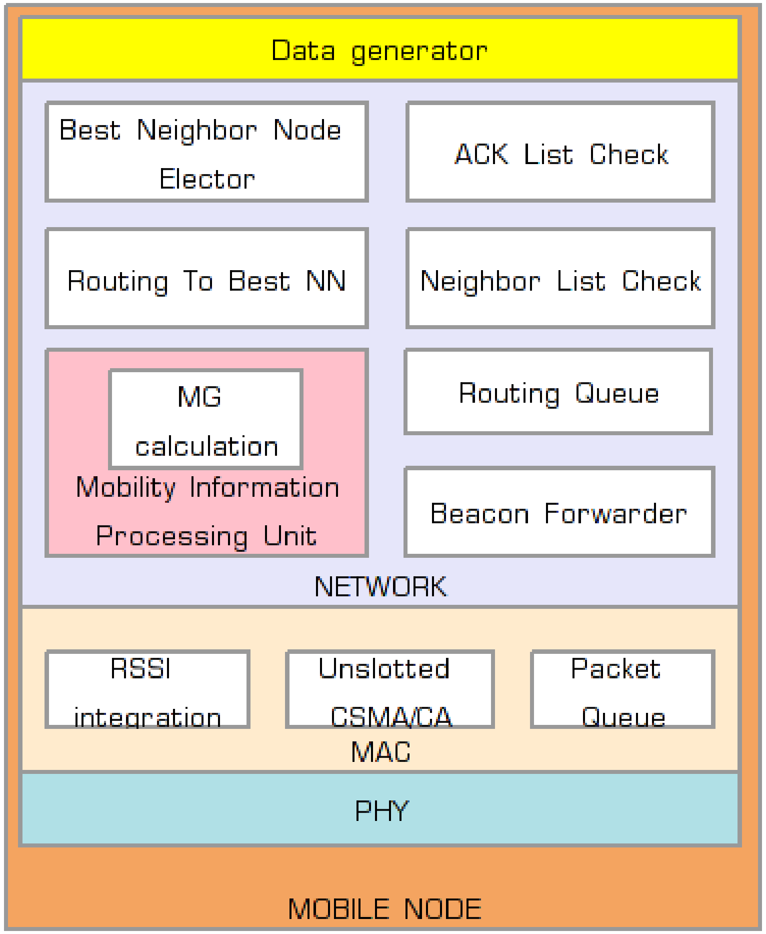


Simulation Model of ORMMA-WSN

Programming model

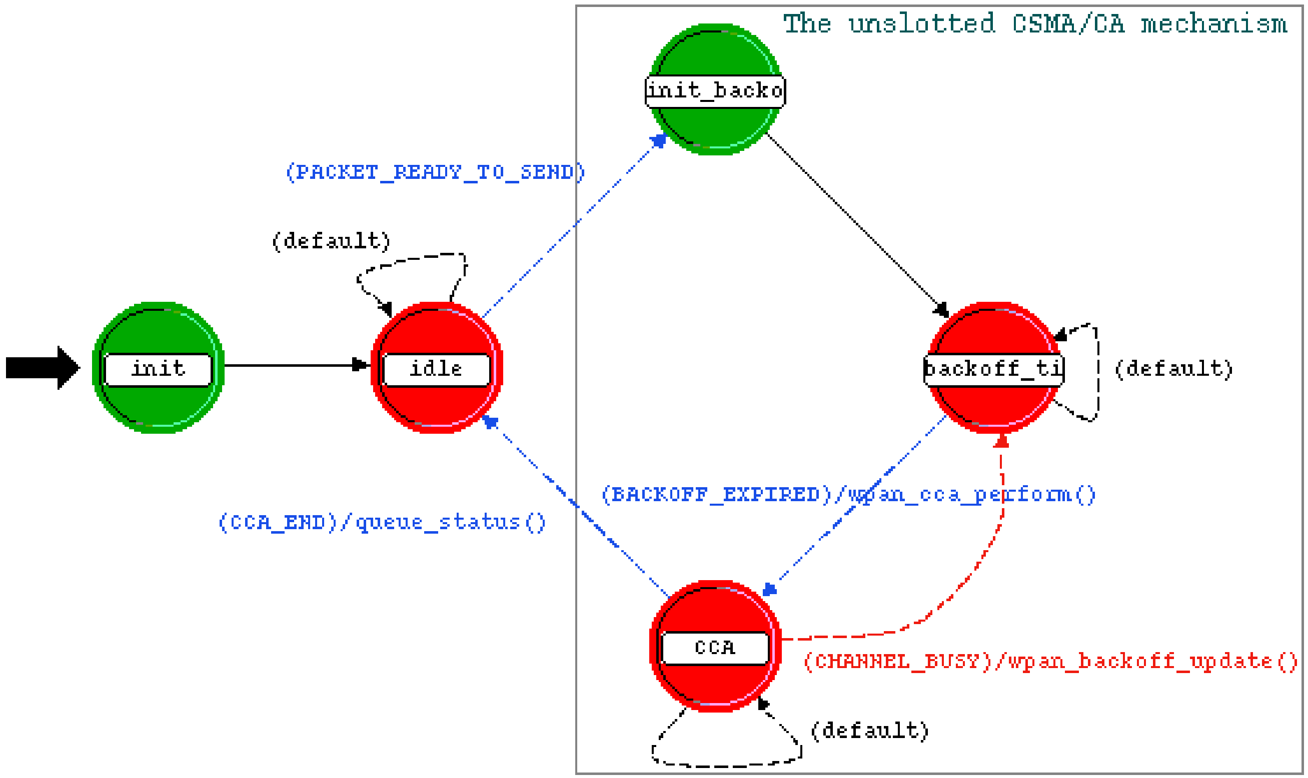
- Programming structure of sensor node is more complex
- All functions implemented in OPNET

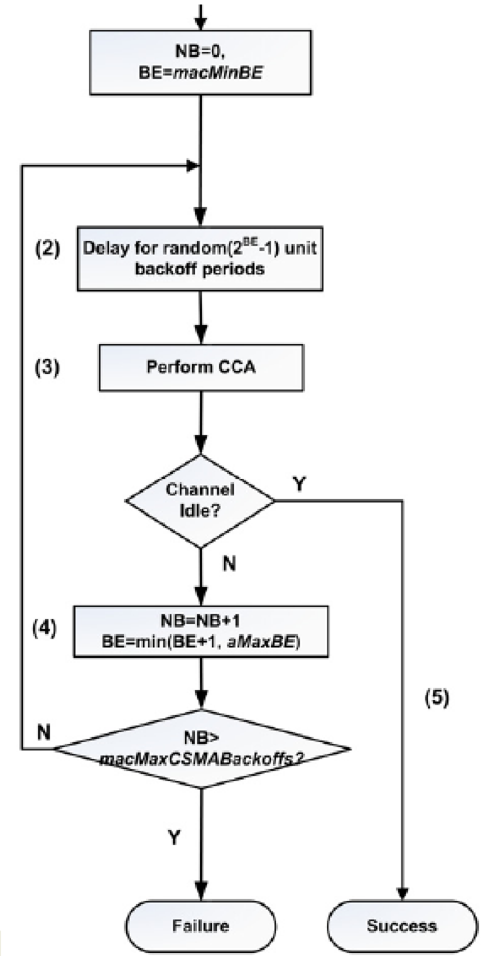




Simulation Model of ORMMA-WSN

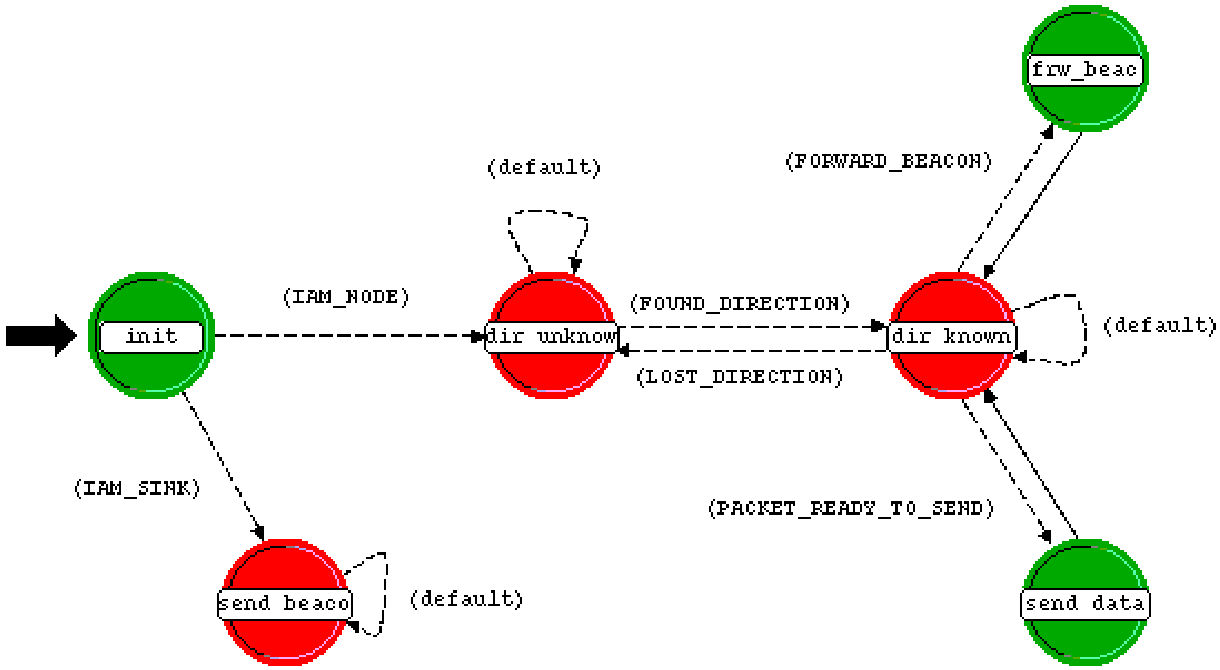
Process model. MAC layer





Simulation Model of ORMMA-WSN

Process model. Network layer

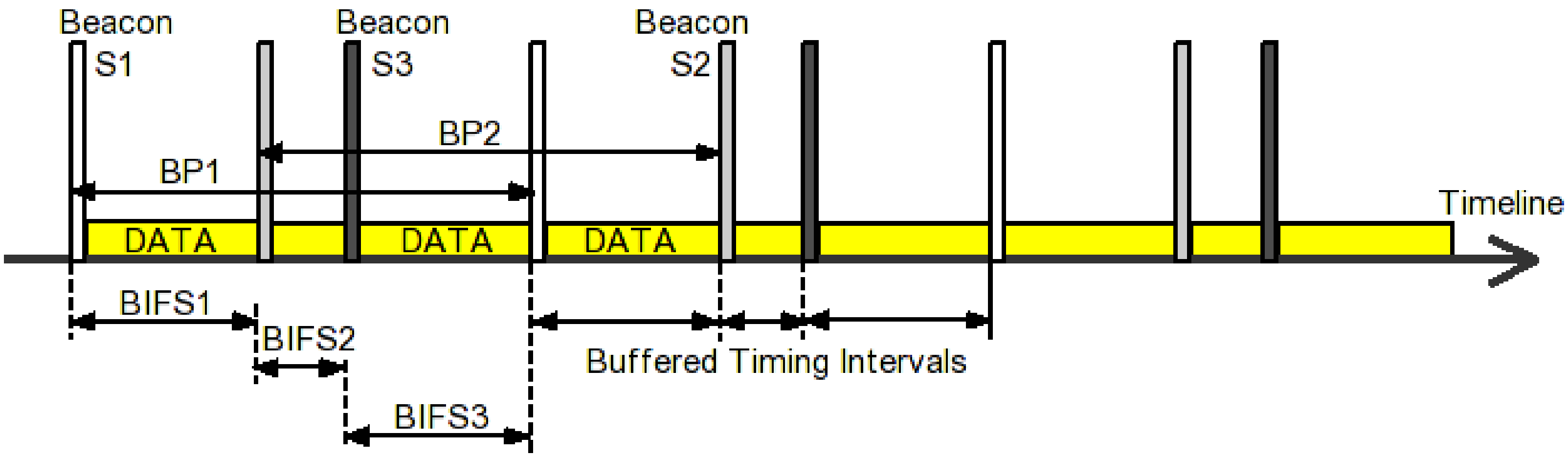


Simulation Model of ORMMA-WSN

Communication model

- APP layer generates a data packet
- NET Layer places it into packet buffer (FIFO) until transmission is available
- When BNN is known, packet is sent to the MAC Layer and transmitted with unslotted CSMA/CA
- An ACK must be transmitted 192 µs after receiving the last byte of a valid frame demanding an ACK
- If ACK is not received, transmission is repeated N times. If still no ACK, failure is indicated to NET Layer
- If ACK is received, packet is removed from MAC and NET packet buffers
- Stop-and-wait data transmission
- Sequence numbers (SEQ) used in MAC and NET packet formats

Reduction of Collision Rate
Synchronization to Beacon Signals



- Sink beacons are transmitted without CSMA/CA (collisions)
- Beacon Period (BP) $t_{BP_1} = t_{S_1}(b) - t_{S_1}(b-1)$
- Next Contention Free Period (CFP) $t_{next\ CFP} = t_{S_n}(b) + t_{BP_n}$
- CFPs set Timing Table of Beacon Inter-Frame Spacing (BIFS)
- Complex structure, most collisions appear due to inappropriate beacon forwarding time

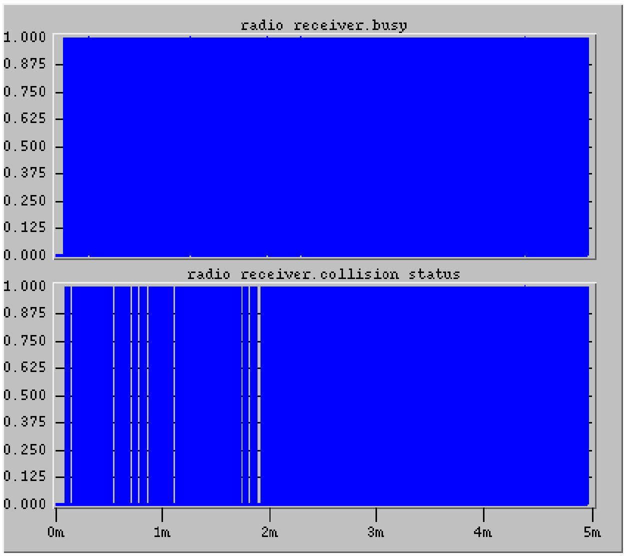
Reduction of Collision Rate
Random Beacon Forwarding

- Simultaneous beacon forwarding causes high collision rate
  - Problem of RNG in OPNET. Results are dependent on RNS
- Multiple beacons from different sinks arriving with close interval will cause redundant beacon forwarding
- Introducing Random Beacon Forwarding Delay

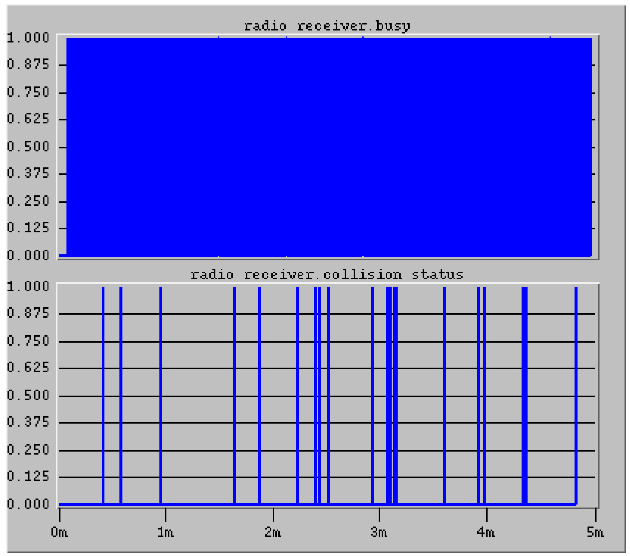
$$t_{forward} = t_{simulation} + t_{\mathrm{wait\_beacon}} + t_{random}$$

  - forward: time of beacon forwarding
  - simulation: current time
  - wait_beacon: interval of waiting for several beacons
  - random: random waiting time (more randomness for CSMA/CA backoff)
- Simple structure, no additional coordination
- Reduced collision ratio <1%

Reduction of Collision Rate
Random Beacon Forwarding (2)



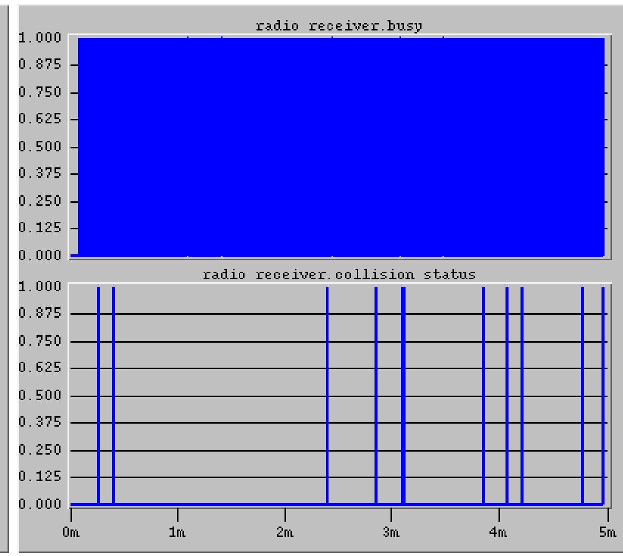
- Simultaneous beacon forwarding
- Collision ratio **20.6 %**
- 2 sinks, 6 nodes
- Beacon interval 1s, delta 0.05s



- Delayed beacon forwarding

$$t_{forward} = t_{simulation} + rand(0.1)$$

- Reduced collision ratio 0.81%



- Delayed beacon forwarding with additional beacon waiting delay

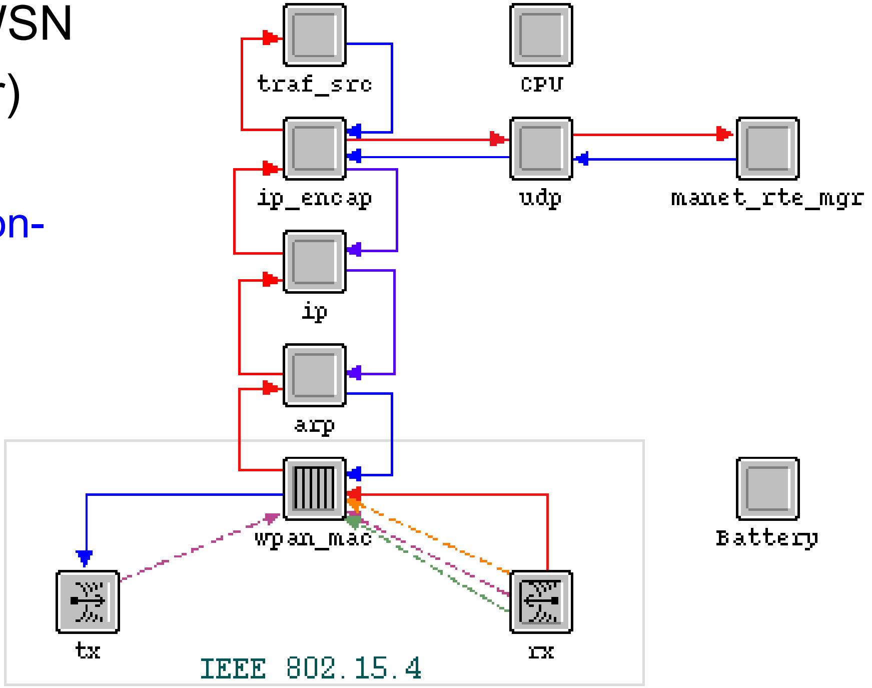
$$t_{\text{wait\_beacon}} = 0.05\ s$$

- Reduced collision ratio **0.48%**

Simulation Model

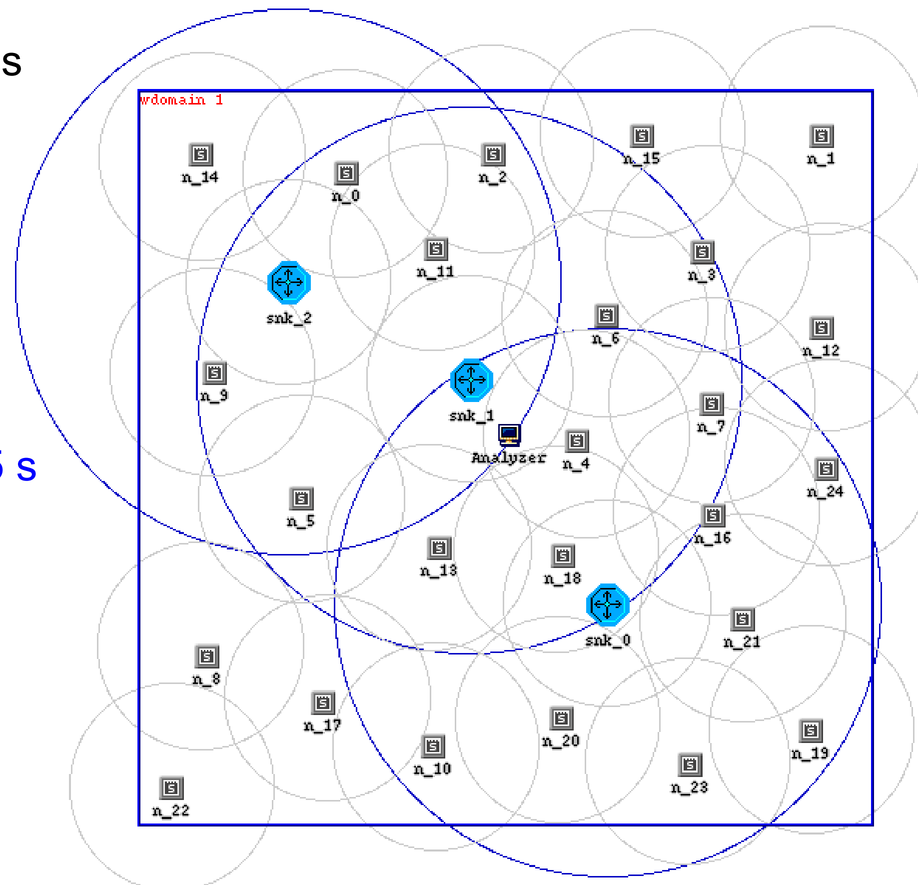
Modified MANET station. Node model

- For comparison with ORMMA-WSN
- AODV routing protocol (IP Layer)
- IEEE 802.15.4 MAC and PHY
  - Unslotted CSMA/CA, non-beacon-enabled MAC
- Battery module



Simulation Setup
Multi-Sink Scenario

- Network: 3 sinks, [5 10 15 20 25] sensor nodes
- Simulation area 100x100 m
- TX power:
  - Node/Sink: 10 nW, 40 nW and 70 nW
  - Sink beacon power multiplier: 7
- Mobility model: random direction, speed 1-5 m/s, pause at the borders 5-10 s
- Beacon period: 1s, Inter-Beacon Interval: 0.05 s
- Data packet: inter-arrival time 5 s, packet size 256 bits
- No. of retransmissions N = 2, min. back-off exponent 2, max. back-off number 4
- RSSI threshold -143 dB
- Simulation runtime 3000 s including 1000 s initialization step



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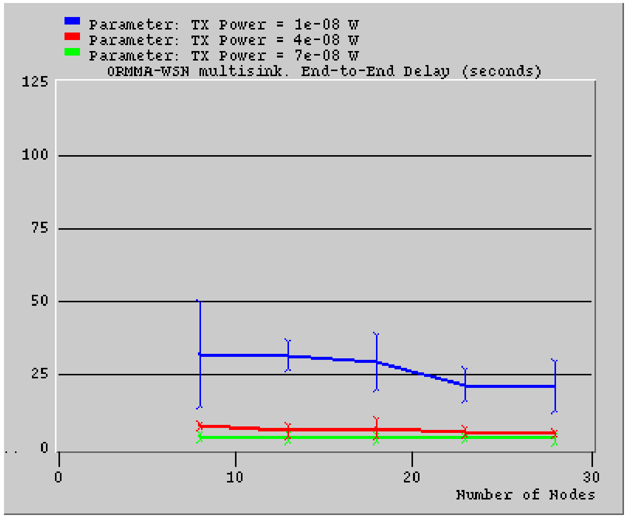
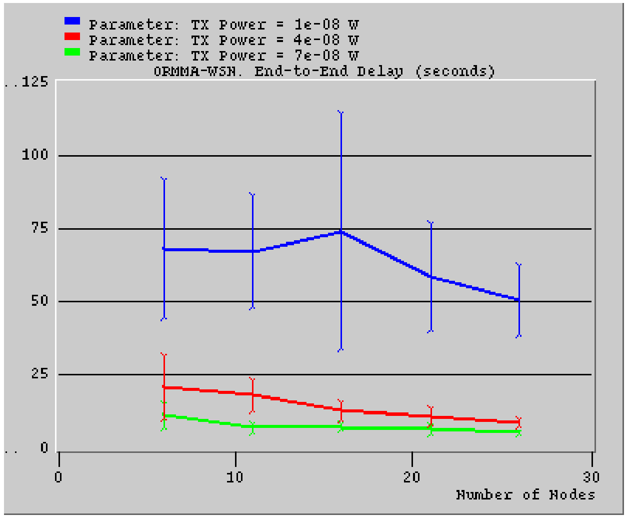
Evaluation of Simulation Results

End-to-end delay

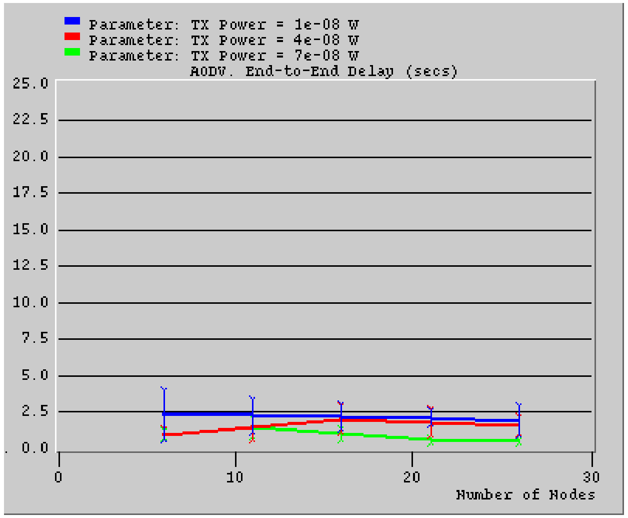
3-Sink ORMMA-WSN



1-Sink ORMMA-WSN



1-Sink AODV

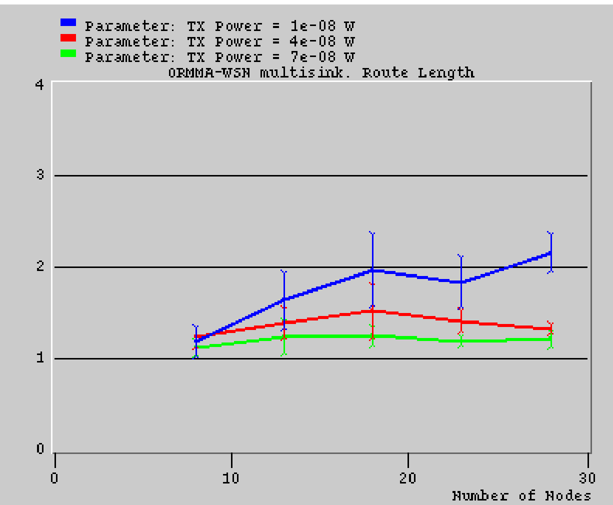


- ORMMA-WSN: long delays due to intermittent connectivity
- AODV: low delays. It only finds several routes with short length (goodput results)
- Results improved at higher TX power level
- Multiple sinks help to decrease end-to-end delays

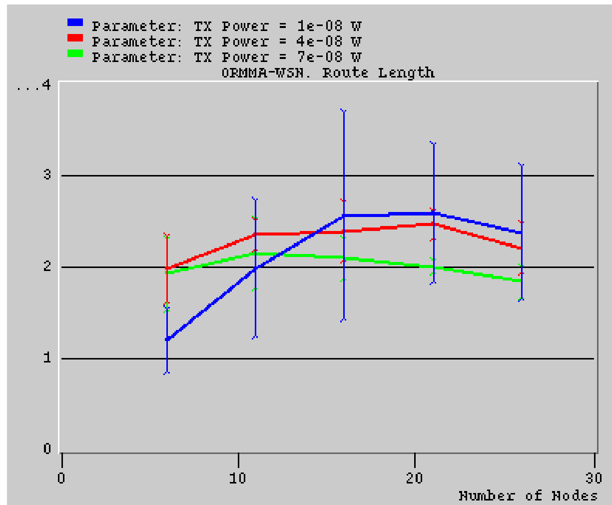
Evaluation of Simulation Results

Route length

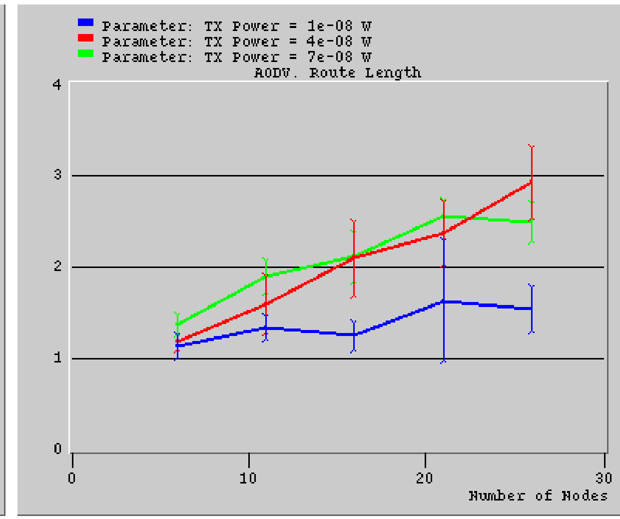
3-Sink ORMMA-WSN



1-Sink ORMMA-WSN



1-Sink AODV

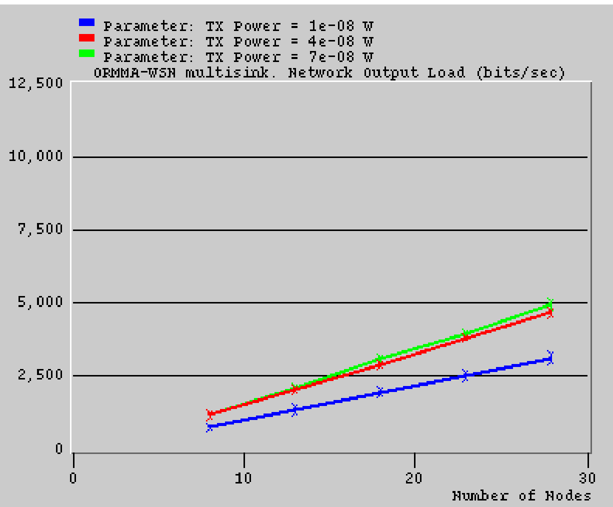


- Route length depends on average nodes mobility between source and sink. Most of the routes have short length
- Routing length increases in larger network (more nodes can participate in routing)
- ORMMA-WSN: Saturation of routing length (large network)
- Multi-Sink scenario: routes are shorter (more sinks available at smaller distances)
- AODV: performs better in larger network with high power

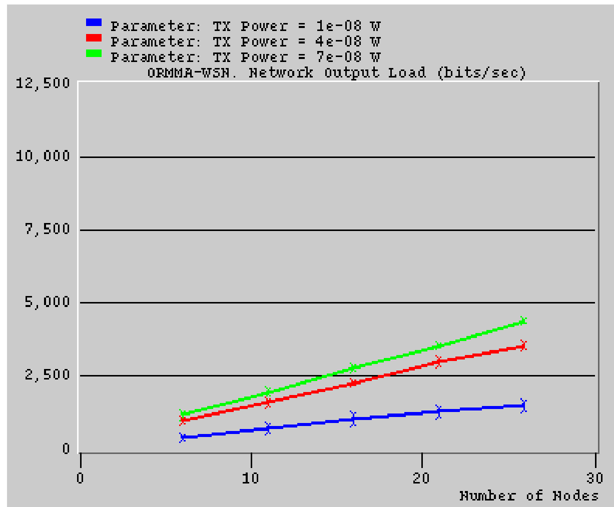
Evaluation of Simulation Results

Network output load

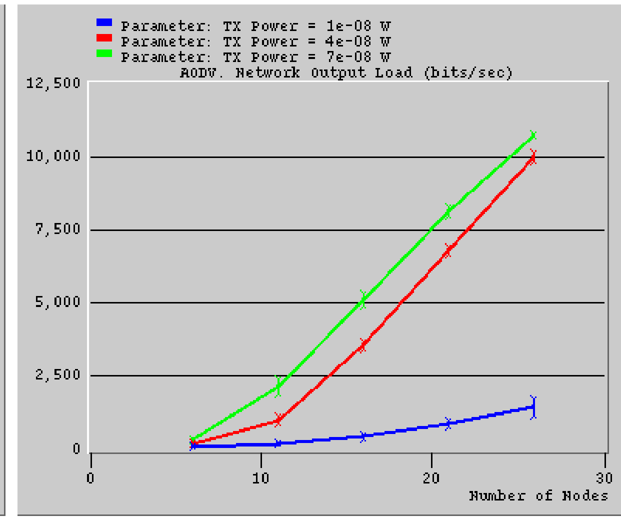
3-Sink ORMMA-WSN



1-Sink ORMMA-WSN



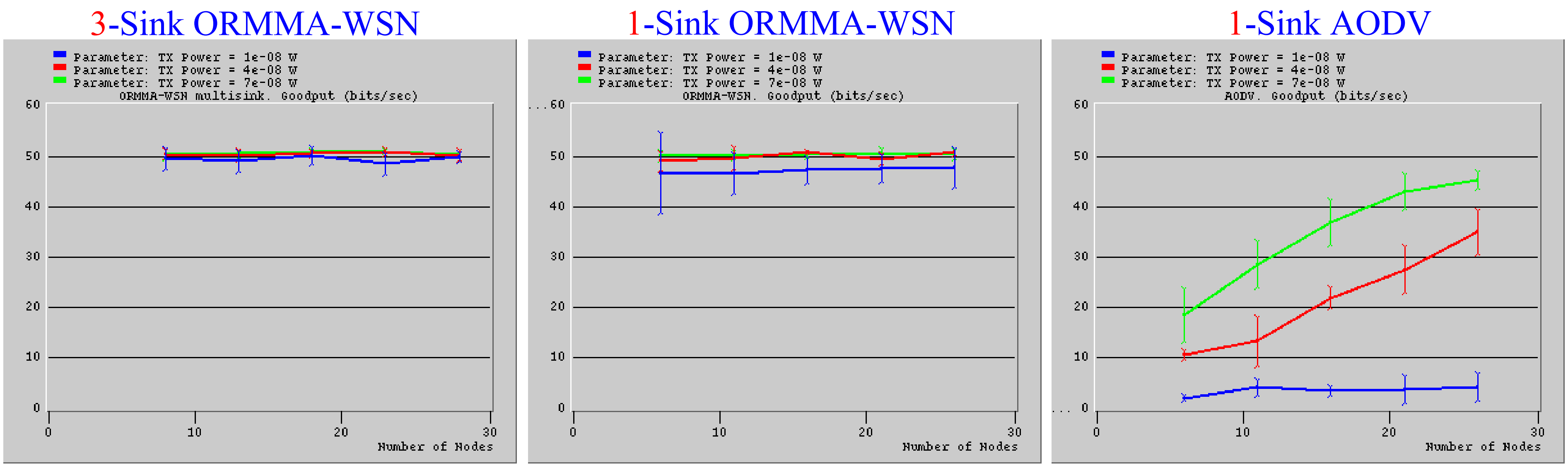
1-Sink AODV



- ORMMA-WSN: Network output load is linearly dependent on number of nodes in the network and TX power
- Multiple sinks load network more than single sink
- ORMMA-WSN: network load is much lower than AODV
- AODV: performance increases at the expense of high network output load

Evaluation of Simulation Results

Goodput

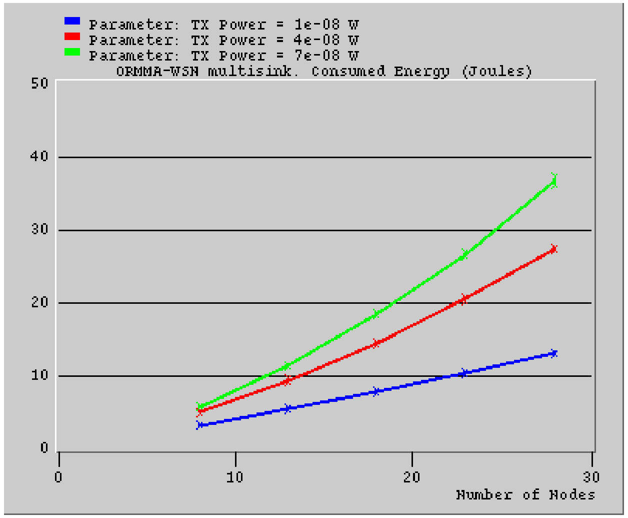


- ORMMA-WSN: reaches the data packet rate even in small network with small TX power
- AODV is outperformed. It cannot establish routes in low TX power and small network

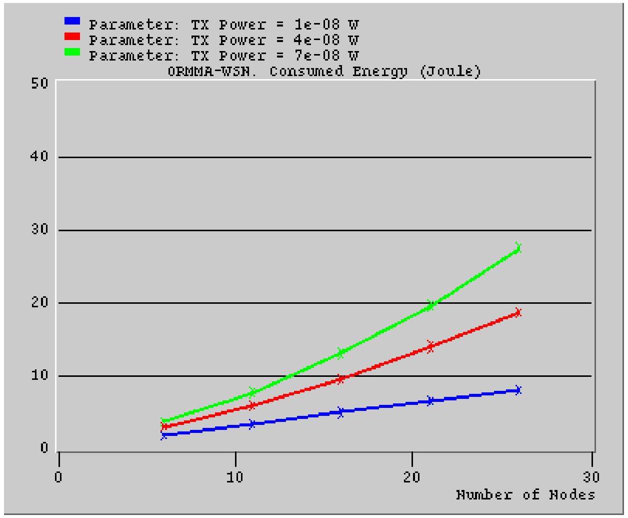
Evaluation of Simulation Results

Energy consumption

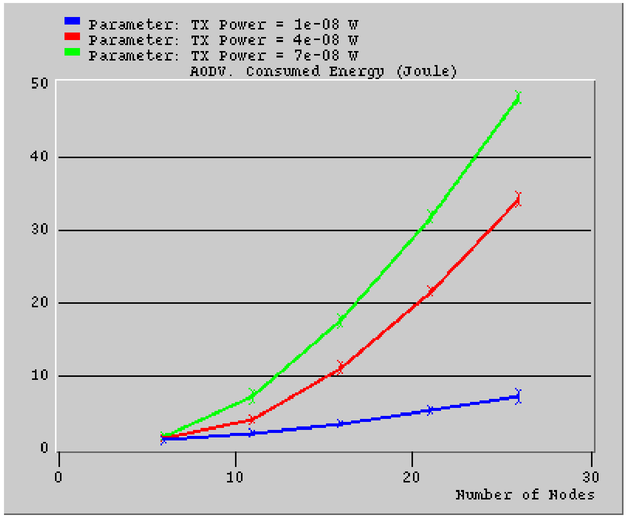
3-Sink ORMMA-WSN



1-Sink ORMMA-WSN



1-Sink AODV



- Power consumption depends on network output load
- AODV: consumes most energy
- Multi-Sink vs. Single-Sink: twice lowered end-to-end delays with relatively higher energy consumption

Summary and Outlook

- ORMMA-WSN is advantageous in low power, intermittently connected mobile WSN
- AODV is outperformed in all scopes except the end-to-end delays
- Multiple-Sink structure gains performance over Single-Sink
- Proposed improvements of ORMMA-WSN:
  - MAC + NET. Final decision in MAC (lower e-t-e delays)
  - Adaptivity to channel conditions (lower packet loss)
  - Dynamic MG (relative speed with direction)
  - Dynamic RSSI thresholding
  - Adaptive TX power control
  - Localization methods for orphaned nodes
  - End-to-end acknowledgments
  - Queries from multiple sinks to sensor nodes, data extraction, distributed configuration
  - Context awareness

Thank You! Questions?

backup slides

Context Awareness
Context types (attributes)

- Power/Energy
  - Battery level, bandwidth, transmission cost, connectivity
- Mobility
  - Relative mobility, collocation with sinks -> adaptive algorithms
- Information
  - Max. information gain, data aggregation, compression
- Privacy
  - Data encryption, cloaking, authentication, access rights
- Quality of Services
  - Energy reserve, delays, service rate

Context Awareness
Utilization function

- Significance-based evaluation of context-aware information
- Context information
  - Set of attributes $(X_1, X_2, \ldots, X_n)$
  - Delivery probability (Utilization) $U(x_1, x_2, \ldots, x_n)$
- Goal function (max. utilization)

$$Maximize\{f(U(x_i))\} = \sum_{i=1}^{n} w_i U(x_i)$$

- Problem. Fixed significance weights w_i (static analysis)
  → use adaptive prediction

Context Awareness
Adaptive Routing

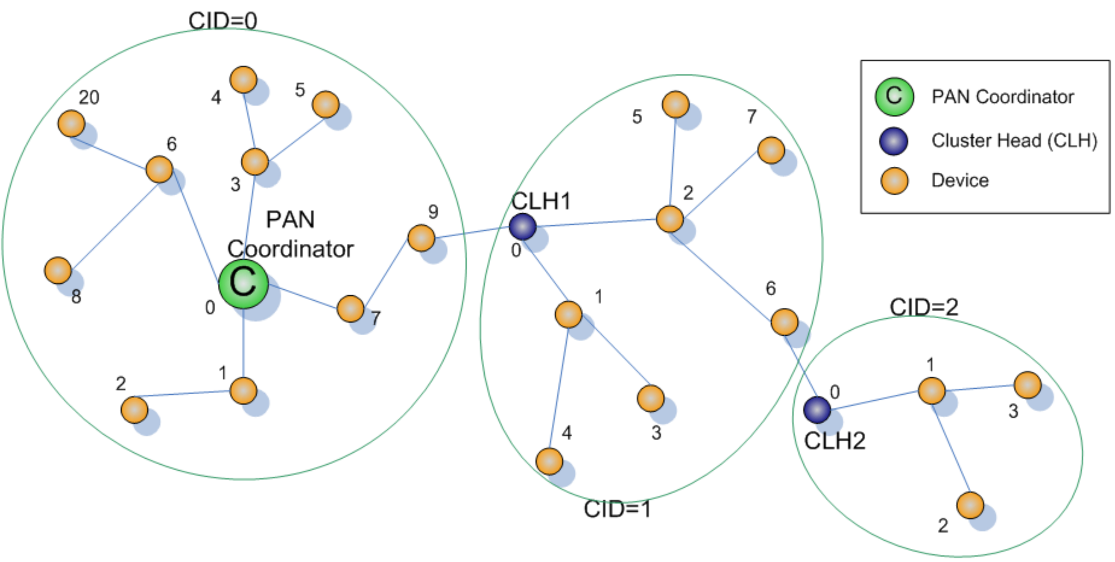
- Adaptive weights $a_i(x_i)$ related to the variation of the context

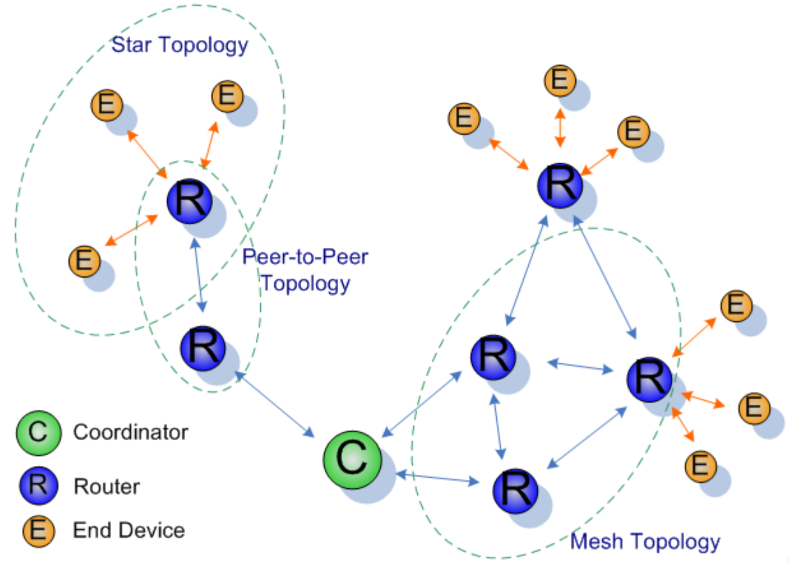
$$Maximize\{f(U(x_i))\} = \sum_{i=1}^{n} a_i(x_i) w_i U(x_i)$$

- Criticality of certain ranges of values, $a_{range_i}(x_i)$
- Predictability of context information, $a_{pred_i}(x_i)$
- Availability of context information, $a_{avail_i}(x_i)$
- also Autocorrelation of data, Kalman Filter prediction techniques

- e.g. If battery of candidate node is depleted faster, find another route

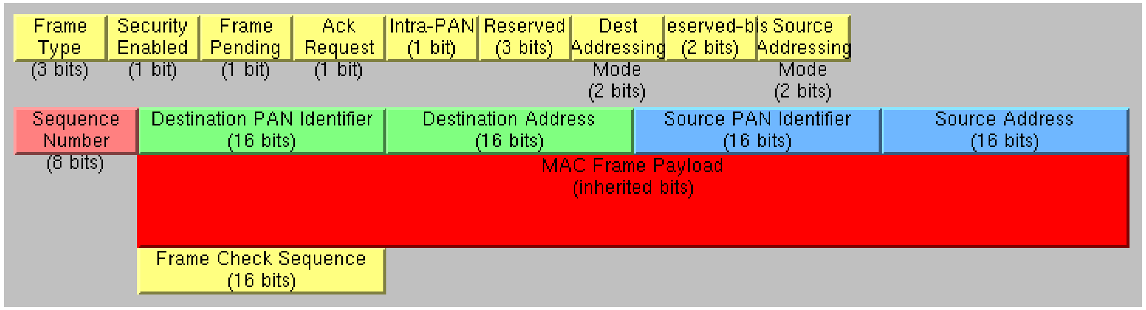
IEEE 802.15.4 Network Topologies

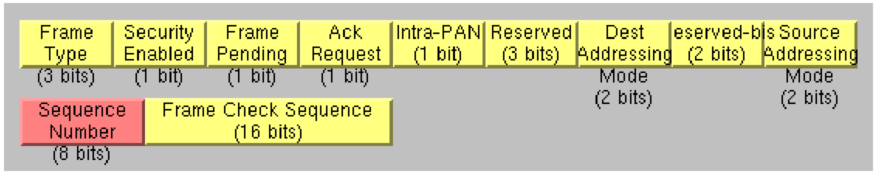


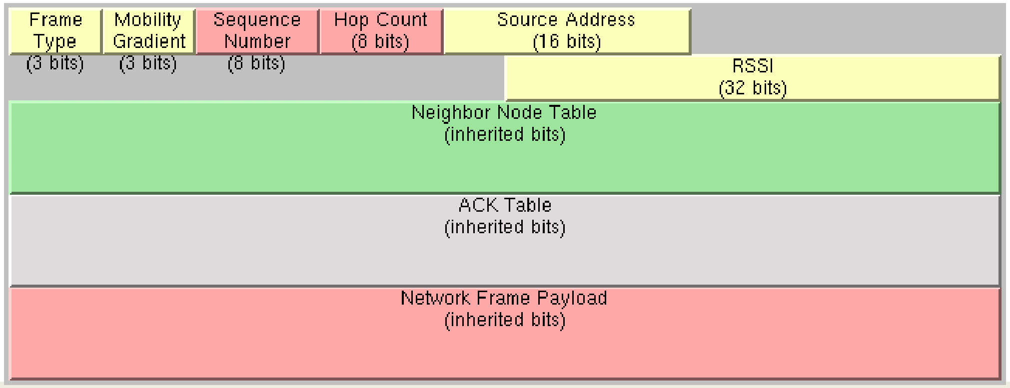


Opportunistic Routing

Programming model – packet formats

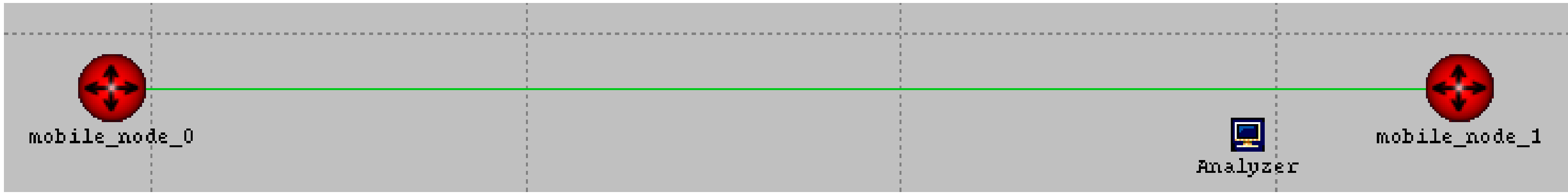




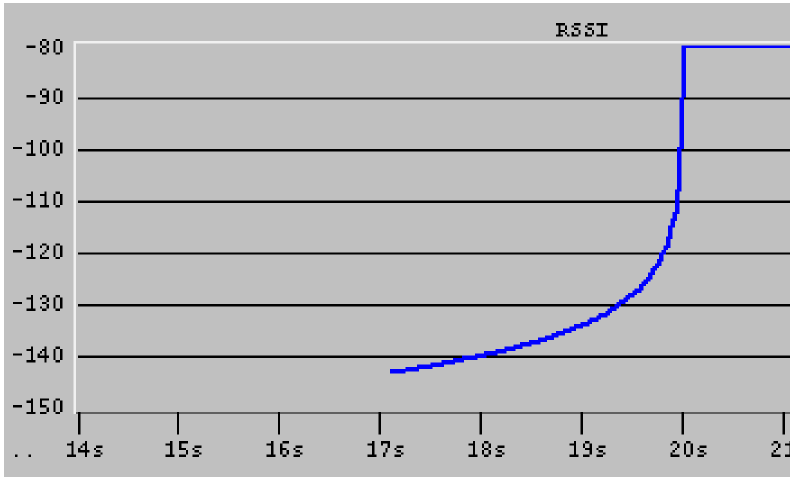


Radio model investigation

RSSI Threshold



Min. mean RSSI, dB	Distance, m	Packet size, bits	Node Speed, m/s
-146.75	21.6	230	0.1
-144.57	16.83	1000	0.1
-144.4	16.49	2000	0.1
-146.26	20.44	230	1.0
-144	15.75	1000	1.0
-144	15.75	2000	1.0
-145.22	18.15	230	5.0
-143.28	14.5	1000	5.0
-143.28	14.45	2000	5.0



- Separating distance 100 m, speed 5 m/s, packet size 2000 bits
- Optimal minimum mean RSSI = -143 dB

Radio model investigation

Free space propagation

$$P_{rx} = P_{tx} \left(\frac{\lambda}{4\pi\, r} \right)^2$$

[TX] Power, W	Distance, m	min_[RSSI], dB
2e-08	20.25	-143.16
4e-08	28.9	-143.26
7e-08	37.9	-143.18
1e-07	46	-143.2
2e-07	63	-143
4e-07	90.4	-143.16