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# Internet of Things

## VIII. Routing

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# Internet of Things: Routing

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## 1. Routing in Mobile Ad-Hoc Networks

**Pro-active routing**

- Pre-calculation and update of routing tables
- Example: Optimized Link State Routing

**Reactive routing**

- Route establishment on-demand
- Example: Ad-hoc On-demand Distance Vector routing

Such protocols can be adapted to wireless sensor networks by considering appropriate routing metrics, in particular for point-to-point communication.

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# 1. Routing in MANETs and WSNs

## 2.1 Requirements on Routing in WSNs

- Large scale networks, scalability
- No global information available
- Robustness to dynamic networks (e.g., topology changes, node failures) and adaptivity
- Low control overhead
- Limited storage for routing tables and state
- Data aggregation
- Real-time constraints
- Broadcast communication
- Point-to-multipoint and multipoint-to-point support
- Geographic addresses might be more important than unique node IDs.

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# 1. Routing in MANETs and WSNs

## 2.2 Routing Metrics for WSNs

- Minimum number of hops
- Energy
  - Maximum minimum available energy
    - Calculate minimum available energy over all nodes of a route
    - Select route with maximum value
  - Minimum required energy
    - Selection of route consuming the minimum energy for packet transmissions
    - Adaptation of reactive routing protocols such as Dynamic Source Routing protocol
      - Include transmission power used in Route Request messages
      - Receiver calculates required transmission power from received power.
      - Recording of required transmission power at each node in Route Request
- Quality-of-Service
  - Latency and jitter
  - Throughput
  - Packet loss and error rates
  - Expected Transmission Count ETX = 1 / (1-p)
    - p: packet error probability
- Link quality and stability

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# 3. IPv6 in Wireless Sensor Networks

## 2.3 Expected Transmission Count

- Packet loss probability in forward and reverse direction: $p_f$, $p_r$
- Probability for non successful packet transmission: $p = 1 - (1-p_f)(1-p_r)$
- Probability for successful delivery after k attempts: $s(k) = p^{k-1}(1-p)$

Expected Transmission Count (ETX) metric

$$ETX = \sum_{k=1}^{\infty} k \cdot s(k) = \frac{1}{1-p}$$

# 2. Wireless Sensor Network Routing Protocols



## Classification of Routing Protocols

1. Flat-Network
2. Data-centric
3. Location-based
4. Hierarchical

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# 2. Wireless Sensor Network Routing Protocols

## 1. Ad-Hoc On-Demand Distance Vector Routing

- Flat network routing, non-hierarchical
- Route Discovery based on
  - Route Request
    - RREQ ID (incremented for new RREQ) and source address for unique identification of a RREQ
    - current sequence number and IP address of originator
    - last known sequence number and IP address of destination
  - Route Reply
    - Originator/destination IP address
    - Destination sequence number
    - Hop count
    - Lifetime: Time for which nodes receiving the RREP consider the route to be valid

- Sequence numbers are incremented prior to generation of RREQ / RREP at originator / destination.
- Routing table entries (not complete)
  - Destination IP address
  - Destination sequence number
  - Hop count
  - Next hop
  - Lifetime

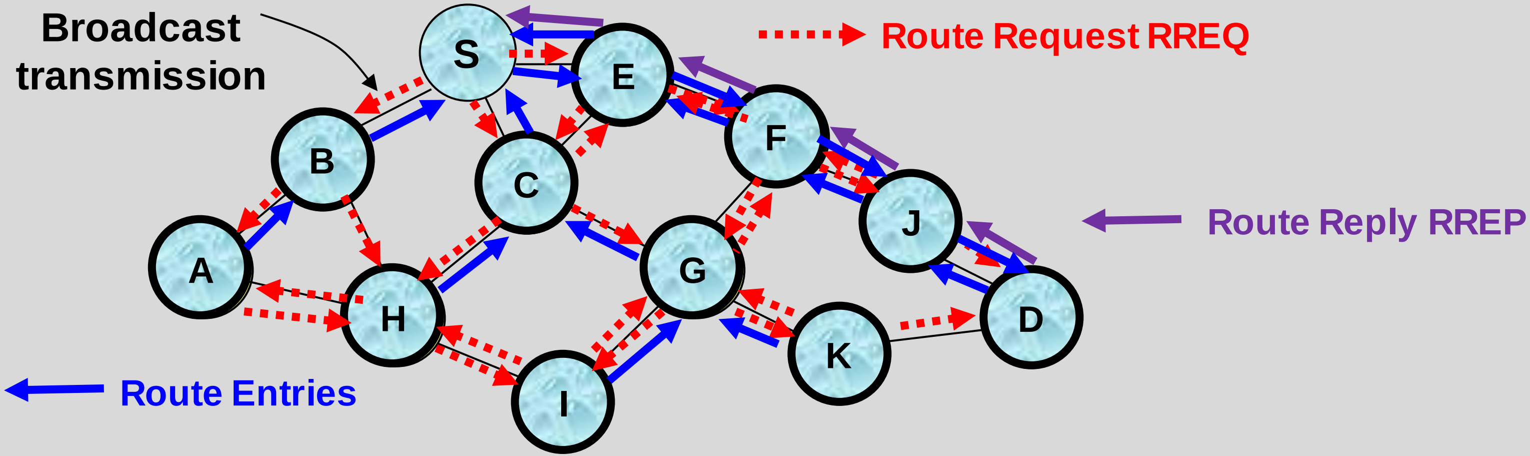
# 2. Wireless Sensor Network Routing Protocols

## 1.1 AODV Operation

- Destination Sequence Number
  - latest sequence number received in the past by the originator for any route towards the destination.
  - updated whenever a node receives new information about the sequence number from RREQ, RREP, or RERR messages
- Generation of RREQs when no valid route is available at a node
  - Destination sequence number = last known destination sequence number for this destination
- For received RREQ
  - RREQ will be discarded, if already received recently. Otherwise: Generation of reverse route entries (with lifetime) for source (storage of predecessor node for forwarding of RREP).
  - Response to RREQ by RREP, if valid entry for destination in routing table. Otherwise: broadcast of RREQ with incremented hop counter.
- Generation of RREP by destination or intermediate nodes, if destination sequence number in RREQ is not larger than in routing table. (freshness !)
  - Intermediate nodes set forward entries for received RREP, no source routing !
  - RREP messages are forwarded, if destination sequence number is higher than in routing table.
- Expiration of routing entries, if those are not used within a certain interval.
- Route Maintenance
  - Generation and transmission of Route Error messages by upstream node, which detects route failure, e.g., in case of mobility.

# 2. Wireless Sensor Network Routing Protocols

## 1.2 AODV: Example



# 2. Wireless Sensor Network Routing Protocols

## 2.2 Data-Centric Routing

Instead of addressing nodes by address identifiers or geographic locations, packets are forwarded according to searched data.

**Examples**

– Directed Diffusion

– Geographic Hash Tables
  → Geographic Routing

# 2. Wireless Sensor Network Routing Protocols

## 2.1 Directed Diffusion

### Attribute based routing

- Attribute value pairs characterize information that a node holds or seeks.
- More general approach than routing based on geographic locations only

### Example

- Node generates event record

```
type = animal
instance = horse
location = [89, 154]
time = 12:34:55
```

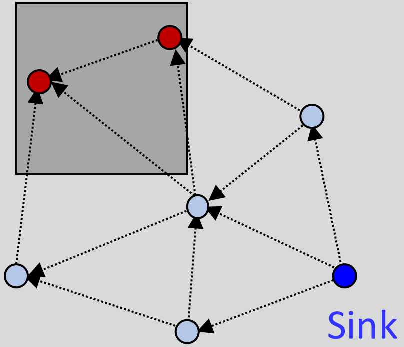
- A node seeking information creates request

```
type = animal
instance = horse
interval = 1 s
rect = [0, 200, 0, 200]
timestamp = 12:34:10
expiresat = 12:39:10
```

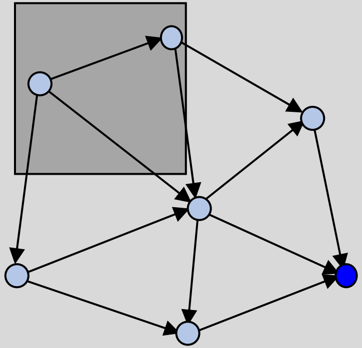
# 2. Wireless Sensor Network Routing Protocols

## 2.2 Directed Diffusion Operation

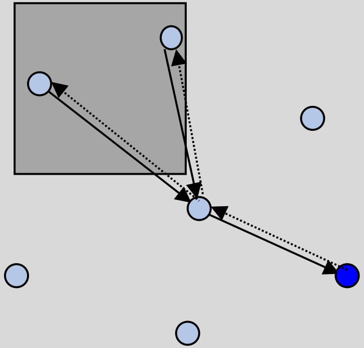
1. Interest Propagation




2. Gradient Setup



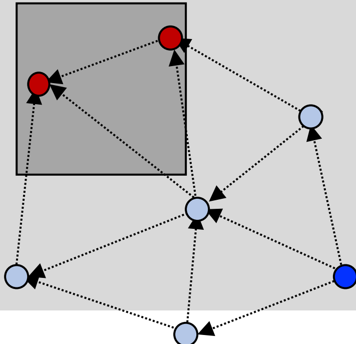
3. Data Propagation along reinforced path



# 2. Wireless Sensor Network Routing Protocols

## 2.2.1 Directed Diffusion: Interest Propagation

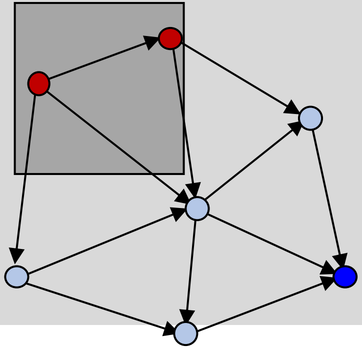
- Interest = a kind of query message describing what data a user wants to receive.
- Sensing task is disseminated throughout the sensor network as an interest for named data by using broadcast / flooding.
- Identical interests received from different neighbors are represented as a single (soft state) entry in a node.
- Periodic refreshments of interests due to unreliable interest transport



# 2. Wireless Sensor Network Routing Protocols

## 2.2.2 Directed Diffusion: Gradient Setup

- Interest dissemination sets up gradients to draw events.
- Each interest entry contains several gradient fields.



- Gradient = direction state in each node that receives an interest
  - Direction is set to neighboring node from which interest has been received.
  - Data rate is derived from interval field of interest message.
  - Duration is derived from timestamp and duration fields (lifetime information) in interests.

# 2. Wireless Sensor Network Routing Protocols

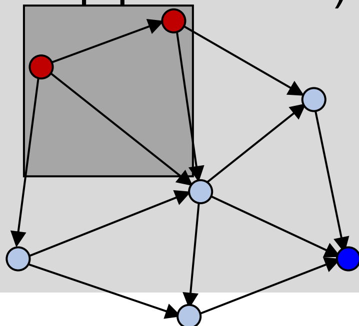
## 2.2.3 Directed Diffusion: Data Propagation

**Source sensor nodes with interest entries matching to events**

- calculate highest event rate among all outgoing gradients,
- generate according event samples,
- and send data (using unicast) to each neighbor for whom it has a gradient.

**Receiving nodes**

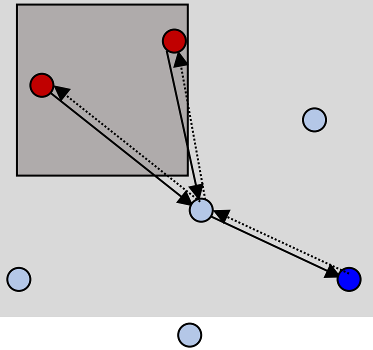
- try to find matching rules in their interest entries
- if match exists:
  - Message is dropped if in data cache (recently received → loop prevention)
  - Forwarding to neighbors with specified data rate,
  - possibly: down-sampling.



# 2. Wireless Sensor Network Routing Protocols

## 2.2.4 Directed Diffusion: Path Reinforcement

- After a sink receives events, it reinforces a particular neighbor (based on local rules) using a higher data rate by using a smaller interval value.
- A node receiving such an interest message must also reinforce at least one neighbor.
- Intermediate nodes can trigger path reinforcement based on their local rules, e.g., for repairing failed paths.
- Negative reinforcements
  - Timeouts
  - Explicit



# 2. Wireless Sensor Network Routing Protocols

# 3. Geographic Routing

## Assumptions

– All nodes know their geographic location.

– Each node knows immediate 1-hop-neighbors.

– Routing destination is specified as node location or geographic region.

– Each packet can hold a bounded amount of additional routing information.

## Examples

– Greedy Perimeter Stateless Routing

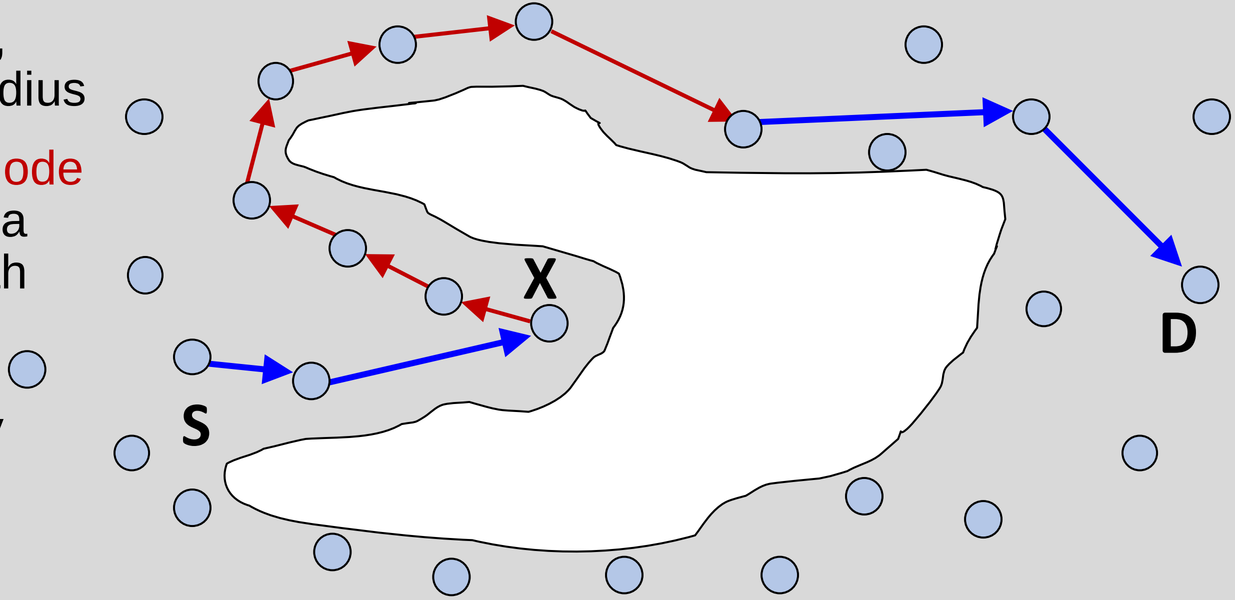
– Geographic Hash Tables

– Two-Tier Data Dissemination → Hierarchical Routing

# 2. Wireless Sensor Network Routing Protocols

## 3.1 Greedy Perimeter Stateless Routing

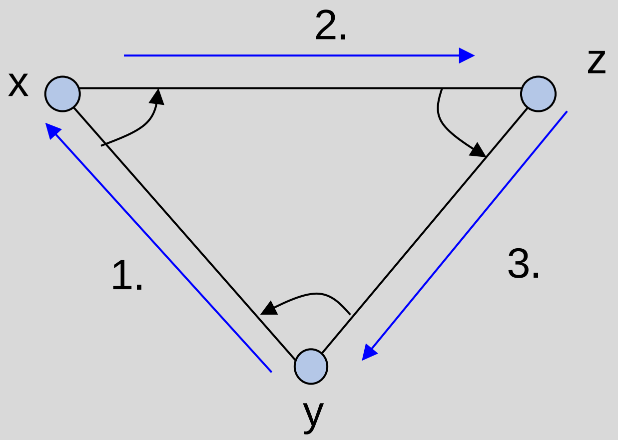
- Greedy forwarding, e.g., Most Forward within Radius
- Switching to recovery mode (perimeter routing) until a node is encountered with closer distance to destination than node where entering recovery mode



# 2. Wireless Sensor Network Routing Protocols

## 3.1.1 Right Hand Rule

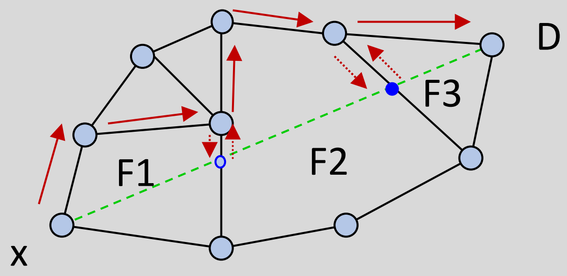
- A packet arriving at node x from node y will be forwarded along the next edge counterclockwise from edge (x, y).
- Right hand rule traverses the interior of a polygonal region (face) in clockwise order (x → z → y → x).



# 2. Wireless Sensor Network Routing Protocols

## 3.1.2 Perimeter Routing

- Packet is forwarded around a face intersected by xD using right hand rule until an edge is reached which intersects xD.
- Forwarding around next face
- …



# 2. Wireless Sensor Network Routing Protocols

## 3.2.1 Geographic Hash Tables

- Hashing of a key (name of object, e.g., “forest fire”) into geographic coordinates
- Storage of a key-value pair at the sensor node geographically nearest of its key
- Data Centric Storage:
  Data are stored at a node determined by the name associated with sensed data.

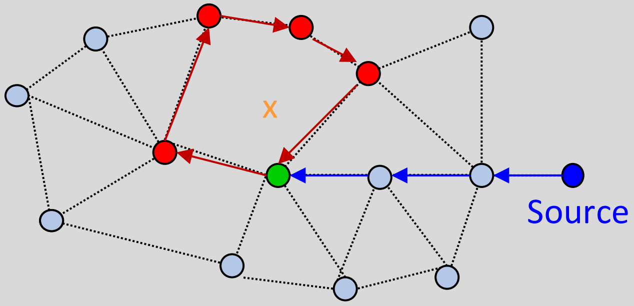
- Advantages
  - All events of a single type are stored at a certain node.
  - Query flooding can be avoided.
- Operations: Put and Get

# 2. Wireless Sensor Network Routing Protocols



## 3.2.2 GHT: Home Node and Home Perimeter

- Home node = node geographically nearest to the destination coordinates of a packet
  - serves as synchronization point for Put and Get operations.




- GPSR routing
  - Packet will enter perimeter routing at home node and then traverse the entire perimeter (home perimeter) that encloses the destination.
- A node becomes a home node when a Put packet arrives after completing its tour around home perimeter.

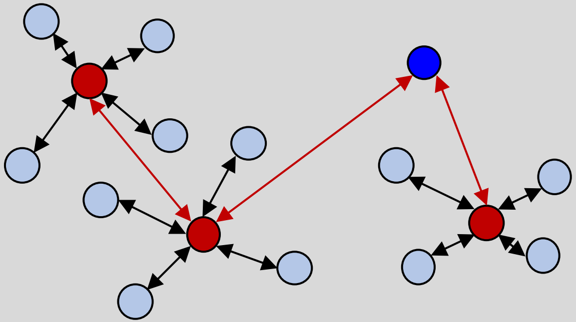
# 2. Wireless Sensor Network Routing Protocols

## 4.1 Hierarchical Routing

- Creation of clusters and assigning special tasks to cluster leaders
- Sensor nodes perform sensing tasks and deliver sensor data to cluster leaders.
- Cluster leaders
  - aggregate received sensor data and
  - forward data (via other cluster leaders) to sink.

**Examples**

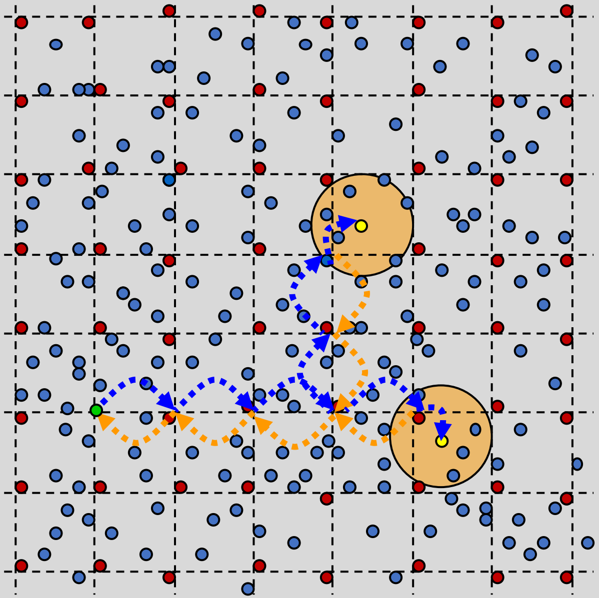
- Low Energy Adaptive Clustering Hierarchy
- Two-Tier Data Dissemination



# 2. Wireless Sensor Network Routing Protocols

## 4.2 Two-Tier Data Dissemination

- Sensors are aware of own location.
- Sensor becomes source of an event.
- Greedy geographical forwarding
- Grid construction
  - Source defines cell size and is located at crossing point.
  - Source sends advertisements to all 4 adjacent crossing points, which become dissemination nodes of the source.
  - Dissemination nodes forward advertisements to adjacent crossing points except the one from which it has been received.
- Query and data forwarding (using soft states) along dissemination nodes of source



# 3. IPv6 in Wireless Sensor Networks



- IP in wireless sensor networks
  - Standard protocols and APIs
  - No need for protocol translation
- Proposal
  - Use IPv6 in networks with low-power devices and lossy wireless networks
  - IPv6 offers address space for massive deployment in many small devices.

**Problems**

- Large transmission overhead by standard IPv6 header (40 bytes)
- IPv6 requires Minimum Transmission Unit of 1280 bytes, whereas IEEE 802.15.4 limits the frame length to 128 bytes to ensure low packet error rate.
- Small devices such as sensors can not run complex routing protocols.
- Low-power and Lossy Networks with temporary disruptions

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# 3. IPv6 in Wireless Sensor Networks

## 1. IETF Working Groups

- IPv6 over Low power Wireless Personal Area Networks (6lowpan, concluded)
  - defines adaptation layer between IP and link layer, e.g., IEEE 802.15.4.
  - 6LowPAN: collection of nodes sharing the same IPv6 prefix
- IPv6 over Networks of Resource-constrained Nodes (6lo)
  - Continuation of 6lowpan WG
  - Header compression
- Routing Over Low power and Lossy networks (roll)
  - defines requirements and specifies routing protocols for their use in LLNs.
  - Example: IPv6 Routing Protocol for LLNs supports multipoint-to-point and point-to-multipoint traffic
- IPv6 over the TSCH mode of IEEE 802.15.4e (6TiSCH)
  - IPv6 over IEEE 802.15.4 timeslotted channel hopping (TSCH) mode
- IPv6 over Low Power Wide-Area Networks (lpwan)
  - IPv6 over LPWAN technologies such as 5G NB-IoT, LoRaWAN etc.
  - Issues of header compression

# 3. IPv6 in Wireless Sensor Networks

## 2.1 IETF 6LowPAN Routing Options

**Mesh Under**

- Link-layer forwarding
- No IP routing in LoWPAN nodes
- Adaptation layer masks lack of broadcast by transparent routing and forwarding
- Emulation of a broadcast link

**Route Over**

- Routing at IP layer
- Each LoWPAN node serves as IP router.
- Limited resources, in particular memory for routing tables

# 3. IPv6 in Wireless Sensor Networks

## 2.2 IETF 6LoWPAN Adaptation Layer Services

**Header Compression**

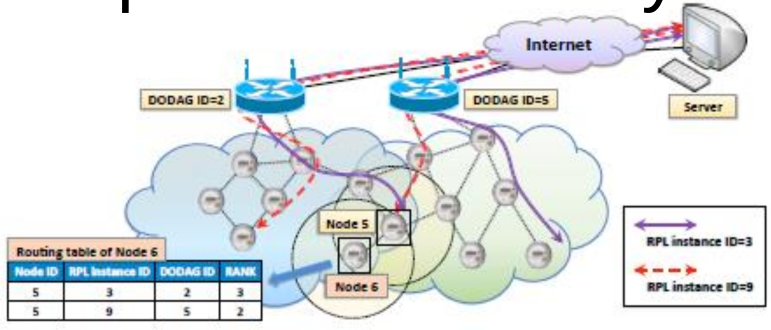
- IPv6 Header Compression
  - Certain fields in an IPv6 header, e.g., Version, Traffic Class, Flow Label, carry usual values.
  - Payload Length can be inferred from link layer information.
  - IP addresses are inferred from MAC address, often link local addresses.
- UDP Header Compression
  - Possible checksum elision
  - Length field can be inferred from link layer information.
  - Port number compression by using ports of a certain range
- Generic Header Compression
  - LZ77 byte code

| | | | |
|---|---|---|---|
| Mesh Header | Fragm. Header | Comp. Header | IPv6 Payload |

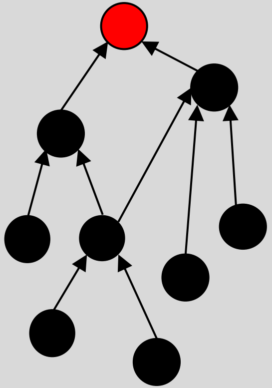
- Fragmentation into multiple link-level frames to accommodate MTU requirement
- Link layer forwarding when multi-hop is used by the link layer (Mesh-Under Routing)
  - Mesh addressing header to carry originator and final destination addresses
  - Note: in 802.15.4 only for FFDs needed, RFDs always send to FFD

# 3. IPv6 in Wireless Sensor Networks

## 3.1 IPv6 Routing Protocol for Low-power and Lossy Networks




- Routing protocol developed in IETF working group ROLL "Routing Over Low-power and Lossy Networks"
- Design issues
  - lossy links
  - variable error rates
  - low resources (bandwidth and energy)
- RPL forms one or more Destination Oriented Directed Acyclic Graphs, with the root being the access point into the WSN.
  - DODAG depends on Objective Function measuring rank / distance of a node to root.
  - Nodes may include redundant paths by having multiple parents.
  - Storing or non-storing mode for downward routes
    → Nodes either store routing tables or do not store them.
    → Source routing by root in case of non-storing mode.
- Why not reactive MANET protocols?
  - Reactive routing protocols are susceptible to route breaks.
  - Link state routing protocols do not scale because of flooding global topology information.



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# 3. IPv6 in Wireless Sensor Networks

## 3.2 RPL Operation

**Upward Routing**

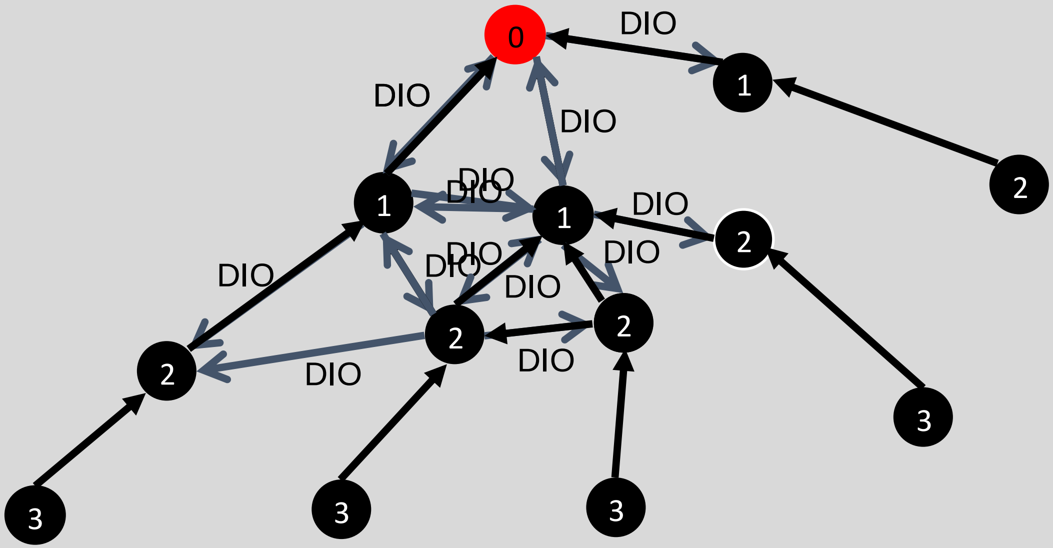
- *DODAG Information Object* messages (ICMP) are broadcast periodically (with increasing sequence number) for discovery, formation, and maintenance of the DODAG.
- Optionally DIO messages can be solicited by *DODAG Information Solicitation* messages.
- DIO includes
  - DODAG id
  - Rank: level of a node in the DODAG, depends on OF and is increased monotonically
  - Sequence number
  - Metric used in RPL might be ETX, which can be advertised by each node.

**Downward Routing**

- *Destination Advertisement Option* messages can be sent by leaf nodes to advertise path to root nodes.
- As a DAO message travels up the DODAG towards Root node, each node that it passes through appends its unique ID. Aggregation of DAO messages.

# 3. IPv6 in Wireless Sensor Networks

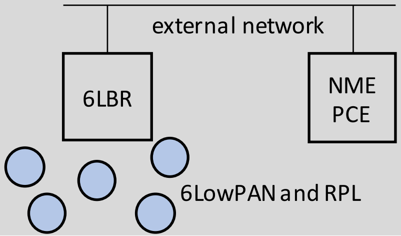
## 3.3 RPL Operation Example



# 3. IPv6 in Wireless Sensor Networks

## 4.1 IPv6 over the TSCH Mode of IEEE 802.15.4e (6TiSCH)

- IEEE 802.15.4 TSCH mode
  - targets industrial applications.
  - combines network-wide synchronization and channel hopping to achieve over 99.999 % end-to-end reliability and longer than a decade of battery lifetime.

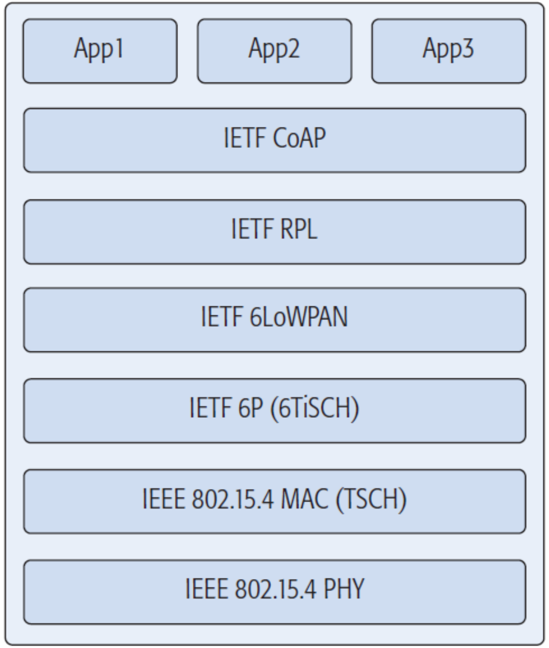



- Major functionality by 6TiSCH
  - support for scheduling transmissions of IPv6 packets by ensuring provision of schedule time to devices that is free from contention.
- Components
  - 6LowPAN Border Router (LLN Border Router)
  - Network Management Entity Path Computation Element

# 3. IPv6 in Wireless Sensor Networks

## 4.2 6TiSCH: 6top Protocol

- is a Logical Link Control layer between 6LoWPAN and TSCH MAC layer.
- provides a link abstraction to higher layers.
- defines a distributed scheduling protocol.
  - Neighbor nodes negotiate to add/remove cells in the TSCH schedule.
  - A cell is a "communication opportunity" for neighbor nodes to exchange a link layer frame.
  - Hard cells are managed by NME PCE, soft cells are managed locally among nodes.
- provides a set of interfaces/commands to upper layers supporting:
  - (i) creation of cell schedule with respect to slot offset and channel offset
  - (ii) transfer of data to TSCH once the schedule is established
  - (iii) retrieval of status information for management & monitoring.



# 3. IPv6 in Wireless Sensor Networks

## 5. IPv6 Low Power Wide Area Networks

- LPWAN components
  - End devices
  - Radio gateway
  - Network gateway or router
  - LPWAN-AAA server
  - Application server

| RuleID | Compression Residue | Payload |
|---|---|---|

compressed header

- Problems running IPv6 over LPWANs
  - IPv6 protocol overhead
  - IPv6 MTU requirement: 1280 byte packets
  - Neighbor Discovery with (too) large messages
- Solution
  - Static Context Header Compression
    - Header (De)Compression
      - Rule contains a list of Field Descriptors: Field Identifier, Field Length, Field Position, Direction Indicator, Target Value, Matching Operator, Compression/ Decompression Action
    - Fragmentation and Reassembly

# Thanks

# for Your Attention

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