Principles of Wireless Sensor Networks

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Lecture 6

Routing

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Course content

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  - Lec 2: Introduction to Programming WSNs
- Part 2
  - Lec 3: Wireless Channel
  - Lec 4: Physical Layer
  - Lec 5: Medium Access Control Layer
  - Lec 6: Routing
- Part 3
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  - Lec 10: Positioning and Localization
  - Lec 11: Time Synchronization
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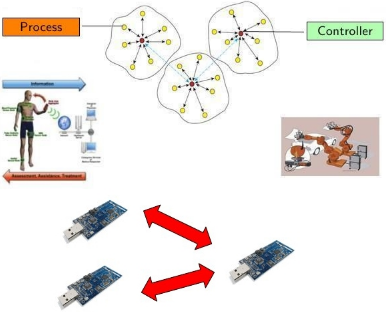
Previous lecture

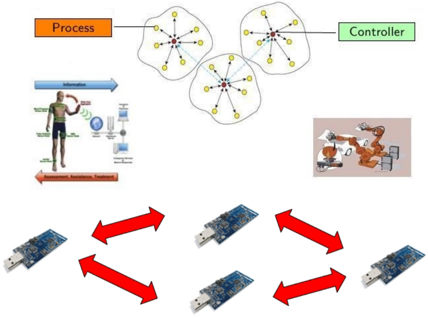
Application
Presentation
Session
Transport
Routing
MAC
Phy



- When a node gets the right to transmit?
- What is the mechanism to get such a right?

Today's lecture

Application
Presentation
Session
Transport
Routing
MAC
Phy



- On which path messages should be routed?

Today's learning goals

- What are the basic routing options?
- How to compute the optimal route?
- Which routing is used in standard protocols?

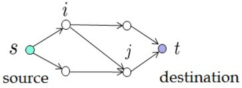
Outline

- Classification of routing protocols for WSNs
- The shortest path routing approach
- Routing algorithms used in standardized protocol stacks

Outline

- Classification of routing protocols for WSNs
- The shortest path routing
- Routing algorithms in standardized protocol stacks
  - IETF RPL
  - ZigBee
  - ISA100
  - WirelessHART

Routing protocols



- Define forwarding policies that allow a packet sent from an arbitrary source node to reach some destination node
- Routing information are contained into data structures (e.g., tables) that associate paths and costs to the possible destinations
  - How to collect and update routing information?
  - How to use routing information during network operation?
- Challenges
  - Mobility: nodes may move, changing neighborhood relations
  - Lossy environment: links may break frequently

Routing protocols classification

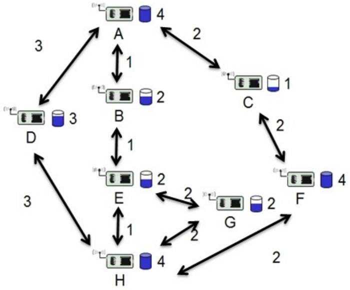
How is routing information collected and updated?

1. **Proactive:** the protocol always tries to keep its routing tables up-to-date and active before tables are actually needed
   - Destination Sequence Distance Vector (DSDV), based on Bellman-Ford search algorithm
   - Optimized Link State Routing Protocol (OLSR), based on Dijkstra's search algorithm
2. **Reactive:** a route is only determined when needed by a node
   - Ad-hoc On Demand Distance Vector (AODV), where the route information is distributed along the route
   - Dynamic Source Routing (DSR), where the route information is collected at the source
3. **Hybrid:** combine the previous two
   - Zone Routing Protocol (ZRP), proactive within each 'zone', reactive to reach other zones.

Routing policies

How is routing information used to select paths?

1. Path with minimum delay
2. Path with minimum packet error rate probability
3. Path with maximum total available battery capacity (sum of battery levels)
4. Path with minimum battery cost (sum of reciprocal battery levels)
5. Path with conditional max-min battery capacity (battery level above a given threshold)
6. Path with minimum variance in battery power levels
7. ...



Many options for routing

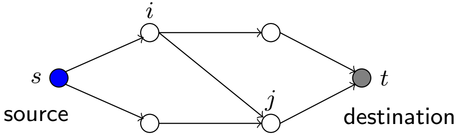
- Is there a basic and common way to model the different options?

- Yes, the shortest path problem

Outline

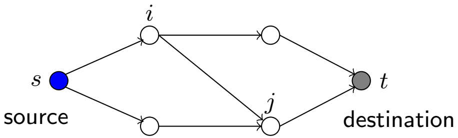
- Classification of routing protocols for WSNs
- The shortest path routing
- Routing algorithms for standardized protocol stack
  - IETF RPL
  - ZigBee
  - ISA100
  - WirelessHART

The shortest path routing



- The shortest path routing problem is a general optimization problem that models ALL the different metrics above, as long as they can be expressed as "additive" costs along the path
- In the following, we study the basic version, when in the network there is one source and one destination
- Multiple sources multiple destinations scenarios represent a simple extension

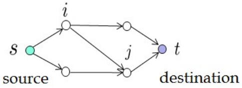
Definitions



N	Number of nodes
$\mathcal{N}$	Set of nodes
$\mathcal{A} = \{(i, j)\}$	Set of arcs
$\mathcal{G} = (\mathcal{N}, \mathcal{A})$	Network
a_{ij}	Routing cost on the link ij (e.g., delay)

What is the shortest (minimum cost) path from source s to destination t ?

The shortest path optimization problem



$$\min_{\mathbf{x}} \sum_{(i,j)\in\mathcal{A}} a_{ij}x_{ij}$$

$$\text{s.t.} \quad \sum_{j:(i,j)\in\mathcal{A}} x_{ij} - \sum_{j:(j,i)\in\mathcal{A}} x_{ji} = s_i \begin{cases} 1 & \text{if } i = s \\ -1 & \text{if } i = t \\ 0 & \text{otherwise} \end{cases}$$

$$x_{ij} \geq 0 \quad \forall (i,j) \in \mathcal{A}$$

$$\mathbf{x} = [x_{12}, x_{13}, ..., x_{i_n}, x_{i_{n+1}}, ...]$$

- x_{ij} is a binary variable.
- Note that x_{ij} can be also a real variable. However, if the optimization problem is feasible, the unique optimal solution is binary!

- The optimal solution gives the shortest source-destination path

The shortest path optimization problem

$$\min_{\mathbf{x}} \sum_{(i,j)\in\mathcal{A}} a_{ij}x_{ij}$$

$$\text{s.t.} \quad \sum_{j:(i,j)\in\mathcal{A}} x_{ij} - \sum_{j:(j,i)\in\mathcal{A}} x_{ji} = s_i \begin{cases} 1 & \text{if } i = s \\ -1 & \text{if } i = t \\ 0 & \text{otherwise} \end{cases}$$

$$x_{ij} \geq 0 \quad \forall (i,j) \in \mathcal{A}$$

- This problem is much more general and can be applied to
  1. Routing over WSNs
  2. Project management
  3. The paragraphing problem
  4. Dynamic programming
  5. ...

How to solve the shortest path problem

- Since it is an optimization problem, one could use standard techniques of optimization theory, such as Lagrangian methods
- However, the solution can be achieved by combinatorial algorithms that don't use optimization theory at all
- We consider now a combinatorial solution algorithm, called the **generic shortest path algorithm**
- The generic shortest path algorithm is the foundation of other more advanced algorithms widely used for routing such as
  1. Bellman-Ford method (see exercises)
  2. Dijkstra method (see exercises)

Complementary slackness conditions for the shortest path problem

A label d_j is associated to node j. The label can be either a scalar or ∞.

Proposition

Let $d_1, d_2, ..., d_N$ *be scalars such that*

$$d_j \leq d_i + a_{ij}, \quad \forall (i,j) \in \mathcal{A}$$

and let P *be a path starting at a node* i_1 *and ending at a node* i_k*.*
If

$$d_j = d_i + a_{ij}, \quad \forall (i,j) \; of \; P$$

then P *is a shortest path from* i_1 *to* i_k*.*

Generic shortest path algorithm: the idea in nuce

- Complementary Slackness conditions (CS) is the foundation of the generic shortest path algorithm
- Some initial vector of labels is assigned to nodes $(d_1, d_2, ..., d_N)$
- The arcs (i, j) that violate the CS condition $d_j > d_i + a_{ij}$ are selected and their labels redefined so that

  $d_j := d_i + a_{ij}$

- This redefinition is continued until the CS condition $d_j \leq d_i + a_{ij}$ is satisfied for all arcs (i, j)

Iterations of the generic shortest path algorithm

Let initially be $V = \{1\} \quad d_1 = 0, d_i = \infty, \ \forall i \neq 1$

Iteration of the Generic Shortest Path Algorithm

Remove a node i from the candidate list V. For each outgoing arc $(i, j) \in \mathcal{A}$, if $d_j > d_i + a_{ij}$, set

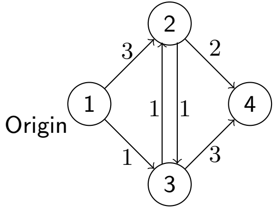
$$d_j := d_i + a_{ij}$$

and add j to V if it does not already belong to V

The removal rule gives

- Bellman-Ford method, distributed approach
- Dijkstra method, centralized approach

An example



Iteration	Candidate List V	Node Labels	Node out of V
1	$\{1\}$	(0,∞,∞,∞)	1
2	$\{2,3\}$	(0,3,1,∞)	2
3	$\{3,4\}$	(0,3,1,5)	3
4	$\{4,2\}$	(0,2,1,4)	4
5	$\{2\}$	(0,2,1,4)	2
	$\emptyset$	(0,2,1,4)	

Generic shortest path algorithm [Bertsekas, 1998]

Convergence of the algorithm

Proposition

Consider the generic shortest path algorithm.

(a) At the end of each iteration, the following conditions hold:

- *If* $d_j < \infty$, *then* d_j *is the length of some path that starts at 1 and ends at* j
- *If* $i \notin V$, *then either* $d_i = \infty$ *or else*
  $d_j \leq d_i + a_{ij}, \quad \forall j$ *such that* $(i, j) \in \mathcal{A}$

(b) If the algorithm terminates, then upon termination, for all j *with* $d_j < \infty$, d_j *is the shortest distance from 1 to* j *and*

$$d_j = \begin{cases} \mathit{min}_{(i,j)\in\mathcal{A}}(d_i + a_{ij}) & \textit{if } j \neq 1 \\ 0 & \textit{if } j = 1 \end{cases}$$

(c) If the algorithm does not terminate, then there exists some node j *and a sequence of paths that start at 1, ends at* j, *and have a length diverging to* $-\infty$

(d) The algorithm terminates if and only if there is no path that starts at 1 and contains a cycle with negative length.

Some consideration

- The convergence properties above are based on sound theoretical analysis
- They are the foundation over which routing protocols, such as the standardized IETF RPL, are built
- Let's have a quick look at RPL and other standardized routing protocols

Outline

- Classification of routing protocols for WSNs
- The shortest path routing
- Routing for standardized protocols
  - IETF RPL
  - ZigBee
  - ISA100
  - WirelessHART

Routing Protocol for Low Power Lossy Networks (RPL)

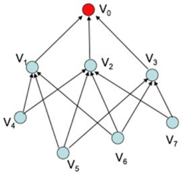
- RPL is a routing protocol standardized by the Internet Engineering Task Force (IETF) www.ietf.org/dyn/wg/charter/roll-charter.html
- RPL is specifically designed for wireless sensor networks.
- Application scenarios:
  - Home automation
  - Industrial automation
  - Healthcare
  - Smart grids

RPL assumptions

- Networks with many embedded nodes with limited power, memory, and processing
- Networks interconnected by a variety of protocols, such as IEEE 802.15.4, Bluetooth, Low Power WiFi, low power Powerline communications,...
- End-to-end Internet Protocol-based solution to avoid the problem of non-interoperable networks interconnected by protocol translation gateways and proxies
- Traffic patterns
  - Multipoint to Point (MP2P)
  - Point to Multipoint (P2MP)
  - Point-to-Point (P2P)

RPL is tree based

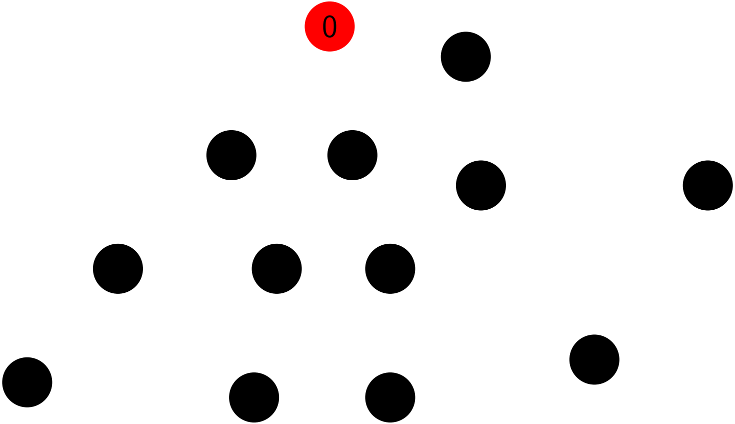
- RPL constructs destination-oriented directed acyclic graphs (DODAGs)
- Nodes build and maintain DODAGs by periodically multicasting messages, the DODAG Information Object (DIO), to their neighbors
- To join a DODAG, a node listens to the DIO messages sent by its neighbors and selects a subset of these nodes as its parents
- Packet forwarding metrics, the a_{ij} see above:
  1. Expected transmissions count (ETX),
  2. Packet delay,
  3. Node energy consumption,
  4. ...



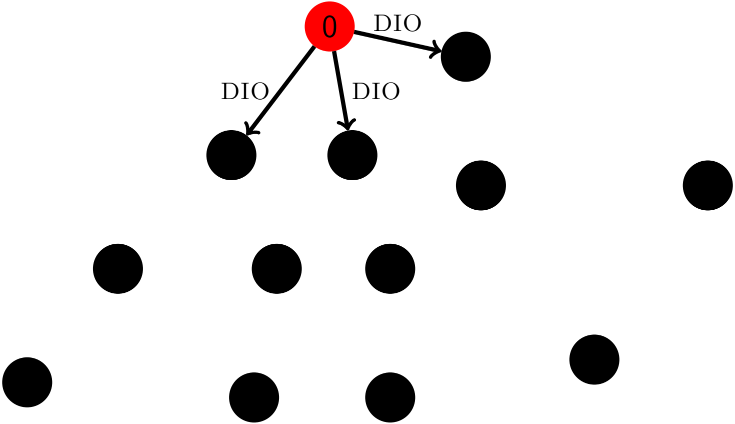
RPL DIO messages

- DODAG minimizes the cost to go to the root (destination node) based on the Objective Function
- DIO messages are broadcast to build the tree; DIO includes
  - A nodes rank (its level) d_j
  - Packet forwarding metric a_{ij}
- A node selects a parent based on the received DIO message and calculates its rank
- Destination Advertisement Option (DAO) messages are sent periodically to notify parent about routes to children nodes

Example



Example



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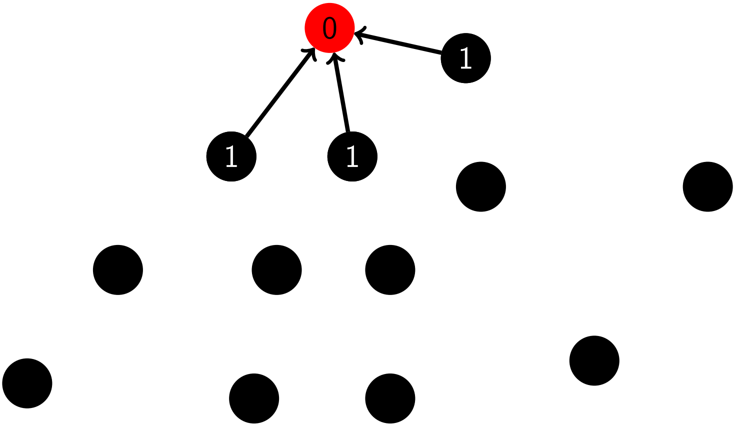

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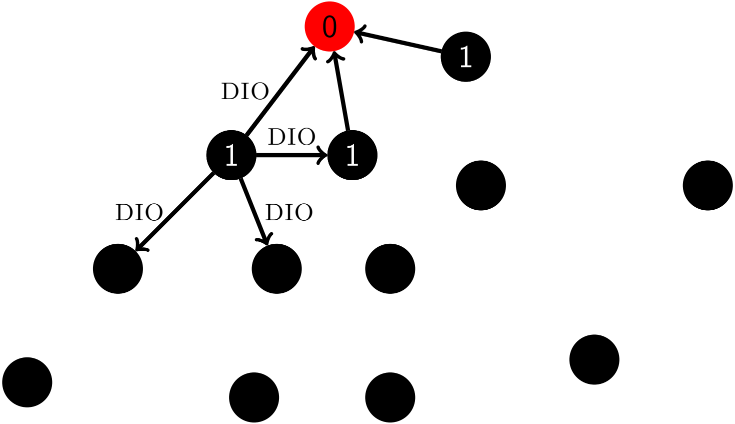

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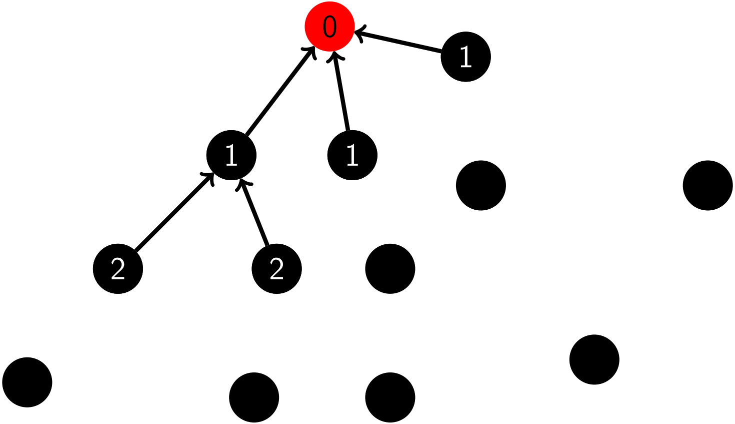

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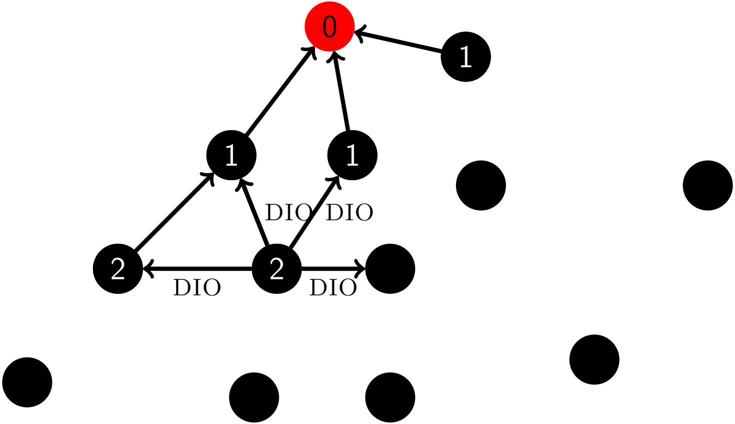

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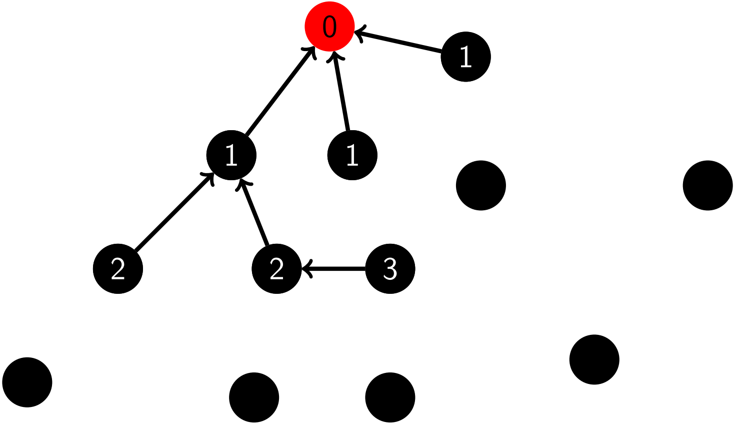

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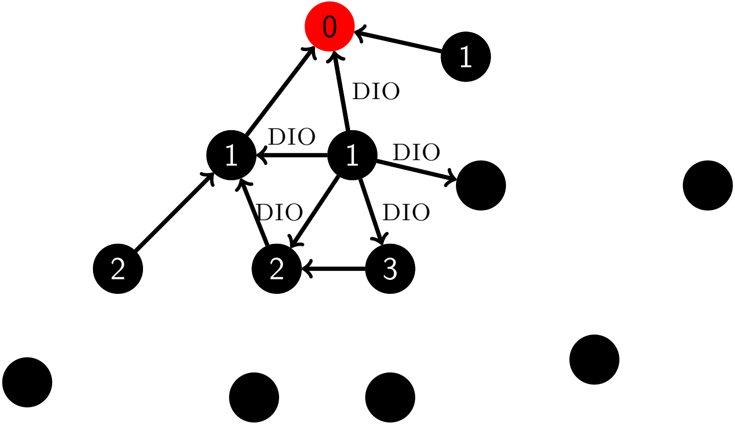

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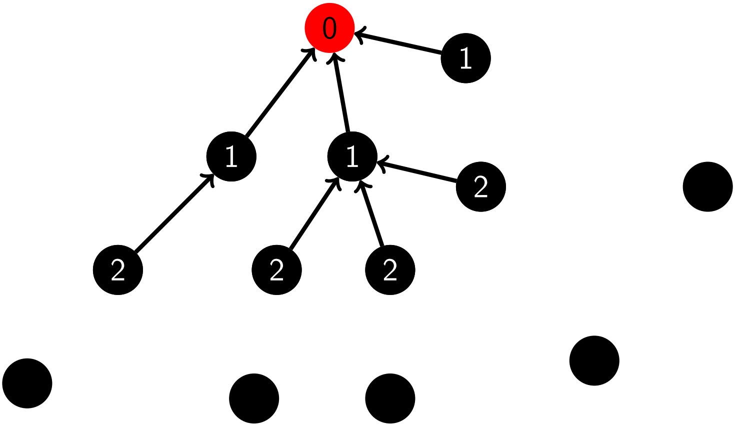

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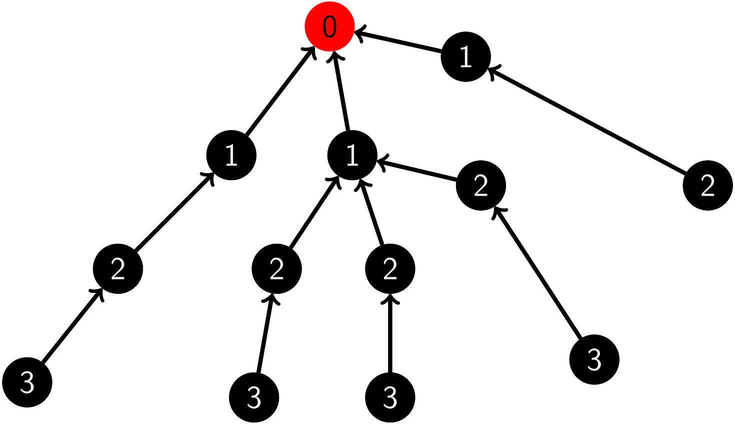


Other standardized protocol stacks

- In the following there is mention of other protocol stacks with standardized routing
- If you have time, read them. There will not be question on them at the exam

ZigBee

- The ZigBee Alliance www.zigbee.org defined standard networking and application layers on top of IEEE 802.15.4
- Nodes:
  - ZigBee End Devices
  - ZigBee Routers
  - ZigBee Coordinator: starts the network
- Networks: star, tree, mesh
- Routing characteristics
  - Tree routing: packets are sent to the coordinator, and then to the destination
  - Mesh routing: AODV protocol for route discovery
- No transport protocol for end-to-end reliability (only hop-by-hop)

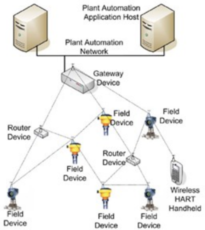
ISA-100

- The International Society of Automation (ISA www.isa.org) defines a family of standards for wireless systems in industrial automation and control applications.
- ISA-100.11a is a standard for non critical processes tolerating delays up to 100ms
- It is based on IEEE 802.15.4 plus a new data link layer and adaptation layer between MAC and data link
- Graph-based routing over mesh topologies.

Wireless HART

- Wireless HART (www.hartcomm.org) is another communication standard designed for process measurements and control applications
  1. Centralized management
  2. Strict timing requirements
  3. Security

WirelessHART network



- Field device, attached to the plant process
- Handheld, a portable computer to configure devices, run diagnostic and perform calibrations
- Gateway, that connect host applications to field devices
- Network manager, responsible for configuring the network, scheduling and managing communication

WirelessHART network

- Topology: Star, Cluster, Mesh
- Central network manager: maintains up-to-date routes and communication schedules for the network
- Basic functionalities:
  - Timer
  - Network wide synchronization
  - Communication security
  - Reliable mesh networking
  - Central network management

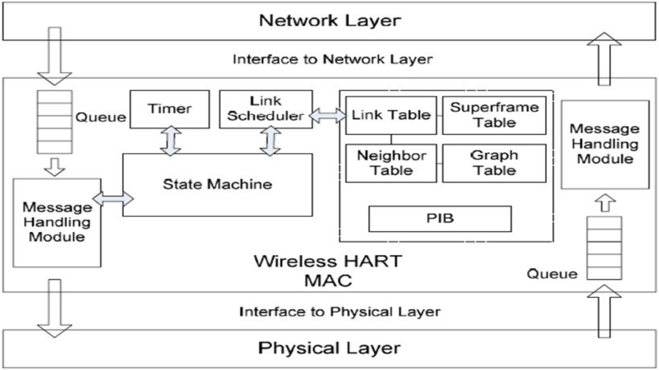
A Five Layers Architecture

OSI Layer	HART	
Application	Command Oriented. Predefined Data Types and Application Procedures	
Presentation		
Session		
Transport	Auto-Segmented transfer of large data sets, reliable stream transport, Negotiated Segment sizes	
Network		Power-Optimized Redundant Path, Mesh to the edge Network
Data Link	A Binary, Byte Oriented, Token Passing, Master/Slave Protocol	Secure, Time Synched TDMA/ CSMA, Frequency Agile with ARQ
Physical	Simultaneous Analog & Digital Signaling 4-20mA Copper Wiring	2.4 GHz Wireless, 802.15.4 based radios, 10dBm Tx Power
	Wired FSK/PSK & RS 485	**Wireless 2.4 GHz**

Layers

- Physical layer:
  - Similar to IEEE 802.15.4
  - 2.4-2.4835 GHz, 26 channels, 250 Kbps per channel
- Data link layer:
  - Network wide synchronization (a fundamental functionality)
  - TDMA with strict 10ms time slots
  - Periodical superfames
  - Channel blacklisting: the network administrator removes the channels with high interference
  - Pseudorandom change of the channel for robustness to fading
  - TDMA security: industry-standard AES-128 ciphers and keys

WirelessHART MAC



WirelessHART Graph Routing

- Graph: collection of paths that connect network nodes
- Graph's paths are created by the network manager and downloaded to each node
- To send a packet, the source node writes a specific graph ID (determined by the destination) in the network header
- All network devices on the way to the destination must be pre-configured with graph information that specifies the neighbors to which the packets may be forwarded

WirelessHART Source Routing

- Source Routing is a supplement of the graph routing aiming at network diagnostics
- To send a packet to destination, the source node includes in the header an ordered list of devices through which the packet must travel
- As the packet is routed, each routing device utilizes the next network device address in the list to determine the next hop until the destination device is reached

Summary

- We have studied routing protocols
- The theoretical foundation of routing is the shortest path optimization problem
  - It gives the basic mechanisms that aim at optimal routing
  - These mechanisms are included in existing WSN standards such as IETF RPL, ZigBee, ISA100, WirelessHart

Next Lecture

- By this lecture, we concluded the networking part of the course
- We move to the signal processing part
  - Distributed detection, i.e., how to reliably detect the happening of events by a WSN