Principles of Wireless Sensor Networks

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Lecture 5

Medium Access Control

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Course content

- Part 1
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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 8: Static Distributed Estimation
  - Lec 9: Dynamic Distributed Estimation
  - Lec 10: Positioning and Localization
  - Lec 11: Time Synchronization
- Part 4
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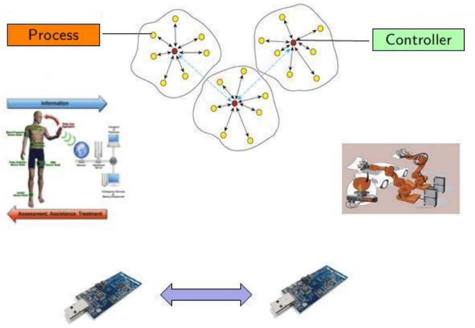
  - Lec 13: Wireless Sensor Network Control Systems 2

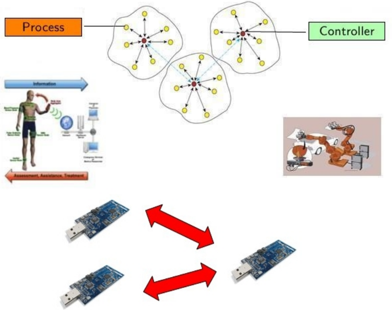
Previous lectures



- How information is modulated and transmitted over the wireless channel?
- What is the successful probability to receive bits?

Today's lecture

Application
Presentation
Session
Transport
Routing
MAC
Phy



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

Today's learning goals

- What is the Medium Access Control (MAC)?
- What are the options to design MACs?
- What is the MAC of IEEE 802.15.4?

Outline

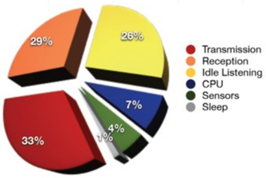
- Definition and classification of MACs
- The IEEE 802.15.4 protocol

Outline

- Definition and classification of MACs
  - TDMA, FDMA, CSMA, ALOHA
  - Hidden and exposed terminals
- The IEEE 802.15.4 protocol

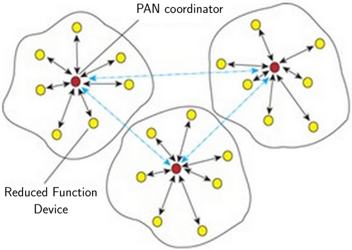
Medium Access Control - MAC

- MAC: mechanism for controlling when sending a message (packet) and when listening for a message
- MAC is one of the major components for energy expenditure in WSNs
  - Receiving packets is about as expensive as transmitting
  - Idle listening for packets is also expensive



Typical power consumption of a node

Problems for MACs



1. Collisions: wasted effort when two messages collide
2. Overhearing: wasted effort in receiving a message destined for another node
3. Idle listening: sitting idly and trying to receive a message when nobody is sending
4. Protocol overhead

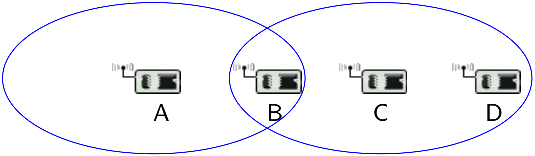
The hidden terminal problem

- Terminal, another word for node
- **Hidden** terminal problem:

The hidden terminal problem

- Terminal, another word for node
- **Hidden** terminal problem:

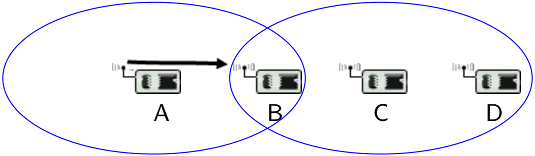
The hidden terminal problem



Transmit range:
(depends on the channel, transmit power,...)
distance past which the SNR is in outage

- Terminal, another word for node
- **Hidden** terminal problem:

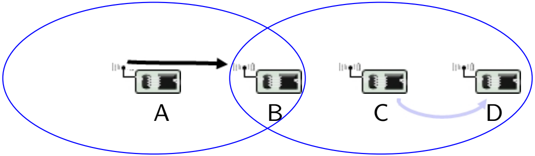
The hidden terminal problem



Transmit range:
(depends on the channel, transmit power,...)
distance past which the SNR is in outage

- Terminal, another word for node
- **Hidden** terminal problem:
  - Node A wants to send a message to B

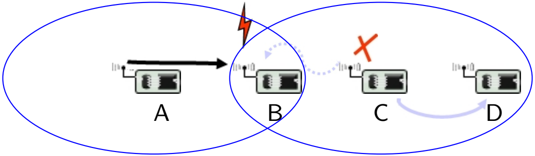
The hidden terminal problem



Transmit range:
(depends on the channel, transmit power,...)
distance past which the SNR is in outage

- Terminal, another word for node
- **Hidden** terminal problem:
  - Node A wants to send a message to B
  - Node C wants to send a message to D

The hidden terminal problem



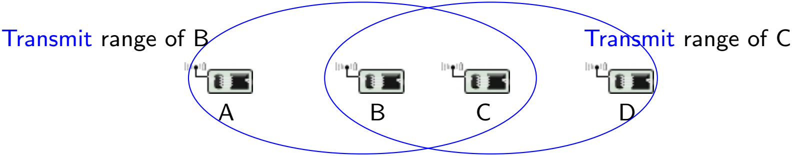
Transmit range:
(depends on the channel, transmit power,...)
distance past which the SNR is in outage

- Terminal, another word for node
- **Hidden** terminal problem:
  - Node A wants to send a message to B
  - Node C wants to send a message to D
  - Node A does not hear transmitter C sending messages that can be received by B and D

The exposed terminal problem

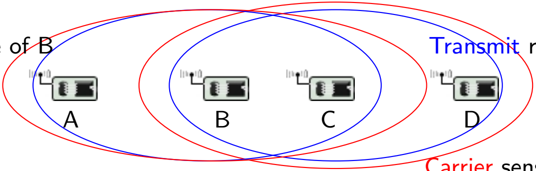
- **Exposed** terminal problem:

The exposed terminal problem



- **Exposed** terminal problem:

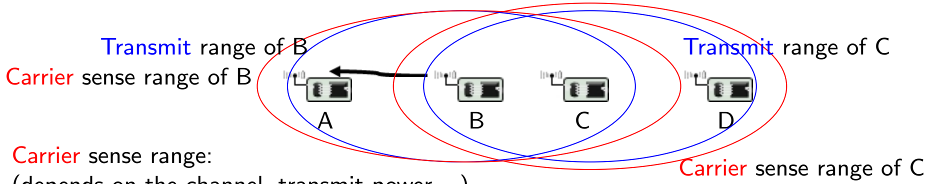
The exposed terminal problem



Carrier sense range:
(depends on the channel, transmit power,...)
distance within a transmitter can be heard/sensed at a receiver

- **Exposed** terminal problem:

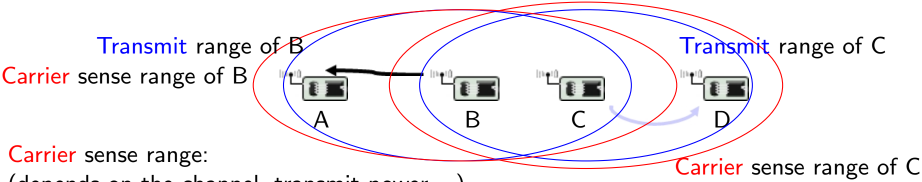
The exposed terminal problem



Carrier sense range:
(depends on the channel, transmit power,...)
distance within a transmitter can be heard/sensed at a receiver

- **Exposed** terminal problem:
  - B wants to send messages to A

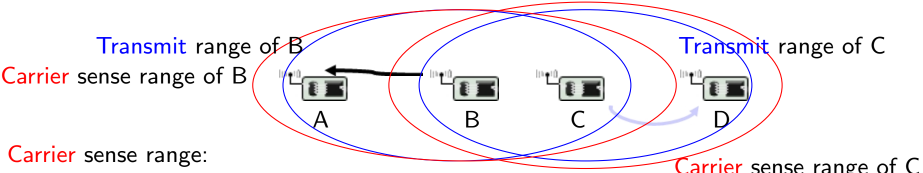
The exposed terminal problem



Carrier sense range:
(depends on the channel, transmit power,...)
distance within a transmitter can be heard/sensed at a receiver

- **Exposed** terminal problem:
  - B wants to send messages to A
  - C wants to send messages to D

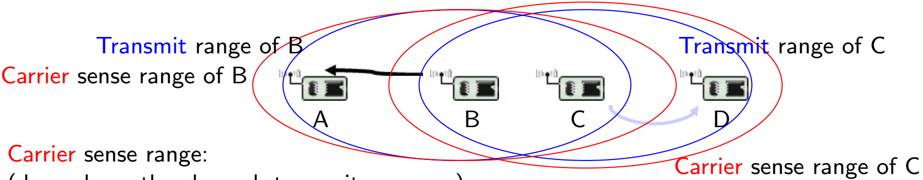
The exposed terminal problem



Carrier sense range:
(depends on the channel, transmit power,...)
distance within a transmitter can be heard/sensed at a receiver

- **Exposed** terminal problem:
  - B wants to send messages to A
  - C wants to send messages to D
  - Transmitter B hears transmitter C which is not causing collisions at the receiver A. A is not in the transmit range of C

The exposed terminal problem



Carrier sense range:
(depends on the channel, transmit power,...)
distance within a transmitter can be heard/sensed at a receiver

- **Exposed** terminal problem:
  - B wants to send messages to A
  - C wants to send messages to D
  - Transmitter B hears transmitter C which is not causing collisions at the receiver A. A is not in the transmit range of C
  - Transmitter C hears B, but D is not in the transmit range of B

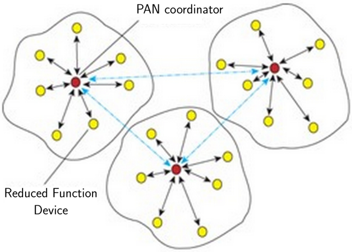
Important MACs for WSNs

- TDMA - Time Division Multiple Access
  - Time is divided into time slots
  - Every node is assigned to transmit at a time slot
- FDMA - Frequency Division Multiple Access
  - As TDMA, but is the carrier frequency to be divided into slots
- CSMA - Carrier Sense Multiple Access
  - A node listens (channel assessment) if the channel if free or busy from other transmissions
  - If free, transmit the message; if busy, back-off the transmission
- ALOHA
  - If a node has a message, it draws a random variable and transmits according to the outcome

TDMA

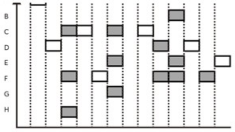
- A central node decides the TDMA schedules
  - Simple and no packet collisions
  - Burdens the central node coordinator
  - Not feasible for large networks

- TDMA is useful when network is divided into smaller clusters
  - In each cluster, MAC can be controlled at local head



Slotted ALOHA

n number of nodes attempting to transmit



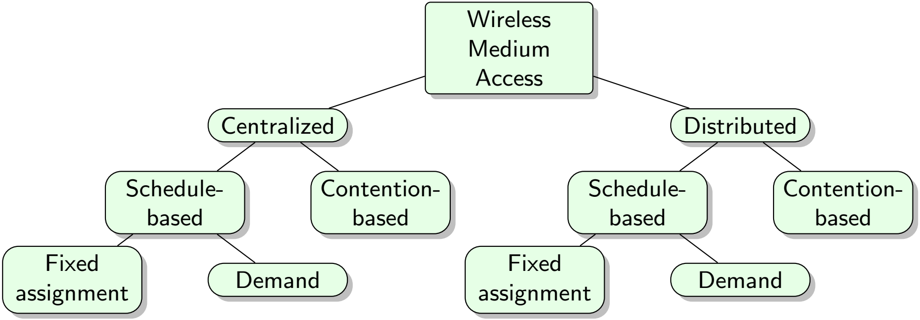
Time slots vs Node ID

- The slotted ALHOA works on top of TDMA
- Nodes are synchronized
- p probability that a node can transmit a message (because of free channel assessment)
- Probability of successful message transmission $p(1-p)^{n-1}$
- Probability that a slot is taken $n.p(1-p)^{n-1}$

Schedule and contention-based MACs

- Schedule-based MACs (TDMA, FDMA)
  - A schedule regulates which node may use which slot at which time
  - Schedule can be fixed or computed on demand
  - Collisions, overhearing, idle listening no issues
  - Time synchronization needed
- Contention-based MACs (CSMA, ALHOA)
  - Based on random access
  - Risk of packet collisions
  - Mechanisms to handle/reduce probability/impact of collisions required

More in general



Outline

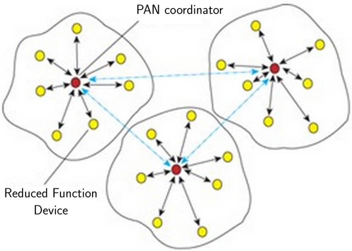
- Definition and classification of MACs
- The IEEE 802.15.4 protocol
  - Introduction
  - Physical layer
  - MAC layer

IEEE 802.15.4 protocol architecture

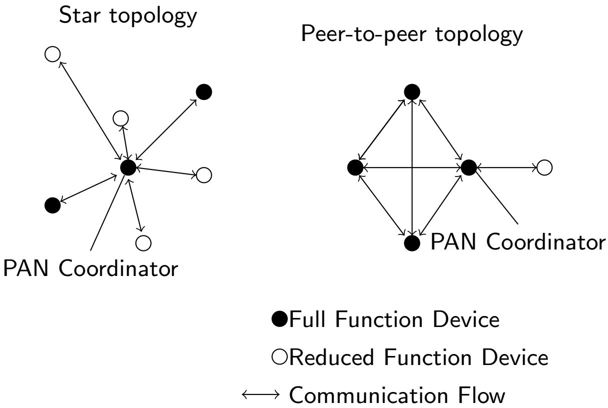
- Now we study the MAC of the standard IEEE 802.15.4
- IEEE 802.15.4 is the de-facto reference standard for low data rate and low power WSNs
- Characteristics:
  - Low data rate for ad hoc self-organizing network of inexpensive fixed, portable and moving devices
  - High network flexibility
  - Very low power consumption
  - Low cost

IEEE 802.15.4 networks

- IEEE 802.15.4 network composed of
  - Full-function device (FFD)
  - Reduced-function device (RFD)
- A network includes at least one FFD
- The FFD can operate in three modes:
  - A personal area network (PAN) coordinator
  - A coordinator
  - A device
- An FFD can talk to RFDs or FFDs
- RFD can only talk to an FFD

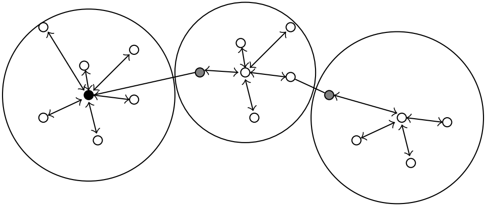


IEEE 802.15.4 network topologies



- 3 types of topologies
  - Star topology
  - Peer-to-peer topology
  - Cluster-tree

Cluster-tree topology

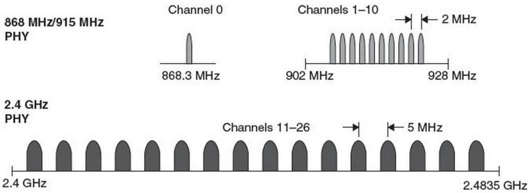


- First PAN Coordinator
- PAN Coordinator
- Device

IEEE 802.15.4 physical layer

- Frequency bands:
  - 2.4 - 2.4835GHz GHz, global, 16 channels, 250Kbps
  - 902.0 - 928.0MHz, America, 10 channels, 40Kbps
  - 868 - 868.6MHz, Europe, 1 channel, 20Kbps
- Features of the PHY layer
  - Activation and deactivation of the radio transceiver
  - Transmitting and receiving packets across the wireless channel
  - Energy detection (ED, from RSS)
  - Link quality indication (LQI)
  - Clear channel assessment (CCA)
  - Dynamic channel selection by a scanning a list of channels in search of beacon, ED, LQI, and channel switching

IEEE 802.15.4 physical layer



PHY (MHz)	Frequency band (MHz)	Spreading parameters		Data parameters		
		Chip rate (kchip/s)	Modulation	Bit rate (kb/s)	Symbol rate (ksymbol/s)	Symbols
868/915	868-868.6	300	BPSK	20	20	Binary
	902-928	600	BPSK	40	40	Binary
868/915868/915 (optional)(optional)	868-868.6	400	ASK	250	12.5	20-bit PSSS
	902-928	1600	ASK	250	50	5-bit PSSS
868/915868/915 (optional)(optional)	868-868.6	400	O-QPSK	100	25	16ary Orthogonal
	902-928	1000	O-QPSK	250	62.5	16ary Orthogonal
2450	2400-2483.5	2000	O-QPSK	250	62.5	16ary Orthogonal

Frequency bands and propagation parameters for IEEE 802.15.4 physical layer

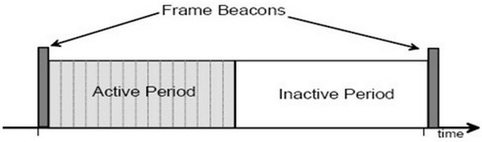
Physical layer data unit

		Octets		
		1		variable
Preamble	SFD	Frame length (7 bits)	Reserved (1 bit)	PSDU
SHR		PHR		PHY payload

SFD indicates the end of the SHR and the start of the packet data

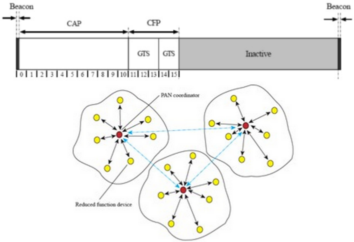
PHR: PHY header
PHY payload $<$ 128 byte

IEEE 802.15.4 MAC



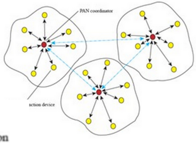
- The MAC provides two services:
  - Data service
  - Management service
- MAC features: beacon management, channel access, GTS management, frame validation, acknowledged frame delivery, association and disassociation

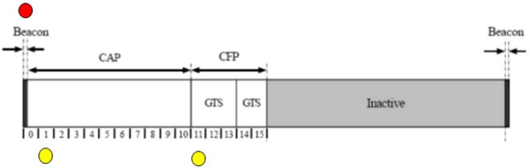
Superframes



- Superframe structure:
  - Format defined by the PAN coordinator
  - Bounded by network beacons
  - Divided into 16 equally sized slots
- Beacons
  - Synchronize the attached nodes, identify the PAN and describe the structure of superframes
  - Sent in the first slot of each superframe
  - Turned off if a coordinator does not use the superframe structure
- Superframe portions: active and an inactive
  - Inactive portion: a node does not interact with its PAN and may enter a low-power mode
  - Active portion: contention access period (CAP) and contention free period (CFP)
  - Any device wishing to communicate during the CAP competes with other devices using a slotted CSMA/CA mechanism
  - The CFP contains guaranteed time slots (GTSs)

IEEE 802.15.4 CSMA/CA





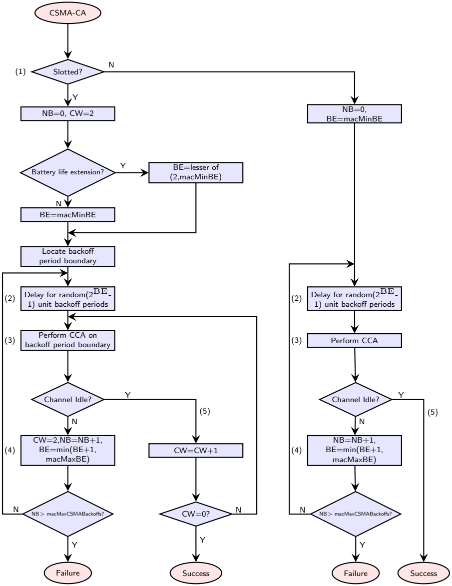
- A Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA) algorithm is implemented at the MAC layer
- If a superframe structure is used in the PAN, then slotted CSMA-CA is used in the CAP period
- If beacons are not used in the PAN or a beacon cannot be located in a beacon-enabled network, unslotted CSMA-CA is used

CSMA/CA

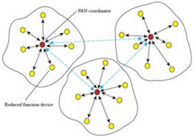
- Each device has 3 variables: NB, CW and BE
- NB: number of times the CSMA/CA algorithm was required to backoff while attempting the current transmission
  - It is initialized to 0 before every new transmission
- BE: backoff exponent
  - How many backoff periods a device shall wait before attempting to assess the channel
- CW: contention window length (used for slotted CSMA/CA)
  - Is the number of backoff periods that need to be clear of activity before the transmission can start
  - It is initialized to 2 before each transmission attempt and reset to 2 each time the channel is assessed to be busy

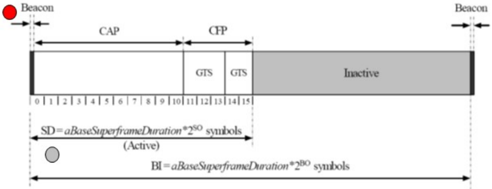
CSMA/CA

Flow diagram to transmit a packet with CSMA/CA in the modalities slotted (left, also called beacon modality) and unslotted (right, also called beaconless modality)



Guarantee Time Slot, GTS



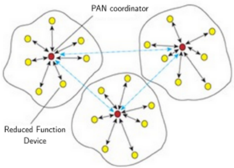


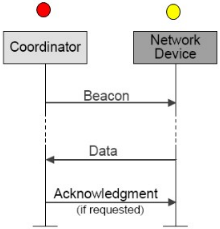
- The GTSs always appear at the end of the active superframe starting at a slot boundary immediately following the CAP
- The PAN coordinator may allocate up to 7 GTSs
- A GTS can occupy more than one slot period
- SO < 15. If SO$=15$, the superframe will not be active anymore after the beacon
- BO < 15. If BO$=15$, the superframe is ignored

GTS

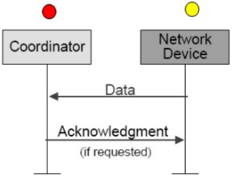
- A GTS allows a device to operate within a portion of the superframe that is dedicated exclusively to it
- A device attempts to allocate and use a GTS only if it is tracking the beacons
- GTS allocation:
  - Undertaken by the PAN coordinator only
  - A GTS is used only for communications between the PAN coordinator and a device
  - The GTS direction is specified as either transmit or receive
  - A single GTS can extend over one or more superframe slots

Uplink MAC: beacon and non-beacon-enabled



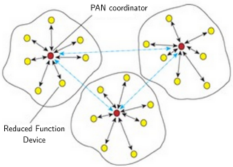


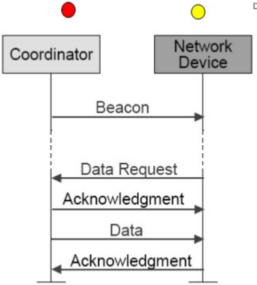
Communication to a coordinator in a beacon-enabled network



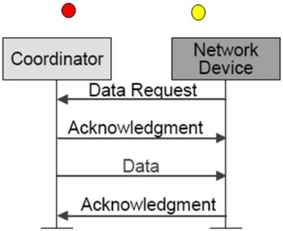
Communication to a coordinator in non-beacon-enabled network

Downlink MAC: beacon and non-beacon-enabled



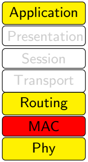


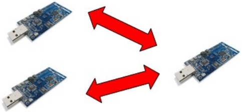
From a coordinator
in a beacon-enabled PAN



From a coordinator
in a nonbeacon-enabled PAN

Conclusions





- We have seen a MAC classification,
  - TDMA, ALOHA, CSMA
- Seen in detail the most popular protocol for WSNs, IEEE 802.15.4
- Identifying interdependencies between MAC protocol and other layers/applications is difficult
  - Which is the best MAC for which application?
  - Need of a MAC engine that optimally selects the best MAC for given conditions

Next lecture

- Now that we know how nodes get the right to access the wireless medium, we would like to see how a message is routed over possible paths
- Routing protocols
  - How a node decides to route a message?
  - What are the mechanisms to get such a decision?