Wireless Sensor Networks

12th Lecture

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CoNe Freiburg

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Overview

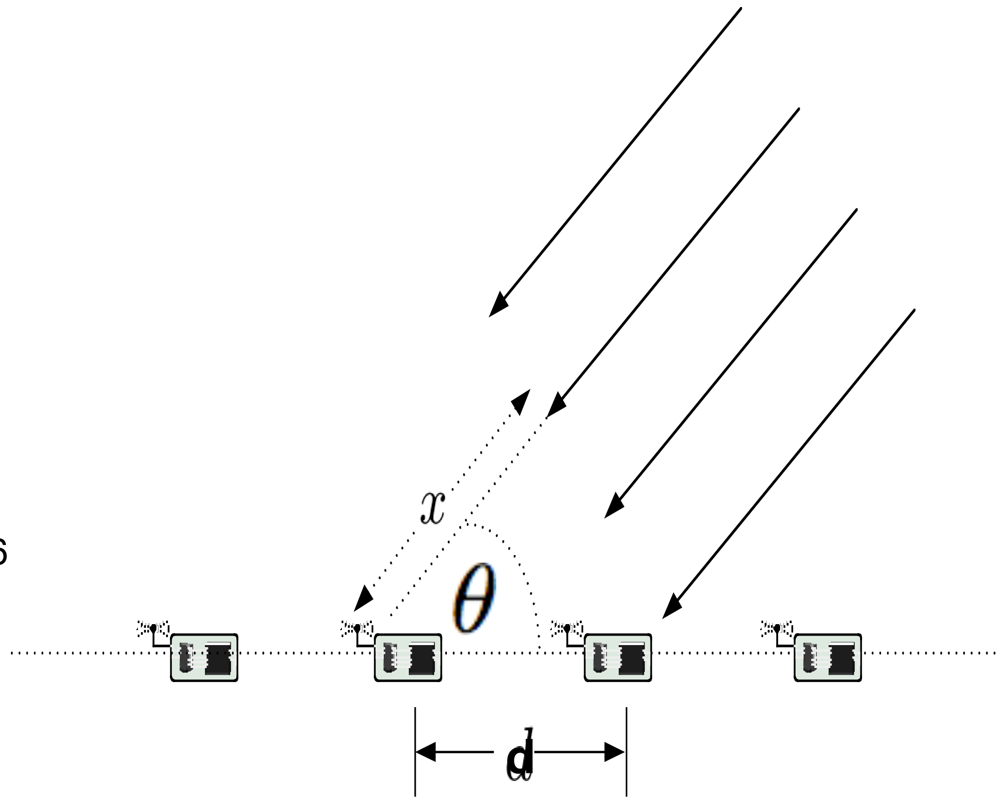
- **The time synchronization problem**
- **Protocols based on sender/receiver synchronization**
- **Protocols based on receiver/receiver synchronization**
- **Summary**

Example

- **Goal: estimate angle of arrival of a very distant sound event using an array of acoustic sensors**
- **From the figure, θ can be estimated when x and d are known:**

$$x = d \sin \theta$$

- **d is known a priori, x must be estimated from differences in time of arrival**
  - $x = C \Delta_t$ where C is the speed of sound
  - For d=1 m and $\Delta_t=0.001$ we get $\theta = 0.336$ radians = 19.3 degree
  - When Δ_t is estimated with 500 μs error, the θ estimates can vary between 0.166 and 0.518 radians (9.5 ... 29 degree)
- **Morale: a seemingly small error in time synch can lead to significantly different angle estimates**



The role of time in WSNs

- **Time synchronization algorithms can be used to better synchronize clocks of sensor nodes**
- **Time synchronization is needed for WSN applications and protocols:**
  - Applications:
    - Arrival of Angle estimation
    - beamforming
  - Protocols:
    - TDMA
    - protocols with coordinated wakeup, ...
  - Distributed debugging
    - timestamping of distributed events is needed to figure out their correct order of appearance

What MAC Relies on Synchronized Clocks?

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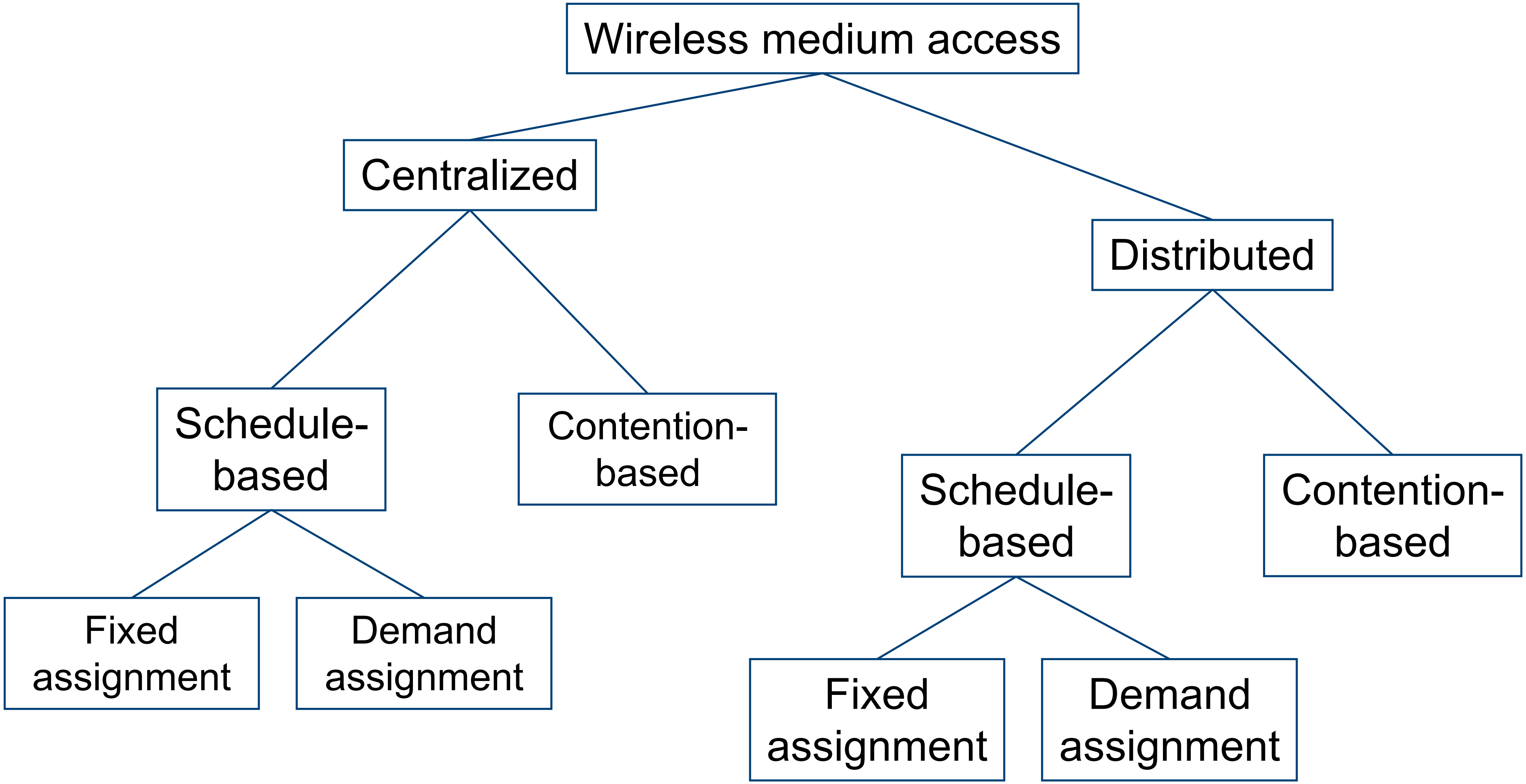

Repetition: Sensor-MAC (S-MAC)

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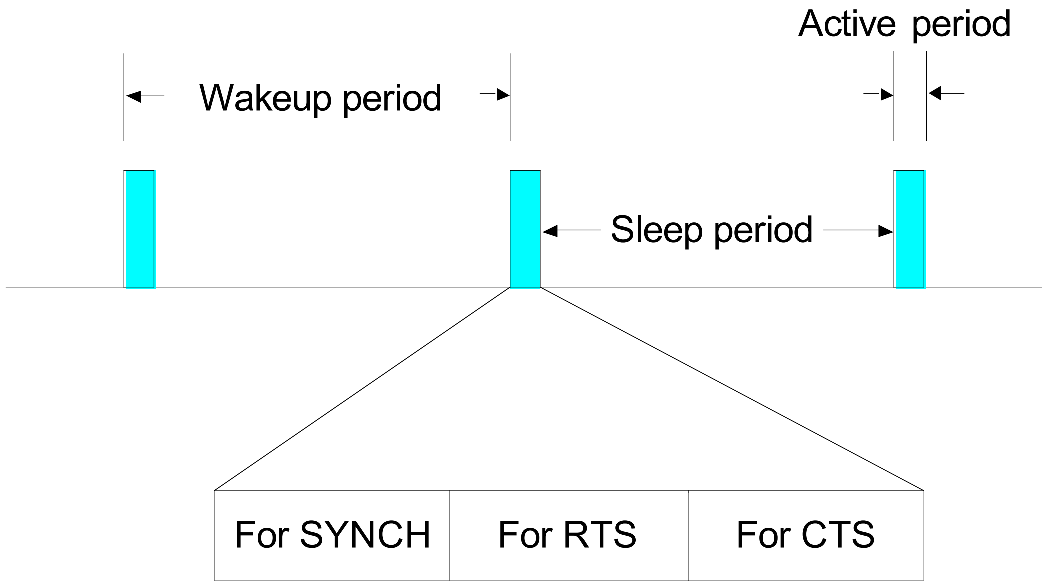
- **MACA's idle listening is particularly unsuitable if average data rate is low**
  - –Most of the time, nothing happens
- **Idea: Switch nodes off, ensure that neighboring nodes turn on simultaneously to allow packet exchange (rendez-vous)**
  - –Only in these ***active periods***, packet exchanges happen
  - –Need to also exchange wakeup schedule between neighbors
  - –When awake, essentially perform RTS/CTS
- **Use SYNCH, RTS, CTS phases**



Repetition: S-MAC synchronized islands

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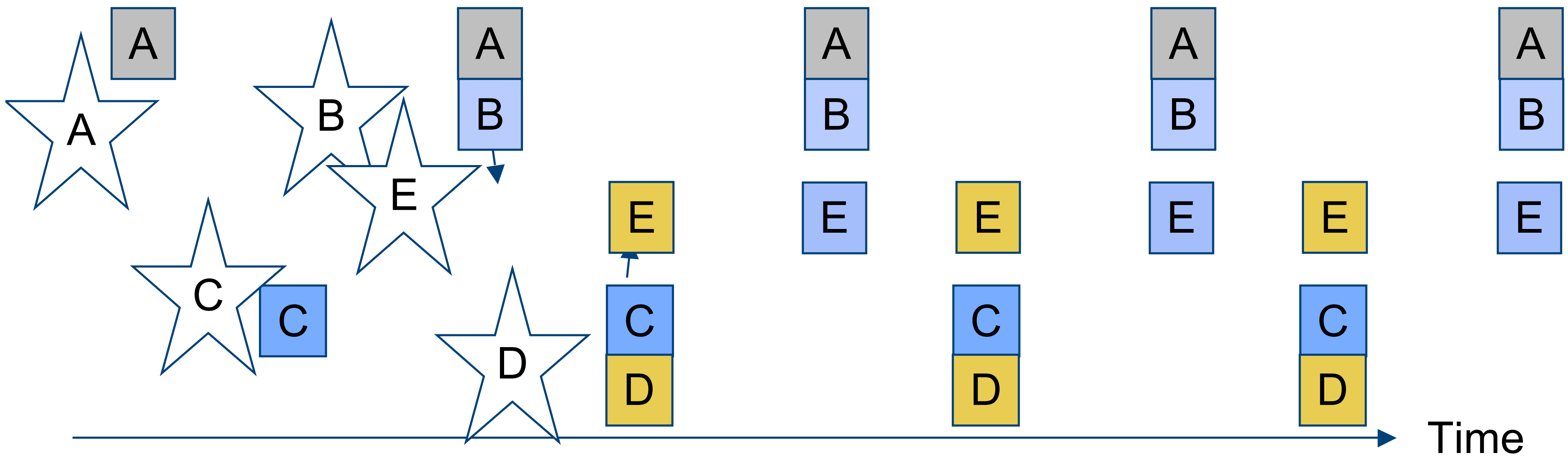
- **Nodes try to pick up schedule synchronization from neighboring nodes**
- **If no neighbor found, nodes pick some schedule to start with**
- **If additional nodes join, some node might learn about two different schedules from different nodes**
  - "Synchronized islands"
- **To bridge this gap, it has to follow both schemes**



Low-Energy Adaptive Clustering Hierarchy (LEACH)

- **Given: dense network of nodes, reporting to a central sink, each node can reach sink directly**
- **Idea: Group nodes into "*clusters*", controlled by** *clusterhead*
  - Setup phase; details: later
  - About 5% of nodes become clusterhead (depends on scenario)
  - Role of clusterhead is rotated to share the burden
  - Clusterheads advertise themselves, ordinary nodes join CH with strongest signal
  - Clusterheads organize
    - CDMA code for all member transmissions
    - TDMA schedule to be used within a cluster
- **In steady state operation**
  - CHs collect & aggregate data from all cluster members
  - Report aggregated data to sink using CDMA

SMACS
Self-Organizing Medium Access Control for Sensor Networks

- **Given: many radio channels, super-frames of known length (not necessarily in phase, but still time synchronization required!)**
- **Goal: set up directional *links* between neighboring nodes**
  - Link: radio channel + time slot at both sender and receiver
  - Free of collisions at receiver
  - Channel picked randomly, slot is searched greedily until a collision-free slot is found
- **Receivers sleep and only wake up in their assigned time slots, once per superframe**
- **In effect: a local construction of a schedule**

TRAMA
Traffic Adaptive Medium Access Protocol

- **Nodes are synchronized**
- **Time divided into cycles, divided into**
  - Random access periods
  - Scheduled access periods
- **Nodes exchange neighborhood information**
  - Learning about their two-hop neighborhood
  - Using ***neighborhood exchange protocol***: In random access period, send small, incremental neighborhood update information in randomly selected time slots
- **Nodes exchange schedules**
  - Using ***schedule exchange protocol***
  - Similar to neighborhood exchange
- **Adaptive Election Protocol**
  - Elect transmitter, receiver and stand-by nodes for each transmission slot
  - Remove nodes without traffic from election

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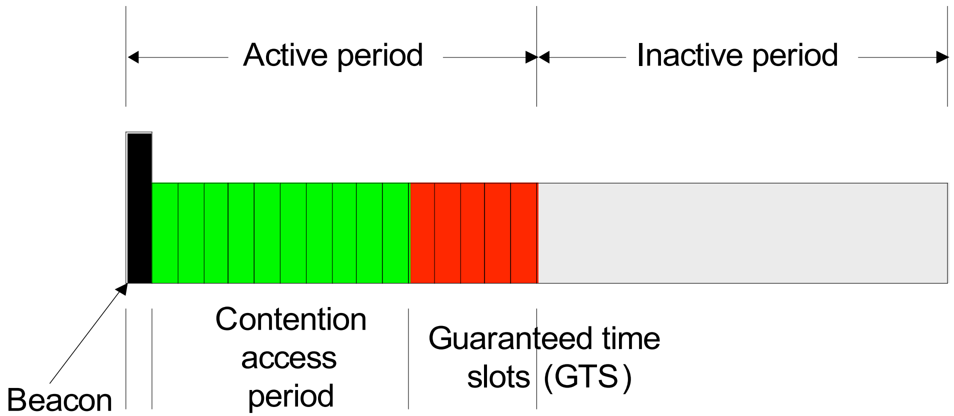
IEEE 802.15.4 MAC needs Synchronized Clocks

- **Star networks:** *devices* **are associated with** *coordinators*
  - Forming a PAN, identified by a PAN identifier
- **MAC protocol**
  - Single channel at any one time
  - Combines contention-based and schedule-based schemes
- **Beacon-mode superframe structure**
  - GTS assigned to devices upon request



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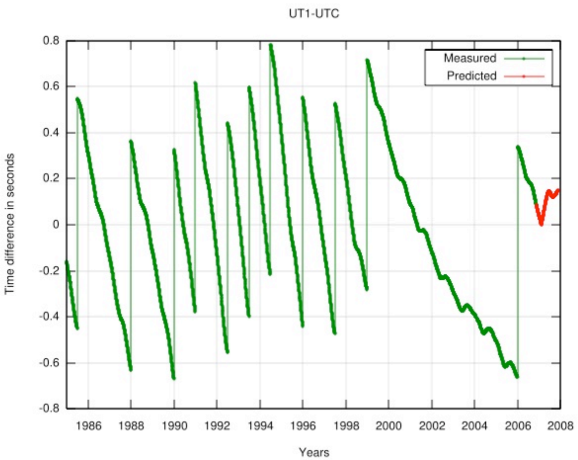
The role of time in WSNs

- **WSN have a direct coupling to the physical world,**
  - notion of time should be related to ***physical time***:
- **physical time = wall clock time, real-time**
  - one second of a WSN clock should be close to one second of real time
- **Commonly agreed time scale for real time is UTC**
  - Coordinated Universal Time
  - generated from atomic clocks
  - modified by insertion of leap seconds to keep in synch with astronomical timescales (one rotation of earth)
- **Universal Time (UT)**
  - timescale based on the rotation of earth
- **Other concept: logical time (Lamport**
  - relative ordering of events counts but not their relation to real time



Clocks in WSN nodes

- **Often, a *hardware clock* is present:**
  - Oscillator generates pulses at a fixed nominal frequency
  - A counter register is incremented after a fixed number of pulses
    - Only register content is available to software
    - Register change rate gives achievable time resolution
  - Node i's register value at real time t is $H_i(t)$
    - Convention: small letters (like t, t') denote real physical times, capital letters denote timestamps or anything else visible to nodes

- **A (node-local) software clock is usually derived as follows:**

$$L_i(t) = \theta_i H_i(t) + \phi_i$$

    - (not considering overruns of the counter-register)
  - θ_i is the (drift) rate, ϕ_i the phase shift
  - Time synchronization algorithms modify θ_i and ϕ_i, but not the counter register

Synchronization accuracy / agreement

- **External synchronization:**
  - synchronization with external real time scale like UTC
  - Nodes i=1, ..., n are accurate at time t within bound δ when

$$|L_i(t) - t| < \delta \text{ for all } i$$

    - Hence, at least one node must have access to the external time scale
- **Internal synchronization**
  - No external timescale, nodes must agree on common time
  - Nodes i=1, ..., n agree on time within bound δ when

$$|L_i(t) - L_j(t)| < \delta \text{ for all } i,j$$

Sources of inaccuracies

- **Nodes are switched on at random times**
  - phases θ_i are random
- **Actual oscillators have random deviations from nominal frequency**
  - (drift, skew)
- **Deviations are specified in ppm (pulses per million)**
  - the ppm value counts the additional pulses or lost pulses over the time of one million pulses at nominal rate
- **The cheaper the oscillators, the larger the average deviation**
  - For sensor nodes
    - values between 1 ppm (one second every 11 days) 100 ppm (one second every 2.8 hours) are assumed
  - Berkeley motes have an average drift of 40 ppm

Sources of inaccuracies

- **Oscillator frequency depends**
  - on time
    - oscillator aging and
  - environment
    - temperature
    - pressure
    - supply voltage, ...
- **Time-dependent drift rates are not sufficient**
  - frequent re-synchronization necessary
  - However, stability over tens of minutes is often a reasonable assumption

General properties of time synchronization algorithms

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- **Physical time versus logical time**
- **External versus internal synchronization**
- **Global versus local algorithms**
  - Keep all nodes of a WSN synchronized or only a local neighborhood?
- **Absolute versus relative time**
- **Hardware versus software-based mechanisms**
  - A GPS, Galileo, GLONASS receiver would be a hardware solution
  - German Broadcasts: A time signal from DCF77
    - Mainflingen, an atomic clock near Frankfurt at about 50.01′N 9.00′E can be received on 77.5 kHz to a range of about 2000 km.
  - Loran-C sends signals for synchronization
  - but often too
    - heavyweight
    - costly
    - energy-consuming in WSN nodes
    - line-of-sight to at least four satellites is required

General properties of time synchronization algorithms

- **A-priori vs. a-posteriori synchronization**
  - Is time synchronization achieved before or after an interesting event?
    - ➔ Post-facto synchronization
- **Deterministic vs. stochastic precision bounds**
- **Local clock update discipline**
  - Should backward jumps of local clocks be avoided?
    - Version control)
  - Avoid sudden jumps?

Performance metrics

- **Precision:**
  - Deterministic algorithms:
    - maximum synchronization error for deterministic algorithms,
  - Stochastic algorithms
    - error mean
    - standard deviation
    - quantiles for stochastic ones
- **Energy costs**
  - # of exchanged packets
  - computational costs
- **Memory requirements**
- **Fault tolerance: what happens when nodes die?**

Fundamental Building Blocks

- **Resynchronization event detection block:**
  - when to trigger a time synchronization round?
    - Periodically or after external event
- **Remote clock estimation block**
  - figuring out the other nodes clocks with the help of exchanging packets
- **Clock correction block**
  - compute adjustments for own local clock based on estimated clocks of other nodes
- **Synchronization mesh setup block**
  - figure out which node synchronizes with which other nodes

Thank you

(and thanks go also to Andreas Willig for providing slides)

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