A man with a watch knows what time it is.
A man with two watches is never sure.

Segal's Law

Fasika Assegei

A Decentralized Frame Synchronization of a TDMA-based Wireless Sensor Network

Fasika Assegei

Advisors: Frits van der Wateren
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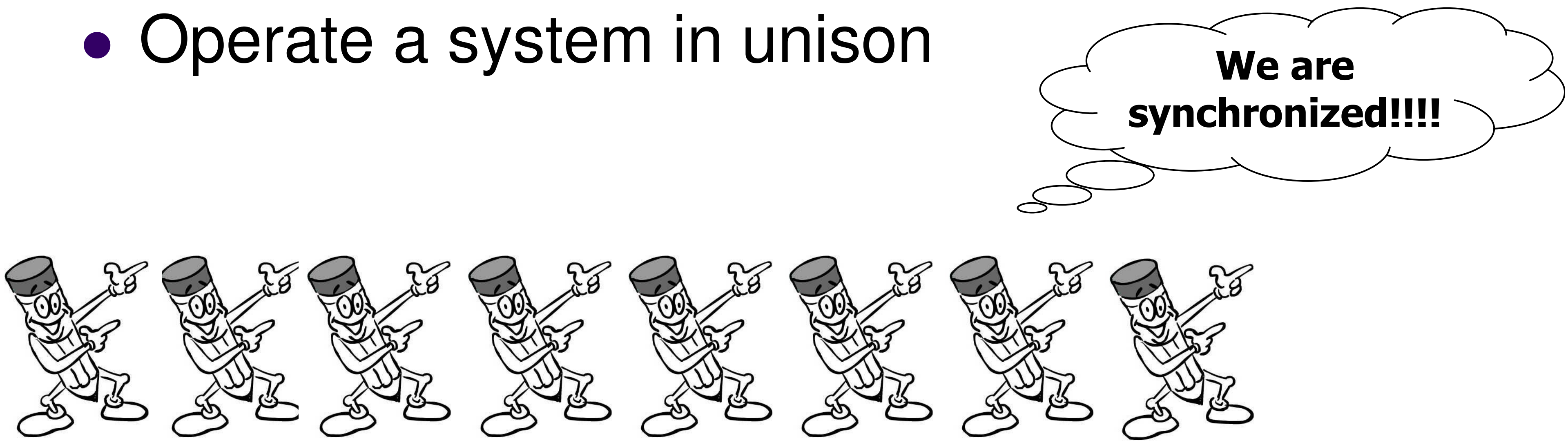
What is synchronization ?

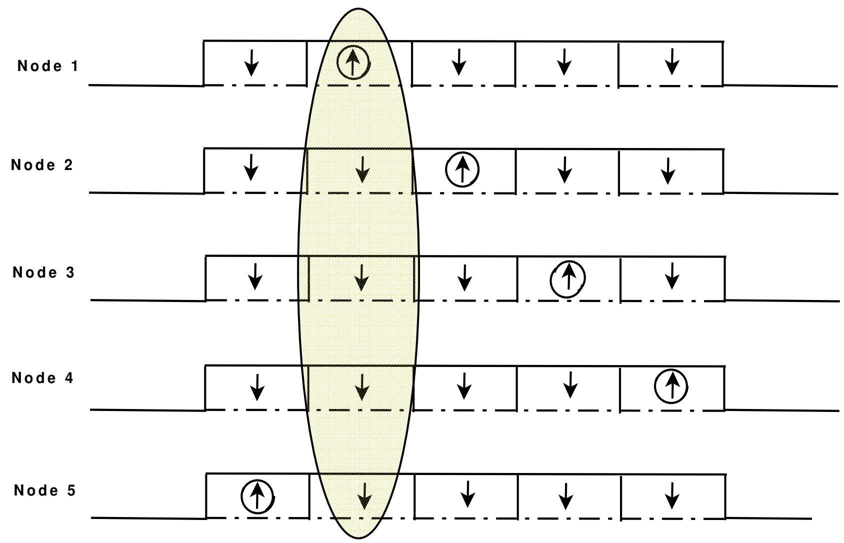
- Having the same time of reference
- Either global (UTC) or local (relative)
- Operate a system in unison

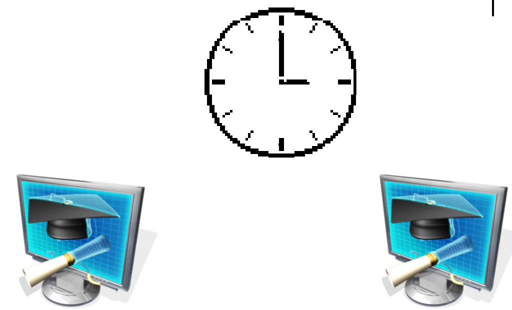


Why synchronization?

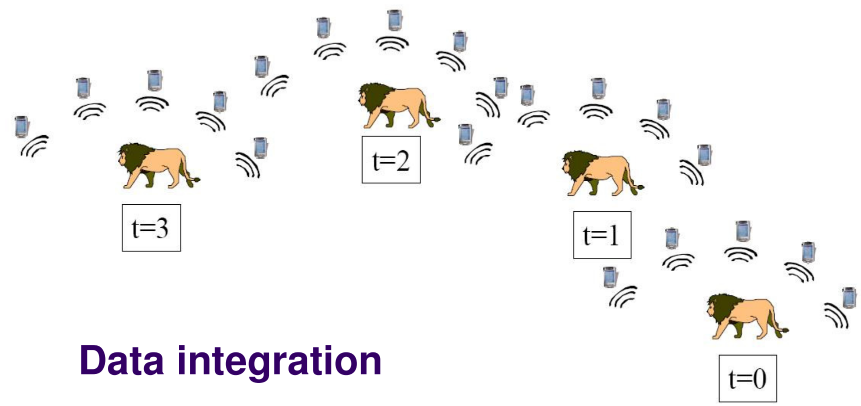
Time is God's way of keeping everything from happening at once.

TDMA Slots





NTP



Data integration

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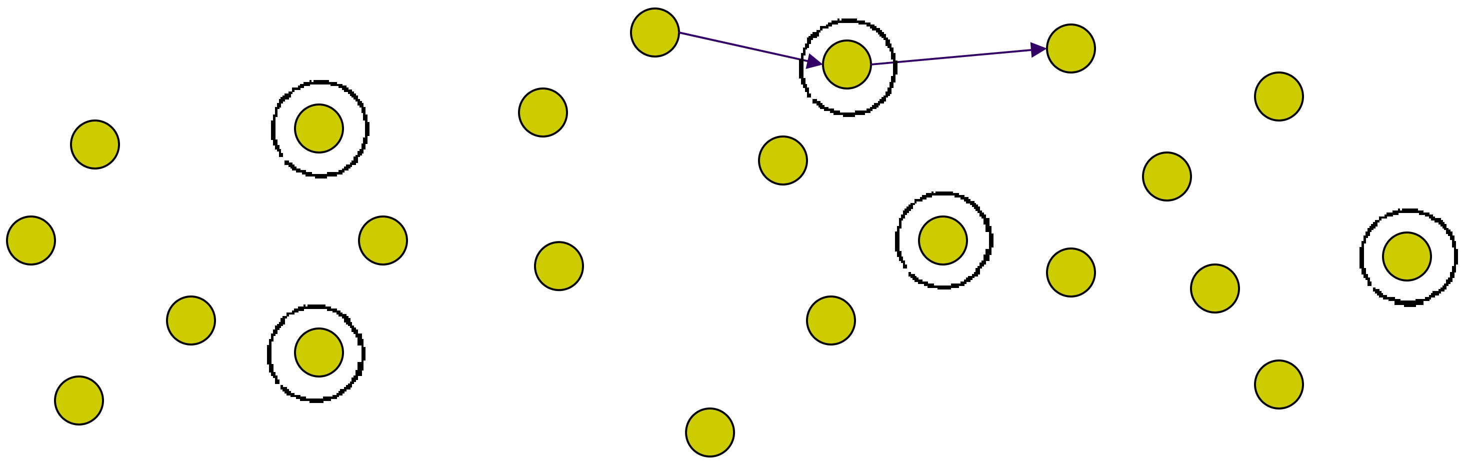
What now ?

- Isn't this a solved problem by now ???
  - NTP, MACs with sync built in (802.11), time broadcasts (GPS, WWVB), high-stability oscillators (Rubidium, Cesium)

- If this isn't the Internet:
  - Important assumptions no longer hold
    - (fewer resources -- such as energy, good connectivity, infrastructure, size, and cost -- are available)
  - Sensor apps have stronger requirements
    - (…but we have to do better than the Internet anyway)

Wireless Sensor Networks



- Wireless network of low **cost** sensors.
- Nodes communicate by **broadcasting.**
- **Multihop** communication needed in order to reach far-away destinations.

Wireless Sensor Networks: Why different ?

- Energy limitation
  - Each node has a limited battery life

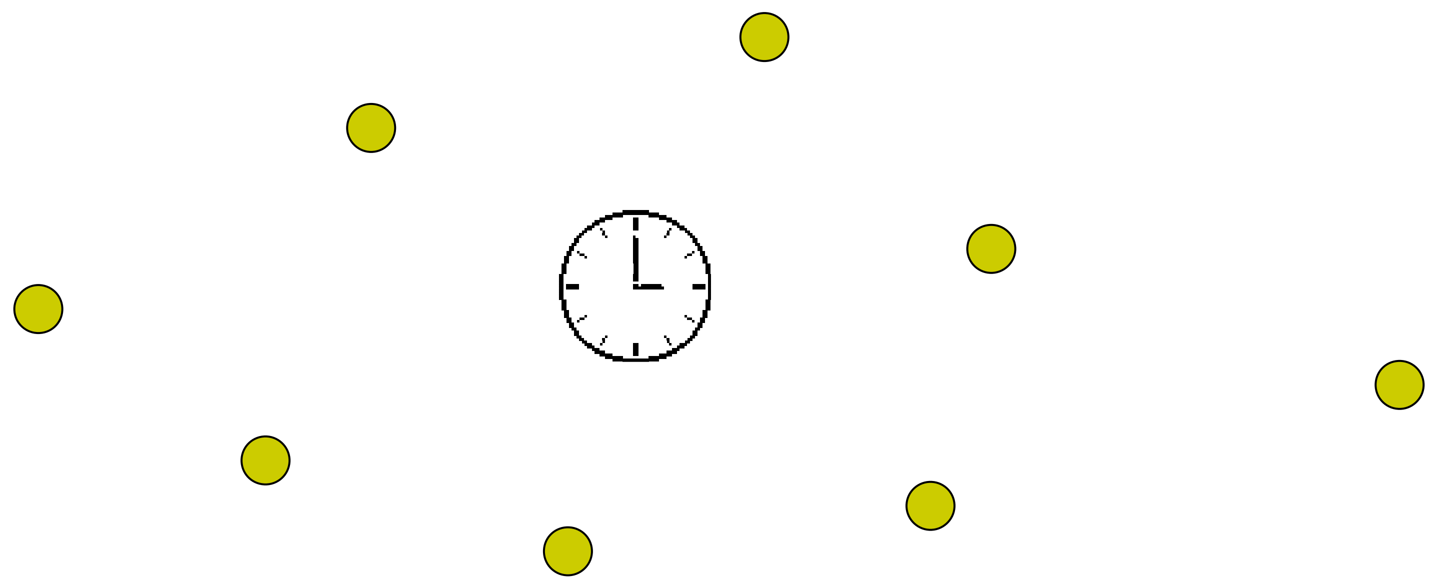
- Dynamic nature of the network, as well as inaccessibility
  - Mobility and interference

- Diverse applications
  - Relative and absolute reference

- Cost of node
  - Cheap node

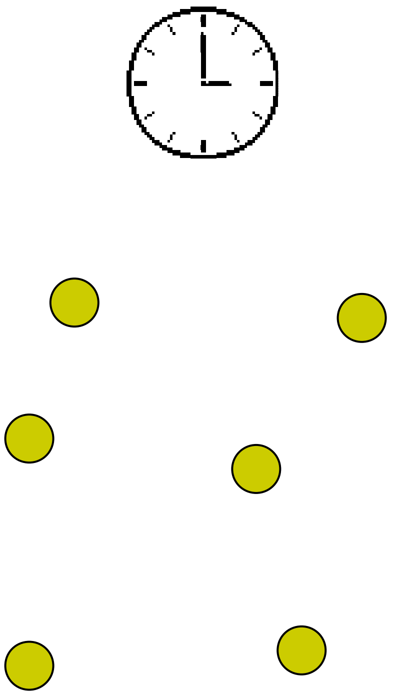
Synchronization Methods- Previously

- Centralized synchronization
  - Central reference time
  - Global or Relative



Synchronization Methods- Previously

- Receiver-Receiver
  - RBS (Receiver Broadcast Synchronization)



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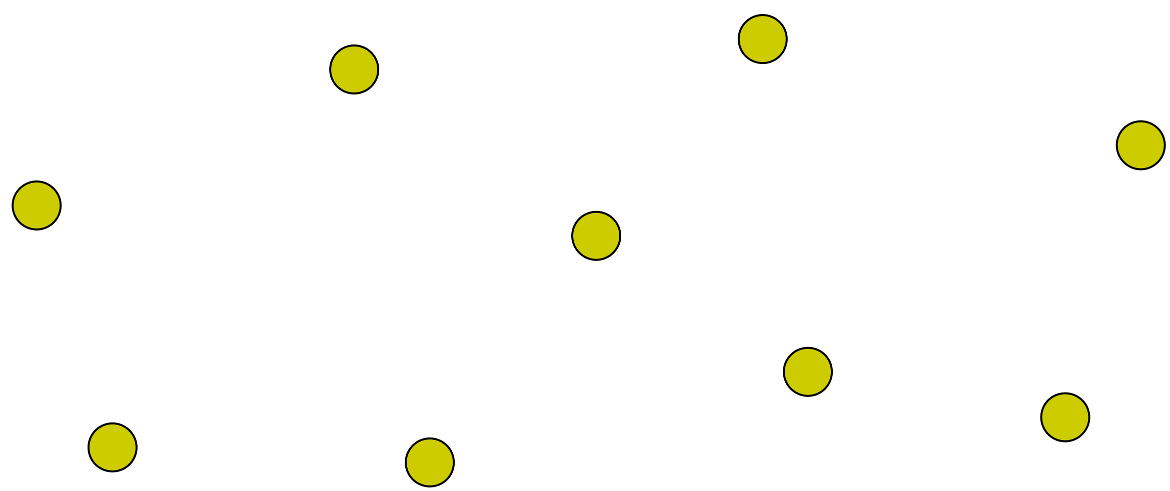
Synchronization Methods- Previously

- Decentralized synchronization
  - Estimation of the other's clock time



What is *NEW* here ?

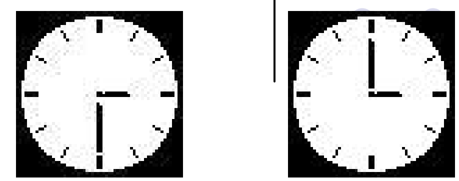
- Decentralized synchronization
  - Relative time references
- No time stamping
  - Low message overhead and no sync message
- Primarily using estimation (biased and unbiased)
- Energy efficient
  - Able to use as low energy as possible

Sources of Error

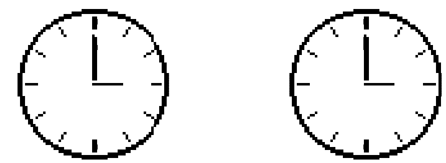
- Oscillator characteristics:
  - **Accuracy**: Difference between ideal frequency and actual frequency of the oscillator.
  - **Stability**: Tendency of the oscillator to stay at the same frequency over time.
- Network and System Parameters
  - **Receive and Transmit Delay**: Time duration between message generation and network injection.
  - **Propagation Delay**: Time to travel from sender to receiver.
  - **Access Delay**: Time to access the channel.

Definitions

- Phase error
  - Time difference between the clocks



- Frequency error
  - The difference in the rates of the clocks



- Clock cycle (*clk*)
  - The time between adjacent pulses of the oscillator

Clock Drift

From the relation of frequency and phase

$$\phi = \int f(t)dt$$

The clock time will be:

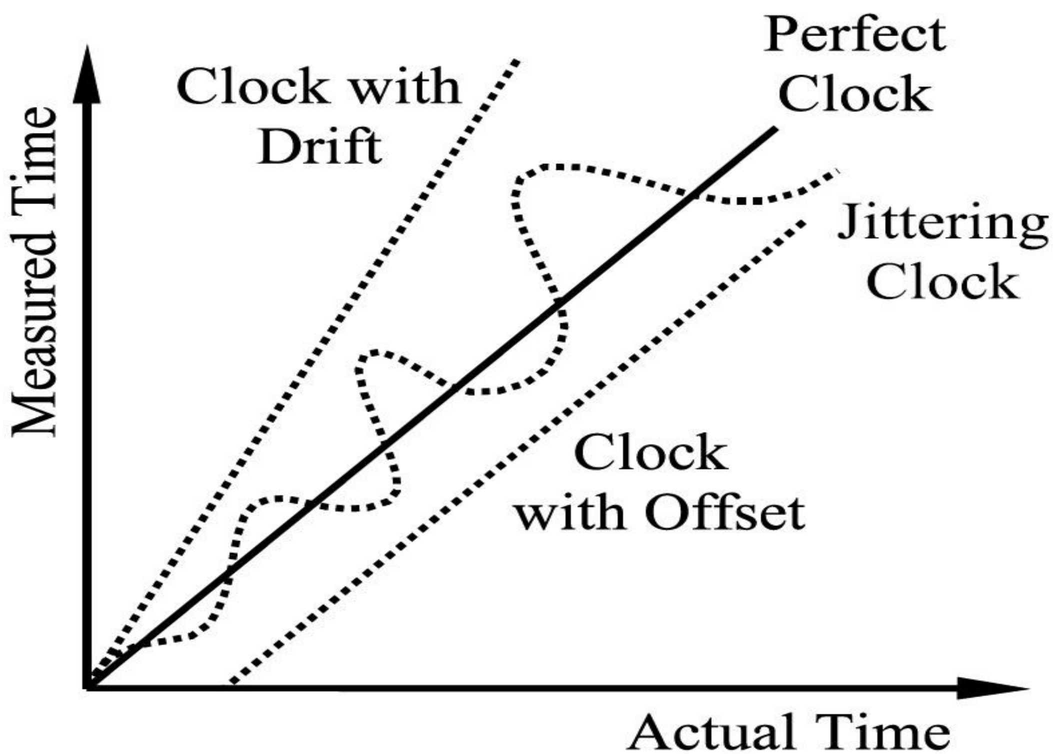
$$C(t) = \frac{1}{f_o}\int f(\tau)d\tau$$

where fo is the nominal frequency of the clock

Clock drift contd.

The nodes clock time is thus bounded as :

$$1-\rho \leq \frac{dC(t)}{dt} \leq 1+\rho$$ where ρ is the maximum clock drift.



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Frequency and its variation

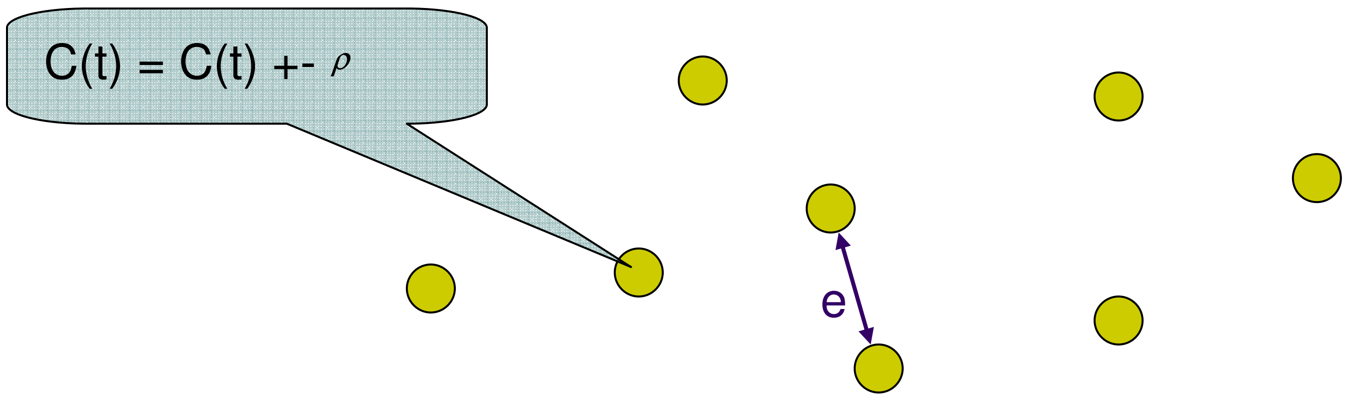
The frequency of the clock is given as :

$$f(t) = f_0 + a(t - t_o) + d(t - t_o) + f_r(t)$$

where :

- a is the aging factor
- d is the environmental factor (temprature..)
- f_r is the noise instability
- f_o is the nominal frequency

Clock drift and the effect



- The clock skew is ρ i.e. 1- ρ < <1+ρ
  - for every time t after the algorithm completes
- Transmissions delays on link *e*
- Symmetric links: same delay, same uncertainty

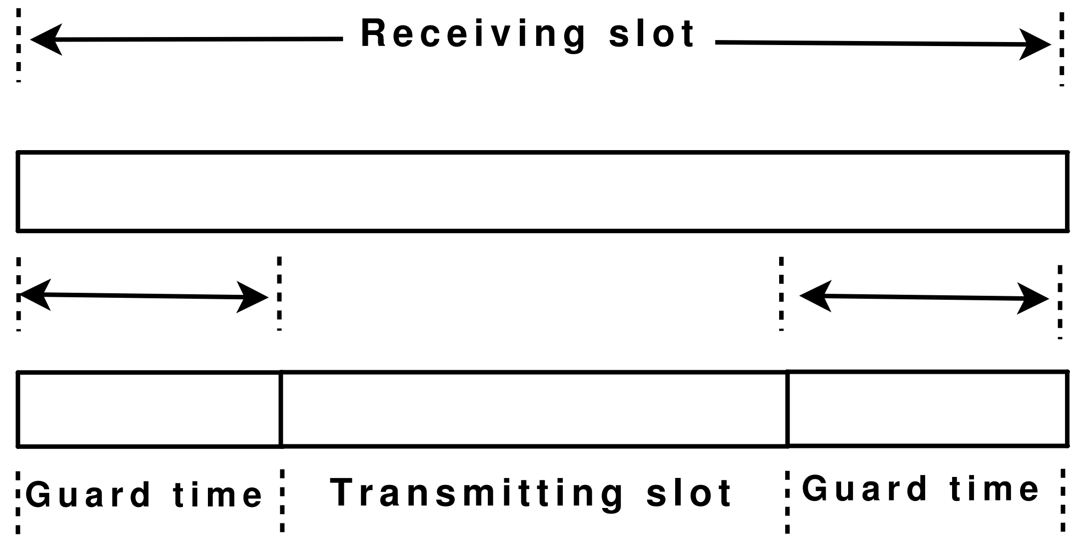
Synchronization frequency

The period in which the network can stay synchronized without the application of the synchronization algorithm.

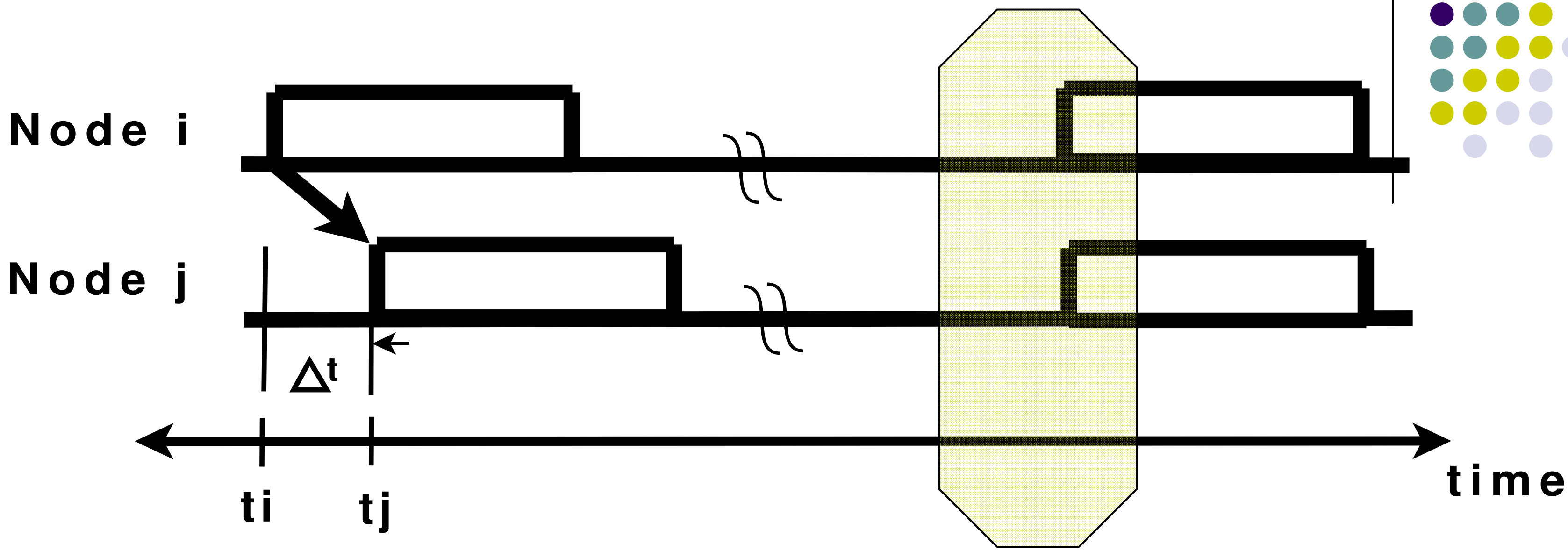
$$t_{slot} \geq t_{guard} + T_x$$

$$t_{diff} = 2\frac{T_{sync}}{T}\rho$$

$$\frac{T_{sync}}{T} \geq 1$$



Mathematical Model



$$t_i^{(n)} = \sum_n T_i^{(n)} + t_{io}$$

$$\Delta t_{ij}^{(n)} = t_i^{(n)} - t_j^{(n)}$$

$$t_i^{(n+1)} = t_i^{(n)} + T_i^{n} - \xi_i^{(n)}$$

$$\xi_i^{(n)} = f(\Delta t_{ij}^{(n)})$$

What is *f* ???

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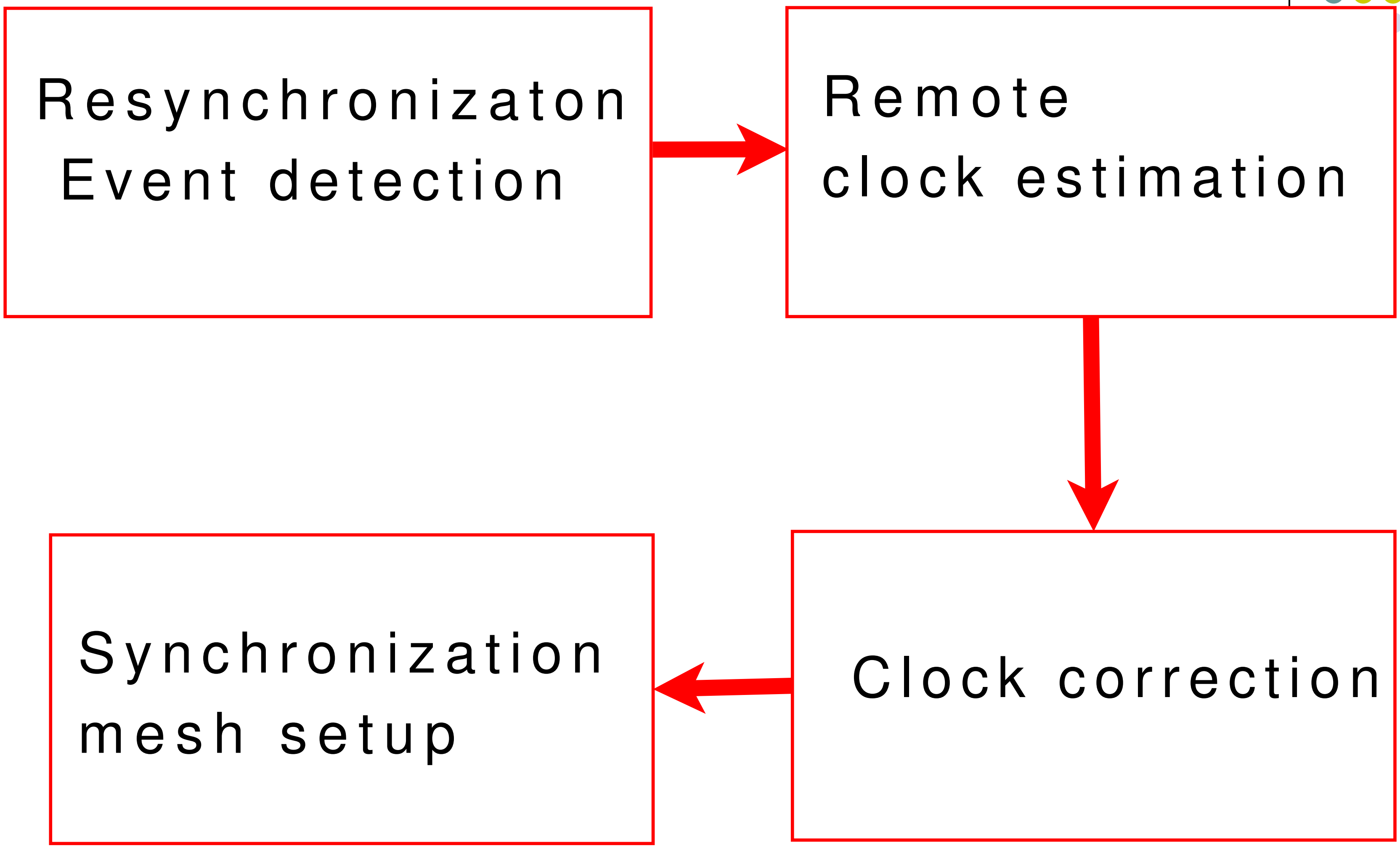
Synchronization algorithms



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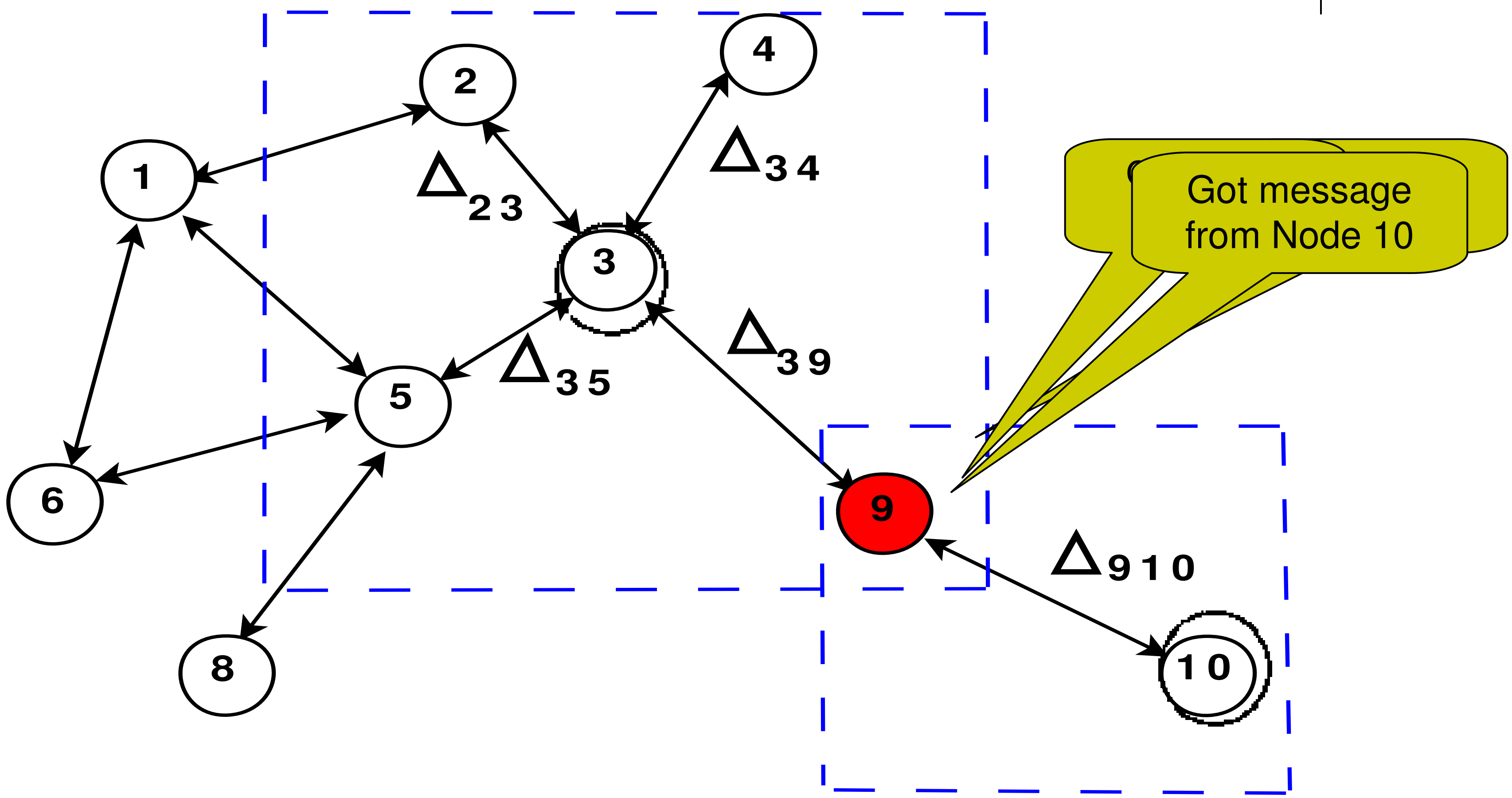
Median as a method for synchronization

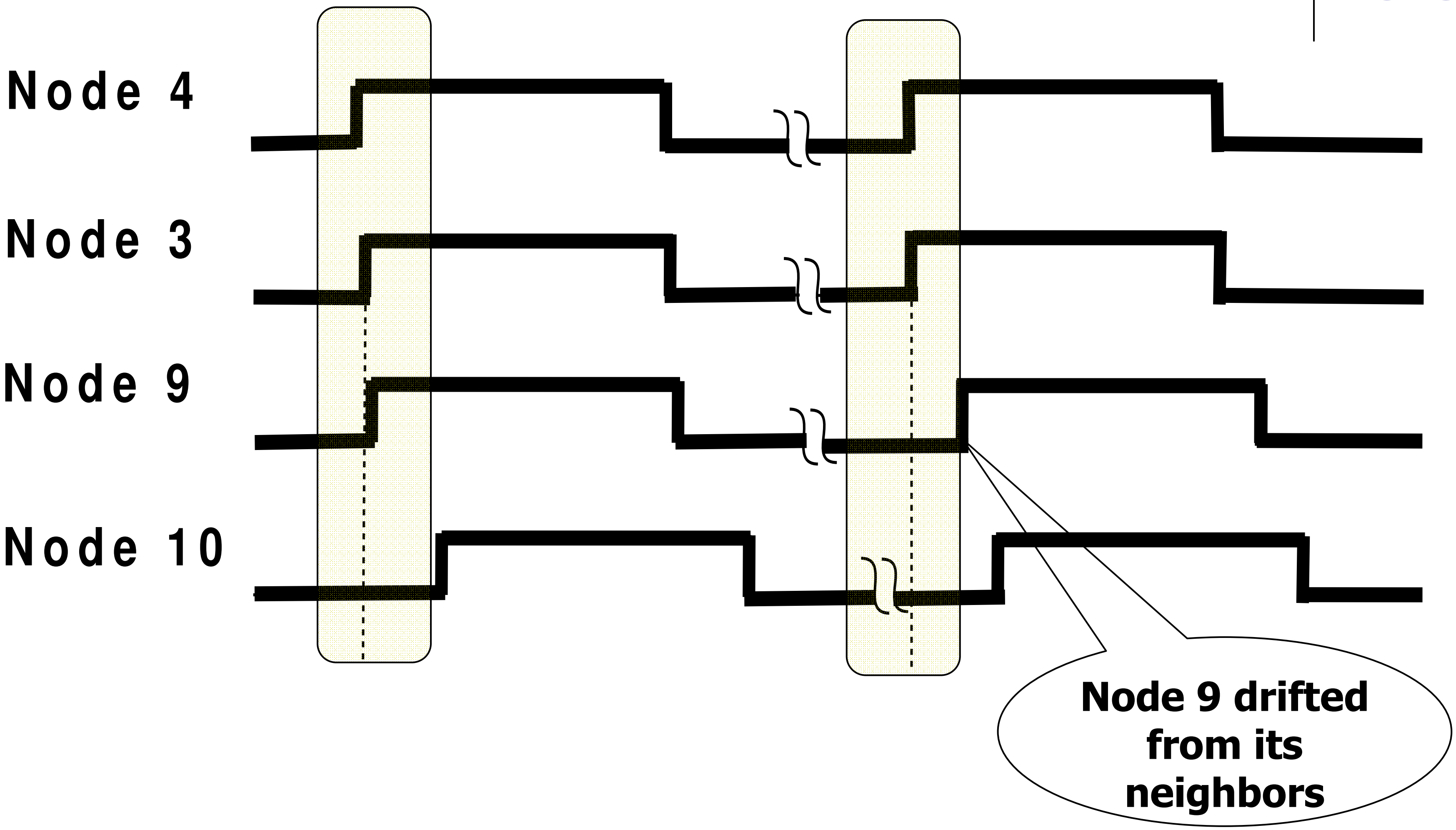
- Nodes broadcast packets.
- Each receiver records the time that the packet is received .
- Each receiver i computes its phase offset to any other node j in the neighborhood
- Receivers compute the median of the offsets
- Receivers adjust their wakeup time by the computed offset value.

A WSN scenario for Median



S1

A WSN scenario for Median contd.



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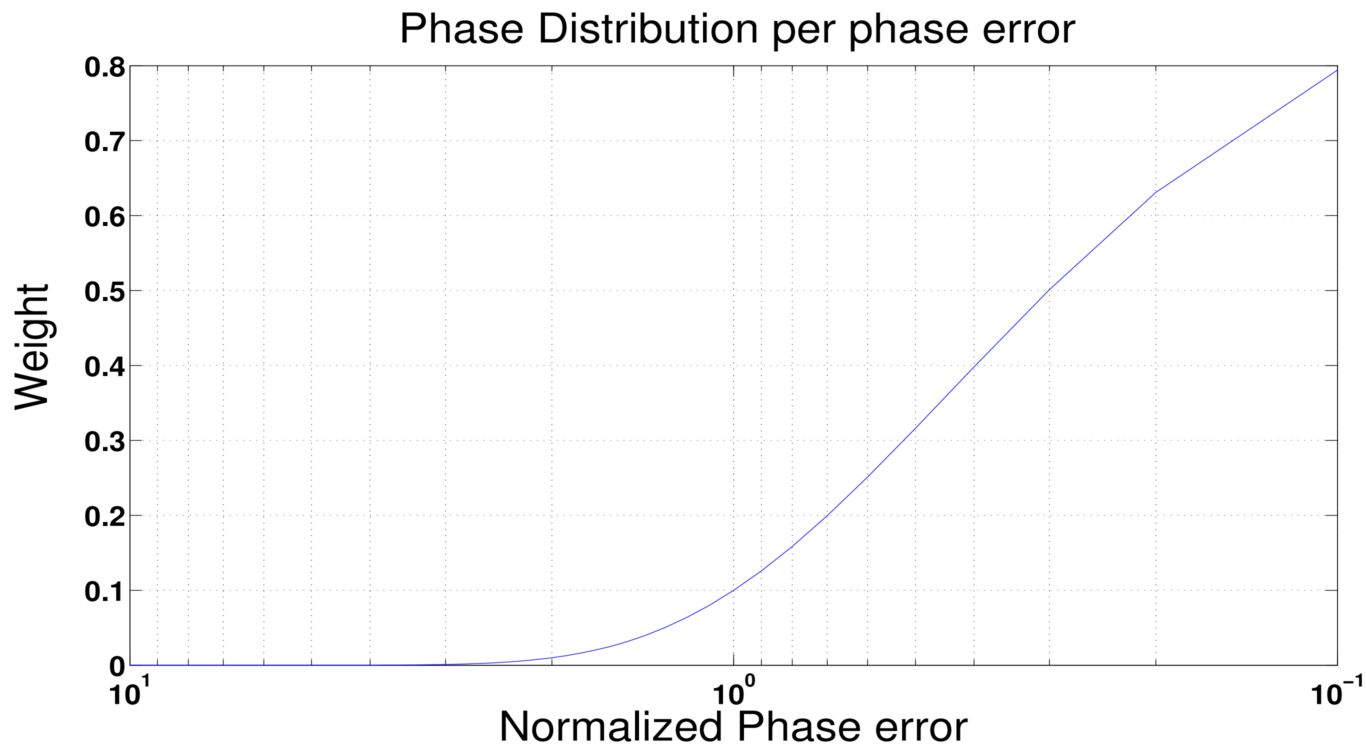
S1 Student; 18-7-2008

Weighted Measurements



$$w_{ij} = ae^{-b\Delta t_{ij}}$$

Weighted measurements Contd.

Weight selection

$$w_{ij} = \delta_{ij}$$

$$w_{ij} = 1 - \delta_{ij}$$

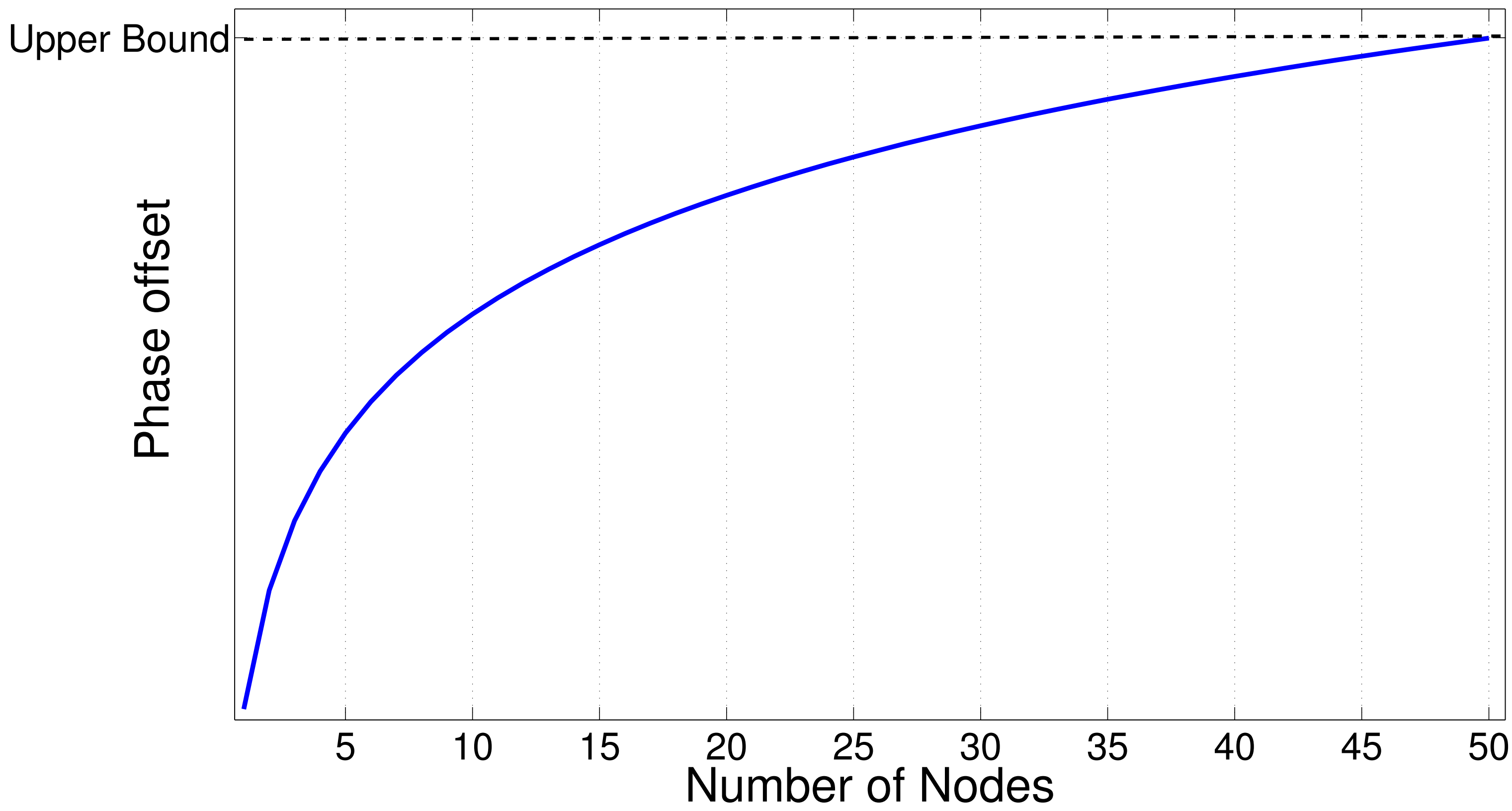
Offset calculation:

$$t_i^{(n+1)} = t_i^{(n)} + T_i^{n} - \xi_i^{(n)}$$

$$t_i^{(n+1)} = t_i^{(n)} + T_i^{(n)} - \sum_{j=0}^{N} w_{ij} \Delta t_{ij}^{(n)}$$

$$t_i^{(n+1)} = T_i^{(n)} + \sum_{j=0}^{N} w_{ij} t_j^{(n)}$$

Non Linear Least Squares approach



Non Linear Least Squares Contd.

Non Linear Least Squares - Curve: $f(x_i, \beta) = \beta_1 + \beta_2 \log(x_i)$

Set of data points : $(x_1, y_1), (x_2, y_2), (x_3, y_3) \ldots (x_n, y_n)$

Squares of error : $S = \sum_{i=1}^{n} r_i^{\ 2}$

where: $r_i = y_i - f(x_i, \beta)$

Iteration of parameters: $\beta_j^{\ k+1} = \beta_j^{\ k} + \Delta\beta_j$

$$(J^T J)\Delta\beta_j = J^T \Delta y$$

where: $J_{ij} = -\frac{\partial r_i}{\partial \beta_j}$

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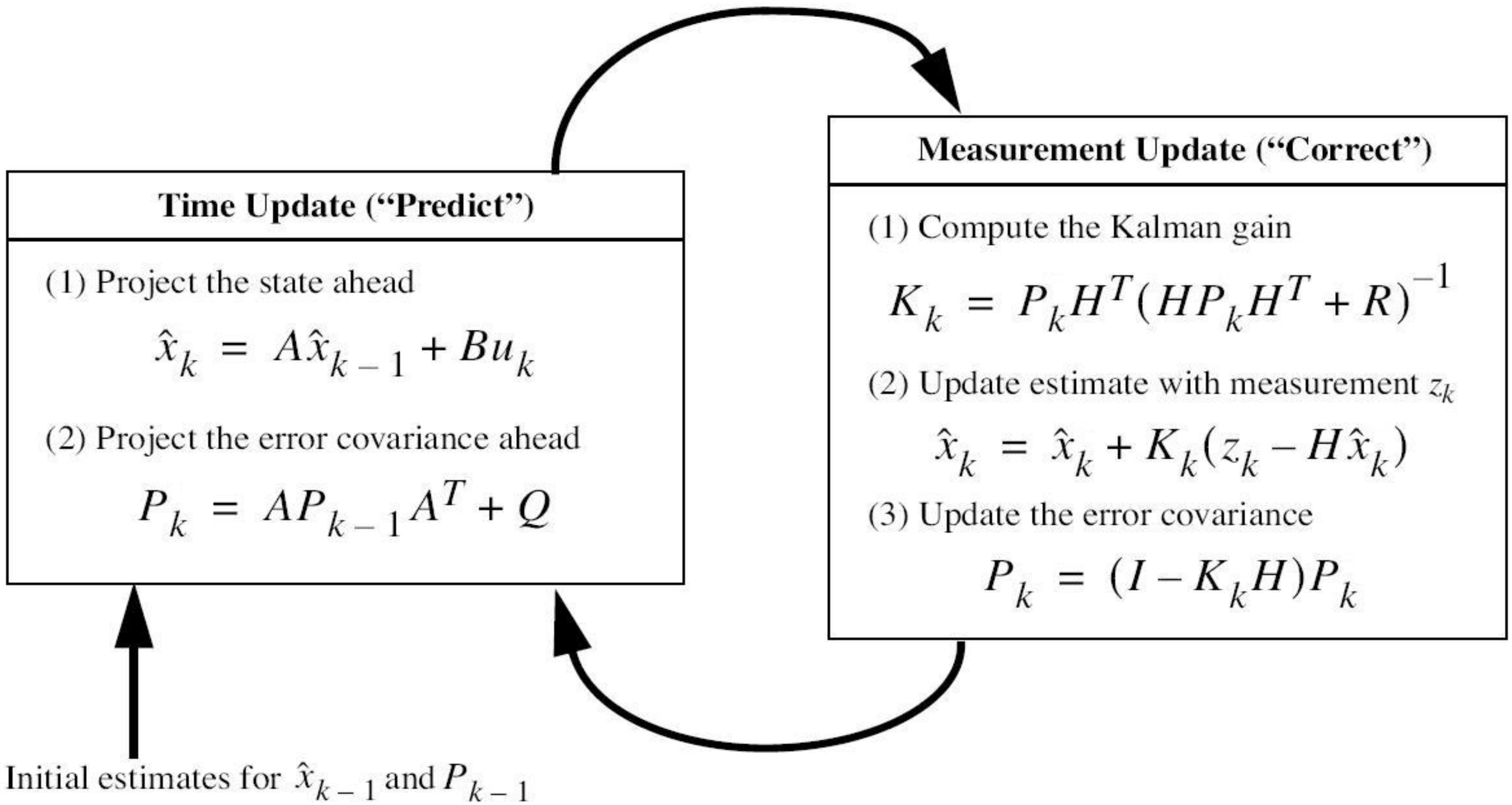
Discrete time Kalman Filter

- Estimator

- Predict equations

- Update equations

Kalman Filter Contd.



$$\lim_{P_k \to 0} K_k = 0 \qquad \lim_{R_k \to 0} K_k = H^{-1}$$

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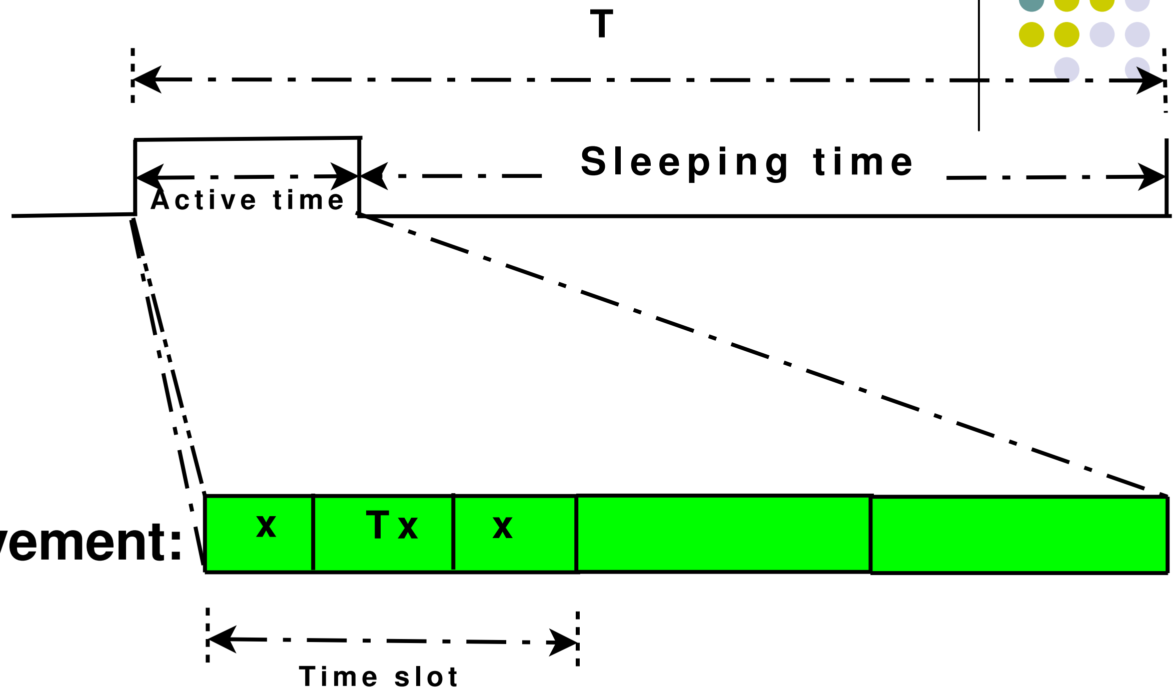
Reducing the duty cycle

$$T_{slot} = 2x + T_x$$

$$D = \frac{NT_{slot}}{T}$$

$$D = \frac{N(2x + T_x)}{T}$$



For a performance improvement:

$$D_n = \frac{N(2(x - \varepsilon) + T_x)}{T}$$

A decrease in the duty cycle: $$\Delta D = \frac{(2\varepsilon)N}{T}$$

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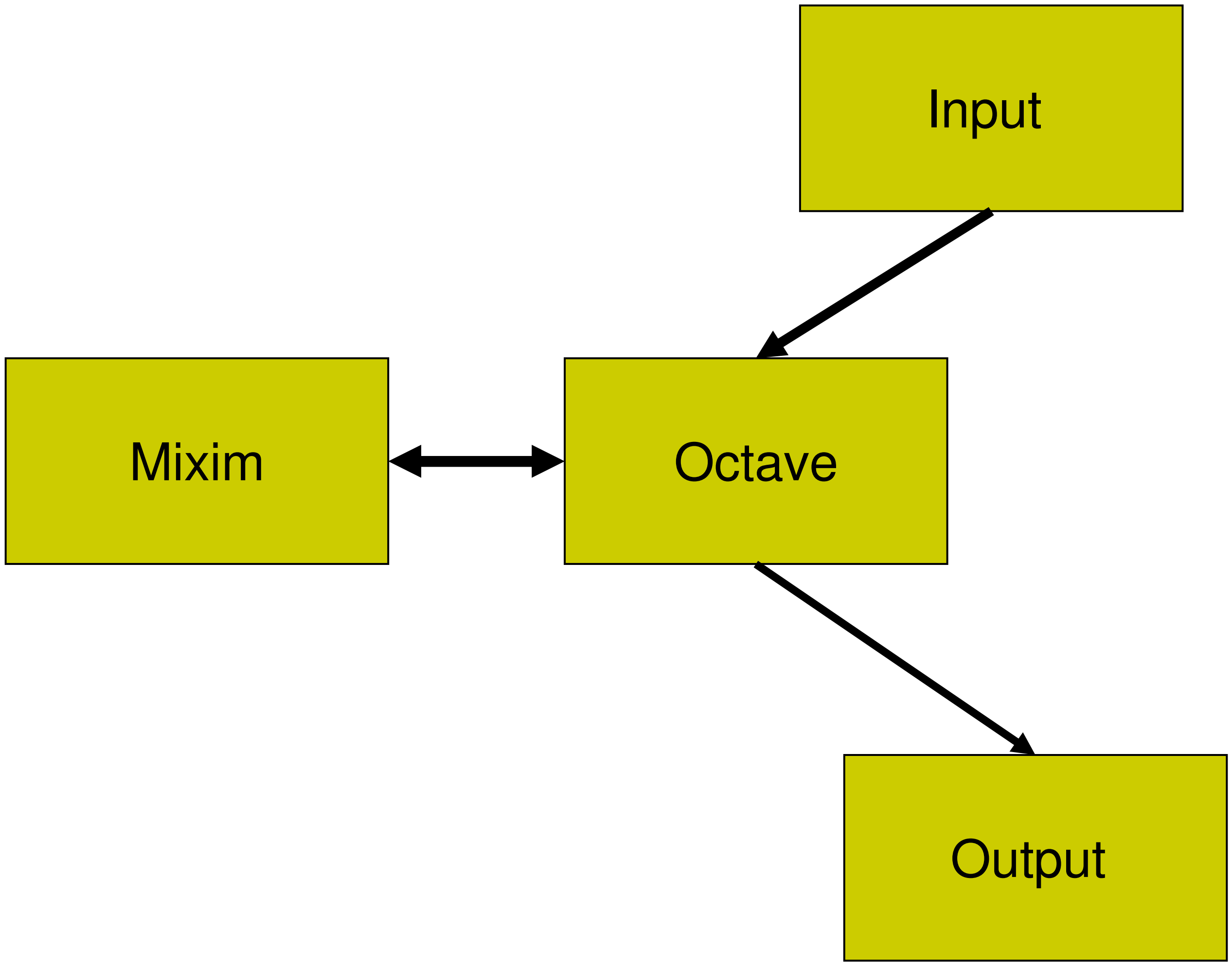
Simulation setup



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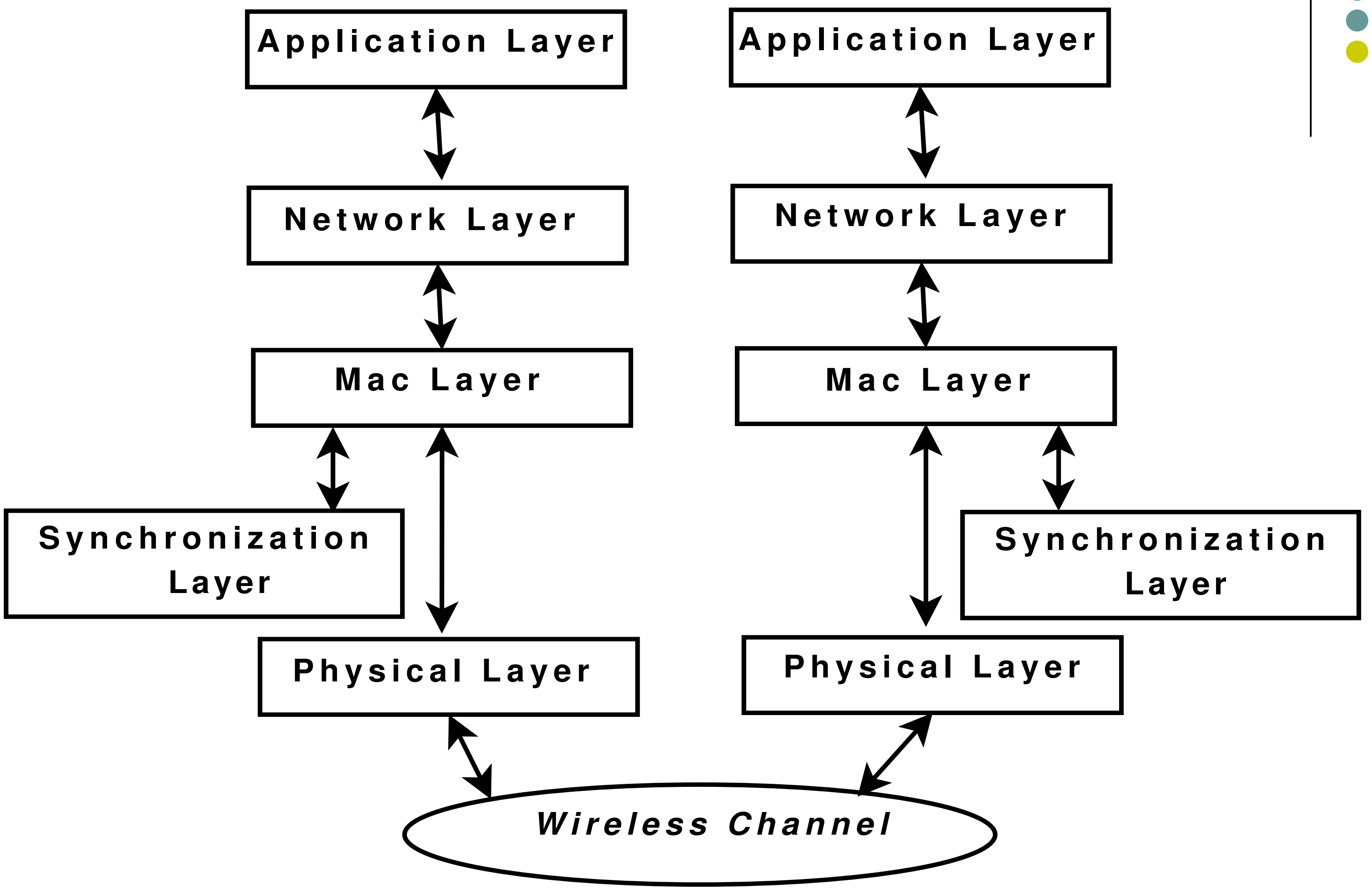
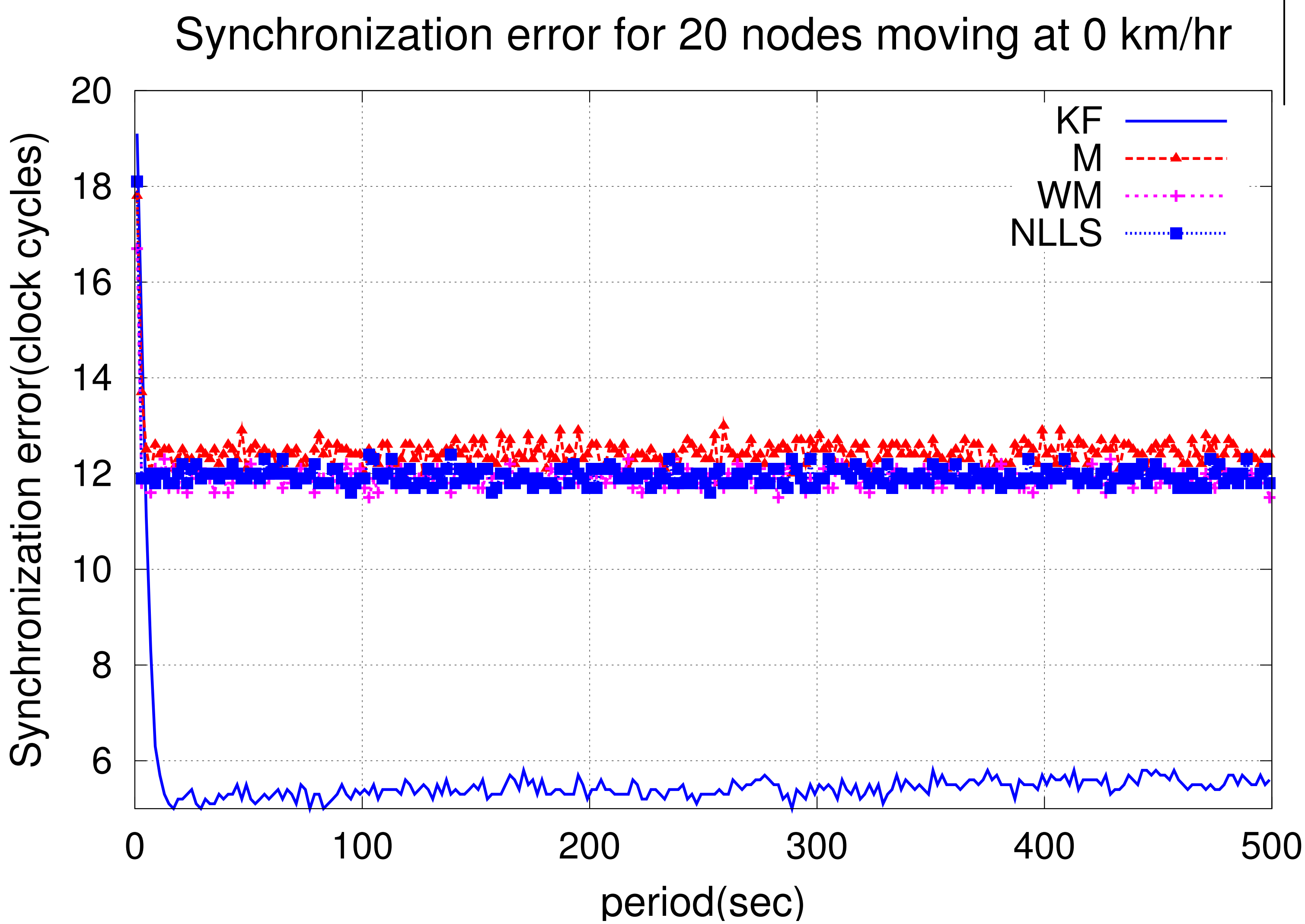
Abstraction



Simulation results



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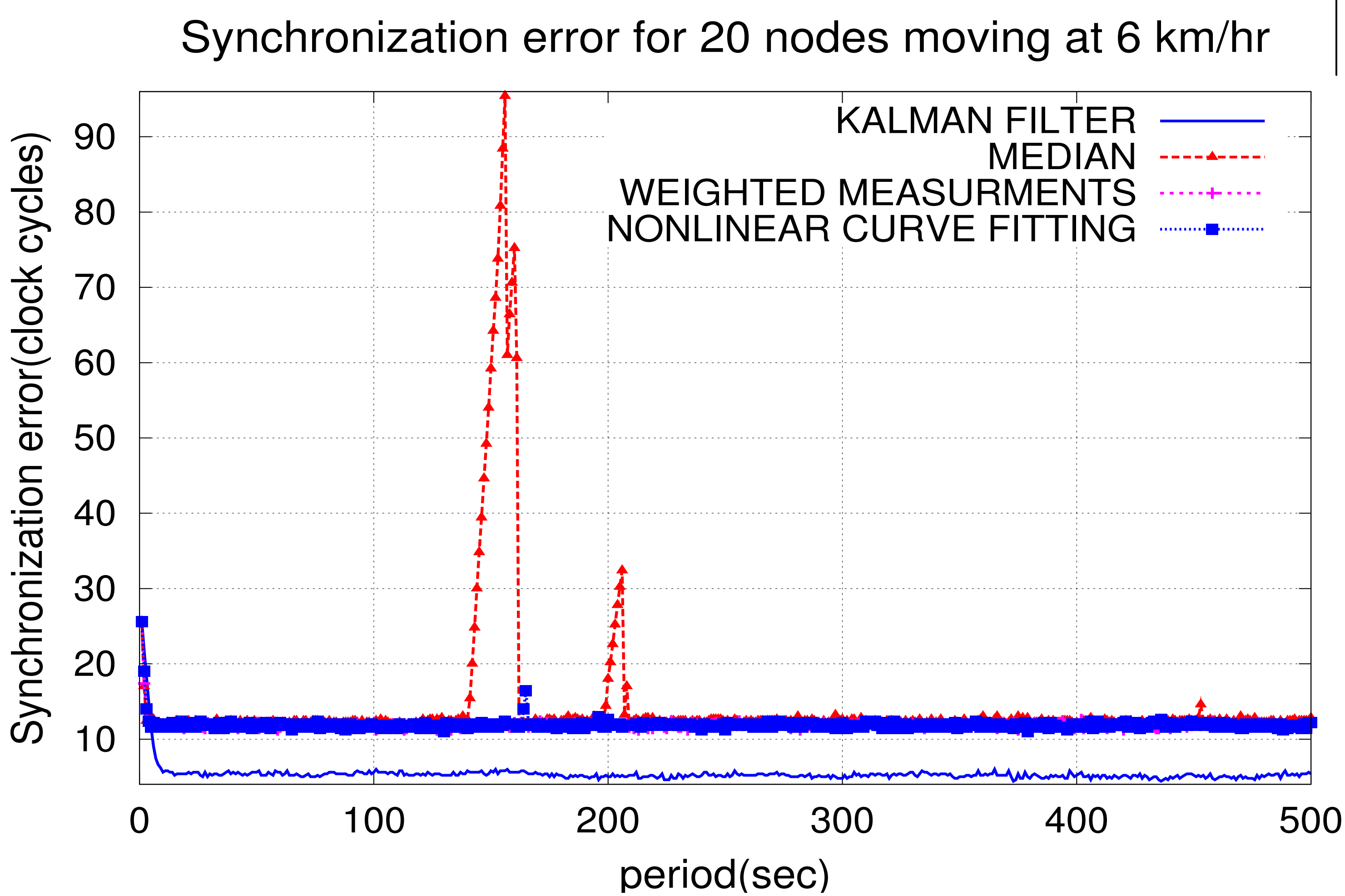
Simulation results Contd.



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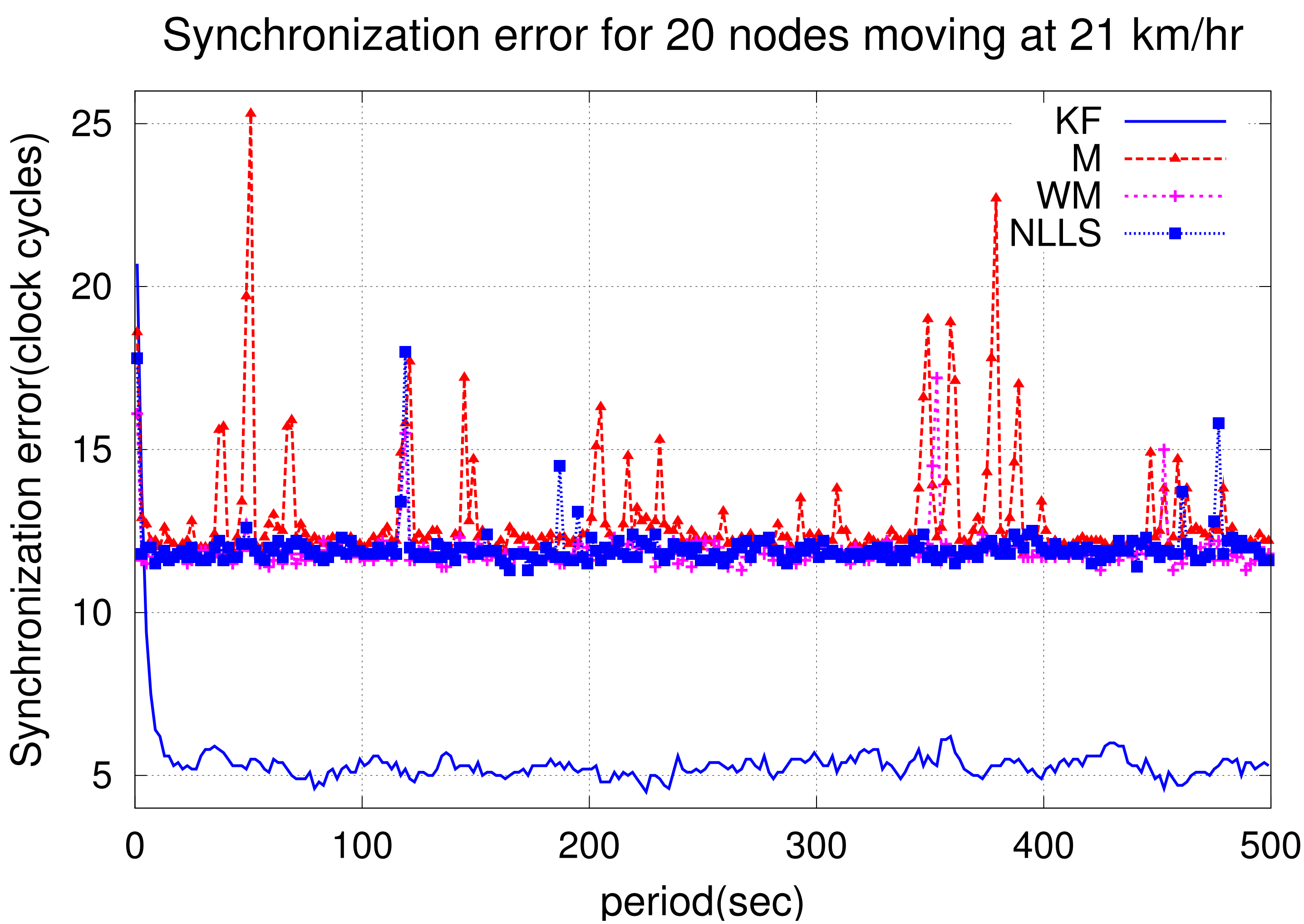
Simulation results Contd.



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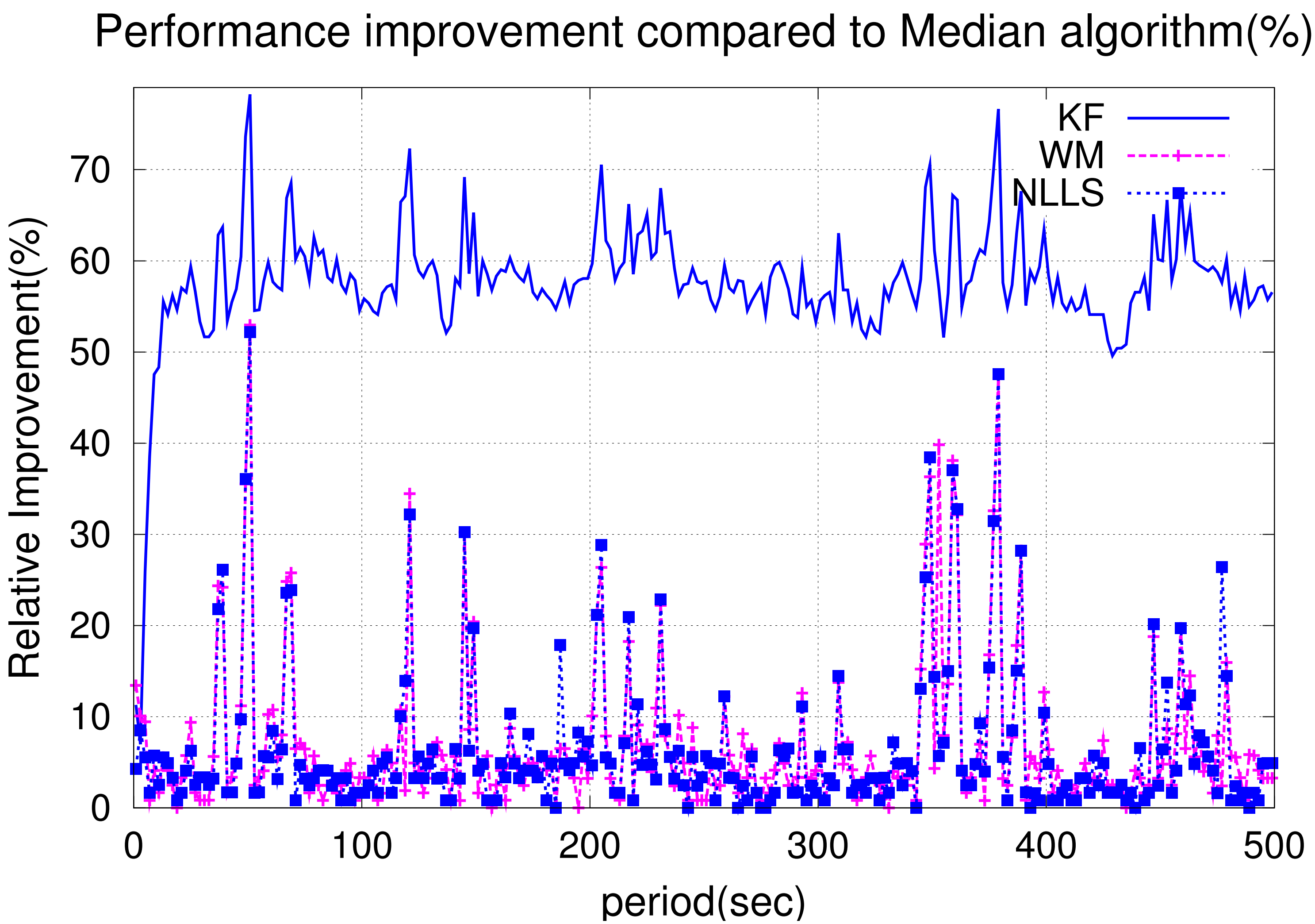
Simulation results Contd.



Energy consumption and Optimization

- It turns out energy is your most valuable resource
  - Traditional notions of resources – memory, CPU, I/O become expenses, not resources

- All components must support low power modes

- What can software do to conserve energy ?

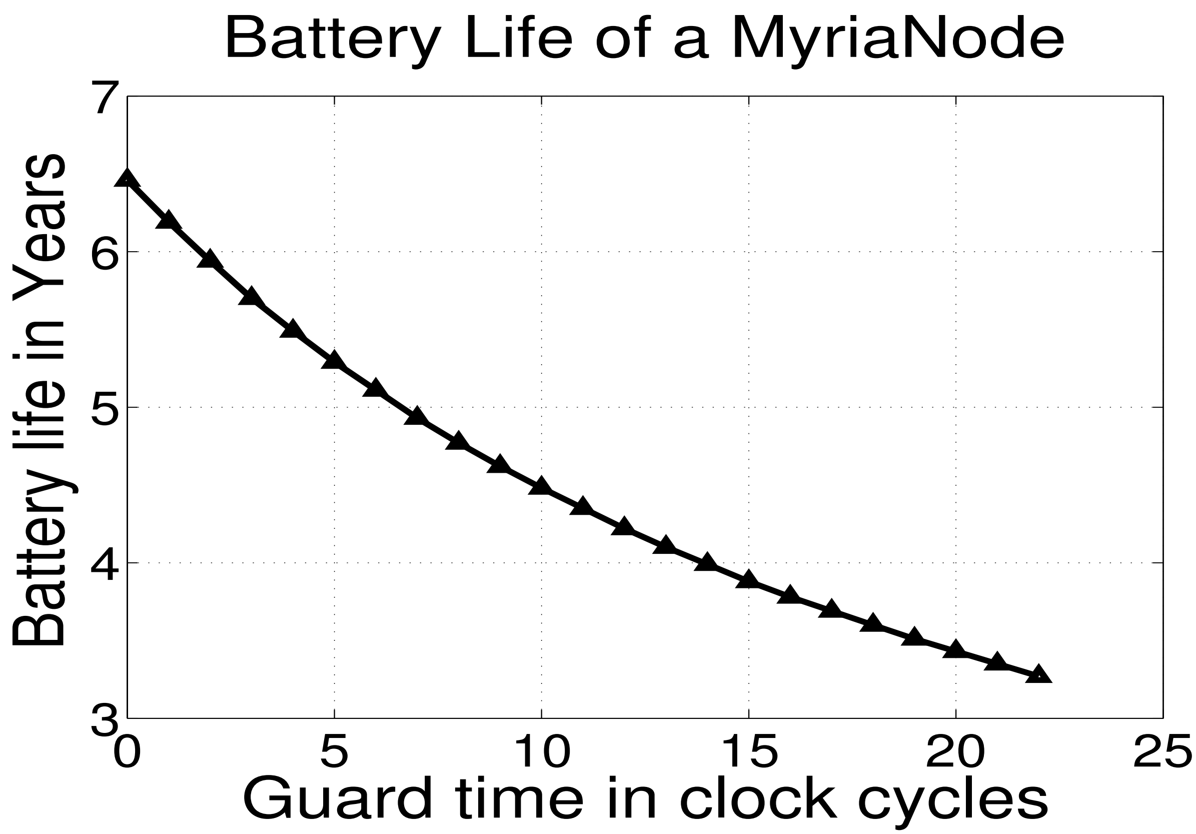
Power Breakdown….

	Active	Idle	Sleep
CPU	3.5 mA	0.01 mA	5 μA
Radio	11.3 mA (TX)	12.3 mA (RX)	5 μA
EE-Prom	3 mA	0	0
LED's	4 mA	0	0
Photo Diode	200 μA	0	0
Temperature	200 μA	0	0

Panasonic
CR2354
560 mAh

- But what does this mean?
  - Lithium Battery runs for 35 hours at peak load and years at minimum load!
  - A one byte transmission uses the same energy as approx 11000 cycles of computation.

Energy Consumption



Communication is more expensive than computing.

Conclusion

- A decentralized clock synchronization is achieved using KF, WM and NLLS.
- WM and NLLS have a better tolerance to the dynamics of the network.
- KF performs the best in all cases, both in static as well as dynamic environments.
- Median is still the choice in static environment, when considered in all aspects (energy and performance).
- Reducing the communication cost and increasing cost of computing is worthy to try.

Recommendation

- Software power minimization techniques to reduce the power consumption of the algorithms.
- SDR for further investigation.
- Additional tools for frequency error minimization, using the available resources.
- More advanced estimation techniques.

Thank you!

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