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Precise clock synchronization for industrial automation and other networked applications

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Presentation Outline

1. Clock / Time Synchronization in Automation Systems

2. PTP and PTCP protocols

3. Error Analysis due to Jitter and Frequency Changes

4. State Space Model and related results

5. Outlook

Time / Clock Synchronization in Automation Systems

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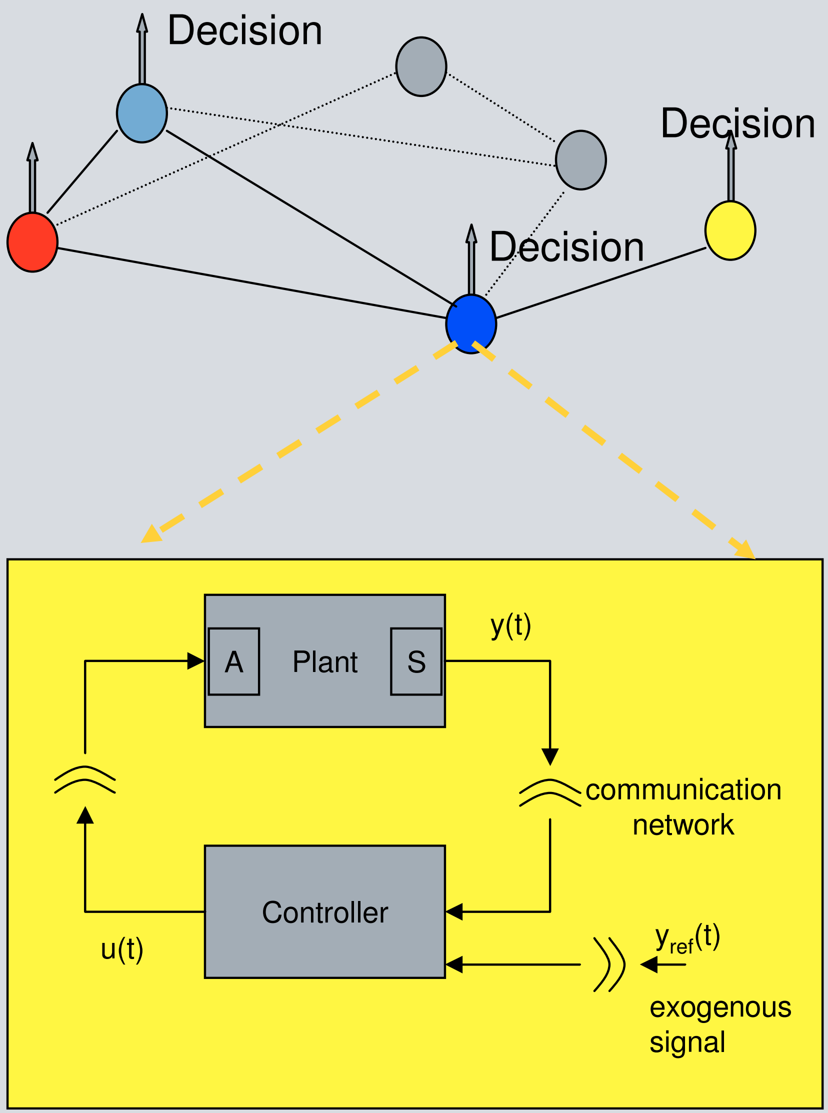
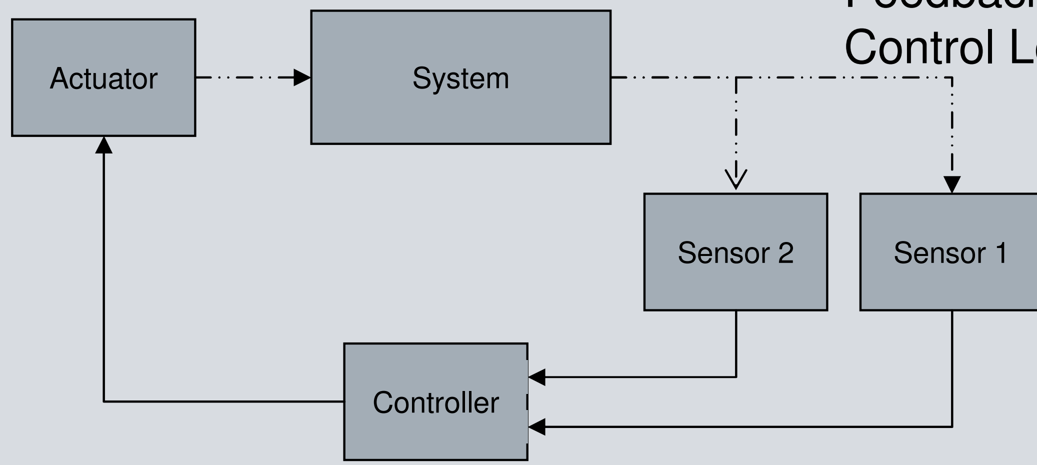
- Many control systems are time discrete, i.e. there is a common tact for exchanging information which all the elements should follow ➔ if the elements posses their own clocks, these clocks have to be synchronized!
- Is this the only need for clock synchronization?
- In fast dynamic systems the dynamics of the underlying communications cannot be neglected since it might cause delays and even information loss ➔ the use of communication resources is time scheduled which requires the common time!
- Monitoring and troubleshooting requires time ordering of event logs of individual elements ➔ time synchronization needed.

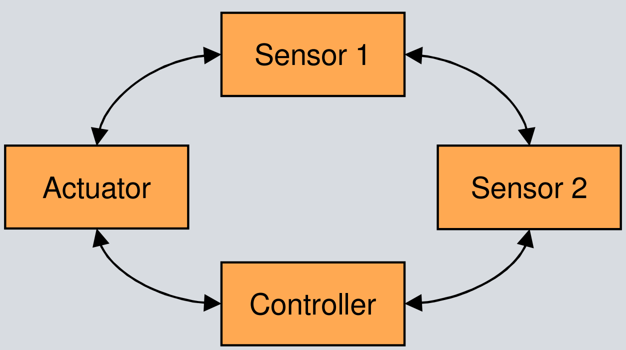


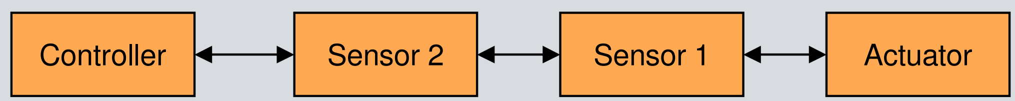
Communication within a closed loop: dedicated bus

Feedback Control Loop



Possible communication system topology!





The traffic consists only of control messages.

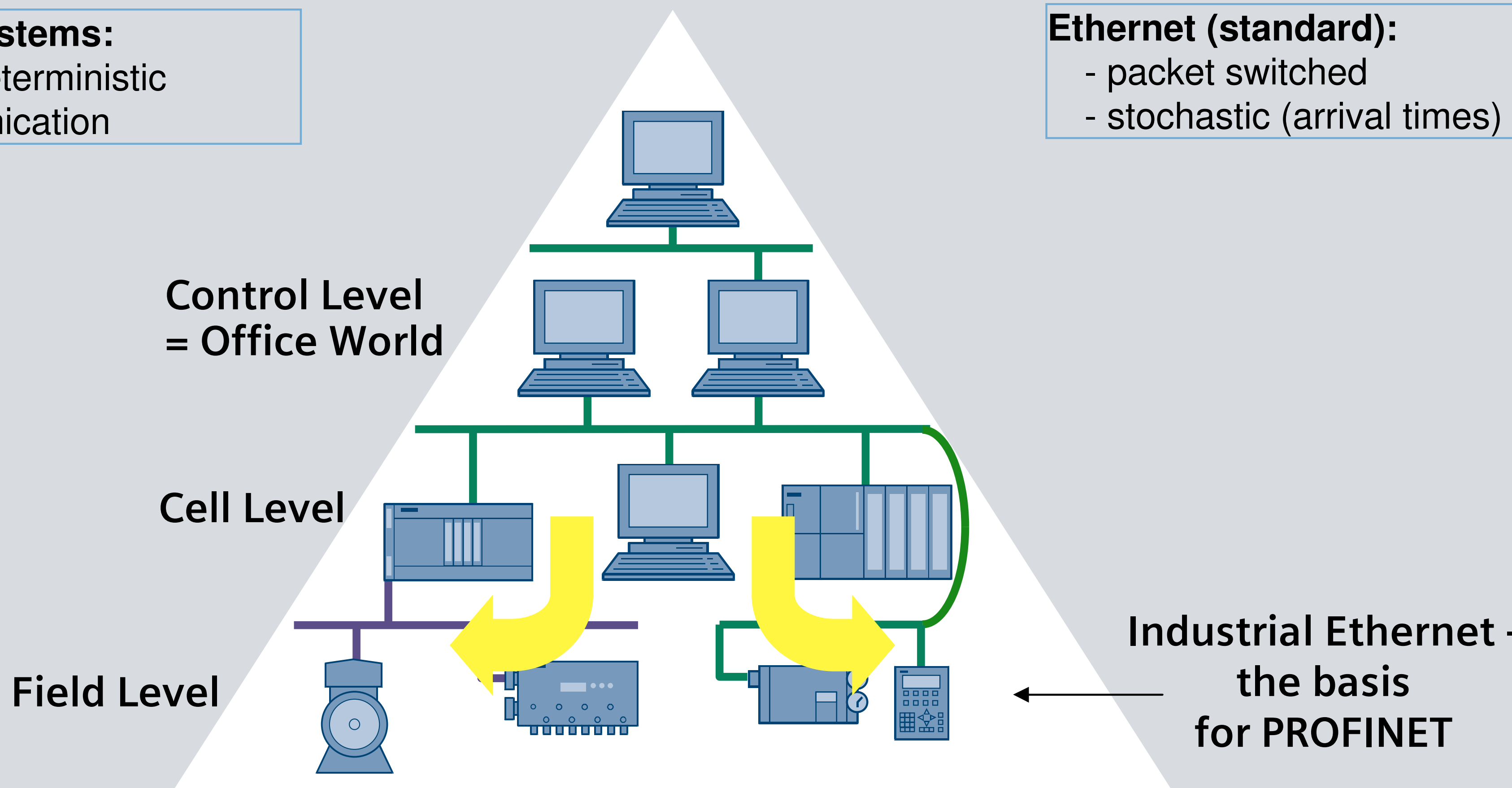
A deterministic schedule of their sending and receiving possible.

No delays occur!

Ethernet goes down to field level!

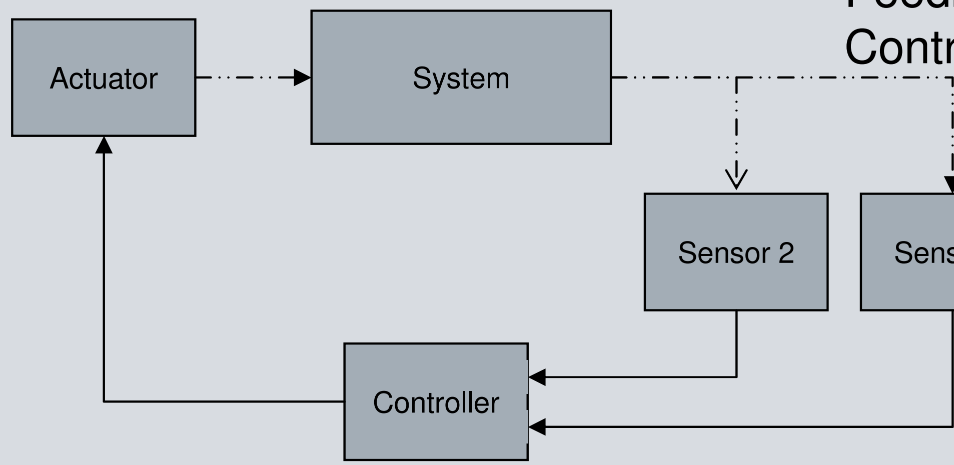
Control Systems:
- need deterministic communication

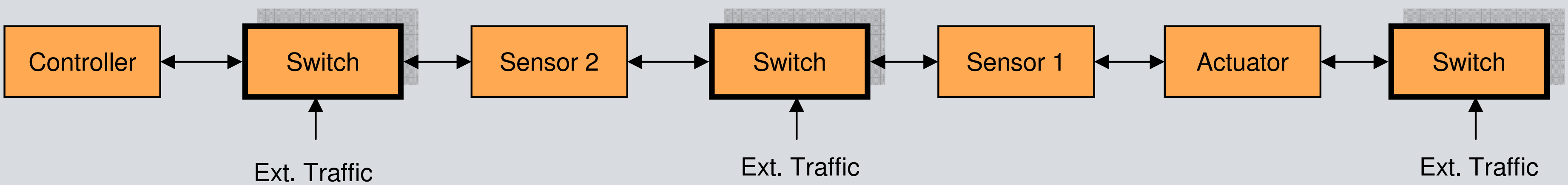
Ethernet (standard):
- packet switched
- stochastic (arrival times)



How to guarantee the required properties in the mixed traffic case?
A Networked Control Systems (NCS) problem!

Communication within a closed loop: shared bus (standard Ethernet)





The traffic consists of the control and external messages.

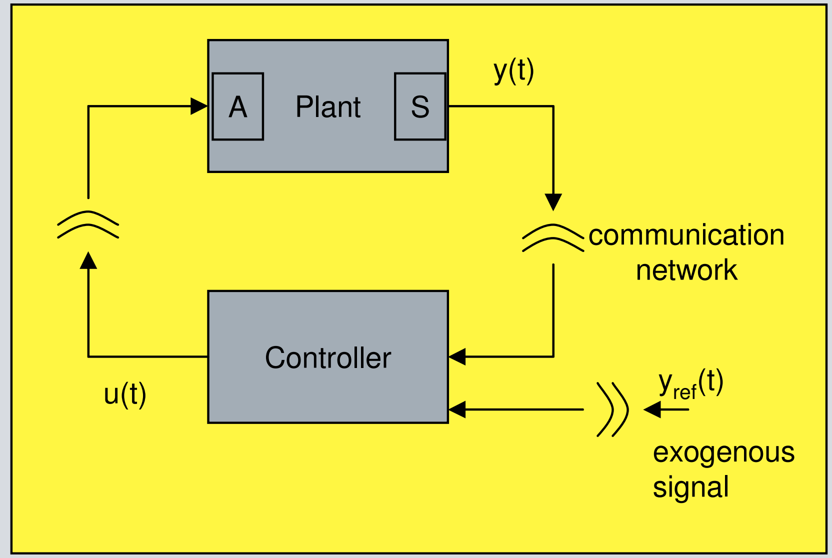
A deterministic schedule of their sending and receiving not possible if external traffic not known.

Delays of control messages occur even if they have the highest priority!

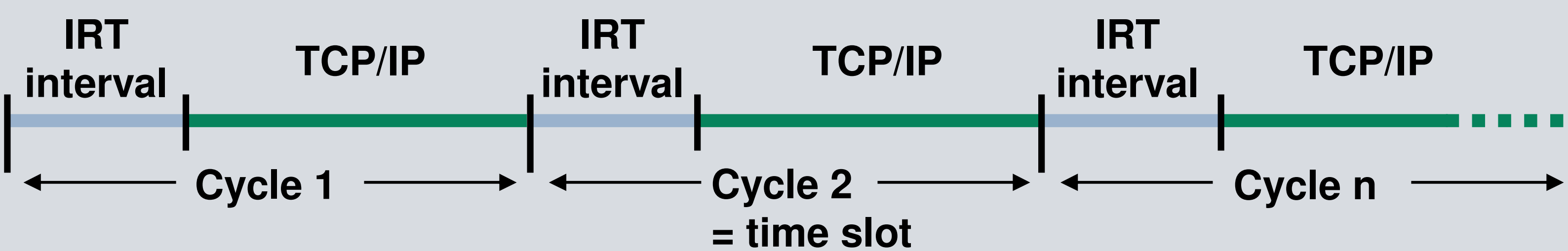
Networked Control Systems

How to deal with the communication system dynamics:

- <u>Application specific approaches:</u>
  - Robust controller design (e.g. with respect to delays)
  - Substitution of “lost” information with its estimates (e.g. Kalman Filter)
  - …
- **<u>General Approach</u>** (of control equipment manufacturers)
  - Make the stochastic communication channel deterministic for control messages ➔ **Industrial Ethernet** (e.g. PROFINET)
  - Achieved by imposing cyclic communication whose part (IRT) is reserved for control messages only!
  - Control messages deterministically scheduled and executed by switches which each has its own clock!



Deterministic schedule requires that all elements (switches) are **synchronized !**



PT(C)P System Model: Master-Slave Approach

(IEEE 1588, IEC 61158/61784)

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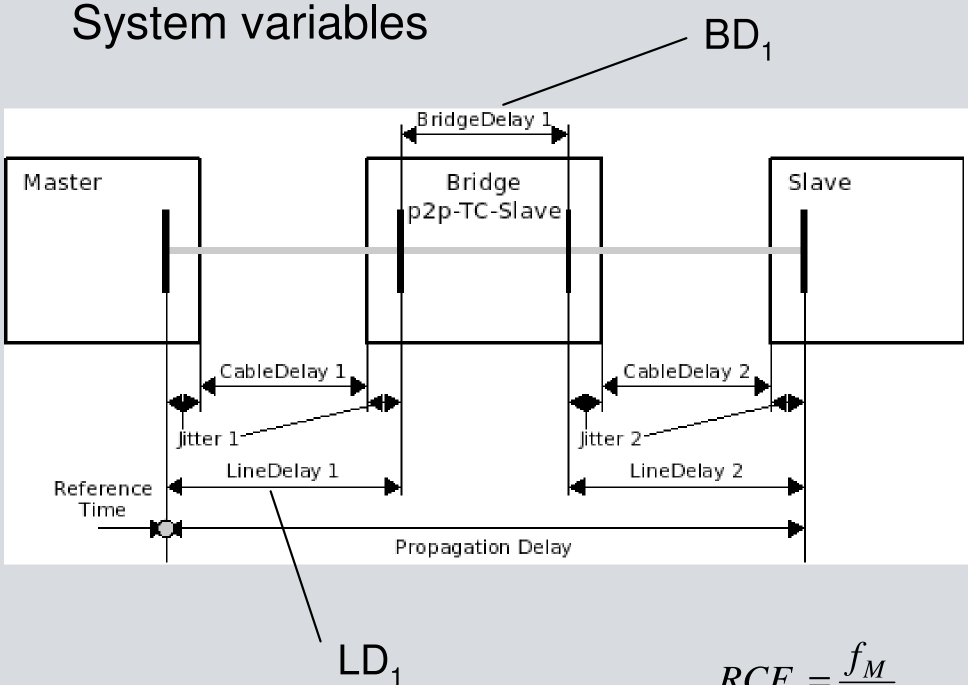
System variables



$$RCF_i = \frac{f_M}{f_{S_i}}$$

Master Element

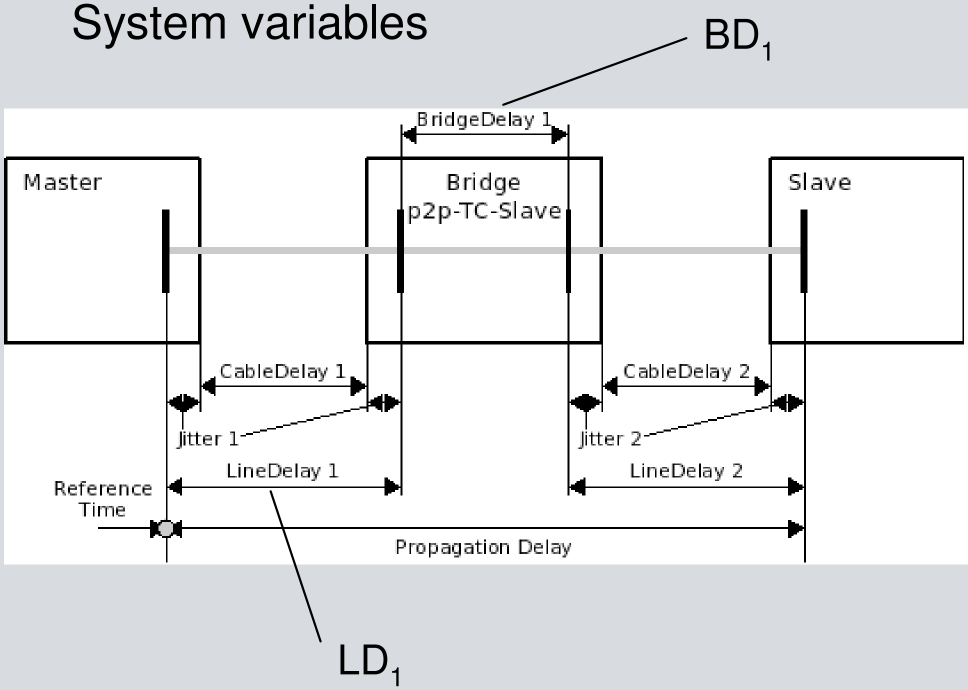
- **Schedules sends its own clock state via "Sync Messages" every T(ms); sending associated with a random delay (transmission jitter).**

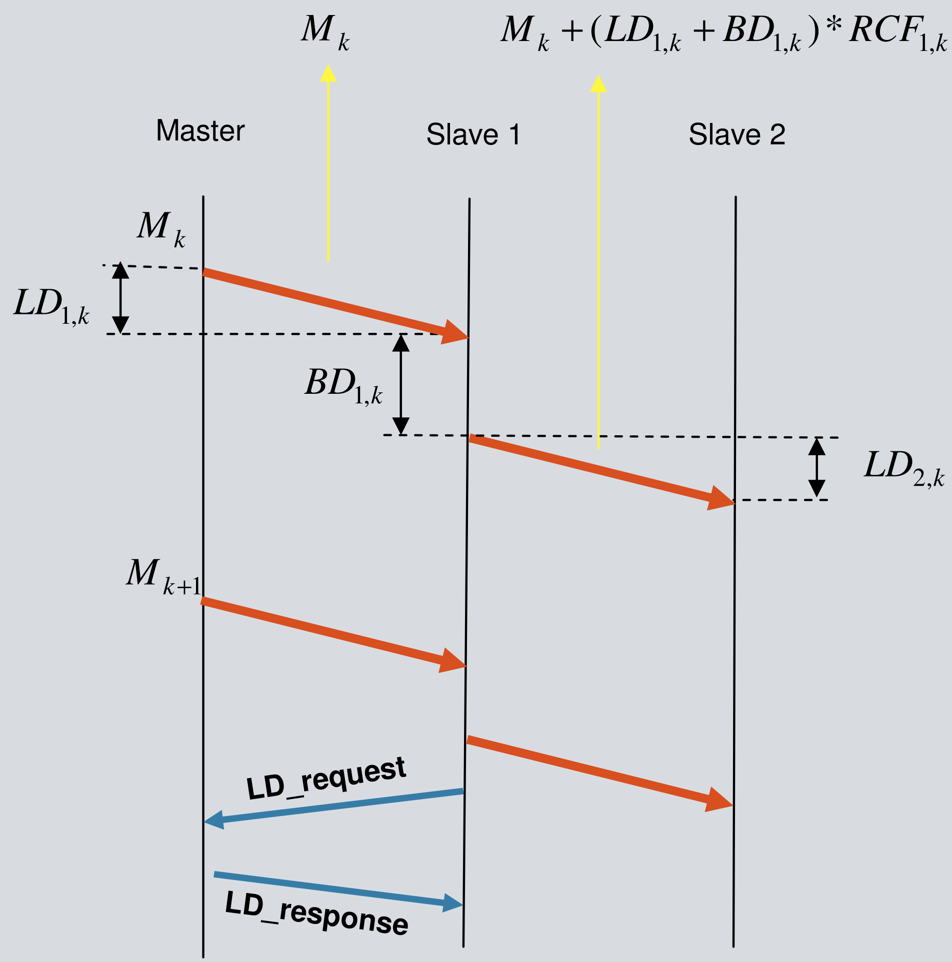
Slave Elements

- **Compute Line Delay (LD) to predecessor by appropriate round time measurements**
- **Calculate Rate Compensation Factor (RCF) from the times of Sync message arrival**
- **Estimate master counter at time of forwarding**
- **Forward the Sync Message after its content is updated to estimated master counter**
- **Calculate Offset between estimated master counter and local counter**
- **Execute local counter update (via controller)**

PT(C)P System Model: Master-Slave Approach

System variables





Two types of messages:

- **Sync Messages**
- **LD_request and LD_response**

PT(C)P System Model: Master-Slave Approach

(IEEE 1588, IEC 61158/61784)

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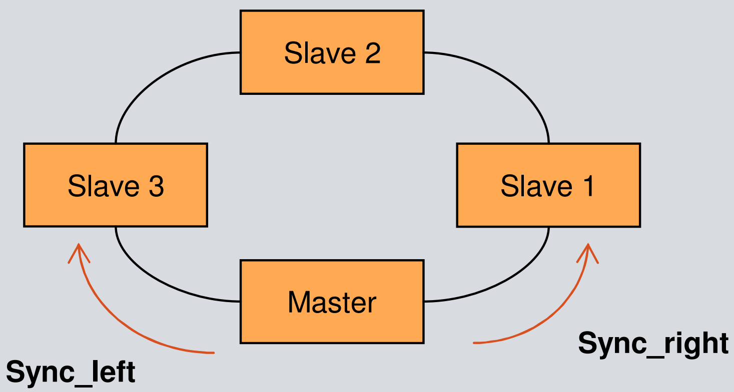
Typical Topologies:

- Line
- Tree
- Star
- Rings
- …

No meshed networks!



Restriction:

- Communication of time information is unidirectional (with exception of Line Delay estimate), even in ring topology

Our focus: Line topology!

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PT(C)P Basics

Open questions:

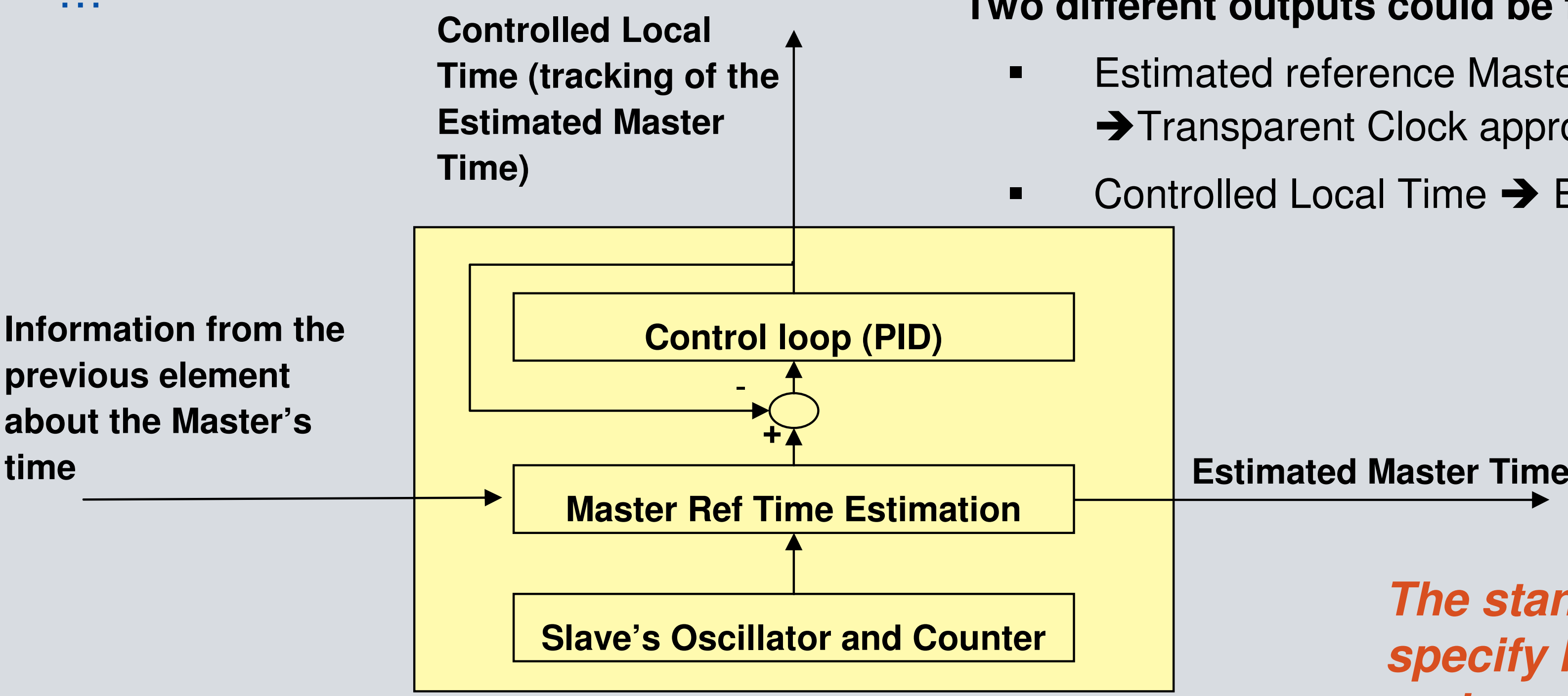
- Hard vs. soft decisions
- Combining estimation and control
- …

Three different "times" (counter states):

- Local oscillator counter state (physical)
- Estimated reference Master's counter state
- Controlled local counter state

Two different outputs could be forwarded:

- Estimated reference Master's counter state ➔Transparent Clock approach
- Controlled Local Time ➔ Boundary Clock approach



The standard does not specify how the estimation and control should be done!

PT(C)P Basics: Degrees of Freedom

(excluding many pure communication parameters)

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Algorithm parameters (to model and / or optimize):

- Frequency of sending Sync Messages (“Sync Interval”)
- Type and frequency of sending LD_request messages (regular or burst)
- Tact of the control loop
- Parameters of the controller
- Estimation algorithm
- Frequency perturbation causes and their model (temperature change, vibration, shocks)
- Jitter sources (stamping)
- Precision of the time information in messages

HW choices:

- Type of quartz (frequency and its stability)
- The location and type of the stamping mechanism
- One-step or Two-step (with a Follow-up message) implementation
- Type of switches (cut-through, …)
- …

Error propagation model for optimization purposes

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Notation - For each slave *n* and time *ti* we denote by:

- $LD_n^i = CD_n + J_n^i$: true LineDelay before slave *n* for SyncMessage *i*
- $L\hat{D}_n^i = CD_n + \bar{J}_n^i$: LineDelay estimate of slave *n* for SyncMessage *i*
- $\breve{J}_{LD}^{i,n} = LD_n^i - L\hat{D}_n^i = J_n^i - \bar{J}_n^i$: error in the LD estimate at slave *n* for SyncMessage *i*
- $\delta_{LD}^{i,n} = LD_n^i - LD_n^{i-1} = J_n^i - J_n^{i-1}$: diff. bet. true slave *n* LD affecting SyncMessages *i* and *i-1*
- BD_n^i : Bridge Delay of SyncMessage *i* at slave *n*, with $B\hat{D}_n^i = BD_n^i$
- $\delta_{BD}^{i,n} = BD_n{}^i - BD_n{}^{i-1}$: diff. bet. BD values at slave *n* that affected SyncMessages *i* and *i-1*
- $LB_n^i = LD_n^i + BD_n^i$: sum of Line Delay plus Bridge Delay of SyncMessage *i* at slave *n*
- $L\hat{B}_n^i = L\hat{D}_n^i + BD_n^i = LB_n^i - \breve{J}_{LD}^{i,n}$: estimated sum of LD plus BD of SyncMessage *i* at slave *n*
- $\delta_{LB}^{i,n} = LB_n{}^i - LB_n{}^{i-1}$: diff. bet. true slave *n* LB value affecting SyncMessages *i* and *i-1*.
- $\rho_{\hat{M}}^{i,n}$: rounding error of the estimated master counter, since counter value that is passed on needs to be an integer; zero-mean r. v. with magnitude $|\rho_{\hat{M}}^{i,n}| \le 1/2$.

Analysis of Error Propagation-Part 1: The Influence of Jitter at Constant Clock Speeds

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The RCF value computed by Slave$_1$ from the SyncMessage transmitted by the master at time t_i is:

$$RCF_1^{\,i} = \frac{M(t_i) - M(t_{i-1})}{S_1(t_i + LD_1^{\,i}) - S_1(t_{i-1} + LD_1^{\,i-1})} = \frac{f_M \cdot T}{(T + LD_1^{\,i} - LD_1^{\,i-1}) \cdot f_{S1}} = \frac{f_M}{f_{S1}} \cdot \frac{1}{1 + \delta_{LD}^{i,1}/T} = \frac{f_M}{f_{S1}} \cdot \left(1 - \frac{\delta_{LD}^{i,1}/T}{1 + \delta_{LD}^{i,1}/T}\right) = \frac{f_M}{f_{S_1}} \cdot \left(1 - \varepsilon_{RCF}^{i,1}\right)$$

The same formula for an arbitrary slave is:

$$RCF_n^i = \frac{f_M}{f_{S_2}} \cdot \left(1 - \varepsilon_{RCF}^{i,n}\right)$$

The true master counter at forwarding is:

$$M\Big|_{t_i + \sum_{n=1}^{N} LB_n^i} = M(t_i) + f_M \cdot \sum_{n=1}^{N} LB_n^i$$

The estimated master counter at an arbitrary slave N is:

$$\hat{M}_{S_N out}\Big|_{t_i + \sum_{n=1}^{N} LB_n^i} = M(t_i) + \sum_{n=1}^{N}\left(L\hat{B}_n^i \cdot f_{S_n} \cdot RCF_n^i + \rho_{\hat{M}}^{i,n}\right) = M(t_i) + \sum_{n=1}^{N}\left[\left(LB_n^i - \breve{J}_{LD}^{i,n}\right) \cdot f_{S_n} \cdot \frac{f_M}{f_{S_n}} \cdot \left(1 - \varepsilon_{RCF}^{i,n}\right) + \rho_{\hat{M}}^{i,n}\right] =$$

$$= M(t_i) + f_M \cdot \sum_{n=1}^{N}\left[\left(LB_n^i - \breve{J}_{LD}^{i,n}\right) \cdot \left(1 - \varepsilon_{RCF}^{i,n}\right) + \frac{\rho_{\hat{M}}^{i,n}}{f_M}\right] = M(t_i) + f_M \cdot \sum_{n=1}^{N} LB_n^i - f_M \cdot \sum_{n=1}^{N}\left((LB_n^i - \breve{J}_{LD}^{i,n}) \cdot \varepsilon_{RCF}^{i,n} + \breve{J}_{LD}^{i,n} - \frac{\rho_{\hat{M}}^{i,n}}{f_M}\right)$$

Jitter Propagation Model: Master Counter Estimate Error due to Jitter

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Recursively defined, corresponds to propagation of error in RCF computation

Cumulative jitter and rounding terms; present even with perfect RCF estimate; zero-mean.

The master counter estimate error at slave N is:

$$M - \hat{M}_{S_N out}\Big|_{t_i + \sum_{n=1}^{N} LB_n^i} \approx f_M \cdot \sum_{n=1}^{N} \left((LB_n^i - \breve{J}_{LD}^{i,n}) \cdot \varepsilon_{RCF}^{i,n} \right) + f_M \cdot \sum_{n=1}^{N} \left(\breve{J}_{LD}^{i,n} - \frac{\rho_{\hat{M}}^{i,n}}{f_M} \right)$$

Where the errors in the RCF propagation are recursively calculated as:

$$\varepsilon_{RCF}^{i,N} \approx \frac{\sum_{n=1}^{N-1} \left(LB_n^i \cdot \varepsilon_{RCF}^{i,n} - LB_n^{i-1} \cdot \varepsilon_{RCF}^{i-1,n} \right) + \sum_{n=1}^{N} (\breve{J}_{LD}^{i,n} - \breve{J}_{LD}^{i-1,n}) + \sum_{n=1}^{N} \frac{\rho_{\hat{M}}^{i,n} - \rho_{\hat{M}}^{i-1,n}}{f_M}}{T + \sum_{n=1}^{N-1} \delta_{BD}^{i,n} + \sum_{n=1}^{N} (\breve{J}_{LD}^{i,n} - \breve{J}_{LD}^{i-1,n})}$$

Jitter Propagation Model: Master Counter Estimate Error due to Jitter - Conclusions

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Analysis:

- The “yellow term” approaches zero (the mean) for large element number N!
- The “orange term” plays the dominant role for large N

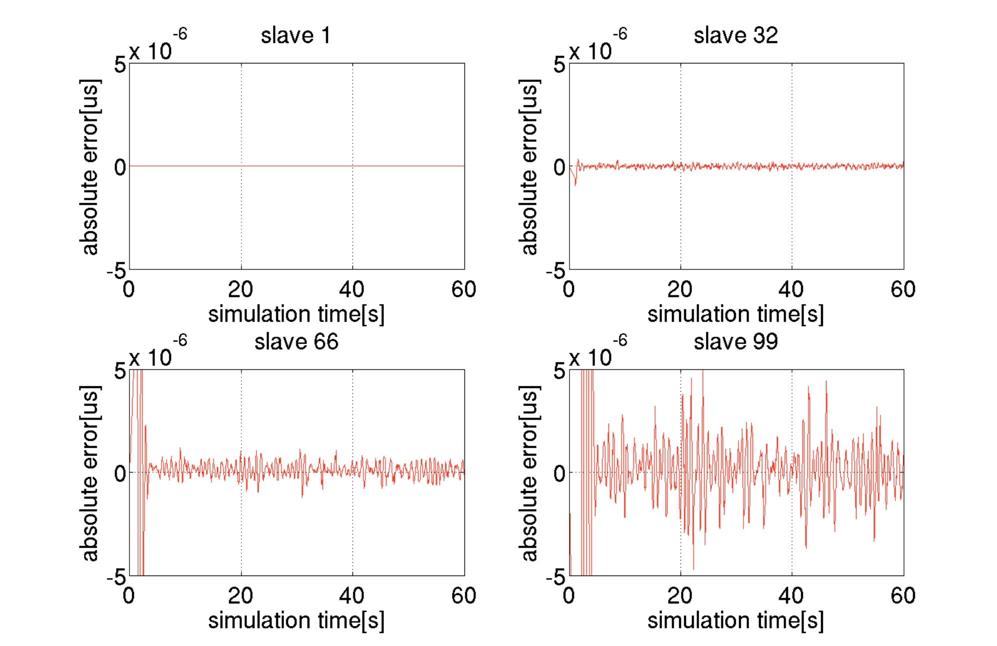
How to reduce the error:

1. Reduce jitter.
2. Reduce the RCF error. This can be done in three ways:
   - Average RCF
   - Increase T (time interval between 2 Sync messages used for RCF calculations)
   - Decrease Bridge Delay (and Cable Delay if of the same order of magnitude)

Simulation Results (1) – Jitter Scenario

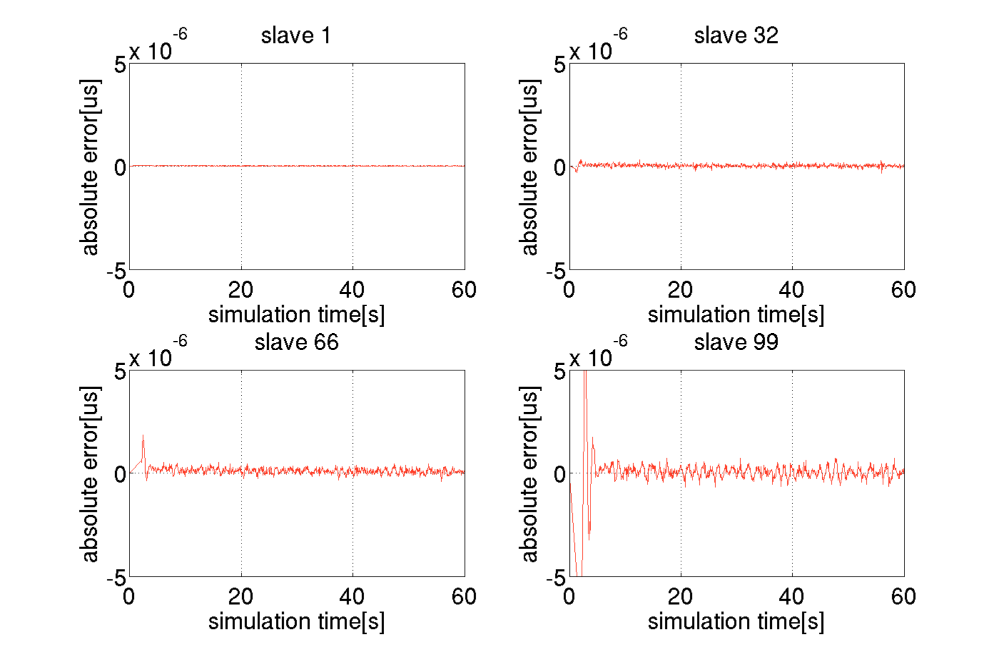
Synchronization error

at slaves 1, 32, 66 and 99:



After increasing the interval

of RCF calculation



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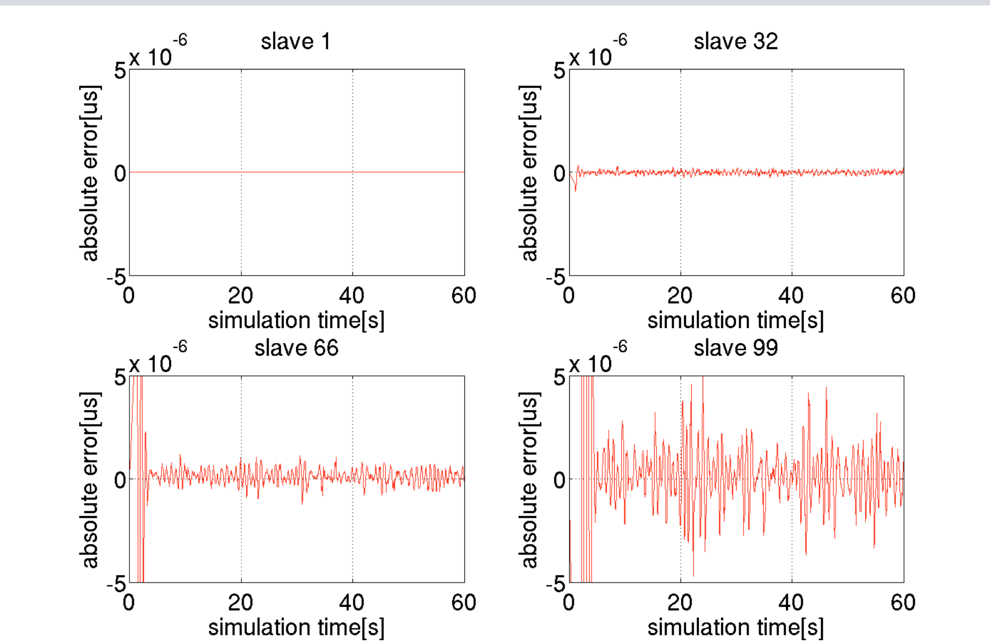
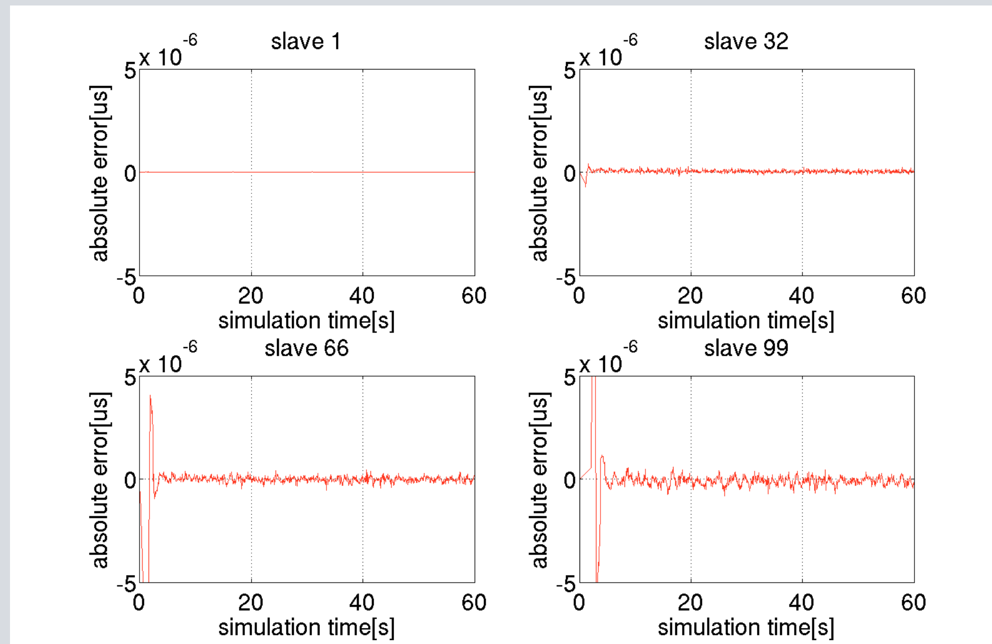
Simulation Results (2) – Jitter Scenario

Synchronization error at slaves 1, 32, 66 and 99:



After averaging over more RCF estimates



Analysis of Error Propagation-Part 2: Effect of Master Clock Drift in the Absence of Jitter

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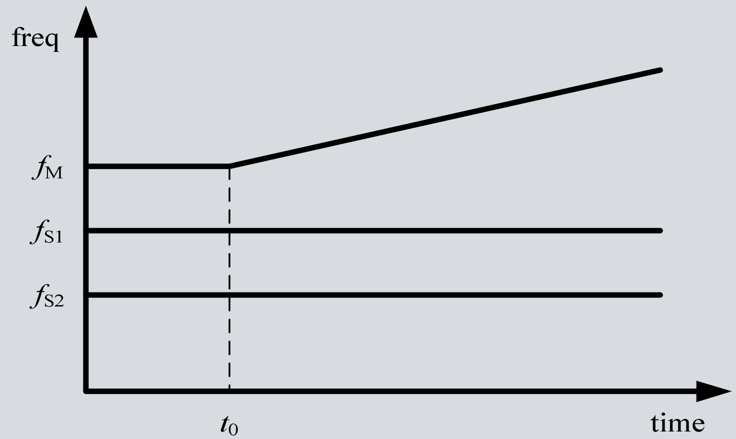
Master frequency increasing after t_0:

$$f_M(t_i) = f_M(t_{i-1}) + \Delta_M \cdot (t_i - t_{i-1}), \quad \text{with } t_i > t_{i-1} > t_0$$

Slaves' frequencies constant:

$$f_{S_n}(t_i) = f_{S_n}(t_{i-1}), \quad \text{with } t_i > t_{i-1} > t_0$$



Master counter increase:

$$M(t_i) - M(t_{i-1}) = \int_{t_{i-1}}^{t_i} f_M(t) \cdot dt = f_M(t_{i-1}) \cdot (t_i - t_{i-1}) + \frac{\Delta_M}{2} \cdot (t_i - t_{i-1})^2$$

Slave counter increase:

$$S_n(t_i) - S_n(t_{i-1}) = \int_{t_{i-1}}^{t_i} f_{S_n}(t) \cdot dt = S_n(t_{i-1}) \cdot (t_i - t_{i-1})$$

Forwarded master counter estimate:

$$\hat{M}_{S_N out}\Big|_{t_i + \sum_{n=1}^{N} LB_n^i} = \hat{M}_{S_{N-1} out}\Big|_{t_i + \sum_{n=1}^{N-1} LB_n^i} + LB_N^i \cdot f_{S_N} \cdot RCF_N^i$$

Drift Propagation Model: Master Counter Estimate Error due to Frequency Drift (LD and BD assumed constant)

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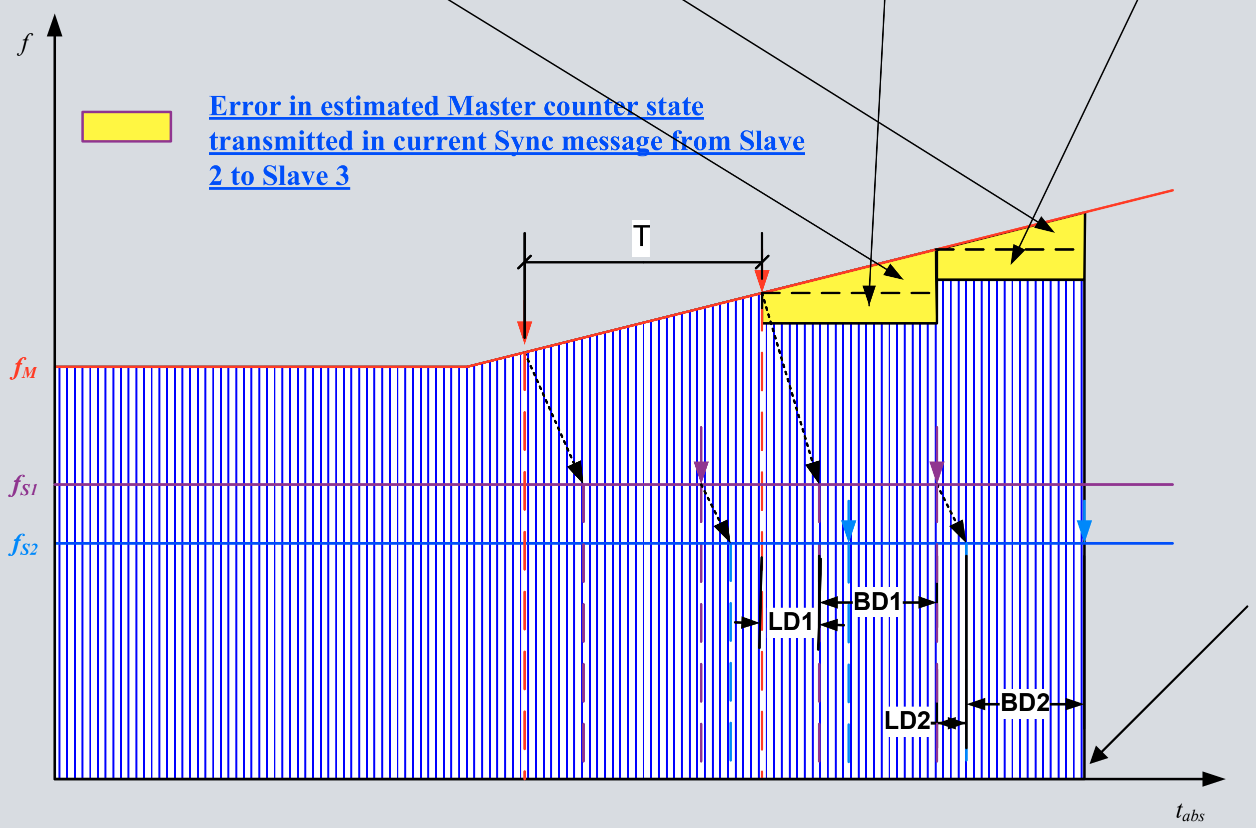
Error in the master counter estimates in Sync Messages leaving slave 1 and slave 2:

$$Error = \Delta_M / 2 \cdot ((LD1 + BD1)^2 + (LD2 + BD2)^2 + (LD1 + BD1) \cdot T + (LD2 + BD2) \cdot T\ )$$

triangle triangle rectangle rectangle



LDi: Line Delay of Slave i

BDi: Bridge Delay of Slave i

Δ_M: slope of the Master element frequency change

T: interval used for calculating RCF

Time of transmission of the current Sync Message from Slave 2 to Slave 3

Drift Propagation Model: Master Counter Estimate Error due to Frequency Drift (more general)

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The master counter estimate error at slave N is:

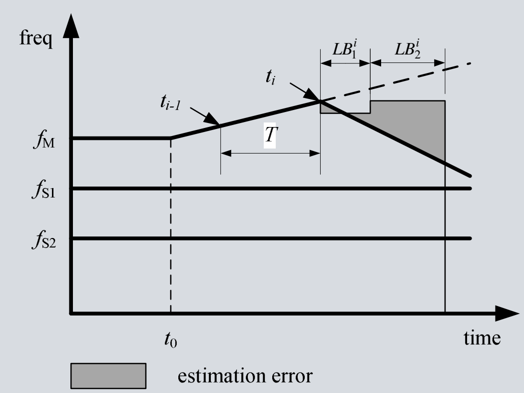
$$M - \hat{M}_{S_N out}\Big|_{t_i + \sum_{n=1}^{N} LB_n^i} = \frac{\Delta_M}{2}\cdot\left[\sum_{n=1}^{N} LB_n^i \cdot T + \sum_{n=1}^{N}(LB_n^i)^2\right] + \Delta_M \cdot \sum_{n=1}^{N} LB_{n+1}^i \cdot \left(\sum_{k=1}^{n}\delta_{LB}^{i,k}\cdot\frac{1+\sum_{k=1}^{n}LB_k^i/T}{1+\sum_{k=1}^{n}\delta_{LB}^{i,k}/T}\right) +$$

Bias Term:
1st summand – rectangles (dominating term);
2nd summand - triangles;
illustrated next for time-invariant line and bridge delays, for slaves 1 and 2

Zero-mean term, present due to variations in the bridge delays and line delays affecting consecutive Sync Messages

$$+ \frac{\Delta'_M - \Delta_M}{2}\cdot\left(\sum_{n=1}^{N}LB_n^i\right)^2$$

Term only present if master frequency drift changed right after Sync Message was transmitted (worst-case scenario)



Drift Propagation Model: Master Counter Estimate Error due to Frequency Drift - Conclusions

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Master counter estimate error at slave N (constant drift gradient):

$$M - \hat{M}_{S_N out}\Big|_{t_i + \sum_{n=1}^{N} LB_n^i} = \frac{\Delta_M}{2} \cdot \left[\sum_{n=1}^{N} LB_n^i \cdot T + \sum_{n=1}^{N} (LB_n^i)^2 \right] + \Delta_M \cdot \sum_{n=1}^{N} LB_{n+1}^i \cdot \left(\sum_{k=1}^{n} \delta_{LB}^{i,k} \cdot \frac{1 + \sum_{k=1}^{n} LB_k^i / T}{1 + \sum_{k=1}^{n} \delta_{LB}^{i,k} / T} \right)$$

How to reduce the error:

1. Minimize the influence of temperature change on the oscillator (e.g. insulation).
2. Choose oscillators that are not sensitive to temperature change.
3. Shorten the synchronization interval (however, this conflicts with the choice to minimize the influence of jitter, as shown before)
4. Regulate the forwarding of Sync messages so that bridge delays are approximately constant over time, to remove the zero mean term.
5. Modify formula used at each slave to compute its estimate of the master time so that the effect of the temperature change is compensated (bias term).

Some intermediate results

- Novel approach to initialization of the synchronization process (based on parallel local calculations)
- Distributions of HW specific jitter sources obtained and exploited
- Different filtering algorithms
- Controller parameter optimization
- Analytic analysis of the error propagation due to Jitter and Frequency Drift as input for the HW optimization
- Support of the standardization activities
- Simulation tool development
- …

Clock synchronization:
A Cascaded Tracking Control problem

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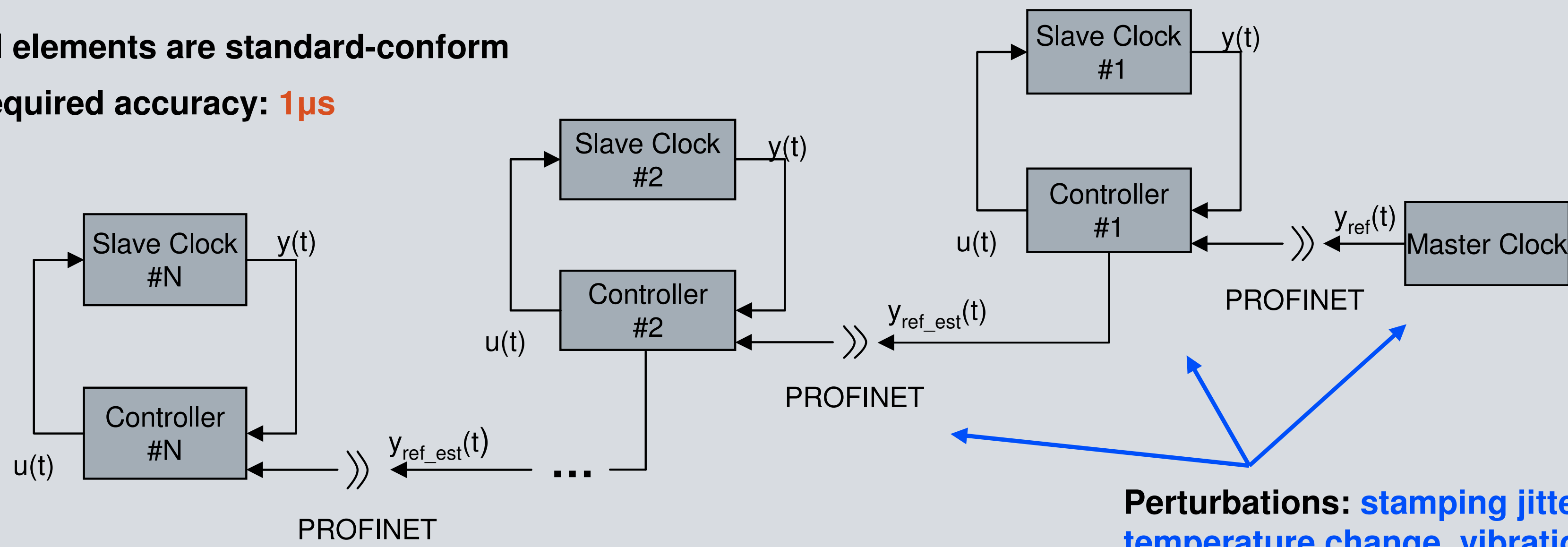
The estimated Master Time at the arrival of a Sync Message is the reference tracking signal for the built in feedback controller which corrects the local Slave counter!

The reference signal is noisy and approximately Gaussian, the system is linear ➔ Optimal linear control approach possible (LQG)!

All elements are standard-conform

Required accuracy: 1µs



Perturbations: stamping jitter, temperature change, vibration, shocks, …

Clock synchronization:
A Cascaded Tracking Control problem

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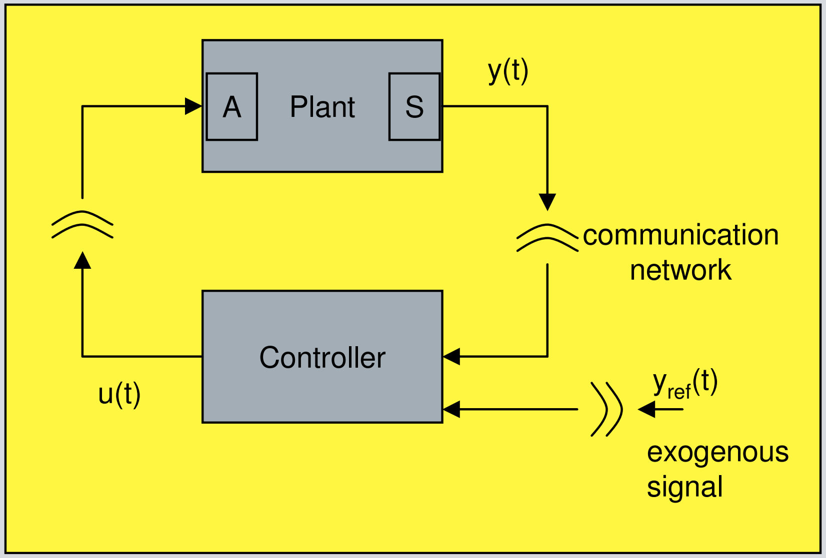
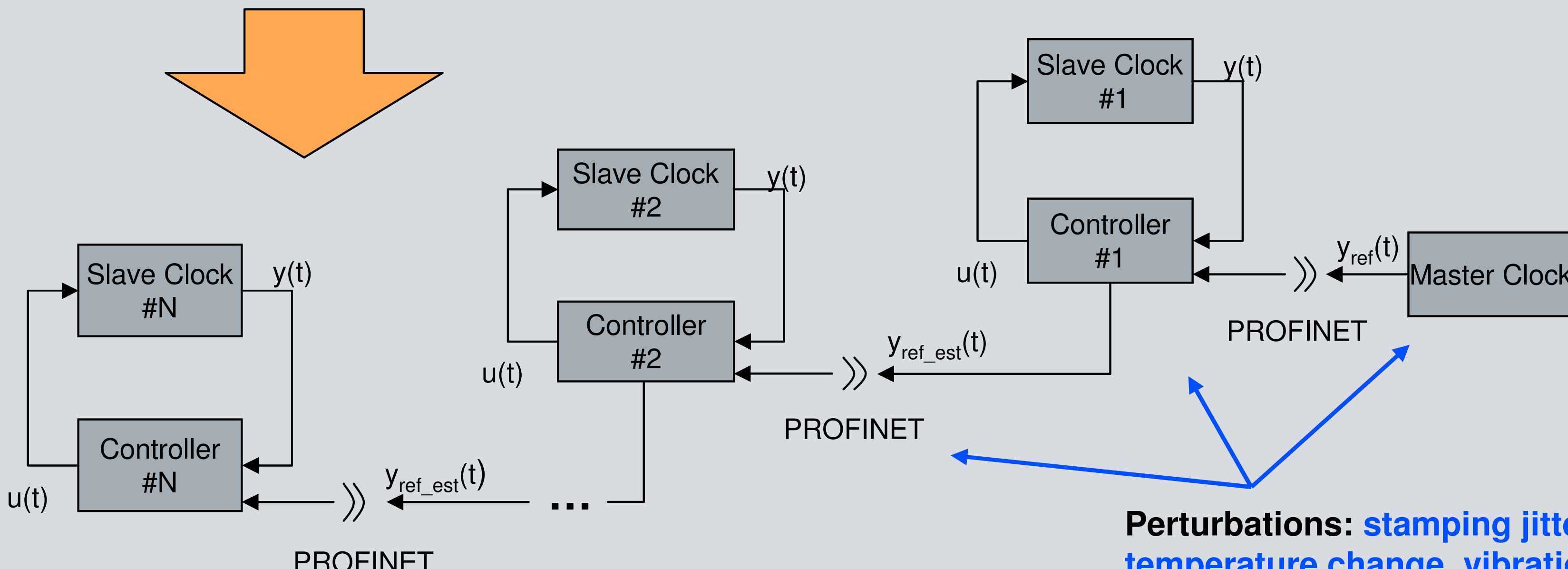


The original application control problem transformed into an embedded cascaded networked control problem!



Perturbations: **stamping jitter, temperature change, vibration, shocks, …**

Clock Synchronization: Mathematical Description

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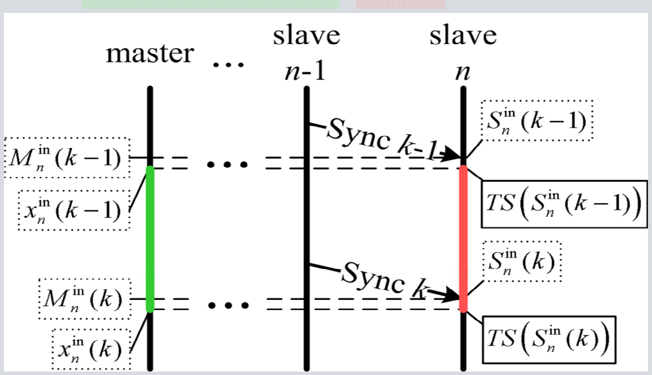
Clock Synchronization is a spatial-temporal dynamic process with the information flow from the Master to Slaves!

A state-space representation can be derived:

- States are the Master counter values at the arrivals of Sync Messages at Slaves. Optionally, the unknown RCF factors can be introduced as auxiliary states (combined state and parameter estimation). ➔ Two states per node!
- Noisy observations are the Master time estimates contained in Sync messages (Gaussian noise due to CLT justified)

state transition of true master counter value

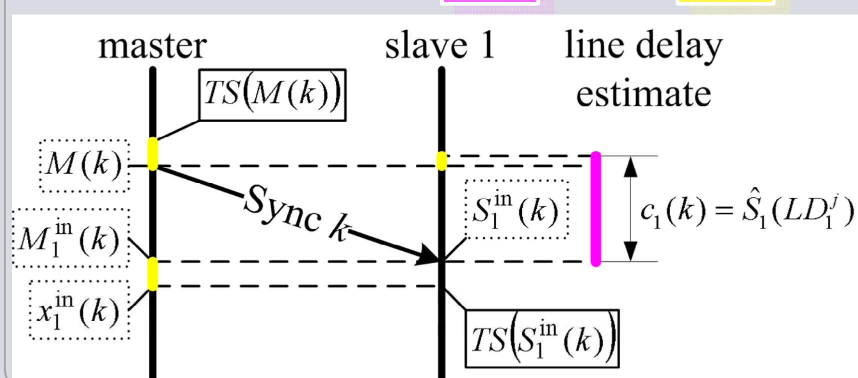
$$x_n^{\text{in}}(k) - x_n^{\text{in}}(k-1) = a_n(k) \cdot R_n(k-1)$$



$$a_n(k) = TS\left(S_n^{\text{in}}(k)\right) - TS\left(S_n^{\text{in}}(k-1)\right)$$

observation model

$$TS(M(k)) = x_1^{\text{in}}(k) - c_1(k) \cdot R_1(k) + \nu_1(k)$$



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Clock Synchronization: Mathematical Description

Global state-space representation:

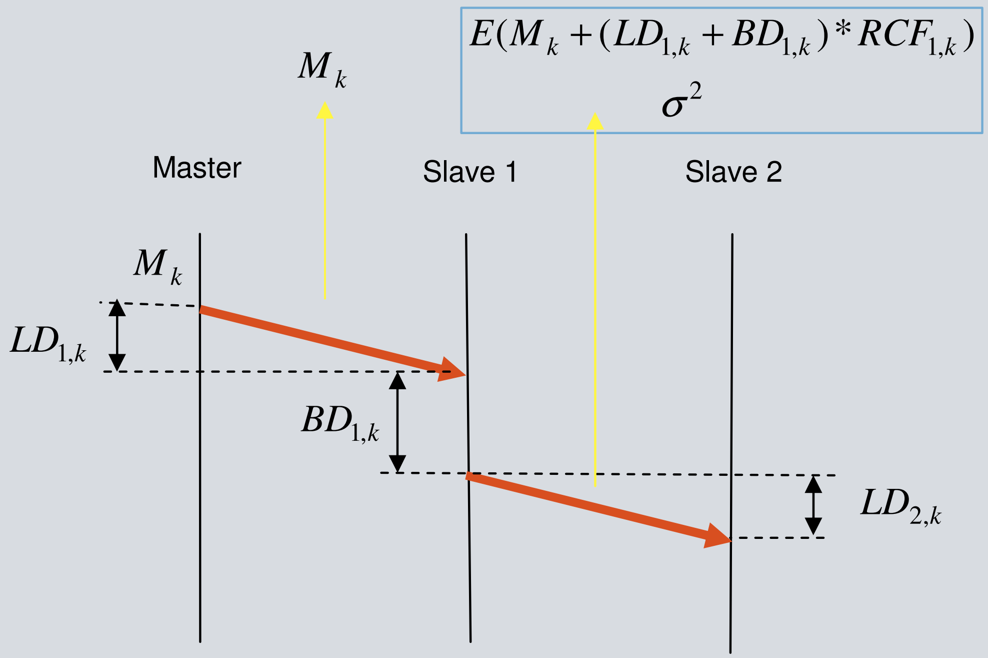
- Each node has two states (or a single state if the estimation of RCF executed separately)
- Provides an upper bound on the both estimation and control performance
- If Gaussian assumption justified, the underlying estimator is a centralized Kalman Filter

(Unidirectional) Message Passing Algorithm:

- Global state space model has a graphical representation (e.g. factor graph) which can be used for belief propagation algorithms
- The message passing can be restricted to the direction Master to Slave

Local Kalman Filter:

- One Kalman Filter and Controller pro Slave
- Realistic, directly applicable
- Receives as an input the whole probabilistic information about the Master time estimate of the previous Slave (the Gaussian pdf)



NCS: Unidirectional state estimation based on the Factor Graph model

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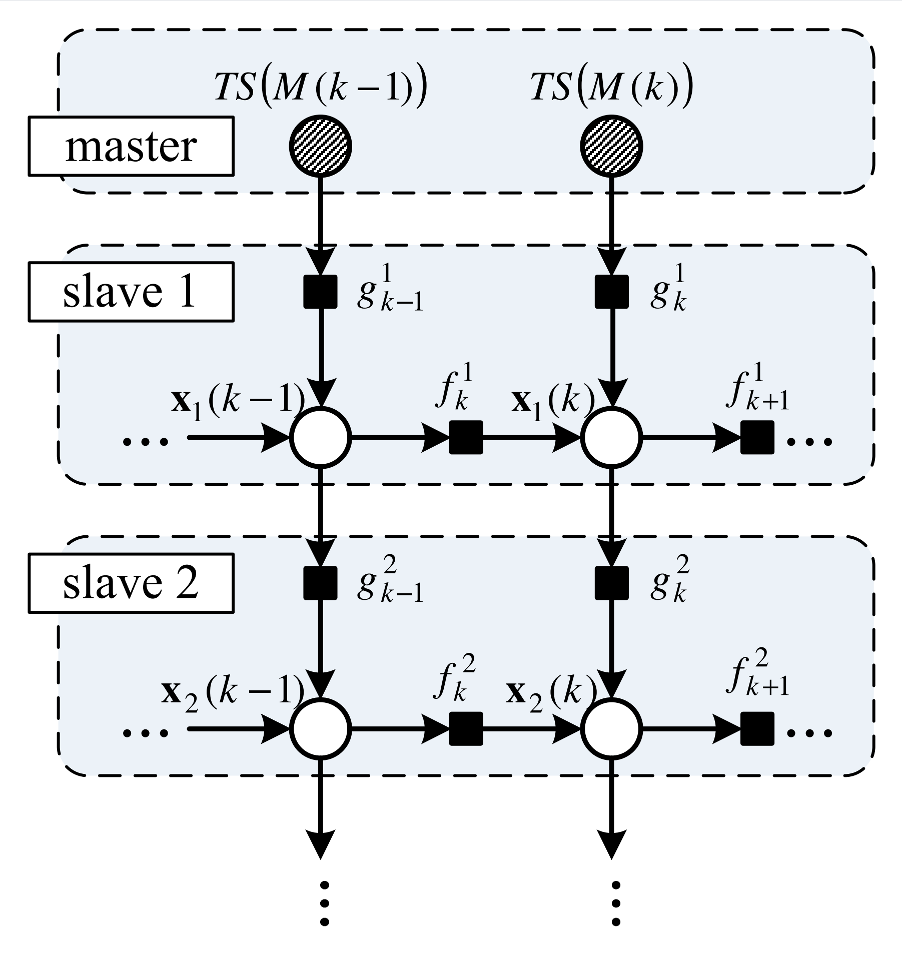
$$p\left(\{\mathbf{x}_n(k);TS(M(k)),\mathbf{A}_n(k),\mathbf{b}_n(k),\mathbf{c}_n(k)\mid n=1,\ldots N,k=0,\ldots K\}\right)$$

$$=\left(\prod_{n=1}^{N} p(\mathbf{x}_n(0))\right)\cdot\prod_{k=1}^{K}\left[\left(\prod_{n=1}^{N} f_k^n(\mathbf{x}_n(k)\mid \mathbf{x}_n(k-1))\right)\cdot g_k^1(\mathbf{x}_1(k)\mid TS(M(k)))\cdot\left(\prod_{n=2}^{N} g_k^n(\mathbf{x}_n(k)\mid \mathbf{x}_{n-1}(k))\right)\right]$$



1

$$f_k^n(\mathbf{x}_n(k)\mid \mathbf{x}_n(k-1))=\frac{1}{\sqrt{2\pi}\sigma_{\omega_n(k)}}\exp\left(-\frac{\left((\mathbf{x}_n(k)-\mathbf{A}_n(k)\mathbf{x}_n(k-1))^{\mathrm{T}}\mathbf{e}\right)^2}{2\sigma_{\omega_n(k)}^2}\right)$$

2

$$g_k^1(\mathbf{x}_1(k)\mid TS(M(k)))=\frac{1}{\sqrt{2\pi}\sigma_{v_1(k)}}\exp\left(-\frac{\left(TS(M(k))-\mathbf{c}_1^{\mathrm{T}}(k)\cdot\mathbf{x}_1(k)\right)^2}{2\sigma_{v_1(k)}^2}\right)$$

3

$$g_k^n(\mathbf{x}_n(k)\mid \mathbf{x}_{n-1}(k))=\frac{1}{\sqrt{2\pi}\sigma_{v_n(k)}}\exp\left(-\frac{\left(\mathbf{b}_{n-1}^{\mathrm{T}}(k)\cdot\mathbf{x}_{n-1}(k)-\mathbf{c}_n^{\mathrm{T}}(k)\cdot\mathbf{x}_n(k)\right)^2}{2\sigma_{v_n(k)}^2}\right)$$

PT(C)P Clock Synchronization: Possible Extensions & Open Questions

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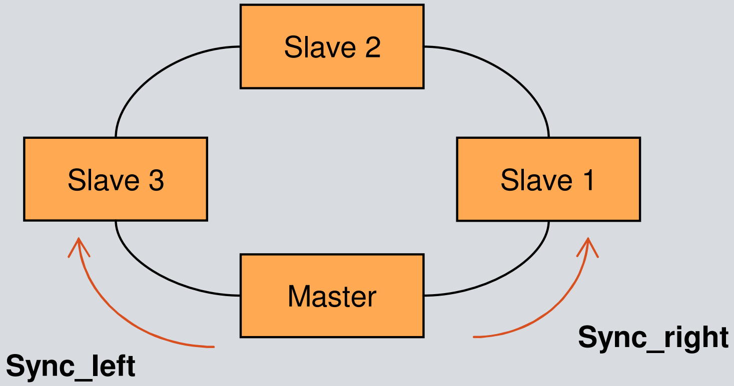
Identify possibly small changes in the protocol with large impact on the performance (precision and conform line length)!

1. **Under which condition is clock synchronization possible if not all the elements are standard conform (do not estimate and report their delays)?**

2. **How to optimally use the Sync message information coming from both sides in a ring topology?**



3. **How to move away from the deterministic schedule, especially in faster than 100Mb/s networks?**

Real-Time Wireless?

PT(C)P Clock Synchronization in other Application

1. **Synchronization of Base Stations (BS) in cellular communication systems (DECT-IP, GSM). Necessary for proper handovers.**
2. **Synchronization of video and audio streaming from several sources: very important topic in the AV bridge community (Cisco, …)**
3. **Phase measurements in electric grid**
4. **Synchronization of protection equipment in power systems**
5. **…**

There is an IEEE sponsored conference on clock synchronization:
International IEEE Symposium on Precision Clock Synchronization for Measurement, Control and Communication (ISPCS)!

Typical publication target: **IEEE Tr. On Instrumentation and Measurement**

THANK YOU FOR YOUR ATTENTION!

