Networked Control System Analysis for Smart Grid Applications

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Outline

1. **NCS as Cyber-Physical System**
   Applications and Research Challenges

2. **Modeling NCSs**
   Integration of Distributed Control Systems and Communication Networks

3. **Performance Analysis**
   Hierarchical Multi-Layer Aggregation Principle

4. **Case Study Application Results**
   Impact of Network Protocols and Delays on Control Performance

5. **Conclusions and Outlook**

1. NCS as Cyber-Physical System

Definition of CPSs

- **Integration of**
  - Physical Processes
  - Computer and DB Systems
  - Communication Networks

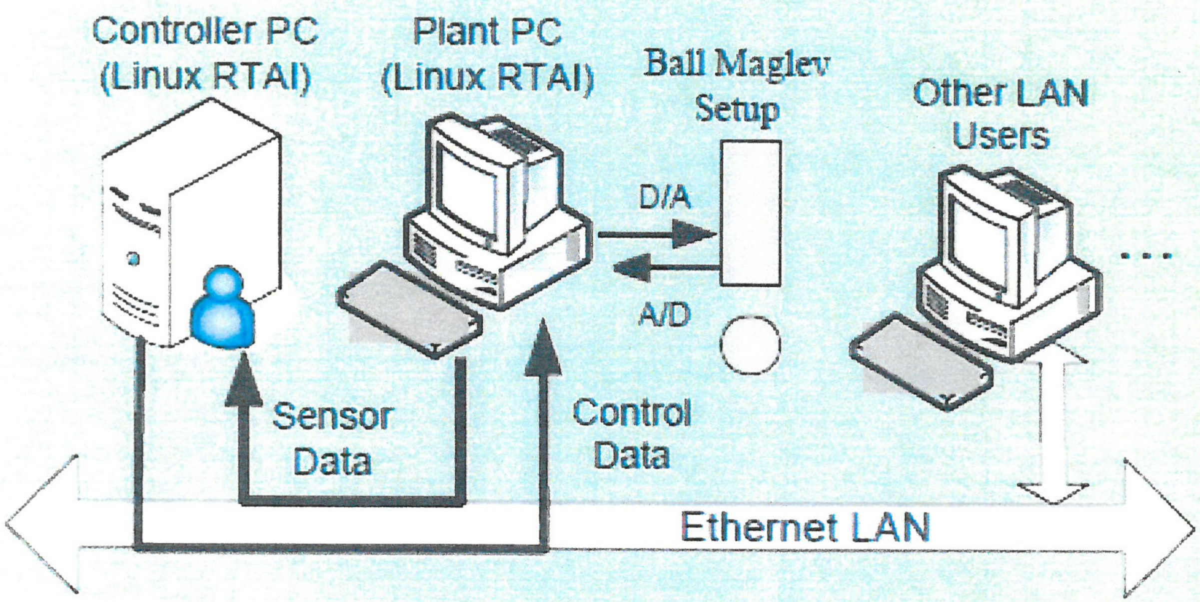
- **"Embedded Systems" Context**
  - Computers Embedded in Distributed Physical Systems
  - Networks Embedded in Distributed Systems

- **Application Contexts**
  - Machine-to Machine (M2M) Communications
  - Internet-of-Things (IoT)
  - Smart-Grid for Distributed Power Generation and Supply
  - Smart Traffic Control and Autonomous Driving
  - Surveyance (Health Control, Desaster Management, ...)

1. NCS as Cyber-Physical System

Challenges of CPSs

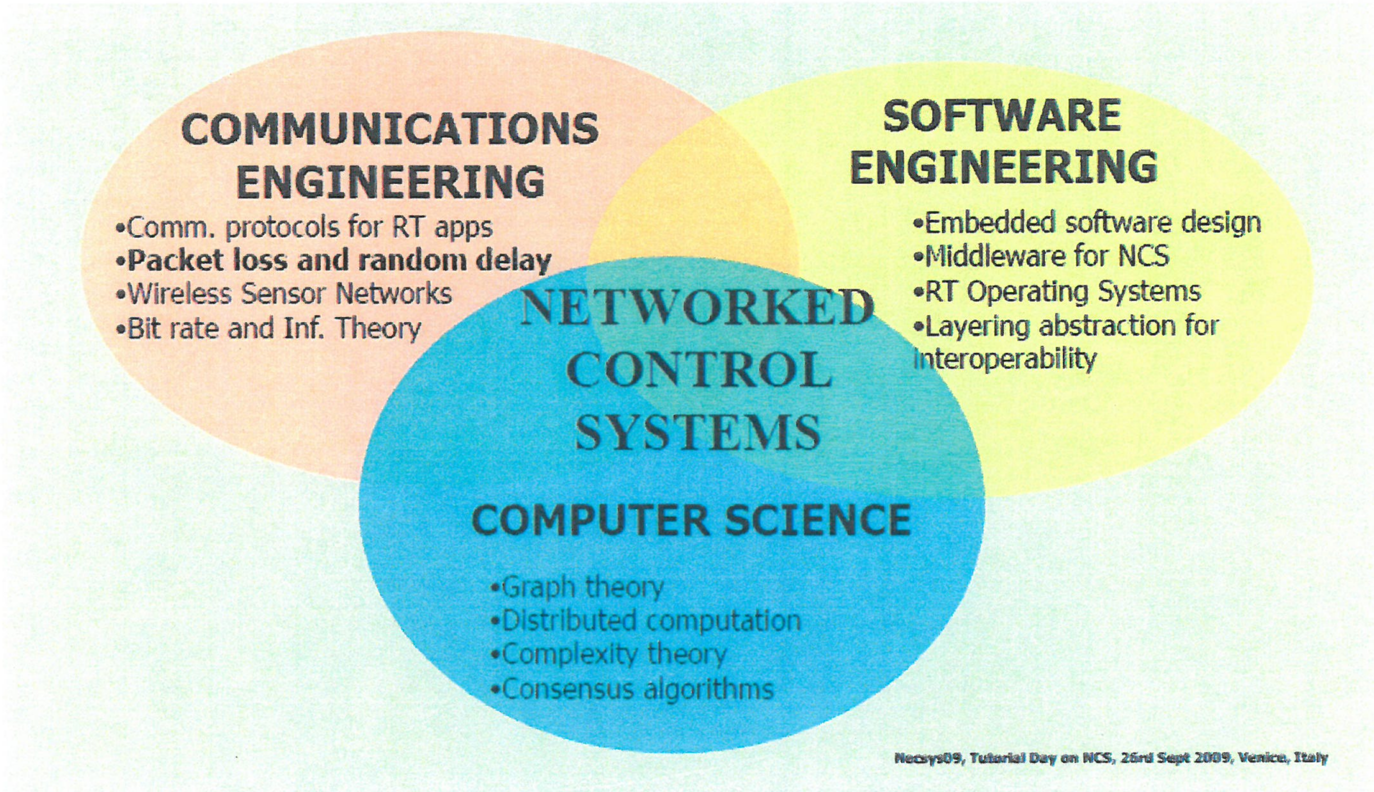
Example of a Networked Control System



1. NCS as Cyber-Physical System

Challenges of CPSs

Interdisciplinary Challenge



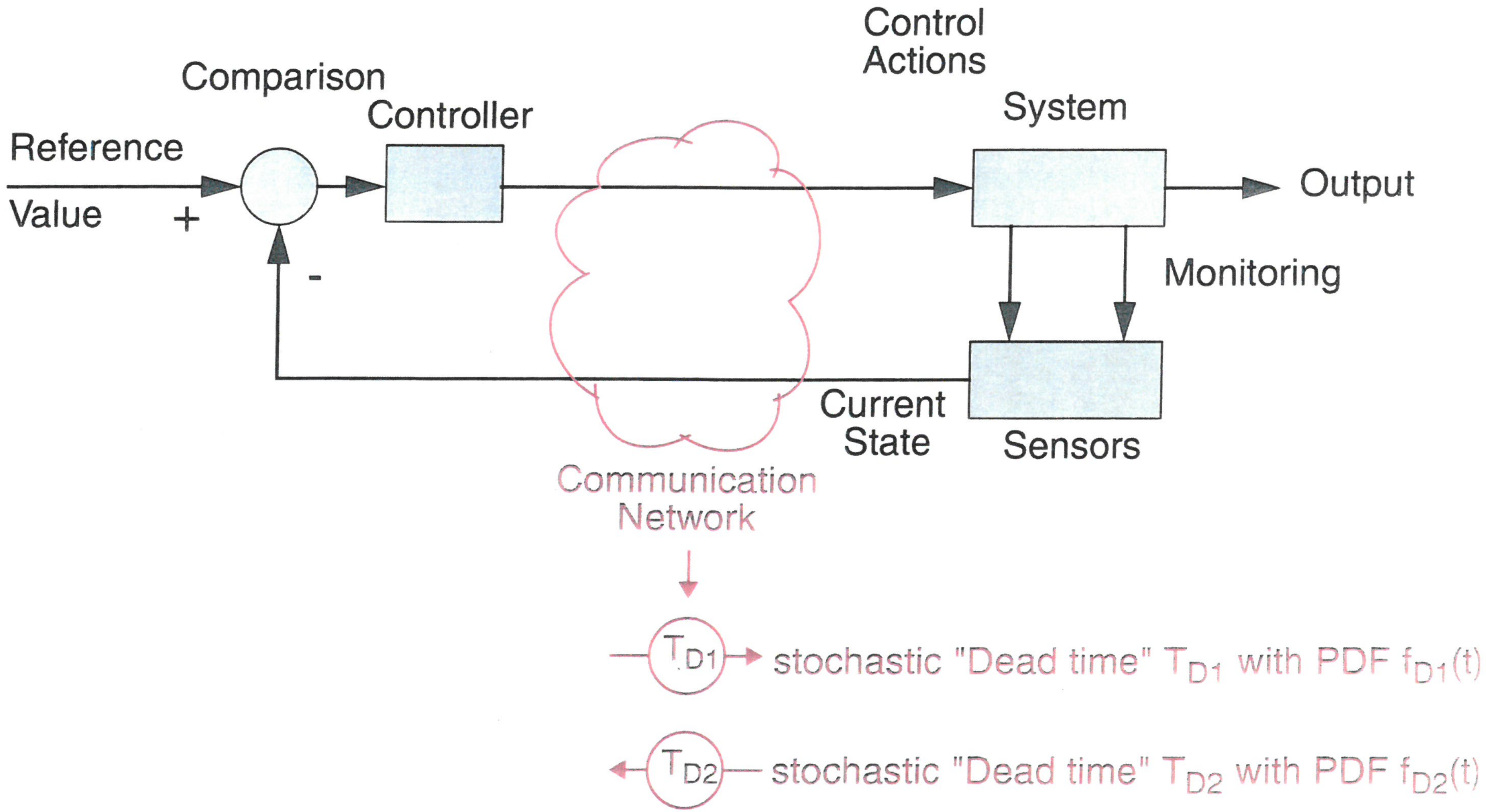
1. NCS as Cyber-Physical System

Challenges of CPSs

1. **Availability**
   - Networks are the critical factor for a distributed system
   - Dedicated Networks vs. Shared Networks
2. **Reliability and Dependability**
   - Resilient Networks
   - Dependable Network Performance
3. **Security**
   - Intrusion Detection and Avoidance
   - Privacy
4. **Network and System Architectures**
   - Interfaces, Protocols, Standards
   - Scalability
   - DB Support
5. **Real-Time Performance**
   - Time-Sensitive Networks
   - Tactile Internet
   - Networked Control Systems
   - Massive MIMO Concepts

2. Modeling Networked Control Systems

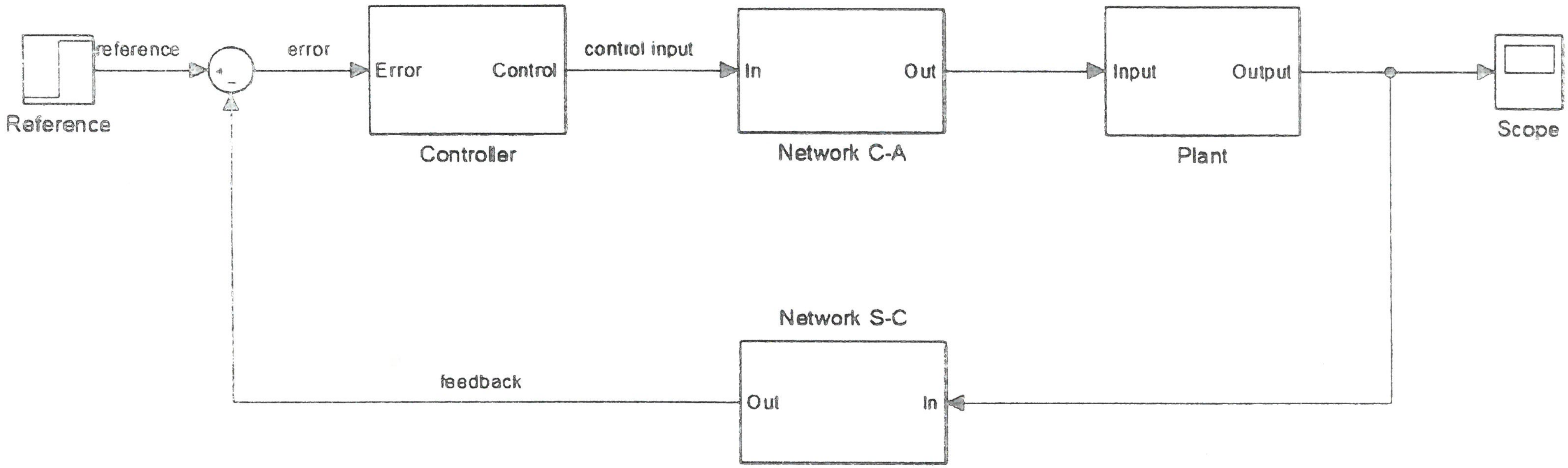
Extended Model of a Feedback Control System



2. Modeling Networked Control Systems

NCS without Network Layer Protocols

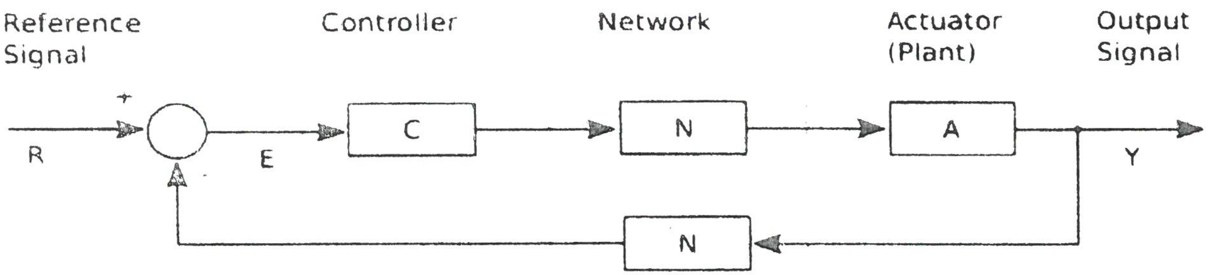
Modeling of a NCS - Extended Model of a Feedback Control System



2. Modeling Networked Control Systems

NCS without Network Layer Protocols

NCS Structure:



NCS Analysis

$$C(s) = P + I \cdot s^{-1} + D \cdot s$$
$$c(t) = LT^{-1}\{C(s)\}$$
$$H(s) = Y(s)/R(s)$$
$$h(t) = LT^{-1}\{H(s)\}$$

NCS System Function

$$H(s) = \frac{Y(s)}{R(s)} = \frac{P(s) \cdot N(s) \cdot A(s)}{1 + P(s) \cdot N^2(s) \cdot A(s)}$$

Types of Networks:

Constant Delay

$$N(s) = exp(-sd)$$

Exponential Delay

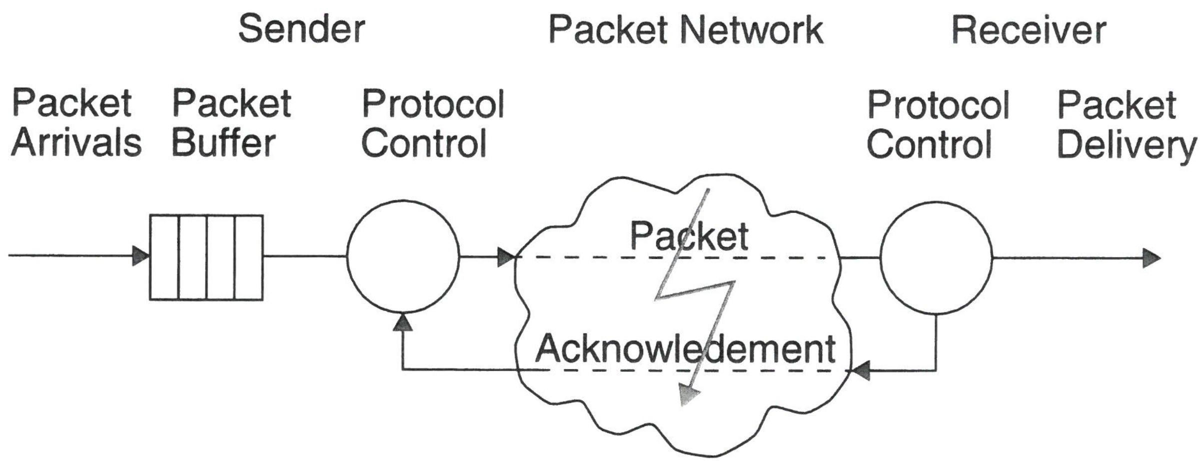
$$\varepsilon/(s+\varepsilon) = \beta$$

Delayed (Shifted) Expone

$$\varepsilon/(s+\varepsilon) \cdot exp(-sd) = \beta \cdot exp(-sd)$$

2. Modeling Networked Control Systems

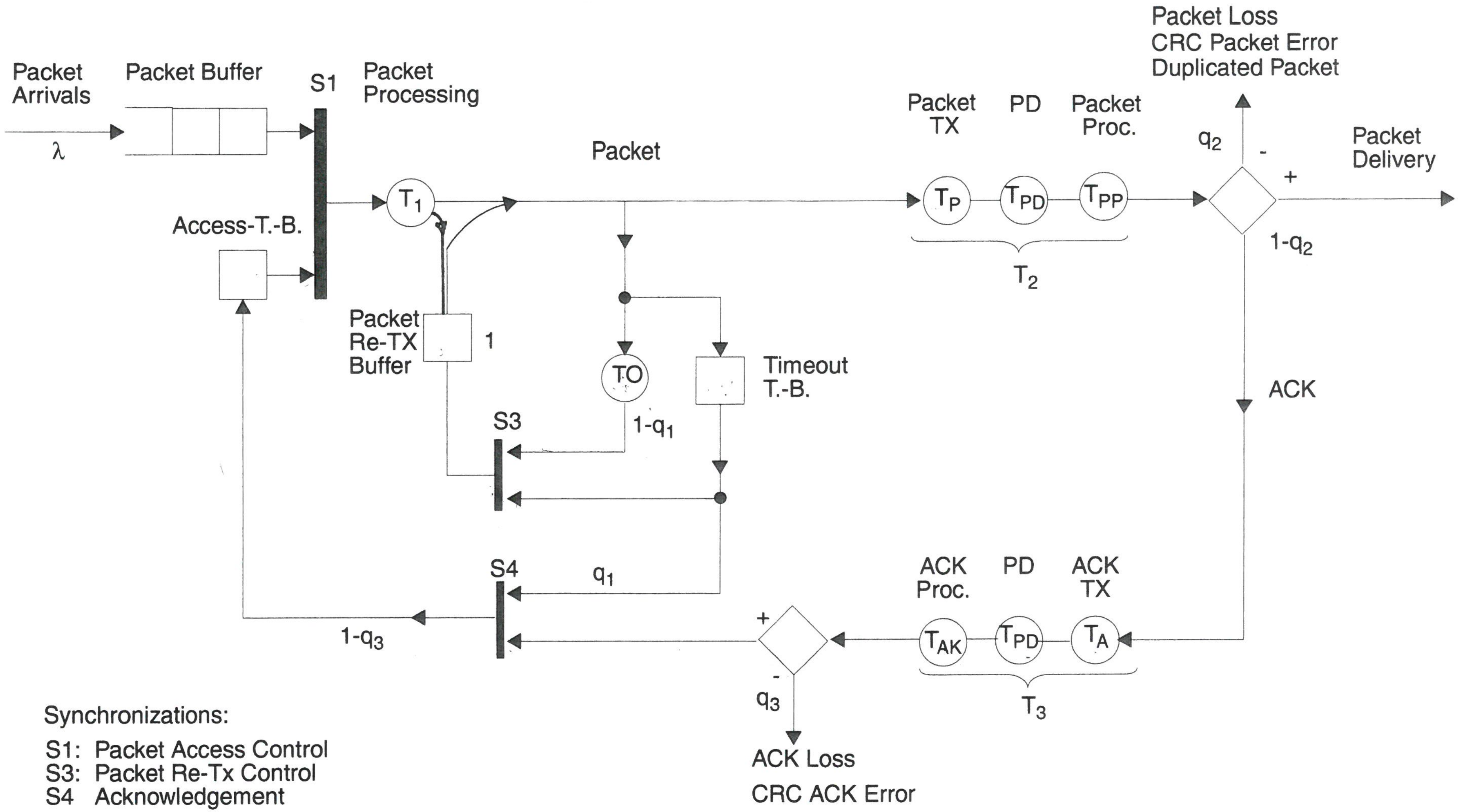
NCS with Network Layer Protocols



- Aims: Secure Information Transfer from Sender to Receiver under strict Delay Requirements (Service Level Agreements, SLA)
- Obstructions:
  - Limited Transmission Speed
  - Signal Propagation Delay
  - Transmission Interferences (Noise, Reflections, ..., Bit Errors)
  - Packet Losses through Buffer Limitations
- Solutions:
  - Error Control (FEC, Repeated Packet Transmissions)
  - Timing Control
  - Formal Protocol Specification and Verifiction of Correctness
  - Performance Analysis

2. Modeling Networked Control Systems

NCS with Network Layer Protocols



Synchronizations:

S1: Packet Access Control
S3: Packet Re-Tx Control
S4 Acknowledgement

3. Performance Analysis

NCS without Network Layer Protocols

NCS System Functions H(s)

Constant Delay

$$H(s) = pa\beta / [1 + pa\beta^2] = \frac{pa\varepsilon\,(s+\varepsilon)}{s^2 + 2\varepsilon s + \varepsilon^2(1+pa)}$$

Exponential Delay

$$H(s) = ap\beta[1 - \beta^2(ap) + \beta^4(ap)2 - \beta^6(ap)3 + -\ldots]$$

Shifted Exponential Delay

$$H(s) = \frac{pa\beta\cdot\cdot exp(-sd)}{1 + pa\beta^2\cdot exp(-s2d)}$$

$$= pa\beta\cdot exp(-sd) - (ap)^2\beta^3\cdot exp(-s3d) + (ap)^3\beta^5\cdot exp(-s5d)$$

Unit-Step Response y(t)

$$y(t) = (pa)\cdot u(t-d) - (pa)^2\cdot u(t-3d) + (pa)^3\cdot u(t-5d) - +.$$

$$y(t) = pa/(1+pa)^{-1} \bullet \{1 + exp(-\varepsilon t)\cdot[cos(\varepsilon\sqrt{ap}\cdot t) - \sqrt{pa}\cdot\cdot sin(\varepsilon\sqrt{pa}\,t)]\}$$

$$y(t) = pa\cdot u(t) - pa\,\varepsilon^2\cdot exp(2\varepsilon d)\cdot\{- t\cdot exp(-\varepsilon t)/\varepsilon - + \ldots\}$$

3. Performance Analysis

NCS with Network Layer Protocols

Method:

- Application of Protocol Analysis for SW-Protocol with ACK/TO-Recovery

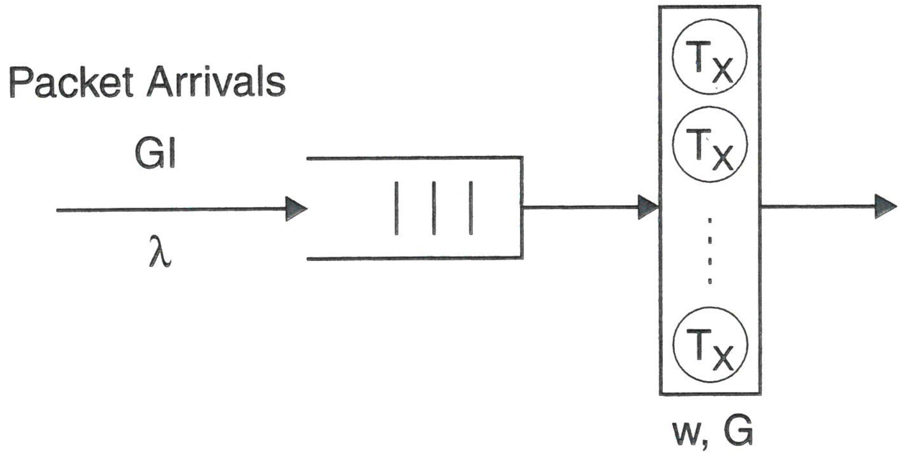
- Result: Virtual Transfer Time T_x of a Frame
  Virtual Queuing System of Type GI/G/1
  Application to a Control System with Event-Triggered Samples (M)
  Flow Time DF of the M/G/1 Queuing System by
  Convolution of the Waiting Time and the Virtual Transit Time PDFs
  Insertion of the Entire Network Functionality by Flow Time PDF in the
  Control Loop
  Verification by Simulation Using MATLAB SIMULINK Tool

- Demonstrated by
  Unit Step Function Response y(t)
  Compl. Delay Time Distribution Function for System Optimization
  with respect to Delay Percentiles of Service Level Agteements

3. Performance Analysis

NCS with Network Layer Protocols

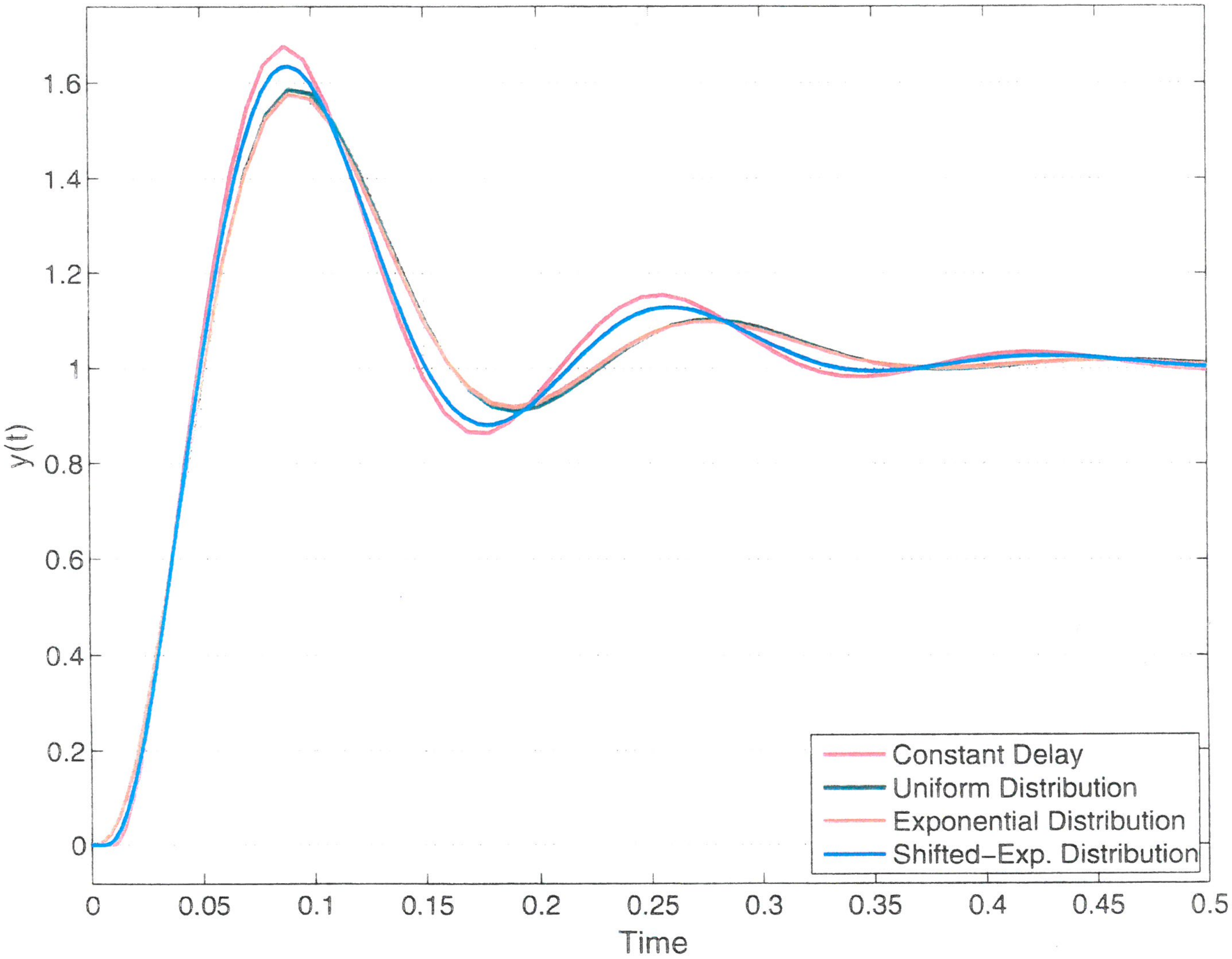
- Up to w ("Window Size") packets ca be in transit
- Each Packet is Timer-Controlled
- IF a Packet or ACK is lost or timed out it will be transmitted again **independent** of all other packets in transit
- The Virtual Transmission Time T_X is identical as for S&W with Timeout Control
- The System can be modeled by a Virtual w-Server model



- Note: An additional delay can happen:
  Conflict of Blocking between Re-TX Packet and newly admitted Packet.
  Solution: Analysis for 2 border cases with additional Phase T_B

4. Case Study Application Results

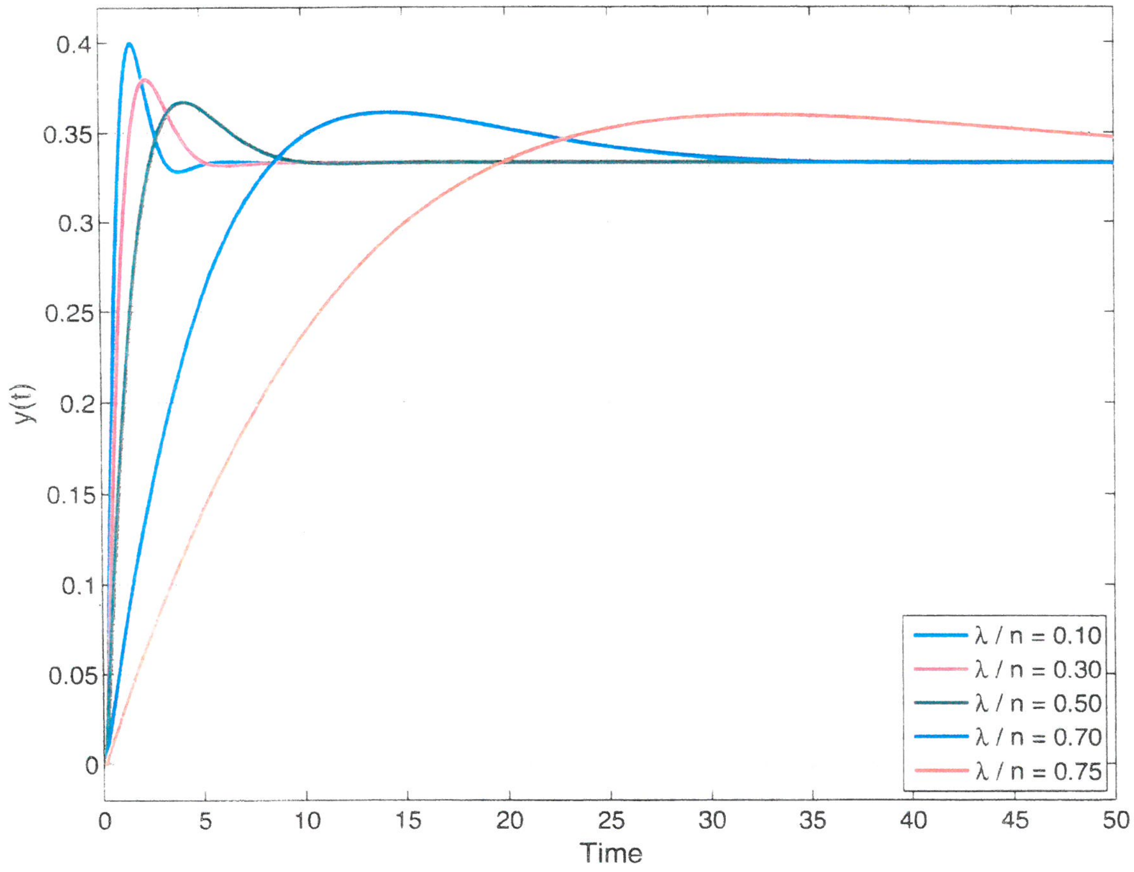
NCS without Network Layer Protocols: Results for Linear Plant System



4. Case Study Application Results

NCS with Network Layer Protocols

Results: Unit Step Function Responses for different Control Loop Sample Rates λ



4. Case Study Application Results

NCS with Network Layer Protocols

Results: Unit Step Function Responses for different Control Loop Sample Rates λ

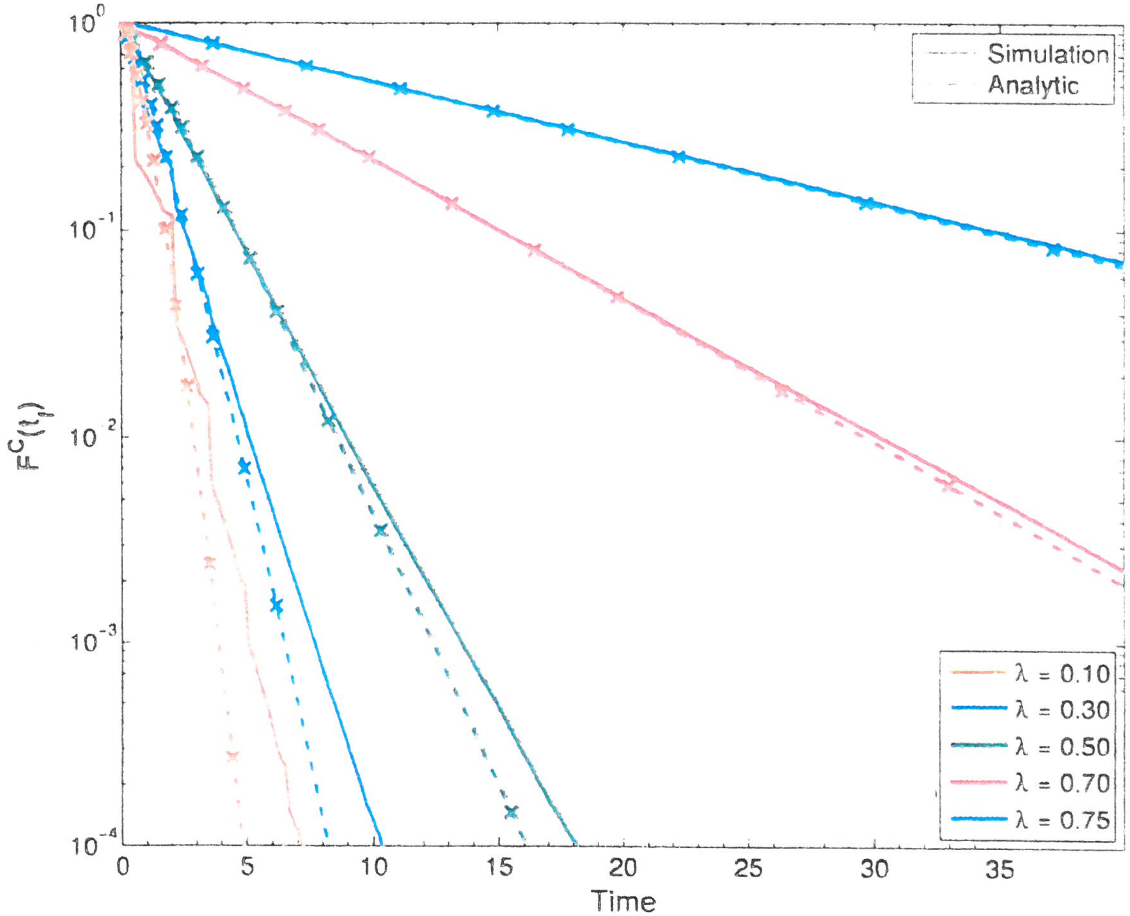


Table 1. Results of the ACK/TO SW Protocol Analysis Together with Computer Simulation Results

SW Protocol with Ack/Timeout Control						
λ/n		0.10	0.30	0.50	0.70	0.75
ρ		0.127	0.380	0.633	0.887	0.950
$E[T_X]$	analytical	1.267	1.267	1.267	1.267	1.267
	simulation	*1.266*	*1.267*	*1.267*	*1.267*	*1.267*
$E[T_W]$	analytical	0.108	0.455	1.283	5.812	14.117
	simulation	*0.108*	*0.457*	*1.290*	*5.856*	*15.093*
t_D	analytical	0.851	1.198	2.026	6.556	14.860
	simulation	*0.853*	*1.210*	*2.034*	*6.660*	*14.346*
c_D	analytical	0.867	0.907	0.946	0.984	0.993
	simulation	*0.872*	*0.911*	*0.949*	*0.988*	*0.995*
$E[T_F]$	analytical	0.894	1.241	2.069	6.599	14.903
	simulation	*0.894*	*1.244*	*2.076*	*6.642*	*15.133*
c_F	analytical	0.731	0.831	0.912	0.976	0.990
	simulation	*0.733*	*0.833*	*0.914*	*0.980*	*0.992*

5. Conclusions and Outlook

1. We could show how our multi-layer aggregation method can be applied to solve Performance Problems of Networked Control Systems

2. Basis is the method of task graph reductions to get an equivalent and precise description of a whole subsystem as, e.g.,

   - a MAC layer functionality (currently under study)
   - a LLC layer protocol (demonstarted for the SW protocol with ACK/TO Control)

3. When fully exact queuing system solutions are not yet available (as for the GI/G/n queuing model) our two-moment approximations give sufficiently precise results which have been verified by accurate full system simulations

4. With the analysis of the distribution functions of the NCS performance we have shown - for the first time - that NCSs can be optimized to meet hard real-time Service Level Agreements (SLA), prescribed by the percentiles of the delay distributions