REAL TIME CONTROL IN 5G:
Embedded Communication Networks - A System-Theoretic Modeling Approach

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Outline

1. Distributed Real-Time Applications
2. Communication Networks as Embedded Systems in Distributed Networked Control Systems (NCS) - A System Theoretic Approach
3. Application Examples
   3.1 Latencies in Error-Control Protocols
   3.2 Other Examples
4. Conclusions

1. Distributed Real-Time Applications

- Distributed Electric Power Control in the "Smart Grid"
  - Feeding highly volatile el. Energy in the Power Grid
  - Feeding Control Based on Phasor Sensing Data
- Smart Traffic Control ("Smart City")
  - Intelligent Traffic Control
  - Accident / Desaster Management
- Integrated Industry Process ("Industry 4.0")
  - Production Automation
  - Integration in Enterprise Business Processes
- Human Health Surveillance
  - Sensoric Health Parameter Monitoring
  - Case Management

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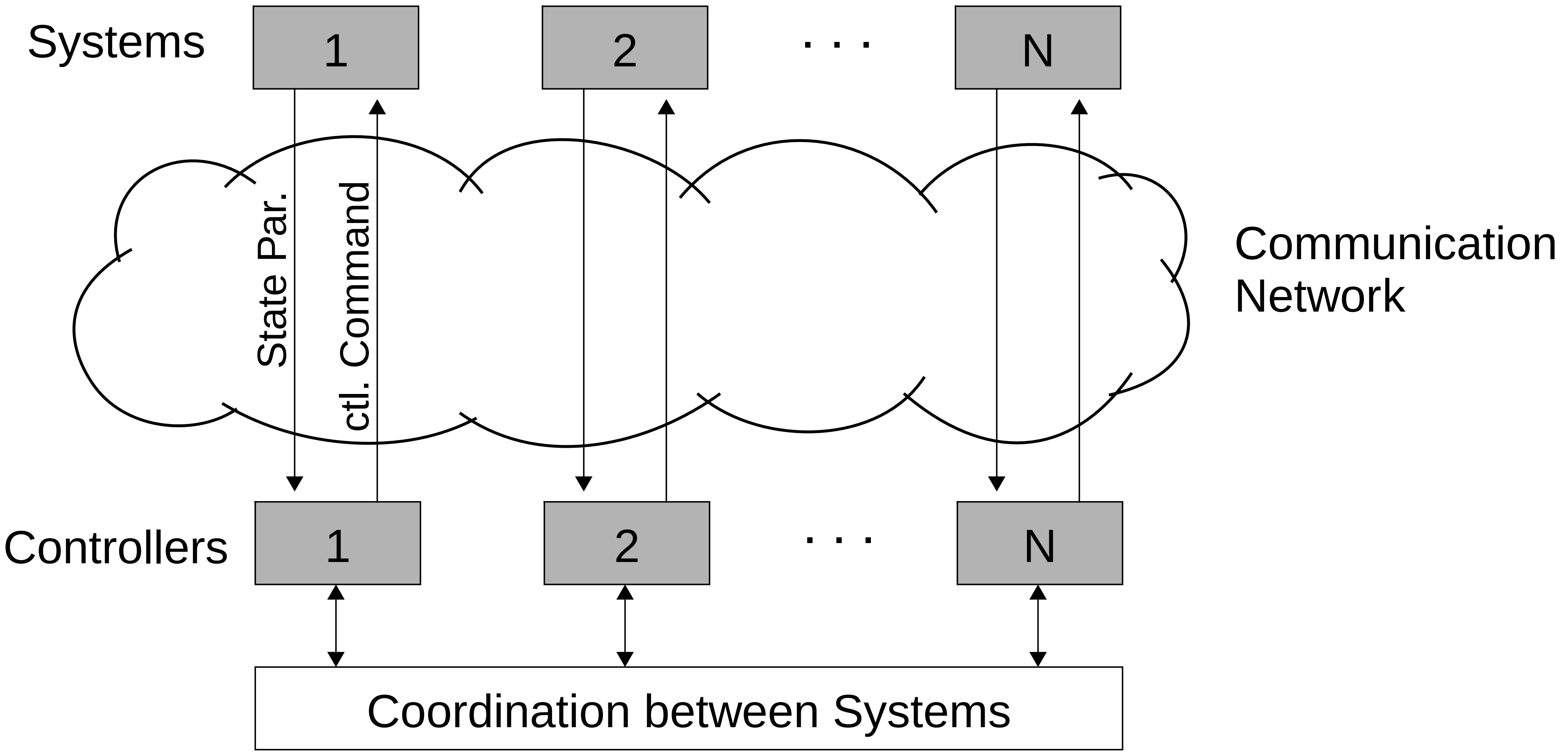
2. Communication Networks as Embedded System in Network Control Systems (NCS)



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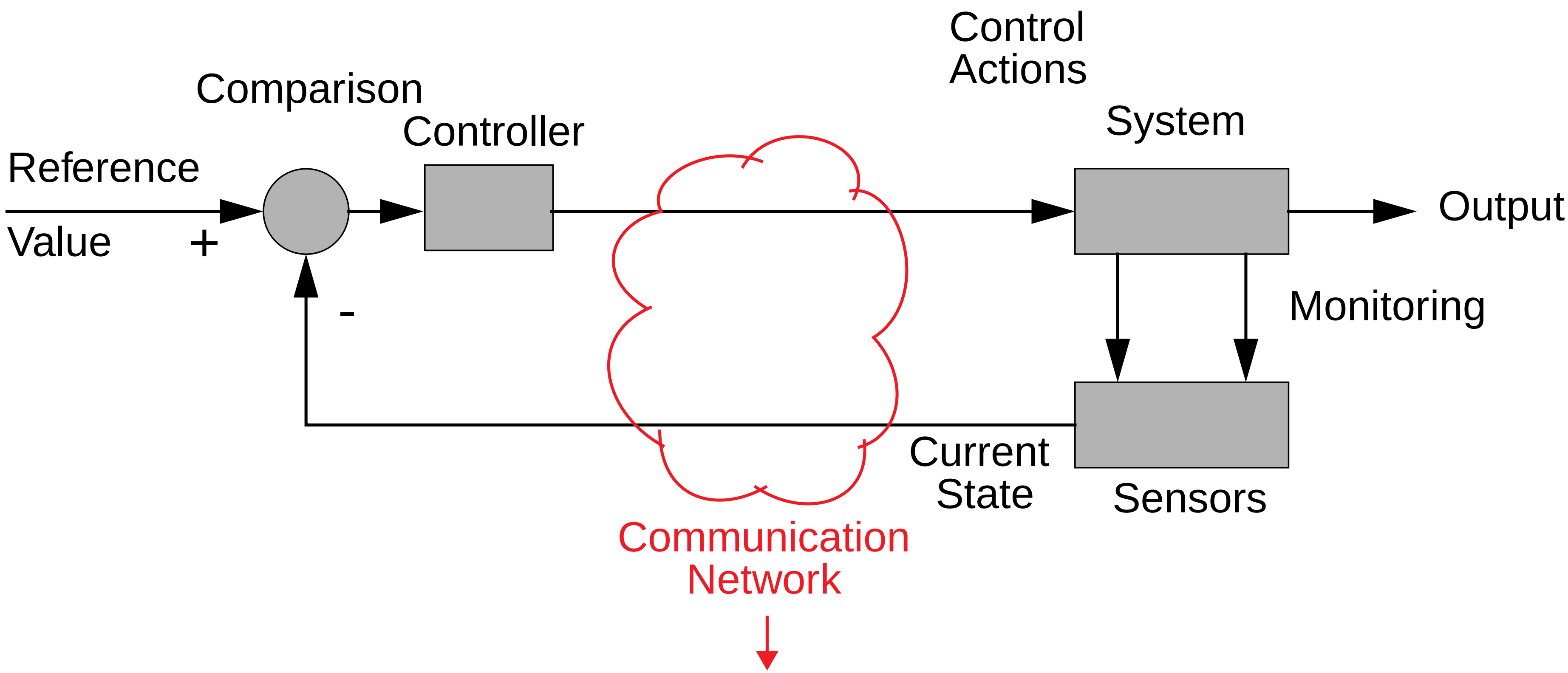

T_{D1} stochastic "Dead time" T_{D1} with PDF $f_{D1}(t)$

T_{D2} stochastic "Dead time" T_{D2} with PDF $f_{D2}(t)$

2. Communication Networks as Embedded System in Network Control Systems (NCS)

Methodology: System Theoretic Approach

1. Modeling

a) **"Top Down" Approach** from Application Contexts to Communication Networks
- Identifying Interactions between Entities, e.g., Control Loops, Manufacturing Stations, ...
- Identifying Communication Requirements between these Entities
- Specifying Communication Network Requirements between Distantly Located Entities in Terms of: Throughput Rates, Latencies, etc. Quantitatively (Metrics)

b) **"Bottum-Up" Approach** from Communication Networks to Applications
- Identifying Available Communication Media (wired, wireless, electric, optic, ...)
- Identifying Network Topologies and Network Technologies
- Specifying Network Services, Architectures and Protocols
  Traffic and Performance Metrics
  Appropriate Communication Network Models

2. Communication Networks as Embedded System in Network Control Systems (NCS)

Methodology: System Theoretic Approach

1. Performance Analysis

a) **Experimental Approach** through Experiments, Measurements and Simulation
- Design of a Physical Environment as Experimental Testbed
- Executing Experiments and Performing Measurements
- Development of System Simulation Models
  Running Simulations for Typical System Scenarios
  Extraction of Performance Results from Simulations

b) **Analytical Approach** through Mathematical Performance Models
- Identifying Existing/Approved Standard Queuing Models
- Developing Complex Queuing Network Models
  Determination of the Main Application Requirements
- Aggregation of Specific Models into higher Layer Models

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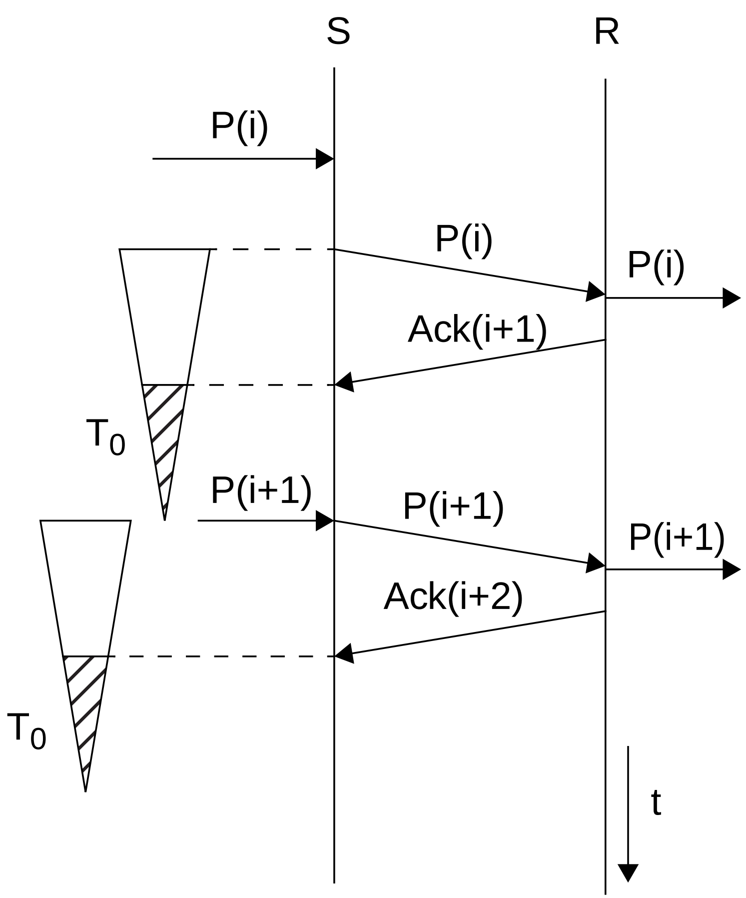
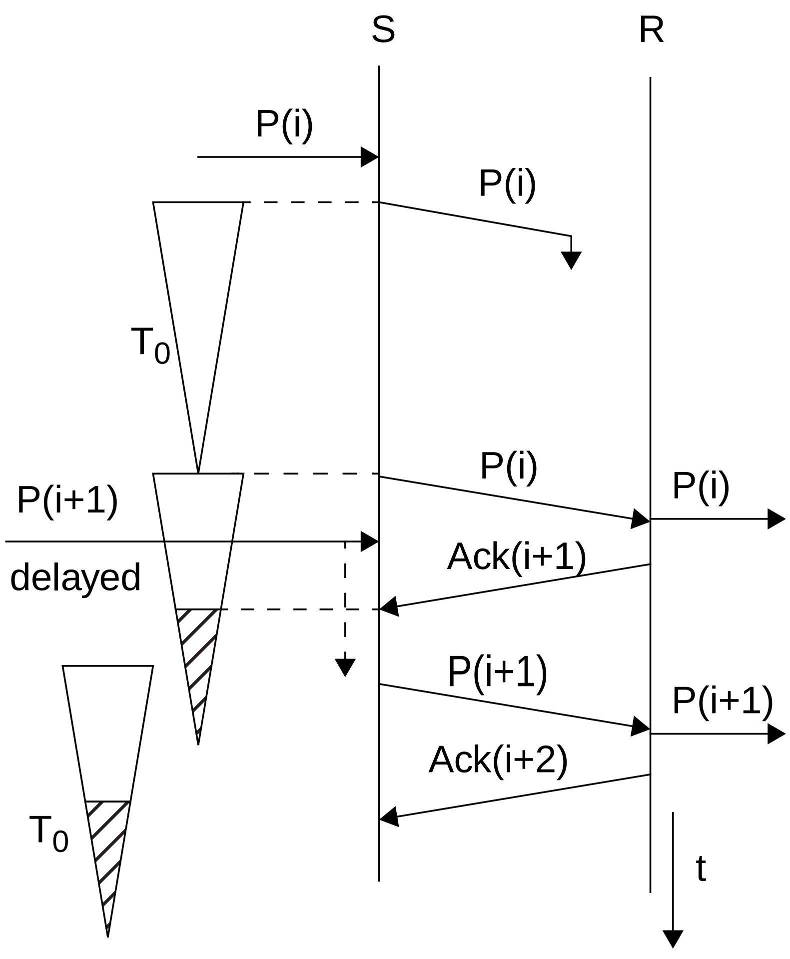
Latencies in Error-Control Protocols

Modeling Protocol Control

Message Sequence Chart for "Send-and-Wait" Protocol with "Timeout Recovery"





Latencies in Error-Control Protocols

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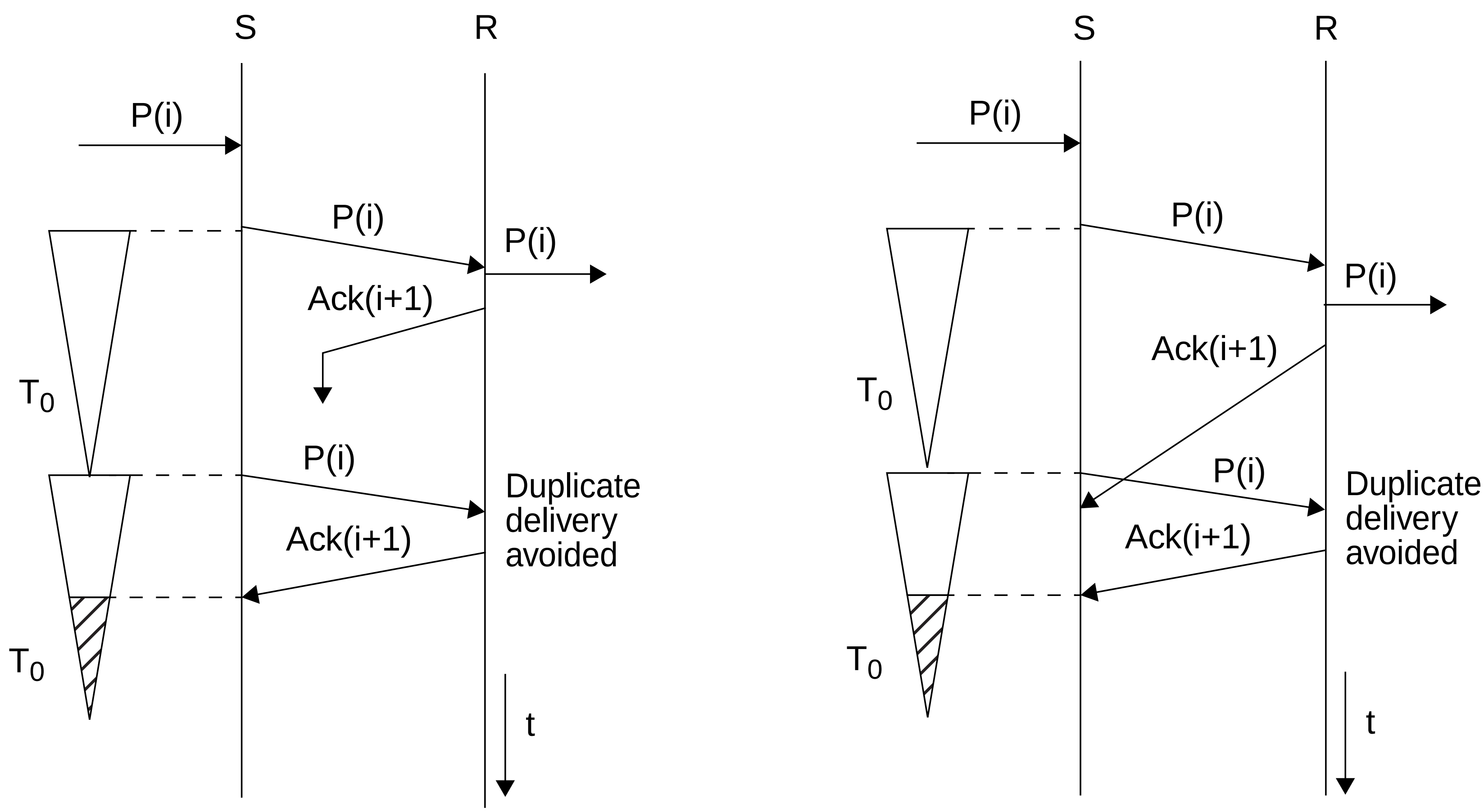
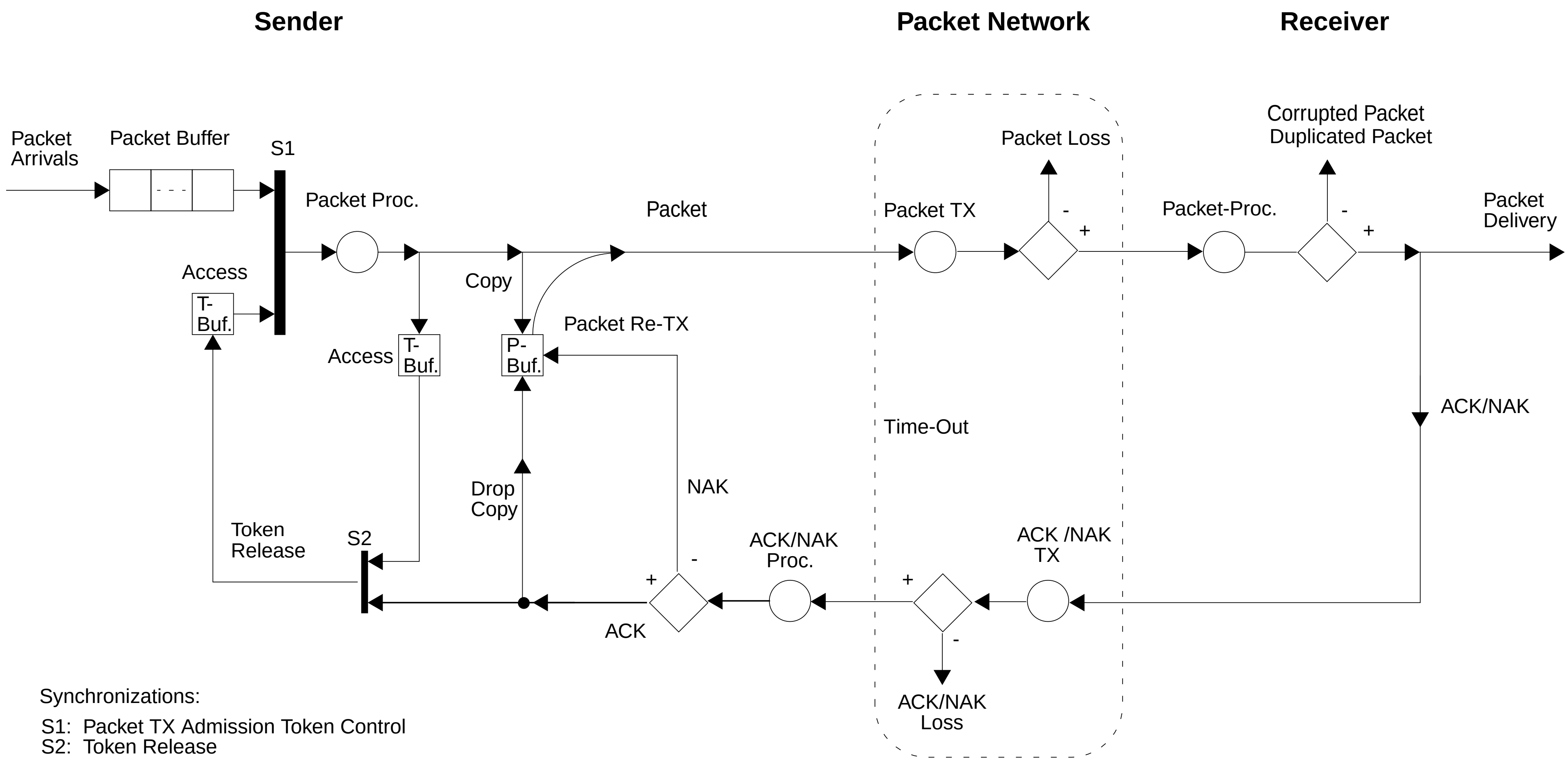


Stop-and-Wait-Protocol with ACK/NAK Control

System Functional Protocol

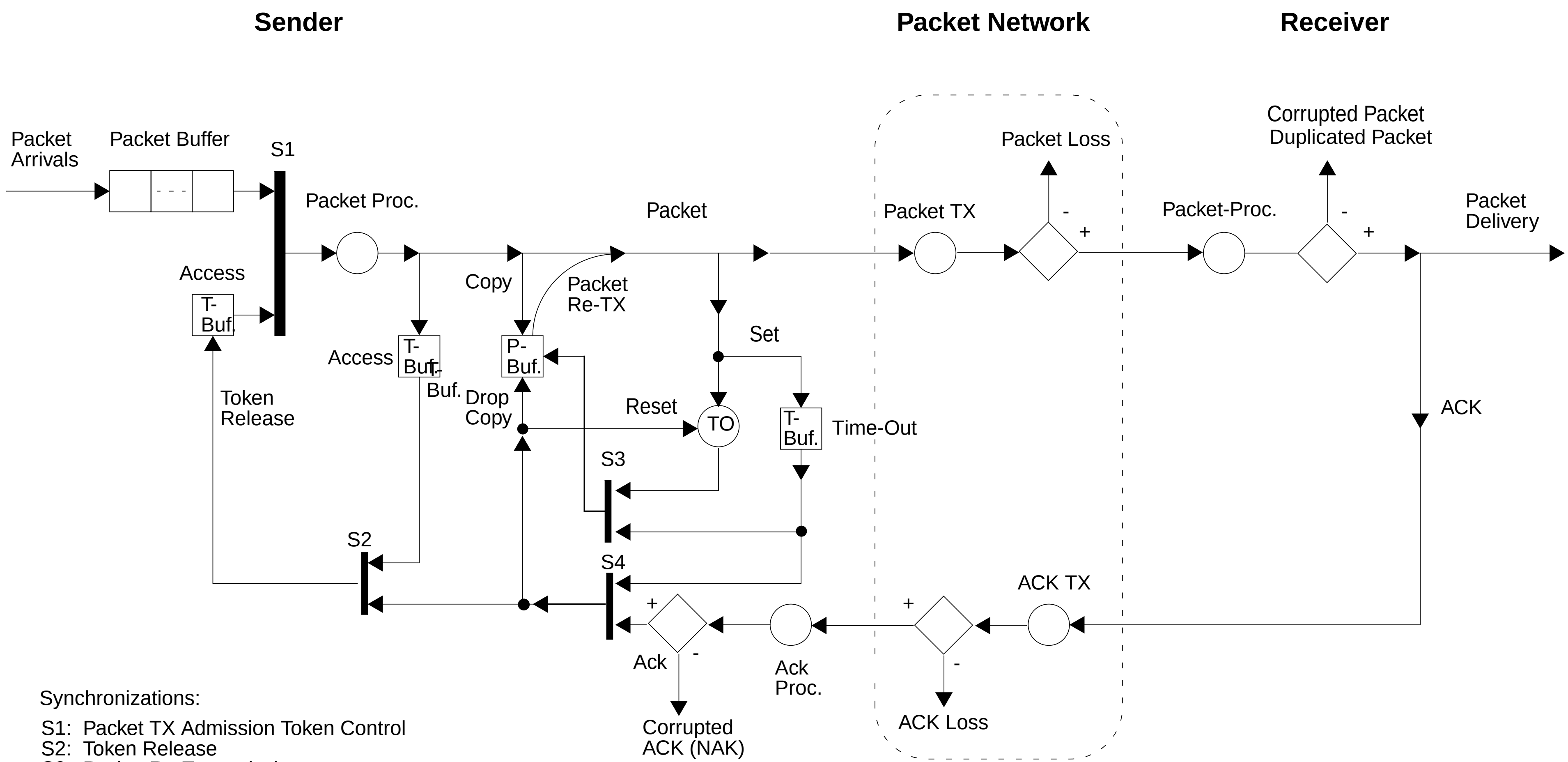


Synchronizations:

S1: Packet TX Admission Token Control
S2: Token Release

Stop-and-Wait-Protocol with Timeout Control

System Functional Protocol

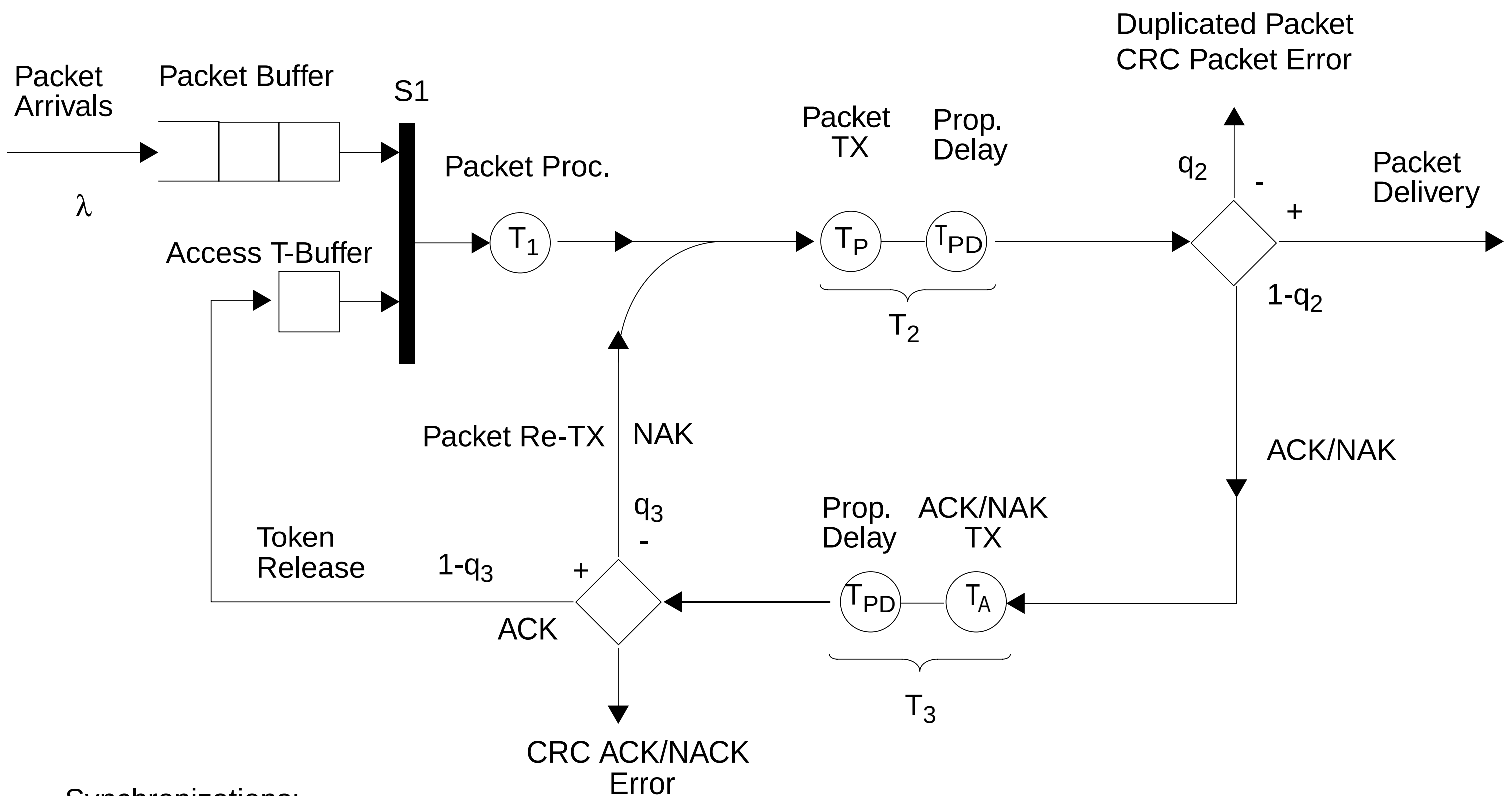


Synchronizations:

S1: Packet TX Admission Token Control
S2: Token Release
S3 Packet Re-Transmission
S4 Acknowledgement

Stop-and-Wait-Protocol with ACK/NAK Control

Performance Evaluation Model

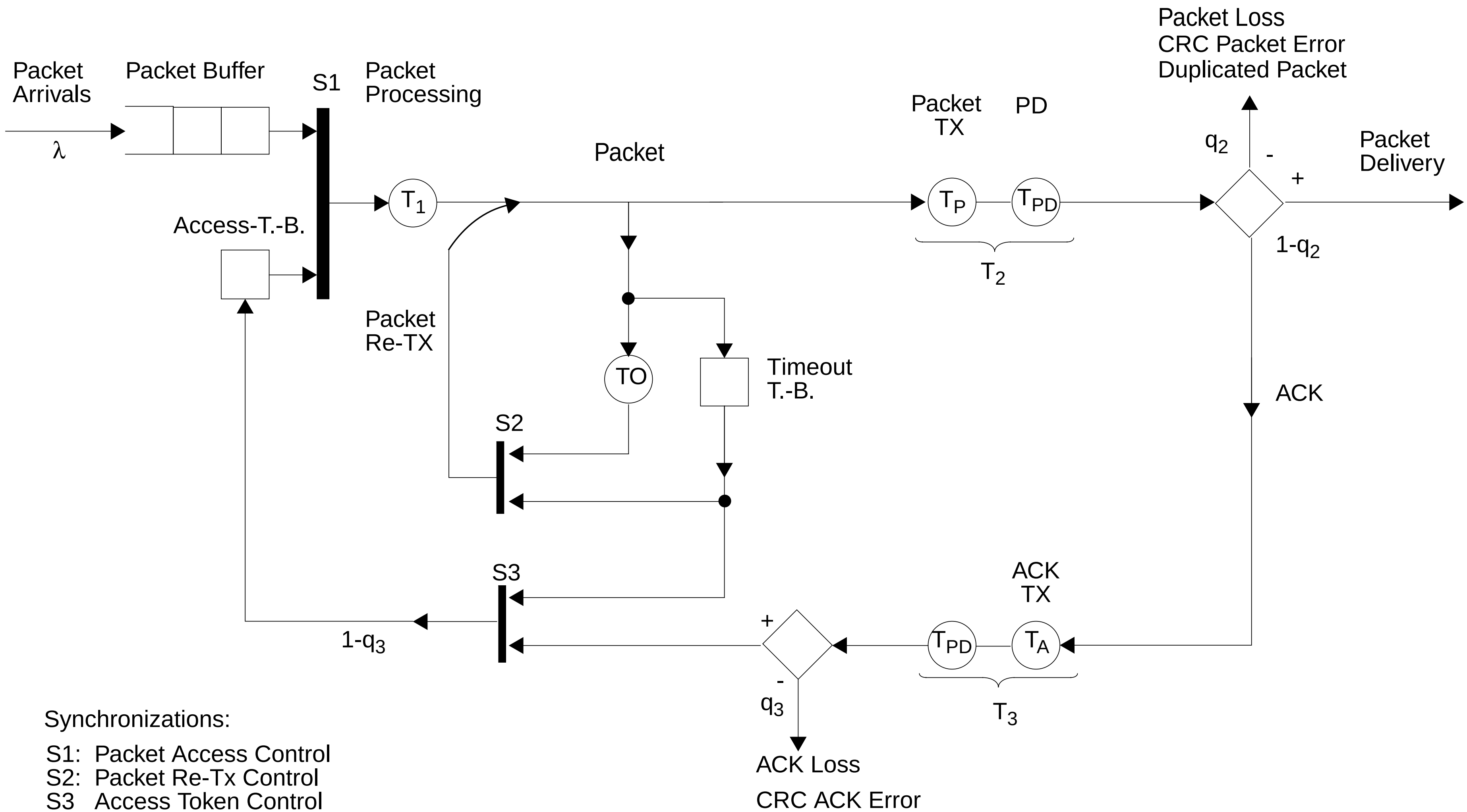


Synchronizations:

S1: Packet Access Token Control

Stop-and-Wait-Protocol with Timeout Control

Performance Evaluation Model



Synchronizations:

S1: Packet Access Control
S2: Packet Re-Tx Control
S3 Access Token Control

Performance Analysis of S&W-Protocol with ACK/NAK Control

Input Parameters:

• Packet length distribution	L_p	PDF of packet TX $f_p(t)$,	$LT\phi_P(s)$
• ACK/NAK length distribution	L_A	PDF of ACK/NAK TX $f_A(t)$,	$LT\phi_A(s)$
• Channel transmission rate	R		
• Propagation delay time	T_{PD}	(typically constant)	$LT\phi_{PD}(s)$
• CRC packet error probability	q_2		
• CRC ACK/NAK error probability	q_3		
• Packetization processing time	T_1	(typically constant)	$LT\phi_1(s)$

(L_p, L_A, R → PDF of packet TX $f_p(t)$, PDF of ACK/NAK TX $f_A(t)$)

Mean Value Performance Analysis:

- Packet TX/ACK failure probability: $q_F = 1-(1-q_2)(1-q_3)$
- Distribution of the number N of packet TXs: $p_n = P\{N=n\} = q_F^{n-1}(1-q_F), \; E[N] = \dfrac{1}{1-q_F}$
- Average ("virtual") packet transmission time: $E[T_X] = E[T_1] + E[N]\cdot(E[T_P] + E[T_A] + 2t_{PD})$
- Maximum packet throughput rate: $\lambda_{max} = 1/E[T_X] = 1/t_X$

Performance Analysis of S&W-Protocol with ACK/NAK Control

Real Time Performance Analysis

PDF of the virtual TX time

$$f_X(t) = f_1(t) \otimes \sum_{n=1}^{\infty} p_n \cdot (f_2(t) \otimes \dots \otimes f_2(t)) \otimes (f_3(t) \otimes \dots f_3(t))$$

$$\phi_X(s) = \phi_1(s) \cdot \sum_{n=1}^{\infty} p_n \phi_2^n(s) \phi_3^n(s) = \phi_1(s) \sum_{n=1}^{\infty} p_n \phi_P^n(s) \phi_A^n(s) \exp(-2nt_{PD}s)$$

Special case: Constant packet processing time t_1, packet and ACK/NAK transmission times t_P, t_{AK}

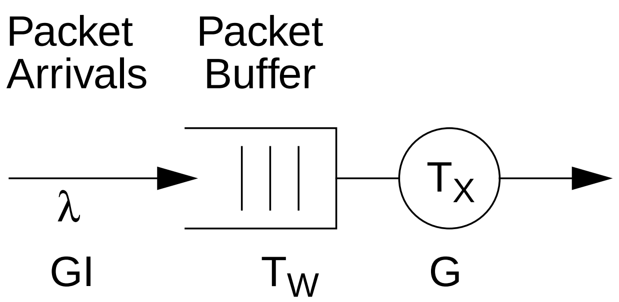
$$\phi_X(s) = \exp(-t_1 s) \sum_{n=1}^{\infty} p_n \exp(-n[t_P + t_A + 2t_{PD}]s) = \frac{(1-q_F)\exp(-(t_1 + [\quad])s)}{1 - q_F \exp(-[\dots]s)}$$

$\bullet\!\!-\!\!\circ$ LP^{-1}, power expansion

$$f_X(t) \cong (1-q_F) \cdot \delta(t - [t_1 + t_P + t_A + 2t_{PD}]) + q_F(1-q_F)\delta(t - [t_1 + 2t_P + 2t_A + 4t_{PD}]) + \dots$$

Performance Analysis of S&W-Protocol with ACK/NAK Control

Resulting Queueing Model: GI/G/1



- Closed-Form Solutions for $M^{[x]}/G/1$, GI/M/1, ... Good Approx. Solutions for other Arrival Processes
- Output Process known for M/M/1, M/D/1, M/G/1 Good Approx. Solutions for general Arrival Processes

Conclusions:

- The S&W-Protocol can be completely represented by a queuing model
- The Network+Protocol Delay is mapped on to the "Queueing Flow Time" $T_F = T_W + T_X$
- From the PDF for T_F we get the delay/latency percentiles, which serve as RT Service Level Agreement
- T_F can be applied as a "Stochastic Dead Time" within a Distributed Control Model

Other Examples of Communication Task Graphs with Parallel Processing

1. Sliding Window Comm. Protocols

- Go-Back-n Protocol
- Selective-Repeat Protocol

2. SDN/NFV Control Plane-Supported Data Plane Connection Setup

- Dynamic MPLS Path Establishment
- Dynamic Optical Light Path Establishment

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- Future Application Fields as Power/Traffic Grids or Integrated Manufacturing Systems lead to Distributed and Highly Complex Systems with High Requirements to Communications and Real-Time Performance ("Tactile Internet")
- Challenges Require Cooperative Approaches between Experts/Methodologies of Different Competences
- Complexity has to be Reduced by Structured Approaches as step-wise Top-Down, Bottom-Up, Decomposition/Aggregation Methods where Existing or Approved Results can be Applied
- Several Examples have been Presented for the Demonstration of the Feasibility of the Proposed Methodology