# 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 SDN- and NFV-Based Control of RT Packet Flow Switching
    - 3.2 Latencies for Error-Control Protocols
    - 3.3 E-E Latency in Core Packet Networks
4. Conclusions

# 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 SDN- and NFV-Based Control of RT Packet Flow Switching

   3.2 Latencies for Error-Control Protocols

   3.3 E-E Latency in Core Packet Networks

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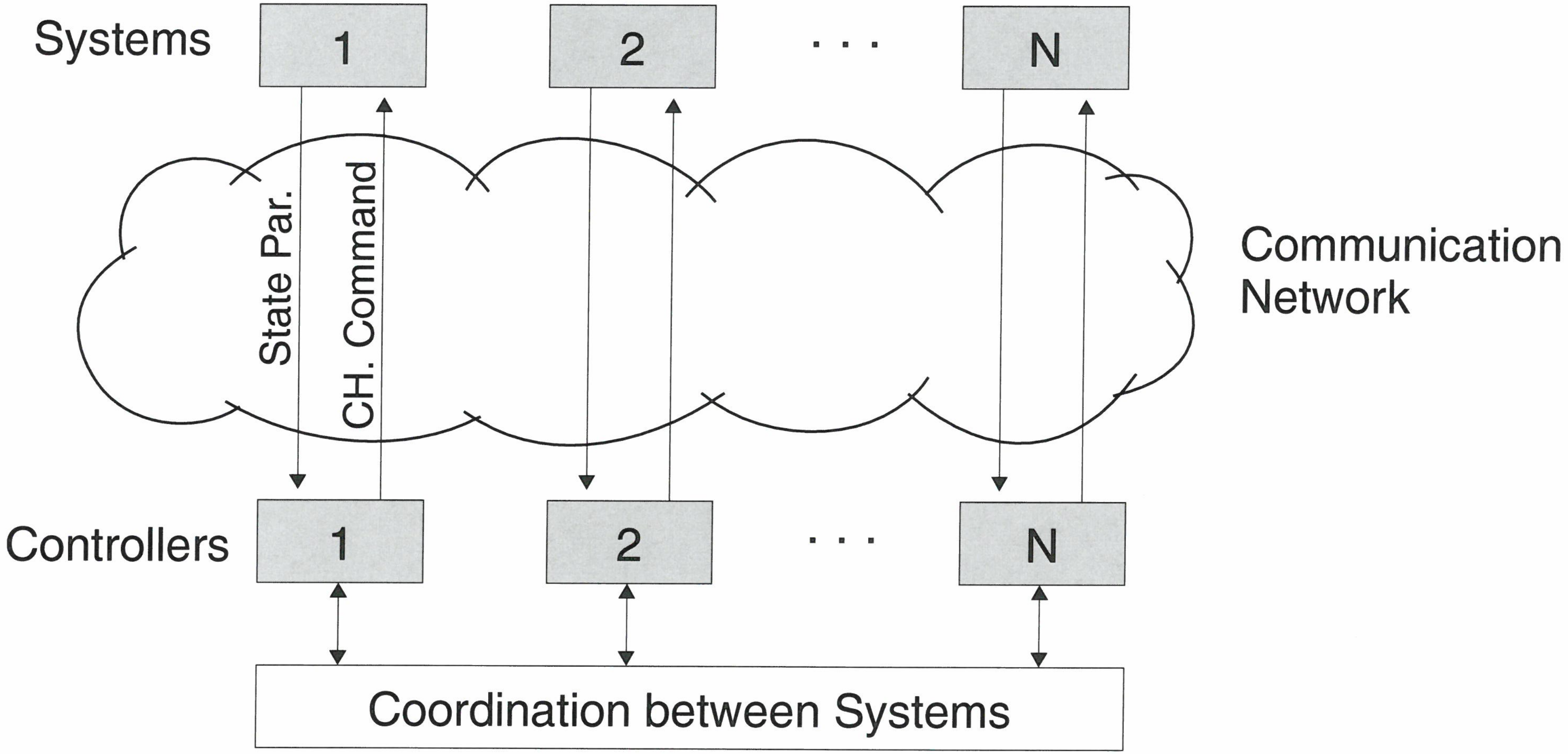
# 2. Communication Networks as Embedded System in Network Control Systems (NCS)



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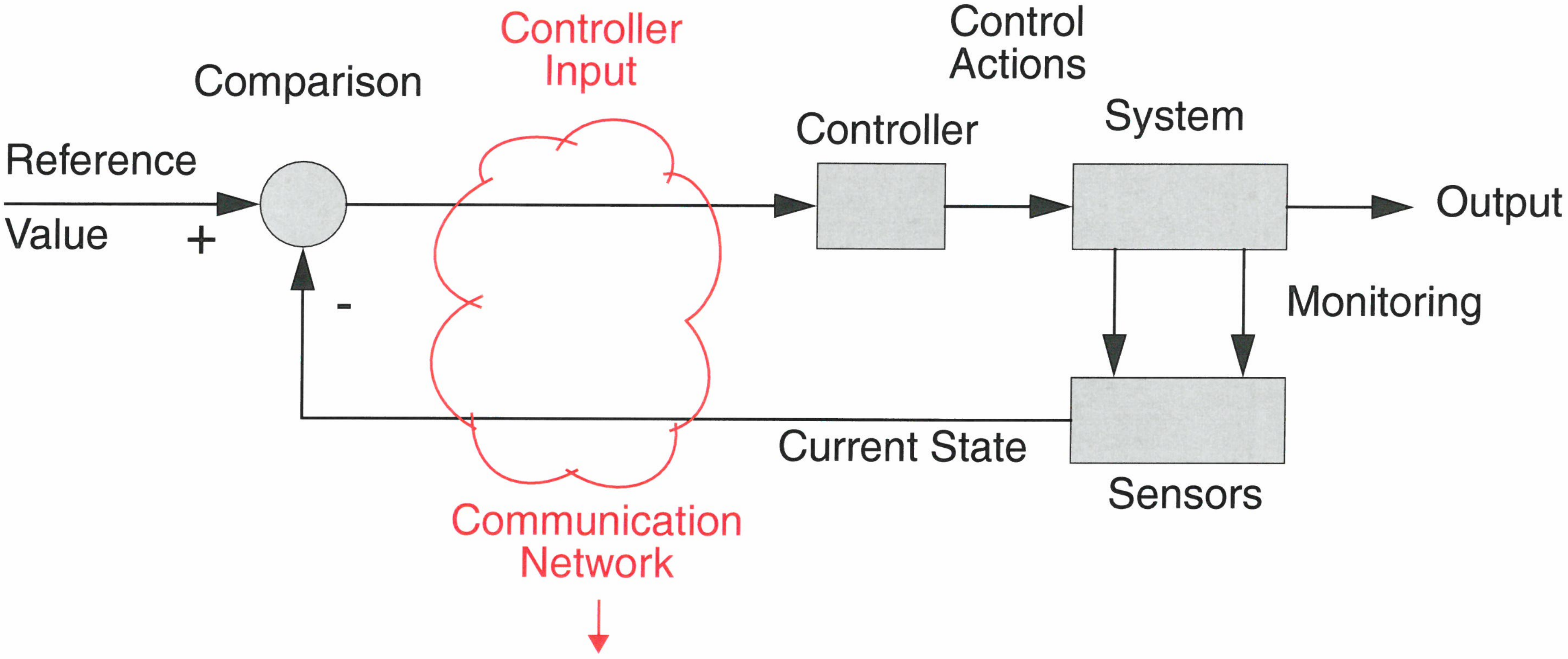

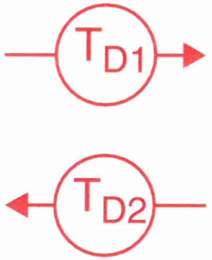

stochastic "Dead time" $T_{D1}$ with PDF $f_{D1}(t)$

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

### 2. 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 by Performance Metrics
- Task Graph Representations and Task Graph Analysis by
- Task Graph Reductions by Stepwise Aggregation of Tasks Probabilistically
- Aggregation of Specific Models into higher Layer Models

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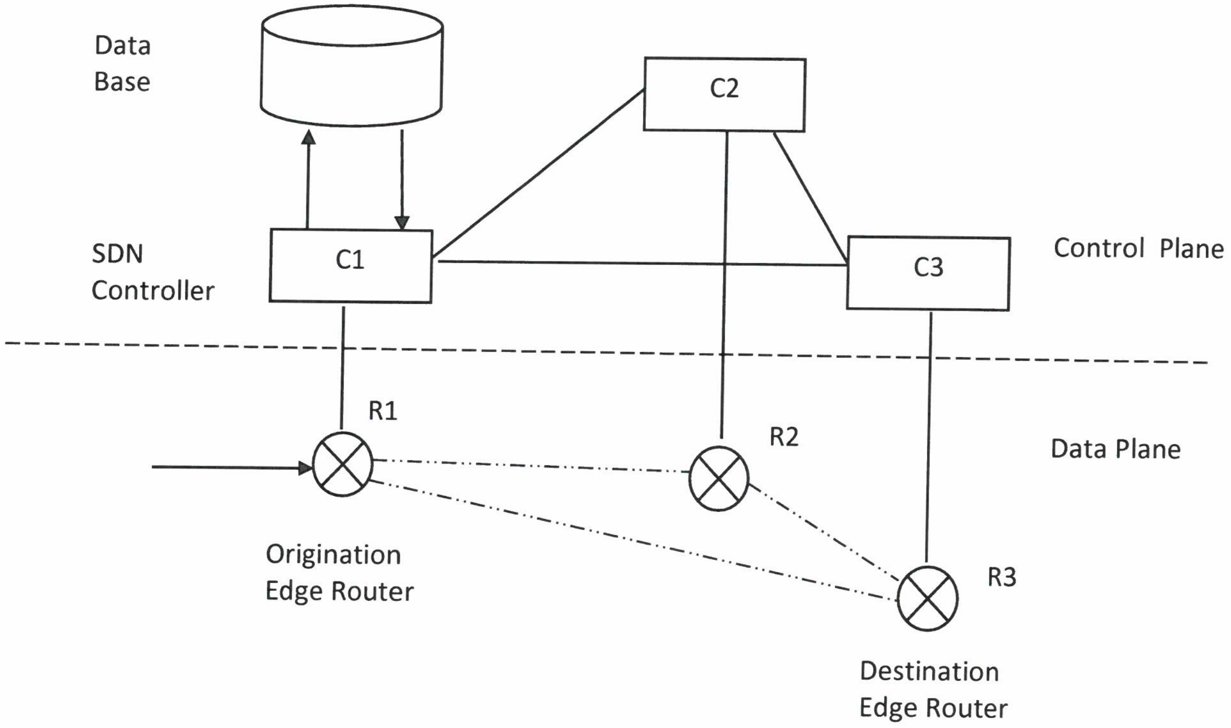
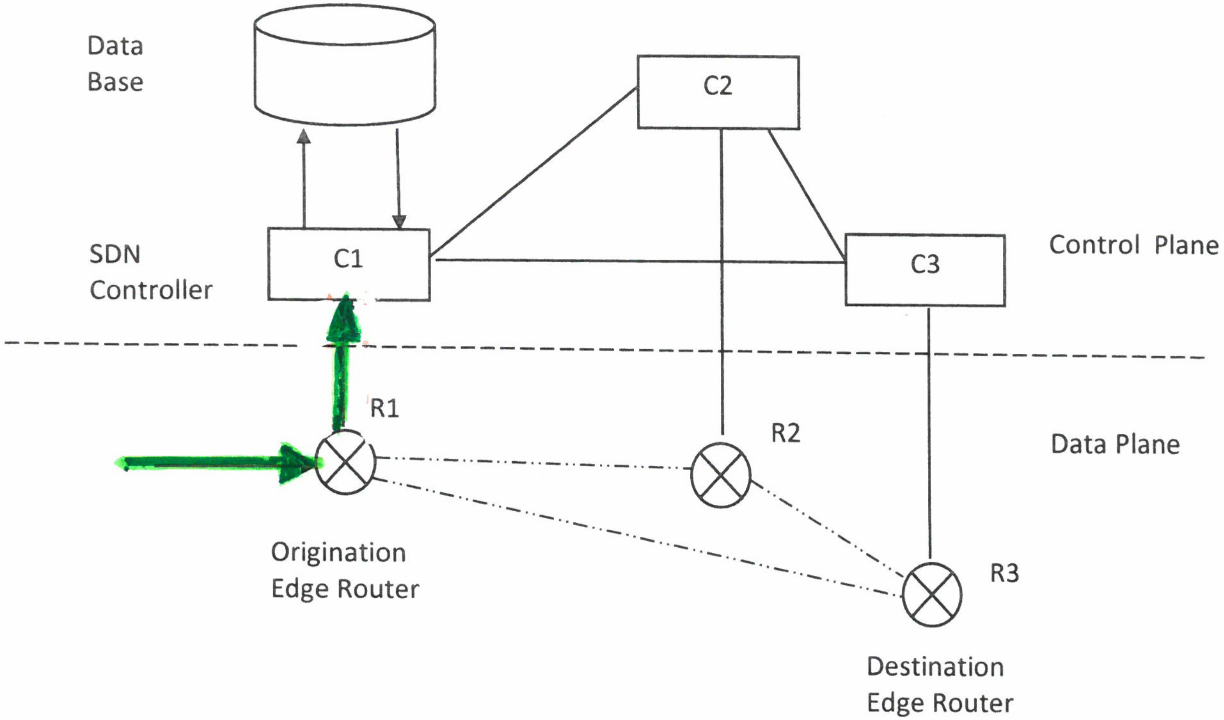
# Parallel Processes in Computation and Communication Control

- **SDN- and NFV-Based Control of Real-Time Packet Flow Switching Network Architecture**



# Parallel Processes in Computation and Communication Control

- **SDN- and NFV-Based Control of Real-Time Packet Flow Switching Control Plane Actions and Data Plane MPLS Path Establishment**



1. Packet Arrival, Flow Detection

# Parallel Processes in Computation and Communication Control

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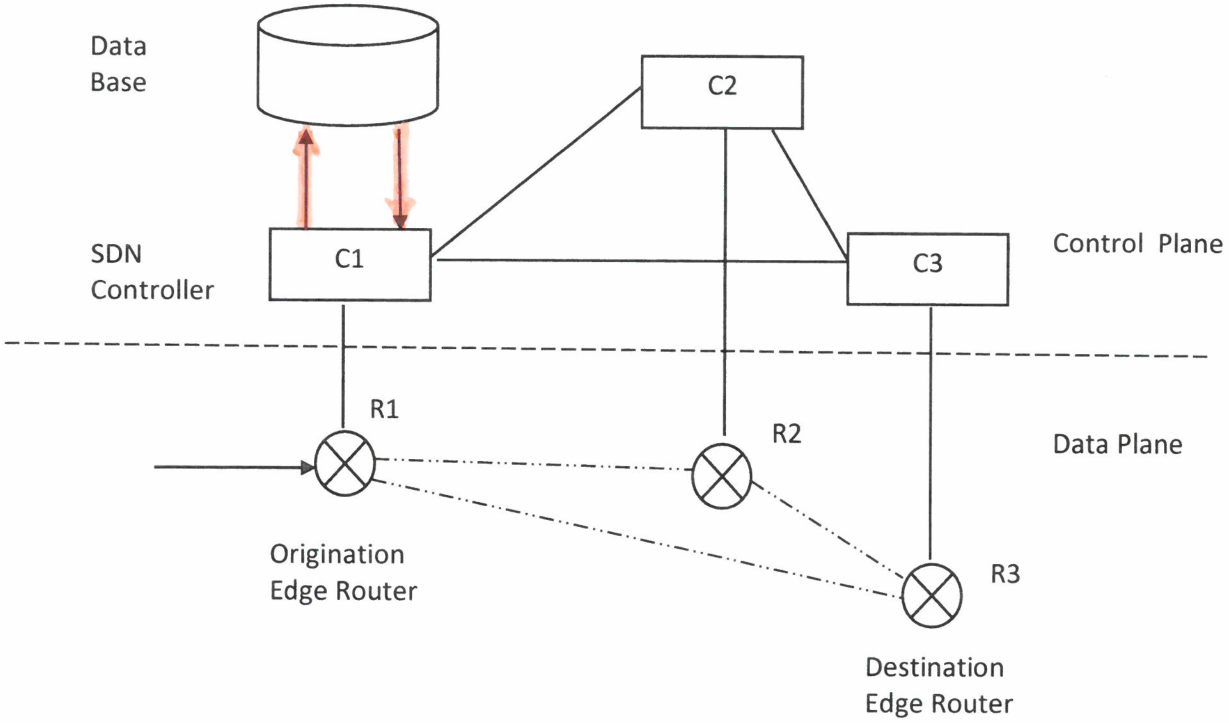

1. Packet Arrival, Flow Detection
2. DB Inquiry

# Parallel Processes in Computation and Communication Control

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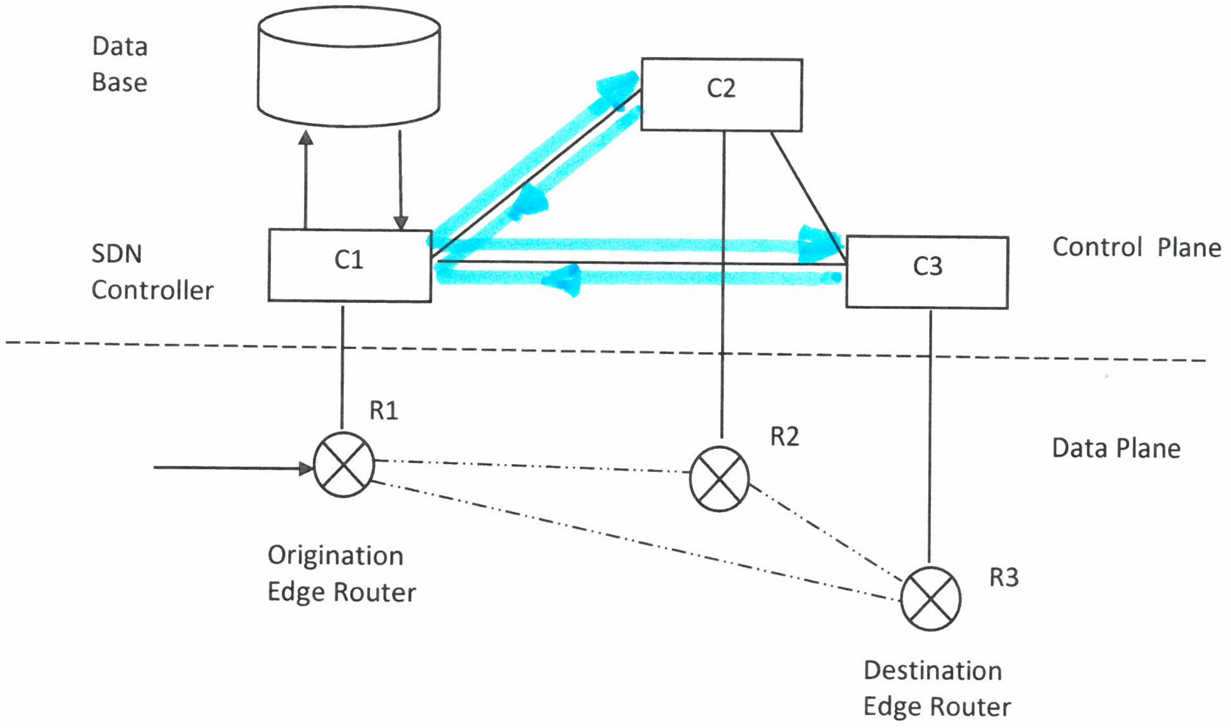

1. Packet Arrival,
   Flow Detection
2. DB Inquiry
3. Controller Communication
   (Request)

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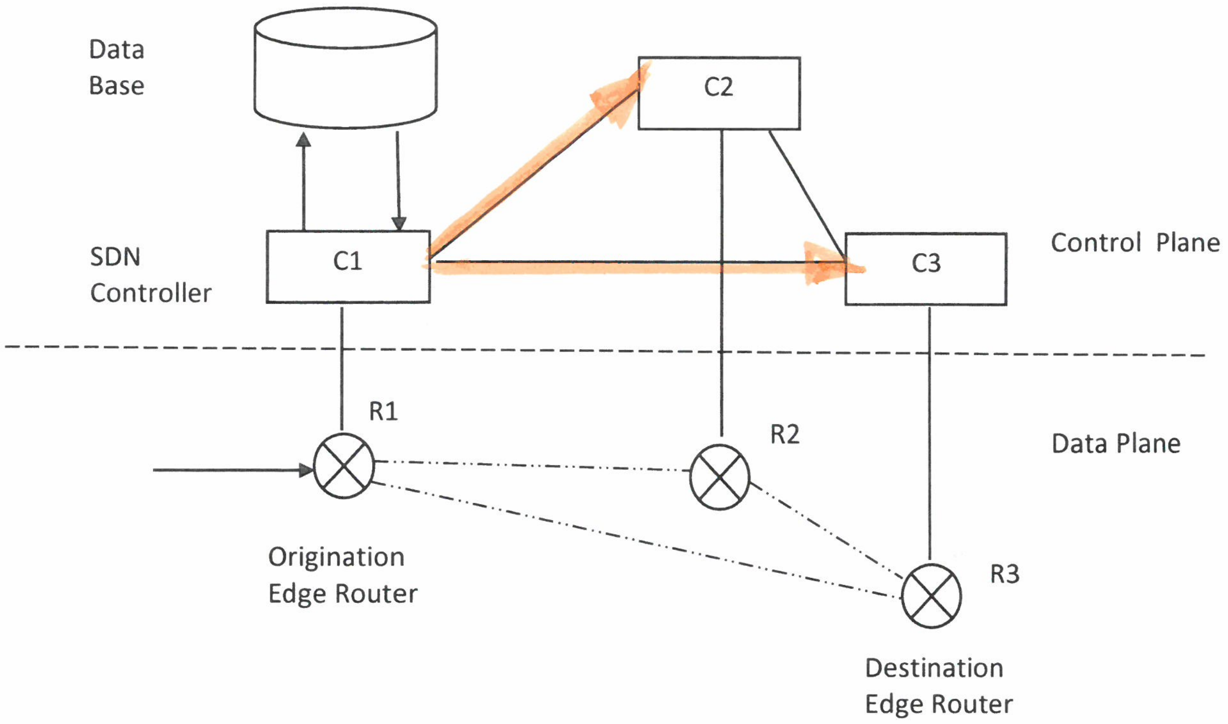

1. Packet Arrival, Flow Detection
2. DB Inquiry
3. Controller Communication (Request)
4. Controller Communication (Command)

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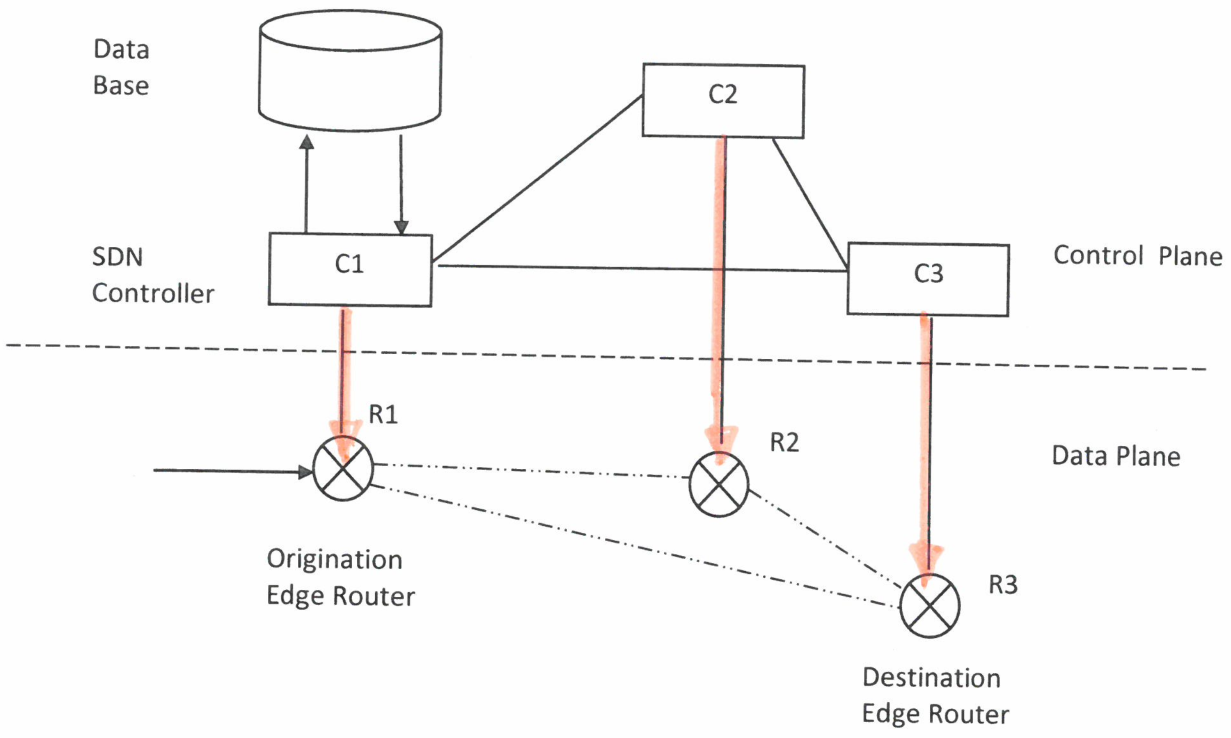

1. Packet Arrival, Flow Detection
2. DB Inquiry
3. Controller Communication (Request)
4. Controller Communication (Command)
5. Label Path Information

# Parallel Processes in Computation and Communication Control

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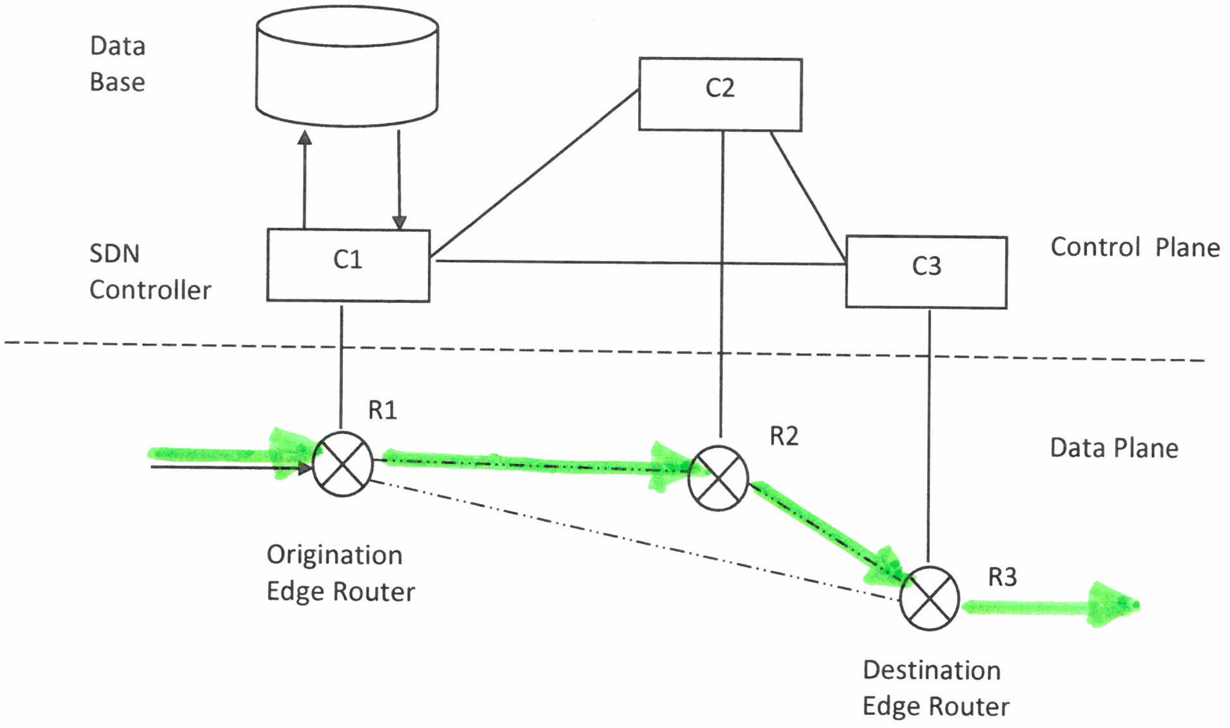
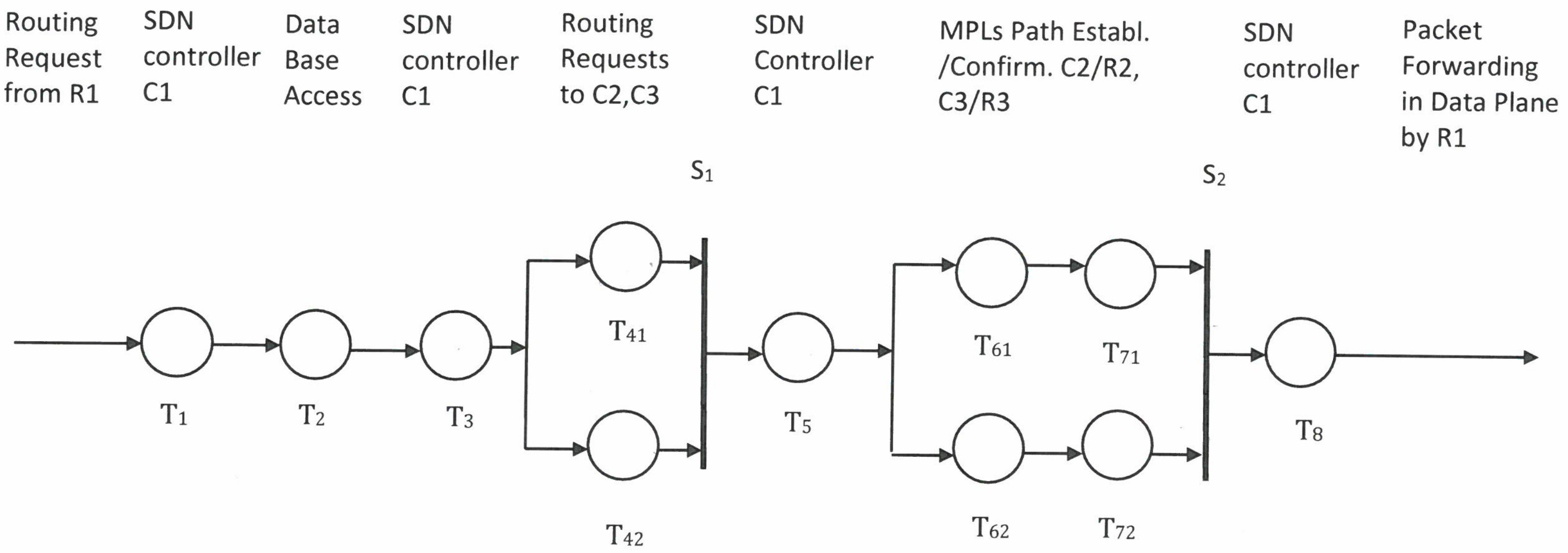


1. Packet Arrival, Flow Detection
2. DB Inquiry
3. Controller Communication (Request)
4. Controller Communication (Command)
5. Label Path Information
6. Label Switched Packet Flow

# Parallel Processes in Computation and Communication Control

- **SDN- and NFV-Based Control of Real-Time Packet Flow Switching Control Plane Task Graph**



Routing Request from R1

SDN controller C1

Data Base Access

SDN controller C1

Routing Requests to C2,C3

SDN Controller C1

MPLs Path Establ. /Confirm. C2/R2, C3/R3

SDN controller C1

Packet Forwarding in Data Plane by R1

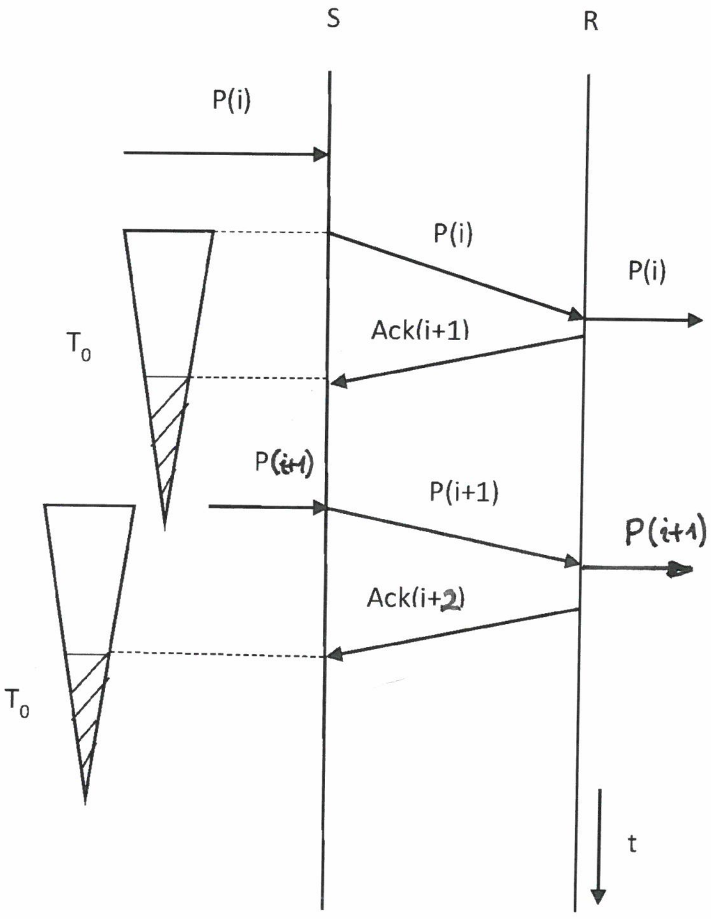
$S_1$, $S_2$ : Re-Synchronization Points (Maximum Operator)
After parallel path

# Parallel Processes in Computation and Communication Control

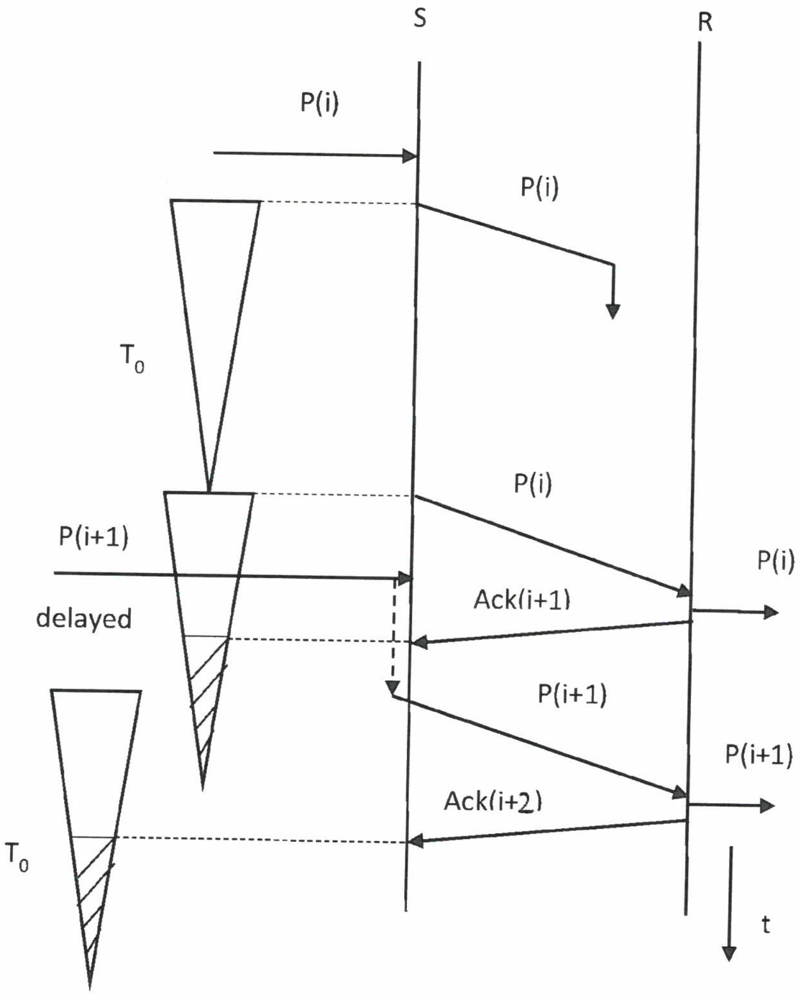
- **Modeling Protocol Control**

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

(1) Successful Packet Transm.



(2) Packet Loss/Error

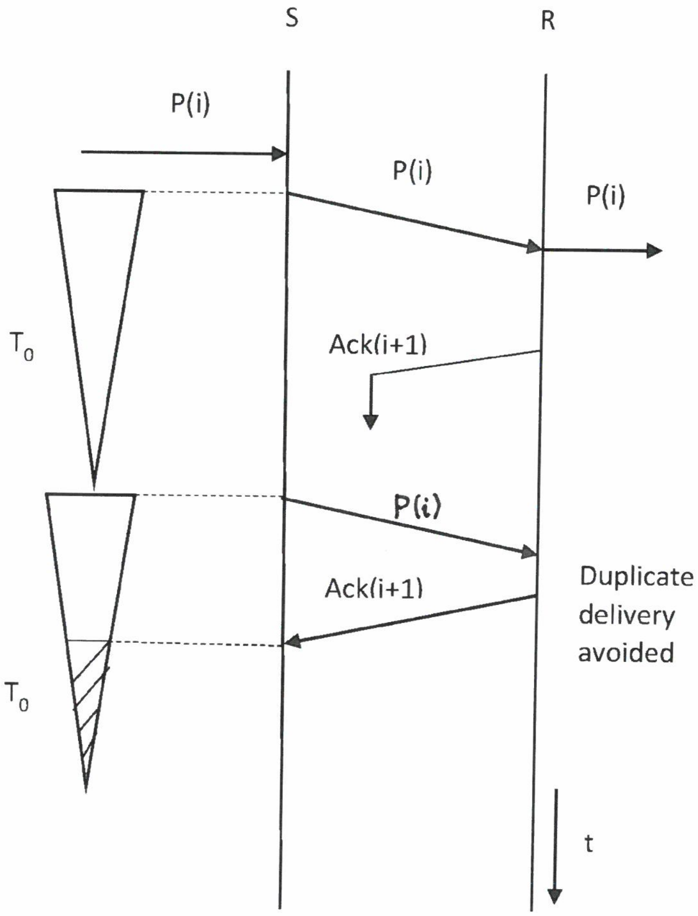


# Parallel Processes in Computation and Communication Control

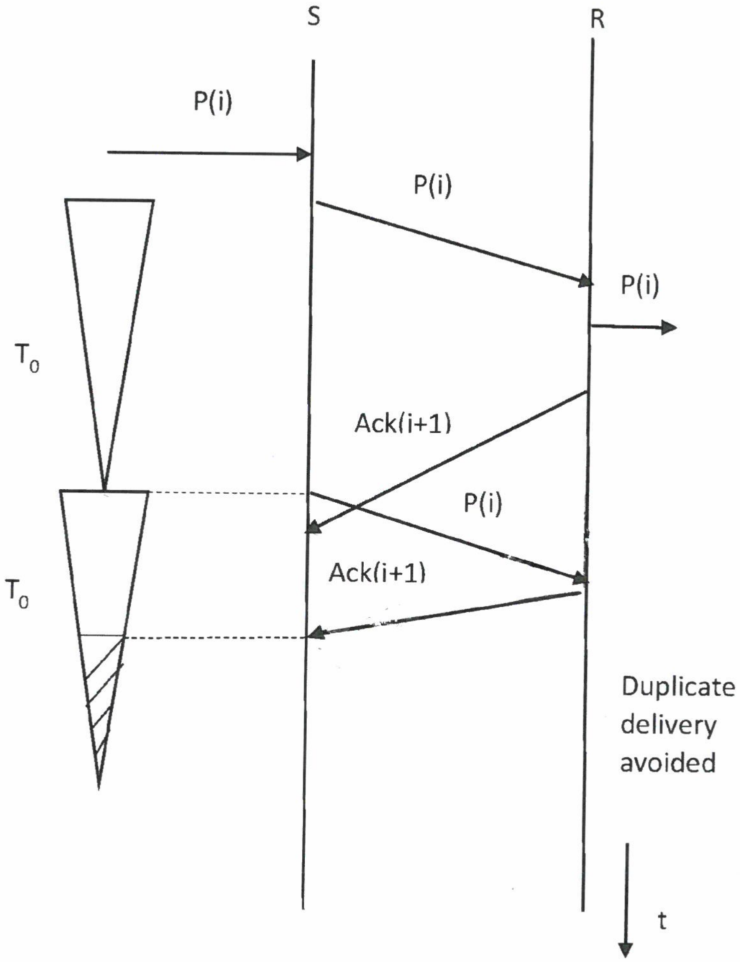
- **Modeling Protocol Control**

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

(3) Acknowledgement Loss/Error

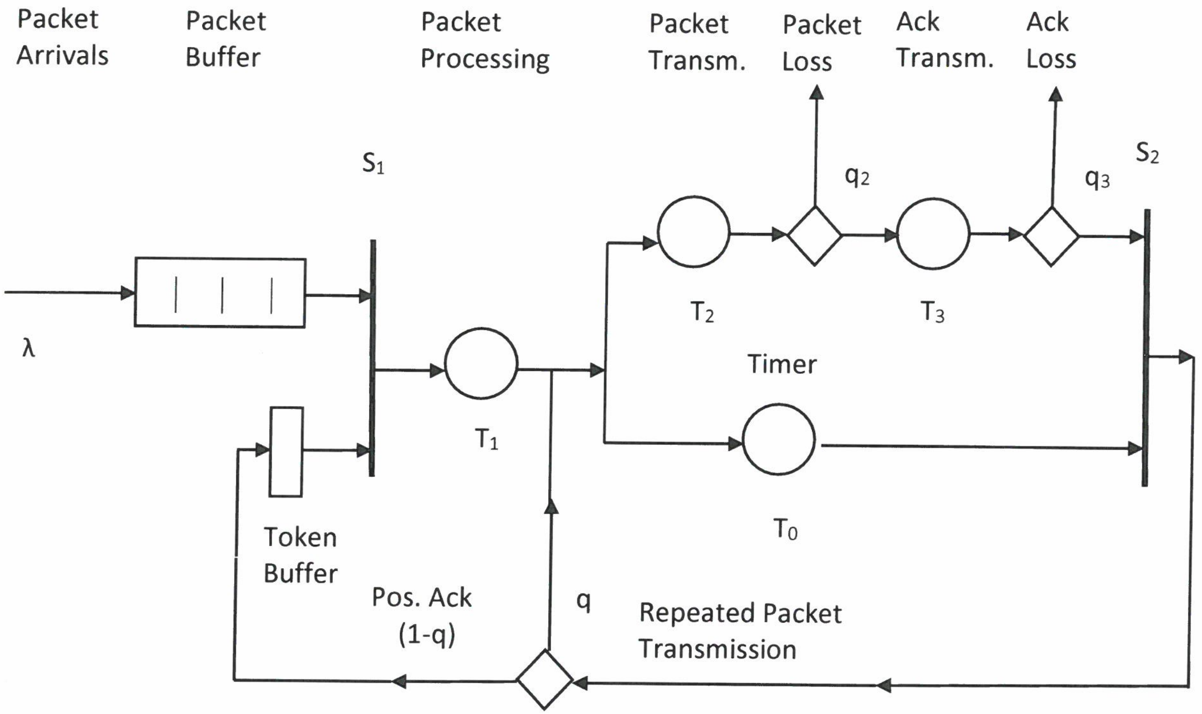


(4) Real Time Application



# Parallel Processes in Computation and Communication Control

- **Task Graph of "Send-and-Wait" Protocol**

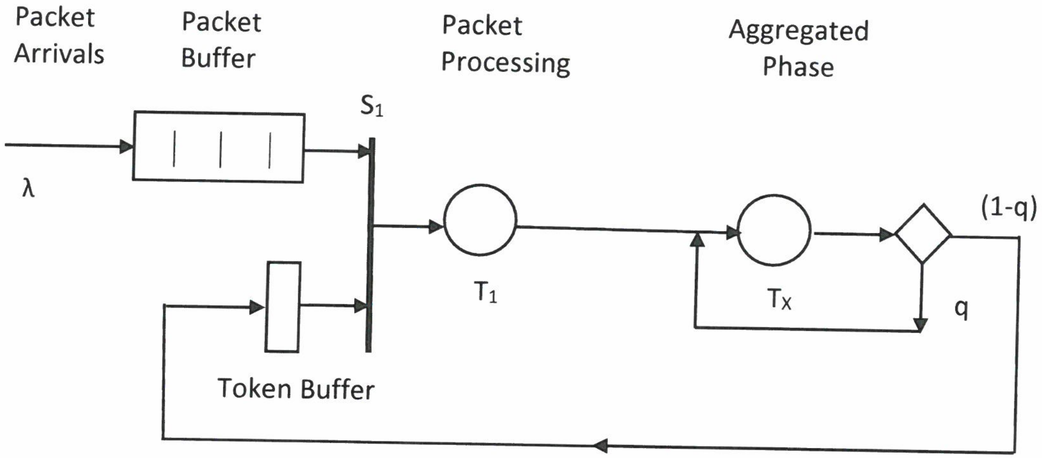


S1: Packet Admission Token Operator

S2: Minimum Path Duration Operator

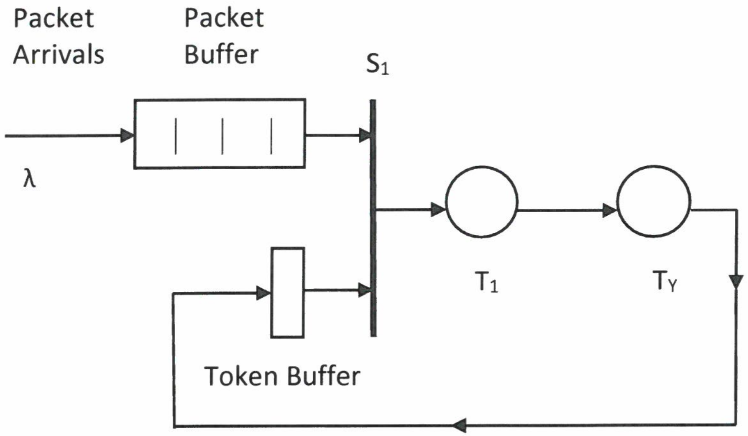
# Parallel Processes in Computation and Communication Control

- **Task Graph Reduction Step 1: Aggregation of Parallel Execution paths by $T_X$**

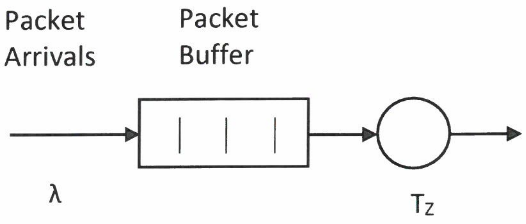


# Parallel Processes in Computation and Communication Control

- **Task Graph Reduction Step 2: Aggregation of Repeated Packet Transmission by $T_Y$**



- **Task Graph Reduction Step 3: Aggregation of Tasks $T_1$ and $T_Y$**



# Parallel Processes in Computation and Communication Control

## Mathematical Operations for Task Graph Reduction: Steps 1 and 2

**Step 1 :** Aggregation of the Serial phases $T_2$ , $T_3$ by $T_X$ (Two-Way Response Time)

$T_X = T_2 + T_3$, $T_2, T_3$ are independent of each other : PDF $f_X(t) = f_2(t) \otimes f_3(t)$

$\otimes$ Convolution Operator

**Step 2 :** Number of Repeated Packet Transmissions

a) Conditions for a Successful Packet and Ack Transmission

a1) Probability of correct Packet (P) and Acknowledgement (A) Transmission:

$(1-q') = (1-q_2)(1-q_3)$ , Where $q_2$ , $q_3$ are the probabilities of Packet, Ack. Loss, resp.

a2) Probability that two-way response time is within the Timeout range $T_0$

$q_X = P\{ T_X \le T_0 \} = \int_{t=0}^{To} f_x(t)dt$

b) Probability for a Repeated Packet Transmission q

$(1-q) = (1-q')\, q_X$ , $q = 1-(1-q_2)(1-q_3)\, q_X$

c) Number of Repeated Packet Transmissions until a Successful Packet Communication

$q_n = P\{n \text{ Repeated Packet Transm.}\} = q^n(1-q)$ , n=0,1,2,... (Geometric Distribution)

# Parallel Processes in Computation and Communication Control

- ## Mathematical Operations for Task Graph Reduction: Steps 3, 4 and 5

**Step 3 :** Aggregation of all Packet Transmissions until completion of a Successful Packet Transmission

CRV $T_y \mid n = n \cdot T0 + T_x \mid T_x <= T_0, \quad n >= 0$

CPDF $f_x(t \mid T_x <= T_0) = f_x(t)\,[1 - u(t - T_0)]$

CPDF $f_y(t \mid n) = \delta(t - nT_0) \otimes f_x(t \mid T_x <= T_0), \quad n >= 1$

PDF $f_y(t) = \sum_{n=0}^{\infty} q_n \cdot f_y(t \mid n) = \sum_{n=0}^{\infty} q_n \cdot f_x(t - nT_0 \mid T_x <= T_0)$

where $\delta(t)$ the Delta-Function (Dirac impulse), $u(t)$ the unit step function.

**Step 4 :** Aggregation of Packet Processing Time $T_1$ and Aggregated Packet Transmission Time $T_Y$

$$f_Z(t) = f_1(t) \otimes f_Y(t)$$

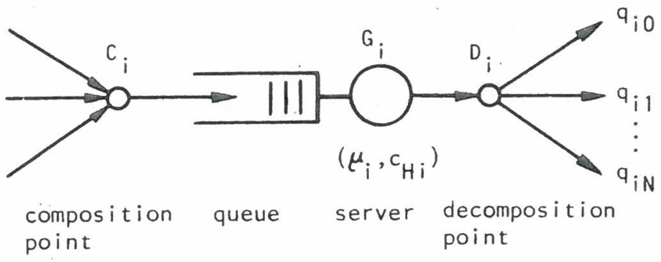
**Step 5 :** Resulting Single-Server Queuing System GI/G/1

After Aggregation of $T_1$ and $T_Y$ by $T_Z$ the Feedback Model is Identical with a GI/G/1 FIFO Queuing System.

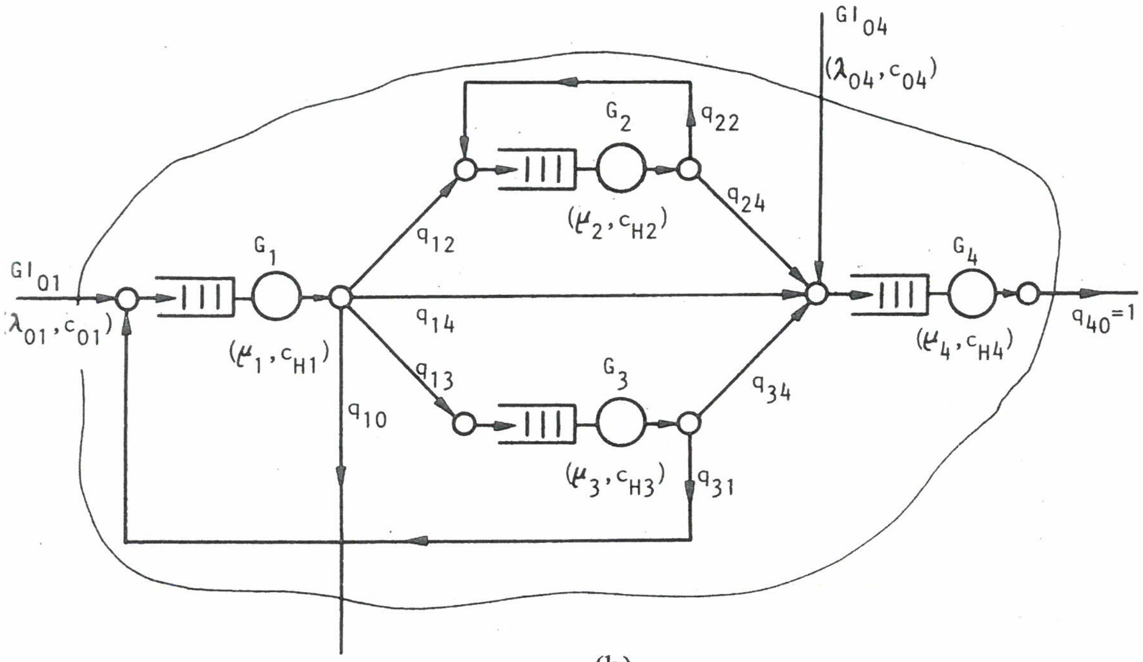
# E - E Latency in Core Packet Networks

## Modeling the Core Network by a General Queuing Network

### (a) One Queuing Station
### (b) Example Queuing Network



(a)



(b)

### Arrival and Service Processes

| | |
|---|---|
| $GI_0 = (GI_{0i})$ | Vector of exogenous arrival processes. |
| $\lambda_0 = (\lambda_{0i})$ | Vector of exogenous arrival rates, where $a_{0i} = 1/\lambda_{0i}$ is the mean exogenous interarrival time at station $i$. |
| $c_0 = (c_{0i})$ | Vector of the coefficients of variation of the exogenous arrival processes. |
| $G = (G_i)$ | Vector of service processes. |
| $\mu = (\mu_i)$ | Vector of service rates, where $h_i = 1/\mu_i$ is the mean service time at station $i$. |
| $c_H = (c_{Hi})$ | Vector of the coefficients of variation of the service processes. |

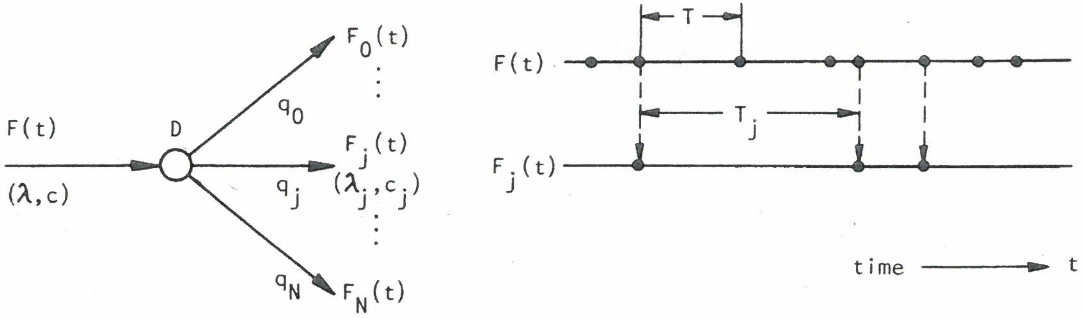
# E - E Latency in Core Packet Networks

## Basic Operations

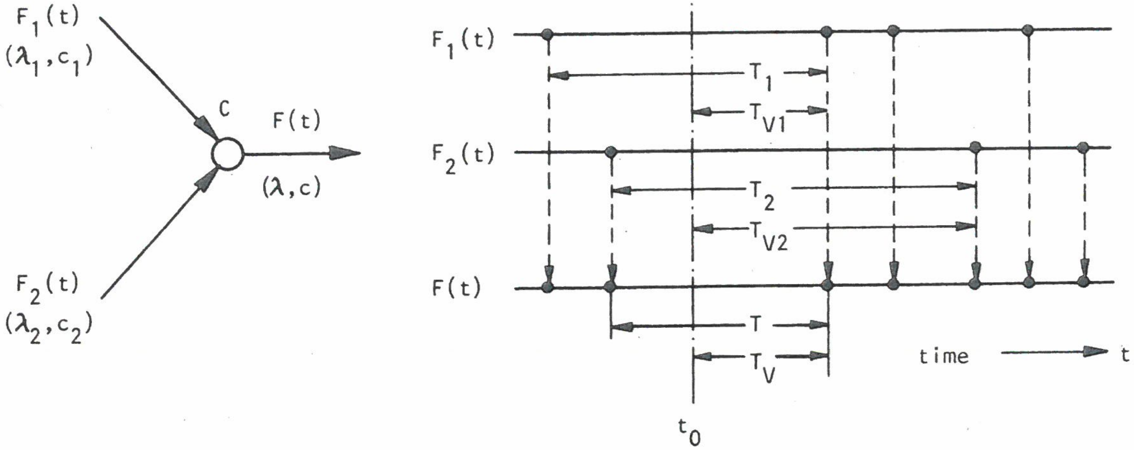
### (a) Packet Traffic Rates at each Queuing Station

Solution of a linear System of Equations ("Conservation of Flows")

### (b) Splitting of Packet Streams ("Probabilistic Routing")



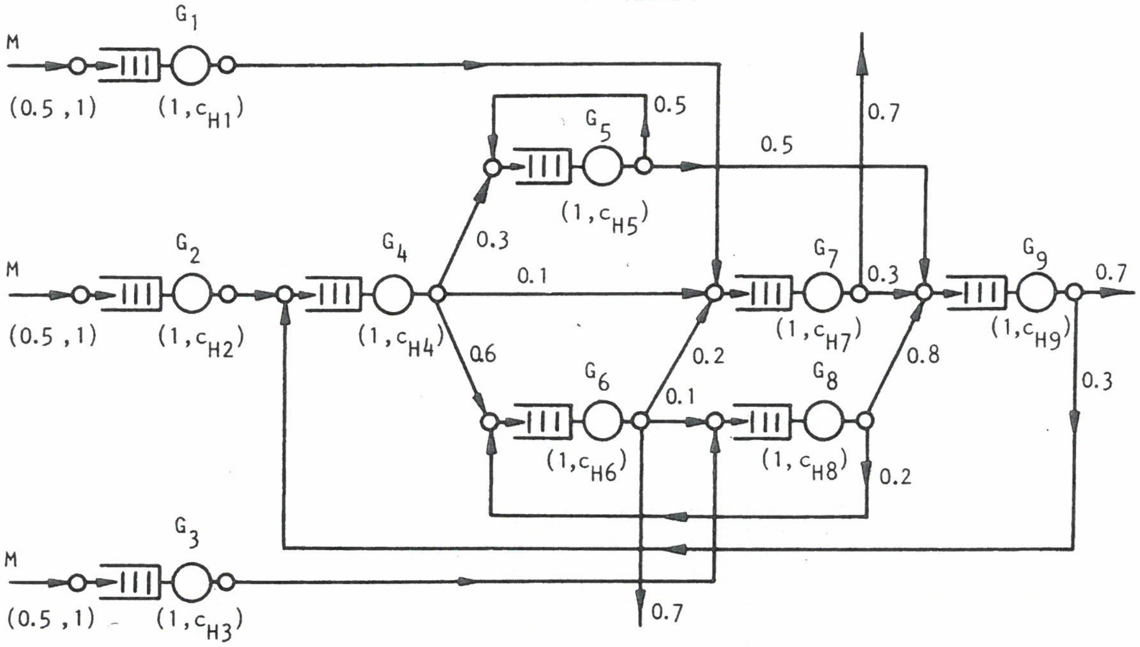
### (c) Superposition of Packet Streams (Renewal Process Assumption)



# E - E Latency in Core Packet Networks

## Numerical Example

### Queuing Network with 9 Queuing Stations



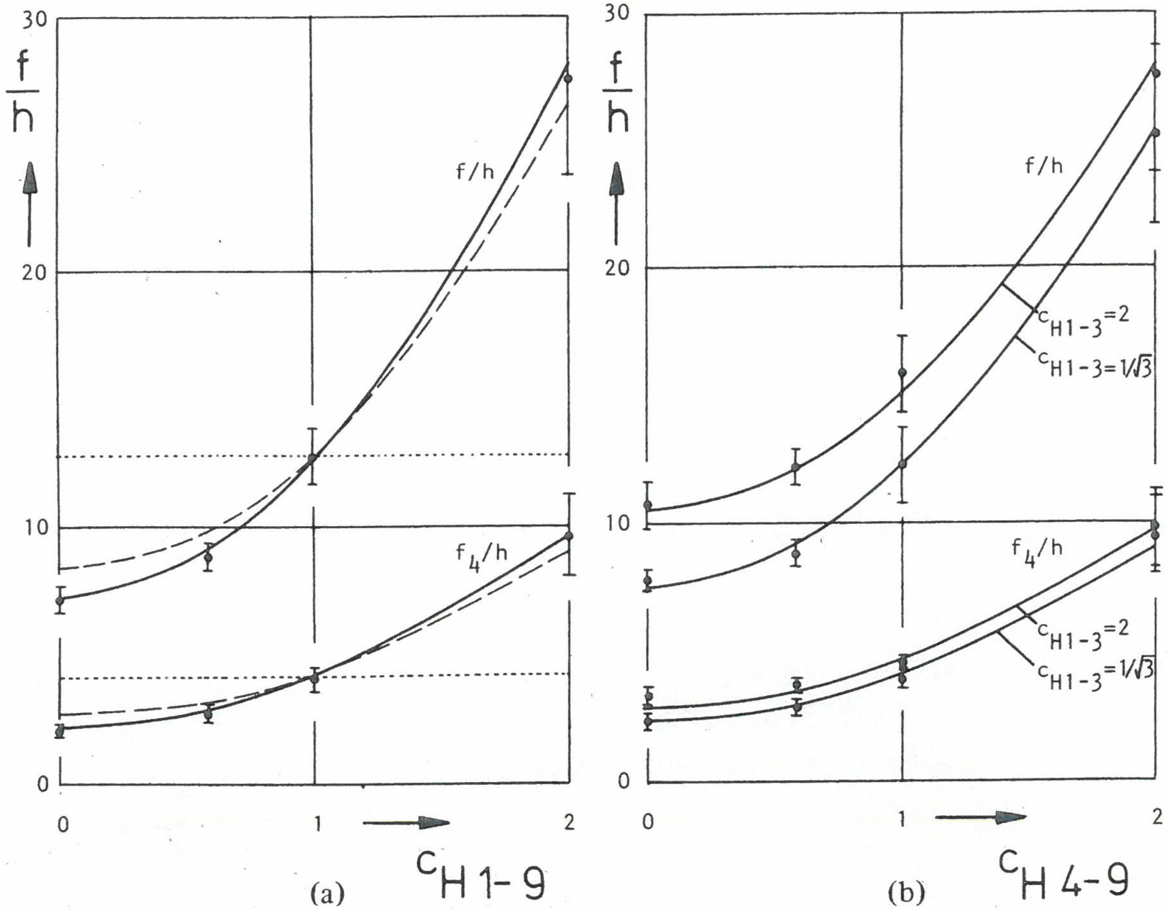
# E - E Latency in Core Packet Networks

## Numerical Example

Results for Total E -E Average Flow Time f and Station Flow Time $f_4$

Dependent on Coefficient of Variation cH of Station Service Times

and Validation by Simulations



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# 4. Conclusions

- 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