Synopsis

- Introduction to Communication Network Performance Prediction
- Overview of Discrete Event Simulation and Approaches
- Discussion of Verification and Validation of Communication Network Simulation Models
- Discussion of Statistical Considerations in the Analysis of Results from Communication Network Simulation Models
- Communication Network Simulation Modeling Tools and Examples
- Future Directions in Computer Aided Analysis and Design of Communications Networks

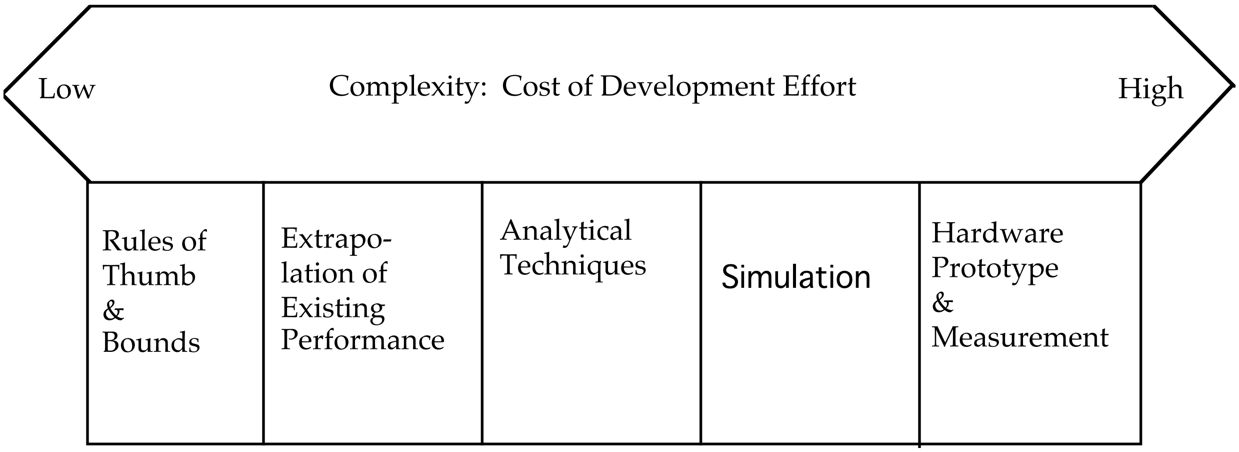
Issues Addressed by Network Analysis

- Comparison of Alternative Network Designs
- Effect of Tuning Network Parameters on Performance
- Effect of Growth and Changes in Traffic Patterns on Performance
- Assessing Effects of Overhead on Performance
- Evaluation of the Performance of a Given Protocol
- Evaluation of Specific Network Components (e.g. Packet Switches) on Overall System Performance

Examples of Network Performance Measures

- Delay
- Throughput
- $\text{Power} = \dfrac{\text{Throughput}}{\text{Delay}}$
- Packet Loss Probability
- Reliability
- Robustness
- Protocol Efficiency

Evaluation Techniques



Attributes of Simulation Techniques

- Simulation can be used to model general communications networks in minute detail.
- Simulation models can be expensive to construct.
- Simulation models can be expensive to run.
- Statistical analysis of the results generated by a simulation can be difficult.
- It can be difficult to gain general insights into system behavior based on simulation results.

Examples of When to Use Simulation

- For studying transient behavior of networks.
- For systems with adaptive routing.
- For systems with adaptive flow control.
- For systems with blocking (finite buffers).
- For systems with general message interarrival statistics.
- Validation of analytic models and approximations.
- For experimentation without disturbing an operational system.

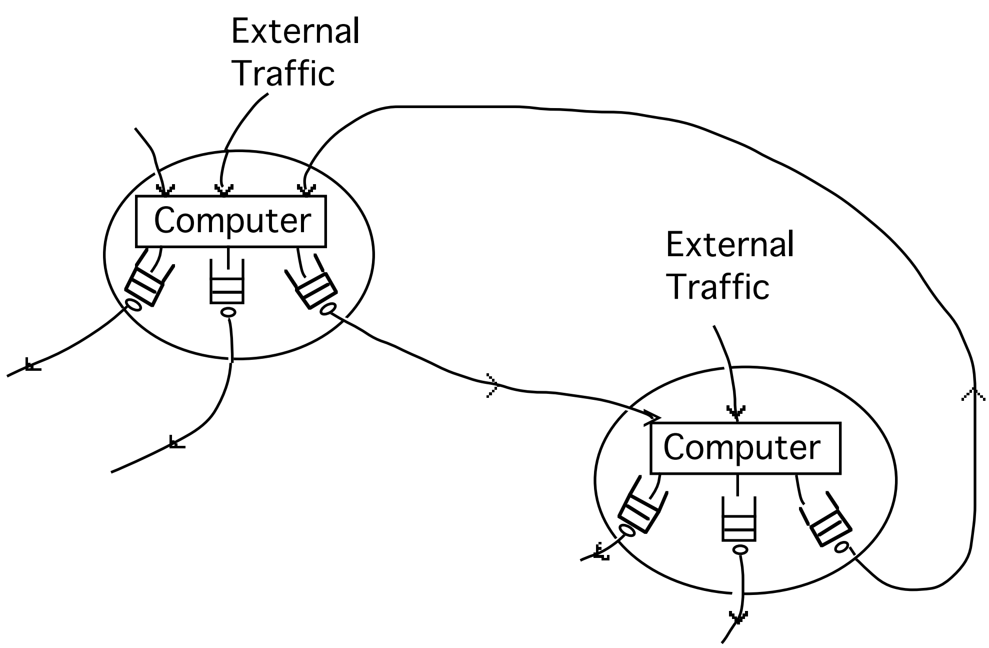
Elements of Communications Networks

- Transmission Facilities (Provides Service)
  - Delay
  - Errors
  - Reliability

- Queueing (Provides Memory)

- Computers (Provides Intelligence)
  - Traffic sources
  - Control the allocation of network resources via protocols

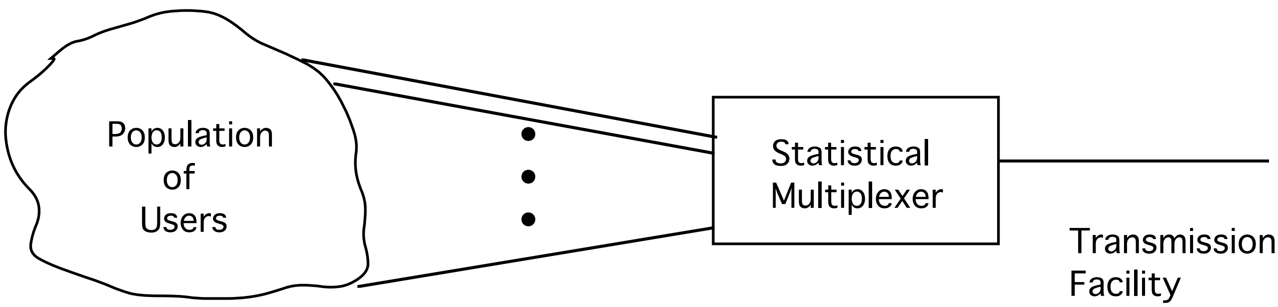
- Traffic Sources
  - Computers
  - Voice
  - Video



A Definition of Communication Network Simulation

Communication network simulation involves generating pseudo-random sequences of message lengths and interarrival times (or other input processes, e.g. time varying link quality) then using these sequences to exercise an algorithmic description of the network operation.

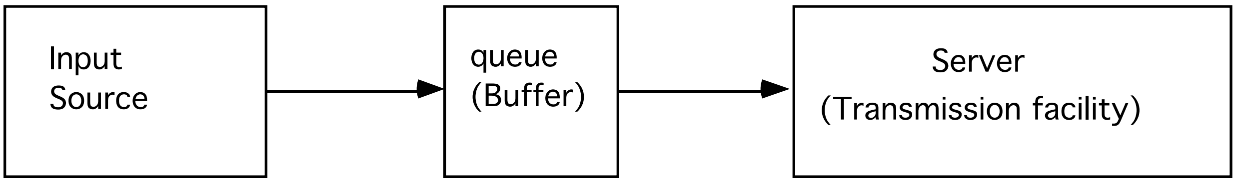
Example of a Single-Channel Statistical Multiplexer



Traffic Characterization — The Input Process

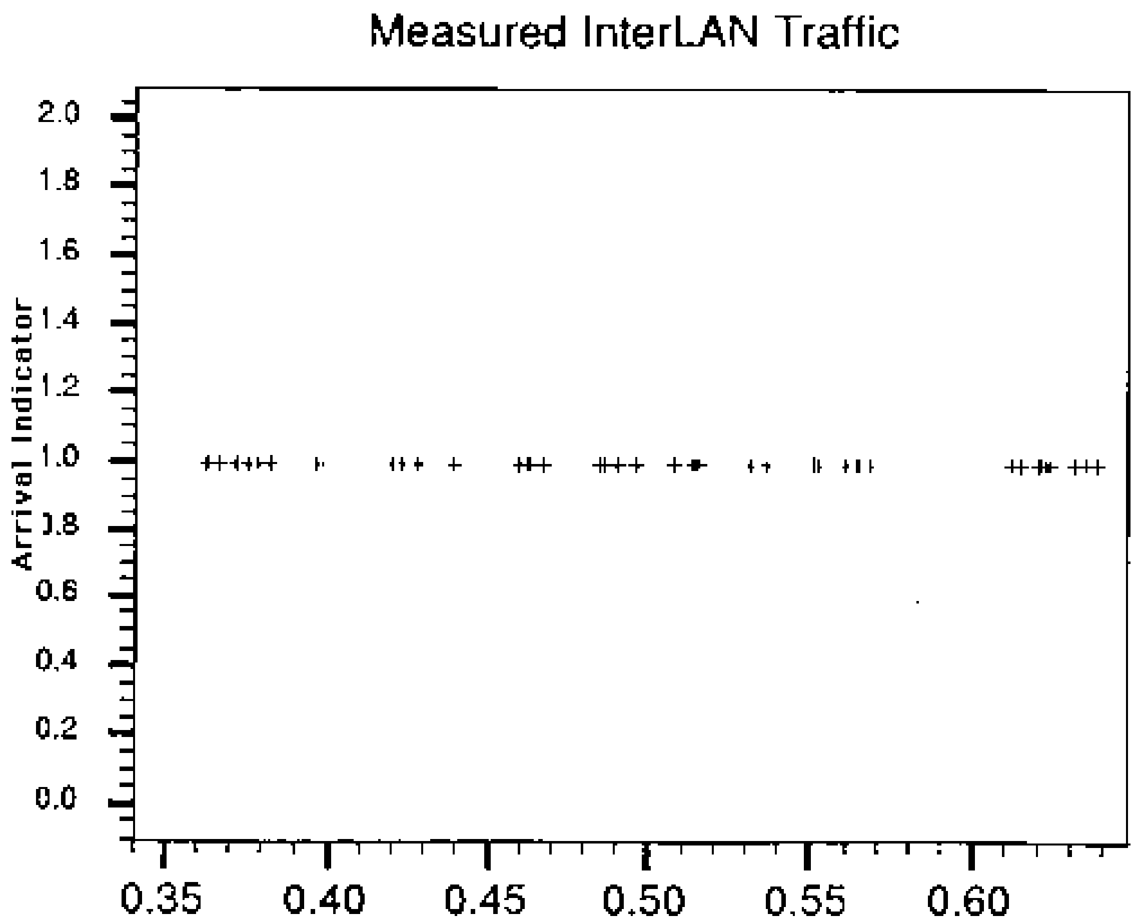
- Message Length
- Message Interarrival Times
- Other
  - BER vs. Time
  - Link Reliability
  - Node Reliability

A Model for the Statistical Multiplexer

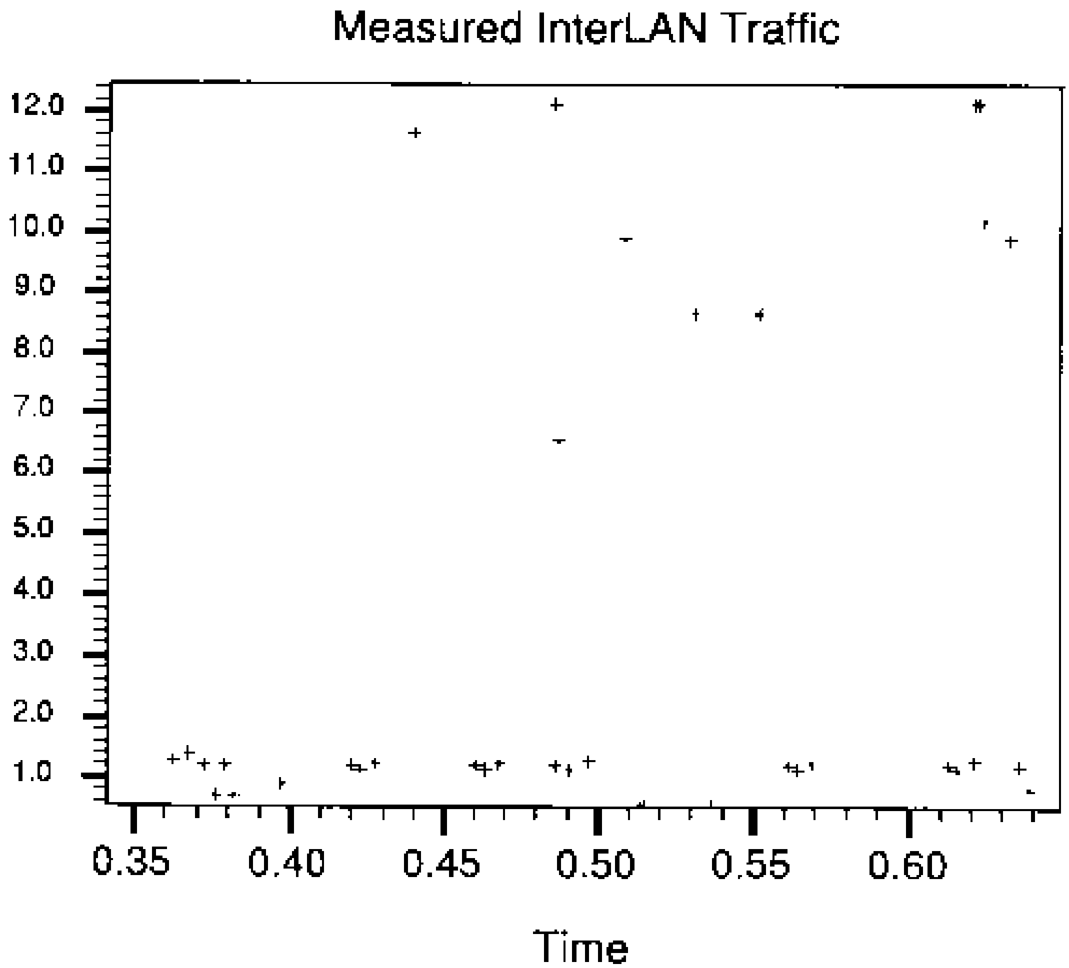


Sample Realization of an Input Process

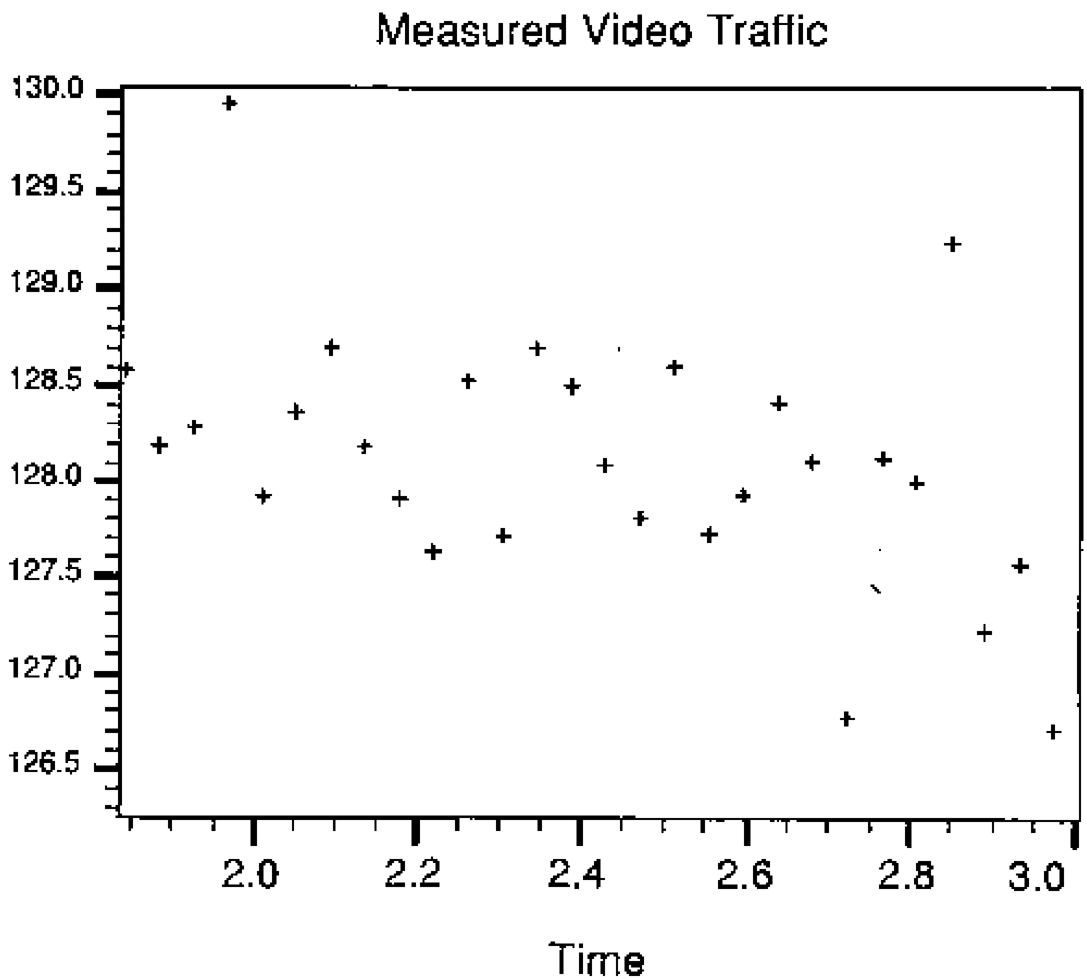
Message number	1	2	3	4	5	6	7	8	9	10	11	12
Interarrival time between i+1 and i message (seconds)	2	1	3	1	1	4	2	5	1	4	2	--
Length of i^{th} message (seconds)	1	3	6	2	1	1	4	2	5	1	1	3



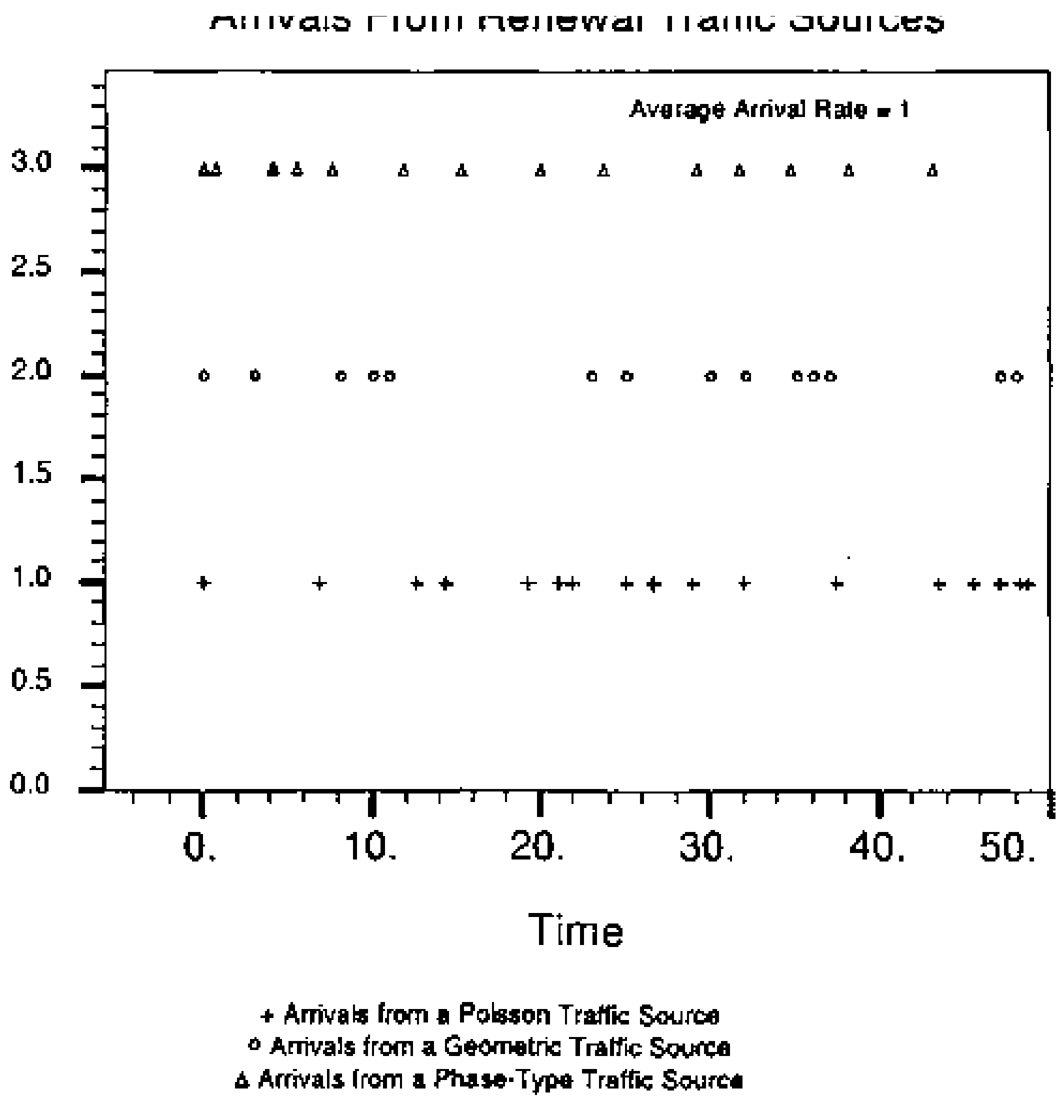
An Empirical LAN Traffic Interarrival Sequence,
An Example Point Process (from [34])



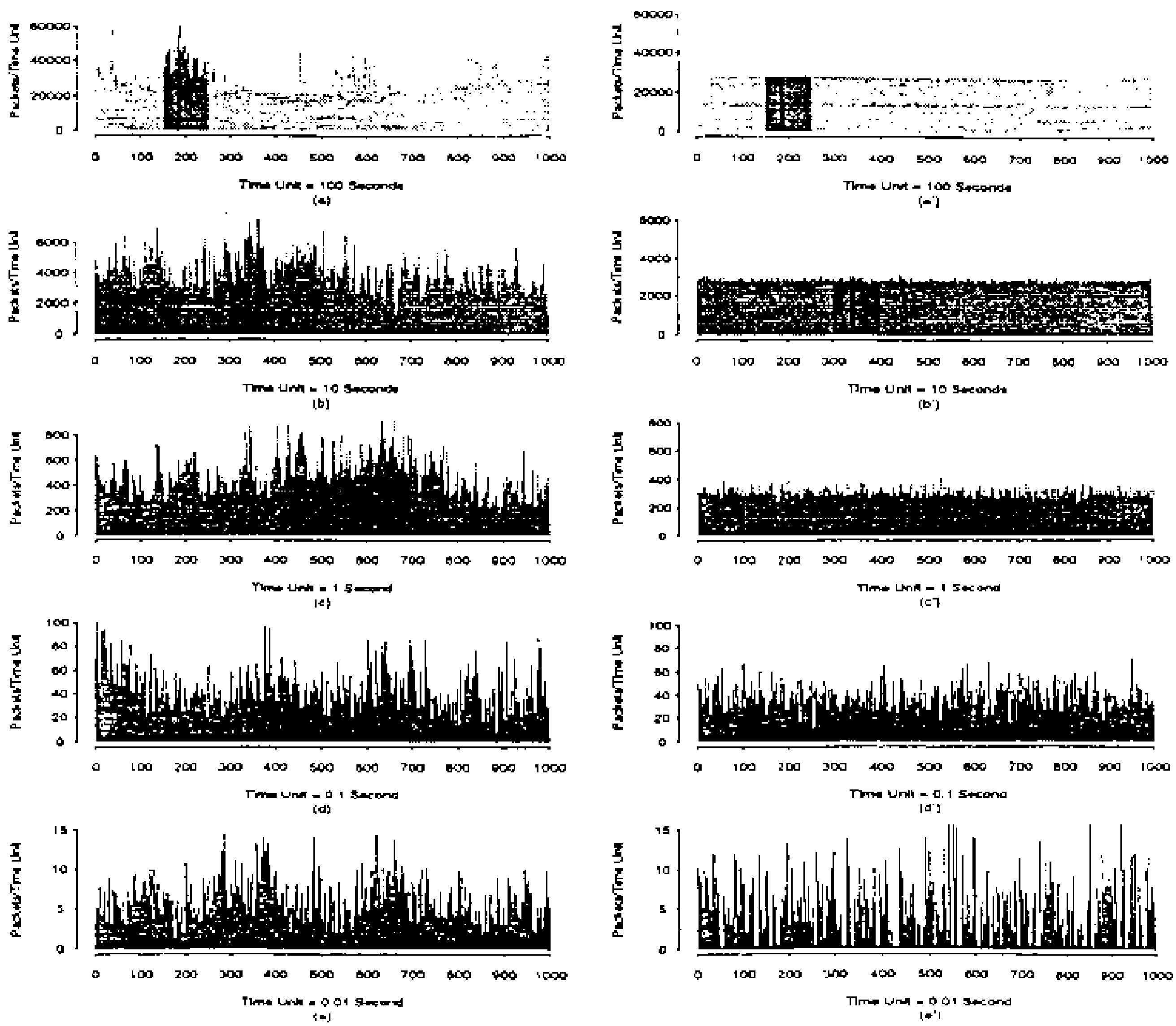
An Example Sequence of Measured LAN Message Lengths
(data from [34])



An Example Sequence of Measured Video Workload
(data from [35])



Example Interarrival Sequences from Renewal Processes



Pictorial “proof” of self-similarity: Ethernet traffic
(packets per time unit) on five different time scales
(from [34])

Overview of Discrete Event Simulation Approaches

- Time Step Approach
- Event-Scheduling Approach
- Process-Interaction Approach
- Activity Scanning

Communications Network Modeling Approaches

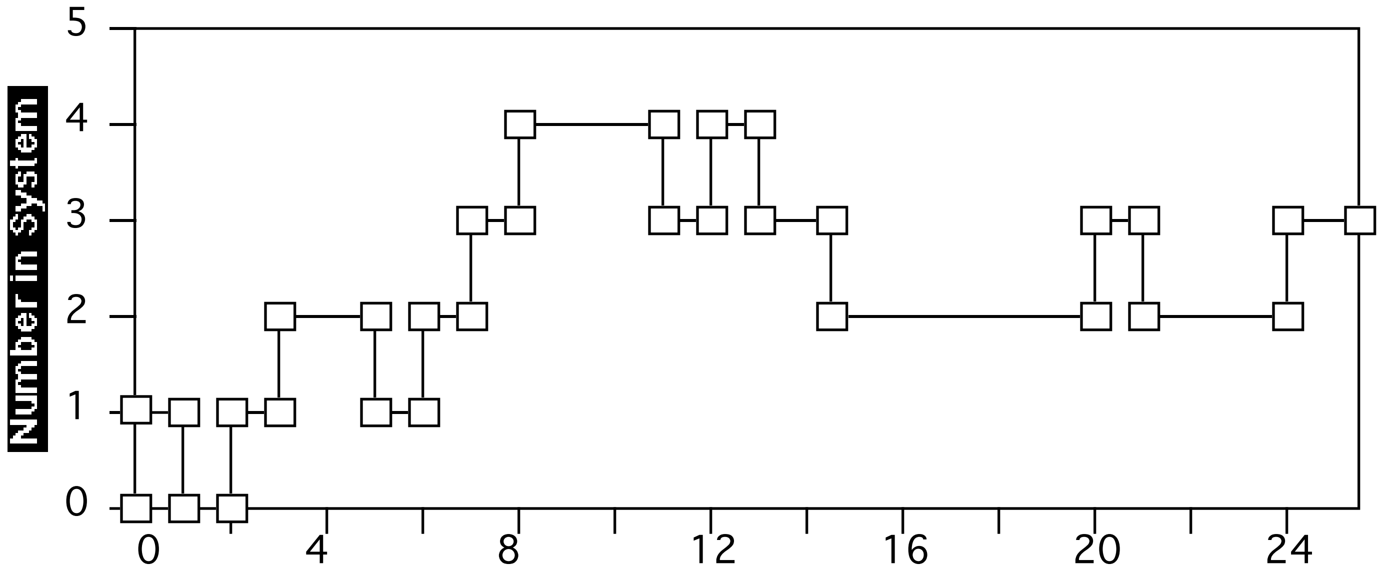
- Extended Queueing Networks
- Finite State Machine
- Petri Nets
- Data Flow Block Diagram

Time Step Approach to Network Simulation

- Fixed-Increment Time Advance
- Update System States at End of Each Fixed Time Interval

Example Time History of Time Step Analysis of Statistical Multiplexer

Simulated Time	Message Arrival	Start of Transmission	End of Transmission	Number in Buffer	Number in System	Time in Buffer	Time in System
0	1	1		0	1	0, 1	
1			1	0	0		1, 1
2	2	2		0	1	0, 2	
3	3			1	2		
4				1	2		
5		3	2	0	1	2, 3	3, 2
6	4			1	2		
7	5			2	3		
8	6			3	4		
9				3	4		
10				3	4		
11		4	3	2	3	5, 4	8, 3
12	7			3	4		
13		5	4	2	3	6, 5	7, 4
14	8	6	5	2	3	6, 6	7, 5
15		7	6	1	2	3, 7	7, 6
16				1	2		
17				1	2		
18				1	2		
19		8	7	1	2	5, 8	7, 7
20				2	3		
21		9	8	1	2	2, 9	7, 8
22				1	2		
23				1	2		
24	11			2	3		
25				2	3		
26	12	10	9	2	3	6, 10	7, 9


Number in System
5
4
3
2
1
0
0
4
8
12
16
20
24

Performance Measures

- $$\text{Average Delay} = \frac{\Sigma \text{ Time in system i}^{\text{th}} \text{ message}}{\text{total number of messages processed}}$$

- $$\text{Average number in system} = \frac{\Sigma \, N(t)}{\text{total time}}$$

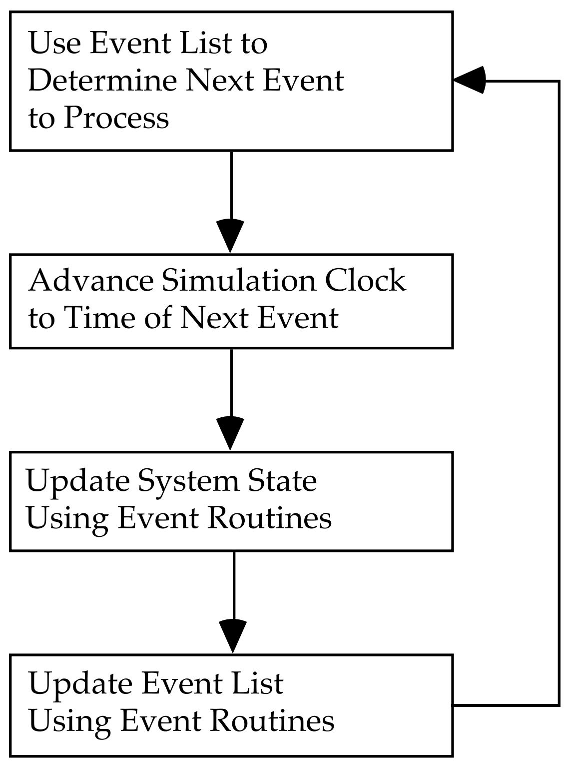
Event Scheduling Approach

- Variable Time Advance
- Update System State Only When Events Occur, e.g. Arrivals or Departures

The Event Calendar

- Events are Instantaneous Occurrences Which Change the State of the System
- An Event is Described by
  - The time the event is to occur
  - The action to take place at the event time
- The Event Calendar is a Time Ordered List of Events

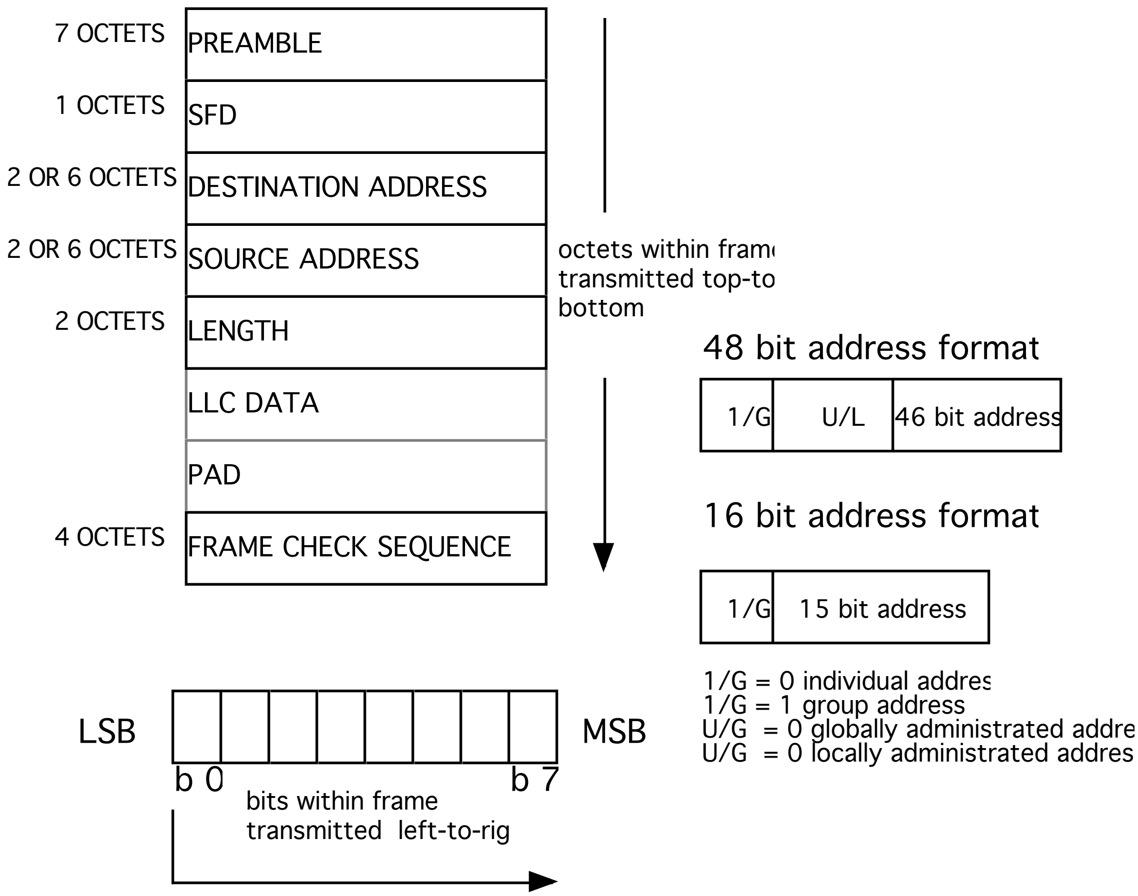
Simplified Flow Control for the Event Scheduling Approach



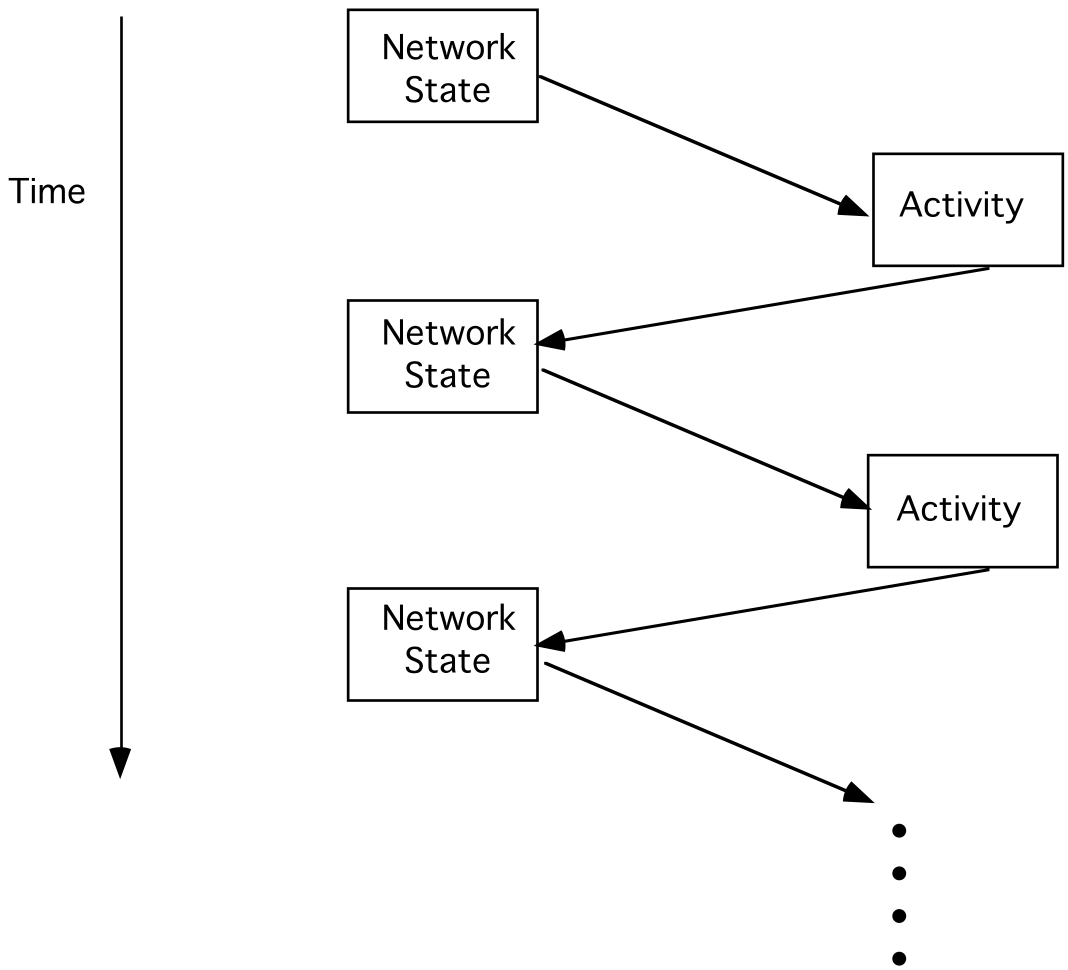
An Executive (or Mainline) Controls the Selection of Next Event

Entities, Attributes, Activities, and Files

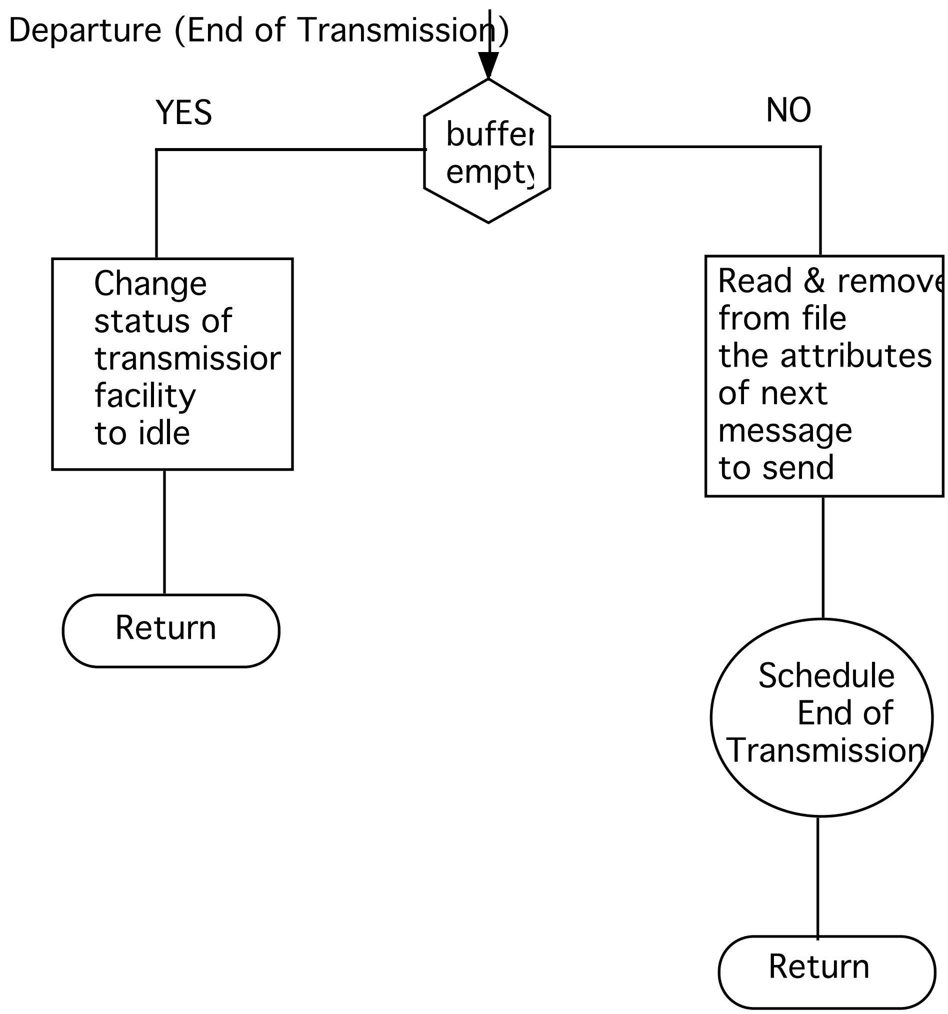
- Entities are the objects upon which action is performed. In network simulation entities are messages.
- Attributes are characteristics which describe entities, e.g. message length or message type.
- Activities are the operations that change the state of the network, e.g. increment number of messages waiting in a buffer.
- Files are groupings of entities which share a common attribute, e.g. all messages waiting in same buffer.



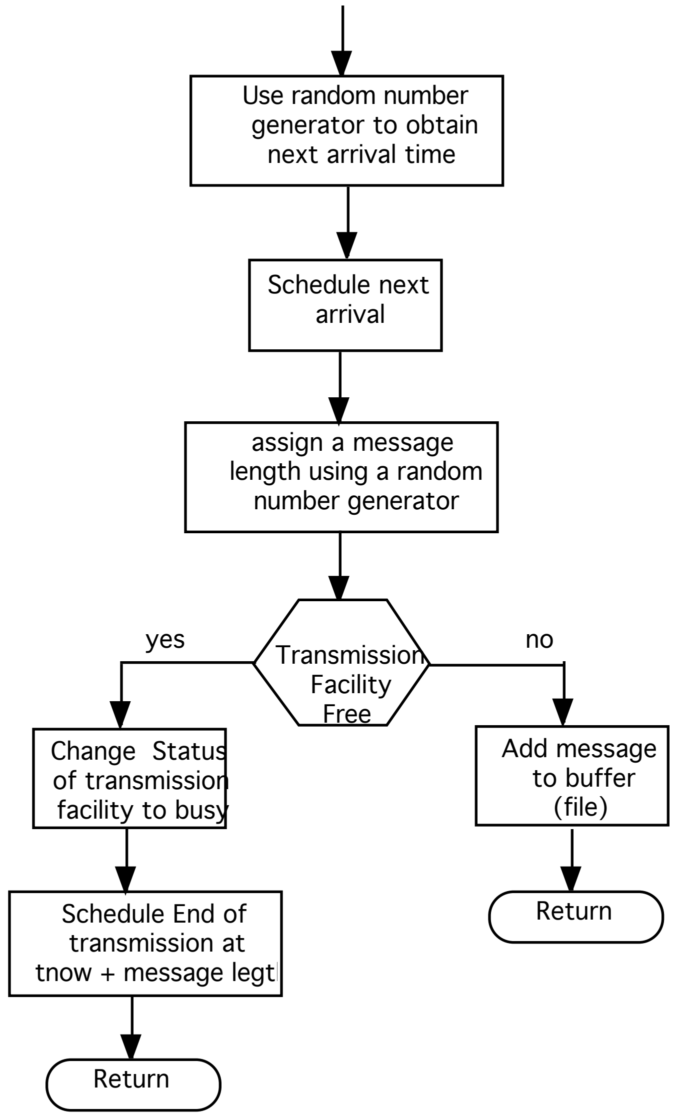
Example of a Communications Packet Data Structure


Time
Network State
Activity
Network State
Activity
Network State

Example of Discrete Event Simulation of the Statistical Multiplexer



Arrival



Use random number generator to obtain next arrival time
Schedule next arrival
assign a message length using a random number generator
yes
Transmission Facility Free
no
Change Status of transmission facility to busy
Add message to buffer (file)
Schedule End of transmission at tnow + message legt
Return
Return

0

Status of Transmission
1 = active
0 = idel

0

Number in Buffer

Message number	Message length	Message Time

Buffer Contents

0^-

System Clock

Activity type	time
Arrival	0

Event Calendar

0

Number of Packets processed

0

Total Delay of completed messages

0

Area Under N(t)

Message number	Message length	Message Time

Buffer Contents

1

Status of Transmission
1 = active
0 = idel

0

Number in Buffer

0

System Clock

Activity type	time
Departure	1
Arrival	2

Event Calendar

0

Number of Packets processed

0

Total Delay of completed messages

0

Area Under N(t)

0

Status of Transmission
1 = active
0 = idel

0

Number in Buffer

Message number	Message length	Message time

Buffer Contents

1

System Clock

Activity type	time
Arrival	2

Event Calendar

1

Number of Packets processed

1

Total Delay of completed messages

1

Area Under N(t)

Message number	Message length	Message time

Buffer Contents

1 — Status of Transmission (1 = active, 0 = idel)

0 — Number in Buffer

2 — System Clock

Activity type	time
Arrival	3
Departure	5

Event Calendar

---

1 — Number of Packets processed

1 — Total Delay of completed messages

1 — Area Under N(t)

Message number	Message length	Message time
3	6	3

Buffer Contents

1

Status of Transmission
1 = active
0 = idel

1

Number in Buffer

3

System Clock

Activity type	time
Arrival	5
Departure	6

Event Calendar

1

Number of Packets processed

1

Total Delay of completed messages

2

Area Under N(t)

Message number	Message length	Message time

Buffer Contents

1

Status of Transmission
1 = active
0 = idel

0

Number in Buffer

5

System Clock

Activity type	time
Arrival	6
Departure	11

Event Calendar

2

Number of Packets processed

4

Total Delay of completed messages

6

Area Under N(t)

Message number	Message length	Message time
4	2	6

Buffer Contents

1

Status of
Transmission
1 = active
0 = idel

1

Number
in
Buffer

6

System
Clock

Activity type	time
Arrival	7
Departure	11

Event Calendar

2

Number of
Packets
processed

4

Total Delay of
completed
messages

7

Area Under
N(t)

1

Status of Transmission
1 = active
0 = idel

2

Number in Buffer

Message number	Message length	Message time
4	2	6
5	1	7

Buffer Contents

7

System Clock

Activity type	time
Arrival	8
Departure	11

Event Calendar

2

Number of Packets processed

4

Total Delay of completed messages

9

Area Under N(t)

1

Status of Transmission
1 = active
0 = idel

3

Number in Buffer

Message number	Message length	Message time
4	2	6
5	1	7
6	1	8

Buffer Contents

8

System Clock

Activity type	time
Departure	11
Arrival	12

Event Calendar

2

Number of Packets processed

4

Total Delay of completed messages

12

Area Under N(t)

1

Status of Transmission
1 = active
0 = idel

2

Number in Buffer

Message number	Message length	Message time
5	1	7
6	1	8

Buffer Contents

11

System Clock

Activity type	time
Arrival	12
Departure	13

Event Calendar

3

Number of Packets processed

12

Total Delay of completed messages

24

Area Under N(t)

Relative Merits of Time Step and Event Scheduling

Approach	Advantages	Disadvantages
Time Step	Efficient for system with very frequently occurring events Efficient for regularly spaced events	Must process at each time step Error induced by fixed finite time increment Must establish rules to order events that occur in same time increment
Event Scheduling	Only process at event times No time increment to select Flexible	Significant programming effort required

Verification and Validation of Communication Network Simulation Models

- Verification is determining whether the simulation model performs as intended

- Validation is determining whether the simulation model is a "accurate" representation of the communication network under study

Verification Methods

- Modular development and verification
- Structured walk-through
- Event trace
- Model simplification and comparison to analytic results
- Graphical display of network status as the model progresses

Some Comments on Validation

- Simulation models are always approximations
- A simulation model developed for one application may not be valid for others
- Model development and validation should be done simultaneously
- Specific modeling assumptions should be tested
- Sensitivity analysis should be performed
- Attempt to establish that the model results resemble the expected performance of the actual system

"For models which attempt to describe new systems where no historical data are available and which are of such a nature that there are no input conditions that correspond to known analytical results, the problem of model validation is, indeed, extremely difficult. About all one can do in this situation is to recheck the logic of the design, run the model over a range of different inputs to determine whether the outputs are within the realm of plausibility, and, if one is so inclined, pray a lot."

(From D. Gross and C.M. Harris, "Fundamentals of Queueing Theory," John Wiley & Sons, Inc., New York, 1985)

Statistical Considerations: Analysis of Results from Communication Network Simulation

- Starting Rules (Overcoming initial transients)
- Quality of Performance Estimates (Variance of estimated performance measures)

Starting Rules

- An initial transient period is present which can bias the performance measurements.

- Achieving Steady State

  - Use a run-in period:
    Determine T_b such that the long-run distribution adequately describes the system for $t > T_b$

  - Use a "typical" starting condition (state) to initialize the model

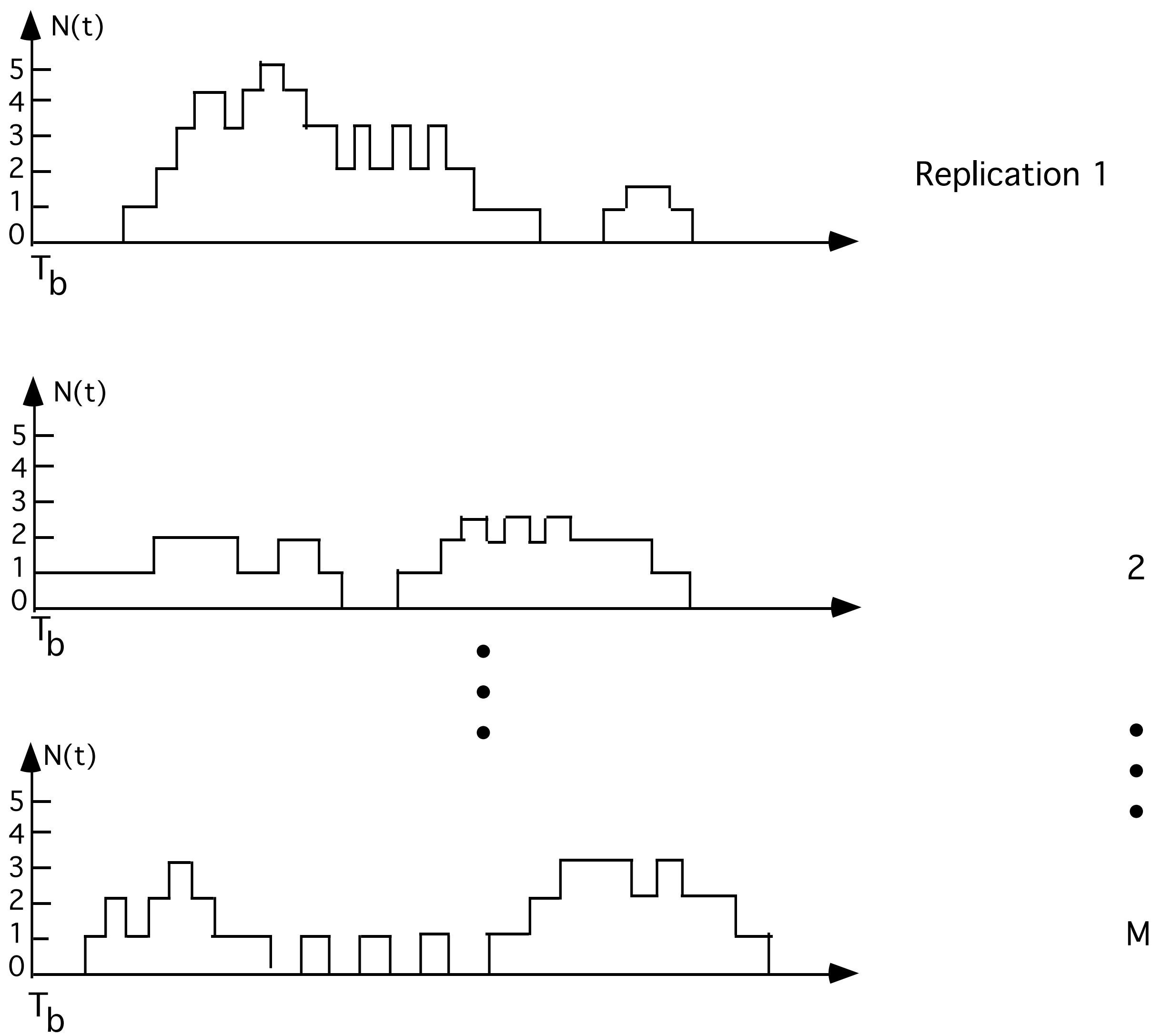
Quality of the Performance Estimate

- Performance estimates should be unbiased
- Performance estimates should have minimum variance
- Confidence intervals are the usual approach for assessing the accuracy of the estimators
- The desired confidence interval width determines the length of the simulation run
- Observations tend to be correlated: we cannot directly apply standard statistical approaches based on independent and identically distributed observations

Common Techniques for Dealing with the Lack of Independence

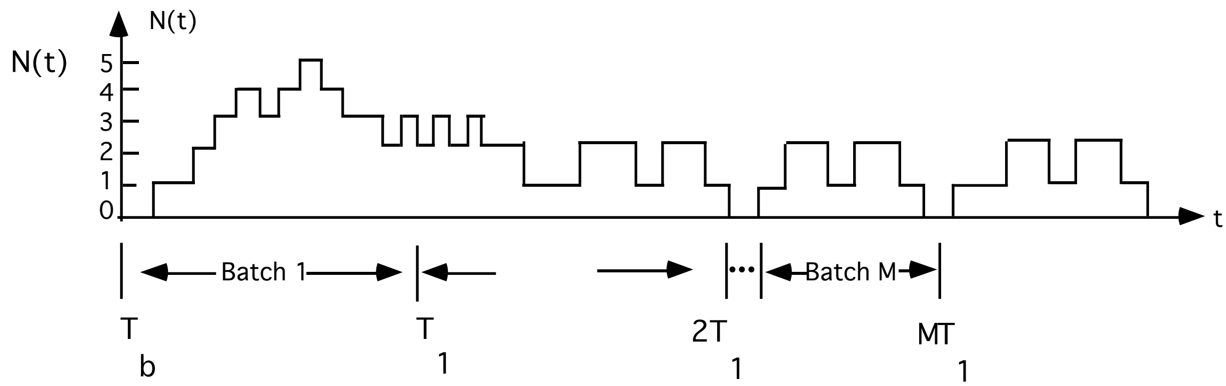
- Simple Replication
- Batching
- Regenerative

Simple Replication



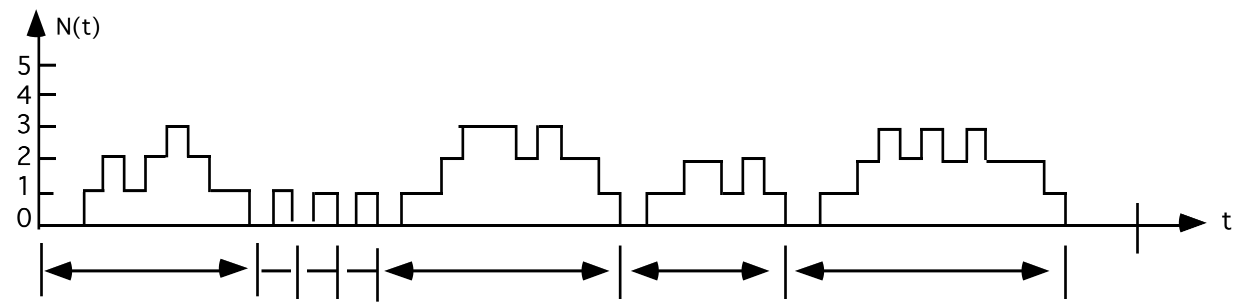
- Assume results for each replication are independent
- Apply standard statistical techniques
- Inefficient because of M startup periods

Batching



- Assume results from each batch are independent
- Apply standard statistical techniques
- Batches can be correlated unless “dead” periods between batches are employed

Regenerative



Regenerative Periods

- Assume results from each regenerative period are independent
- Apply standard statistical techniques
- Regenerative period can become very long in some cases
- Note the regenerative technique overcomes the initial transient problem

Evolution of Computer-Aided Analysis and Design Tools for Networks

- "Zeroth" generation — general purpose languages
  - Fortran
  - C
  - Pascal
  - Basic

- "First" generation — general purpose queueing system simulations
  - GPSS
  - SLAM
  - SIMSCRIPT

- "Second" generation — application specific: computer systems and wide-area communication networks
  - RESQ [see Ref. 20]
  - PAWS [see Ref. 25]

- "Third" generation — integration of second generation languages with a graphics-oriented analysis and modeling environment
  - Q+ (Q+ is a trademark of AT&T [see Ref. 24])
  - GENESIS (from University of Massachusetts [see Ref. 27])
  - BONeS (BONeS is a trademark of COMDISCO Systems, Inc., Lawrence, Kansas [see Ref. 29])
  - SES/Workbench (SES/Workbench is a trademark of Scientific and Engineering Software, Inc., Austin, TX [see Ref. 33])
  - OPNET (Mil 3, Inc., Washington, DC [see Ref. 30])

Relative Merits of General Purpose Languages

Advantages	**Disadvantages**
Wide Availability	Longer programming and debugging time
Few restrictions imposed on the model	Difficult verification
User may have prior knowledge of the language	Unless object-oriented, limited ability to reuse models
Generally more computationally efficient	Model enhancement and evolution are difficult

Relative Merits of Special Purpose Languages

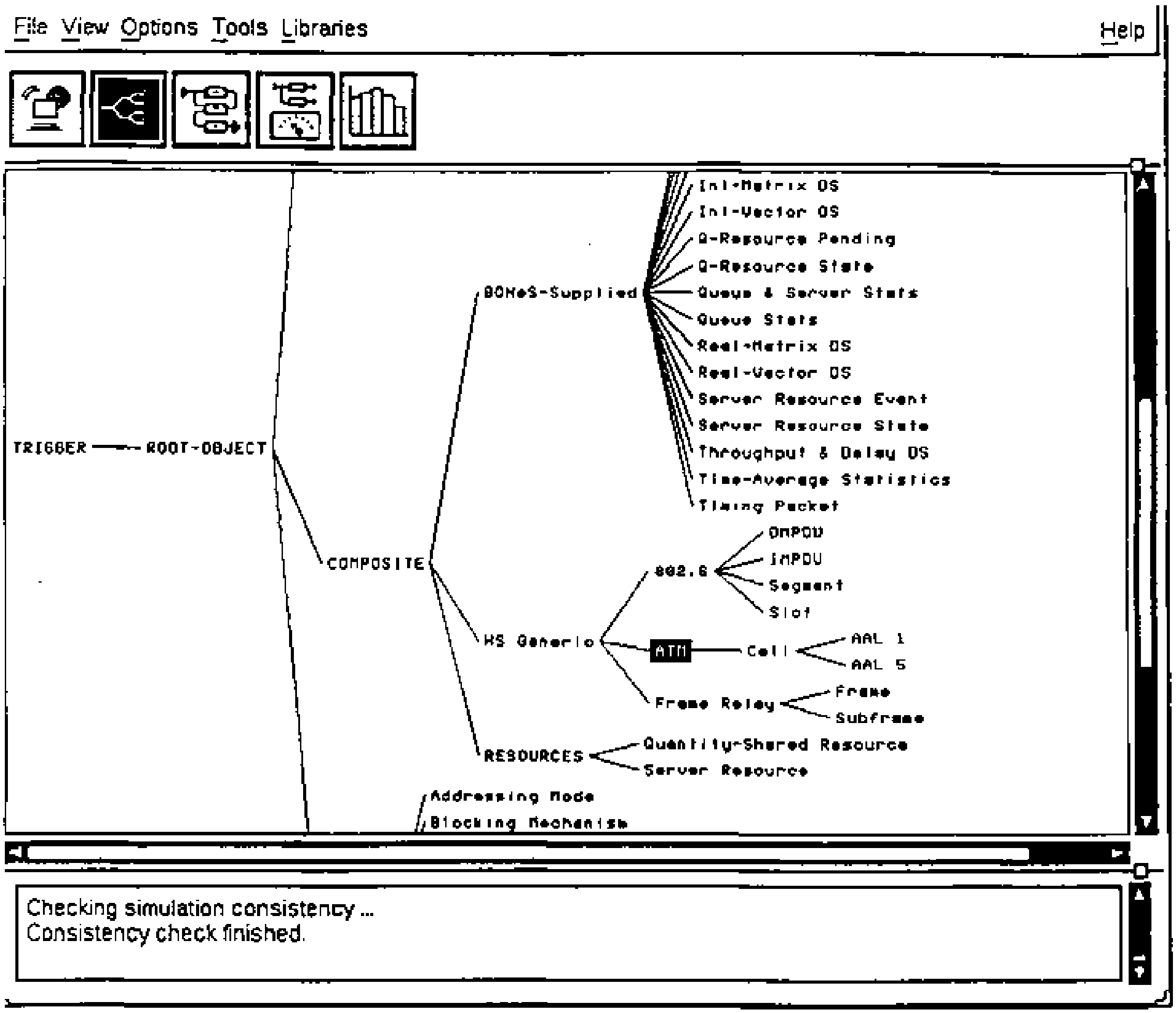
Advantages	Disadvantages
Provide built-in simulation services to reduce programming effort	Must adhere to a particular “world view” of the language
Provide error-checking techniques superior to those provided in general purpose languages	Availability and support
Provide a brief, direct vehicle for expressing the concepts arising in a simulation study	Cost
Provide ability to construct user subroutines required as a part of any simulation routine	Increased computer running time
Contain set of subroutines for common random numbers	Training required to learn the language and modeling paradigm
Facilitate collection and display of data produced	
Facilitate model reuse	

Relative Merits of Computer-Aided Analysis and Design Environments

Advantages	**Disadvantages**
Provide a complete integrated performance analysis environment	Tailored to a specific modeling paradigm
Graphically based	May be tied to a specific hardware platform
Typically integrate language, database, prior knowledge, and statistical analysis packages	Increased execution time
Support management of models and input/output data	Cost
Facilitate model reuse and group model development	

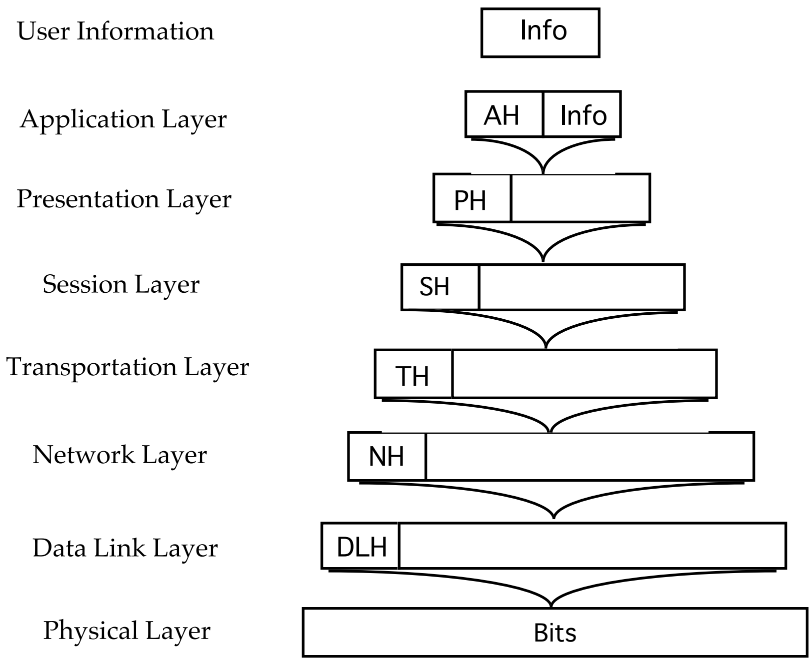
Criteria for Selecting a Computer-Aided Analysis and Design Tool

- Availability
- Cost
- Usage
- Documentation
- Ease of Learning
- Memory Requirements
- Computation Efficiency
- Flexibility
- Portability
- User Interface
- Extendability



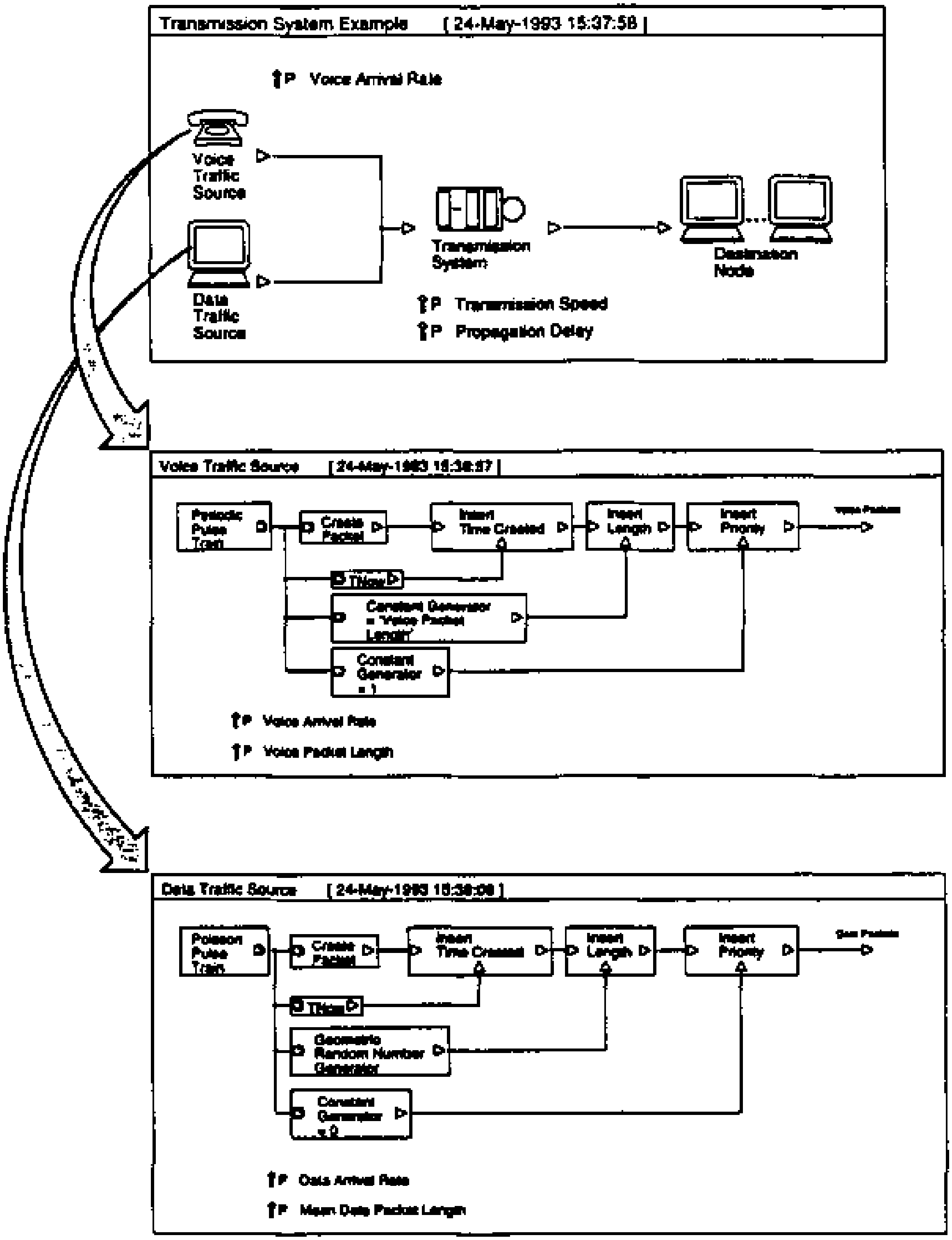
Name: ATM [WAN Data Structures]
Date: Tuesday, 9/20/94 12:21:39 pm CST

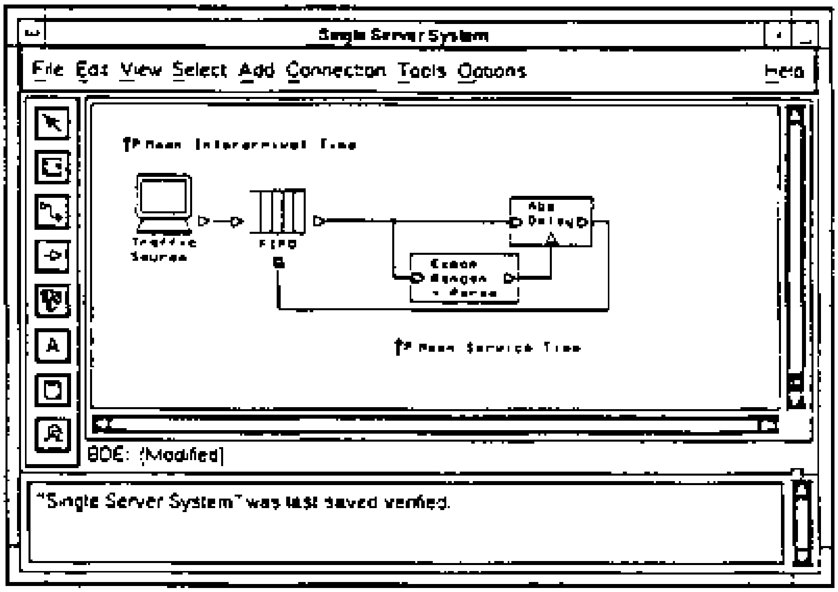
Name	Type	Subrange	Default Value
VC	*INTEGER*	*[0, +Infinity)*	...
Data	*ROOT-OBJECT*	...	...
Length	*INTEGER*	*[0, +Infinity)*	...
Service Priority	*INTEGER*	*[0, +Infinity)*	*0*
Sequence Number	*INTEGER*	*(-Infinity, +Infinity)*	...
Order Number	*INTEGER*	*[0, +Infinity)*	...
Time Generated	*REAL*	*[0, +Infinity)*	...
Hop Count	*INTEGER*	*(-Infinity, +Infinity)*	*0*
Future Expansion 2	*ROOT-OBJECT*	...	...

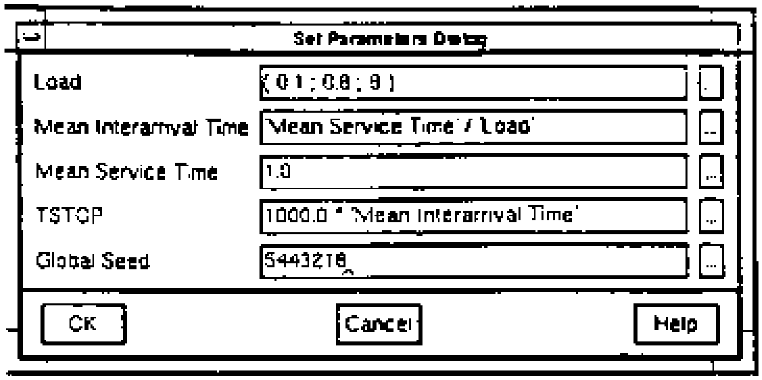


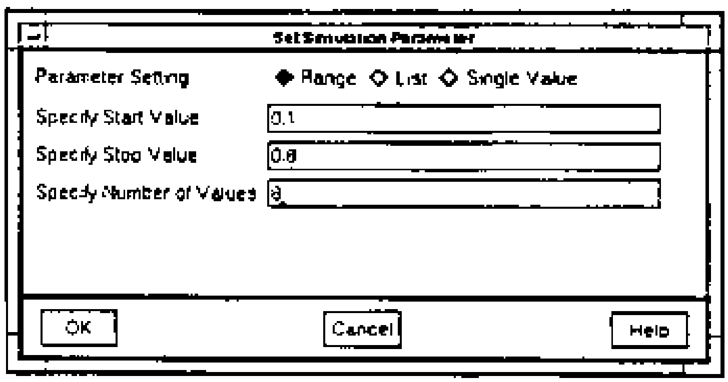
AH	Applicaton Header	TH	Transport Header
PH	Presentation Header	NH	Network Header
SH	Session Header	DLH	Data Link Header

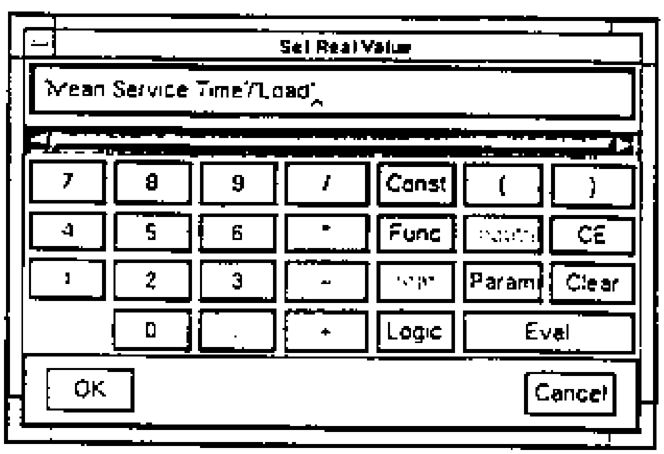
Data Structure Encapsulation in the OSI Layered Architecture

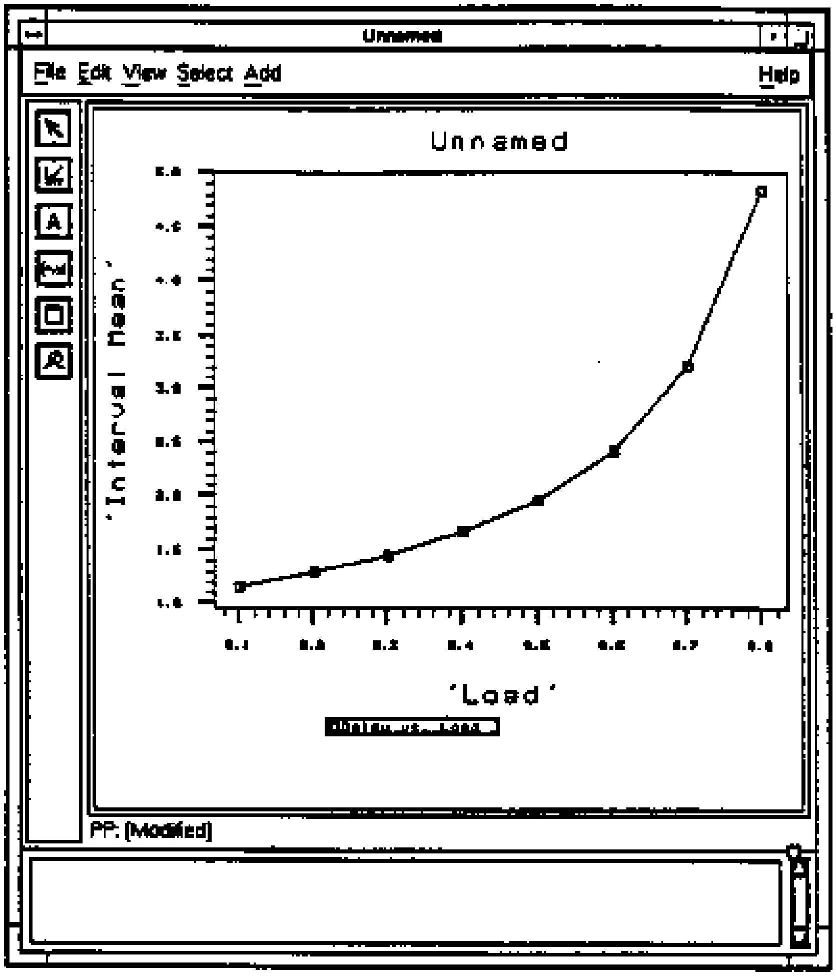

Transmission System Example [24-May-1993 15:37:58]
P Voice Arrival Rate
Voice Traffic Source
Data Traffic Source
Transmission System
Destination Node
P Transmission Speed
P Propagation Delay
Voice Traffic Source
Periodic Pulse Train
Create Packet
Insert Time Created
Insert Length
Insert Priority
TNow
Constant Generator = 'Voice Packet Length'
Constant Generator = 1
P Voice Arrival Rate
P Voice Packet Length
Data Traffic Source
Poisson Pulse Train
Create Packet
Insert Time Created
Insert Length
Insert Priority
TNow
Geometric Random Number Generator
Constant Generator = 0
P Data Arrival Rate
P Mean Data Packet Length

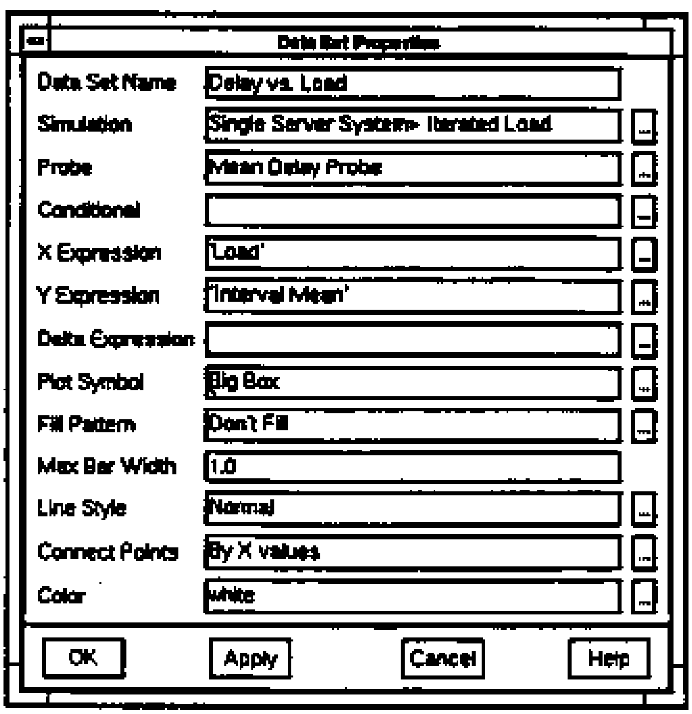

Single Server System
File Edit View Select Add Connection Tools Options Help
Mean Interarrival Time
Traffic Source
FIFO
Mean Service Time
BDE: (Modified)
"Single Server System" was last saved verified.


Load
{ 0.1 ; 0.8 ; 8 }
Mean Interarrival Time
'Mean Service Time' / 'Load'
Mean Service Time
1.0
TSTOP
1000.0 * 'Mean Interarrival Time'
Global Seed
5443218
OK
Cancel
Help


Parameter Setting
Range
List
Single Value
Specify Start Value
0.1
Specify Stop Value
0.8
Specify Number of Values
8
OK
Cancel
Help


Set Real Value
'Mean Service Time'/'Load'
7
8
9
/
Const
(
)
4
5
6
*
Func
CE
1
2
3
-
Param
Clear
0
.
+
Logic
Eval
OK
Cancel


Unnamed
File Edit View Select Add
Help
Unnamed
'Interval Mean'
'Load'
PP: (Modified)


Data Set Properties
Data Set Name
Delay vs. Load
Simulation
Single Server System- Iterated Load
Probe
Mean Delay Probe
Conditional
X Expression
'Load'
Y Expression
'Interval Mean'
Delta Expression
Plot Symbol
Big Box
Fill Pattern
Don't Fill
Max Bar Width
1.0
Line Style
Normal
Connect Points
By X values
Color
white
OK
Apply
Cancel
Help

Guidelines to Simulation Modeling and Analysis of Communications Networks

- Know the customer
- Know the network
- Know the important performance metrics
- Know how to establish a credible model
- Expect the model to evolve
- Know how to apply good software management techniques

Features Expected in Future Simulation Models and Tools

I. Computational Features

   A. Importance Sampling

   B. Perturbation Analysis

   C. Distributed Simulation

   D. Merging of elements of operational component with simulation models.

   E. Use of more efficient model abstractions

II. Enhancements to the User Environment

   A. More animation

   B. Enhanced debugging facilities

   C. Development of standards for file formats and possible models to encourage team effort and collaboration

III. Broadening the Scope of Simulation and Modeling Tools

A. Transition from a purely analysis tool to an element used for suggesting plans and designs based on previous cases and prior knowledge

B. Integration of simulation tools into the complete life cycle of a product or network

C. Interface to operational networks

1. This interface will be used to capture network topology, existing traffic parameters, and parameters of network devices. Possibly culminating in the automatic generation of the network model

2. Interface to existing network management systems

3. Provide access to operational network for use in hybrid simulation/emulation experiments

4. Reciprocal use of network and simulation software. Use operational network software as part of simulation and use simulation software as part of operational network.

IV. Integration of Expert System Technology

A. Decision Support

B. Intelligent User Interface

1. Advice-giving on various aspects of the modeling process

2. Advice on interpretation of results.

C. Advice on modeling method

D. Advice on modeling abstraction

Conclusions

- Simulation can be an important tool for communication network design and analysis
- Care and thought must go into construction of communication network models
- Care and thought must go into interpretation of model output

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