

# High-Speed Networking: A Systematic Approach to High-Bandwidth Low-Latency Communication

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Introduction

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## Abstract

This tutorial presents a comprehensive introduction to all aspects of high-speed networking, based on the book *High-Speed Networking: A Systematic Approach to High-Bandwidth Low-Latency Communication*, James P.G. Sterbenz and Joseph D. Touch, John Wiley, 2001. The target audience includes computer scientists and engineers who may have expertise in a narrow aspect of high-speed networking (such as switch design), but want to gain a broader understanding of all aspects of high-speed networking and the impact that their designs have on overall network performance. This tutorial is not about any particular protocols and standards, but is rather a systemic and systematic approach to the principles that guide the research and design of high-speed networks, protocols, and applications.

The network is a complex system of systems, and high-speed networking does not result from the design of individual components or protocols in isolation. Thus, this tutorial presents a systemic approach to high-speed networks, where the goal is to provide high bandwidth and low latency to distributed applications, and to deal with the high bandwidth-x-delay product that results from high-speed networking over long distances. A set of fundamental axioms is presented (Know the past present and future, Application primacy, High-performance paths, Limiting constraints, and Systemic optimisation) followed by the major topics: Network architecture and topology; Network control and signalling; Communication links; Switches and routers; End systems; End-to-end protocols; Networked applications.

A set of design principles are defined and applied to each of the topics:

1. Selective optimisation; 2. Resource tradeoffs; 3. End-to-end arguments; 4. Protocol layering; 5. State management; 6. Control mechanism latency; 7. Distributed data; 8. Protocol data unit structure.

A set of design techniques (scaling time and space, masking the speed of light, specialised hardware implementation, parallelism and pipelining, data structure optimisation, cut-through and remapping) are introduced and applied as appropriate.

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## Revision History

1.0	IEEE Hot Interconnects, Stanford,	23 Aug. 2002
1.1	IEEE Networks 2002, Atlanta,	27 Aug. 2002
2.0	IEEE Hot Interconnects, Stanford,	22 Aug. 2003
2.1	IEEE MILCOM, Boston	15 Oct. 2003
2.2	Universität der Bundeswehr München	15 Mar. 2004
2.3	IEEE Hot Interconnects, Stanford,	27 Aug. 2004
2.4	IEEE Hot Interconnects, Stanford,	17 Aug. 2005
2.5	IEEE Hot Interconnects, Stanford	25 Aug. 2006

## Sources

This tutorial is based on...

- James P.G. Sterbenz and Joseph D. Touch,  
*High-Speed Networking: A Systematic Approach to  
High-Bandwidth Low-Latency Communication*,  
John Wiley, New York NY US, 2001
  - with contributions from
  - Julio Escobar
  - Rajesh Krishnan
  - Chunming Qiao
  - A. Lyman Chapin

## Introduction

1. Introduction
2. Fundamentals and design principles
3. Network architecture and topology
4. Network control and signalling
5. Network components
  - 5.1 links
  - 5.2 switches and routers
6. End systems
7. End-to-end protocols
8. Networked applications
9. Future directions

## Scope

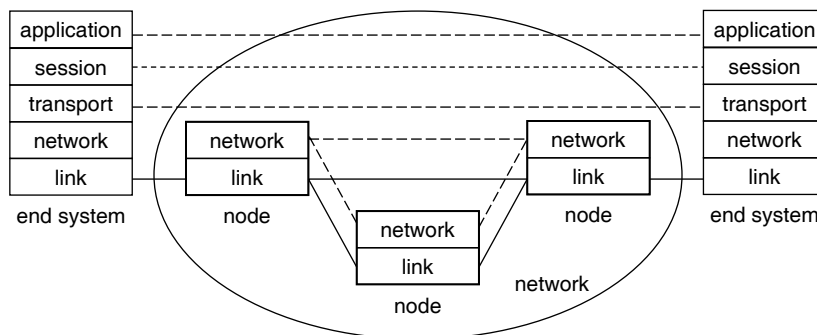
- All factors needed for high-speed networking
  - network components
  - protocols
  - network: a complex system of systems
  - end-to-end delivery of data to applications
  - applications that use and drive high-speed networks
- Lots of networking topics are *not* covered
- Ask questions throughout!

# What is High Speed?

## Bandwidth and Latency

- Delay
  - $D$  end-to-end
  - $d$  per hop
- Bandwidth
  - $B$  aggregate
  - $b$  per flow
- Bandwidth- $\times$ -delay product
  - number of bits in flight on a high-speed path
  - $b$  [bits/sec]  $\times$   $d$  [sec] = [bits]

# Tutorial Structure



- Bottom up
  - network components
  - applications
- Inside out
  - network components
  - end systems

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## Network Architecture and Topology

The diagram illustrates the network architecture and topology. On the left and right, two 'end system' protocol stacks are shown, each with five layers: application, session, transport, network, and link. The central network consists of three nodes. Each node has a 'network' layer and a 'link' layer. The nodes are interconnected: the top two nodes are connected to each other and to the bottom node. The bottom node is also connected to the two end systems via their link layers.

3.1. Topology and geography  
 3.2. Scale  
 3.3. Resource Tradeoffs

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## Network Control and Signalling

The diagram illustrates network control and signalling. It features the same network topology as the previous slide. In this version, the 'session' layer in the end system stacks and the 'network' layer in the node stacks are highlighted in grey. Dotted lines represent session-level signalling between the end systems and the nodes. Dashed lines represent network-level signalling between the nodes and the end systems.

4.1. Signalling and control  
 4.2. Traffic management  
 4.3. Path routing dynamics  
 4.4. Monitoring & management

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## Network Components: Links

The diagram illustrates the network components. On the left and right are end systems, each with a protocol stack consisting of application, session, transport, network, and link layers. In the center, three nodes are shown, each with a network and link layer. The nodes are interconnected by links. The top two nodes are connected to each other and to the end systems. The bottom node is connected to the top two nodes. The link layer is highlighted in grey in the original image.

5.1.1. Physical transmission      5.1.3. Link layer components  
 5.1.2. Link technologies      5.1.4. Support for higher layers

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## Switches and Routers

The diagram illustrates switches and routers. It shows the same end systems and nodes as the previous diagram. However, the nodes now have a network layer and a link layer, and they are connected to each other and to the end systems. The network layer is highlighted in grey in the original image.

5.2. Switches and routers      5.5. Fast datagram switches  
 5.3. Fast packet switches      5.6. Higher layer and active processing  
 5.4. Switch fabric architecture

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## End Systems

The diagram illustrates the architecture of end systems and their connection to a network. On the left and right, two 'end system' blocks are shown, each containing a vertical stack of five protocol layers: application, session, transport, network, and link. The 'link' layer is highlighted in grey. Dashed lines represent connections between the application and session layers of both end systems, and between the network and link layers of both end systems. In the center, a network topology is shown within a large oval. It consists of three nodes. Each node contains a 'network' layer and a 'link' layer. The nodes are interconnected: the top two nodes are connected to each other and to the bottom node, and the bottom node is also connected to the top two nodes. The word 'network' is also written to the right of the bottom node.

6.1. End system components      6.3. End system organisation  
 6.2. Protocols and OS software      6.4. Host-network interface

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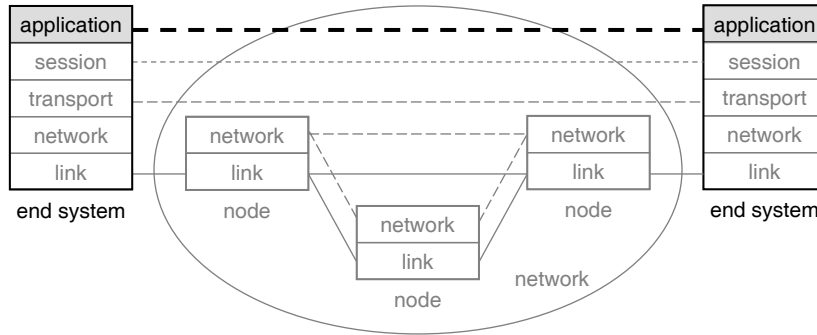
## End-to-End Protocols

This diagram is identical to the one above, showing the end system protocol stacks and network topology. However, the 'transport' layer in both end system stacks is highlighted in grey, and a thick dashed horizontal line spans across the transport layers of both end systems, indicating the focus on end-to-end protocols. The network topology in the center remains the same.

7.1. Functions and mechanisms      7.4. Error control  
 7.2. State management      7.5. Flow & congestion control  
 7.3. Framing and multiplexing      7.6. Security & info assurance

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# Networked Applications



8.1. Application characteristics

8.3. Application adaptation

8.2. Application categories

8.4. Network interaction