Communication Networks
University of Kansas EECS 780
Preliminaries and Foundations

James P.G. Sterbenz

Department of Electrical Engineering & Computer Science
Information Technology & Telecommunications Research Center
The University of Kansas

jgps@eecs.ku.edu

http://www.ittc.ku.edu/~jgps/courses/nets

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Comm. Network Preliminaries

PR.1 Network Architecture and Topology

- PR.1 Network architecture and topology
- PR.2 Performance metrics and style
- PR.3 Theoretical foundations and network science
- PR.4 Scope of communication
- PR.5 Protocols and layering
- PR.6 Communication flow diagrams
Network Architecture and Topology

The Network

- Collection *nodes* or *intermediate systems* (IS)
  - switches, routers, bridges, etc.
- Interconnected by *links* that
- Provide connectivity among *end systems* (ES) or *hosts* or *terminals*
  - desktops, laptops, servers, telephone handsets, etc.
  - note: in some networks nodes may be both ES and IS
- To support distributed *applications*
  - e.g. email, Web browsing, peer-to-peer file sharing
Network Architecture and Topology

The Network

- End system
- Intermediate system
  - edge or access switch
  - core or backbone switch
- multihomed
Network Architecture and Topology

Heterogeneous Networks

- Disparate networks are interconnected by *gateways*
  - translate data packet formats
  - interoperate signalling and control
Network Architecture and Topology

Application Relationships

- **Client/server**
  - e.g. Web browsing
  - data streams with embedded synchronisation
- **Peer-to-peer**
  - e.g. telepresence (video-conferencing)
Network Architecture and Topology

Group Communication Topologies

- Group communication
  - communication among participants in a group of nodes
- Topologies
  - unicast
  - anycast
  - $k$-cast
  - multicast
  - broadcast
Group Communication Topologies

Unicast

- Unicast
  - point-to-point
- Anycast
  - point-to-any in group
- $k$-cast
  - point-to-$k$ receivers in group
- Multicast
  - point-to-multipoint
  - multipoint-to-multipoint
  - multipoint-to-point (reverse multicast or Concast)
- Broadcast
  - point-to-all
  - broadcast and select multicast
Group Communication Topologies

Anycast

- **Unicast**
  - point-to-point

- **Anycast**
  - point-to-any in group

- **k-cast**
  - point-to-\( k \) receivers in group

- **Multicast**
  - point-to-multipoint
  - multipoint-to-multipoint
  - multipoint-to-point (reverse multicast or Concast)

- **Broadcast**
  - point-to-all
  - broadcast and select multicast
Group Communication Topologies

\( k \)-cast

- **Unicast**
  - point-to-point
- **Anycast**
  - point-to-any in group
- **\( k \)-cast**
  - point-to-\( k \) receivers in group
- **Multicast**
  - point-to-multipoint
  - multipoint-to-multipoint
  - multipoint-to-point (reverse multicast or Concast)
- **Broadcast**
  - point-to-all
  - broadcast and select multicast

\( k = 3 \)
Group Communication Topologies

Multicast: Point-to-Multipoint

- **Unicast**
  - point-to-point
- **Anycast**
  - point-to-any in group
- **k-cast**
  - point-to-$k$ receivers in group
- **Multicast**
  - point-to-multipoint
  - multipoint-to-multipoint
  - multipoint-to-point (reverse multicast or Concast)
- **Broadcast**
  - point-to-all
  - broadcast and select multicast
Group Communication Topologies

Multicast: Multipoint-to-Multipoint

- **Unicast**
  - point-to-point

- **Anycast**
  - point-to-any in group

- **k-cast**
  - point-to-\( k \) receivers in group

- **Multicast**
  - point-to-multipoint
    - multipoint-to-multipoint
    - multipoint-to-point (reverse multicast or Concast)

- **Broadcast**
  - point-to-all
  - broadcast and select multicast
Group Communication Topologies

Concast: Multipoint-to-Point

- **Unicast**
  - point-to-point
- **Anycast**
  - point-to-any in group
- **$k$-cast**
  - point-to-$k$ receivers in group
- **Multicast**
  - point-to-multipoint
  - multipoint-to-multipoint
  - multipoint-to-point (reverse multicast or Concast)
- **Broadcast**
  - point-to-all
  - broadcast and select multicast
Group Communication Topologies

Broadcast

- **Unicast**
  - point-to-point

- **Anycast**
  - point-to-any in group

- **k-cast**
  - point-to-\(k\) receivers in group

- **Multicast**
  - point-to-multipoint
  - multipoint-to-multipoint
  - multipoint-to-point (reverse multicast or Concast)

- **Broadcast**
  - point-to-all
  - broadcast and select multicast
Group Communication Topologies

Multicast: Broadcast and Select

- **Unicast**
  - point-to-point
- **Anycast**
  - point-to-any in group
- **k-cast**
  - point-to-\(k\) receivers in group
- **Multicast**
  - point-to-multipoint
  - multipoint-to-multipoint
  - multipoint-to-point (reverse multicast or Concast)
- **Broadcast**
  - point-to-all
  - broadcast and select multicast
Network Architecture and Topology

Star vs. Mesh Topologies

- Star hierarchy
- Centralised control
- Examples
  - PSTN
  - early enterprise nets (SNA)
    - later became meshes

- Mesh
- Fully distributed control
- Examples
  - ARPANET, Internet
  - DECnet
- Spanning tree may be overlaid
Comm. Network Preliminaries

PR.2 Performance Metrics

PR.1 Network architecture and topology
PR.2 Performance metrics and style
PR.3 Theoretical foundations
PR.4 Scope of communication
PR.5 Protocols and layering
PR.6 Communication flow diagrams
Performance Metrics

Style and Usage: Variables

• Proper style in formulæ is important
  – sloppy style can lead to ambiguity
  – guidelines at physics.nist.gov/cuu/Units/

• Variables, indices, constants, and parameters (scalar)
  – italic serif font if single character
    • \( \pi = 3.14159... \)
    • \( c \approx 3 \times 10^8 \) m/s speed of light
    • \( r_i \) rate of the \( i \)th link
    • \( r_{ij} \) rate of the \( (i,j) \)th link
    • multiplication is implicit: \( ab = a \times b = a \cdot b \)
      – never use * for multiplication in typeset documents
Performance Metrics
Style and Usage: Variables

- Variables, indices, constants, and parameters (scalar)
  - italic serif font if single character
  - Roman serif font if multiple characters
    - RTT round trip time
      - warning: $RTT = RTT = RT^2 \neq RT$ 
    - queue\_len queue length
    - adjacent multiplication must be explicit, e.g.: $a \times RTT$
    - in LaTeX math mode declare using \text{ ...}
    - in MathType (MS Equation Editor) change style to “Text”
Performance Metrics
Style and Usage: Variables

- Variables, indices, constants, and parameters (scalar)
  - italic serif font if single character
  - Roman serif font if multiple characters
  - may use fixed-width or sans-serif font for variables
    - cwnd   TCP congestion window
    - init\_val initialisation value
    - conlsolas (Windows) or Monaco (Mac) are better than courier
    - multiplication must be explicit
## Performance Metrics

### Greek Letters

<table>
<thead>
<tr>
<th>Name</th>
<th>Lower</th>
<th>Capital</th>
<th>Name</th>
<th>Lower</th>
<th>Capital</th>
</tr>
</thead>
<tbody>
<tr>
<td>alpha</td>
<td>$\alpha$</td>
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<td>$\nu$</td>
<td>$N$</td>
</tr>
<tr>
<td>beta</td>
<td>$\beta$</td>
<td>$B$</td>
<td>xi</td>
<td>$\xi$</td>
<td>$\Xi$</td>
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<tr>
<td>gamma</td>
<td>$\gamma$</td>
<td>$\Gamma$</td>
<td>omicron</td>
<td>$\omicron$</td>
<td>$O$</td>
</tr>
<tr>
<td>delta</td>
<td>$\delta$</td>
<td>$\Delta$</td>
<td>pi</td>
<td>$\pi$</td>
<td>$\Pi$</td>
</tr>
<tr>
<td>epsilon</td>
<td>$\epsilon$</td>
<td>$E$</td>
<td>rho</td>
<td>$\rho$</td>
<td>$P$</td>
</tr>
<tr>
<td>zeta</td>
<td>$\zeta$</td>
<td>$Z$</td>
<td>sigma</td>
<td>$\sigma$, $\varsigma$</td>
<td>$\Sigma$</td>
</tr>
<tr>
<td>eta</td>
<td>$\eta$</td>
<td>$H$</td>
<td>tau</td>
<td>$\tau$</td>
<td>$T$</td>
</tr>
<tr>
<td>theta</td>
<td>$\theta$, $\vartheta$</td>
<td>$\Theta$</td>
<td>upsilon</td>
<td>$\upsilon$</td>
<td>$\Upsilon$</td>
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<td>iota</td>
<td>$i$</td>
<td>$I$</td>
<td>phi</td>
<td>$\phi$, $\varphi$</td>
<td>$\Phi$</td>
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<tr>
<td>kappa</td>
<td>$\kappa$</td>
<td>$K$</td>
<td>chi</td>
<td>$\chi$</td>
<td>$X$</td>
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<td>lambda</td>
<td>$\lambda$</td>
<td>$\Lambda$</td>
<td>psi</td>
<td>$\psi$</td>
<td>$\Psi$</td>
</tr>
<tr>
<td>mu</td>
<td>$\mu$</td>
<td>$M$</td>
<td>omega</td>
<td>$\omega$</td>
<td>$\Omega$</td>
</tr>
<tr>
<td></td>
<td>$i$, $o$, $\nu$, capitals identical to Latin</td>
<td>rarely used</td>
<td>digamma</td>
<td>$\digamma$</td>
<td>$F$</td>
</tr>
</tbody>
</table>

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22 January 2013

KU EECS 780 – Comm Nets – Preliminaries

NET-PR-21
Performance Metrics

Style and Usage: Attributes

• Attributes
  – Roman font even if single character
    • $d_q$ delay due to queuing: note $q$ is \textit{not} an index
    • $d^q$ delay due to queuing: note $q$ is \textit{not} an exponent
    • explicitly declare in LaTeX math mode or MathType
Performance Metrics
Style and Usage: Num., Delimiters, Operators

• Numerals, delimiters, operators, numerals in Roman
  – *never* italic
  – e.g. \( z = 4 (x + y) \) not \( z = 4 (x + y) \)
  – e.g. \( \sum_i d_i \) not \( \Sigma_i d_i \)
  – LaTeX math mode and MathType do it properly
  – be selective when selecting inline PowerPoint or Word style

• Do not use hyphen for subtraction
  – en-dash approximation but does not perfectly vertically align
  – e.g.: \( a = b - c \) not \( a = b - c \)
Performance Metrics

Style and Usage: Functions

- Functions: similar rules to variables
  - italic font if single character
    - $f(x)$ function $f$ applied to $x$
  - roman font if multiple characters
    - $\text{max}(x)$ maximum value of $x$
# Performance Metrics

## Unit Multipliers

<table>
<thead>
<tr>
<th>SI decimal</th>
<th>EIC binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-1}$</td>
<td>d</td>
</tr>
<tr>
<td>$10^{-2}$</td>
<td>c</td>
</tr>
<tr>
<td>$10^{-3}$</td>
<td>m</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td>µ</td>
</tr>
<tr>
<td>$10^{-9}$</td>
<td>n</td>
</tr>
<tr>
<td>$10^{-12}$</td>
<td>p</td>
</tr>
<tr>
<td>$10^{-15}$</td>
<td>f</td>
</tr>
<tr>
<td>$10^{-18}$</td>
<td>a</td>
</tr>
<tr>
<td>$10^{-21}$</td>
<td>z</td>
</tr>
<tr>
<td>$10^{-24}$</td>
<td>y</td>
</tr>
</tbody>
</table>

$m, \mu, n, k, M, G, T, P$ are essential for networking and must be memorised.

In networking $K = 1024 = 2^{10}$. Typically used for disk storage.
Performance Metrics

Style and Usage: Units and Prefixes

• Units and prefixes
  – Roman font
    • μs microseconds
  – always insert space between number and unit
    • e.g. 4 m/s not 4m/s
  – use solidus or exponent for division rather than “p” (“per”)
    • e.g. 2.4 Gb/s or 2.4 Gbs⁻¹ not 2.4 Gbps
  – optionally use square brackets for unit dimensions
    • e.g. 3.25 [m/s]
  – data unit conventions
    • b for bit, B for Byte
    • k prefix for 10³, K prefix for 1024
Performance Metrics

Style and Usage: Plain Text\textsubscript{1}

- Plain text style
  - frequently necessary to put formulæ in plain text, e.g. email
  - no standard, but generally combination of C and LaTeX
Performance Metrics

Style and Usage: Plain Text

- **Operators**
  - * for explicit multiplication, e.g. \( a * b = a \times b \)
  - ^ for exponentiation, e.g. \( e^x = e^x \)

- **Variables**
  - _ for subscripts, e.g. \( x_i = x_i \)
  - ^ for superscripts, e.g. \( x^i = x^i \)

- **Scientific notation**
  - * and ^, e.g. \( 3 * 10^{-5} = 3.5 \times 10^{-5} \)

- **Greek letters**
  - spell out, e.g. \( 3 \times \pi = 3\pi \)
  - u for micro (\( \mu \)) prefix if unambiguous, e.g. \( 50 \ \mu s = 50 \ \mu s \)
Performance Metrics

Delay and Bandwidth

• Delay or latency
  \[ D \text{ end-to-end} \]
  \[ d \text{ per hop} \]
  – jitter is delay variance

• Bandwidth or data rate
  \[ B \text{ aggregate} \]
  \[ b \text{ per flow} \]
  – not channel capacity (bandwidth in EE sense)

• Bandwidth-×-delay product
  – number of bits in flight on a high-speed path
  \[ b \text{ [bits/sec]} \times d \text{ [sec]} = \text{ [bits]} \]
Performance Metrics
Network Path Latency

\[ D = \sum d_i \]

- Delays sum along a path
  - benefit of optimising link directly proportional to contribution
## Performance Metrics

### Path Length and Network Type

<table>
<thead>
<tr>
<th>Type</th>
<th>- area network</th>
<th>- earth orbiting</th>
<th>Channel</th>
<th>Distance</th>
<th>RTT</th>
<th>BW-×-delay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 Mb/s</td>
</tr>
<tr>
<td>PAN</td>
<td>personal</td>
<td>RF</td>
<td>10 m</td>
<td>100 ns</td>
<td>.05 b</td>
<td>50 b</td>
</tr>
<tr>
<td>SAN</td>
<td>system</td>
<td>Cu/Fiber</td>
<td>100 m</td>
<td>1 µs</td>
<td>½ b</td>
<td>500 b</td>
</tr>
<tr>
<td>LAN</td>
<td>local</td>
<td>Cu/Fiber/RF</td>
<td>1 km</td>
<td>10 µs</td>
<td>5 b</td>
<td>5 kb</td>
</tr>
<tr>
<td>MAN</td>
<td>metropolitan</td>
<td>Fiber/RF</td>
<td>100 km</td>
<td>1 ms</td>
<td>500 b</td>
<td>500 kb</td>
</tr>
<tr>
<td>WAN</td>
<td>transcon. wide</td>
<td>Fiber</td>
<td>5 000 km</td>
<td>50 ms</td>
<td>25 kb</td>
<td>25 Mb</td>
</tr>
<tr>
<td>WAN</td>
<td>global wide</td>
<td>Fiber</td>
<td>20 000 km</td>
<td>200 ms</td>
<td>100 kb</td>
<td>100 Mb</td>
</tr>
<tr>
<td>LEO*</td>
<td>low earth</td>
<td>RF</td>
<td>2×1 000 km</td>
<td>25 ms</td>
<td>12 kb</td>
<td>12 Mb</td>
</tr>
<tr>
<td>GEO</td>
<td>geosynchronous</td>
<td>RF/laser</td>
<td>2×36 000 km</td>
<td>480 ms</td>
<td>240 kb</td>
<td>240 Mb</td>
</tr>
<tr>
<td>DSN</td>
<td>earth–moon</td>
<td>RF/laser</td>
<td>400 000 km</td>
<td>2.5 s</td>
<td>1.2 Mb</td>
<td>1.2 Gb</td>
</tr>
<tr>
<td>IPN ♂</td>
<td>interplanetary</td>
<td>RF/laser</td>
<td>55–400×10⁶ km</td>
<td>6–45 min</td>
<td>1.3 Gb</td>
<td>1.3 Tb</td>
</tr>
<tr>
<td>IPN ♀</td>
<td>interplanetary</td>
<td>RF/laser</td>
<td>10⁹ km</td>
<td>2 hr</td>
<td>3.6 Gb</td>
<td>3.6 Tb</td>
</tr>
<tr>
<td>IPN ♂</td>
<td>interplanetary</td>
<td>RF/laser</td>
<td>10¹⁰ km</td>
<td>20 hr</td>
<td>36 Gb</td>
<td>36 Tb</td>
</tr>
</tbody>
</table>

*3000 km footprint
Performance Metrics

Network Path Bandwidth

- Maximum bandwidth limited by bottleneck link
  - there is no point in optimising a link that is not a bottleneck

\[ R = \min(r_i) \]
Performance Metrics

Error and Loss Characteristics

• Error and loss characteristics
  – Pr[bit-error]
  – burst error (multibit)
  – channel fades (e.g. rain)
  – episodic link connectivity
  – link and node failures

*We’ll discuss why these happen later*
Comm. Network Preliminaries

PR.3 Theoretical Foundations

PR.1 Network architecture and topology
PR.2 Performance metrics and style
PR.3 Theoretical foundations and network science
  PR.3.1 Probability, queueing theory, and performance
  PR.3.2 Graph theory and network topology
  PR.3.3 Game theory and tussle
  PR.3.4 Control Theory
  PR.3.5 Fault tolerance and dependability
  PR.3.6 Complex systems
PR.4 Scope of communication
PR.5 Protocols and layering
PR.6 Communication flow diagrams
Network Science

Introduction

• Network science
  – “organized knowledge of networks based on their study using the scientific method” [NRC 2005]
  – theory of the interactions of entities organised as nets
  – network examples [Newman 2010]
    • technological networks (e.g. PSTN, Internet, grid, transport)
    • social networks (e.g. genealogy, friendship)
    • information networks (e.g. citation nets, Web)
    • biological networks (e.g. biochemical, ecological)

• We are primarily interested with
  – communication networks (including the Web and social)
Network Science
Science of Communication Networks

- Fundamental disciplines (e.g.)
  - graph theory and flows
  - game theory and tussle
  - control theory and automata
  - fault tolerance and dependability
  - queuing theory
Graph Theory
Graph Components

• Model network as a graph
• Vertex | node
• Edge | link
Graph Theory
Graph Components

- Model network as a graph
- Vertex | node: \( v \)
  - switch, Internet router, end system
  - represented as \( \circ \) \( \bullet \)
- Edge | link
Graph Theory
Graph Components

• Model network as a graph

• Vertex | node: \( v \)
  – switch, Internet router, end system
  – represented as \( \bullet \) \( \bullet \)

• Edge | link: \( e_i = \{v_j, v_k\} \)
  – \( e_i \) is joins and is incident to \( v_j \) and \( v_k \)
  – \( v_j \leftrightarrow v_k \) denotes neighbours such that \( v_j \) is adjacent to \( v_k \)
  – wired physical link, wireless link association, P2P relationship
  – generally undirected | bidirectional link
  – may be directed | unidirectional link
  \( \leftrightarrow \) bidirectional link
Graph Theory
Graph Definition

- **Graph** $G = (V, E)$ is a triple $E \subseteq V \times V$
  - set of vertices $V(G) = \{v_0, v_1, \ldots\}$ correspond to links
  - set of edges $E(G) = \{e_0, e_1, \ldots\}$ correspond to nodes
  - mapping of $\forall e_i \rightarrow$ endpoint pairs $\{v_j, v_k\}$ gives net topology
    - not the mathematical definition of topology but in common use

- **Example**
  Königsberg graph with multiedges + (self-)loop
  - $V = \{v_0, v_1, v_2, v_3\}$
  - $E = \{e_0, e_1, e_2, e_3, e_4, e_5, e_6, e_7\}$
  - $e_0, e_1 = \{v_0, v_1\}$, $e_2, e_3 = \{v_0, v_2\}$, $e_4 = \{v_0, v_3\}$, $e_5 = \{v_1, v_3\}$, $e_6 = \{v_2, v_3\}$, $e_7 = \{v_3, v_3\}$
Graph Theory

Graph Properties

- **Structural**
  - adjacency matrix
  - degree distribution

- **Connectivity**
  - how well connected, e.g. clustering coefficient

- **Centrality**
  - importance of a node or link, e.g. betweenness
Comm. Network Preliminaries

PR.4 Scope of Communication

PR.1 Network architecture and topology
PR.2 Performance metrics and style
PR.3 Theoretical foundations and network science
PR.4 Scope of communication
PR.5 Protocols and layering
PR.5 Communication flow diagrams
Network Components
ES vs. IS

- End system (ES)
  
  *what is it?*
Network Components
ES vs. IS

- End system (ES)
  - computing system that runs applications (e.g. server)
  - may be used by a human user (e.g. client)
Network Components

ES vs. IS

- End system (ES)
  - computing system that runs applications (e.g. server)
  - may be used by a human user (e.g. client)

- Intermediate system (IS)
  
  what is it?
Network Components

ES vs. IS

- **End system (ES)**
  - computing system that runs applications (e.g. server)
  - may be used by a human user (e.g. client)

- **Intermediate system (IS)**
  - network component used to interconnected distributed ESs
  - examples: switches, routers, hubs
Network Components
ES vs. IS

- **End system (ES)**
  - computing system that runs applications (e.g. server)
  - may be used by a human user (e.g. client)

- **Intermediate system (IS)**
  - network component used to interconnected distributed ESs
  - examples: switches, routers, hubs

- **Some systems may be both ES and IS**

  examples?
Network Components

ES vs. IS

• End system (ES)
  – computing system that runs applications (e.g. server)
  – may be used by a human user (e.g. client)

• Intermediate system (IS)
  – network component used to interconnected distributed ESs
  – examples: switches, routers, hubs

• Some systems may be both ES and IS
  – ES may also transit traffic in multihop MANET
  – IS may also run applications in active programmable net
Scope of Communication

E2E vs. HBH Definitions

- Hop-by-hop (HBH)
  *what is it?*
Scope of Communication
E2E vs. HBH Definitions

• Hop-by-hop (HBH)
  – communication or link between directly attached nodes
  – typically IS – IS or ES – IS
  – may rarely be ES – ES (no network)
Scope of Communication
E2E vs. HBH Definitions

• Hop-by-hop (HBH)
  – communication or link between directly attached nodes
  – typically IS – IS or ES – IS
  – may rarely by ES – ES (no network)

• Edge-to-edge
  – communication or link between edges of a subnetwork
Scope of Communication
E2E vs. HBH Definitions

• Hop-by-hop (HBH)
  – communication or link between directly attached nodes
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  – may rarely by ES – ES (no network)

• Edge-to-edge
  – communication or link between edges of a subnetwork

• End-to-end (E2E)
  *what is it?*
Scope of Communication

E2E vs. HBH Definitions

• Hop-by-hop (HBH)
  – communication or link between directly attached nodes
  – typically IS – IS or ES – IS
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• Edge-to-edge
  – communication or link between edges of a subnetwork

• End-to-end (E2E)
  – communication or path between end systems: ES – ES
  – typically involves multiple HBH segments
Scope of Communication
E2E vs. HBH Definitions

- **Hop-by-hop (HBH)**
  - communication or link between directly attached nodes
  - typically IS – IS or ES – IS
  - may rarely be ES – ES (no network)

- **Edge-to-edge**
  - communication or link between edges of a subnetwork

- **End-to-end (E2E)**
  - communication or path between end systems: ES – ES
  - typically involves multiple HBH segments

- **Application-to-application (A2A)**
  - communication between applications (similar to E2E)
Scope of Communication

Examples

- **End system**
- **Intermediate system**
  - edge or access switch
  - core or backbone switch

Diagram:
- Edge2Edge
- HBH
- multihomed
- E2E
Comm. Network Preliminaries

PR.5 Protocols and Layering

PR.1 Network architecture and topology
PR.2 Performance metrics and style
PR.3 Theoretical foundations and network science
PR.4 Scope of communication
PR.5 Protocols and layering
PR.6 Communication flow diagrams
Protocols and Services

Definition

What is a protocol?
Protocols and Services

Definition

- Protocol: rules for communication between entities
Protocols and Services

Definition

- Protocol: rules for communication between entities
  - message format and sequence
    - information transfer (data plane)
    - signalling of control information (control plane)
    - monitoring and management (management plane)
  - definition of actions (state machine)
Protocols and Services
Definition

• Protocol: rules for communication between entities
  – message format and sequence
    • information transfer (data plane)
    • signalling of control information (control plane)
    • monitoring and management (management plane)
  – definition of actions (state machine)

• Service
  – functional primitives provided by layer

• Interface
  – service interface to layers above and below

Proper design separates protocols from services
Protocol Layering

Layering provides service abstraction
- isolate: protocols, components, technology
  - any transport layer over IP
  - IP over any link layer
  - commodity link layer chip evolution, e.g.
    - 10BASE-T → 100BASE-T → 1000BASE-X
    → 802.11b → 802.11g
Protocol Layering

Layering is useful abstraction
- thinking about networking system architecture
- organising protocols based on role
  2. link
  3. switch
  4. end system
Protocol Layering
OSI Model

• ISO 7498: open systems interconnection
• Attempt to formalise needed:
  – protocol layers and their services
  – interfaces between layers
Protocol Layering

OSI Model

- ISO 7498: open systems interconnection
  - protocol: rules for communication between entities

<table>
<thead>
<tr>
<th>Layer</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>application</td>
</tr>
<tr>
<td>6</td>
<td>presentation</td>
</tr>
<tr>
<td>5</td>
<td>session</td>
</tr>
<tr>
<td>4</td>
<td>transport</td>
</tr>
<tr>
<td>3</td>
<td>network</td>
</tr>
<tr>
<td>2</td>
<td>link</td>
</tr>
<tr>
<td>1</td>
<td>physical</td>
</tr>
<tr>
<td></td>
<td>MAC</td>
</tr>
<tr>
<td></td>
<td>physical</td>
</tr>
</tbody>
</table>

- application–application
- data formatting
- dialogue management
- end-to-end
- forwarding/routing
- hop-by-hop
- medium access control
- transmission
Protocol Layering

OSI Model

- Real implementations
  - ISO model missed medium access control
  - presentation layer
    - not sensible to standardise
    - not necessarily right layer of stack
  - session layer
    - generally not needed for data
    - useful for control (e.g. SIP, H.323)
Protocol Layering
OSI Model

Send ES

7 application
6 presentation
5 session
4 transport
3 network
2 link
1 physical

Receive ES

ADU
PH APDU
SH PPDU
TH SPDU TT
NH TPDU
LH NPDU LT
coded LPDU

NPDU
LT
PH
ADU
Protocol Layering
Performance Issues

- Layered implementations may perform very poorly
- Inter-layer transfers involve non-trivial overhead
  - encapsulation/decapsulation of PDUs
  - inter-layer control transfer
    - context switching and data copying
    - effects of overlapping intra-layer control mechanisms
- Protocol layers should be designed with this in mind
  - antithesis of layering to isolate protocols and technology
Protocol Layering

Planes

- Data plane

role of data plane?
Protocol Layering

Planes

- **Data plane**
  - information transfer
    - **8**: social layer  social information exchange
    - **7**: application layer  application-to-application exchange
    - **4**: transport layer  end-to-end flow
    - **3**: network layer  forwarded through switch/router
    - **2.5**: virtual link layer  hop-by-hop over virtual link (concatenation of physical links)
    - **2**: link layer  hop-by-hop over a link
    - **1**: physical layer  bits as signals in a medium
Protocol Layering

Hybrid Layer/Plane Cube

- Physical (L1)
- Link (L2)
- Network (L3)
- Transport (L4)
- Application (L7)
- Social (L8)
- Virtual Link (L2.5)
- Link (L2)
- Network (L3)
- Transport (L4)
- Application (L7)
- Social (L8)

Data Plane
Protocol Layering

Planes

- **Data plane**
  - information transfer

- **Control plane**
  
  *role of control plane?*
Protocol Layering

Planes

- **Data plane**
  - information transfer

- **Control plane**
  - signalling to control information transfer, including:
    - flow or connection establishment/modification/termination
    - error control
    - flow and congestion control
  - control of network components and organisation, e.g.
    - network topology and connectivity
  - some **control plane layers do not correspond to data plane**
    - 5: session layer coördination multiple transport flows
    - 1.5: MAC layer medium access control
Protocol Layering
Hybrid Layer/Plane Cube

L1   L1.5  L7  L4  L3  L5  L2  L2.5  L8
| physical | | | | | | | | data plane
| MAC      | | | | | | | | control plane

0  L1.5  L2  L2.5  L3  L4  L5  L7  L8
  | link   | virtual link | session | application | social
  | MAC    | | | | |
Protocol Layering
Planes

- **Data plane**
  - information transfer

- **Control plane**
  - signalling to control information transfer
  - control of network components and organisation

- **Management plane**
  
  *role of management plane?*
Protocol Layering

Planes

• **Data plane**
  – information transfer

• **Control plane**
  – signalling to control information transfer
  – control of network components and organisation

• **Management plane**
  – monitoring and management of network and its elements
  – cuts across all layers and across control/data planes
Protocol Layering
Hybrid Layer/Plane Cube

<table>
<thead>
<tr>
<th>Layer</th>
<th>Plane</th>
<th>Plane</th>
<th>Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>L8</td>
<td>social</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L7</td>
<td>application</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L5</td>
<td>session</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L4</td>
<td>transport</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L3</td>
<td>network</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L2.5</td>
<td>virtual link</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L2</td>
<td>link</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1.5</td>
<td>MAC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>physical</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Protocol Layering

Overlays

- Sometimes reasons to run additional *overlay* layers
  - layer 3 over layer 3
    - e.g. IP over ATM
  - layer 3 over layer 7
    - e.g. P2P addressing and routing for file sharing

- Overlay definition
  - layer *n* over layer *m*, where *n* ≤ *m*
  - overlay is over an *underlay*
Protocol Layering

Internet Hourglass

- Internet “hourglass”
- Common network layer: **IP**
  - common addressing essential for seamless interworking
  - compatible routing & signalling
Protocol Layering

Internet Hourglass

- Internet “hourglass”
- Common network layer: IP
- Any transport layer above
  - in practice: TCP or UDP

TCP  |  UDP  |  RTP  |  ...  

IP
Protocol Layering

Internet Hourglass

- Internet “hourglass”
- Common network layer: IP
- Any transport layer above
- Any link layer below
  - SONET, 802.n, ...

\[
\begin{array}{cccc}
\text{TCP} & \text{UDP} & \text{RTP} & \cdots \\
\end{array}
\]

\[
\begin{array}{cccccccc}
\text{Enet} & \text{SONET} & 802.11 & \text{HFC} & \text{OTN} & 802.16 & \cdots \\
\end{array}
\]
# Internet Protocols

## Important Link and MAC Protocols

<table>
<thead>
<tr>
<th>Common name</th>
<th>Standard</th>
<th>Scope</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethernet</td>
<td>IEEE 802.3</td>
<td>LAN/MAN</td>
<td>wire, fiber</td>
</tr>
<tr>
<td>Token ring</td>
<td>IEEE 802.5</td>
<td>LAN</td>
<td>wire</td>
</tr>
<tr>
<td>WirelessLAN WiFi</td>
<td>IEEE 802.11</td>
<td>LAN</td>
<td>RF, (IR)</td>
</tr>
<tr>
<td>WPAN</td>
<td>IEEE 802.15</td>
<td>PAN</td>
<td>RF</td>
</tr>
<tr>
<td>WirelessMAN WiMAX</td>
<td>IEEE 802.16</td>
<td>MAN</td>
<td>RF</td>
</tr>
<tr>
<td>SONET</td>
<td>ANSI T1.105ITU G.707</td>
<td>MAN/WAN</td>
<td>fiber electronic switch</td>
</tr>
<tr>
<td>OTN</td>
<td>ITU G.709</td>
<td>MAN/WAN</td>
<td>fiber optical switch</td>
</tr>
</tbody>
</table>

IEEE 802 network standards are available from [standards.ieee.org/getieee802/portfolio.html](https://standards.ieee.org/getieee802/portfolio.html)

# Internet Protocols

## Important Network Protocols

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Name</th>
<th>Function</th>
<th>Status</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP</td>
<td>Internet protocol</td>
<td>addressing</td>
<td>standard</td>
<td>RFC 0791 STD 0005</td>
</tr>
<tr>
<td></td>
<td></td>
<td>datagram forwarding</td>
<td></td>
<td>STD 0005</td>
</tr>
<tr>
<td>ICMP</td>
<td>Internet control message protocol</td>
<td>signalling</td>
<td>standard</td>
<td>RFC 0792 STD 0005</td>
</tr>
<tr>
<td>IGMP</td>
<td>Internet group management protocol</td>
<td>multicast signalling</td>
<td>proposed standard</td>
<td>RFC 3376</td>
</tr>
<tr>
<td>BGP</td>
<td>border gateway protocol</td>
<td>interdomain routing</td>
<td>draft standard</td>
<td>RFC 1771</td>
</tr>
<tr>
<td>OSPF</td>
<td>open shortest path routing</td>
<td>intradomain routing</td>
<td>standard</td>
<td>RFC 2328 STD 0054</td>
</tr>
<tr>
<td>ISIS</td>
<td>intermediate system–intermediate system</td>
<td>intradomain routing</td>
<td>proposed standard</td>
<td>ISO10589 (RFC 908)</td>
</tr>
<tr>
<td>DNS</td>
<td>domain name system</td>
<td>domain name to IP address</td>
<td>standard</td>
<td>RFC 1035 STD 0013</td>
</tr>
<tr>
<td></td>
<td></td>
<td>resolution</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

RFCs are available from [www.rfc-editor.org](http://www.rfc-editor.org)
# Internet Protocols

## Important Transport Protocols

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Name</th>
<th>Function</th>
<th>Status</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCP</td>
<td>transmission control protocol</td>
<td>reliable data transfer with congestion control</td>
<td>standard</td>
<td>RFC 0793</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>STD 0007</td>
</tr>
<tr>
<td>UDP</td>
<td>user datagram protocol</td>
<td>socket access to unreliable IP datagrams</td>
<td>standard</td>
<td>RFC 0768</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>STD 0006</td>
</tr>
<tr>
<td>RTP</td>
<td>real-time protocol</td>
<td>streaming media (typically over UDP)</td>
<td>standards</td>
<td>RFC 1889</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>track</td>
<td></td>
</tr>
<tr>
<td>T/TCP</td>
<td>TCP for transactions</td>
<td>remote login</td>
<td>experimental</td>
<td>RFC 1644</td>
</tr>
<tr>
<td>RDP</td>
<td>reliable data protocol</td>
<td>reliable data transfer with no congestion control</td>
<td>experimental</td>
<td>RFC 0908</td>
</tr>
<tr>
<td>SCTP</td>
<td>stream control transmission protocol</td>
<td>signalling proposed for wireless</td>
<td>proposed standard</td>
<td>RFC 2960</td>
</tr>
</tbody>
</table>
## Internet Protocols

### Important “Application Layer” Protocols

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Name</th>
<th>Function/Use</th>
<th>Status</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTTP</td>
<td>hypertext transfer protocol</td>
<td>Web browsing</td>
<td>draft standard</td>
<td>RFC 2616</td>
</tr>
<tr>
<td>FTP</td>
<td>file transfer protocol</td>
<td>file and document transfer</td>
<td>standard</td>
<td>RFC 0959 STD 0009</td>
</tr>
<tr>
<td>Telnet</td>
<td>telnet</td>
<td>remote login</td>
<td>standard</td>
<td>RFC 0854 STD 0008</td>
</tr>
<tr>
<td>SMTP</td>
<td>simple mail transfer protocol</td>
<td>email relay and delivery</td>
<td>standard</td>
<td>RFC 0821 STD 0010</td>
</tr>
<tr>
<td>POP</td>
<td>post office protocol</td>
<td>server mail download</td>
<td>standard</td>
<td>RFC 1939 STD 0053</td>
</tr>
<tr>
<td>IMAP</td>
<td>internet message access protocol</td>
<td>server mail access</td>
<td>proposed standard</td>
<td>RFC 3501</td>
</tr>
<tr>
<td>NFS</td>
<td>network file system</td>
<td>remote access to files</td>
<td>proposed standard</td>
<td>RFC 3530</td>
</tr>
<tr>
<td>RTSP</td>
<td>real-time streaming protocol</td>
<td>control of multimedia streaming</td>
<td>proposed standard</td>
<td>RFC 2326</td>
</tr>
</tbody>
</table>
Comm. Network Preliminaries

PR.6 Communication Flow Diagrams

PR.1 Network architecture and topology
PR.2 Performance metrics and style
PR.3 Theoretical foundations and network science
PR.4 Scope of communication
PR.5 Protocols and layering
PR.6 Communication flow diagrams
Communication Flow Diagrams

Motivation

- Complex network interactions are hard to understand
- Visualisation technique: *communication flow diagram*
Communication Flow Diagrams

Concepts

1  2  3

- Time and space
Communication Flow Diagrams

Concepts: Distance

- Time and space
  - distance represented horizontally

1 \hspace{1cm} \hspace{1cm} 2 \hspace{1cm} 3

\[ d_{12} \hspace{5cm} d_{23} \]
Communication Flow Diagrams

Concepts: Time

- Time and space
  - distance represented horizontally
  - time represented vertically
Communication Flow Diagrams

Concepts: Bit Propagation

- Bit propagation *how represented?*

```
  1   2   3
  \----\----\----
  \    \    \    \\
  |    |    |    |
  |    |    |    |
  |    |    |    |
  |    |    |    |
  |    \----\----\----
  \time\    \    \    \time
  \    \    \    \    \\
  |    |    |    |    |
  |    |    |    |    |
  |    |    |    |    |
  |    |    |    |    |
  \    \    \    \    \time
  \    \    \    \    \\
  |    |    |    |    |
  |    |    |    |    |
  |    |    |    |    |
  |    |    |    |    |
  \    \    \    \    \time
```

$d_{12}$

$d_{23}$
Communication Flow Diagrams

Concepts: Bit Propagation

- Bit propagation
  - distance \( d_{12} \) from node 1 to node 2
  - propagation delay \( t_p \)

How computed?
Communication Flow Diagrams

Concepts: Bit Propagation

- Bit propagation
  - distance $d_{12}$ from node 1 to node 2
  - propagation delay
    
    $t_p [s] = \frac{d_{12} [m]}{kc [m/s]}$
    
    - $k$ constant for particular medium
    - speed of light
      $c \approx 3 \times 10^8$ m/s
Communication Flow Diagrams

Concepts: Bit Propagation

- Bit propagation
  - distance $d_{12}$ from node 1 to node 2
  - propagation delay
    \[ t_p [s] = \frac{d_{12} [m]}{kc [m/s]} \]
    - $k$ constant for particular medium
    - speed of light $c \approx 3 \times 10^8$ m/s
  - slope of bit flow
    - can this vary within a diagram?
Communication Flow Diagrams
Concepts: Bit Propagation

- Bit propagation
  - distance \( d_{12} \) from node 1 to node 2
  - propagation delay
    \[ t_p [s] = \frac{d_{12} [m]}{kc [m/s]} \]
    - \( k \) constant for particular medium
    - speed of light \( c \approx 3 \times 10^8 \) m/s
  - slope is velocity: only affected by \( k \) (\( k \approx 0.6 \) for fiber)
    - \( c \) constant unless you alter the laws of physics
    - *don’t sketch these with widely varying slopes!*
Communication Flow Diagrams
Concepts: Packet Transmission

- Packet transmission
  - sequence of bits transmitted on an interface
  - transmission delay $t_b$

*how computed?*
Communication Flow Diagrams

Concepts: Packet Transmission

- Packet transmission
  - sequence of bits transmitted on an interface
  - transmission delay
    \[ t_b [s] = \frac{b [b]}{r [b/s]} \]
    - \( r \) rate in bits/sec
    - \( b \) number of bits
Communication Flow Diagrams

Concepts: Packet Propagation

- Packet propagation
  - how to represent?
  - what shape?

```
  1  d_{12}  2  d_{23}  3
```

time
Communication Flow Diagrams

Concepts: Packet Propagation

- Packet propagation
  - packet is parallelogram
    - width is distance
    - thickness is packet size
Communication Flow Diagrams

Concepts: Packet Propagation

- Packet propagation
  - Packet is parallelogram
    - Width is distance
    - Thickness is packet size
  
  total delay?
Communication Flow Diagrams

Concepts: Packet Propagation

• Packet propagation
  – packet is parallelogram
    • width is distance
    • thickness is packet size
  – total HBH delay:
    \[ t_b + t_p \]
    • \( t_b \) to transmit object
    • \( t_p \) for last bit to propagate
Communication Flow Diagrams

Concepts: Multihop Packet Propagation

• Multihop propagation
  – processing delay in switches and routers
  – forwarding delay
    • processing time $t_f$
Communication Flow Diagrams

Concepts: Multihop Packet Propagation

- Multihop propagation
  - processing delay in switches and routers
  - forwarding delay
    - processing time $t_f$
  - before retransmission
    - on next hop

\[ \begin{align*}
  d_{12} & \quad d_{23} \\
  t_b & \quad t_f \\
  t_p & \quad t_f \\
\end{align*} \]
Communication Flow Diagrams

Concepts: Signalling Message

- **Packets** are parallelograms
- **Signalling messages** are directed line segments

*Why?*
**Communication Flow Diagrams**

**Concepts: Signalling Message**

- **Packets** are parallelograms
- **Signalling messages** are directed line segments
  - generally short with respect to data (thin parallelogram)
  - makes diagrams easier to draw and read
    - labelled with message name and parameters

![Diagram of Communication Flow Diagrams](image-url)
Communication Flow Diagrams

Summary

• Complex network interactions are hard to understand
• Visualisation technique: *communication flow diagram*
  – distance is represented horizontally
  – time is represented vertically
  – *signalling messages* are arcs with labels
  – *packets* are parallelograms
  – keep slope constant
• It is *essential* that you are *very* confident with these!
  – you will need to *properly* draw these on the exams
Communication Flow Diagrams
Example: Connection Establishment

- Signalling message exchange
Communication Flow Diagrams

Example: Connection Establishment

- Signalling message exchange
  - connection SETUP
Communication Flow Diagrams
Example: Connection Establishment

- Signalling message exchange
  - connection SETUP
Communication Flow Diagrams
Example: Connection Establishment

• Signalling message exchange
  – connection SETUP
Communication Flow Diagrams
Example: Connection Establishment

• Signalling message exchange
  – connection SETUP
  – CONNECTion established
Communication Flow Diagrams
Example: Connection Establishment

- Signalling message exchange
  - connection **SETUP**
  - **CONNECT**ion established
Communication Flow Diagrams

Example: Connection Establishment

• Signalling message exchange
  – connection **SETUP**
  – **CONNECT**ion established
Communication Flow Diagrams
Example: Connection Establishment

- Signalling message exchange
  - connection **SETUP**
  - **CONNECT**ion established

- Data transfer
Some material in these foils is based on the textbook
- Sterbenz and Touch,
  *High-Speed Networking, A Systematic Approach to High-Bandwidth Low Latency Communication*