Communication Networks
The University of Kansas EECS 780
Link Layer and LANs

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Link Layer and LANs

Outline

LL.1  Link layer functions and services
LL.2  Framing and delineation
LL.3  LAN types and topologies
LL.4  Multiplexing and switching
LL.5  Per-hop error and flow control
LL.6  Link layer components
LL.8  IP address resolution
LL.7  Residential broadband
**Link Layer and LANs**

**LL.1  Link Layer Functions and Services**

- LL.1  Link layer functions and services
- LL.2  Framing and delineation
- LL.3  LAN types and topologies
- LL.4  Multiplexing and switching
- LL.5  Per-hop error and flow control
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- LL.7  IP address resolution
- LL.8  Residential broadband

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**Link Layer**

**Hybrid Layer/Plane Cube**

Layer 2: hop-by-hop data transfer in data and control planes
Link Layer

Link Definition

- **Link** is the interconnection between **nodes**
  - intermediate systems (switches or routers)
  - end systems (or hosts)

Link Layer

Link Protocol

- **Link protocol**
  - is responsible for per hop transfer of data frame
  - assume dedicated links for now: no MAC **lecture MW**
Link Layer
Service and Interfaces

• Link layer is HBH analog of E2E transport layer
  – transport layer (L4) transfers packets E2E

• Link layer (L2) service to network layer (L3)
  – transfer frame HBH (hop-by-hop)
    • sender: encapsulate packet into frame and transmit
    • receiver: receive frame and decapsulate into packet
Link Layer
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- Link layer is HBH analog of E2E transport layer
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  - transfer frame HBH (hop-by-hop)
    - sender: encapsulate packet into frame and transmit
    - receiver: receive frame and decapsulate into packet
  - error checking / optional correction or retransmission
    - recall end-to-end arguments:
      - E2E reliability with HBH error control only for performance
  - flow control possible but not generally needed at link layer
    - parameter negotiation typical (e.g. data rate)
Link Layer

Service and Interfaces

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- Link layer multiplexing and switching

Link Layer Service and Interfaces

- Link layer *frame* encapsulates network layer *packet*
  - packet (NPDU – network layer protocol data unit)
  - frame (LPDU link layer protocol data unit)
    - frame = header + packet + (trailer)
Link Layer Functional Placement

- Link layer functionality per line interface
  - end system: network interface (NIC)
  - switch/router: line card

Link Layer and LANs

LL.1 Link layer functions and services
LL.2 Framing and delineation
LL.3 LAN types and topologies
LL.4 Multiplexing and switching
LL.5 Per-hop error and flow control
LL.6 Link layer components
LL.7 IP address resolution
LL.8 Residential broadband
Link Framing
Structure and Fields

• Link protocols need to delimit link layer frame

  *why?*

  – physical layer is coded bit stream
  – *receiver* needs to delimit frames
Link Framing
Structure and Fields

- Delimits link layer frame
  - physical layer is coded bit stream
  - receiver needs to delimit frames
- Header: where the frame goes
  - beginning of frame
  - multiplexing information for multiplexed links
  - addressing information for multiple access links
- Trailer: what to do with the frame once arrived
  - integrity check (typically strong CRC)
Key problem: how to detect start of frame in the presence of errors.
Link Framing
Receiver Delineation Techniques

- Synchronous clocks
- Counting
- Flags with
  - byte stuffing
  - bit stuffing
- Preamble pattern
- Special physical layer code

Link Framing
Receiver Delineation: Synchronous Clocks

- Synchronous links
- Sender and receiver maintain tight synchronisation
  - receive clock carefully matched to sender
  - clock recovery
- Example
  - SONET/SDH
Link Framing
Receiver Delineation: Counting

- Counting (bit, byte, or word)
  - count bytes to determine frame length
  - use length field in header for variable length frames

```
4 3 2 1 6 5 4 3 2 1 3 2 1 8 7 6 5 4 3 2 1
5 | | | | 7 | | | | 4 | | | | 9 | | | | |
```

Effect of errors?
Link Framing  
Receiver Delineation: Counting

- Counting (bit, byte, or word)
  - count bytes to determine frame length
  - use length field in header for variable length frames

```
4 3 2 1 6 5 4 3 2 1 3 2 1 8 7 6 5 4 3 2 1
5 7 4 9
```

- Effect of errors
  - difficult to maintain frame synchronisation
  - serious problem if length field is corrupted

```
4 3 2 1 2 1 8 7 6 5 4 3 2 1 2 1 6 5 4 3
5 3 9 4 9 3 7
```

- checksums don't help
  - why?
Link Framing
Receiver Delineation: Flags

- Flags
  - special sequence of bits at beginning and end of frame

  what if data stream contains flag bitstring?
Link Framing
Receiver Delineation: Flags with Byte Stuffing

- **Flags**
  - special byte at beginning and end of frame
  - data transparency: flag byte must be allowed in data

- **Byte stuffing**
  - escape byte stuffed when flag (or escape) is in data

Example: PPP 01111110 flag 01111101 escape
Link Framing

**Receiver Delineation: Flags with Byte Stuffing**

- **Flags**
  - special byte at beginning and end of frame
  - data transparency: flag byte must be allowed in data
- **Byte stuffing**
  - escape byte stuffed when flag (or escape) is in data
- **Example:** PPP **01111110** flag **01111101** escape
  - data: B B B F B B E B B F F B B
  - sender insertion: F B B F E B B E B B F F E E B B F F

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ITTC
Link Framing

**Receiver Delineation: Flags with Byte Stuffing**

- **Flags**
  - special byte at beginning and end of frame
  - data transparency: flag byte must be allowed in data
- **Byte stuffing**
  - escape byte stuffed when flag (or escape) is in data
- **Example: PPP**
  - data: `0111110` flag `01111101` escape
  - sender insertion: `B B B F B B E B E E B B F F B B`
  - receiver strips: `B B B F B B E B B F F B B`
  - escaped escape: remove escape `E E` → `E`
  - escaped flag: remove flag `F E` → `F`
  - flag: frame boundary `F`

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Link Framing

**Receiver Delineation: Flags with Bit Stuffing**

- **Flags**
  - special byte at beginning and end of frame
  - data transparency: flag byte must be allowed in data

---
### Link Framing

**Receiver Delineation: Flags with Bit Stuffing**

- **Flags**
  - Special sequence of bits: $n$ 1s delineated by 0 bits
  - Stuffing can be applied at bit level as well as byte level

- **Bit stuffing**
  - 0-bit is stuffed in data stream after $n-1$ bit sequence occurs

**Example:** 01111110 flag (run of six 1 bits)
Link Framing

Receiver Delineation: Flags with Bit Stuffing

- Flags
  - special sequence of bits: $n$ 1s delineated by $0$ bits
  - stuffing can be applied at bit level as well as byte level
- Bit stuffing
  - $0$-bit is stuffed in data stream after $n-1$ bit sequence occurs
- Example: $01111110$ flag (run of six $1$ bits)
  - data $00111001111111111111101011$

- Example (continued)
  - data $00111001111111111111101011$ groups of $5$
Link Framing

Receiver Delineation: Flags with Bit Stuffing

- Flags
  - special sequence of bits: \( n \) 1s delineated by 0 bits
  - stuffing can be applied at bit level as well as byte level

- Bit stuffing
  - 0-bit is stuffed in data stream after \( n-1 \) bit sequence occurs

- Example: \( 01111110 \) flag (run of six 1 bits)
  - data: \( 00111001111111111111101011 \)
  - insertion: \( 01111110001110011111111110110111110 \)
  - escaped flag \( n-1 \) 1-bits: remove 0-flag \( 01111 \rightarrow 1111 \)
  - flag \( n \) 1-bits: frame boundary \( 01111110 \)
Link Framing

Receiver Delineation: Flags with Stuffing

- **Flags**
  - special sequence of bits
- **Stuffing**
  - add escape (byte or 0-bit) for data transparency

*Problem?*
Link Framing

**Receiver Delineation: Flags with Stuffing**

- **Flags**
  - special sequence of bits
- **Stuffing**
  - add escape (byte or 0-bit) for data transparency
- **Data stream transformation**
  - bits or bytes *inserted*
  - data rate *non-deterministically* altered
  - sufficient link-capacity headroom must be provided

---

Link Framing

**Preamble Pattern**

- *Preamble* pattern
  - special pattern in header (like a flag)
  
  *How to handle data transparency?*
**Link Framing**

**Preamble Pattern**

- *Preamble* pattern
  - special pattern in header (like a flag)

*How to handle data transparency? without flags*
### Link Framing
#### Preamble Pattern

- **Preamble** pattern
  - special pattern in header (like a flag)
- Significantly longer than flag
  - lowers probability of bit error impacting
- **Length field in header**
  - allows preamble in payload
- **Error check in trailer**
  - protects against errors
  - e.g. FCS (frame check sequence)

<table>
<thead>
<tr>
<th>preamble</th>
<th>header</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>length</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>payload</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>trailer</td>
</tr>
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<td></td>
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</table>
Link Framing

Preamble Pattern

- **Preamble** pattern
  - special pattern in header (like a flag)
- Significantly longer than flag
  - lowers probability of bit error impacting
- **Length field in header**
  - allows preamble bits in payload
- Error check in trailer
  - protects against errors
  - e.g. FCS (frame check sequence)
- Example: Ethernet 10101010...

Link Framing

Special Physical Layer Code

- Physical layer *codes* bits on within channel *Lecture PL*
- Special physical code may be reserved for framing
  *how to handle data transparency?*
Link Framing

Special Physical Layer Code

- Physical layer *codes* bits on within channel Lecture PL
- Special physical code may be reserved for framing
  - choose code symbol that doesn't represent valid data
Link Types and Topologies

Point-to-Point vs. Shared Medium

- Point-to-point links
  - one transmitter per medium
    - dedicated
  - multiplexed (layer 2) *more later*
Link Types and Topologies
Point-to-Point vs. Shared Medium

- Point-to-point links
  - one transmitter per medium
  - dedicated
  - multiplexed (layer 2) more later

- Shared medium (multiple access)
  - multiple transmitters per medium
  - results in contention for medium problem?
Link Types and Topologies

Point-to-Point vs. Shared Medium

- **Point-to-point links**
  - one transmitter per medium
    - dedicated
    - multiplexed (layer 2) *more later*

- **Shared medium (multiple access)**
  - multiple transmitters per medium
  - results in contention for medium
    - medium access control (MAC) needed
      - lecture MW

- examples
  - wireless networks
  - original Ethernet
Link Layer and LANs

LL.3.1: LAN Topologies

- LL.1 Link layer functions and services
- LL.2 Framing and delineation
- LL.3 LAN types and topologies
  - LL.3.1 LAN topologies
  - LL.3.2 Point-to-point protocol
  - LL.3.3 802 and Ethernet
  - LL.3.4 Ring LANs
- LL.4 Multiplexing and switching
- LL.5 Per-hop error and flow control
- LL.6 Link layer components
- LL.7 IP address resolution
- LL.8 Residential broadband

Link Topologies

Point-to-Point Links

- Point-to-point links between switches
  - space division mesh

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NET-LL-60
Point-to-Point Links

- Point-to-point links between switches
  - space division mesh

Network scalability?
Link Topologies

Point-to-Point Links

- Point-to-point links between switches
  - *space division mesh*
- Scalable:
  - add links and expand switches
  - add switches

Link Technologies

Point-to-Point Dedicated Links

- Point-to-point *dedicated* links
  - sequence of framed packets along a link
- **Point-to-point dedicated** links
  - sequence of framed packets along a link

- **No layer 2** multiplexing
  - higher layers *are* multiplexed onto a single link
  - packets belonging to different E2E flows
Link Topologies

Shared Medium Bus

- Bus topology
  - topology constrained by medium
    - longest path
    - limited to LAN lengths due to delay
Link Topologies

Shared Medium Bus

- Bus topology
  - topology constrained by medium
  - longest path
  - limited to LAN lengths due to delay

*Network scalability?*

- Limited scalability
  - all hosts *share capacity of bus*
Link Topologies

Shared Medium Bus

- **Bus topology**
  - topology constrained by medium
  - longest path
  - limited to LAN lengths due to delay

- **Limited scalability**
  - all hosts share capacity of bus
  - *contention* for shared medium

- **Collisions in shared medium**
  - need MAC *lecture MW*
Link Topologies

**Shared Medium Bus**

- Bus topology
  - topology constrained by medium
  - longest path
  - limited to LAN lengths due to delay
- Limited scalability
  - all hosts share capacity of bus
  - contention for shared medium
    - collisions in shared medium
    - need MAC *lecture MW*
- Example
  - original DIX Ethernet

**Shared Medium LAN/MAN: Ring**

- Ring topology
  - *advantages and problems?*
Link Topologies

Shared Medium LAN/MAN: Ring

- Ring topology
  - topology constraints
  - interstation distance an issue
    - host is frequently called a *station*

Network scalability?
Link Topologies

Shared Medium LAN/MAN: Ring

- Ring topology
  - topology constraints
  - interstation distance an issue
- Limited scalability
  - all stations *share capacity of ring*

- contention for shared medium
Link Topologies
Shared Medium LAN/MAN: Ring

- Ring topology
  - topology constraints
  - interstation distance an issue
- Limited scalability
  - all stations share capacity of ring
  - contention for shared medium
  - possible to prevent collisions
  - need MAC lecture MW

- Resilience
  how?
Link Topologies

Shared Medium LAN/MAN: Ring

- Ring topology
  - topology constraints
  - interstation distance an issue
- Limited scalability
  - all stations share capacity of ring
  - contention for shared medium
    - possible to prevent collisions
    - need MAC *lecture MW*
- Resilience
  - dual ring can survive cut

Example: token ring
• Ring vs. bus

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<thead>
<tr>
<th>Characteristic</th>
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<th>Ring</th>
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<tbody>
<tr>
<td>Scalability</td>
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<tr>
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### Link Topologies

#### Shared Medium Bus and Ring Comparison

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- Ring vs. bus
### Link Topologies

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<td>contention</td>
</tr>
<tr>
<td>Resilience</td>
<td>poor</td>
<td>single fault</td>
</tr>
<tr>
<td>Topology</td>
<td>linear</td>
<td>ring</td>
</tr>
</tbody>
</table>

- **Ring vs. bus**

#### Ring vs. bus LAN debate

- Ethernet vs. token ring: famous networking *holy wars*
- Token ring advocates touted superior capacity
- Ethernet advocates claimed that differences not significant
Link Layer and LANs

LL.3.2: Point-to-Point Protocol

LL.1  Link layer functions and services
LL.2  Framing and delineation
LL.3  LAN types and topologies
   LL.3.1  LAN topologies
   LL.3.2  Point-to-point protocol
   LL.3.3  802 and Ethernet
   LL.3.4  Ring LANs
LL.4  Multiplexing and switching
LL.5  Per-hop error and flow control
LL.6  Link layer components
LL.7  IP address resolution
LL.8  Residential broadband

Point-to-Point Links

PPP Overview

- PPP: point-to-point protocol [RFC 1557]
  - link protocol for modem access
- Widely used for dialup Internet access
  - far more common than SLIP (serial line IP) [RFC 1055]
- Diminishing importance with broadband alternatives
  - HFC (CATV)
  - DSL (PSTN)
  - 802.11  \textit{lecture MW}
  - 802.16 and WiMAX  \textit{lecture MW}
Point-to-Point Links
PPP Design Requirements

• Requirements
  – packet framing: L3 packet encapsulation
  – simultaneously carry any network layer
    • not just IP
  – ability to demultiplex upwards to multiple L3 protocols
  – bit transparency: any bit pattern in the packet
  – error detection
  – connection liveness
    • detect
    • signal failure to L3
  – network layer address negotiation for end systems

Point-to-Point Links
PPP Design Decisions

• Non-requirements
  – no error correction/recovery
  – no flow control
  – no requirements on delivery order
  – no need to support multipoint links

Why?
Point-to-Point Links
PPP Design Decisions

- Non-requirements
  - no error correction/recovery
  - no flow control
  - no requirements on delivery order
  - no need to support multipoint links
- These functions performed by higher layers
  - typically transport layer
  - recall end-to-end arguments!
  - PPP designed for relatively reliable wired links

Point-to-Point Links
PPP Data Frame

- Header
  - flag: 01111110 delimiter for framing
  - address, control: not used
  - protocol: upper layer protocol to deliver frame
    - PPP-LCP, IP, IPCP, etc.
- Payload
  - L3 packet with byte stuffing
- Trailer
  - check: cyclic redundancy check for error detection
  - flag: 01111110 delimiter for framing
Point-to-Point Links

PPP Data Control Protocol

- PPP link establishment
  - configure PPP link: max. frame length, authentication
  - learn/configure network layer
- IP over PPP
  - carry IP Control Protocol (IPCP) messages
    - configure/learn IP address
    - protocol field: 8021

Link Layer and LANs

LL.3.3: 802 and Ethernet

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  LL.3.1 LAN topologies
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IEEE 802 LAN/MAN standards [IEEE 802.1]  
www.ieee802.org

Definition of LAN/MAN protocols for L1–L2
- does not align perfectly with conventional layers
  - L2 defined by LLC (logical link control) and MAC header

<table>
<thead>
<tr>
<th>802.2</th>
<th>802.n</th>
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<tbody>
<tr>
<td>LLC sublayer</td>
<td>MAC sublayer</td>
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<tr>
<td>logical link control</td>
<td>medium access control</td>
</tr>
<tr>
<td></td>
<td>MI sublayer</td>
</tr>
<tr>
<td></td>
<td>media independent</td>
</tr>
<tr>
<td></td>
<td>PMD sublayer</td>
</tr>
<tr>
<td></td>
<td>physical media dependent</td>
</tr>
</tbody>
</table>

PMD_1  PMD_2  ⋯  PMD_k
## Internet Protocols

### Important IEEE 802 Protocols

<table>
<thead>
<tr>
<th>Common name</th>
<th>Standard</th>
<th>Scope</th>
<th>Technology</th>
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<tbody>
<tr>
<td>architecture</td>
<td>IEEE 802.1</td>
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<td>media independent</td>
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<tr>
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<td>LAN/MAN</td>
<td>media independent</td>
</tr>
<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>WLAN</td>
<td>IEEE 802.11</td>
<td>LAN</td>
<td>RF, (IR)</td>
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<td>WPAN</td>
<td>IEEE 802.15</td>
<td>PAN</td>
<td>RF</td>
</tr>
<tr>
<td>WMAN</td>
<td>IEEE 802.16</td>
<td>MAN</td>
<td>RF</td>
</tr>
</tbody>
</table>

- Many other 802.\textit{n} protocols
  - some important, but obsolete, e.g. 802.5
  - some never important, e.g. 802.6 DQDB
  - some becoming important, e.g. 802.15, 802.16
  - the jury is still out on others, e.g. 802.17, 802.20, 802.22

## Shared Medium Links

### Ethernet

- Early LAN technology (1973)
  - DIX: Digital, Intel, Xerox
    - IPv4 over DIX [RFC 0894]
  - IEEE 802.3 using 802.2 LLC
    - IPv4 over 802.3 [RFC 1042]
  - note: DIX and 802.3 similar
    - but not identical
Shared Medium Links

**Ethernet**

- **Early LAN technology (1973)**
  - DIX: Digital, Intel, Xerox
  - IEEE 802.3 using **802.2 LLC**
- **Initially shared coaxial medium**
  - CSMA/CD MAC *lecture MW*
  - performs well in light load < 50%
  - performs poorly in heavy load > 80%
- **Dominant 1980s LAN**
  - token ring only significant competitor
  - evolved 10 to 100 Mb/s to ...
Point-to-Point Links

**Ethernet**

- ...Evolved to 1Gb/s

**Modification**
- support higher data rates
  - slot time increased × 8
    - 512b → 512B
- extension trailer
  - inefficient small frames
- frame bursting
  - increased efficiency

*EECS 881*
Point-to-Point Links

Ethernet

- Evolved to 1Gb/s
- Modification
  - support higher data rates
    - slot time increased $\times 8$
      - 512b $\rightarrow$ 512B
  - extension trailer
    - inefficient small frames
  - frame bursting
    - increased efficiency
  - point-to-point only
    - fiber dominant
    - short reach copper

Point-to-Point Links

Ethernet

- Evolved to 10Gb/s
Point-to-Point Links

Ethernet

- ...Evolved to 10Gb/s
- Modification
  - initially fiber only
    - recent short reach copper
  - full duplex only (separate xmit and recv fibers *required*)
    - no CSMA/CD or related slot and distance constraints
    - no extension trailer needed
    - frame bursting not needed nor supported
Point-to-Point Links

Ethernet

• ...Evolved to 10Gb/s
• Modification
  – initially fiber only
  • recent short reach copper
  – full duplex only (separate xmit and recv fibers *required*)
  • no CSMA/CD or related slot and distance constraints
  • no extension trailer needed
  • frame bursting not needed nor supported
  – compatible with SONET coding and physical transmission
  • pacing for 10Gb/s (LAN) → 9.95 Gb/s (WAN)
  • § in table

Point-to-Point Links

Ethernet

• ...Evolving to 40Gb/s *and* 100Gb/s
  – 802.3ba: June 2010 target for standard
  – based on IEEE 802 HSSG (high speed study group)
• Objectives
  – 40 Gb/s for SONET OC-192 and OTN ODU3 compatibility
  – 100 Gb/s for Ethernet order-of-magnitude trajectory
  – single- and multimode fiber and short-reach copper
    • 10-km multimode distance for MANs
  – full duplex only
  – 802.3 backward compatible framing
Point-to-Point Links

Ethernet

<table>
<thead>
<tr>
<th>Link Type</th>
<th>Rate</th>
<th>Year</th>
<th>Media</th>
<th>Full</th>
<th>Coding</th>
<th>Range</th>
<th>Topo</th>
<th>OH</th>
<th>Payload</th>
</tr>
</thead>
<tbody>
<tr>
<td>PARC</td>
<td>2.94 Mb/s</td>
<td>1972-1976</td>
<td>coax</td>
<td>H</td>
<td>Manchester</td>
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<td>≤4K B</td>
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<tr>
<td>10Base5</td>
<td>10 Mb/s</td>
<td>1980</td>
<td>DIX</td>
<td>M</td>
<td>F</td>
<td>Manchester</td>
<td>500–2500 m</td>
<td>185–925 m</td>
<td>100 m</td>
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<tr>
<td>10Base2</td>
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<td>thin coax</td>
<td>H</td>
<td>M</td>
<td>F</td>
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<td>500–2500 m</td>
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<tr>
<td>10BaseT</td>
<td>10 Mb/s</td>
<td>1980</td>
<td>2 pair UTP-3</td>
<td>H</td>
<td>M</td>
<td>F</td>
<td>Manchester</td>
<td>500–2500 m</td>
<td>185–925 m</td>
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<tr>
<td>100BaseT4</td>
<td>100 Mb/s</td>
<td>1995</td>
<td>4 pair UTP-3</td>
<td>H</td>
<td>M</td>
<td>F</td>
<td>4B/5B</td>
<td>100 m</td>
<td>100 m</td>
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<tr>
<td>100BaseTX</td>
<td>100 Mb/s</td>
<td>1995</td>
<td>2 pair UTP-3</td>
<td>H</td>
<td>M</td>
<td>F</td>
<td>4B/5B</td>
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<td>100 m</td>
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<td>100BaseT2</td>
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<td>1995</td>
<td>2 pair UTP-3</td>
<td>H</td>
<td>M</td>
<td>F</td>
<td>4B/5B</td>
<td>100 m</td>
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<td>100BaseFX</td>
<td>100 Mb/s</td>
<td>1995</td>
<td>4 pair UTP-3</td>
<td>H</td>
<td>M</td>
<td>F</td>
<td>4B/5B</td>
<td>100 m</td>
<td>100 m</td>
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<tr>
<td>1000BaseX</td>
<td>1 Gb/s</td>
<td>1998</td>
<td>4 pair UTP-6</td>
<td>H</td>
<td>M</td>
<td>F</td>
<td>4B/5B/PAM5</td>
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<td>25 m</td>
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<td>1000BaseSX</td>
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<td>1998</td>
<td>4 pair UTP-6</td>
<td>H</td>
<td>M</td>
<td>F</td>
<td>4B/5B/PAM5</td>
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<td>25 m</td>
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<td>10GBaseX</td>
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<td>2002</td>
<td>parallel fiber</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>8B108 FCS 64B/66B</td>
<td>65 m–40 km</td>
<td>switch pt-2-pt</td>
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<td>10GBaseR</td>
<td>10 Gb/s</td>
<td>2002</td>
<td>fiber</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>8B108 FCS 64B/66B</td>
<td>65 m–40 km</td>
<td>switch pt-2-pt</td>
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<td>10 Gb/s</td>
<td>2002</td>
<td>4 pair UTP-7</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>8B108 FCS 64B/66B</td>
<td>65 m–40 km</td>
<td>switch pt-2-pt</td>
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<tr>
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<td>40 Gb/s</td>
<td>2002</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>8B108 FCS 64B/66B</td>
<td>65 m–40 km</td>
<td>switch pt-2-pt</td>
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<tr>
<td>100GBase</td>
<td>100 Gb/s</td>
<td>2002</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>8B108 FCS 64B/66B</td>
<td>65 m–40 km</td>
<td>switch pt-2-pt</td>
<td></td>
</tr>
</tbody>
</table>

Link Layer and LANs

LL.3.4: Ring LANs

LL.1 Link layer functions and services
LL.2 Framing and delineation
LL.3 LAN types and topologies
  LL.3.1 LAN topologies
  LL.3.2 Point-to-point protocol
  LL.3.3 802 and Ethernet
LL.3.4 Ring LANs

LL.4 Multiplexing and switching
LL.5 Per-hop error and flow control
LL.6 Link layer components
LL.7 IP address resolution
LL.8 Residential broadband
Ring Links

Token Ring

• Early LAN technology (1972)
  – DCS and Cambridge rings provided foundation

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  – IBM LAN technology; standardised as IEEE 802.5
Ring Links

Token Ring

- Early LAN technology (1972)
  - DCS and Cambridge rings provided foundation
  - IBM LAN technology; standardised as IEEE 802.5
- Shared wire medium
  - token passing ring
  - performs well to heavy load > 80%
    - 16 Mb/s TR significantly outperformed 10Base5

- Significant 1980s LAN
  - but Ethernet had greater market share
  - evolved to 16 Mb/s (1988)
  - evolution to hubs required double STP to end systems
Ring Links

Token Ring

• Logical successor: FDDI
  – fiber distributed digital interface
  – only 100 Mb/s LAN technology of time
    • ANSI X3.139-1987 (MAC), X3.148.1988 (PHY)
    • 100BaseT vs. 100BaseVG wars hadn’t even begun
    • OC-3 ATM LANs were just appearing (and expensive)

• Dual fiber token-passing ring
  – contra-rotating rings with automatic protection from cuts
    • single ring option with no protection
  – later adapted for STP and UTP-5: CDDI (copper DDI)
Ring Links

Token Ring

- FDDI-II proposal for integrated services
  - slotted ring adds circuit service to basic FDDI packet service

- But 100BaseT killed FDDI (and ATM to the desktop)
Ring Links

Token Ring

- FDDI-II proposal for integrated services
  - slotted ring adds circuit service to basic FDDI packet service
- But 100BaseT killed FDDI (and ATM to the desktop)
- High-speed token ring (HSTR) proposals DOA*
  - 100 Mb/s 803.5t 1998 draft (a few products)
  - 1Gb/s 803.5v working group

*dead on arrival

<table>
<thead>
<tr>
<th>Link Type</th>
<th>Rate</th>
<th>Media</th>
<th>Coding</th>
<th>Access</th>
<th>Link Len</th>
<th>Circum</th>
<th>Topology</th>
<th>Ovhd</th>
<th>Payload</th>
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<tr>
<td>DCS 1972</td>
<td>2.5 Mb/s</td>
<td></td>
<td></td>
<td>token</td>
<td></td>
<td>ring</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Cambridge 1979</td>
<td>10 Mb/s</td>
<td>2 x TP</td>
<td>STP</td>
<td>slot</td>
<td>250 m</td>
<td>ring</td>
<td>22 b</td>
<td>16 b</td>
<td></td>
</tr>
<tr>
<td>Token Ring 1981 IBM 1985 802.5</td>
<td>4 Mb/s</td>
<td>16 Mb/s</td>
<td>STP</td>
<td>Manch.</td>
<td></td>
<td>ring</td>
<td>21 B</td>
<td>0 – 4529 0</td>
<td>0 – 18279 0</td>
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<tr>
<td>HSTR 802.5i 1998 802.5v fiber 4B/5B 8B/10B FCS DTR</td>
<td>100 Mb/s</td>
<td>100 Mb/s</td>
<td>1 Gb/s</td>
<td>(US)TP fiber</td>
<td>MLT-3</td>
<td>DTR</td>
<td>–</td>
<td>star</td>
<td>21 B</td>
</tr>
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<td>FDDI 1988</td>
<td>100 Mb/s</td>
<td>fiber</td>
<td>4B/5B</td>
<td>token</td>
<td>2 km</td>
<td>200 km</td>
<td>2-ring</td>
<td>28 B</td>
<td>0 – 4522 0</td>
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<tr>
<td>CDDI 1979</td>
<td>100 Mb/s</td>
<td>STP UTP-5</td>
<td>MLT-3</td>
<td>token</td>
<td>100 m</td>
<td>10 km</td>
<td>2-ring</td>
<td>28 B</td>
<td>0 – 4522 0</td>
</tr>
</tbody>
</table>

* DTR (dedicated token ring) for switched mode added in 1998 to 4 Mb/s and 16 Mb/s 802.5
  some switch NICs supported full duplex at 32 Mb/s
  *2 m for UTP
Ring Links
SONET Rings

- SONET links in ring configuration
  - dual rings provide fault tolerance
  - APS: automatic protection switching
    - restoration after fiber cut (aka backhoe fade)

more on SONET later

LL.4  Multiplexing and Switching

LL.1  Link layer functions and services
LL.2  Framing and delineation
LL.3  LAN types and topologies
LL.4  Multiplexing and switching
  LL.4.1  Link layer multiplexing
  LL.4.2  Link layer switching
  LL.4.3  TDM transport networks: PDH, SDH/SONET, OTN
LL.5  Per-hop error and flow control
LL.6  Link layer components
LL.7  IP address resolution
LL.8  Residential broadband
Link-Layer Multiplexing & Switching

Overview

- Link-layer multiplexing
  - multiplexing multiple lower rate links $\Rightarrow$ higher rate link
  - demultiplexing to lower rate links $\Leftarrow$ higher rate link
- Link-layer switching (L2 switching)
  - switching in space or time at the link layer
  - transparent to layer 3

Multiplexing and Switching

LL.4.1 Link-Layer Multiplexing

LL.1 Link layer functions and services
LL.2 Framing and delineation
LL.3 LAN types and topologies
LL.4 Multiplexing and switching
  LL.4.1 Link-layer multiplexing
  LL.4.2 Link-layer switching
  LL.4.3 TDM transport networks: PDH, SDH/SONET, OTN
LL.5 Per-hop error and flow control
LL.6 Link layer components
LL.7 IP address resolution
LL.8 Residential broadband
Link-Layer Multiplexing

Overview

- Link layer multiplexing
- PSTN evolution
  - synchronous multiplexing for traffic aggregation
- Broadband Internet access
  - PONs (passive optical networks)

Link-Layer Multiplexing

PSTN

- PSTN and PON multiplexing
  - multiplexing for traffic aggregation
Link-Layer Multiplexing

PSTN

- PSTN and PON multiplexing
  - multiplexing for traffic aggregation
- PSTN access to SONET rings
  - **ADM**: add-drop multiplexor
  - insert into ring
  - extract from ring

Link-Layer Multiplexing

**Multiplexing Schemes**

- **TDM**: time division multiplexing
  - synchronous (e.g. PDH, SDH/SONET)
  - asynchronous or statistical (e.g. ATM)
- **FDM**: frequency division multiplexing (typically RF)
  - **WDM**: wavelength division multiplexing (light)
Link-Layer Multiplexing

Synchronous TDM Links

- Synchronous time-division multiplexing (STDM)
  - $n \times R/n$ rate signals combined
  - fixed-size slots round-robin: 0, 1, ..., $n-1$, 0, 1, ..., $n-1$, 0, ...

**Advantages?**

**Disadvantages?**

+ Simple multiplexing scheme
- Difficult to efficiently use link
  - time slot allocation problem
  - wasted/oversubscribed slots
Link-Layer Multiplexing
Synchronous TDM Links

- Synchronous time-division multiplexing (STDM)
  - $n \times R/n$ rate signals combined
  - fixed-size slots round-robin: 0, 1, ..., $n-1$, 0, 1, ..., $n-1$, 0, ...

  + Simple multiplexing scheme
  - Difficult to efficiently use link
    - time slot allocation problem
    - wasted/oversubscribed slots

- Common in PSTN-derived systems (e.g. SONET)

Link-Layer Multiplexing
Asynchronous TDM Links

- Asynchronous time division multiplexing (ATDM)
  - aka statistical multiplexing
  - variable size time slots

  Advantages?
  Disadvantages?
Link-Layer Multiplexing

Asynchronous TDM Links

- Asynchronous time division multiplexing (ATDM)
  - aka statistical multiplexing
  - variable size time slots
- May be more complex
  - unless FIFO service discipline which is unfair
+ Better link efficiency
  + each sender uses proportion of link needed

Link-Layer Multiplexing

Multiplexing vs. Multiple Access

- Multiplexing vs. multiple access
- Link multiplexing
  - single transmitter
  - dedicated point-to-point link
Link-Layer Multiplexing

**Multiplexing vs. Multiple Access**

- **Multiplexing vs. multiple access**
- **Link multiplexing**
  - single transmitter
  - dedicated point-to-point link
- **Multiple access**
  - multiple transmitters
  - shared medium
  - essentially *physical layer* multiplexing
  - MAC algorithm needed to arbitrate

---

**Higher Layer Multiplexing**

- Higher layers multiplex into lower layers
  - $L_7 \mapsto L_4$ multiple applications use end-to-end transport flow
  - $L_4 \mapsto L_3$ multiple transport flows use network paths
  - $L_3 \mapsto L_2$ multiple network path use links
Link-Layer Multiplexing

Higher layers multiplex into lower layers
- L7 ⇐⇒ L4 multiple applications use end-to-end transport flow
- L4 ⇐⇒ L3 multiple transport flows use network paths
- L3 ⇐⇒ L2 multiple network path use links

Link layer multiplexing: L2 ⇐⇒ L2
- some link layers also provide native multiplexing
  - mux/demux without network layer switching

Recall historical precedence
- PSTN has minimal layer 3 switching
- time division multiplexing from premises–CO–long-distance
- digital hierarchy: T-carrier and SONET/SDH
Link-Layer Multiplexing

**Link Layer Simple Multiplexing**

- Link layer multiplexing
- Layer 2 combine/split
  - of lower rate signals
- Examples
  - SONET/T-carrier
    - \( \text{OC-}m \Rightarrow \text{OC-}n, \ m < n \)
    - T3 \( \Rightarrow \) OC-3
  - PONs (passive optical nets)
    - residential broadband
      - more later

Multiplexing and Switching

**LL.4.2 Link-Layer Switching**

- LL.1 Link layer functions and services
- LL.2 Framing and delineation
- LL.3 LAN types and topologies
- **LL.4 Multiplexing and switching**
  - LL.4.1 Link-layer multiplexing
  - LL.4.2 Link-layer switching
  - LL.4.3 TDM transport networks: PDH, SDH/SONET, OTN
- LL.5 Per-hop error and flow control
- LL.6 Link layer components
- LL.7 IP address resolution
- LL.8 Residential broadband

31 March 2010
Link-Layer Switching

Overview

• Traditionally switching is a network layer 3 function
  – but...

Why do layer 2 switching?
Link-Layer Switching

Overview

- Link layer switching
  - switching done by L2 components
  - supported by link protocol
    - e.g. SONET
    - e.g. 802.1D bridging for Ethernet
- Evolved with PSTN and Internet

PSTN SONET Rings

- PSTN synchronous multiplexing
  - multiplexing for traffic aggregation
- PSTN SONET inter-ring switching
  - XC: cross-connect
  - ADM: add-drop multiplexor
Link-Layer Switching

Internet LANs

- Internet LAN switching
  - shared-medium segments

- Internet LAN switching
  - shared-medium segments replaced by Ethernet switches
  - more on this evolution later
  - no awareness, involvement, or management of IP
Link-Layer Switching

Evolution

• Link layer switching
  – native layer 2 protocol and device switching
• Evolved with PSTN and Internet
  – migration from shared medium to switched LAN
    • e.g. Ethernet
  – add switching functionality to multiplexing structure
    • e.g. SONET cross-connects

Advantages?

Advantages

• Potential advantages
  – simpler, cheaper switches than L3 (IP switch/router)
    • less important with fast IP lookup hardware
  – no need to manage IP in small networks
    • less important with DHCP and router auto-configuration
  – faster restoration on link failure
    • IP routing convergence much slower than ring restoration

Disadvantages?
Link-Layer Switching

Disadvantages

- Potential advantages
  - simpler, cheaper switches than L3 (IP switch/router)
  - no need to manage IP in small networks
  - faster restoration on link failure
- Disadvantages
  - duplication of L3 functions in L2
  - where should functionality really go?
    - if IP converged rapidly, SONET APS might not be necessary

Space-Division Switching

- Space division \textit{switches the links} that frames traverse
  - multiple inputs links interconnected to multiple output links
  - \textit{switch fabric} responsible for input $\rightarrow$ output interconnection
- Variety of switching technologies
  - crossbar, shared memory, MIN, etc. \textit{Lecture NL}
Link-Layer Switching

**Space-Division Switching**

- Space-division switching
  
  _sufficient for TDM-based link layers such as SONET?_

**Time-Division Switching**

- Space-division switching
  - solves only part of the problems in TDM-based link layers
- Time-division switching:
  - TDM networks also need to be switched in _time_
  - switching _time slots_ for synchronous TDM
Link-Layer Switching

Time-Division Switching: TSI

- TSI: time slot interchange
  - switching *time slots* for synchronous TDM

- Reordered in switch memory
  - received frames written into memory sequentially $i_0, i_1, \ldots, i_{n-1}$
  - frames read in different order for transmission $o_j$...
Link-Layer Switching
Space- and Time-Division Switching

How to switch in both space and time?

• Combination space/time switching
  – needed for interconnection of multiple TDM links
    • e.g. SONET cross-connect at intersection of two rings
Link-Layer Switching

Space- and Time-Division Switching

- Combination space/time switching
  - needed for interconnection of multiple TDM links
    - e.g. SONET cross-connect at intersection of two rings
- Multiple combinations possible, e.g.
  - T-S-T: time-space-time (shown): TSIs – space switch – TSIs
  - S-T-S: space-time-space: space – TSIs – space

Multiplexing and Switching

LL.4.3 TDM Transport Networks

LL.1 Link layer functions and services
LL.2 Framing and delineation
LL.3 LAN types and topologies
LL.4 Multiplexing and switching
  LL.4.1 Link-layer multiplexing
  LL.4.2 Link-layer switching
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LL.5 Per-hop error and flow control
LL.6 Link layer components
LL.7 IP address resolution
LL.8 Residential broadband
TDM Transport Networks

**Overview**

- **Transport networks**
  - link layer (L2) infrastructure in the PSTN context
  - not to be confused with end-to-end (L4) transport
  - used in Internet protocol terminology

- **Transport network evolution**
  - PDH: digital hierarchy, generally over wires (e.g. T-carriers)
  - SDH/SONET: digital hierarchy over optical fiber
  - OTN: optical transport network with WDM switches

---

**ITU Hierarchy**

- **PDH**: pleisiochronous digital hierarchy
- **SDH/SONET**: synchronous digital hierarchy
- **ATM/B-ISDN**: Ethernet
- **OTN**: optical transport network
- **CBRk**, **GFP**, **AAL**, **ATM**, **ETH**, **GFP**, **CBRk**
- **PNNI**, **GMPLS**, **ASON**
- **proprietary DWDM**
TDM Transport Networks

ITU Hierarchy

- Data and management planes
  - **OTN**: optical transport network WDM links
  - **SDH**: synchronous digital hierarchy (SONET) links
  - **Ethernet**: long-haul point-to-point Ethernet links
  - **ATM/B-ISDN**: asynchronous transfer mode / broadband ISDN

- Control plane (layer 2 switching)
  - **ASON**: automatically switched optical network
    - **GMPLS**: generalised multiprotocol label switching
      - RSVP-TE, CR-LDP (IETF deprecated)
    - **PNNI**: (ATM) private NNI signalling (layer 3 switching)
Multiplexing and Switching

LL.4.3.1 PSTN Digital Hierarchy

- Link layer functions and services
- Framing and delineation
- LAN types and topologies
- Multiplexing and switching
  - Link-layer multiplexing
  - Link-layer switching
  - TDM transport networks: PDH, SDH/SONET, OTN
- Per-hop error and flow control
- Link layer components
- IP address resolution
- Residential broadband

TDM Transport Networks

PSTN Digital Hierarchy

- PSTN digital hierarchy
  - digital multiplexing structure to replace analog circuits
  - hierarchy of increasing rates for aggregation in network core
  - multiplexors and demultiplexors independent of switching
- Plesiochronous
  - from the Greek: πλησίος = nearly + χρόνος = time
  - digital signals are nearly synchronous
    - bit slips tolerated with bit-stuffing in frame structure
  - signals are bit streams
    - framing not visible to next-higher level
    - no relative synchronisation among signals below given level
### PSTN Digital Hierarchy
#### Relationship to Protocol Stack

**PDH**: plesiochronous digital hierarchy  
**SDH**: synchronous digital hierarchy  
**ATM/B-ISDN**: Ethernet  
**OTN**: optical transport network

<table>
<thead>
<tr>
<th>Protocol</th>
<th>CBRk</th>
<th>GFP</th>
<th>AAL</th>
<th>control planes</th>
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<tr>
<td>PDH</td>
<td>SDH/SONET</td>
<td>ATM</td>
<td>ETH</td>
<td>GFP</td>
</tr>
<tr>
<td></td>
<td>proprietary DWDM</td>
<td>OTN</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Standards

- **PSTN WAN/MAN** near-synchronous electrical links  
  - **PDH**: plesiochronous digital hierarchy (ITU-T)  
    - **E-carriers**  
  - **DH**: digital hierarchy (Bellcore, ANSI)  
    - **T-carriers** (US)  
    - **J-carriers** (Japan)

- **Standards suite:**  
  - format specification: G.702, G.704, G.706, T1.107  
  - equipment: G.705  
  - physical interfaces: G.703, T1.102, T1.403, T1.404
PSTN Digital Hierarchy
US Multiplexing Structure

- Digital signals (DS) on T-carriers (others for DS-4)
  - DS0: digital voice channel or 56 kb/s leased data line
  - DS1: $24 \times DS0$ or 1.5 Mb/s T-1 data service
  - DS2: $4 \times DS1$
  - DS3: $7 \times DS2$ or 45 Mb/s T-3 data service
  - DS4: $3 \times DS3$ (historical – now replaced by SONET)

US Multiplexing Structure
Frame Structure

- **Framing**
  - bit patterns distributed throughout frames
- **Alarms**
  - indicate loss of signal or framing to other end of link
  - used by networking monitoring and management
- **Error detection**
  - parity or CRC
- **Signalling and data channels**
  - robbed from DS0 or distributed throughout frame
US Multiplexing Structure

Alarms

- **Alarms**
  - indicate and signal integrity and framing problems
  - historically designated with colors (now deprecated)
- **Red alarm**
  - local alarm when unable to recover framing
- **Yellow alarm**: RAI (remote alarm indication)
  - report of red alarm received from other end of link
  - encoding dependent on multiplexing level
- **Blue alarm**: AIS (alarm indication signal)
  - unframed sequence of all 1s to maintain signal

DS1 Frame Basis

- **DS0 channel** [8b]
  - information payload: PCM-coded voice or 56 kb/s data
  - overhead payload: signalling or stuffing channel

[ANSI T1.107]
US Multiplexing Structure  
**DS1 Frame Construction**

<table>
<thead>
<tr>
<th>ch</th>
<th>DS0 channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>ch 01</td>
<td>ch 02</td>
</tr>
</tbody>
</table>

- DS0 channel [8b]: information or overhead payload
- DS1 frame [193b]
  - frame overhead [1b]: "header" bit – part of superframe
  - 24 DS0 channels [192b]: 12:1 multiplexing into DS1

*note: numbering starts at 1 rather than 0*

**US Multiplexing Structure  
**DS1 Superframe Construction**

<table>
<thead>
<tr>
<th>ch</th>
<th>DS0 channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>ch 01</td>
<td>ch 02</td>
</tr>
</tbody>
</table>

| frame 01 | frame 02 | ... | frame 11 | frame 12 |

- DS0 channel [8b]: information or overhead payload
- DS1 frame [193b/125μs]: frame overhead + 24 DS0 chan.
- DS1 superframe [2316b]
  - 12 DS1 frames: cyclic sequence of 24 DS0 channels
  - overhead [12b]: embedded in & distributed through frames
    - frame alignment, frame transfer, data transfer, alarm transfer
### US Multiplexing Structure

#### DS1 Superframe Format and Overhead

- **Frame alignment**
  - odd overhead bits $F_1F_3F_5F_7F_9F_{11} = 101010$

- **Superframe alignment**
  - even frame overhead bits $F_2F_4F_6F_8F_{10}F_{12} = 001110$

---

### US Multiplexing Structure

#### DS1 Superframe Alarms

- **Frame alignment**
  - odd overhead bits $F_1F_3F_5F_7F_9F_{11} = 101010$

- **Superframe alignment**
  - even frame overhead bits $F_2F_4F_6F_8F_{10}F_{12} = 001110$

- **Alarms**
  - AIS (alarm indication signal): all bits = 1 (unframed)
  - RAI (remote alarm indication): 2nd bit of every channel = 0
    - signals inability to frame or loss of signal
US Multiplexing Structure

**DS1 Superframe Signalling Channel**

- **Frame alignment**
  - odd overhead bits
    \[ F_1F_3F_5F_7F_9F_{11} = 101010 \]
- **Superframe alignment**
  - even frame overhead bits
    \[ F_2F_4F_6F_{10}F_{12} = 001110 \]
- **Signalling channel (optional)**
  - 8th information bit *robbed* from frames 6 and 12
    - one 1.333 kb/s channel or two 667 b/s channels
    - PCM voice relatively insensitive to low-order bit errors

---

**DS1 Extended Frame Construction**

- **DS0 channel [8b]**: information or overhead payload
- **DS1 frame [193b]**: frame overhead + 24 DS0 chan.
- **DS1 extended superframe [4632b]**
  - 24 DS1 frames: cyclic sequence of 24 DS0 channels
  - overhead [24b]: embedded in & distributed through frames
    - frame alignment, frame transfer, data transfer, alarm transfer
    - doubling superframe adds CRC and 4 kb/s data channel
US Multiplexing Structure

**DS1 Extended Superframe Format & Overhead**

- **Alignment**
  - \( F_4 F_8 F_{12} F_{16} F_{20} F_{24} = 001011 \)

- **Error detection**
  - CRC-6:
    - \( F_2 F_6 F_{10} F_{14} F_{18} F_{22} \)
    - \( C_1 C_2 C_3 C_4 C_5 C_6 \)

- **Data link**:
  - 4 kb/s
    - \( F_1 F_3 F_5 F_7 F_9 F_{11} \)
    - \( F_{13} F_{15} F_{17} F_{19} F_{21} F_{23} \)
    - \( M_1 - 12 \)

**DS1 Extended Superframe Signalling Channel**

- **Alignment**
  - \( F_4 F_8 F_{12} F_{16} F_{20} F_{24} = 001011 \)

- **Error detection**
  - CRC-6

- **Data link**
  - 4 kb/s

- **Signalling channel**
  - 8th bit robbed
  - frames 6, 12, 18, 24
    - one 1.333 kb/s, two 667, or four 333 b/s channels
US Multiplexing Structure

**DS1 Extended Superframe Alarm**

- **Alignment**
  - \( F_4F_8F_{12}F_{16}F_{20}F_{24} = 001011 \)
- **Error detection**
  - CRC-6
- **Data link**
  - 4 kb/s
  - RAI alarm repeating pattern 00000000 11111111

---

**US Multiplexing Structure**

**M12 Multiplexing**

- **M12**: DS1 to DS2 multiplexing
  - 4 DS1 bitstreams: DS1 framing not visible to DS2
    - plesiochronous: not synchronised with respect to one-another
  - bit-by-bit multiplexing into DS2 multiframe (M-frame)
  - 1 overhead bit preceding 48-bit groups
• DS1 channels: 4 channels multiplexed bit-by-bit
• DS2 M-subframe [294b]
  – six groups of 1 overhead-bit followed by 48 information bits
  – overhead bit sequence [6b]: M | X | C_1 | F_1 | C_2 | F_2
    • M | X: frame alignment or alarm – used in M-frame
    • F: subframe alignment F_1 F_2 = 01
    • C: inter-DS2 equipment signalling: stuffing

• DS1 channels: 4 channels multiplexed bit-by-bit
• DS2 M-subframe [294b]: six groups of 49 bits
• DS2 M-frame (multiframe) [1176b]
  – 4 DS2 M-subframes including [24b] overhead
  – sequence of first subframe bits: M_1 M_2 M_3 X
    • M: frame alignment M_1 M_2 M_3 = 011
    • X: alarm channel
US Multiplexing Structure

DS2 Multiframe Format and Overhead

- Subframe align
  - \( F_1 F_2 = 01 \)

- Multiframe align
  - \( M_1 M_2 M_3 = 011 \)

- Alarm channel
  - \( X = 0 \) (alarm) or \( 1 \) (no alarm)

- Inter-DS2 equipment signalling channel
  - \( C_1 C_2 C_3 \times 4 \) to indicate bit stuffing or parity

US Multiplexing Structure

M23 Multiplexing

- M23: DS2 to DS3 multiplexing
  - 7 DS2 bitstreams: DS2 framing not visible to DS3
    - plesiochronous: not synchronised with respect to one-another
  - bit-by-bit multiplexing into DS3 multiframe (M-frame)
  - 1 overhead bit preceding 84-bit groups
US Multiplexing Structure

**DS3 Subframe Construction**

- DS2 channels: 7 channels multiplexed bit-by-bit
- DS3 M-subframe [680b]
  - 8 groups of 1 overhead-bit followed by 84 information bits
  - overhead bit seq. [8b]: \{M|P|X\} F_1 C_1 F_2 C_2 F_3 C_3 F_4
    - M|X|P: frame alignment, alarm, parity – used in M-frame
    - F: subframe alignment \( F_1 F_2 F_3 F_4 = 1001 \)
    - C: inter-DS3 equipment signalling: stuffing and parity

**DS3 Multiframe Construction**

- DS2 channels: 7 channels multiplexed bit-by-bit
- DS3 M-subframe [680b]: 8 groups of 85 bits
- DS3 multiframe (M-frame) [4760b]
  - 7 DS3 M-subframes including [56b] overhead
  - sequence of first subframe bits: \( X_1 X_2 P_1 P_2 M_1 M_2 M_3 \)
    - M: frame alignment \( M_1 M_2 M_3 = 010 \)
    - X: alarm channel
    - P: parity preceding M-frame \( P_1 P_2 = 00 \) (even) or \( 00 \) (odd)
US Multiplexing Structure
DS3 Multiframe Format and Overhead

- Subframe align
  - \( F_1F_2F_3F_4 = 1001 \)
- Multiframe align
  - \( M_1M_2M_3 = 010 \)
- Alarm channel
  - \( X_1X_2 = 00 \) (alarm) or \( 11 \) (no alarm)
- Performance monitoring: parity of preceding frame
  - \( P_1P_2 = 00 \) (even) or \( 11 \) (odd)
- Inter-DS3 equipment signalling channel
  - \( C_1C_2C_3 \times 7 \) to indicate bit stuffing or parity

PSTN Digital Hierarchy
Summary and Comparison

<table>
<thead>
<tr>
<th></th>
<th>PDH</th>
<th>SDH/SONET</th>
<th>OTN DW</th>
<th>OTN OTM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission</td>
<td>electronic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mux &amp; switching</td>
<td>electronic</td>
<td></td>
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<td></td>
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<tr>
<td>Multiplex domain</td>
<td>TDM</td>
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<tr>
<td>Synchronisation</td>
<td>plesiochronous</td>
<td></td>
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<td></td>
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<td>Levels*</td>
<td>4</td>
<td></td>
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<tr>
<td>Transparency</td>
<td>opaque</td>
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<td></td>
</tr>
<tr>
<td>Rates†</td>
<td>1.5 – 45 Mb/s</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* as currently defined in standards, not including sub- and intermediate levels
† approximate as currently defined in standards, not including STS-1 and sub-rates (DS0 and VTs)
PSTN Digital Hierarchy
PDH Carrier Characteristics

<table>
<thead>
<tr>
<th>Link type</th>
<th>Carrier</th>
<th>Channel</th>
<th>Media</th>
<th>Coding</th>
<th>Channels</th>
<th>Rate</th>
<th>Frame Size (super/ multi)</th>
<th>Frame Overhd</th>
<th>Payload Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS-0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>64 kb/s</td>
<td>8 b</td>
<td></td>
<td>56 kb/s</td>
</tr>
<tr>
<td>T1</td>
<td>D1</td>
<td>E1</td>
<td>twisted pair</td>
<td>bipolar</td>
<td>24</td>
<td>1.544 Mb/s</td>
<td>2316 b</td>
<td>12 b</td>
<td>1.536 Mb/s</td>
</tr>
<tr>
<td>T2</td>
<td>D2</td>
<td>E2</td>
<td>twisted pair</td>
<td>B6ZS</td>
<td>96</td>
<td>6.312 Mb/s</td>
<td>8.448 Mb/s</td>
<td>24 b</td>
<td>6.183 Mb/s</td>
</tr>
<tr>
<td>T3</td>
<td>D3</td>
<td>E3</td>
<td>twisted pair</td>
<td>twisted pair</td>
<td>672/480</td>
<td>44.736 Mb/s</td>
<td>32.064 Mb/s</td>
<td>4760 b</td>
<td>44.210 Mb/s</td>
</tr>
<tr>
<td>WT4</td>
<td>T4M</td>
<td>Dk 18</td>
<td>waveguide</td>
<td>coax</td>
<td>RF</td>
<td>4032</td>
<td>274.176 Mb/s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multiplexing and Switching

LL.4.3.2 SDH and SONET

LL.1 Link layer functions and services
LL.2 Framing and delineation
LL.3 LAN types and topologies
LL.4 Multiplexing and switching
  LL.4.1 Link-layer multiplexing
  LL.4.2 Link-layer switching
  LL.4.3 TDM transport networks: PDH, SDH/SONET, OTN
LL.5 Per-hop error and flow control
LL.6 Link layer components
LL.7 IP address resolution
LL.8 Residential broadband
TDM Transport Networks

Generic Framing Procedure (GFP)

- Framing for *synchronous* transport networks
  
  *problem*?
TDM Transport Networks

Generic Framing Procedure (GFP)

- Framing for *synchronous* transport networks
  - problem: synchronous networks designed for voice
  - CBR (constant bit rate) stream in TDM
  - IP packets need additional framing
- POS: packet over SONET
  - initial deployments:
    PPP framing of IP over SONET [RFC 2615]

- Motivation for new solution
  - PPP not designed for this application
  - goal: new generic framing protocol
    - IP and CBR over synchronous links
### TDM Transport Networks

#### Generic Framing Procedure (GFP)

- **Framing for transport networks**
  - ITU-T G.7041 over OTN, SDH/SONET
  - 4B common header (length, check HEC)
  - client specific headers
  - FCS frame check

- **Transfer of:**
  - variable size frames (GFP-F)
    - IP, PPP
    - Ethernet MAC
  - block code (transparent – GFP-T)
    - FCS
    - ESCON/FICON (IBM I/O channels)

#### Table: Generic Framing Procedure (GFP)

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLI</td>
<td>client payload information field</td>
</tr>
<tr>
<td>type</td>
<td></td>
</tr>
<tr>
<td>tHEC</td>
<td></td>
</tr>
<tr>
<td>eHEC</td>
<td></td>
</tr>
<tr>
<td>ext header</td>
<td></td>
</tr>
<tr>
<td>FCS</td>
<td></td>
</tr>
</tbody>
</table>

### TDM Transport Networks

#### SONET/SDH Overview

- **SONET:** synchronous optical network
  - evolution of T-carrier digital hierarchy in the Bell System
  - extension of TDM multiplexing structure
  - higher data rates over fiber optic cable
    - OC: optical carrier
  - electronic multiplexing and cross-connects
    - O/E: optical to electrical conversion at inputs
    - E/O: electrical to optical conversion at outputs

- **SDH:** synchronous digital hierarchy
  - ITU standard similar to SONET
### TDM Transport Networks

#### SONET/SDH Standards

- **WAN/MAN synchronous optical links**
  - SDH: synchronous digital hierarchy (ITU-T)
  - SONET: synchronous optical network (Bellcore*, ANSI)

- **Standards suite:**
  - architecture G.803, T1.105, Bellcore GR-253
  - framing and multiplexing G.707, T1.105.02
  - equipment G.671, G.783
  - physical interfaces G.691, G.692, T1.105.06, T1.106
  - OAM&P G.784, G.831
  - protection G.841, T1.105.01

* now Telcordia

---

### TDM Transport Networks

#### SONET/SDH Sublayers

- **Path** (F3)
  - link \(_2\) between switch\(_{L3}\)-to-switch\(_{L3}\)
  - STS-\(n\) generation, HEC, and framing

- **Tandem connection** (optional)

- **Line / Digital Section** (F2)
  - de/multiplexing STS-\(n\) ↔ STS-\(N\)
  - concatenation 4×STS-\(n\) ↔ STS-4\(n\)

- **Section** / regenerator section (F1)
  - STS-\(n\) transport, framing, scrambling

- **Physical / photonic section**
  - between EO STS-\(n\) → OC-\(n\) → OC-\(n\) → STS-\(n\) OE
  - between EOE regeneration
SONET Topology: Mesh

- SONET mesh
  - mesh of SONET links
  - switched at L3
    - between ATM switches
    - between IP routers

SONET Topology: Rings

- SONET rings
  - multiplexed at L2
    - 4:1 multiplexing for aggregation
    - ADMs for ring insertion/extraction
  - switched at L2
    - cross-connects for ring interconnection
  - fault tolerant
    - dual ring APS
      - automatic protection switching
TDM Transport Networks

SONET Add/Drop Multiplexing

- ADM: add/drop multiplexor
  - electronic device
  - optical transceivers
- Layer 2 insertion/extraction
  - of lower rate signals
    - optical OC-\(m\), \(m < n\)
    - electrical T-\(k\), typically T3
  - to/from OC-\(n\) SONET
- Typically on SONET ring
  - but may be point-to-point link

TDM Transport Networks

SONET Cross Connect

- XC: Cross-connect
  - electronic switch
    - 2x2 switch shown
    - larger cross-connects possible
  - optical transceivers
- Space division between:
  - point-to-point links
  - rings
- Time division
  - multiplexing hierarchy
SONET Hierarchy
US Multiplexing Structure

- Synchronous transport signals (STS) on optical carriers (OC)
  - used for higher-level aggregation of voice circuits
  - OC-n data services

SONET/SDH Links
Structure and Terminology

- SONET/SDH path
  - SONET/SDH link (edge-to-edge of SONET subnet)
  - appears as L2 link to L3 routers/switches

- SONET/SDH tandem connection
  - bundle of STS-n/STM-n transported as group (no add/drop)

- SONET line / SDH multiplex section
  - transmission line across regenerators (may be multiple)

- SONET section / SDH regenerator section
SONET Transport Networks

STS-1 Frame Format

- STS-1 frame [810B] arranged 9 rows x 90B [ANSI T.105.1]
  - transport overhead: 9 x 3B
    - section overhead 3 x 3B and line overhead 6 x 3B
  - envelope capacity: 9 x 87B
  - SPE (synchronous payload envelope): floats in envelope capacity
    - path overhead: 9 x 1B at 1st byte in each SPE row
    - stuff bits: 9 x 2B at 30th and 59th byte in each SPE row
    - information payload: 9 x 84B

SONET Transport Networks

STS-1 Floating Payload

- STS-1 SPE floats in STS-1 payload envelope
  - SPE may begin anywhere within envelope
  - H1H2 pointer in LOH indicates offset to beginning of SPE
SONET Transport Networks

STS-1 Path Overhead

- Path overhead (POH)
  - SONET edge-to-edge
  - signalling between path terminating equipment (PTE)

- POH content
  - payload-independent functions
  - mapping-dependent overhead: dependent on payload type
  - application-specific functions
  - undefined overhead for future use

- J1 STS Path trace path access point ID to verify connectivity
- B3 BIP-8 bit-interleaved parity for path error monitoring
- C2 STS path signal label identifies payload content / defect
- G1 path status returned from receiving PTE
- F2 path user channel for arbitrary PTE–PTE signalling
- H4 multiframe indicator for VTs and virtual concatenation
- Z3Z4 growth 2B reserved for future use
- N1 tandem connection maintenance and data link
SONET Transport Networks

STS-1 Section Overhead

- $A_1A_2$ Framing  
  = $F6\ 28$
- $C_1$ ID  
  (depricated)
- $J_0$ section trace verify connectivity between STEs
- $Z_0$ section growth 1B reserved for future use
- $B_1$ BIP-8 bit-interleaved parity for section error monitoring
- $S$ media-dependent bytes
- $E_1$ orderwire voice channel between STEs
- $F_1$ section user channel for arbitrary STE–STE signalling
- $D_{10}D_{12}$ section data comm. channel 192kb/s alarms, OAM

---

SONET Transport Networks

STS-1 Line Overhead

- $H_1H_2$ pointer  
  offset to 1st byte of SPE
- $H_3$ pointer action adjust input buffer fill for freq justification
- $B_2$ BIP-8 bit-interleaved parity for line error monitoring
- $K_1K_2$ APS channel APS signalling between LTEs
- $D_{13}D_{12}$ line data comm. channel 576kb/s for alarms, OAM
- $S_1$ synchronisation messaging for clock sync
- $M_0M_1$ line REI remote error indication; returns # BIP-8 errors
- $Z_1Z_2$ line growth 2B reserved for future use
- $E_2$ orderwire voice channel between LTEs
- $D_{13}D_{156}$ extended data comm. chan 9216kb/s (OC-768)
SONET Transport Networks

Higher-Level Rates

- SONET and SDH designed to be scalable
  - in rate
  - in multiplexing structure
- STS-\textit{n}
  - synchronous transport signal \textit{multiplexed} from \( n \times \text{STS-1} \)
  - useful for aggregated services
- STS-\textit{nc}
  - synchronous transport signal at rate \( n \times \text{STS-1} \)
  - provides single data stream
    - no need to stripe across \( n \) streams and maintain skew

SONET Transport Networks

STS-3 Frame Format

- STS-3c frame [810B] arranged 9 rows \( \times \) 90B [ANSI T.105.1]
  - transport overhead: 9 \( \times \) 3B
    - \textit{section overhead} 3\( \times \)3B and \textit{line overhead} 6\( \times \)3B
  - envelope capacity: \( 9 \times 87B \)
  - SPE (synchronous payload envelope): floats in envelope capacity
    - \textit{path overhead}: 9 \( \times \) 3B at 1st byte in each SPE row
    - \textit{stuff bits}: 9 \( \times \) 2B at 30th and 59th byte in each SPE row
    - \textit{information payload}: 9 \( \times \) 84B

31 March 2010
### SONET Transport Networks

#### Subrate Overview

- **Fractional STS-1**
  - VT: SONET virtual tributary
  - TU: SDH tributary unit
  - 6 increments of sub-rate STS-1
  - needed for efficient transport of non-TDM (e.g. Ethernet)

- **LCAS: link capacity adjustment scheme [ITU G.7042]**
  - allows dynamic adjustment of VT size used by flow

#### VT-TU Table

<table>
<thead>
<tr>
<th>VT</th>
<th>TU</th>
<th>Fraction</th>
<th>Col.</th>
<th>Rate</th>
<th>PDH</th>
</tr>
</thead>
<tbody>
<tr>
<td>VT1.5</td>
<td>TU-11</td>
<td>1/28</td>
<td>3</td>
<td>1.728 Mb/s</td>
<td>DS1</td>
</tr>
<tr>
<td>VT2</td>
<td>TU-12</td>
<td>1/21</td>
<td>4</td>
<td>2.304 Mb/s</td>
<td>E1</td>
</tr>
<tr>
<td>VT3</td>
<td>–</td>
<td>1/14</td>
<td>6</td>
<td>3.456 Mb/s</td>
<td>DS1C</td>
</tr>
<tr>
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<td>TU-2</td>
<td>1/7</td>
<td>12</td>
<td>6.912 Mb/s</td>
<td>DS2</td>
</tr>
<tr>
<td>STS-1</td>
<td>–</td>
<td>1/1</td>
<td>84</td>
<td>51.840 Mb/s</td>
<td>DS3</td>
</tr>
</tbody>
</table>

### TDM Transport Networks

#### SONET/SDH Summary and Comparison

<table>
<thead>
<tr>
<th></th>
<th>PDH</th>
<th>SDH/SONET</th>
<th>OTN DW</th>
<th>OTN OTM</th>
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<td>Transmission</td>
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<td>optical</td>
<td></td>
<td></td>
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<tr>
<td>Mux &amp; switching</td>
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<td></td>
</tr>
<tr>
<td>Multiplex domain</td>
<td>TDM</td>
<td>TDM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synchronisation</td>
<td>plesiochronous</td>
<td>synchronous</td>
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</tr>
<tr>
<td>Levels*</td>
<td>4</td>
<td>5</td>
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<tr>
<td>Transparency</td>
<td>opaque</td>
<td>transparent</td>
<td></td>
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<tr>
<td>Rates‡</td>
<td>1.5 – 45 Mb/s</td>
<td>1.155 – 40 Gb/s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* as currently defined in standards, not including sub- and intermediate levels
‡ approximate as currently defined in standards, not including STS-1 and sub-rates (DS0 and VTs)
## TDM Transport Networks
### SONET/SDH Hierarchy

<table>
<thead>
<tr>
<th>Link Type</th>
<th>Rate</th>
<th>Transport Overhead</th>
<th>Payload</th>
<th>Payload rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SONET</td>
</tr>
<tr>
<td>SONET</td>
<td>SDH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STS-1</td>
<td>STM-0</td>
<td>51.84 Mb/s</td>
<td>27 B</td>
<td>774 B</td>
</tr>
<tr>
<td>OC-3c</td>
<td>STM-1c</td>
<td>155.52 Mb/s</td>
<td>81 B</td>
<td>2340 B</td>
</tr>
<tr>
<td>OC-12c</td>
<td>STM-4c</td>
<td>622.08 Mb/s</td>
<td>324 B</td>
<td>9387 B</td>
</tr>
<tr>
<td>OC-48c</td>
<td>STM-16c</td>
<td>2.49 Gb/s</td>
<td>1296 B</td>
<td>37575 B</td>
</tr>
<tr>
<td>OC-192c</td>
<td>STM-64c</td>
<td>9.95 Gb/s</td>
<td>5184 B</td>
<td>15327 B</td>
</tr>
<tr>
<td>OC-768c</td>
<td>STM-256c</td>
<td>39.81 Gb/s</td>
<td>20736 B</td>
<td>601335 B</td>
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<tr>
<td>OC-3072c</td>
<td>STM-1024c</td>
<td>159.25 Gb/s</td>
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<tr>
<td>OC-Nc</td>
<td>STM-(N/3)c</td>
<td>N × 51.84 Mb/s</td>
<td>N × 27 B</td>
<td>N × 87-9 – 9 B</td>
</tr>
</tbody>
</table>

### Multiplexing and Switching
#### LL.4.3.3 Optical Transport Networks

- **LL.1** Link layer functions and services
- **LL.2** Framing and delineation
- **LL.3** LAN types and topologies
- **LL.4** Multiplexing and switching
  - **LL.4.1** Link-layer multiplexing
  - **LL.4.2** Link-layer switching
  - **LL.4.3** TDM transport networks: PDH, SDH/SONET, OTN
- **LL.5** Per-hop error and flow control
- **LL.6** Link layer components
- **LL.7** IP address resolution
- **LL.8** Residential broadband
WDM Transport Networks
Wavelength Division Multiplexed Links

- Optical WDM: wavelength division multiplexing
  - FDM where frequencies are wavelengths (shades of IR)
  - number of wavelengths inversely proportional to distance
    - stimulated Raman scattering due to molecular vibrations
    - stimulated Brillouin scattering interacting with acoustic waves
    - carrier-induced cross-phase modulation causes phase shifts
    - four-wave mixing induces sum and difference frequencies

  *much more about this in EECS 881*

WDM Transport Networks
OTN Overview

- All optical network motivation
  - increase capacity on fiber with multiple wavelengths
  - WDM: wavelength division multiplexing
- OTN: optical transport network
  - evolution of transport network to WDM optical switches
    - no need for O/E/O conversion
  - matches SDH/SONET hierarchy
    - eases replacement of optical for electronic switches
    - SDH over OTN hierarchy
  - adds interfaces between service providers
    - SONET/SDH were designed before deregulation

*More in EECS 881*
WDM Transport Networks

OTN Standards

- OTN: Optical transport network
- ITU-T standards suite:
  - architecture \( \text{G.871/Y.1301, G.872} \)
  - OTH framing/multiplexing \( \text{G.709/Y.1331} \)
  - equipment \( \text{G.798} \)
  - physical interfaces \( \text{G.694, G.959.1, G.8251} \)
  - OAM&P \( \text{G.874, G.875} \)
  - protection \( \text{G.873} \)
  - ASON \( \text{G.8080/Y.1304} \)
  - automatically switched optical network

WDM Transport Networks

OTN Link Hierarchy

- Trails
  - undirectional and bidirectional
  - point-to-point and point-to-multipoint
- Interfaces
  - OUNI (OIF implementation agreement)
  - IrDI / E-NNI interdomain (OIF implementation agreement)
  - IaDI / I-NNI intradomain
- Framing and multiplexing hierarchy
  - digital wrapper
    - digital encapsulation with associated overhead
  - optical transport module (OTM)
    - optical/photonic with non-associated overhead
• ONNI: optical network node interface
  – Interdomain: IrDI (data) / E-NNI (signaling exterior NNI)
    • may or may not terminate OCh
  – Intradomain: IaDI (data) / I-NNI (signaling interior NNI)
    • IrVI/IaVI: inter-/intra vendor interface
• OUNI: optical user–network interface

• Digital over optical multiplexing hierarchy
  – client trail (SONET, ATM, GFP)
  – digital wrapper (in band)
    • OPUk – OCh payload unit
    • OPU1 ≈ 2.4Gb/s, OPU2 ≈ 10Gb/s, OPU3 ≈ 40Gb/s
  – OTM n.m – optical transport module
    • OCh optical channel
      • edge-to-edge lightpath between 3R
    • out of band signalling overhead
    • n = max number of wavelengths
    • m = rate identifier =
      – \{1,2,3,...\} OPUk TDM
      – \{12,23,123\} combinations
WDM Transport Networks

OTN Framing and Multiplexing

- OTN digital multiplexing hierarchy
  - OPUk – OCh payload unit: carries client signals
    - OPU1 ≈ 2.4Gb/s, OPU2 ≈ 10Gb/s, OPU3 ≈ 40Gb/s
  - ODUk – OCh data unit (digital path)
  - OTUk – OCh transport unit (digital section)
- Intended for nearer-term deployment
WDM Transport Networks

OTN Optical Transport Module

- OTM optical multiplexing hierarchy
  - OCh: optical channel (between 3R, 3ROADM, 3ROXC)
  - OMS: optical multiplex section (between PADM, PXC)
  - OTS: optical transport section (between 2R, OMS, OA_{mg})

- PADM: photonic ADM
- ROADM: reconfigurable optical ADM

- Intended for longer-term photonic control

Optical channel OCh
- edge-to-edge optical link_{L2}
- connection rearrangement for flexible routing (ASON)
- information integrity
- OAM&P

Optical multiplex section OMS
- wavelength de/multiplexing $\leftrightarrow$
- integrity, OAM&P

Optical transmission section OTS
- medium specific transmission
- OAM&P, integrity, survivability
### WDM Transport Hierarchy

#### Summary and Comparison

<table>
<thead>
<tr>
<th></th>
<th>PDH</th>
<th>SDH/SONET</th>
<th>OTN DW</th>
<th>OTN OTM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transmission</strong></td>
<td>electronic</td>
<td>optical</td>
<td>optical</td>
<td>optical</td>
</tr>
<tr>
<td><strong>Mux &amp; switching</strong></td>
<td>electronic</td>
<td>electronic</td>
<td>electronic</td>
<td>optical</td>
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<tr>
<td><strong>Multiplex domain</strong></td>
<td>TDM</td>
<td>TDM</td>
<td>TDM</td>
<td>WDM</td>
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<tr>
<td><strong>Synchronisation</strong></td>
<td>plesiochronous</td>
<td>synchronous</td>
<td>synchronous</td>
<td>asynchronous</td>
</tr>
<tr>
<td><strong>Levels</strong></td>
<td>4</td>
<td>5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td><strong>Transparency</strong></td>
<td>opaque</td>
<td>transparent</td>
<td>transparent</td>
<td>opaque</td>
</tr>
<tr>
<td><strong>Rates‡</strong></td>
<td>1.5 – 45 Mb/s</td>
<td>155 – 40 Gb/s</td>
<td>2.5 – 160 Gb/s</td>
<td>–</td>
</tr>
</tbody>
</table>

* as currently defined in standards, not including sub- and intermediate levels
‡ approximate as currently defined in standards, not including STS-1 and sub-rates (DS0 and VTs)

---

### WDM Transport Networks

#### OTN OTH Rates

<table>
<thead>
<tr>
<th>Link type</th>
<th>OTU/ Och rate</th>
<th>DW Ovhd</th>
<th>FEC</th>
<th>OPU Payload</th>
<th>OPU rate</th>
<th>Payloads</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTH</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SO NET</td>
</tr>
<tr>
<td>OTN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>GFP+CRC</td>
</tr>
<tr>
<td>1.25 Gb/s</td>
<td>64 B</td>
<td>1024 B</td>
<td>15 232 B</td>
<td>2.49 Gb/s</td>
<td>STS-192c</td>
<td>Ethernet</td>
</tr>
<tr>
<td>2.49 Gb/s</td>
<td>64 B</td>
<td>1024 B</td>
<td>15 232 B</td>
<td>9.95 Gb/s</td>
<td>STS-384c</td>
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<tr>
<td>4.98 Gb/s</td>
<td>64 B</td>
<td>1024 B</td>
<td>15 232 B</td>
<td>19.9 Gb/s</td>
<td>STS-768c</td>
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<tr>
<td>6.22 Gb/s</td>
<td>64 B</td>
<td>1024 B</td>
<td>15 232 B</td>
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<td>7.44 Gb/s</td>
<td>64 B</td>
<td>1024 B</td>
<td>15 232 B</td>
<td>39.9 Gb/s</td>
<td>STS-2304c</td>
<td></td>
</tr>
</tbody>
</table>

---

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## Link Layer Error Control

### Introduction

- Per-hop error control for frame transfers

*Why?*
Link Layer Error Control

Introduction

- Per-hop error control for frame transfers
- Recall end-to-end arguments:
  - if error checking and correction needed E2E ...
  - it must be done end-to-end by transport (or application)
- Link error control to improve overall performance
  - e.g. ARQ for wireless and satellite links
  - e.g. FEC for fiber optic links

Per Hop Error and Flow Control

LL.5.1 Error Detection and Correction

LL.1 Link layer functions and services
LL.2 Framing and delineation
LL.3 LAN types and topologies
LL.4 Multiplexing and switching
LL.5 Per-hop error and flow control
  LL.5.1 Error detection and correction
  LL.5.2 Error control
  LL.5.3 Flow control
LL.6 Link layer components
LL.7 IP address resolution
LL.8 Residential broadband
Link Layer Error Control
Detection vs. Correction

- Error detection
  - generally useful at link layer to detect errors
  - corrupted frames typically dropped
    why?

- useless data not sent through network consuming resources
- transport layer detects (or signalled) and corrects as necessary
  - it needs to do this anyway
- link layer checks frequently stronger than E2E
  - link frame CRC much stronger than TCP checksum
Link Layer Error Control

Detection vs. Correction

• Error detection
  – generally useful at link layer to *detect* errors
  – corrupted frames typically dropped
    • useless data not sent through network consuming resources
    • transport layer detects (or signalled) and corrects as necessary
      – it needs to do this anyway
  – link layer checks frequently stronger than E2E
    • link frame CRC much stronger than TCP checksum

• Error correction
  – used when hop-by-hop correction needed

Link Layer Error Control

Detection Techniques

• Byte, word, or block
  – parity
  – 2-dimensional parity
  – Hamming codes

• Frame
  – checksum
  – CRC
What is simplest error detection method?

Parity

- **Parity**: detect single errors
  - no ability to correct errors
  - only an odd number of bit errors detected
    - only useful if bit error probability *very low*
Block Error Detection

Parity

- Parity: detect single errors
  - no ability to correct errors
  - only an odd number of bit errors detected
    - only useful if bit error probability very low
- Parity bit covers \( n \) bit block
- Even parity: even number of 1s (including parity)
  - example: 0111 0001 1010 1011 ?
- Odd parity: odd number of 1s (including parity)
  - example: 0111 0001 1010 1011 ?
Block Error Detection

Parity

- Parity: detect single errors
  - no ability to correct errors
  - only an odd number of bit errors detected
    - only useful if bit error probability very low
- Parity bit covers n bit block
- Even parity: even number of 1s (including parity)
  - example: 0111 0001 1010 1011 1
- Odd parity: odd number of 1s (including parity)
  - example: 0111 0001 1010 1011 0

Extension to detect which bit in error?

Block Error Detection & Correction

2-Dimensional Parity

- 2-dimensional parity: correct single bit errors
  - detects which bit flipped and can therefore correct
Block Error Detection & Correction

2-Dimensional Parity

- 2-dimensional parity: correct single bit errors
  - detects which bit flipped and can therefore correct
- \( n + m \) parity bits covers \( n \times m \) bit block
  - \( n \) row parity bits cover \( m \) data bits each
  - \( m \) column parity bits cover \( n \) data bits each

Example (odd parity)

\[
\begin{align*}
0111 & \ 0 \\
0001 & \ 0 \\
1010 & \ 1 \\
1011 & \ 0 \\
1000 & \ \end{align*}
\]
Block Error Detection & Correction

2-Dimensional Parity

- 2-dimensional parity: correct single bit errors
  - detects *which* bit flipped and can therefore correct
- $n + m$ parity bits covers $n \times m$ bit block
  - $n$ row parity bits cover $m$ data bits each
  - $m$ column parity bits cover $n$ data bits each
- Example (odd parity)

```
0111 0
0001 0
1010 1
1011 0
1000 1
```

← detects and can correct flip

Block Error Detection & Correction

Hamming Codes

- Hamming codes: correct single bit errors
  - detects *which* bit flipped and can therefore correct
  - $k$ parity bits per block cover different sets of $n$ data bits
Block Error Detection & Correction

Hamming Codes

- Hamming codes: correct single bit errors
  - detects *which* bit flipped and can therefore correct
  - $k$ parity bits per block cover different sets of $n$ data bits

- SECDED: single error correct double error detect

Example 4 data bits covered by 3 parity bits
- parity bits $p_2, p_1, p_0$ interleaved with data bits $d_3, d_2, d_1, d_0$

- $1011010$ covered by $p_0$
- $1110100$ covered by $p_1$
- $1011010$ covered by $p_2$
Block Error Detection & Correction

Hamming Codes

- Hamming codes: correct single bit errors
  - detects *which* bit flipped and can therefore correct
  - *k* parity bits per block cover different sets of *n* data bits
- SECDED: single error correct double error detect
- Example 4 data bits covered by 3 parity bits
  - parity bits *p*₂ *p*₁ *p*₀ interleaved with data bits *d*₃ *d*₂ *d*₁ *d*₀

```
1011010  d₃ d₂ d₁ d₀ p₂ p₁ p₀ 1111010
```

```
1-1-0-1  d₁ d₀ covered by p₀  1-1-0-1
10-00-  d₃ d₂ d₀ covered by p₁  11-00-  p₁ detects error
1011-   d₃ d₂ d₁ covered by p₂  1111-  p₂ detects error
```

Frame Error Detection

Checksum

- Detect errors in PDU
- Binary addition of bytes/words
  - sender: compute checksum and insert in header/trailer
  - receiver: compute checksum and compare to header/trailer

*Advantages?  
*Disadvantages?*
Frame Error Detection

Checksum

- Detect errors in PDU
- Binary addition of bytes/words
  - sender: compute checksum and insert in header/trailer
  - receiver: compute checksum and compare to header/trailer
- Advantage:
  - simple to compute
- Disadvantage:
  - weak detection of errors
  - some bit-flip combinations may remain undetected
Frame Error Detection

CRC

- Cyclic redundancy check
  - stronger error detection for PDU

- View data bits, $D$, as a binary number
  - choose $r + 1$ bit pattern (generator), $G$

- Goal: choose $r$ CRC bits $R$ such that
  - $<D,R>$ exactly divisible by $G$ (modulo 2)
  - receiver knows $G$, divides $<D,R>$ by $G$
    - if non-zero remainder: error detected
  - can detect all burst errors less than $r + 1$ bits
Frame Error Detection & Correction

**FEC**

- Forward error correction
  - each PDU has error correcting header
  - combination of header/payload allows significant correction

- Open-loop error control
  - errors corrected at the receiver without retransmissions

*how does this help?*
Frame Error Detection & Correction

**FEC**

- **Forward error correction**
  - each PDU has error correcting header
  - combination of header/payload allows significant correction

- **Open-loop error control**
  - errors corrected at the receiver without retransmissions
  - reduces need for over long delay links for:
    - retransmissions
    - sender buffers
  - statistical reliability good enough for some applications
  - e.g. G.975 (255,239) Reed Solomon code in SDH/SONET

- Note: FEC can also be done end-to-end
  - but TCP doesn't support it
Per Hop Error and Flow Control

LL.5.2 Error Control

Error Control

Overview

- Error control mechanisms
  - detect lost or corrupted frames
  - retransmit as needed
  - generally only for very lossy links
    - satellite, wireless, optical with long inter-regen spans
      - why?
Error Control

Overview

- Error control mechanisms
  - detect lost or corrupted frames
  - retransmit as needed
  - generally only for very lossy links
    - satellite, wireless, optical with long inter-regen spans
    - recall end-to-end arguments

- Same as E2E mechanisms *Lecture TL*
  - unrestricted simplex (baseline no error control)
  - stop-and-wait
  - go-back-\(n\)
  - selective repeat
Per Hop Error and Flow Control

**LL.5.3 Flow Control**

LL.1 Link layer functions and services
LL.2 Framing and delineation
LL.3 LAN types and topologies
LL.4 Multiplexing and switching
LL.5 Per-hop error and flow control
   LL.5.1 Error detection and correction
   LL.5.2 Error control
   LL.5.3 Flow control
LL.6 Link layer components
LL.7 IP address resolution
LL.8 Residential broadband

Link Flow Control

**Negotiation**

- Flow control

*why?*
Link Flow Control

Negotiation

- Flow control
  - sender transmits at a rate that will not overwhelm receiver

- Initial rate negotiation
  - automatic negotiation of parameters
    - e.g. modem rate
    - e.g. Ethernet rate (10M/100M/1G) b/s
Link Flow Control

**Negotiation**

- **Flow control**
  - sender transmits at a rate that will not overwhelm **receiver**
- **Initial rate negotiation**
  - automatic negotiation of parameters
    - e.g. modem rate
    - e.g. Ethernet rate (10M/100M/1G) b/s
- **Dynamic flow control**
  - may be needed end-to-end
  - most modern links do **not** need HBH flow control
Link Layer Components

Types

- Amplifiers and regenerators
- Multiplexors and cross-connects
- Optical wavelength converters
- Hubs and bridges
- Time slot interchangers (TSI)
  - time division switches

Amplifiers and Regenerators

- Amplifiers: analog
  - example: optical EDFA (erbium doped fiber amplifier)
    every few hundred km
**Link Layer Components**

**Amplifiers and Regenerators**

- **Amplifiers:** analog
  - example: optical EDFA (erbium doped fiber amplifier) every few hundred km
- **Regenerators:** A/D/A
  - 2R: regeneration and reshaping preserves timing
  - 3R: regeneration, reshaping, and retiming
  - examples:
    - optical 2R and 3R
    - microwave relays
    - bent-path satellite links

**Multiplexors and Cross-Connects**

- **Multiplexors / demultiplexors**
  - aggregate multiple virtual links onto a physical link
    - example: T-carrier, point-to-point SONET, WDM multiplexors
    - example: SONET ring add-drop multiplexors
Link Layer Components

Multiplexors and Cross-Connects

- Multiplexors / demultiplexors
  - aggregate multiple virtual links onto a physical link
    - example: T-carrier, point-to-point SONET, WDM multiplexors
    - example: SONET ring add-drop multiplexors
- Cross-connects
  - layer 2 switch with relatively static configuration
    - example: SONET cross-connect between rings

Link Layer Components

Optical Wavelength Converters

- O/E/O: convert through electronic domain
  - expensive
  - lose advantages of all-optical lightpaths
## Link Layer Components

### Optical Wavelength Converters

- **O/E/O:** convert through electronic domain
  - expensive
  - lose advantages of all-optical lightpaths
- **Optical domain:** future technology
  - cross-modulation: input modulates laser output at new $\lambda$
  - coherent effects: similar to four wave mixing
- **Small cheap DWDM multiwavelength converters will**
  - reduce some lightpath assignment constraints
  - will require modification of lightpath routing algorithms

---

### LAN Components

**How to extend the reach of LAN segment?**

*original shared medium bus or ring*
Link Layer Components

**Bridges**

- Bridges connect LAN *segments*
  - extend reach beyond limits
  - important for early LANS
    - e.g. Ethernet extension

- Promiscuous
  - repeat (pass) *all* frames

*network scalability?*
Link Layer Components

Bridges

• Bridges connect LAN segments
  – extend reach beyond limits
  – important for early LANS
    • e.g. Ethernet extension

• Promiscuous
  – repeat (pass) all frames
  – all interconnected segments share intra-segment frames
    alternative?

Learning bridge
  – learns local segment addresses
    • snooped on source MAC address in frame header
  – only repeat frames destined for other segments
Link Layer Components

Hubs

• Early LANs dictated wiring topology
  – linear segments for Ethernet
  – loops for token ring

Problems?
Link Layer Components

Hubs

- Early LANs dictated wiring topology
  - linear segments for Ethernet
  - rings for token ring
- Office topology frequently didn’t match LAN topology
  - Ethernet bridges frequently needed to bridge hallways
- End user could take down network
  - by disconnecting network interface
    - token ring
    - some Ethernet links (e.g. 10Base2)
  - sys/netadmins would have to run from office to office

Response?

- Alternative
  - use a star wiring plan
  - host/station links all go to a hub in a wiring closet
Link Layer Components

Hubs

- Alternative
  - use a star wiring plan
  - host/station links all go to a *hub* in a *wiring closet*
- More flexible wiring plan
- Central location for debugging

Network scalability?
Link Layer Components

Hubs

- Alternative
  - use a star wiring plan
  - host/station links all go to a hub in a wiring closet
- More flexible wiring plan
- Central location for debugging
- Hub is still shared medium bottleneck

Alternative?

Link Layer Components

LAN Switches

- Alternative
  - replace hub with a space division switch
Link Layer Components

LAN Switches

- Alternative
  - replace hub with a space division switch
- LAN switch
  - switches on layer 2 (MAC address) header
  - full bandwidth of each link available
    - assuming non-blocking switch fabric

why?
Link Layer Components

LAN Switches

- Alternative
  - replace hub with a space division switch
- LAN switch
  - switches on layer 2 (MAC address) header
  - full bandwidth of each link available
    - assuming non-blocking switch fabric
  - not a substitute for L3 (IP) switch (router)
    - no IP routing and forwarding capability

Link Layer and LANs

LL.7 VLANs, L2 Tunnels, and ARP

- LL.1 Link layer functions and services
- LL.2 Framing and delineation
- LL.3 LAN types and topologies
- LL.4 Multiplexing and switching
- LL.5 Per-hop error and flow control
- LL.6 Link layer components
- LL.7 VLANs, L2 tunnels, and ARP
  - LL.7.1 Virtual LANs
  - LL.7.2 Layer 2 tunnels
  - LL.7.3 IP address resolution
- LL.8 Residential broadband
VLANs, L2 Tunnels, and ARP

**Motivation**

- LANs operate as part of Global Internet
  - using IP
- Several technologies needed for this
  - VLANs: Virtual LANs
  - L2 tunnels: link emulation over IP
  - ARP: IP address resolution protocol

---

**LL.7.1 Virtual LANs**

- Link layer functions and services
- Framing and delineation
- LAN types and topologies
- Multiplexing and switching
- Per-hop error and flow control
- Link layer components
- VLANs, L2 tunnels, and ARP
  - Virtual LANs
  - Layer 2 tunnels
  - IP address resolution
- Residential broadband
Virtual LANs

Motivation

- LANs provide useful infrastructure at network edge
  - cheap and simple interconnection for workgroup
  - “plug-and-play” interfaces
  - no need to understand or configure IP routing

**What if workgroup doesn’t match physical topology?**

- reasons?

- Workgroup may not match physical topology
  - multiple workgroups share LAN infrastructure
  - workgroups scattered across wide area Internet
Virtual LANs

VLAN Topology Alternatives

- Workgroup may not match physical topology
  - *virtual LANs* (VLANs)
- Multiple workgroups share LAN infrastructure
  - VLANs segregate physical LANs
  - traffic isolation
    - separate L2 broadcast domain
    - security: prevent L2 frames to be visible across VLANs
- Workgroup scattered across wide-area Internet
  - layer 2 tunnels extend LAN with L2 tunnel in IP datagram

How to configure VLANs in a L2 switch?
Virtual LANs

L2 Switch Configuration

- VLANs defined by assigning VLAN id to switch port
  - end systems must plug into correct physical port subset
  - logical division into multiple switches

How to interconnect VLANs?

VLAN interconnection
- must be done with IP router
Virtual LANs

L2 Switch Configuration

- VLANs defined by assigning VLAN id to switch port
  - end systems must plug into correct physical port subset
  - logical division into multiple switches
- VLAN interconnection
  - must be done with IP router
  - some VLAN switches have built-in router for this

Virtual LANs

Scaling to Multiple Switches

- VLANs defined by assigning VLAN id to switch port
  - end systems must plug into correct physical port subset
  - logical division into multiple switches

How to extend to multiple switches?
Virtual LANs
Scaling to Multiple Switches

- VLANs defined by assigning VLAN id to switch port
  - end systems must plug into correct physical port subset
  - logical division into multiple switches
- VLAN extension
  - link/VLAN between switches
    - problem?

- VLAN extension
  - link/VLAN between switches
    - not scalable
Virtual LANs
Scaling to Multiple Switches

- VLANs defined by assigning VLAN id to switch port
  - end systems must plug into correct physical port subset
  - logical division into multiple switches
- VLAN extension
  - link/VLAN between switches
  - VLAN trunking

how to segregate frames?
Virtual LANs
802.1Q Tagging

- VLAN tagging
  - additional field with VLAN id

where must it go?

MAC header
30B

LLC/SNAP subheader
8B

payload

len/type

FCS

preamble + SFD

Virtual LANs
802.1Q Tagging

- VLAN tagging: IEEE 802.1Q
  - additional field with VLAN id
  - VLAN tag must go after preamble
    - inserted into header after addresses
Virtual LANs

802.1Q Tagging

- VLAN tag [4B]
  - TPID (tag prot. id) [2B] = 0800
    - located at type/len position
    - defines tagged/non-tagged
  - PCP: prty. ctl. point [3b]
    - 802.1p frame priority [0..7]
  - CFI: cannonical fmt. id [1b]
    - compatibility with non-Enet
      - 0 = Ethernet
      - 1 = do not bridge to untagged port
  - VID: VLAN id [12b]
    - $2^{12} = 4096$ possible VLANs/trunk

VLANs, L2 Tunnels, and ARP

LL.7.2 Layer 2 Tunnels

LL.1 Link layer functions and services
LL.2 Framing and delineation
LL.3 LAN types and topologies
LL.4 Multiplexing and switching
LL.5 Per-hop error and switching
LL.6 Link layer components
LL.7 VLANs, L2 tunnels, and ARP
  LL.7.1 Virtual LANs
  LL.7.2 Layer 2 tunnels
  LL.7.3 IP address resolution
LL.8 Residential broadband
Layer 2 Tunnels

Motivation

- Layer 2 tunnels
  - permit LAN extension across longer-than-LAN networks
  - permits VLAN interconnection across IP Internet

L2TP Encapsulation

- L2TP: layer 2 tunneling protocol
  - L2TPv3: current version [RFC 3931]
- L2 frame encapsulated in
  - L2TP data message in
  - UDP datagram flow in
  - IP datagram through Internet in
  - L2 frames on each link
Layer 2 Tunnels

L2TP Operation

- L2TP operation
  - L2TP establishes reliable control channel
  - transfers data in unreliable data channel

L2TP Data Format

- Data message format
  - flags [1b each] and version info
    - T: type 0=data, 1=control
    - L: length present
    - S: sequence present
    - O: offset present
    - P: priority for data msg.
      version [4b]
  - ...

- Flags & version
  - length
    - tunnel id
    - session id
    - Ns
    - Nr
    - offset size
    - offset pad
  - data
Layer 2 Tunnels
L2TP Data Format

- Data message format
  - flags and version info [16b]
  - length: total in B [16b]
  - tunnel id [16b]
  - session id in tunnel [16b]
  - Ns: seq. # (opt) [16b]
  - Nr: seq. # exp. (opt) [16b]
  - offset id: # bytes until payload [16b]
  - offset pad [variable]
  - payload: encapsulated L2 frame

<table>
<thead>
<tr>
<th>flags &amp; version</th>
<th>length</th>
</tr>
</thead>
<tbody>
<tr>
<td>tunnel id</td>
<td>session id</td>
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<tr>
<td>offset size</td>
<td>offset pad</td>
</tr>
<tr>
<td>data</td>
<td></td>
</tr>
</tbody>
</table>
IP Address Resolution

ARP Motivation

- Addresses used for forwarding
  - IP addresses for Internet layer 3 IP switching (routing)
- What about layer 2 addressing?
  
  motivation?
IP Address Resolution

ARP Motivation

• Addresses used for forwarding
  – IP addresses for Internet layer 3 IP switching (routing)

• What about layer 2 addressing?
  – in shared medium MAC address specifies destination station
  – legacy Ethernet and thus switched Ethernet
  – 802.11 lecture MW
IP Address Resolution

ARP Motivation

- Addresses used for forwarding
  - IP addresses for Internet layer 3 IP switching (routing)
- What about layer 2 addressing?
  - in shared medium MAC address specifies destination station
  - legacy Ethernet and thus switched Ethernet
  - 802.11 *lecture MW*
- Problem: incoming IP packet has only address
  - *how to determine station address to put in MAC header?*
IP Address Resolution

ARP Overview

- ARP (address resolution protocol) [RFC 0826]
  - translates IP address → L2 LAN (MAC) address
  - router broadcasts REQUEST; node responds with REPLY

- IP router at LAN edge has *ARP table*
  - IP → MAC mappings for some nodes
**IP Address Resolution**

**ARP Overview**

- ARP (address resolution protocol) [RFC 0826]
  - translates IP address → L2 LAN (MAC) address
  - router broadcasts REQUEST; node responds with REPLY
- IP router at LAN edge has **ARP table**
  - IP → MAC mappings for some nodes
- ARP designed as multiprotocol
  - any network protocol over any LAN/MAC protocol
  - type and address length fields define L2 and L3 protocol
- Reverse ARP (RARP) [RFC 0903]
  - L2 LAN → L3 IP address translation
IP Address Resolution

ARP Packets: Layer 2 Fields

- L2 MAC fields (hardware)
  - hardware type: 1 = Ethernet (non LLC/SNAP)
  - 6 = IEEE802 (with LLC/SNAP)
  - address length: 6 for a 48b MAC address
  - source hardware address (SHA)
  - target hardware address (THA)

<table>
<thead>
<tr>
<th>Hardware Type</th>
<th>Protocol Type 0800</th>
<th>Operation Code</th>
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<tbody>
<tr>
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<th>THA31-32</th>
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<tr>
<td>SPA15-0</td>
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IP Address Resolution

ARP Packets: Layer 3 Fields

- L3 network fields (protocol)
  - protocol type: IP = 0800  Ethertype
    [http://www.iana.org/assignments/ethernet-numbers]
  - address length: 4 for a 32b IP address
  - source protocol address (SPA)
  - target protocol address (TPA)

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IP Address Resolution
ARP Operation: ARP Table

- IP router at LAN edge has **ARP table**
  - IP → MAC mappings for some nodes
  - (IP-addr, MAC-addr, TTL)
    - soft state: TTL time to live before entry flushed (typ. 20 min.)

### ARP Packets: Operation Codes

- **Operation code**
  - [http://www.iana.org/assignments/arp-parameters]
  - \( \text{\textbackslash h}01 = \text{ARP REQUEST} \quad \text{\textbackslash h}03 = \text{reverse REQUEST} \)
  - \( \text{\textbackslash h}02 = \text{ARP REPLY} \quad \text{\textbackslash h}04 = \text{reverse REPLY} \)

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</tr>
<tr>
<td>THA\text{\textbackslash h}15-0</td>
<td>TPA\text{\textbackslash h}15-0</td>
</tr>
</tbody>
</table>

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IP Address Resolution

**ARP Operation: Request**

- IP router at LAN edge has ARP table
  - IP → MAC mappings for some nodes
- When source node on LAN needs to send datagram
  - check ARP table for entry
  - if present use MAC address
  - if not present, broadcast ARP REQUEST to LAN segment
    - THA = FF-FF-FF-FF-FF-FF
    - SPA,SHA = IP, MAC address of sender
IP Address Resolution

ARP Operation: Request

- IP router at LAN edge has ARP table
  - IP → MAC mappings for some nodes
- When source node on LAN needs to send datagram
  - check ARP table for entry
  - if present use MAC address
  - if not present, broadcast ARP REQUEST to LAN segment
    - THA = FF-FF-FF-FF-FF for broadcast
    - TPA = IP address of target
    - SPA,SHA = IP,MAC address of sender (why?)
IP Address Resolution

ARP Operation: Request

- IP router at LAN edge has ARP table
  - IP → MAC mappings for some nodes
- When source node on LAN needs to send datagram
  - check ARP table for entry
  - if present use MAC address
  - if not present, broadcast ARP REQUEST to LAN segment
    - THA = FF-FF-FF-FF-FF for broadcast
    - TPA = IP address of target
    - SPA,SHA = IP,MAC address of sender (needed for REPLY)
    - all other nodes see and cache SHA→SPA into their ARP tables

ARP Operation: Reply

- IP router at LAN edge has ARP table
  - IP → MAC mappings for some nodes
- When source node on LAN needs to send datagram
  - check ARP table for entry
  - if present use MAC address
  - if not present, broadcast ARP REQUEST to LAN segment
    - target unicasts REPLY to source
      - THA = MAC address of source
      - SHA = IP address of source
      - SPA,SHA = IP,MAC address of target (now source in REPLY)
IP Address Resolution

ARP Operation: Reply

- IP router at LAN edge has ARP table
  - IP → MAC mappings for some nodes
- When source node on LAN needs to send datagram
  - check ARP table for entry
  - if present use MAC address
  - if not present, broadcast ARP REQUEST to LAN segment
  - target *unicasts* REPLY to source
    - THA = MAC address of source
    - SHA = IP address of source
    - SPA,SHA = IP,MAC address of target (now source in REPLY)
    - other nodes do not cache THA→TPA since unicast
Residential Broadband Overview

- **RBB** (residential broadband)
  - umbrella term for residential Internet access technologies
  - significantly higher data rates than 56kb/s dialup modem
  - typically a combination of link and physical layers
  - frequently called *last mile* or *first mile*

- **Standards**
  - proprietary technologies
  - ad hoc standards from industry fora
  - standards (ITU, ANSI, IEEE)

Residential Broadband Motivation

- **Better Internet access**
  - higher data rates
  - always connected without interfering with telephone

- **Supports** *triple play* service
  - data to/from Internet
  - voice to/from PSTN
  - video from head-end
Residential Broadband Deployment Strategies

- Reusing existing infrastructure
  - PSTN: DSL – digital subscriber line
  - CATV: HFC – hybrid fiber coax
  - power grid: broadband over power line
- Deployment of new infrastructure
  - fiber
    - to the neighbourhood: FTTN
    - to the home: FTTH
  - wireless
    - 802.16 lecture MW
Residential Broadband
Digital Subscriber Line Overview

- DSL (digital subscriber line) also xDSL
  - based on PSTN local loop infrastructure
- Local loop reuse
  - entire local loop: central office to home

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<td>copper</td>
<td>reuse</td>
<td>future</td>
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KU EECS 780 – Communication Networks – Link Layer and LANs

Residential Broadband
Digital Subscriber Line Overview

- DSL (digital subscriber line) also xDSL
  - based on PSTN local loop infrastructure
- Local loop reuse
  - entire local loop: central office to home
  - may be hybrid
    - fiber to neighbourhood node (e.g. FTTN, VDSL)
    - twisted pair to and in home
- POTS sharing alternatives
  - transparent multiplexing with POTS for residential use
  - dedicated pair originally for business use
- DSL forum dslforum.org
ADSL
Original Motivation

- ADSL (asymmetric DSL) [ANSI T1.413] / [ITU G.992.1]
  - developed by Bellcore to deliver video to home
    - video market didn’t develop and not enough streams supported
    - but demand for always-on higher-rate Internet access did
  - assumed asymmetric data access
    - Web access and video download
    - not peer-to-peer file sharing
    - exploits asymmetry to reduce interference in DSLAM
  - frequency multiplexed with POTS
    - uses DMT coding to provide
    - requires splitter in home to segregate data from POTS

Digital Subscriber Lines
Standards Development

- Original development: Bellcore
- Early deployments in the 1990s
  - CAP (carrierless amplitude phase modulation) line coding
  - DMT (discrete multitone) line coding
- Subsequent standards: ITU Q.99X
  - handshake procedures [Q.994.1] 2003 between transceivers
  - progressive increases in line rate with DMT enhancements
- Industry forum: DSL Forum technical reports
  - www.dslforum.org/techwork/treports.shtml
  - DSL forum rounds up; rates more optimistic than standards
Digital Subscriber Lines

HDSL Motivation

- HDSL [G991.1] 1999
  - replacement for T1 (1.544 Mb/s) and E1 (2.048 Mb/s) loops
  - repeaters not needed
  - 2 dedicated pairs cannot be shared with POTS
  - generally only used by businesses
  - relatively expensive due to market and tariffs

- SHDSL [G991.2]
  - higher rate evolution of HDSL
  - 2.312 Mb/s over 2 pairs in 2001
  - 5.696 Mb/s over 4 pairs in 2003

ADSL

Modulation and Spectrum

- POTS telephony
  - UTP (unshielded twisted pair) local loop
  - analog baseband signal to 12 kHz
  - significantly more bandwidth available with clever coding

- ADSL uses frequencies above 12 kHz
  - upstream: 25.875 – 138 kHz
  - downstream: 138 – 1104 kHz
ADSL
Central Office and Residence Architecture

- DSL multiplexed with POTS between home and CO
  - splitters on each side

ADSL Lite Motivation

- ADSL Lite [ANSI T1.413] / [ITU G.992.2]
  - eliminates need for splitters
  - DSL modems can be plugged into any jack
ADSL Lite
Central Office and Residence Architecture

- DSL multiplexed with POTS between home and CO
  - subscriber side does not need splitter
  - DSL modems can be plugged into any RJ-11 phone jack

ADSL
Transfer Modes and Framing

- ATM

- STM
Digital Subscriber Lines

ADSL2 Motivation

- **ADSL2**
  - splitter [ITU G.992.3] 2002 updated 2005
  - splitterless [ITU G.992.3] 2002
  - evolution of ADSL and ADSL lite to higher rates
  - choice of longer reach or higher rates than ADSL
- **ADSL2+ (extended bandwidth ADSL2)** [ITU G.992.5]
  - doubles ADSL2 carrier frequency and rates

Digital Subscriber Lines

VDSL Motivation

- **VDSL (very-high-speed DSL)** [ITU G.993.1] 2004
  - field trials began in the mid 1990s
- **Higher rates than available with ADSL**
  - by using FTTN (fiber to the node)
  - but reusing twisted pair into home
  - symmetric VDSL: 26 Mb/s full duplex up to ~300 m
  - asymmetric VDSL: 52 Mb/s downstream, 12 Mb/s upstream
- **VDSL2** [ITU G.993.2] 2006
  - higher rate version of VDSL
  - symmetric VDSL2: 100 Mb/s full duplex
  - degraded to ADSL-like performance for long reach
• DSL data rates fall significantly with loop length

**Digital Subscriber Lines**

**Advantages and Disadvantages**

*Advantages of ADSL?*
Advantages of ADSL
- reuse of existing local loops in their entirety
  - shared with POTS without need for additional pair
- dedicated point-to-point links
  - bandwidth not shared with other users
  - better latency characteristics

Disadvantages of ADSL?

- lower rates than FTTN architectures (VDSL and HFC)
- rate dependent length, gauge, wire and termination quality
- blocked by load coils (POTS line extenders)
- ADSL lite limited by number and spacing of bridge taps
Digital Subscriber Lines

**Advantages and Disadvantages**

- **Advantages of VDSL**
  - reuse of existing twisted pair from street to premise

- **Disadvantages of VDSL**
  - significant incremental cost of deployment over ADSL
  - rate drops rapidly with distance
  - rate highly dependent on wire gauge and quality

- **Advantage of HDSL/SDSL**
  - T1/E1 repeaterless circuit extension over existing local loop

- **Disadvantage of HDSL/SDSL**
  - traditionally limited to businesses due to rate structure
### Digital Subscriber Lines
#### Varieties and Characteristics

<table>
<thead>
<tr>
<th>Link Type</th>
<th>Standard</th>
<th>Year</th>
<th>Type</th>
<th>Down Rate</th>
<th>Up Rate</th>
<th>Range</th>
<th>Coding</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDSL</td>
<td>G.991.1</td>
<td>1996</td>
<td>dedicated two pairs</td>
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<td>2.048 Mb/s</td>
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<td>2001</td>
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<td>2.312 Mb/s</td>
<td>2.312 Mb/s</td>
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<td>1995</td>
<td>POTS shared</td>
<td>6.144 Mb/s</td>
<td>640 kb/s</td>
<td>3 km</td>
<td>DMT</td>
<td>requires splitter</td>
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<td>8–12 Mb/s</td>
<td>8–12 Mb/s</td>
<td>1–3.5 Mb/s</td>
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<td>26 Mb/s</td>
<td>12 Mb/s</td>
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<td>300 m</td>
<td>DMT</td>
<td>FTTN</td>
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</tbody>
</table>

### Residential Broadband
#### LL.8.2 Hybrid Fiber Coax

- LL.1 Link layer functions and services
- LL.2 Framing and delineation
- LL.3 LAN types and topologies
- LL.4 Multiplexing and switching
- LL.5 Per-hop error and flow control
- LL.6 Link layer components
- LL.7 IP address resolution

**LL.8 Residential broadband**

- LL.8.1 DSL
- LL.8.2 HFC
- LL.8.3 FTTx and PONs
- LL.8.4 BPL
Residential Broadband
Hybrid Fiber Coax Overview

- HFC (hybrid fiber coax)
  - based on CATV distribution infrastructure
  - fiber to neighbourhood node
  - coax to and within home

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Head end is CATV equivalent to PTSN central office
- fiber links from head end to fiber node in neighbourhoods
  - optical ↔ electrical conversion
- coax distribution lines serve multiple houses (10 – 2000)
  - amplifiers may be used to extend coax runs
  - subscriber drops tap into distribution cable
Data multiplexed with analog and digital TV channels
- IP telephony delivered over data stream

Data spectrum: FDM – frequency division multiplexed
- Upstream: 5 – 42 MHz
  - below broadcast channel 2
  - QPSK typical, QAM-16 optional
- Downstream: 91 – 857 MHz
  - spectrum divided with analog and digital television
  - QAM-64 or -256 downlink shared among users
    - per user bandwidth depends on network engineering and load
DOCSIS Overview

- Data over cable interface specification (DOCSIS)
  - Originally begun as IEEE 802.14
  - CableLabs standard specification
    - DOCSIS 2.0 and 3.0 www.cablemodem.com/specifications/
  - DOCSIS 2.0 standardised as ITU J.122

- DOCSIS versions
  - 1.0: downstream over HFC, upstream using POTS
  - 1.1: downstream and upstream using HFC
  - 2.0: higher upstream rate of 30.72 Mb/s
  - 3.0: higher upstream and downstream rates > 100 Mb/s

DOCSIS Protocol Stack

- DOCSIS standards
  - operations interfaces
  - security
  - physical layer
  - MAC

---

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ITTC

HFC

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ITTC
HFC

DOCSIS Frame Formats

- Convergence sublayer header
  - downstream: MPEG header type=data
  - upstream: PMD preamble
- MAC header
  - FC: frame control – type of header [1B]
  - MAC_PARM: MAC parameters [1B]
  - LEN: length of EDR+payload [2B]
  - EHDR: extended header [0–240B]
  - HCS: header check sequence [2B]
- Payload
  - Ethernet frame encapsulating user data

<table>
<thead>
<tr>
<th>MPEG (downstream)</th>
<th>PMD (upstream)</th>
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<tbody>
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<td>FC</td>
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Advantages and Disadvantages

Advantages of HFC?
Advantages and Disadvantages

• Advantages of HFC
  – reuse of existing CATV plant
    • but required upgrades for upstream channels

• Disadvantages of HFC
  – shared medium infrastructure
  – usable data rate and latency per user highly dependent on...
    • number of homes in fiber node area
    • take rate (number of subscribers in fiber node area)
    • traffic demand
HFC

DOCSIS Varieties and Characteristics

<table>
<thead>
<tr>
<th>Link Type</th>
<th>Standard</th>
<th>Year</th>
<th>Downstream</th>
<th>Rate</th>
<th>Coding</th>
<th>Rate</th>
<th>Coding</th>
<th>MAC</th>
<th>Notes</th>
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<tr>
<td>DOCSIS 1.0</td>
<td>1.112</td>
<td>1999</td>
<td>30.342 Mb/s</td>
<td>16-QAM, 128-QAM</td>
<td>2001</td>
<td>16-QAM, 128-QAM</td>
<td>120 kbps</td>
<td>QPSK 16-QAM</td>
<td>PSTN upstream</td>
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<td>1.112</td>
<td>1999</td>
<td>30.342 Mb/s</td>
<td>64-QAM, 256-QAM</td>
<td>2001</td>
<td>64-QAM, 256-QAM</td>
<td>120 kbps</td>
<td>QPSK 16-QAM</td>
<td>QoS X.509 sec</td>
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<td></td>
<td>1.222</td>
<td>2006</td>
<td>160 Mb/s</td>
<td>64-QAM, 256-QAM</td>
<td>2006</td>
<td>64-QAM, 256-QAM</td>
<td>120 Mb/s</td>
<td>QPSK 16-QAM</td>
<td>QoS X.509 sec</td>
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</table>

Residential Broadband

LL.8.3 FTTx and PONs

LL.1 Link layer functions and services
LL.2 Framing and delineation
LL.3 LAN types and topologies
LL.4 Multiplexing and switching
LL.5 Per-hop error and flow control
LL.6 Link layer components
LL.7 IP address resolution
LL.8 Residential broadband
   LL.8.1 DSL
   LL.8.2 HFC
   LL.8.3 FTTx and PONs
   LL.8.4 BPL
Residential Broadband
Fiber to the Premises Overview

- FTTx (fiber to the x)
  - fiber replaces the local loop
  - may reuse entire local loop: central office to home
  - may be hybrid
    - fiber to neighbourhood node
    - twisted pair to and in home
- FTTx varieties
  - FTTH/FTTB: fiber to the home / building
  - FTTC: fiber to the curb – coax or twisted pair to the home
  - FTTN: fiber to the node / neighborhood = VDSL

Residential Broadband
Passive Optical Network (PON) Overview

- PON (passive optical network)
  - cost-efficient way of delivering FTTH, FTTC, and FTTN/VDSL

<table>
<thead>
<tr>
<th>Technology</th>
<th>Medium</th>
<th>Deployment</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSL</td>
<td>twisted pair</td>
<td>widespread</td>
</tr>
<tr>
<td>HFC</td>
<td>coax</td>
<td>widespread</td>
</tr>
<tr>
<td>FTTX PON</td>
<td>fiber</td>
<td>emerging</td>
</tr>
<tr>
<td>BPL</td>
<td>copper</td>
<td>future</td>
</tr>
</tbody>
</table>
Residential Broadband
Passive Optical Network (PON) Overview

- PON (passive optical network)
  - cost-efficient way of delivering FTTH, FTTC, and FTTN/VDSL
- Uses shared fiber infrastructure
  - tree topology CWDM (coarse WDM)
  - downstream broadcast and select
  - upstream TDM

Residential Broadband
Passive Optical Network (PON) Overview

- CWDM (coarse WDM): 3 of 18 G.694.2 frequencies
  - 1310nm upstream data+voice TDMA
    - large band gap from other two frequencies
    - outside non-temperature controlled transmitter drift
  - 1490nm downstream data+voice broadcast and select
  - 1550nm downstream video broadcast
Residential Broadband

Passive Optical Network (PON) Architecture

- Provider side – OLT (optical line terminal)
  - connects to Internet, PSTN, & CATV infrastructure (satellite, wired)
- Subscriber side
  - ONT/U (optical network terminal/unit) for FTTH/FTTC

Residential Broadband

LL.8.4 Broadband over Power Line

LL.1 Link layer functions and services
LL.2 Framing and delineation
LL.3 LAN types and topologies
LL.4 Multiplexing and switching
LL.5 Per-hop error and flow control
LL.6 Link layer components
LL.7 IP address resolution
LL.8 Residential broadband
   LL.8.1 DSL
   LL.8.2 HFC
   LL.8.3 FTTx and PONs
   LL.8.4 BPL
Residential Broadband

Broadband Over Power Line Overview

- BPL (broadband over power line)
  - last ubiquitous infrastructure practical to consider as communication medium

<table>
<thead>
<tr>
<th>Technology</th>
<th>Medium</th>
<th>Infrastructure</th>
<th>Deployment</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSL</td>
<td>twisted pair</td>
<td>reuse</td>
<td>widespread</td>
</tr>
<tr>
<td>HFC</td>
<td>coax</td>
<td>reuse</td>
<td>widespread</td>
</tr>
<tr>
<td>FTTX PON</td>
<td>fiber</td>
<td>new</td>
<td>emerging</td>
</tr>
<tr>
<td>BPL</td>
<td>copper</td>
<td>reuse</td>
<td>future</td>
</tr>
</tbody>
</table>

- BPL types
  - home automation (e.g. lighting)
    - not a data networking technology
    - e.g. X10 and Insteon
  - in home
    - LAN interconnection of devices within a home
  - access
    - Internet access though public utility power lines
Residential Broadband

**BPL Challenges**

- BPL challenges
  - home wiring and power grid not designed for data
  - interference and noise effects of powered devices
  - transformers between distribution segments (esp. US)
  - European and US power distribution very different

**In-Home BPL Products**

- In-home BPL
  - various products available now
  - proprietary HomePlug Power Alliance specifications
Residential Broadband

Emerging BPL Technology

- UPA: Universal Powerline Association  www.upaplc.org
  - industry forum to promote open standards
    - in-home standard
    - access standard based on EU-funded OPERA
  - standards submitted but not adopted to IEEE P1900
- HomePlug Powerline Alliance  www.homeplug.org
  - industry forum for powerline communication
  - suite of standards for BPL, access, and home control
  - standards submitted to IEEE P1810
    - turbo FEC

Residential Broadband

Emerging BPL Standards

- IEEE P1901 working group  grouper.ieee.org/groups/1901
  - web site does not contain any useful public information
  - BPL requirements
    - >100 Mb/s
  - contentious standards meetings
  - incompatible HomePlug and ITU standards being considered
Communication Networks
Acknowledgements

Some material in these foils comes from the textbook supplementary materials:

- Kurose & Ross, *Computer Networking: A Top-Down Approach Featuring the Internet*
- Sterbenz & Touch, *High-Speed Networking: A Systematic Approach to High-Bandwidth Low-Latency Communication*  
http://hsn-book.sterbenz.org