High-Performance Networking
University of Kansas EECS 881
Links and LANs

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http://www.ittc.ku.edu/~jugs/courses/hsnets
Links
Outline

LL.1 Transmission and physical media
LL.2 Link layer technologies
LL.3 Link layer components
LL.4 Support for higher layers
Links
Outline

LL.1 Physical transmission
LL.2 Link technologies
LL.3 Link layer components
LL.4 Support for higher layers
Network Link Principle

Network links must provide high-bandwidth connections between network nodes. Link-layer protocol processing should not introduce significant latency.
## Links

**Physical Media and Transmission**

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Transmission and Physical Media
Analog and Digital Signals

LL.1 Transmission and physical media
  LL.1.1 Analog and digital signals
  LL.1.2 Communication challenges
  LL.1.3 Physical media types and performance
  LL.1.4 Line coding and symbol rate

LL.2 Link layer technologies

LL.3 Link layer components

LL.4 Support for higher layers
Communication

Signal Types

• Transmission of a *signal* through a *medium*
Communication

Signal Types

• Transmission of a *signal* through a *medium*

• Analog signal: time-varying levels
  – electrical: voltage levels
  – photonic: light intensity
Communication

Signal Types

• Transmission of a signal through a medium

• Analog signal: time-varying levels
  – electrical: voltage levels
  – photonic: light intensity

• Digital signal: sequence of bits represented as levels
  – electrical: voltage pulses
  – photonic: light pulses
  – two levels for binary digital signal
    • more levels in some coding schemes

more later
Communication
Digital vs. Analog

- Digital bits are reconstructed at the receiver
Communication
Digital vs. Analog

- Digital bits are reconstructed at the receiver
  - all transmission is *actually* analog!
  - frequency response determines
    - pulse rate that can be transmitted
    - shape of pulse → ability for receiver to recognise pulse
Communication
Digital vs. Analog

- Digital bits are reconstructed at the receiver
  - all transmission is *actually* analog!
  - frequency response determines
    - pulse rate that can be transmitted
    - shape of pulse → ability for receiver to recognise pulse
  - high-frequency attenuation reduces quality of pulse

adapted from [Tanenbaum 2003]
Communication

Medium Types

- Guided through waveguide
  - wire (generally copper)
  - fiber optic cable
Communication
Medium Types

• Guided through waveguide
  – wire (generally copper)
  – fiber optic cable

• Unguided (wireless) free space propagation
  – wireless
    (generally implying RF – radio frequency)
  • free-space optical
Transmission and Physical Media

LL.1.2 Communication Challenges

LL.1 Transmission and physical media
   LL.1.1 Analog and digital signals
   LL.1.2 Communication challenges
   LL.1.3 Physical media types and performance
   LL.1.4 Line coding and symbol rate

LL.2 Link layer technologies
LL.3 Link layer components
LL.4 Support for higher layers
Communication Challenges

- Goal: receiver reconstruct signal transmitter sent
Communication Challenges

• **Goal:** receiver reconstruct signal transmitter sent
• **Noise makes this difficult**
  – background noise $N_o$ interferes with the signal bit energy $E_b$
    • SNR: signal to noise ratio $= 10 \log_{10} \left( \frac{E_b}{N_o} \right)$ dB
  – interference from other signals in shared medium
    • collisions among multiple transmitters
    • jamming from adversaries
  – imperfections in the physical medium that alters the signal
    • especially in fiber optic cables
Communication
Challenges

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• Attenuation over distance that reduces the amplitude
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Communication Challenges

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- **Attenuation over distance that reduces the amplitude**
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- **Frequency response of the medium**
Communication Challenges

- Result: difficulty in reconstructing signal
Communication Challenges

- Result: difficulty in reconstructing signal
- Analog: distortion of received waveforms
Communication Challenges

- Result: difficulty in reconstructing signal
- Analog: distortion of received waveforms
- Digital: bit errors – an artifact of distortion
  - distance attenuation reduces level of pulse
  - frequency attenuation distorts shape of pulse
  - distortion changes shape of pulse
  - dispersion smears pulses
Communication
Challenges

- Result: difficulty in reconstructing signal
- Analog: distortion of received waveforms
- Digital: bit errors — an artifact of distortion
  - distance attenuation reduces level of pulse
  - frequency attenuation distorts shape of pulse
  - distortion changes shape of pulse
  - dispersion smears pulses
- Physical and link layer devices help
  - amplifiers ameliorate attenuation
  - regenerators and repeaters reconstruct digital signals
    - spaced closely enough to keep bit error rate low
Transmission and Physical Media

Physical Media Types and Performance

LL.1 Transmission and physical media
  LL.1.1 Analog and digital signals
  LL.1.2 Communication challenges
  LL.1.3 Physical media types and performance
  LL.1.4 Line coding and symbol rate

LL.2 Link layer technologies

LL.3 Link layer components

LL.4 Support for higher layers
Physical Media Sharing
Point-to-Point vs. Shared Medium

• Point-to-point dedicated links
  – one transmitter per medium
    • dedicated
Physical Media Sharing
Point-to-Point vs. Shared Medium

• Point-to-point links
  – one transmitter per medium
    • dedicated
    • multiplexed (layer 2) *more later*
Physical Media Sharing
Point-to-Point vs. Shared Medium

- Point-to-point links
  - one \textit{transmitter} per \textit{medium}
    - dedicated
    - \textit{multiplexed} (layer 2) \textit{more later}
- Shared medium (multiple access)
  - multiple \textit{transmitters} per \textit{medium}
    \textit{implication?}
Physical Media Sharing
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
  - bandwidth shared among users
  - results in contention for medium

*problem?
Physical Media Sharing
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    • medium access control (MAC) needed

\textit{EECS 780 lecture MW}
Physical Media Sharing

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  – bandwidth shared among users
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    • medium access control (MAC) needed
      *EECS 7870 lecture MW*

  – examples
    • wireless networks, original Ethernet
Physical Media Types

Wire

- Unshielded twisted pair
  - cheap, moderate bandwidth (~100Mb/s)
- Shielded twisted pair
  - expensive, higher bandwidth
- Coaxial cable
  - expensive, high bandwidth (~ 500 MHz)
Physical Media Types

Wire: Twisted Pair

• **UTP**: unshielded twisted pair
  - twisting reduces radiation and noise susceptibility
  - used for most wired LANs
    • CAT-{5|6|7} for data applications such as Ethernet
    • 100 Mb/s supported over 100 m for 100BaseT Ethernet
  - legacy telephone wiring
    • supports much lower data rates (1–10 Mb/s)
    • used by DSL (digital subscriber line)

• **STP**: shielded twisted pair
  - not commonly used
**Physical Media Types**

**Wire: Coaxial Cable**

- **High quality shielded cable**
  - used in some LANs (and early Ethernet)
  - used in CATV (RG6 better than RG59)
    - HFC: hybrid fiber coax for data
    - 10 Mb/s downstream shared | 300 kb/s upstream typical
Physical Media Types

Fiber Optics

- Fiber optics
  - bandwidth \( \approx 20 \text{ THz} \) within 800–1700 nm
  - attenuation [dB/km]
  - dispersion: waveform smearing limits bandwidth-×-distance
Physical Media Types
Fiber Optic Cable

- Lightwave travels along glass or plastic core
  - multimode: reflected
  - single mode: guided with no reflections
- Transmitter
  - LED or solid-state laser
Physical Media Types

Fiber Optic Cable Modes

- **Multimode**: 50 – 85 μm core
  - signal reflected in multiple modes
  - intermodal dispersion limits length to a few km

*why?*
Physical Media Types

Fiber Optic Cable Modes

- **Multimode**: 50 – 85 μm core
  - signal reflected in multiple modes
  - intermodal dispersion limits length to a few km
    *why?*

- **Single mode**: 8–10 μm core
  - core acts as waveguide with *no* reflections
  - suitable for 10s of km between digital regenerators
Physical Media Types
Fiber Optic Cable Constraints

- Attenuation
- Dispersion: smearing limits bandwidth-×-delay
  - intermodal: different modes travel different distances
  - chromatic: different wavelengths travel different velocities
  - polarisation mode: diff. polarisation states travel at diff. ν
- Nonlinearities limit WDM
  - stimulated Raman scattering (due to molecular vibrations)
  - stimulated Brillouin scattering (acoustic wave interaction)
  - carrier-induced cross-phase modulation (c↑ w/other signals)
  - four-wave mixing (3 wavelengths induce fourth sum/diff)
Physical Media Types

Wireless Free Space

- Signals transmitted through free space
  - no waveguide
- Spectrum \((\lambda f = c ; c = 3 \times 10^5 \text{ km/s})\)
  - only some spectrum usable for communication
  - RF: radio frequency
  - optical
    - infrared 800–900 nm = 333–375 THz  41 THz spectrum

Much more about wireless communication in EECS 882

Physical Media Types

Wireless Free Space Licensing

- Licensed and regulated spectrum
  - ITU (international) and each country (FCC in US) regulate
  - most frequency bands require license to transmit
    - e.g. broadcast TV, radio, amateur radio, GMRS
  - some bands do not require explicit license application
    - e.g. US CB, FRS
Physical Media Types

Microwave Terrestrial Links

- Microwave links
  - typically point-to-point directional links
  - once ubiquitous for long-distance telephony
  - 4 GHz TD radio and 6 GHz TH radios
  - mostly replaced by fiber optic cables
  - subject to fading during rain storms
  - new interest for local loops and MANs
Physical Media Types

Satellite Characteristics

• Satellite orbit characteristics

<table>
<thead>
<tr>
<th>Type</th>
<th>Altitude</th>
<th>Constellation Size</th>
<th>Link Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO low earth orbit</td>
<td>100 km – 1000 km</td>
<td>~50–1000</td>
<td>~1–10 ms</td>
</tr>
<tr>
<td>MEO medium earth orbit</td>
<td>5000 km – 15000 km</td>
<td>~10</td>
<td>~35–85 ms</td>
</tr>
<tr>
<td>GEO geosynchronous EO</td>
<td>36786 km</td>
<td>3 (plus polar)</td>
<td>270 ms</td>
</tr>
</tbody>
</table>

• Tradeoffs
  – cost per satellite (GEO), high link power, high delay
  – total cost of constellation, constellation management
## Physical Media Types

### Microwave Satellite Links

- **Satellite links**

<table>
<thead>
<tr>
<th>Band</th>
<th>Typical Frequency [GHz]</th>
<th>Bandwidth</th>
<th>Issues</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Downlink</td>
<td>Uplink</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>1.5</td>
<td>1.6</td>
<td>15 MHz</td>
</tr>
<tr>
<td>S</td>
<td>1.9</td>
<td>2.2</td>
<td>70 MHz</td>
</tr>
<tr>
<td>C</td>
<td>4.0</td>
<td>6.0</td>
<td>500 MHz</td>
</tr>
<tr>
<td>Ku</td>
<td>11</td>
<td>14</td>
<td>500 MHz</td>
</tr>
<tr>
<td>Ka</td>
<td>20</td>
<td>30</td>
<td>3.5 GHz</td>
</tr>
</tbody>
</table>
Physical Media Types

Wireless RF Spectrum

• Unlicensed spectrum
  – regulations for use (FCC 15.243–249)
    • e.g. max xmit power
    • e.g. spread spectrum parameters
  – ISM: industrial, scientific, and medical
    • 900 MHz, 2.4 GHz, 5.8 GHz, ...
  – UNII: unlicensed national information infrastructure
    • 5.8 GHz
  – may be use by anyone for any purpose (subject to regulations)
  – interference a significant problem
    • e.g. 2.4 GHz FHSS cordless phones against 802.11b
    • e.g. interference among 802.11 hubs in dense environments
Physical Media Types

Wireless RF Antennae and Attenuation

• Antennae
  – omnidirectional: RF radiated in all directions
  – directional: focused beam of radiation
    • reduces contention and improves spatial reuse
    • significantly complicates network design: beam steering
    • laser/maser: focused coherent light/microwave transmission

• Attenuation
  – signal strength decreases as $1/r^2$ in perfect medium
  – signal may decrease as $1/r^x$ with multipath interference
    • rural environments: $x > 2$
    • urban environments: $x \to 4$
Physical Media Performance

Velocity

- Velocity \( v = \frac{c}{n} \) [m/s]
  - speed of light \( c = 3 \times 10^5 \) km/s
  - index of refraction \( n \)

Consequences?
Physical Media Performance
Velocity and Delay

- **Velocity** \( v = \frac{c}{n} \) [m/s]
  - speed of light \( c = 3 \times 10^5 \) km/s
  - index of refraction \( n \)

- **Delay** \( d = \frac{1}{v} \) [s/m]
  - generally we will express delay in [s] given a path length
Physical Media Performance
Link Length

- Link Length
  - distance over which signals propagate
    - point-to-point: wire or fiber length
    - shared medium: longest path through medium
  - constrained by physical properties of medium

Consequences?
Physical Media Performance

Link Length and Attenuation

- **Link Length**
  - distance over which signals propagate
    - point-to-point: wire or fiber length
    - shared medium: longest path through medium
  - constrained by physical properties of medium

- **Attenuation**: decrease in signal intensity
  - over distance expressed as \([\text{dB/m}]\)
  - at a particular signal frequency
Physical Media Performance
Frequency Response and Attenuation

- Frequency range and attenuation
  - ability to propagate signals of a given frequency
- Characteristics of guided media
  - wire: generally falls off above a certain $f_{\text{max}}$
  - fiber optic cable & free space transparent to certain ranges

  *analogy:*

  *UV blocking sunglasses*  (high attenuation)
  *vs.*
  *standard glass*  (moderate attenuation)
  *vs.*
  *UV transparent black light glass*  (low attenuation)
Physical Media Performance

Frequency Response and Attenuation: Optical

- Fiber-optic cable transparency bands
  - 1300 and 1550 nm
  - 850 nm for lower cost

![Graph showing attenuation vs wavelength for different wavelengths: 850 nm, 1300 nm, 1550 nm. The graph is adapted from Tannenbaum 2003.](image-url)
Physical Media Performance

Frequency Response and Attenuation: RF

- Atmospheric transparency bands
  - RF: 10MHz – 10GHz
    - VHF meter band, UHF millimeter band
  - Infrared: N-band

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Physical Media Performance

Frequency Response and Attenuation: RF

- Atmospheric transparency bands
  - RF: 10MHz – 10GHz
    - VHF meter band, UHF millimeter band
  - Infrared: N-band
## Physical Media Types

### Performance Characteristics Summary

<table>
<thead>
<tr>
<th>Type</th>
<th>Medium</th>
<th>Frequency Range</th>
<th>Velocity</th>
<th>Delay</th>
<th>Typical Attenuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire</td>
<td>twisted pair</td>
<td>0–1 MHz</td>
<td>0.67c</td>
<td>5 s/km</td>
<td>0.7 dB/km</td>
</tr>
<tr>
<td></td>
<td>coax</td>
<td>0–500 MHz</td>
<td>0.66–0.95c</td>
<td>4 s/km</td>
<td>7.0 dB/km</td>
</tr>
<tr>
<td>Optical fiber</td>
<td>glass</td>
<td>120–250 THz, 1700–800 nm</td>
<td>0.68c</td>
<td>5 s/km</td>
<td>0.2–0.5 dB/km</td>
</tr>
<tr>
<td>Wireless</td>
<td>microwave</td>
<td>1–300 GHz</td>
<td>1.0c</td>
<td>3.3 s/km</td>
<td>1/r^2</td>
</tr>
<tr>
<td></td>
<td>infrared</td>
<td>0.3–428 THz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>visible</td>
<td>428–750 THz</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Transmission and Physical Media
Line Coding and Symbol Rate

LL.1 Transmission and physical media
   LL.1.1 Analog and digital signals
   LL.1.2 Communication challenges
   LL.1.3 Physical media types and performance
   LL.1.4 Line coding and symbol rate

LL.2 Link layer technologies
LL.3 Link layer components
LL.4 Support for higher layers
Line Coding and Symbol Rate

Line Coding

- Line coding
  - way in which bits are encoded for transmission
    - digital (binary, trinary, ...) or analog modulation
Line Coding and Symbol Rate

Symbol Rate

• Line coding
  – way in which bits are encoded for transmission
    • digital (binary, trinary, ...) or analog modulation

• Symbol rate
  – baud rate [symbols/s]
    • baud = b/s only if one symbol/bit
  – clever encodings (e.g. QAM) allow high baud rates
Line Coding and Symbol Rate
Example Codes

- Analog line coding:
  - modulate a *carrier*

- Amplitude modulation
  - each symbol a different level

- Frequency modulation
  - each symbol a different frequency

- Phase modulation
  - each symbol a different phase

- Combinations possible
  - e.g. amplitude and phase
Line Coding and Symbol Rate

Example: QPSK and QAM

- Combination of amplitude- and phase-modulation
  - allows more bits per symbol

- QAM: quadrature amplitude modulation
  - quadrature = 4 phases carried on two sine waves
  - PAM is case for only one phase
  - QPSK is case for only one amplitude

<table>
<thead>
<tr>
<th>Name</th>
<th>Amplitudes</th>
<th>Phases</th>
<th>Bits/Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK</td>
<td>1</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>QAM-16</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>QAM-64</td>
<td>3</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>QAM-256</td>
<td>4</td>
<td>4</td>
<td>8</td>
</tr>
</tbody>
</table>
Line Coding and Symbol Rate

Example: QPSK and QAM

- QAM: amplitude- and phase modulation
- Represented by *constellation diagram*
  - amplitude is distance from origin
  - phase is angle

<table>
<thead>
<tr>
<th>QPSK</th>
<th>90°</th>
<th>QAM-16</th>
<th>90°</th>
<th>QAM-64</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>180°</td>
<td></td>
<td>180°</td>
<td></td>
<td>180°</td>
<td></td>
</tr>
<tr>
<td>270°</td>
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Transmission and Physical Media
High-Performance Network Summary

• Improved performance of links dependent on:
  – physical media type
  – dedicated vs. shared links
  – minimisation of impairments
    • attenuation
    • noise (e.g. twisted pairs, shielding)
  – more sophisticated coding techniques to maximise symbol rate
    • e.g. QPSK → QAM-\(n\)
Links

Link Layer Technologies

LL.1 Transmission and physical media

LL.2 Link layer technologies
   LL.2.1 Services and interfaces
   LL.2.2 Point-to-point dedicated links
       examples: Ethernet, 802.16, DSL
   LL.2.3 Point-to-point multiplexed links
       examples: SONET/SDH, OTN
   LL.2.4 Shared medium links
       examples: Ethernet, token ring, 802.11, 802.15, HFC

LL.3 Link layer components

LL.4 Support for higher layers
Link Layer
Hybrid Layer/Plane Cube

Layer 2:
hop-by-hop
data transfer
in data and
control planes
Links and LANs
Link Layer Services and Interfaces

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LL.3 Link layer components

LL.4 Support for higher layers
Link Layer
Service and Interfaces

- Link layer is HBH analog of E2E transport layer
  - transport layer (L4) transfers packets E2E
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
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Service and Interfaces

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    - recall end-to-end arguments:
      E2E reliability with HBH error control only for performance
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      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 multiplexing and switching
• 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 Technologies

Bandwidth Scalability

• Link protocol bandwidth scalability
  – variable: generally not practical for component manufacture
  – discrete: power-of-two or order-of-magnitude
  – permit evolution
    • minimal standards rewriting at link layer
    • may need new physical layer standards

Link Protocol Scalability Principle

*Link protocols should be scalable in bandwidth, either variably or in discrete intervals (power-of-two or order of magnitude). Header/trailer lengths and fields that relate to bandwidth should be long enough or contain a scale factor.*
Link Technologies
IEEE 802

- IEEE 802 LAN/MAN standards [IEEE 802.1]
  - www.ieee802.org
- Definition of LAN/MAN protocols for L1–L2
  - 802.2: logical link control
  - 802.\(n\): MAC and physical media dependent

<table>
<thead>
<tr>
<th></th>
<th>LLC sublayer</th>
<th>link layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.2</td>
<td>logical link control</td>
<td>MAC layer</td>
</tr>
<tr>
<td>802.(n)</td>
<td>medium access control</td>
<td>physical layer</td>
</tr>
<tr>
<td>PMD(_1)</td>
<td>PMD(_2)</td>
<td>(\cdots)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Media Independent</th>
<th>Physical Media Dependent</th>
</tr>
</thead>
<tbody>
<tr>
<td>MI sublayer</td>
<td>PMD sublayer</td>
</tr>
<tr>
<td>medium independent</td>
<td>physical media dependent</td>
</tr>
</tbody>
</table>
## Important IEEE 802 Protocols

<table>
<thead>
<tr>
<th>Common name</th>
<th>Standard</th>
<th>Scope</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>architecture</td>
<td>IEEE 802.1</td>
<td>LAN/MAN</td>
<td>media independent</td>
</tr>
<tr>
<td>LLC</td>
<td>IEEE 802.2</td>
<td>LAN/MAN</td>
<td>media independent</td>
</tr>
<tr>
<td>Ethernet</td>
<td>IEEE 802.3</td>
<td>LAN/MAN/(WAN)</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 (Wi-Fi)</td>
<td>IEEE 802.11</td>
<td>LAN</td>
<td>RF, (IR)</td>
</tr>
<tr>
<td>WPAN</td>
<td>IEEE 802.15</td>
<td>PAN</td>
<td>RF</td>
</tr>
<tr>
<td>WMAN (WiMAX)</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 likely to become important, e.g. 802.15, 802.16
  - the jury is still out on others, e.g. 802.17, 802.20, 802.22
Links and LANs
Point-to-Point Dedicated Links

LL.1 Transmission and physical media

LL.2 Link layer technologies
   LL.2.1 Services and interfaces
   LL.2.2 Point-to-point dedicated links
      examples: Ethernet, 802.16, DSL
   LL.2.3 Point-to-point multiplexed links
      examples: SONET/SDH, OTN
   LL.2.4 Shared medium links
      examples: Ethernet, token ring, 802.11, 802.15, HFC

LL.3 Link layer components

LL.4 Support for higher layers
• Sequence of framed packets along a link
  – space division mesh network
  – multiplexing occurs at a higher layer
    • network layer (e.g. IP forwarding)
    • transport layer (e.g. TCP sockets)
Point-to-Point Links
Example $5_M$ 802.16

- IEEE 802.16 *more detail in EECS 882 lecture WN*
  - part of 2nd set of 802 wireless protocols (802.15 & 802.16)
  - design motivated by MMDS
  - *no* similarity to 802.11/Ethernet framing or operation
Point-to-Point Links

Example 802.16

- WirelessMAN: Wireless Metropolitan Area Networks
  - IEEE 802.16 grouper.ieee.org/groups/802/16
- Metropolitan wireless networks
  - originally intended for \textit{fixed} wireless access
  - standardisation and replacement for MMDS in 10 – 66 GHz
  - 802.16a additional operation in licensed bands 2 – 11 GHz
  - 802.16b additional operation in unlicensed 5.8 GHz band
- Later support for mobility
  - 802.16e
  - overlaps with IEEE 802.20 MBWA charter
Point-to-Point Links

Example 802.16 WiMAX

• WiMAX
  – worldwide interoperability for microwave access
  – www.wimaxforum.org
  – 802.16 service deployment and architecture
    • needed by carriers
    • similar in concept to WiFi for 802.11

• 802.16 ≠ WiMAX
Point-to-Point Links

Example 5.M 802.16 Topology: Links

- Mesh of point-to-point full duplex links
- FDD (frequency division duplex)
  - uses two frequencies
- TDD (time division duplex)
  - up and downstream share single frequency
Point-to-Point Links

Example 5.M 802.16 Link Characteristics

- **802.16 (original)**
  - 10-66 GHz licensed spectrum; LOS (line of sight)
  - 2 – 5 km transmission radius
  - 32 – 134 Mb/s

- **802.16a and 802.16b**
  - 2 – 11 GHz; non-LOS
  - 7 – 10 km typical; 50 km max transmission radius
  - 75 Mb/s

- **802.16e (mobile)**
  - 2 – 6 GHz; non-LOS
  - 2 – 5 km transmission radius
  - 15 Mb/s
Point-to-Point Links

Example 5.8 802.16 Topology: Nodes

- **Base station**
  - directly connected to Internet infrastructure
  - arranged as mesh with other base stations
- **Fixed subscriber station**
  - 802.16 communication with base station
  - connected to LAN infrastructure, e.g.
    - Ethernet
    - 802.11
- **Mobile node**
  - 802.16e
Point-to-Point Links

Example 802.16 Topology: PMP Mode

- PMP: point-to-multipoint topology
  - BS: base station
    - communicates with multiple SSs
    - typically sectorised cell using multiple directional antennae
  - SS subscriber stations
    - communicate through BSs

802.11 and Ethernet LAN

Internet
Mesh mode (PMP and mesh)
- BS – SS (as in PMP)
- BS – BS multihop relay to SS
- BS – BS mesh network (e.g. for backhaul)
- SS – SS ad hoc mode

802.11 and Ethernet LAN
Point-to-Point Links

Example 5.8 802.16e Topology: Mobile Terminals

- Mobile terminals (PMP and mesh)
  - BS – MT SS
  - SS – MT SS ad hoc mode
  - MT SS – MT SS ad hoc mode
Point-to-Point Links

Example 802.16 Evolution

• 802.16 licensed spectrum uses highest frequencies
  – highest rate
  – adaptive coding: tradeoff between distance and rate

• 802.16m
  – advanced air interface targetted to 4G cellular
    • lost to LTE-A in the market
  – data rates of 100 Mb/s mobile, 1 Gb/s fixed

• Higher rate links
  – may need to use millimeter-waveband (60–90 GHz)
    • 10 Gb/s links possible
    • proprietary transceivers now available
# Point-to-Point Links

## Example 802.16 Link Characteristics

<table>
<thead>
<tr>
<th>Link type</th>
<th>year</th>
<th>band</th>
<th>topology</th>
<th>channel BW</th>
<th>coding duplex</th>
<th>MAC rate</th>
<th>typical range</th>
<th>payload</th>
<th>typical goodput</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMDS MMDS</td>
<td></td>
<td>24–40 GHz 2–3 GHz</td>
<td>pt-to-pt pt-to-mp</td>
<td></td>
<td></td>
<td></td>
<td>8–36 Mb/s</td>
<td>3–5 km</td>
<td></td>
</tr>
<tr>
<td>802.16</td>
<td>2001</td>
<td>10–66 GHz licensed</td>
<td>point-to-point</td>
<td>LOS SC</td>
<td>TDD &amp; FDD</td>
<td>34–134 MB/s</td>
<td>2–5 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>802.16a</td>
<td>2002</td>
<td>2–11 GHz licensed</td>
<td>point-to-multipoint</td>
<td>non-LOS OFDM OFDMA</td>
<td>75 Mb/s</td>
<td>7–10 km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>802.16b</td>
<td></td>
<td>5.8 GHz UNII</td>
<td></td>
<td></td>
<td></td>
<td>75 Mb/s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>802.16e</td>
<td>2006</td>
<td>2–6 GHz</td>
<td></td>
<td>1.25–20 MHz</td>
<td>non-LOS OFDMA</td>
<td>15 Mb/s*</td>
<td>2–5 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>802.16m</td>
<td>2010</td>
<td>450 MHz – 3.6 GHz licensed</td>
<td>5–40 MHz</td>
<td>TDD &amp; FDD MIMO OFDMA</td>
<td>≤100 Mb/s* ≤1 Gb/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*mobile
Point-to-Point Links

Example 5.4 DSL Residential Broadband

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

<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>shared 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>
Point-to-Point Links

Example 5.D DSL Residential Broadband 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
Point-to-Point Links

Example 5.D ADSL Original Motivation

- ADSL (asymmetric DSL) [ANSI T1.413] / [ITU G.992.1]
  - developed by Bellcore in late 1980s 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
Point-to-Point Links

Example 5.D ADSL 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
Point-to-Point Links

Example 5.D 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
Point-to-Point Links

Example 5.D  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
Point-to-Point Links

Example 5.D ADSL CO and Residence Architecture

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

DSLAM: DSL access multiplexer
NID: network interface device
DSLx: hub or switch with DSL modem
Point-to-Point Links

Example 5.D  DSL Lite Motivation

  - eliminates need for splitters
  - DSL modems can be plugged into any jack
Point-to-Point Links

Example 5.D DSL Lite 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

DSLAM: DSL access mux
NID: network interface device
DSL: hub or switch with DSL modem

DSLAM: DSL access mux
NID: network interface device
PC

Internet

Central office

PSTN

• 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
Point-to-Point Links
Example 5.D 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
Point-to-Point Links

Example 5.D 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
## Point-to-Point Links

### Example 5.D DSL Link Characteristics

<table>
<thead>
<tr>
<th>Link Type</th>
<th>Standard</th>
<th>Year</th>
<th>Type</th>
<th>Down R</th>
<th>Up Rate</th>
<th>Range</th>
<th>Coding</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDSL</td>
<td>G991.1</td>
<td>1998</td>
<td>dedicated</td>
<td>1.544 Mb/s</td>
<td>1.544 Mb/s</td>
<td></td>
<td>2B1Q</td>
<td>T1 circuit extension</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>two pairs</td>
<td>2.048 Mb/s</td>
<td>2.048 Mb/s</td>
<td></td>
<td>CAP</td>
<td></td>
</tr>
<tr>
<td>SHDSL</td>
<td>G991.2</td>
<td>2001</td>
<td>ded. 2-pair</td>
<td>2.312 Mb/s</td>
<td>2.312 Mb/s</td>
<td></td>
<td>TC PAM</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2003</td>
<td>ded. 4-pair</td>
<td>5.696 Mb/s</td>
<td>5.696 Mb/s</td>
<td></td>
<td>HDSL successor</td>
<td></td>
</tr>
<tr>
<td>ADSL</td>
<td>T1.413</td>
<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>
</tr>
<tr>
<td></td>
<td>G.992.1</td>
<td>1999</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADSL Lite</td>
<td>G.992.2</td>
<td>1999</td>
<td>POTS shared</td>
<td>1.535 Mb/s</td>
<td>512 kb/s</td>
<td>3 km</td>
<td>DMT</td>
<td>splitterless</td>
</tr>
<tr>
<td>ADSL2</td>
<td>G.992.3</td>
<td>2002</td>
<td>POTS shared</td>
<td>8–12 Mb/s</td>
<td>1–3.5 Mb/s</td>
<td></td>
<td>DMT</td>
<td>splitter</td>
</tr>
<tr>
<td>ADSL2 Lite</td>
<td>G.992.4</td>
<td>2002</td>
<td>POTS shared</td>
<td>8–12 Mb/s</td>
<td>1–3.5 Mb/s</td>
<td></td>
<td>DMT</td>
<td>splitterless</td>
</tr>
<tr>
<td>ADSL2+</td>
<td>G.992.5</td>
<td>2005</td>
<td>POTS shared</td>
<td>24 Mb/s</td>
<td>1–3.5 Mb/s</td>
<td></td>
<td>DMT</td>
<td>split</td>
</tr>
<tr>
<td>VDSL</td>
<td>G.993.1</td>
<td>2004</td>
<td>hybrid FDD</td>
<td>26 Mb/s</td>
<td>26 Mb/s</td>
<td>300 m</td>
<td>QAM DMT</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>52 Mb/s</td>
<td>12 MB/s</td>
<td></td>
<td></td>
<td>FTTN</td>
</tr>
<tr>
<td>VDSL2</td>
<td>G.993.2</td>
<td>2006</td>
<td>hybrid FDD</td>
<td>100 Mb/s</td>
<td>100 Mb/s</td>
<td>300 m</td>
<td>DMT</td>
<td>FTTN</td>
</tr>
<tr>
<td>FAST</td>
<td>G.970X</td>
<td>2014</td>
<td>hybrid TDD</td>
<td>1 GB/s</td>
<td>100 Mb/s</td>
<td>250 m</td>
<td>DMT</td>
<td>FTTN</td>
</tr>
</tbody>
</table>
Point-to-Point Links

Example 5.D ADSL Summary

- 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
### Point-to-Point Links

**Example 5.D  ADSL Summary**

- **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
Point-to-Point Links
Example 5.D  VDSL Summary

- 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
Point-to-Point Links

Example 5.3  DSL Summary

- 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
Point-to-Point Links

Example 5.D  DSL Summary and Evolution

• Advantages of DSL
  – reuse of existing local loop (ADSL)
  – reuse of existing loop from street to house (VDSL)

• Disadvantages of DSL
  – shared medium infrastructure
  – usable data rate and latency per user highly variable

• Evolution for high speed
  – hack of local loop infrastructure for Internet access
  – physical layer coding improvements limited to several Mb/s
  – VDSL replaces of legacy infrastructure with fiber
    • significant cost but not all the way to the residence
Links and LANs
Point-to-Point Multiplexed Links

LL.1 Transmission and physical media

LL.2 Link layer technologies
   LL.2.1 Services and interfaces
   LL.2.2 Point-to-point dedicated links
       examples: Ethernet, 802.16, DSL
   LL.2.3 Point-to-point multiplexed links
       examples: SONET/SDH, OTN
   LL.2.4 Shared medium links
       examples: Ethernet, token ring, 802.11, 802.15, HFC

LL.3 Link layer components

LL.4 Support for higher layers
Multiplexing and Switching
Synchronous TDM Links

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

**Advantages?**

**Disadvantages?**
Multiplexing and Switching
Synchronous TDM Links

• Synchronous time-division multiplexing (STDM)
  – \( n \times \frac{R}{n} \) 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
Multiplexing and Switching
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)
Multiplexing and Switching
Asynchronous TDM Links

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

*Advantages?*

*Disadvantages?*
Multiplexing and Switching

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

*Lecture OQ*
Links and LANs

LL.2.4 Shared Medium Links

LL.1 Transmission and physical media

LL.2 Link layer technologies
   LL.2.1 Services and interfaces
   LL.2.2 Point-to-point dedicated links
       examples: Ethernet, 802.16, DSL
   LL.2.3 Point-to-point multiplexed links
       examples: SONET/SDH, OTN
   LL.2.4 Shared medium links
       examples: Ethernet, token ring, 802.11, 802.15, HFC

LL.3 Link layer components
LL.4 Support for higher layers
• Frames sharing a medium
  – MAC: medium access control needed to arbitrate
    • e.g. TDMA, dynamic TDMA: time division multiple access
    • e.g. CDMA: code division multiple access

Medium Access Control Principle

The MAC protocol should efficiently arbitrate the shared medium, in either a fair manner or with the desired proportion.
Shared Medium Links

Example 5.2 Ethernet

- Early LAN technology (1973)
  - DIX: Digital, Intel, Xerox
  - IEEE 802.3

- Shared wire medium
  - CSMA/CD MAC
  - 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 ...
Shared Medium Links: WLAN

Example 802.3 Evolution to Higher Rates

- Scaling to high data rates
  - 10 Mb/s → 100 Mb/s → 1 Gb/s → 10 Gb/s → 40/100 Gb/s
  - → 802.3u → 802.3ab → 802.3an → 802.3ba Cu
  - → 802.3z → 802.3ae → 802.3ba fib.
  - fiber standards and deployment first for 1 and 10 Gb/s
  - consistent with aggregation for enterprise and metro use

- More sophisticated coding
  - DSSS → OFDM → STBC

- MAC and link framing enhancements
  - slot time increase, frame extension, and bursting for 1 Gb/s
  - elimination of CSMA/CD for 10 Gb/s: full duplex only
Shared Medium Links: LAN

Example 5.2 Ethernet Evolution

• ...Evolved to 1 Gb/s

Problems?

```
10101010 10101010
1010 preamble 010
1010 +SFD 010
10101010 10101011

--- destination address ---
--- source address ---
--- length / type ---
--- LLC ---
--- SNAP ---

frame body 38 – 1492 B
```

```
10101010 10101010
1010 preamble 010
1010 +SFD 010
10101010 10101011

--- MAC header 14B ---
--- LLC/MAC subheader 8B ---
--- trailer 4B ---
```
Shared Medium Links: LAN

Example 5.2 Ethernet Evolution

- Evolved to 1 Gb/s
- Problems: Ethernet design
  - Not inherently scalable
    - 100 Mb/s: several-year standards battle
  - Designed for shared medium
    - Thickwire and thinwire with taps
    - Later hubs with half-duplex pt-to-pt links
    - CSMA/CD time constants and overhead
Shared Medium Links: LAN

Example 5.2 Ethernet Evolution

- Evolved to 1 Gb/s

Problems: Ethernet design
  - not inherently scalable
    - 100 Mb/s: several-year standards battle
  - designed for shared medium
    - thickwire and thinwire with taps
    - later hubs with half-duplex pt-to-pt links
    - CSMA/CD time constants and overhead

- 802.3z decision
  - retain CSMA/CD
  - modify MAC for higher rates
Shared Medium Links: LAN

Example 5.2 Ethernet Evolution

- ...Evolved to 1 Gb/s
- Modifications
  - still supporting CSMA/CD
    - slot time increased \( \times 8 \)
    - 512b → 512B
  - extension trailer need for longer slot
    problem?
Shared Medium Links: LAN

Example 5.2 Ethernet Evolution

- ...Evolved to 1 Gb/s
- Modifications
  - still supporting CSMA/CD
    - slot time increased × 8
    - 512b → 512B
  - extension trailer need for longer slot
    - larger minimum frame size
    - but very inefficient for small frames

_solution_?
Shared Medium Links: LAN

Example 5.2 Ethernet Evolution

- Evolved to 1 Gb/s
- Modifications
  - still supporting CSMA/CD
    - slot time increased $\times 8$
      - $512b \rightarrow 512B$
    - extension trailer need for longer slot
      - larger minimum frame size
      - but *very* inefficient small frames
  - frame bursting
    - burst of frames in a single slot
    - significantly increased efficiency
Shared Medium Links: LAN

Example 5.2 Ethernet Evolution

- ...Evolved to 10 Gb/s

Problems?
Shared Medium Links: LAN

Example 5.2 Ethernet Evolution

- ...Evolved to 10 Gb/s
- Problems?
  - CSMA overheads and time constants much bigger problem
    - further scaling of slot time and extension headers not practical

Solution?
Shared → Dedicated Links: LAN

Example 5.2 Ethernet Evolution

• ...Evolved to 10 Gb/s
• Solution
  – half-duplex shared medium probably never used at 1 Gb/s
  – 802.ae decided to completely eliminate CSMA/CD
  – only point-to-point full-duplex dual cables supported
Dedicated Links: LAN
Example 5.2 Ethernet Evolution

• ...Evolved to 10 Gb/s

• Modification
  – point-to-point only
    • initially fiber only (802.3ae) later copper (802.3ak / 802.3an)
  – full duplex only (separate xmit and recv cables *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
Dedicated Links: LAN

Example 5.2 Ethernet Evolution

• ...Evolved to 40 Gb/s and 100 Gb/s
  – 802.3 HSSG (high speed study group)
  – 802.3ba: June 2010 standard issued

• Objectives
  – 40 Gb/s for SONET OC-192 and OTN ODU3 compatibility
    • will probably see deployment before 10 Gb/s
  – 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
Dedicated Links:  LAN

Example 5.2  Ethernet Evolution

• ...Evolve to 1Tb/s?
Dedicated Links: LAN

Example 5.2  Ethernet Evolution

• Ethernet also evolving from LAN to MAN technology
  – IEEE 802.3 retains control of MAC and PHY standards

• ITU-T Ethernet transport networks
  – ITU-T G.8010 series specifications
  – specification of Ethernet in transport networks
  – relationship to SONET/OTN transport networks

• Metro Ethernet service deployments
  – MEF: Metro Ethernet Forum
    • www.metroethernetforum.org
    • implementation agreements and specifications
## Ethernet Link Characteristics

<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>Topology</th>
<th>Ovhd</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>
<td>500 –2500* m</td>
<td>shared</td>
<td>10 B</td>
<td>＜ 4K B</td>
</tr>
<tr>
<td>10Base5</td>
<td>10 Mb/s</td>
<td>1980</td>
<td>thick coax</td>
<td>H</td>
<td>Manchester</td>
<td>185 – 925* m</td>
<td>shared</td>
<td>38 B</td>
<td>38–1492 B</td>
</tr>
<tr>
<td>10Base2</td>
<td>10 Mb/s</td>
<td>1980</td>
<td>thin coax</td>
<td>H</td>
<td>Manchester</td>
<td>185 – 925* m</td>
<td>hub</td>
<td>38 B</td>
<td>38–1492 B</td>
</tr>
<tr>
<td>10BaseT</td>
<td>10 Mb/s</td>
<td>1980</td>
<td>thin coax</td>
<td>H</td>
<td>Manchester</td>
<td>100 m</td>
<td>hub</td>
<td>38 B</td>
<td>38–1492 B</td>
</tr>
<tr>
<td>100BaseTX</td>
<td>100 Mb/s</td>
<td>1995</td>
<td>2 pair UTP-5</td>
<td>H</td>
<td>4B/5B PAM5x5</td>
<td>100 m</td>
<td>star:</td>
<td>38 B</td>
<td>38–1492 B</td>
</tr>
<tr>
<td>100BaseT2</td>
<td>100 Mb/s</td>
<td>1995</td>
<td>2 pair UTP-3</td>
<td>H</td>
<td>4B/5B PAM5x5</td>
<td>100 m</td>
<td>switch</td>
<td>38 B</td>
<td>38–1492 B</td>
</tr>
<tr>
<td>100BaseTX+</td>
<td>100 Mb/s</td>
<td>1995</td>
<td>4 pair UTP-3</td>
<td>H</td>
<td>4B/5B PAM5x5</td>
<td>316 – 5000 m</td>
<td>pt-2-pt</td>
<td>38 B</td>
<td>38–1492 B</td>
</tr>
<tr>
<td>1000BaseT</td>
<td>1 Gb/s</td>
<td>1998</td>
<td>4 pair UTP-6</td>
<td>H</td>
<td>4B/5B PAM5x5</td>
<td>275 – 550 m</td>
<td>switch</td>
<td>38 B</td>
<td>38–1492 B</td>
</tr>
<tr>
<td>1000BaseCX</td>
<td>1 Gb/s</td>
<td>1998</td>
<td>4 pair UTP-6</td>
<td>H</td>
<td>4B/5B PAM5x5</td>
<td>275 – 550 m</td>
<td>switch</td>
<td>38 B</td>
<td>38–1492 B</td>
</tr>
<tr>
<td>1000BaseFX</td>
<td>1 Gb/s</td>
<td>1998</td>
<td>4 pair UTP-6</td>
<td>H</td>
<td>4B/5B PAM5x5</td>
<td>275 – 550 m</td>
<td>switch</td>
<td>38 B</td>
<td>38–1492 B</td>
</tr>
<tr>
<td>10GBaseX</td>
<td>10 Gb/s</td>
<td>2002</td>
<td>parallel fiber</td>
<td>F</td>
<td>8B10B FCS</td>
<td>65 m – 40 km</td>
<td>switch</td>
<td>38 B</td>
<td>38–1492 B</td>
</tr>
<tr>
<td>10GBaseR</td>
<td>10 Gb/s</td>
<td>2002</td>
<td>parallel fiber</td>
<td>F</td>
<td>8B10B FCS</td>
<td>100 m</td>
<td>switch</td>
<td>38 B</td>
<td>38–1492 B</td>
</tr>
<tr>
<td>10GBaseW</td>
<td>10 Gb/s</td>
<td>2002</td>
<td>parallel fiber</td>
<td>F</td>
<td>8B10B FCS</td>
<td>100 m</td>
<td>switch</td>
<td>38 B</td>
<td>38–1492 B</td>
</tr>
<tr>
<td>10GBaseT</td>
<td>10 Gb/s</td>
<td>2002</td>
<td>parallel fiber</td>
<td>F</td>
<td>8B10B FCS</td>
<td>100 m</td>
<td>switch</td>
<td>38 B</td>
<td>38–1492 B</td>
</tr>
<tr>
<td>40GBase...</td>
<td>40/100Gb/s</td>
<td>2002</td>
<td>parallel fiber</td>
<td>F</td>
<td>8B10B FCS</td>
<td>100 m</td>
<td>switch</td>
<td>38 B</td>
<td>38–1492 B</td>
</tr>
<tr>
<td>100GBase...</td>
<td>40/100Gb/s</td>
<td>2002</td>
<td>parallel fiber</td>
<td>F</td>
<td>8B10B FCS</td>
<td>100 m</td>
<td>switch</td>
<td>38 B</td>
<td>38–1492 B</td>
</tr>
</tbody>
</table>
Shared Medium Links: LAN

Example 5.1 Token Ring (TR)

• 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
Shared Medium Links: LAN

Example 5.T FDDI: Evolution & Death of TR

- 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)
Shared Medium Links: LAN  
Example  
FDDI: Evolution & Death of TR

- 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
## Shared Medium Links: LAN Example

### Ring LAN Characteristics

<table>
<thead>
<tr>
<th>Link type</th>
<th>rate</th>
<th>media</th>
<th>coding</th>
<th>access</th>
<th>link range</th>
<th>ring circum.</th>
<th>topology</th>
<th>OH</th>
<th>payload</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCS 1972</td>
<td>2.5 Mb/s</td>
<td></td>
<td>token</td>
<td>ring</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cambridge 1979</td>
<td>10 Mb/s</td>
<td>2 x TP</td>
<td>slot</td>
<td>ring</td>
<td></td>
<td></td>
<td></td>
<td>22 b</td>
<td>16 b</td>
</tr>
<tr>
<td>Token Ring 1981 IBM 1985 802.5</td>
<td>4 Mb/s</td>
<td>STP</td>
<td>Δ Manch.</td>
<td>token*</td>
<td>250 m(^1)</td>
<td>ring</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HSTR 802.5t 1998 802.5t 802.5v</td>
<td>100 Mb/s</td>
<td>{US}TP fiber</td>
<td>MLT-3 4B/5B</td>
<td>DTR</td>
<td>–</td>
<td>star</td>
<td></td>
<td>21 B</td>
<td>0 – 18279 B</td>
</tr>
<tr>
<td>FDDI 1988</td>
<td>100 Mb/s</td>
<td>fiber</td>
<td>4B/5B</td>
<td>token</td>
<td>2 km</td>
<td>2×ring</td>
<td></td>
<td>28 B</td>
<td>0 – 4522 B</td>
</tr>
<tr>
<td>CDDI</td>
<td>100 Mb/s</td>
<td>STP UTP-5</td>
<td>MLT-3</td>
<td>token</td>
<td>100 m</td>
<td>2×ring</td>
<td></td>
<td>28 B</td>
<td>0 – 4522 B</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

\(^1\)72 m for UTP
**Shared Medium Links: WLAN**

**Example 802.11**

- **IEEE 802.11**
  - first of the 802 wireless protocols
  - design motivated by Ethernet
    - sometimes called “wireless Ethernet”
Shared Medium Links: WLAN

Example 802.11

- **IEEE 802.11**
  - wireless links based loosely on Ethernet framing
    - 6B addresses, 4B FCS
    - 802.2 SNAP/LLC subheader
  - enables simple cheap 802.3+802.11 hubs and switches

- **Unlicensed ISM/U-NII bands**
  - 900 MHz {*,ah}, 2.4 {b,g,n}, 5.8 {a,n,ac}, 24, 61 {ad} GHz
  - significant interference from FHSS 2.4 GHz cordless phones
Shared Medium Links: WLAN

Example\textsuperscript{5.W} 802.11 Wi-Fi

- Wi-Fi
  - Wi-Fi alliance: www.wi-fi.org
  - 802.11 standards compliance and interoperability testing
  - commonly (but incorrectly) used as synonym for 802.11
Shared Medium Links: WLAN
Example 802.11 Coding and MAC

- IEEE 802.11 is CSMA and CDMA hybrid
- Variety of coding schemes
  - DSSS: direct sequence spread spectrum
  - FHSS: frequency hopping spread spectrum (rarely used)
  - OFDM: orthogonal frequency division multiplexing (newer)
- Over which CSMA/CA MAC is run
  - CSMA with optional RTS/CTS

performance implications?
Shared Medium Links: WLAN

Example 5.8 802.11 Coding and MAC

- IEEE 802.11 is CSMA and CDMA hybrid
- Variety of coding schemes
  - DSSS: direct sequence spread spectrum
  - FHSS: frequency hopping spread spectrum (rarely used)
  - OFDM: orthogonal frequency division multiplexing (newer)
  - STBC: space-time block coding (newest)
- Over which CSMA/CA MAC is run
  - CSMA with optional RTS/CTS
  - RTS/CTS not needed for single user (dedicated link)
    • and frequently turned off for multiple users
CSMA/CA: collision avoidance
- RTS/CTS to reduce \( \text{Pr}[\text{collision}] \)

**EECS 882**

- **Sender**
  - sense, wait for DIFS, send RTS
- **Receiver**
  - wait for SIFS, return CTS
- **Sender**
  - wait for SIFS, transmit frame
- **Receiver**
  - wait for SIFS interval and return ACK
Shared Medium Links: WLAN

Example $\text{IEEE 802.11b}$

- **IEEE 802.11b** (HR – high rate)
  - 2.4 GHz ISM/U-NII band
  - formerly widest deployment
  - 11 Mb/s maximum MAC rate
    - actual performance *highly* dependent on environment
    - 5Mb/s goodput typical over 60m range with few obstructions
    - adequate for most home, SOHO, and hotspot use
    - exceeds rate of most HFC and DSL access links
  - DSSS coding; all stations use same chipping sequences

*what does this mean?*
Shared Medium Links: WLAN

Example 5.W 802.11a

- IEEE 802.11a
  - 5.8 GHz ISM/U-NII band
    - higher rate alternative to 802.11b but more expensive
    - simultaneously available with 802.11b
      - a and b were IEEE 802.11 working group numbers
  - 54 Mb/s maximum MAC rate
    - actual performance highly dependent on environment
    - 24Mb/s goodput over 35m range typical
  - deployment limited to users that needed higher rate
    - high rate LAN applications
    - users and campuses with higher rate Internet access links
      - e.g. T3, 100M/1G Ethernet, SONET
Shared Medium Links: WLAN

Example 802.11g

- IEEE 802.11g (ER – extended rate)
  - 2.4 GHz ISM/U-NII band
    - backward compatible with 802.11b
    - higher rate successor to 802.11b using OFDM
  - 54 Mb/s maximum MAC rate
    - actual performance generally far less
    - higher usable rates at longer ranges than 802.11b
    - enhanced performance for
      - enterprise and campus LANS
      - home and SOHO with premium broadband access
  - has become most common deployment
    - virtually all laptops and hubs are now 802.11g
    - many are a/b/g compatible
Shared Medium Links: WLAN
Example 802.11 Frame

- **MAC Header** [10–34B]
  - frame control [2B]
  - duration/ID [2B]
  - address 1 [6B]
  - address 2 [6B]
  - address 3 [6B]
  - sequence control [2B]
  - address 4 [6B]
  - QoS control [2B] (802.11e)
  - HT control [2B] (802.11n)

- **Frame body** [0–2312–7955B]

- **Trailer:** FCS [4B]
Shared Medium Links: WLAN

Example 802.11 Evolution to Higher Rates

- Scaling to high data rates
  - $802.11 \rightarrow 802.11b \rightarrow 802.11g \rightarrow 802.11n \rightarrow 802.11ac/d \rightarrow 802.11ax$
  - $802.11 \rightarrow HR \rightarrow ER \rightarrow HT \rightarrow VHT \rightarrow UHT$

- Increased frequency
  - $900 \text{ MHz} \rightarrow 2.4 \text{ GHz} \rightarrow 5.8 \text{ GHz} \rightarrow 60 \text{ GHz}$

- More sophisticated coding
  - DSSS $\rightarrow$ OFDM $\rightarrow$ STBC

- More sophisticated antennæ
  - single $\rightarrow$ MIMO

- MAC and link framing enhancements
  - single small frames $\rightarrow$ larger frames with burst ACKs
Shared Medium Links: WLAN
Example $^{5.W} 802.11n$

- **IEEE 802.11n (HT – high throughput)**
  - next generation 802.11 after 802.11g
  - 5.8 GHz with 2.4 GHz 802.11g (degraded) interoperability
  - MAC rate of at least 100Mb/s
- **Standard published 2009**
  - based on EWC proposal; merge of TgnSync and WWiSE
  - process held up for several years by intellectual property
    - CSIRO owned fundamental wireless networking patents
  - products based on draft standards became widely available
- **Currently (2015) most common 802.11 interface**
Shared Medium Links: WLAN

Example 802.11n Enhancements

- **802.11n physical layer**
  - MIMO (multiple-in multiple-output) antennae
  - spatial multiplexing and beamforming
  - new coding techniques

- **802.11n MAC**
  - frame aggregation
  - block acknowledgements

- **802.11n link layer framing**
  - new header fields
  - longer payload: up to 7955B
Shared Medium Links: WLAN Example

- 802.11n physical layer: 600 Mb/s max rate
  - MIMO (multiple-in multiple-output)
  - antenna selection
  - spatial multiplexing (across MIMO antennae)
  - beamforming (directional transmission)
  - channel bonding ($2 \times 20$ MHz)
  - new coding
    - STBC: space-time block code – redundant data across streams
    - LDPC: low density parity check – optimal error correction

- 802.11n MAC
- 802.11n link layer framing
Shared Medium Links: WLAN
Example 802.11n MAC Enhancements

- **802.11n physical layer**
- **802.11n MAC**
  - frame aggregation
  - shorter SIFS between give pair of STAs
    - RIFS (reduced IFS) = 2μs instead of SIFS = 16μs
  - block acknowledgements
    - introduced in 802.11e, modified for 802.11n
  - power save multi-poll scheduling for medium access
  - reverse direction
  - protection mechanism for coexistence with 802.11abg
- **802.11n link layer framing**
Shared Medium Links: WLAN
Example 802.11n Link Enhancements

- 802.11n physical layer
- 802.11n MAC
- 802.11n link layer framing
  - new header fields for HT (high throughput)
    - link adaptation and negotiation
    - antenna selection and steering
    - code selection
  - QoS from 802.11e
  - longer max payload for greater efficiency: 7955 B
Shared Medium Links: WLAN

Example W 802.11n Frame Aggregation

- A-MPDU: aggregate MAC PDU
  - sequence of A-MPDU subframes
  - all destined to same receiver
  - all with same QoS ACK policy
  - up to 64KB long

- A-MPDU subframe
  - reserved [4b]
  - MPDU length [3B]
  - CRC-8 [1B]
  - delimiter sig [1B] = 4E (ASCII N)
  - MPDU [0–7993?B]
  - pad [0–3b]
Shared Medium Links: WLAN
Example 5.W 802.11n Block Acknowledgements

• Block acknowledgements
  – introduced in 802.11e
    part of 802.11-2007
    modified in 802.11n
  – negotiated between base station and terminal

• Types
  – immediate
    • intended for high-speed; used in 802.11n
  – delayed
Shared Medium Links: WLAN

Example 802.11n Block Negotiation

- Block ACK initialisation
  - ADDBA add request
  - ADDBA add response

- Data transfer
  - after recommended RTS/CTS
    - more important for larger transfer

- Block ACK termination
  - DELBA delete request
  - DELBA delete response
Shared Medium Links: WLAN
Example 802.11n Block Transfer

- Block data transfer
  - after RTS/CTS
  - sequence of MPDUs
  - separated by RIFS (reduced IFS)

- Block acknowledgement
  - after end of MPDU block
  - BlockAckReq sent
  - BlockAck returned
    - after SIFS in immediate mode
Shared Medium Links: WLAN

Example 802.11ac

- **802.11ac** (VHT – very high throughput)
  - next generation 802.11 after 802.11n
  - 5.8 GHz only
  - MAC rate of at least 100Mb/s

- **Expected PHY modifications**
  - new 802.11 clause for 60GHz ISM PHY
    - possible relationship with 802.15.3c
  - coexistence with other 60 GHz communication

- **Expected MAC and link modifications**
  - changes to support 60 GHz directional antennae
  - multi-band capability
  - efficiency enhancements
  - fast session transfer to 802.11a/b/g/n (<6GHz)
Shared Medium Links: WLAN

Example 802.11ad

- **802.11ac** (VHT – very high throughput)
  - 61.25 GHz (61.0–61.5) commonly called 60 GHz

- **Expected PHY modifications**
  - new 802.11 clause for 60GHz ISM PHY
    - possible relationship with 802.15.3c
  - coexistence with other 60 GHz communication

- **Expected MAC and link modifications**
  - changes to support 60 GHz directional antennae
  - multi-band capability
  - efficiency enhancements
  - fast session transfer to 802.11a/b/g/n (<6GHz)
Shared Medium Links: WLAN

Example 802.11ax Future

- Work beginning on next version of 802.11ad
  - 802.11 UHT (ultra high throughput)
  - NG60 SG (study group)
- 802.11ax (UHT – ultra high throughput)
  - next generation 802.11 after 802.11ac
  - 60 GHz only
  - MAC rate up to 20Gb/s
## Shared Medium Links: WLAN

### Example 5.5 802.11 Link Characteristics

<table>
<thead>
<tr>
<th>Link Type</th>
<th>Year</th>
<th>Band (US)</th>
<th>Channel bw US/EU</th>
<th>Channels US/EU/JP/*</th>
<th>Coding</th>
<th>MAC Rate</th>
<th>Typical Range</th>
<th>Payload</th>
<th>Typical Goodput</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALOHA</td>
<td>1970</td>
<td>400 MHz</td>
<td>2×100 kHz</td>
<td>1</td>
<td></td>
<td>9.6 kb/s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wavelan</td>
<td>1991</td>
<td>915 MHz</td>
<td>26 MHz</td>
<td>DSSS</td>
<td>1 – 2 Mb/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>802.11</td>
<td>1997</td>
<td>2.4 GHz</td>
<td>83.5 MHz</td>
<td>DSSS/FHSS</td>
<td>1 – 2 Mb/s</td>
<td></td>
<td>0–2304 B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>802.11ah (M2M)</td>
<td>2015</td>
<td>900 MHz</td>
<td>83.5 MHz</td>
<td>DSSS/FHSS</td>
<td>1 – 11 Mb/s</td>
<td>60 m</td>
<td>0–2304 B</td>
<td></td>
<td>5 Mb/s</td>
</tr>
<tr>
<td>802.11af (whitespace)</td>
<td>1999</td>
<td>54–698 MHz</td>
<td>US 6 MHz, EU 8 MHz</td>
<td>VHF 2,5,6, UHF 14–35, 38–51</td>
<td>OFDM</td>
<td>6 – 54 Mb/s</td>
<td>35 m</td>
<td>0–2304 B</td>
<td>24 Mb/s</td>
</tr>
<tr>
<td>802.11ad</td>
<td></td>
<td>61 GHz</td>
<td>500 MHz</td>
<td>*number non-overlapping</td>
<td></td>
<td>~ 1 Gb/s</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Shared Medium Links: WLAN

## Example 5.8 802.11 Link Characteristics

<table>
<thead>
<tr>
<th>Link type</th>
<th>year</th>
<th>band (US)</th>
<th>channel bw (US)</th>
<th>channels us/eu/jp/*</th>
<th>coding</th>
<th>MAC rate</th>
<th>typical range</th>
<th>payload</th>
<th>typical goodput</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11b</td>
<td>1999</td>
<td>2.4 GHz</td>
<td>83.5 MHz</td>
<td>11</td>
<td>13</td>
<td>14</td>
<td>3</td>
<td>DSSS FHSS</td>
<td>1 – 11 Mb/s</td>
</tr>
<tr>
<td>802.11a</td>
<td>1999</td>
<td>5.8 GHz</td>
<td>300 MHz</td>
<td>12</td>
<td>19</td>
<td>4</td>
<td>OFDM</td>
<td>6 – 54 Mb/s</td>
<td>35 m</td>
</tr>
<tr>
<td>802.11g</td>
<td>2003</td>
<td>2.4 GHz</td>
<td>83.5 MHz</td>
<td>8</td>
<td>OFDM DSSS</td>
<td>6 – 54 Mb/s</td>
<td>0–2304 B</td>
<td>24 Mb/s</td>
<td></td>
</tr>
<tr>
<td>802.11y</td>
<td>2008</td>
<td>3.7 GHz licensed</td>
<td>50 MHz</td>
<td></td>
<td></td>
<td></td>
<td>0–2304 B</td>
<td>24 Mb/s</td>
<td></td>
</tr>
<tr>
<td>802.11n</td>
<td>2009</td>
<td>2.4 GHz 5.8 GHz</td>
<td>83.5 MHz 300 MHz</td>
<td>OFDM MIMO</td>
<td>&lt; 248 Mb/s</td>
<td>75 m</td>
<td>0–7955 B</td>
<td>75 Mb/s</td>
<td></td>
</tr>
<tr>
<td>802.11ac</td>
<td>2009</td>
<td>5.8 GHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>802.11ad</td>
<td>2009</td>
<td>61 GHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>802.11aj</td>
<td>2016</td>
<td>45 GHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>802.11ax</td>
<td>2019</td>
<td>61 GHz</td>
<td>500 MHz</td>
<td></td>
<td></td>
<td></td>
<td>20 Gb/s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Shared Medium Links: WPAN

Example 5.8 Bluetooth and 802.15

- IEEE 802.15 and Bluetooth
  - part of 2nd set of 802 wireless protocols (802.15 & 802.16)
  - design motivated by Bluetooth consortium
  - no similarity to 802.11/Ethernet framing or operation
Shared Medium Links: WPAN

Example \textsubscript{5.W} Bluetooth and 802.15

- **PAN**: local area network
  - links or subnetwork of shorter reach than LAN
  - replacement for interconnect cables
    - computer peripherals
    - mobile phone headsets
  - private intimate group of personal devices [IEEE 802]
    - in personal operating space (POS)
  - several meters: \( O(10 \text{ m}) \)

- **Examples**
  - wired: USB, IEEE 1394 Firewire
  - wireless: IrDA, 802.15.1/Bluetooth, 802.15.3, Wireless USB
Shared Medium Links: WPAN
Example Bluetooth and 802.15

- Initial work done at Ericsson in Sweden
  - Bluetooth named after Harald I
- Bluetooth SIG (special interest group) formed 1998
  - mobile telephone vendors: Ericsson, Nokia
  - other electronics vendors: IBM, Intel, Toshiba
- Proprietary specification development
  - membership was required to see draft specifications
  - specifications now freely available (2.1 is current)
    - www.bluetooth.com/Bluetooth/Learn/Technology/Specification
- Stovepipe protocol stack for very specialised domain
  - IEEE reworked PHY and MAC as 802.15.1
Shared Medium Links: WPAN

Example $W_5$ Bluetooth Deployment Issues

- Problems and issues
  - closed development process driven by mobile telephony
  - incompatible with Internet and 802 architecture
    - rectified by IEEE 802.15.1 (future?)
  - interference not considered
    - interference with 802.11
    - poor scalability in dense deployments (e.g. 2001 CeBIT debacle)
  - numerous security flaws
  - competition looming from wireless USB
  - architectural limitations ...
Shared Medium Links: WPAN

Example 5.5

Bluetooth Architectural Limitations

- Significant architectural restrictions
  - 3-bit address space ⇒ only 8 active devices / piconet
    - *appalling* lack of foresight
      - evidently driven mobile telephone marketing folk
    - personal networks easily *far* exceed 8 devices
    - computer manufacturers (IBM, Intel) deny responsibility
  - not appropriate for high-performance applications
    - modest transmission rate: 721 kb/s (later 3 Mb/s)
    - master/slave configuration
  - problems largely rectified by IEEE 802.15.3
    - future uncertain
Shared Medium Links: WPAN

Example 802.15 WPAN Overview

- WPAN: Wireless Personal Area Networks
  - IEEE 802.15 grouper.ieee.org/groups/802/15

- Personal and short-reach wireless network
  - shorter range than 802.11
  - initially motivated by Bluetooth & compatibility with 802.11
Shared Medium Links: WPAN

Example 802.15 WPAN Standards

- IEEE 802.15
  - wireless personal area networks
- Personal and short-reach wireless network
  - 802.15.1: standardisation of Bluetooth physical/MAC layers
  - 802.15.2: co-existence of 802.11 and 802.15 in 2.4 GHz
    - original goal of 802.15.1 was to interoperate with 802.11
  - 802.15.3: high rate and larger addresses
  - 802.15.4: low energy for sensor networks
  - 802.15.5: mesh networking (work in progress)
  - 802.15 BAN SG (study group)
Shared Medium Links: WPAN
Example 802.15.1 Physical Layer

- 2.4 GHz unlicensed ISM band
- Three power classes: 1–100 mW with power control
- Three line coding options: 1, 2, or 3 Mb/s
- Low sensitivity receivers
  - intended to permit low cost receivers
Shared Medium Links: WPAN

Example 802.15.1 Medium Access Control

- TDD (time division duplexing)
  - simple to achieve over very short distances
    - independent clocks are frequently synchronised
- FHSS (frequency hopping spread spectrum)
  - FHSS robust to narrow-band interference
  - pseudorandom hopping sequence determined by master
  - significant interference problems with 802.11 DSSS

\[ f(k) \quad f(k+1) \quad f(k+2) \quad f(k+3) \quad f(k+4) \quad f(k+5) \quad f(k+6) \quad \ldots \]
Shared Medium Links: WPAN

Example 802.15.1 Frame Format: Access

- Access code [68 or 72b]
  - preamble [4b] alternating bit pattern chosen so bit change to sync word
  - sync word [64b] derived from lower address part of 48-bit MAC address
  - trailer [4b] alternating bit pattern only if header follows

- Header
- Payload
Shared Medium Links: WPAN

Example:\(^5.W\) 802.15.1 Frame Format: Header

- Access code
- Header
  - logical transport address [3b]
    LT_ADDR \textit{ASTONISHING!!}
  - type [4b] logical transport type and traffic class
  - flow [1b] control
  - ARQN [1b] ACK or NAK
  - SEQN [1b] 1-bit sequence no.
  - HEC [8b] header CRC
- Payload
Shared Medium Links: WPAN

Example 802.15.1 Frame Format: Payload

- Access code
- Header
- Payload
  - contents dependent on logical transport and packet type
Shared Medium Links: WPAN

Example 802.15.1 Piconet

- **Piconet**: up to 256 devices
  - transmission range of master
Shared Medium Links: WPAN

Example 802.15.1 Piconet

- **Piconet**: up to 256 devices
  - transmission range of master
- **Master** dictates timing
  - transmits in odd-numbered slots
Shared Medium Links: WPAN

Example 802.15.1 Piconet

- **Piconet**: up to 256 devices
  - transmission range of master
- **Master** dictates timing
  - transmits in odd-numbered slots
- **Slaves**
  - max of only 7 active at a time
  - use even-numbered slots
Shared Medium Links: WPAN

Example of 802.15.1 Piconet

- **Piconet**: up to 256 devices
  - transmission range of master
- **Master** dictates timing
  - transmits in odd-numbered slots
- **Slaves**
  - max of only 7 active at a time
  - use even-numbered slots
  - all slave–slave communication through master
Shared Medium Links: WPAN

Example 802.15.1 Piconet

- **Piconet**: up to 256 devices
  - transmission range of **master**
- **Master** dictates timing
  - transmits in odd-numbered slots
- **Slaves**
  - max of only 7 active at a time
  - use even-numbered slots
  - all slave–slave communication through master
- **Parked** (inactive) devices
  - max 247
Shared Medium Links: WPAN

Example 802.15.1 Scatternet

• Scatternet
  – collection of piconets that share devices

• Barely mentioned in the Bluetooth specs
  – theoretical construct to deflect criticism on architectural limits of Bluetooth?
Shared Medium Links: WPAN

Example 802.15.3 Overview

- 802.15 Task Group 3: High Rate PANs
  - higher data rates
  - multimedia and QoS
  - ad-hoc and peer-to-peer networking
  - better co-existence with 802.11
### Shared Medium Links: WPAN

#### Example 5.W

#### 802.15.3 Physical Layer Coding

- **802.15.3 physical layer: 11 – 55 Mb/s**

<table>
<thead>
<tr>
<th>Rate</th>
<th>Modulation</th>
<th>Coding</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 Mb/s</td>
<td>QPSK</td>
<td>8-TCM</td>
</tr>
<tr>
<td>22 Mb/s</td>
<td>DQPSK</td>
<td>–</td>
</tr>
<tr>
<td>33 Mb/s</td>
<td>16-QAM</td>
<td>8-TCM</td>
</tr>
<tr>
<td>44 Mb/s</td>
<td>32-QAM</td>
<td>8-TCM</td>
</tr>
<tr>
<td>55 Mb/s</td>
<td>64-QAM</td>
<td>8-TCM</td>
</tr>
</tbody>
</table>

![Diagram showing signal directions with 0°, 90°, 180°, and 270° labels]
Shared Medium Links: WPAN

Example 802.15.3 Piconets

- Piconets

*how to improve over Bluetooth/802.15.1?*
Shared Medium Links: WPAN

Example 802.15.3 Piconets

- Piconets: 64K devices
  - 16 b DEV address
  - peer-to-peer data
    - *doesn’t* need to go via PNC

*why do we need a controller?*
Shared Medium Links: WPAN

Example 802.15.3 Piconets

- Piconets: 64K devices
  - 16 b DEV address
  - peer-to-peer data
    - *doesn't* need to go via PNC
  - PNC piconet coördinator
    - *beacons* to all DEVs in piconet
    - distributes timing
Shared Medium Links: WPAN

Example 802.15.3 Frame Format

- Header
- Payload
Shared Medium Links: WPAN

Example Additional 802.15.3 TGs

- 802.15.3 task groups
- 802.15.3a: high rate alternative PHY
  - group deadlocked and disbanded
- 802.15.3b: MAC amendment
  - corrections and updates to 802.15.3
- 802.15.3c: millimeter wave
  - alternate physical layer in millimeter wave bands
Shared Medium Links: WPAN

Example 802.15.3a Alternative PHY

- 802.15.3a: alternative PHY for 802.3.15
- Goal:
  - higher data rate in excess of 100 Mb/s
- Multiple proposals
  - combined and down-selected to two competitors
    1. DS-UWB (direct sequence – ultra wide band)
      - UWB pulses in two channels: 3.1–4.85 and 6.2–9.7GHz
      - 26 Mb/s – 1.32 Gb/s
    2. MB-OFDM (multiband – orthogonal freq. div. multiplexing)
      - OFDM in 3.1 –10.6GHz band
      - 480 Mb/s per 528MHz of spectrum in 14 channels
Shared Medium Links: WPAN

Example 802.15a Alternative PHY

• Problem:
  – deadlock between proposals

• Typical solutions to standards deadlock
  – compromise even if bad (e.g. ATM cell size)
  – do both as alternatives (not uncommon for IEEE 802)
  – choose one at higher level (difficult due to politics)
  – give up (perhaps let marketplace decide)

• 802.15.3 fate
  – one group was unwilling to compromise
  – study group disbanded
  – challenges: regulatory problems with UWB interference
Shared Medium Links: WPAN
Example WiMedia MB-OFDM UWB

- WiMedia Alliance www.wimedia.org
- Evolution of 802.15.3a MB-OFDM
  - standardised as ISO/IEC 26907 and 26908
Shared Medium Links: WPAN

Example 5.802.15.3c Millimeter Wave PHY

- **802.15.3c**: millimeter wave WPAN
  - 57–64 GHz unlicensed spectrum
  - goal: data rate > 1 Gb/s up to 10 m

- **Status**
  - currently down to 9 proposals
  - goal to agree by end of 2007
  - goal to finish standard by end of 2008
### 802.15 Link Characteristics

<table>
<thead>
<tr>
<th>Link type</th>
<th>year</th>
<th>band</th>
<th>channel bw</th>
<th>channels</th>
<th>coding</th>
<th>MAC rate</th>
<th>typical range</th>
<th>payload</th>
<th>typical goodput</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bluetooth 1.0</td>
<td>1998</td>
<td>2.4 GHz</td>
<td>83.5 MHz</td>
<td>FHSS 79 \times 1MHz</td>
<td>TDMA/TDD GFSK</td>
<td>721 kb/s</td>
<td>1–100 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bluetooth 1.1</td>
<td>2002</td>
<td>2.4 GHz</td>
<td>83.5 MHz</td>
<td>FHSS 79 \times 1MHz</td>
<td>TDMA/TDD GFSK</td>
<td>721 kb/s</td>
<td>1–100 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>802.15.1</td>
<td>2003</td>
<td>2.4 GHz</td>
<td>83.5 MHz</td>
<td>FHSS 79 \times 1MHz</td>
<td>TDMA/TDD GFSK</td>
<td>721 kb/s</td>
<td>1–100 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bluetooth 2.0</td>
<td>2005</td>
<td>2.4 GHz</td>
<td>83.5 MHz</td>
<td>AFHSS 79 \times 1MHz</td>
<td>π/4-DQPSK 8-DPSK</td>
<td>2 Mb/s</td>
<td>1–100 m</td>
<td>&lt;2.1 Mb/s</td>
<td></td>
</tr>
<tr>
<td>802.15.3</td>
<td>2003</td>
<td>2.4 GHz</td>
<td>83.5 MHz</td>
<td>5 \times 15MHz</td>
<td>QPSK/QAM TCM-8</td>
<td>11 – 55 Mb/s</td>
<td>1–100 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>802.15.3a</td>
<td>2005</td>
<td>3.1–10.6 GHz UWB</td>
<td>7.4 GHz</td>
<td>14 \times 528 MHz UWB 30 channels</td>
<td>MB-OFDM TFC</td>
<td>53.3–480 Mb/s</td>
<td>3–10 m</td>
<td>0–4096 B</td>
<td></td>
</tr>
<tr>
<td>Bluetooth 3.0</td>
<td></td>
<td>57–64 GHz mm</td>
<td>~7 GHz</td>
<td>~14 GHz mm</td>
<td>~2 Gb/s</td>
<td>&gt;10 m</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Shared Medium Links: WPAN

**Example** Wireless USB Overview

- **Wireless USB:** Universal Serial Bus
  - wireless version from [www.usb.org/developers/wusb/](http://www.usb.org/developers/wusb/)

- **USB**
  - actually become the *universal* PC peripheral interconnect
  - largely replacing serial, parallel, and SCSI for consumers

- **Wireless USB**
  - high-rate wireless link with USB interface
  - 480 Mb/s at 3 m; 110 Mb/s at 10 m

- **Wireless USB future uncertain**
Shared Medium Links: RBB

Example 5.H HFC Residential Broadband

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

<table>
<thead>
<tr>
<th>RBB 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>shared 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>
Shared Medium Links: RBB

Example 5.H HFC Network Architecture

- **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
Shared Medium Links: RBB

HFC Residential Architecture

- Data multiplexed with analog and digital TV channels
  - IP telephony delivered over data stream

CMTS: cable modem termination system
DOCSIS×: hub or switch with DOCSIS modem
LIS: local insertion video server (weather, ads)
TRAC: telco return access concentrator

Example 5.H
**Shared Medium Links: RBB**

**Example 5.H**

**HFC Modulation and Spectrum**

- 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
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
Shared Medium Links: RBB

Example 5.H

HFC DOCSIS Protocol Stack

- DOCSIS standards
  - operations interfaces
  - security
  - MAC (+link)
    - link framing
    - TDM downstream
    - TDMA upstream
  - physical layer
    - RF on coax
    - QPSK/QAM

PHY

Ethernet LLC+MAC

MAC filter

cable modem mgt.

DHCP

TFTP

SNMP

security mgt.

UDP

IP + ARP

802.2 LLC

DIX/802.3 MAC

security

MAC

convergence

PHY

RF on coax.

cat-n to CPE

22 February 2017

KU EECS 881 – High-Speed Networking – Administrivia

HSN-LL-193
### Shared Medium Links: RBB

#### Example

**HFC DOCSIS Frame Format**

- **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: HFC DOCSIS Frame Format**

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC</td>
<td>Frame control type [1B]</td>
</tr>
<tr>
<td>MAC_PARM</td>
<td>MAC parameters [1B]</td>
</tr>
<tr>
<td>LEN</td>
<td>Length of EDR+payload [2B]</td>
</tr>
<tr>
<td>EHDR</td>
<td>Extended header [0–240B]</td>
</tr>
<tr>
<td>HCS</td>
<td>Header check sequence [2B]</td>
</tr>
<tr>
<td>Ethernet header</td>
<td>IP packet</td>
</tr>
<tr>
<td>Ethernet CRC</td>
<td></td>
</tr>
</tbody>
</table>
### Shared Medium Links: RBB Example

**HFC Link Characteristics**

<table>
<thead>
<tr>
<th>Link Type</th>
<th>Standard</th>
<th>Year</th>
<th><strong>Downstream</strong></th>
<th><strong>Upstream</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rate</td>
<td>Coding</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rate</td>
</tr>
<tr>
<td>DOCSIS 1.0</td>
<td></td>
<td>1996</td>
<td>30.342 Mb/s</td>
<td>64-QAM</td>
</tr>
<tr>
<td>DOCSIS 1.1</td>
<td>J.112</td>
<td>1999</td>
<td>30.342 Mb/s</td>
<td>64-QAM</td>
</tr>
<tr>
<td>Euro</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DOCSIS 2.0</td>
<td>J.122</td>
<td>2001</td>
<td>30.342 Mb/s</td>
<td>64-QAM</td>
</tr>
<tr>
<td>DOCSIS 3.0</td>
<td></td>
<td>2006</td>
<td>160 Mb/s</td>
<td>64-QAM</td>
</tr>
</tbody>
</table>
Advantages of HFC?
Shared Medium Links: RBB

Example: HFC Summary

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

Disadvantages of HFC?
Shared Medium Links: RBB

Example HFC Summary

- 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
Shared Medium Links: RBB

Example HFC Summary and Evolution

- **Advantages of HFC**
  - reuse of existing CATV plant

- **Disadvantages of HFC**
  - shared medium infrastructure
  - usable data rate and latency per user highly variable

- **Evolution for high speed**
  - hack of video distribution network for Internet access
  - replacement of legacy wired CATV infrastructure with fiber
    - but not all the way to the residence
  - higher baud rate QAM coding with DOCSIS evolution
Links

LL.3 Link Layer Components

LL.1 Transmission and physical media
LL.2 Link layer technologies
LL.3 Link layer components
  LL.3.1 Amplifiers, regenerators, and repeaters
  LL.3.2 Multiplexors and cross-connects
  LL.3.3 Bridges, hubs, and switches
LL.4 Support for higher layers
Link Layer Components

Example Types

- Amplifiers and regenerators
  - optical
  - microwave relays
  - bent-path satellite links
- Bridges and hubs
- Multiplexors and cross-connects
  - space division switches
- Time slot interchangers (TSI)
  - time division switches
- Optical wavelength converters
Link Layer Components

Performance Requirements

• Performance requirements
  – must sustain link rate
  – must not introduce unacceptable delay

Link layer components must sustain the data rate of the link, while not introducing significant delay.
Links and LANs

LL.3.1 Amplifiers, Regenerators, and Repeaters

LL.1 Transmission and physical media
LL.2 Link layer technologies
LL.3 Link layer components
   LL.3.1 Amplifiers, regenerators, and repeaters
   LL.3.2 Multiplexors and cross-connects
   LL.3.3 Bridges, hubs, and switches
LL.4 Support for higher layers
Link Layer Components
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
Link Layer Components

Lightpath Transparency

- Rate specific bit stream
  - OTN Och {2.5, 10, 40 Gb/s}
- Bit stream
  - With 3R retiming
  - Protocol transparent
- Digital
  - With 2R regen
  - Timing transparent
- Analog (approximate)
  - With EDFAs
  - O-CDMA
- Photonic
  - Waveform O-CDMA
  - Quantum crypto
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: opaque optical networks
  - lose advantages of all-optical lightpaths
- Optical domain: emergent technology
  - expensive
  - 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
Links and LANs
Multiplexors and Cross-Connects

LL.1 Transmission and physical media
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LL.3 Link layer components
  LL.3.1 Amplifiers, regenerators, and repeaters
  LL.3.2 Multiplexors and cross-connects
  LL.3.3 Bridges, hubs, and switches
LL.4 Support for higher layers
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
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
Multiplexors and Cross-Connects
SONET Topology: Mesh

- SONET mesh
  - mesh of SONET links
  - switched at L3
    - between ATM switches
    - between IP routers
Multiplexors and Cross-Connects

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
Multiplexors and Cross-Connects
SONET Add/Drop Multiplexors

- 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
Multiplexors and Cross-Connects
SONET Cross Connects

- 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
Links and LANs
Bridges, Hubs, and Switches

LL.1 Transmission and physical media
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  LL.3.2 Multiplexors and cross-connects
  LL.3.3 Bridges, hubs, and switches
LL.4 Support for higher layers
Link Layer Components

Bridges

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

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- 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?*
Link Layer Components

Bridges

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

- 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
  - rings 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
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?
Link Layer Components

Hubs

- 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
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 \textit{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
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 L2 (IP) switch (router)

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 L2 (IP) switch (router)
    - no IP routing and forwarding capability
Links
Support for Higher Layers

LL.1  Transmission and physical media
LL.2  Link layer technologies
LL.3  Link layer components
LL.4  Support for higher layers
Link Support for Higher Layers
Loss Characterisation

• Higher layer response depends on type of L2 loss
  – net configuration/rerouting based on path characteristics
  – transport layer response to corruption, fades vs. congestion
• Long term and aggregate path characteristics
• Dynamic and per packet information
  – reason for loss

Loss Characterisation Principle

Provide long-term and dynamic information on the reason for loss to high layers so that network and end-to-end mechanisms respond appropriately.
Link Support for Higher Layers

Filtering

- Filtering PDUs not destined for higher layer protocols
  - PDU headers must be processed
- Discard early at low layers
  - minimises PDU processing by higher layers

**Early Filtering Principle**

Filter the incoming data not destined for a node as early as possible, and discard as much as possible at each layer.
Link Support for Higher Layers

Broadcast Support

- Key infrastructure protocols need broadcast
  - e.g. ARP, DHCP
- Shared medium LANs/MANs support natively
- Mesh networks need to provide broadcast emulation

Link Layer Multicast Principle

Shared medium links provide native support for broadcast, essential for higher-layer control protocols and in support of multicast applications. Nonbroadcast point-to-point mesh LANs should provide broadcast and multicast support.
Links
Further Reading


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

- Sterbenz & Touch, *High-Speed Networking: A Systematic Approach to High-Bandwidth Low-Latency Communication*  
  http://hsn-book.sterbenz.org