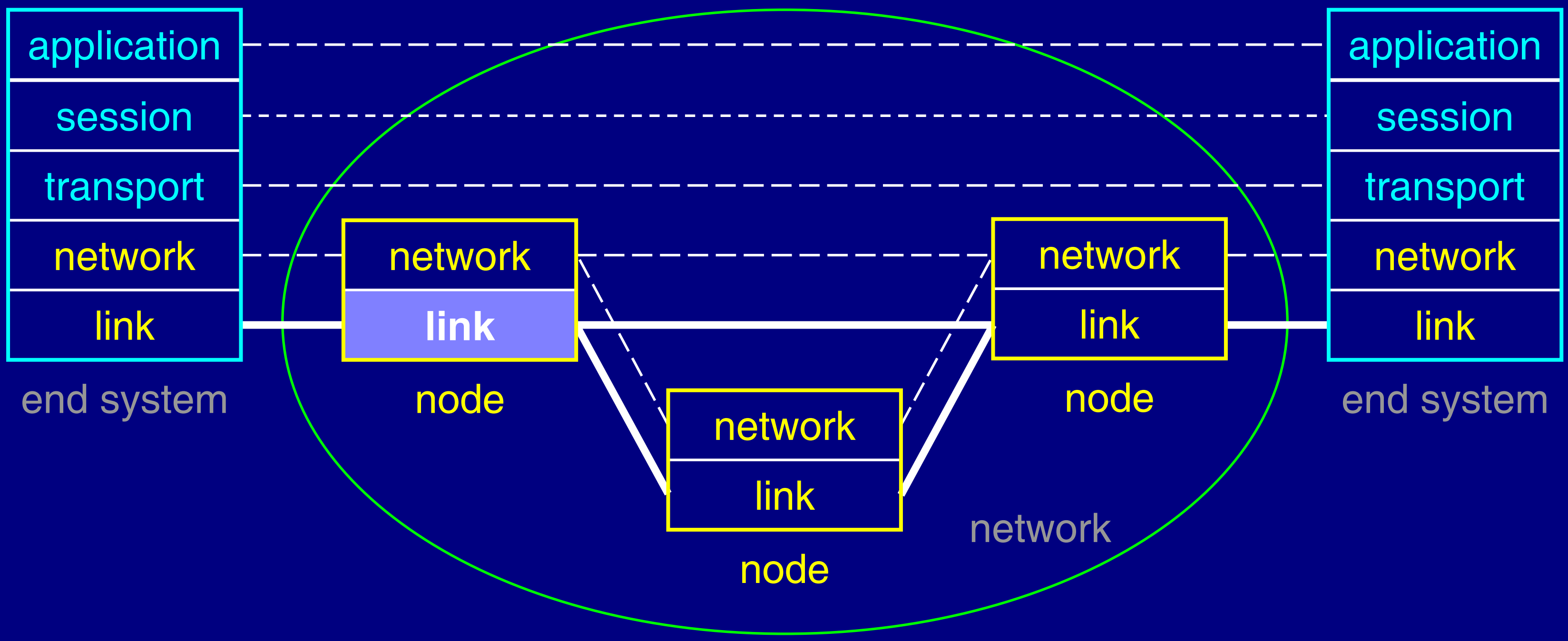
Network Components: Links

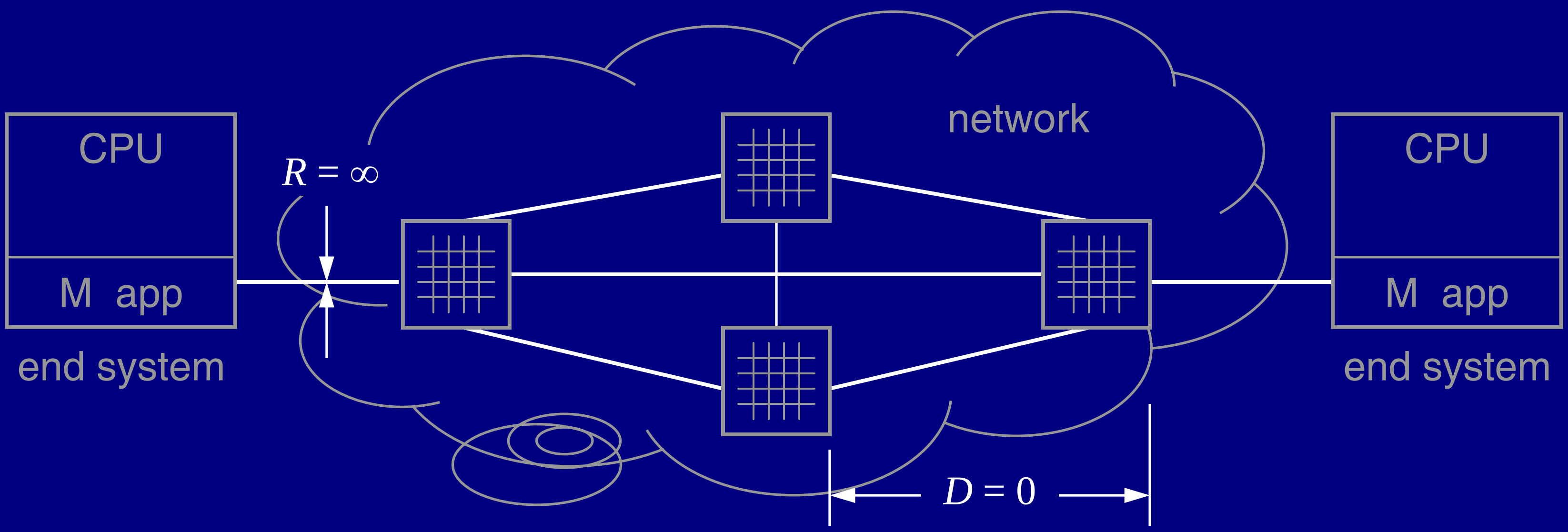
1. Introduction
2. Fundamentals and design principles
3. Network architecture and topology
4. Network control and signalling
5. Network components
   - 5.1 links
   - 5.2 switches and routers
6. End systems
7. End-to-end protocols
8. Networked applications
9. Future directions

Network Components: Links



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

Ideal Network
Network Link Principle



Network Link Principle L-II

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

Links

Physical Transmission
Properties and Characteristics

- Physical properties
  - signal propagation velocity: fraction of speed-of-light
  - link length
  - symbol rate: baud = symbols/s
  - encoding
    - bits/baud: may be <1, =1, >1
    - coding delay
  - modulation: baseband or frequency spectrum
- High-speed network characteristics
  - latency
  - bandwidth = data rate (not spectrum bandwidth)
  - bandwidth-×-delay product

Physical Transmission
Properties and Characteristics

- Wire
- Optical fiber
- Wireless

Type	Medium	Frequency range	Velocity	Delay	Typical attenuation
Wire	twisted pair	0–1MHz	0.67c	5 μs/km	0.7 dB/km
	coax	0–50MHz	0.66–0.95c	4 μs/km	7.0 dB/km
Optical fiber	glass	120–250 THz 1700–800 nm	0.68c	5 μs/km	0.2–0.5 dB/km
Wireless	microwave	1–300 GHz	1.0c	3.3 μs/km	$1/r^2$
	infrared	.3–428 THz			
	visible	428–750 THz			

Physical Transmission
Link Types: Wire

- Wire
  - unshielded twisted pair
    - cheap, moderate bandwidth (~100Mb/s)
  - shielded twisted pair
    - expensive, higher bandwidth
  - coaxial cable
    - expensive, high bandwidth (~ 500 MHz)

Physical Transmission
Link Types: Fiber Optics$_1$

- Fiber optics
  - bandwidth ≈ 20 THz within 800–1700 nm
  - attenuation [dB/km]
    - material absorption
    - Rayleigh scattering: varying index of refraction due to nonuniform molecular density
    - waveguide geometric imperfections
  - dispersion: waveform smearing limits bandwidth-×-distance
    - intermodal: differing distance per reflection mode
    - chromatic: differing velocity per λ
    - polarisation mode: differing velocity per polarisation state

Physical Transmission

Link Types: Fiber Optics$_2$

- Fiber optics
  - types
    - multimode: multiple reflection modes
      - 850 nm with 50–85 μm core
    - single mode: single reflection mode
      - 1310 nm with 8–10 μm core
      - 1550 nm: less attenuation but chromatic dispersion
      - 1550 nm dispersion shifted fiber
        - OC-768 over long distance
        - unsuitable for WDM
      - 1310–1610 dispersion compensated fiber
        - suitable for DWDM

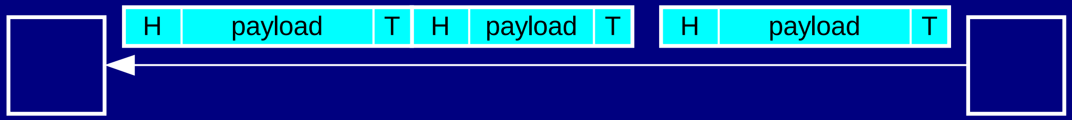
Physical Transmission
Link Types: Wireless$_1$

- Wireless: no waveguide
  - RF: radio frequency
    - ISM unregulated bands
      - 900 MHz 902–928 MHz 26 MHz spectrum
      - 2.4 GHz 2.4000–2.4835 GHz 83.5MHz spectrum
      - 5.8 GHz 5.725–5.850 GHz 125 MHz spectrum
      - ...
    - satellite: microwave bands
      - 1–40 GHz L, S bands
      - 4–20 GHz C, X, Ku bands
      - 20–40 GHz Ka band
      - ...
  - Optical
    - infrared 800–900 nm = 333–375 THz 41 THz spectrum

Physical Transmission
Link Types: Wireless_2

- Wireless
  - signal propagation
    - $1/r^2$ attenuation
    - multipath interference: $1/r^x$
      rural $2 < x < 4$ urban
    - channel fades
  - antennæ
    - omnidirectional
    - directional: spatial reuse mesh
      - fixed
      - steering for mobility

Link Technologies
Point-to-Point Dedicated Links



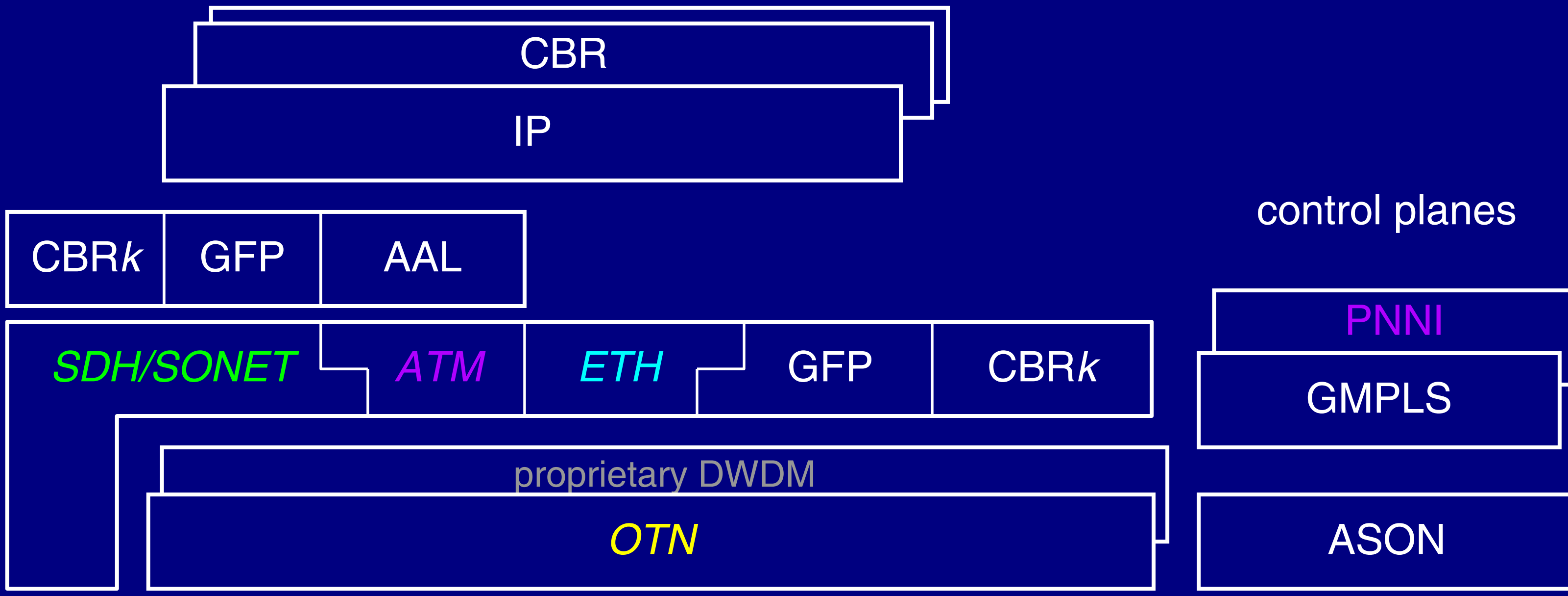
- Sequence of framed packets along a link
  - space division mesh network

Link Protocol Scalability Principle L-8C

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.

Point-to-Point Links

Example$_{5.0}$ ITU Transport Networks



OTN: optical transport network

SDH: synchronous digital hierarchy

Ethernet

ATM/B-ISDN

ASON

GMPLS

PNNI

Point-to-Point Links

Example$_{5.0}$ ITU Transport Networks

- Data and management planes
  - OTN: optical transport network
  - SDH: synchronous digital hierarchy
  - Ethernet
  - 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)

Link Technologies

Example$_{5.0}$ Generic Framing Procedure (GFP)

- Data encapsulation transport networks ITU-T G.7041
  - OTN, SDH/SONET
  - 4B common header (length, HEC)
  - client specific headers
- Transfer of:
  - variable size frames (GFP-F)
    - IP, PPP
    - Ethernet MAC
  - block code (transparent – GFP-T)
    - FCS
    - ESCON/FICON

Link Technologies

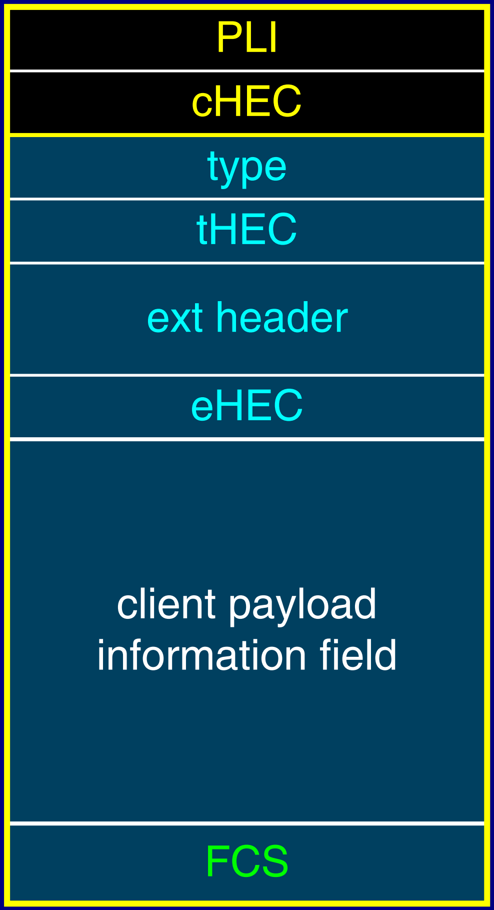
Example$_{5.0}$ GFP Formats

Core header$_{4B}$

- PLI$_{2B}$ PDU length indicator
- cHEC$_{2B}$ core header CRC-16 HEC

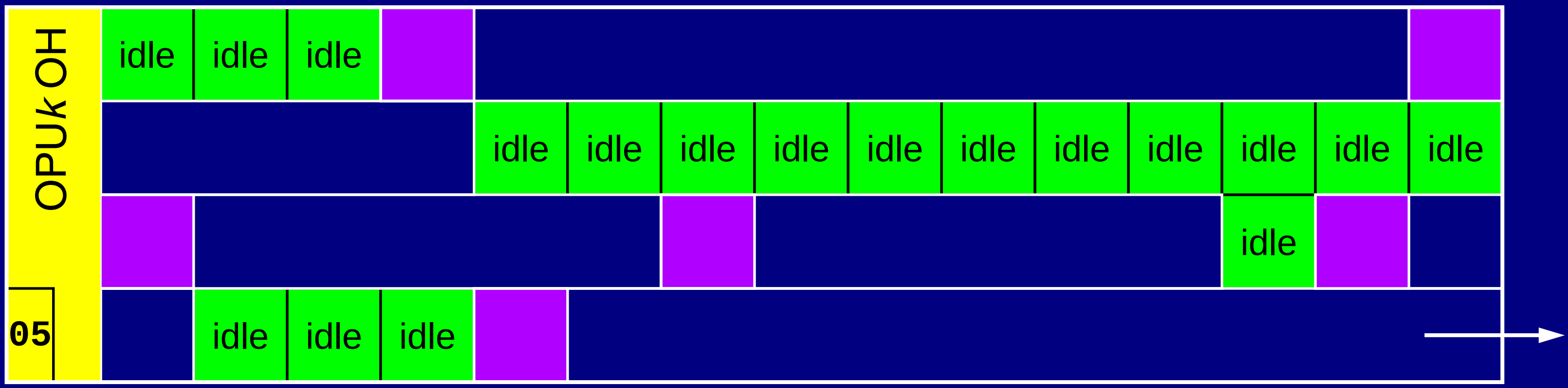
Payload$_{4–65536B}$

- payload headers$_{4–64B}$
  - type$_{2B}$
    - PTI$_{3b}$ payload type id (data/mgt)
    - PFI$_{1b}$ payload FCS identifier
    - EXI$_{4b}$ extension header indicator
  - tHEC$_{2B}$ CRC-16
  - extension header field$_{0\text{-}60B}$
  - eHEC$_{2B}$ CRC-16
- client payload (x^{43}+1 scrambled)
- FCS CRC-32 (optional)$_{4B}$



Link Technologies

Example$_{5.0}$ GFP in OTN



- GFP frames in OPU*k*
  - OH PSI = **05**
- GFP frames arbitrarily packed in OPU
  - Frames (8B–64KB) may span multiple OPUs
  - Idle frames fill gaps

Point-to-Point Links
$\text{Example}_{5.1}$ SONET/SDH

- WAN/MAN synchronous optical links
  - SDH: synchronous digital hierarchy (ITU-T)
  - SONET: synchronous optical network (Bellcore, ANSI)
- Standards suite:
  - architecture G.803, T1.105
  - 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

Point-to-Point Links

Example: SONET/SDH[5.1] Multiplexing Hierarchy

- Path F3
  - link$_{L2}$ between switch$_{L3}$-to-switch$_{L3}$ (ATM or IP switch)
  - STS-*n* generation, HEC, and framing
- Line (SDH digital section) F2
  - de/multiplexing STS-*n* ↔↕ STS-*N*
  - concatenation 4×STS-*n* ↔ STS-4*n*
- Section (SDH regenerator section) F1
  - STS-*n* transport, framing, scrambling
- Photonic section
  - between EO STS-*n*→OC-*n* – OC-*n*→STS-*n* OE
  - between EOE regeneration

Point-to-Point Links

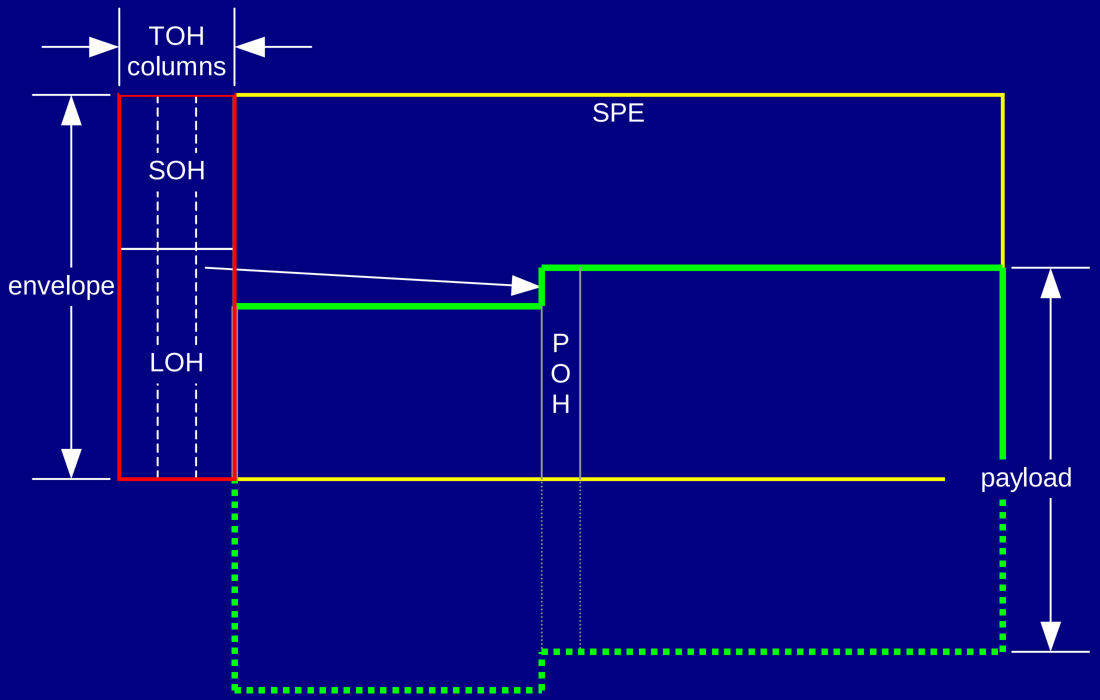
Example$_{5.1}$ SONET/SDH Rates

Link type		Rate	Transport overhead	Payload	Payload rate	
SONET	SDH				SONET	ATM_{max}
STS-1	STM-0	51.84 Mb/s	27 B	774 B	49.54 Mb/s	44.87 Mb/s
OC-3c	STM-1c	155.52 Mb/s	81 B	2 340 B	149.75 Mb/s	135.63 Mb/s
OC-12c	STM-4c	622.08 Mb/s	324 B	9 387 B	600.77 Mb/s	544.09 Gb/s
OC-48c	STM-16c	2.49 Gb/s	1 296 B	37 575 B	2.40 Gb/s	2.16 Gb/s
OC-192c	STM-64c	9.95 Gb/s	5 184 B	150 327 B	9.62 Gb/s	8.71 Gb/s
OC-768c	STM-256c	39.81 Gb/s	20 736 B	601 335 B	38.48 Gb/s	34.85 Gb/s
OC-3072c	STM-1024c	159.25 Gb/s	82 944 B	2 405 367 B	153.94 Gb/s	139.42 Gb/s
OC-*N*c	STM-(*N*/3)c	$N \times$ 51.84 Mb/s	$N \times 3 \times 9$ B	$N \times 87 \times 9 - 9$ B	1.0 SONET	48/53 SONET

Point-to-Point Links

Example$_{5.1}$ SONET Frame Structure

Payload floats in synchronous envelope



TOH transport overhead
- $3 \times N$ columns

SOH section overhead

LOH line overhead

POH path overhead
- 1 column for OC-Nc
- N columns for OC-N

SPE synchronous payload envelope

Point-to-Point Links

$\text{Example}_{5.M}$ 802.16

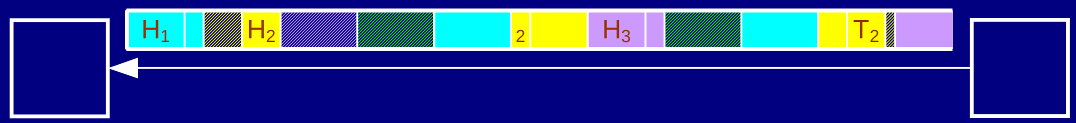
- IEEE 802.16 WirelessMAN
- Metropolitan wireless networks
  - originally intended for *fixed* wireless access
  - standardisation and replacement for MMDS in 10 – 66 GHz
  - 802.16a additional operation in licensed bands 2 – 11 GHz
  - 802.16b additional operation in unlicensed 5.8 GHz band
- Later support for mobility
  - 802.16e overlaps with IEEE 802.20 MBWA charter
- Mesh of point-to-point links
  - FDD (frequency division duplex)
  - TDD (time division duplex): full duplex shares frequency

Point-to-Point Links

Example$_{5.M}$ 802.16 Link Characteristics

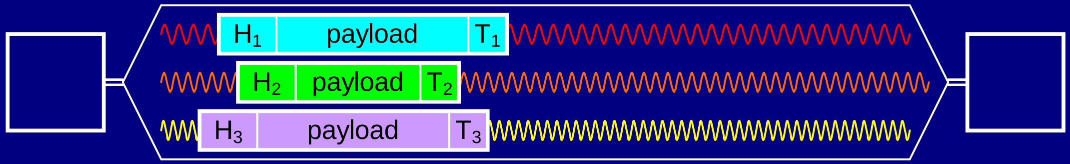
- 802.16 (original)
  - 10-66 GHz licensed spectrum; LOS (line of sight)
  - 2 – 5 km transmission radius
  - 32 – 134 Mb/s
- 802.16a and 802.16b
  - 2 – 11 GHz; non-LOS
  - 7 – 10 km typical; 50 km max transmission radius
  - 75 Mb/s
- 802.16e (mobile)
  - 2 – 6 GHz; non-LOS
  - 2 – 5 km transmission radius
  - 15 Mb/s

Link Technologies
Multiplexed Links



- Multiplexing
  - synchronous TDM: time division multiplexing
  - asynchronous time division multiplexing (statistical)
  - frequency division
    - FDM: frequency division multiplexing (RF)
    - WDM: wavelength division multiplexing (optical)

Link Technologies
Multiplexed Links



- Optical WDM
  - synchronous TDM: time division multiplexing
  - asynchronous time division multiplexing (statistical)
  - 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

WDM Multiplexing Degree
Point-to-Point Dedicated Links

- Constrained by nonlinearities
  - stimulated Raman scattering (molecular vibrations)
  - stimulated Brillouin scattering (acoustic waves)
  - carrier-induced cross-phase modulation (increased velocity)
  - four-wave mixing (FWM): $\lambda_i + \lambda_j - \lambda_k$
- Cost tradeoff (OC-192 in early 2000s):
  - system cost of bleeding edge OEO vs. multiple sets

WDM Multiplexing Degree Tradeoff L-??

The optimal degree of wavelength division multiplexing is a tradeoff between the cost per wavelength of higher rates vs. the costs of multiple wavelengths.

Multiplexed Links

Example$_{5.A}$ OTN

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

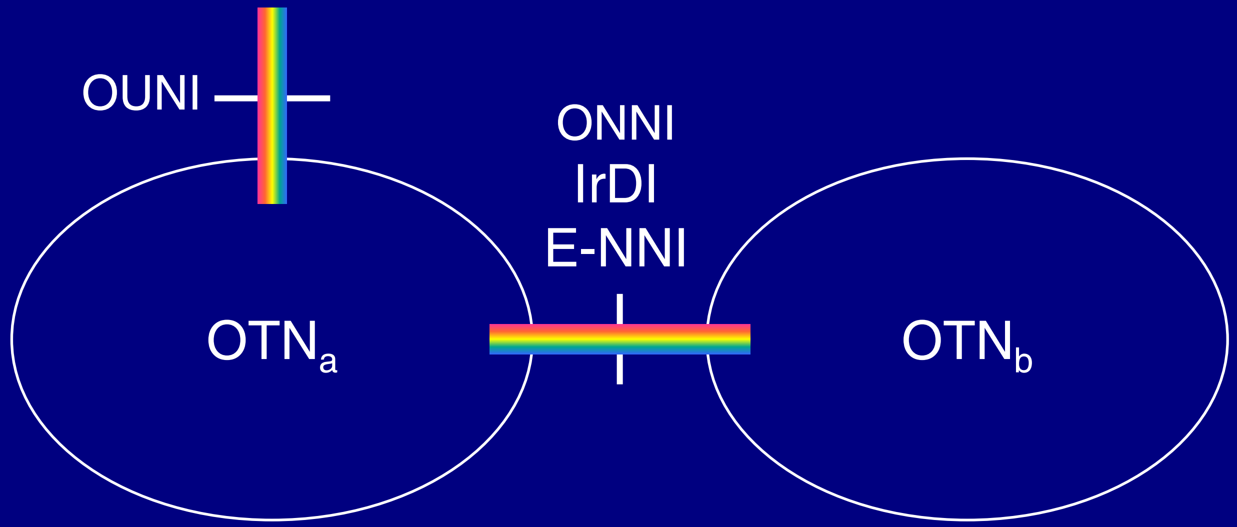
Multiplexed Links

Example[5.A] OTN Overview

- Trails
  - undirectional and bidirectional
  - point-to-point and point-to-multipoint
- Interfaces
  - OUNI (not yet standardised by OIF)
  - IrDI / E-NNI interdomain
  - 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

Multiplexed Links

Example$_{5.A}$ OTN Interfaces



- 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

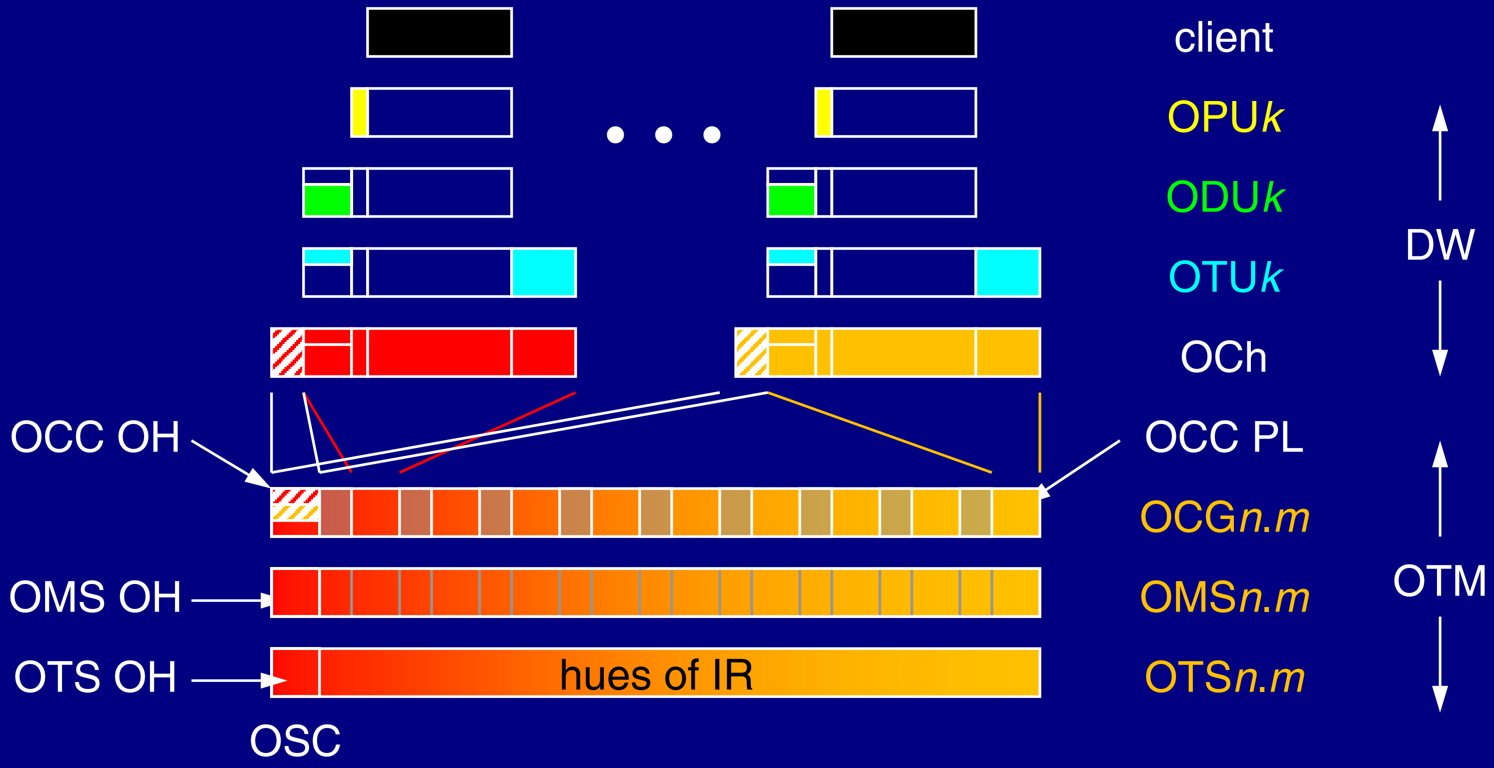
Multiplexed Links

Example$_{5.A}$ OTN Multiplexing and Framing

- Digital over optical multiplexing hierarchy
  - Client trail (SONET, ATM, GFP)
  - Digital wrapper (in band)
    - OPU*k* – 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,...} OPU*k* TDM
      - {...12,23,123} combinations

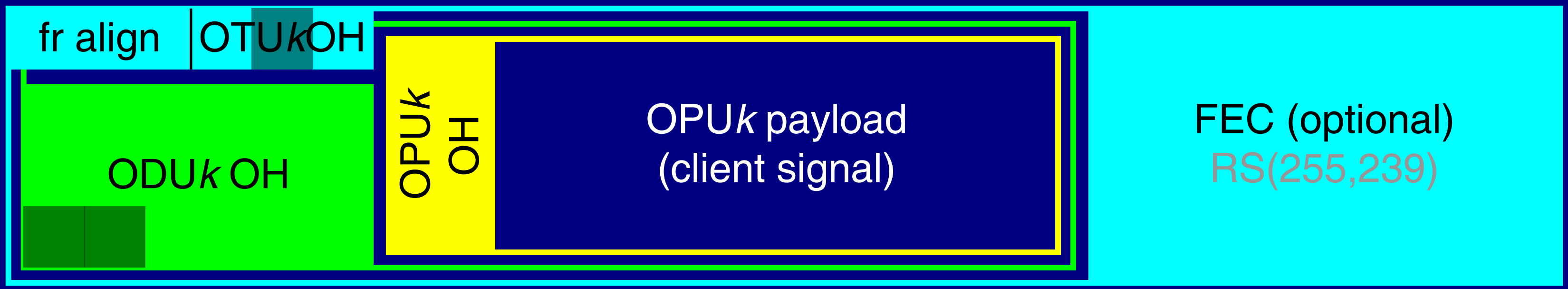
Multiplexed Links

Example 5.A OTN Framing and Multiplexing



Multiplexed Links

Example$_{5.A}$ OTN Digital Wrapper



- OPU*k* – OCh payload unit: carries client signals
  - OPU1 ≈> 2.4Gb/s, OPU2 ≈> 10Gb/s, OPU3 ≈> 40Gb/s
- ODU*k* – OCh data unit (digital path)
- OTU*k* – OCh transport unit (digital section)

Multiplexed Links

Example$_{5.A}$ OTN Digital Wrapper$_{OPU}$

- OPU*k* – OCh payload unit: carries client signals
  - OPU1 ≈ 2.4Gb/s, OPU2 ≈ 10Gb/s, OPU3 ≈ 40Gb/s
  - OPU*k* OH
    - PSI$_{1B}$: payload structure identifier
      - PT {CBR (SONET) , ATM, GFP, bit stream, Ethernet?}
- ODU*k* – OCh data unit (digital path)
- OTU*k* – OCh transport unit (digital section)

Multiplexed Links

Example$_{5.A}$ OTN Digital Wrapper$_{ODU}$

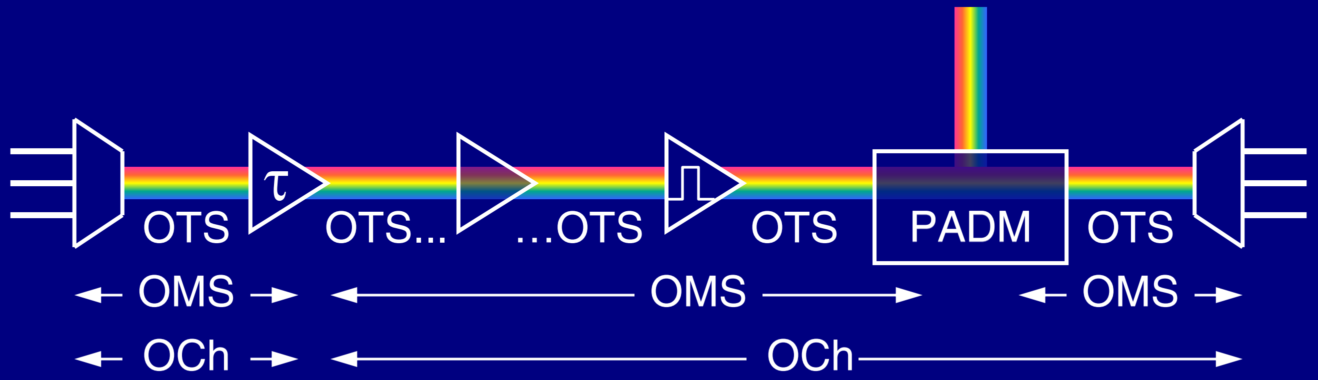
- OPU*k* – OCh payload unit: carries client signals
- ODU*k* – OCh data unit (digital path)
  - ODU*k* OH
    - PM$_{3B}$: path monitoring
    - TCM1–6$_{18B}$: tandem connection monitoring
    - GCC1,2$_{4B}$: general comm channels for ASON signaling
    - APS/ACC$_{4B}$: auto protection switching & prot comm channel
    - FTFL$_{1B}$: fault type and location reporting comm channel
    - EXP$_{2B}$: experimental (vendor/service provider)
    - RES$_{9B}$: reserved (000000000)
- OTU*k* – OCh transport unit (digital section)

Multiplexed Links
Example$_{5.A}$ OTN Digital Wrapper$_{OTU}$

- OPU*k* – OCh payload unit
- ODU*k* – OCh data unit (digital path)
- OTU*k* – OCh transport unit (digital section)
  - $1 + x + x^3 + x^{12} + x^{16}$ scrambled
  - Frame alignment$_{7B}$
  - OTU*k* OH
    - SM$_{3B}$: section monitoring
    - GCC0$_{2B}$: general comm channel 0 for ASON signaling
    - RES$_{2B}$: reserved (00)
  - FEC$_{1024B}$
    - optional RS(255,239) per row
    - zero if FEC not used

Multiplexed Links

Example$_{5.A}$ OTN Optical Transport Module



- 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})

Multiplexed Links

Example$_{5.A}$ OTN Optical Multiplexing Hierarchy

- 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 ↔↕
  - integrity, OAM&P
- Optical transmission section OTS
  - medium specific transmission
  - OAM&P, integrity, survivability

Multiplexed Links

Example[5.A] OTN Optical Transport Module

- Types
  - OTM-*n.m* *n* channels, *m* rates
    - *n* = {1,2,3,12,23,123} *k* individually or in combination
    - Non-associated OSC (optical supervisory channel)
      - OTS and OMS overhead out of band
  - OTM-*n* r.*m* *n* channels, *m* rates
    - Reduced functionality: no specified OSC, OTS/OMS OH not required
  - OTM-0.*m* 1 channel, *m*={1,2,3}=*k*
    - No OTS/OMS overhead

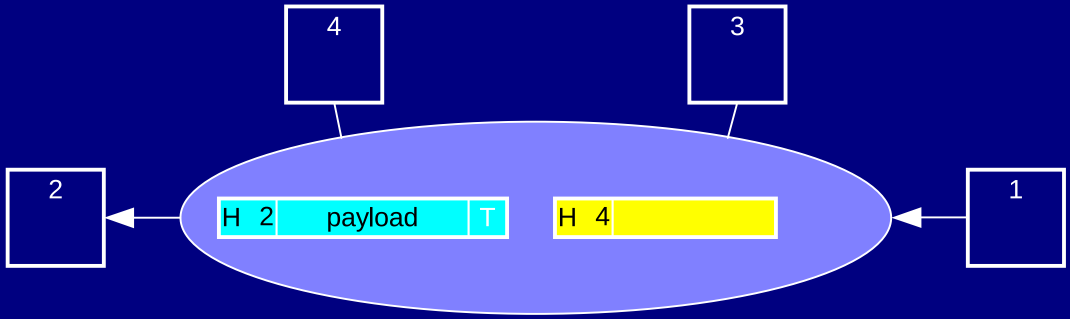
Multiplexed Links

Example$_{5.A}$ OTN OTH Rates

Link type	OTU/Och rate	DW OH	FEC	OPU Payload	OPU rate	Payloads		
OTH						SONET	GFP+CRC$_{max}$	Ethernet
–					51.84 Mb/s	STS-1		
–					155.52 Mb/s	STS-3c		
–					622.08 Mb/s	STS-12c		
OPU1	2.67 Gb/s	64 B	1024 B	15 232 B	2.49 Gb/s	STS-48c	2.49 Gb/s	1000Base
OPU2	10.71 Gb/s	64 B	1024 B	15 232 B	9.95 Gb/s	STS-192c	9.96 Gb/s	=10GBase
OPU3	43.02 Gb/s	64 B	1024 B	15 232 B	39.81 Gb/s	STS-768c	39.79 Gb/s	=40G?
OPU4	172.80 Gb/s	64 B	1024 B	15 232 B	159.25 Gb/s	STS-3072c	159.15 Gb/s	100G?
OPU*k*	255/(239–*k*) × SONET	16×4 B	256×4 B	3808×4 B	= SONET line rate		$\frac{65495}{65535}$	

Link Technologies

Shared Medium Links



- 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

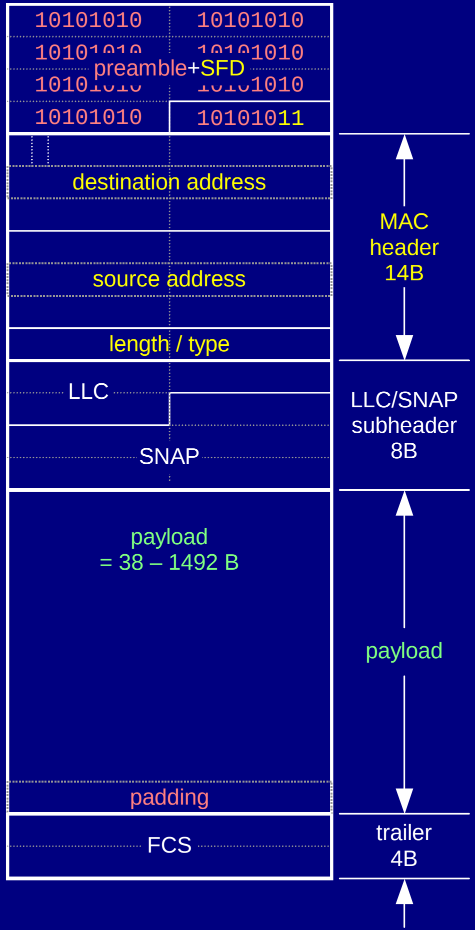
Medium Access Control Principle L-II.2

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

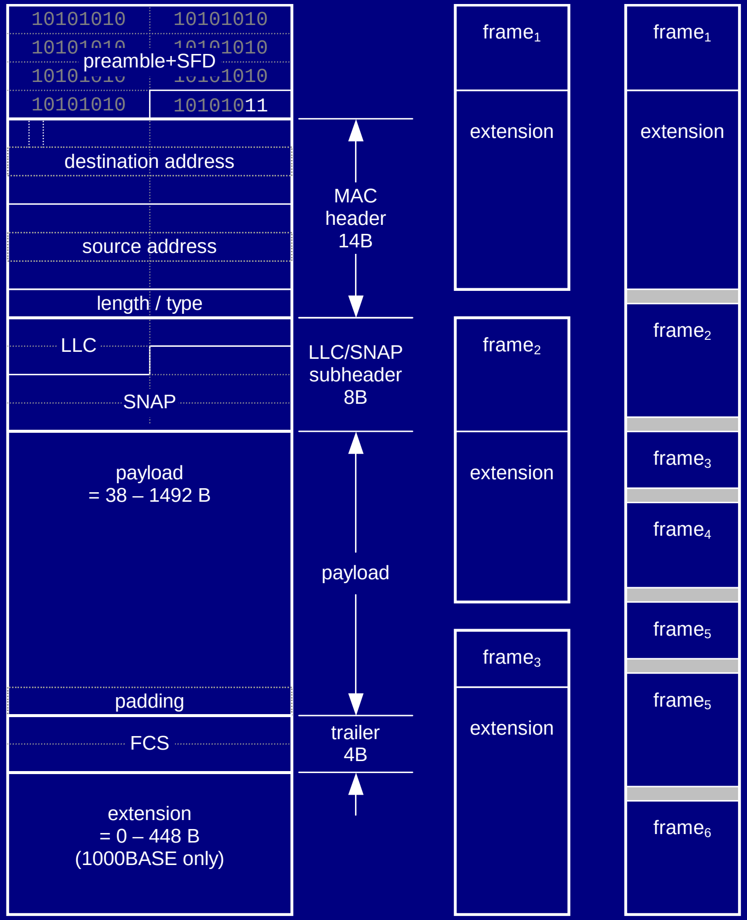
- Early LAN technology (1973)
  - DIX: Digital, Intel, Xerox
  - IEEE 802.3
- Shared wire medium
  - CSMA/CD MAC
  - performs well in light load < 50%
  - performs poorly in heavy load > 80%
- Dominant 1980s LAN
  - token ring only significant competitor
  - evolved 10 to 100 Mb/s to ...



Shared Medium Links

Example$_{5.2}$ Ethernet Evolution

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



Shared Medium Links

Example$_{5.2}$ Ethernet Evolution

- ...Evolved to 10Gb/s
- Modification
  - point-to-point only
    - fiber only
  - 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) $\rightarrow$ 9.95 Gb/s (WAN)
    - § in table

Shared Medium Links

$Example_{5.2}$ Ethernet Link Characteristics

Link type	rate/year	media	full	coding	range	topology	OH	payload
PARC	2.94 Mb/s 1972-1976	coax	H	Manchester		shared	10 B	≲ 4K B
10Base5 10Base2 10BaseT	10 Mb/s DIX 1980 802.3 1985	thick coax thin coax 2 pair UTP-3	H H H | F	Manchester	500 –2500* m 185 – 925* m 100 m	shared shared hub	38 B	38–1492 B
100BaseTX 100BaseT2 100BaseT4 100BaseFX	100 Mb/s 802.3u 1995	2 pair UTP-5 2 pair UTP-3 4 pair UTP-3 mm fiber	H | F H | F H H | F	4B/5B PAM5x5 8B/6T 4B/5B	100 m 100 m 100 m 412 – 2000† m	star: hub/ switch	38 B	38–1492 B
1000BaseT 1000BaseCX 1000BaseLX 1000BaseSX	1 Gb/s 802.3z 1998	4 pair UTP-5 twinax STP ↑λ s/m fiber ↓λ mm fiber	H | F H | F H | F H | F	4B/5B|PAM5 8B/10B FCS 8B/10B FCS 8B/10B FCS	100 m 25 m 316 – 5000 m 275 – 550 m	switch pt-2-pt	38 B + ≤448 /burst	38–1492 B
10GBaseX 10GBaseR 10GBaseW	10 Gb/s 802.3ae 2002	parallel fiber fiber fiber	F F F	8B10B FCS 64B/66B 64B/66B §	65 m – 40 km	switch pt-2-pt	38 B	38–1492 B
40GBase ? 100GBase ?	40 Gb/s 100 Gb/s	fiber	F		*w/repeaters †full duplex	switch pt-2-pt		38–1492 B

Shared Medium Links

Example$_{5.T}$ 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

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

Example$_{5.T}$ 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

Example5.T Ring LAN Characteristics

Link type	rate	media	coding	access	link range	ring circum.	topology	OH	payload
DCS 1972	2.5 Mb/s			token			ring		
Cambridge 1979	10 Mb/s	2 x TP		slot			ring	22 b	16 b
Token Ring 1981 IBM 1985 802.5	4 Mb/s 16 Mb/s	STP	Δ Manch.	token*	250 m†		ring	21 B	0 – 4529 B 0 – 18279 B
HSTR 802.5t 1998 802.5t 802.5v	100 Mb/s 100 Mb/s 1 Gb/s	{US}TP fiber fiber	MLT-3 4B/5B 8B/10B FCS	DTR		–	star	21 B	0 – 18279 B
FDDI 1988	100 Mb/s	fiber	4B/5B	token	2 km	200 km	2×ring	28 B	0 – 4522 B
CDDI	100 Mb/s	STP UTP-5	MLT-3	token	100 m	10 km	2×ring	28 B	0 – 4522 B

*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

†72 m for UTP

Shared Medium Links

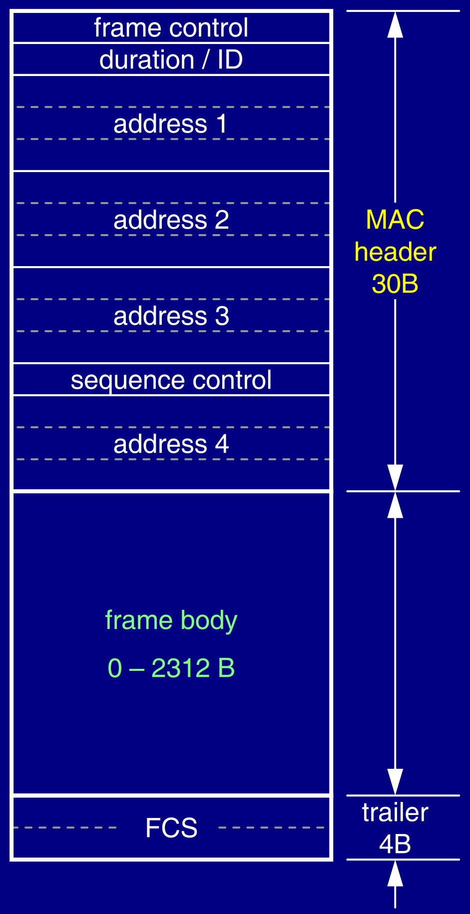
$\text{Example}_{5.W}$ 802.11 / Wi-Fi

- 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, 2.4, 5 GHz
  - significant interference from FHSS 2.4 GHz cordless phones
- Variety of coding schemes
  - DSSS: direct sequence spread spectrum
  - FHSS: frequency hopping spread spectrum
  - OFDM: orthogonal frequency division multiplexing

Shared Medium Links

Example$_{5.W}$ 802.11 Frame

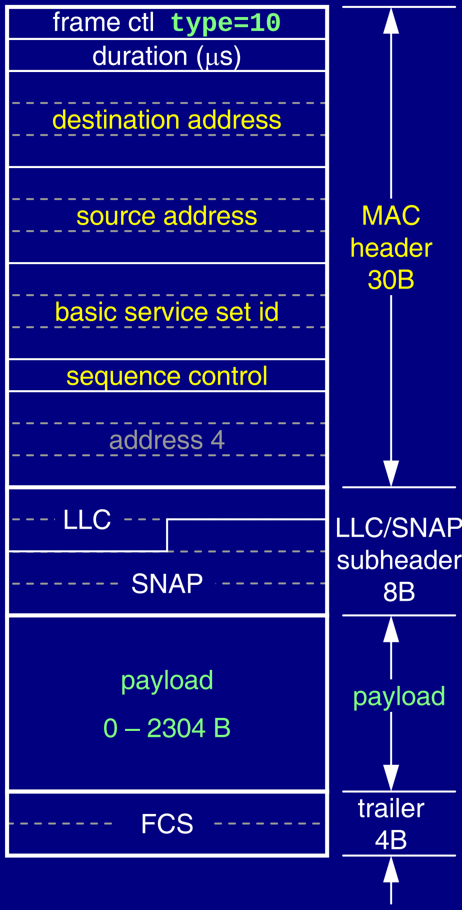
- Frame types
  - management (**`type=00`**):
    - (re)association {request|response}
    - probe {request|response}
    - disassociation
    - (de)authentication
  - control (**`type=01`**):
    - PS-poll (power save)
    - RTS, CTS
    - CF-end, CF-end+CF-ACK (contention free)
    - ACK
  - data (**`type=10`**)



Shared Medium Links

Example$_{5.W}$ 802.11 Frame

- Frame types
  - data frame (`type=10`)



Shared Medium Links

$\text{Example}_{5.W}$ 802.11 Link Characteristics

Link type	year	band (US)	channel bw (US)	channels us/eu/jp/*	coding	MAC rate	typical range	payload	typical goodput
ALOHA	1970	400 MHz	2×100 kHz	1		9.6 kb/s			
NCR Wavelan	1991	915 MHz	26 MHz		DSSS	1 Mb/s 2 Mb/s			
802.11	1997	2.4 GHz	83.5 MHz	11|13|14|3	DSSS FHSS	1 – 2 Mb/s		0–2304 B	
802.11b	1999	2.4 GHz	83.5 MHz	11|13|14|3	DSSS FHSS	1 – 11 Mb/s	60 m	0–2304 B	5 Mb/s
802.11a	1999	5.8 GHz	300 MHz	12|19|4	OFDM	6 – 54 Mb/s	35 m	0–2304 B	24 Mb/s
802.11g	2003	2.4 GHz	83.5 MHz	8	OFDM DSSS	6 – 54 Mb/s 1 – 11 Mb/s		0–2304 B	24 Mb/s
802.11n	2007	5.8 GHz			OFDM MIMO	>100 MB/s		0–2304 B	

*number of non-overlapping channels for 802.11 and 802.11b
†

Link Layer Components
Performance Requirements

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

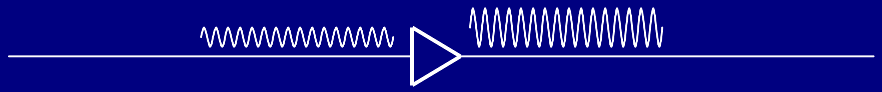
Link Layer Components L-II*c*

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

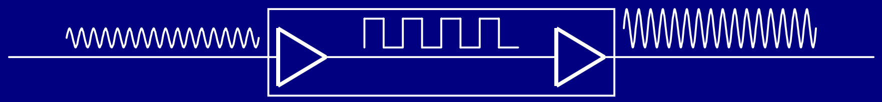
Link Layer Components

Amplifiers and Regenerators

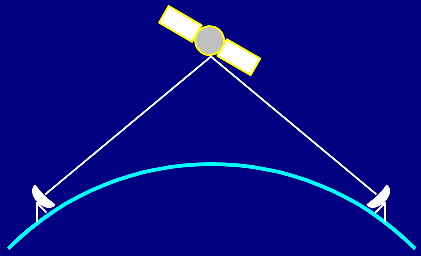
- Amplifiers: analog



  – example: optical EDFA (erbium doped fiber amplifier) every few hundred km



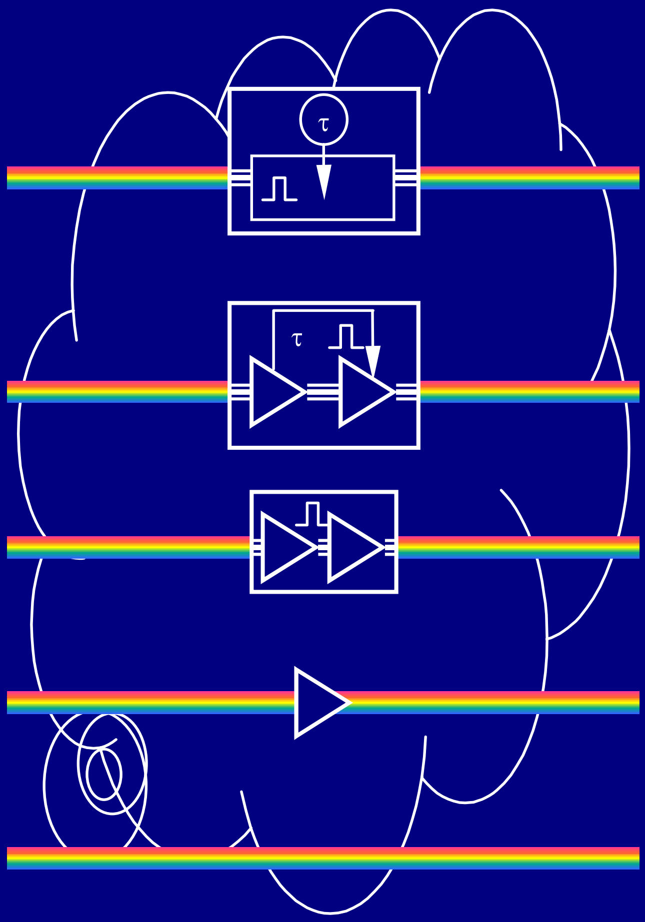
- Regenerators: A/D/A
  – 2R: regeneration and reshaping preserves timing
  – 3R: regeneration, reshaping, and retiming
  – examples:
    - optical 2R and 3R
    - microwave relays
    - bent-path satellite links



Link Layer Components

Lightpath Transparency

- Rate specific bit stream
  - OTN Och {2.5,10,40Gb/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
Multiplexors and Cross-Connects

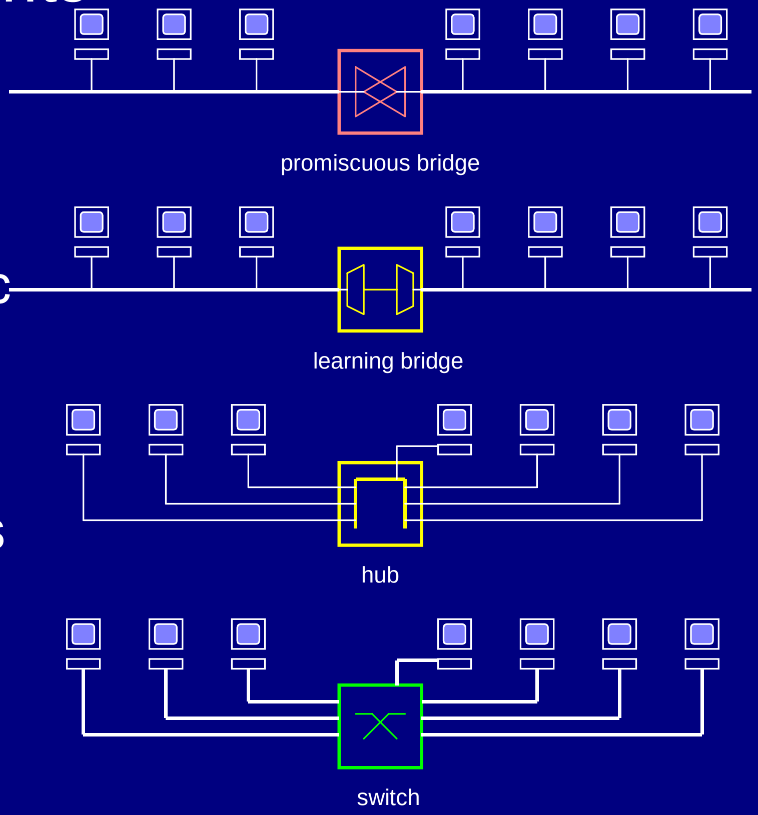
- Multiplexors / demultiplexors
  - aggregate multiple virtual links onto a physical link
    - example: T-carrier, point-to-point SONET, WDM multiplexors
    - example: SONET ring add-drop multiplexors
- Cross-connects
  - layer 2 switch with relatively static configuration
    - example: SONET cross-connect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

Link Layer Components
Optical Wavelength Converters

- O/E/O: convert through electronic domain
  - expensive
  - lose advantages of all-optical lightpaths
- Optical domain: future technology
  - cross-modulation: input modulates laser output at new λ
  - 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

Link Layer Components
Hubs and Bridges

- Bridges connect LAN segments
  - extend reach beyond limits
    - e.g. Ethernet extension
  - promiscuous: pass all frames
  - learning: filter & reduce traffic
- Hubs centralise wiring
  - allow star to wiring closet
  - inter-hub learning bridge links
- Switches
  - switch on layer 2 header
  - full bandwidth per link



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 L-4F

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 L-4*f*

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 L-2C

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.