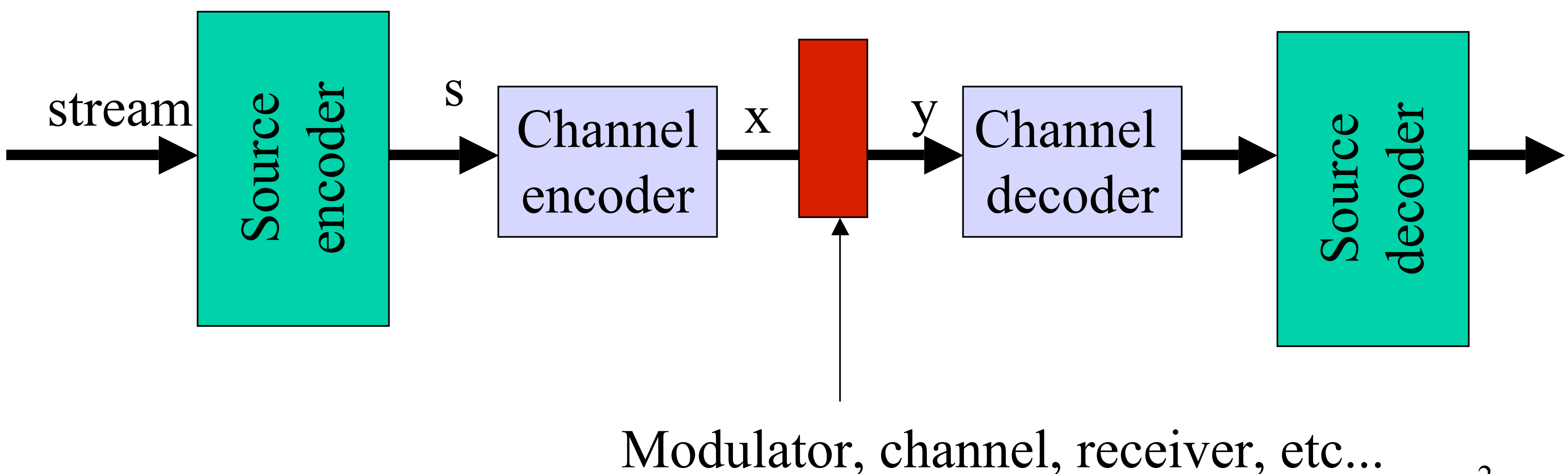
Wireless Communications and Networks

Muriel Medard

When do we use codes

- Two different types of codes:
  - source codes: compression
  - channel codes: error-correction
  - Source-channel separation theorem says the two can be done independently for a large family of channels

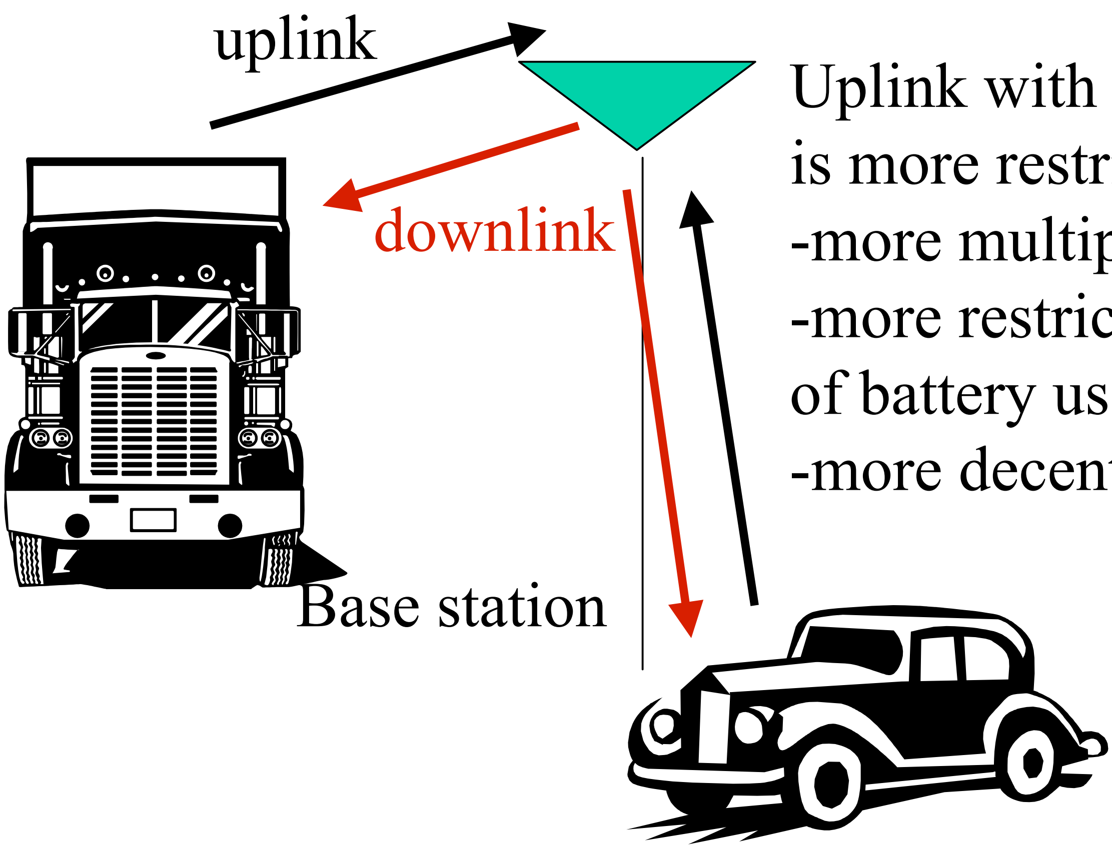


Overview

- The physical layer
- Wireless telephony:
  - FDMA
  - TDMA
  - CDMA
  - UWB
  - 3G
- Wireless networking:
  - 802.11
  - Bluetooth
- Ad hoc networks

Physical layer

- The physical layer plays a very important role in wireless network because it has severe limitation on transmissions

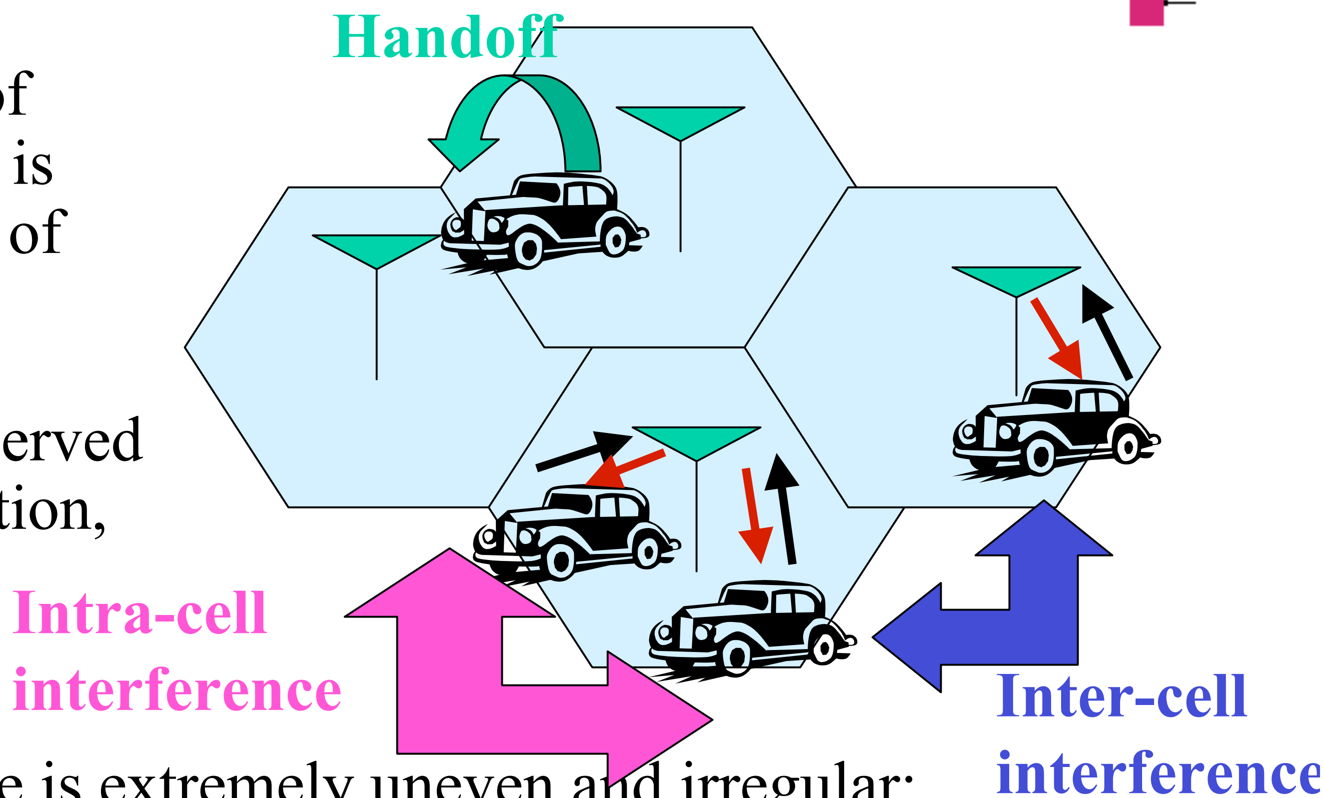


Uplink with respect to downlink
is more restricted:
-more multiple access interference
-more restrictions on power because
of battery use and because or user safety
-more decentralized problem

The “cellular” system

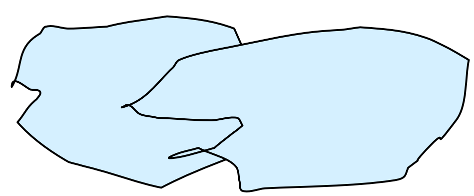
The area of coverage of Different base stations is logically a tessellation of the space

When a user is better served By a different base station, hand-off occurs



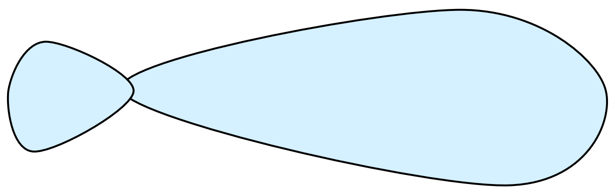
In reality, cell coverage is extremely uneven and irregular:

There are dead spots and areas of overlap



Antennas

- Base stations are generally antennas on towers or on top of buildings, with heavy tendency towards co-location, as the real estate is generally owned by a few companies
- Antennas can have directionality, giving sectors of the cells

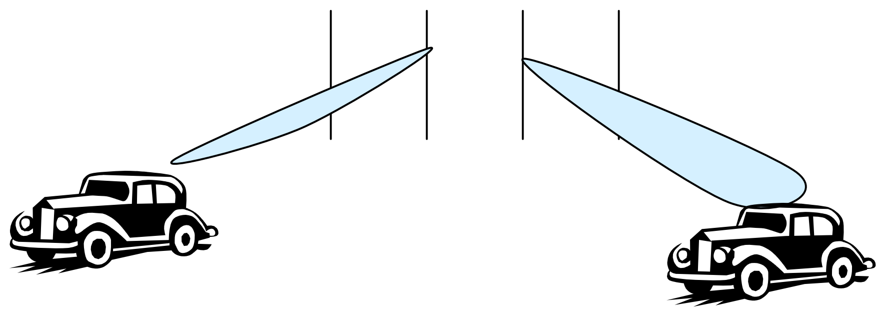


Antenna lobes

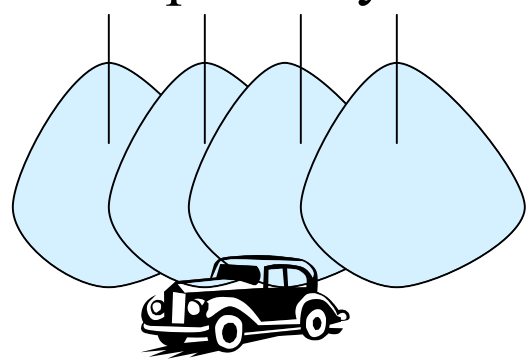
- Sectors reduce interference, but also pose coverage issues

Use of multiple antennas

- Multiple antennas can be used in two ways:
  - In an adaptive fashion to cancel out interference



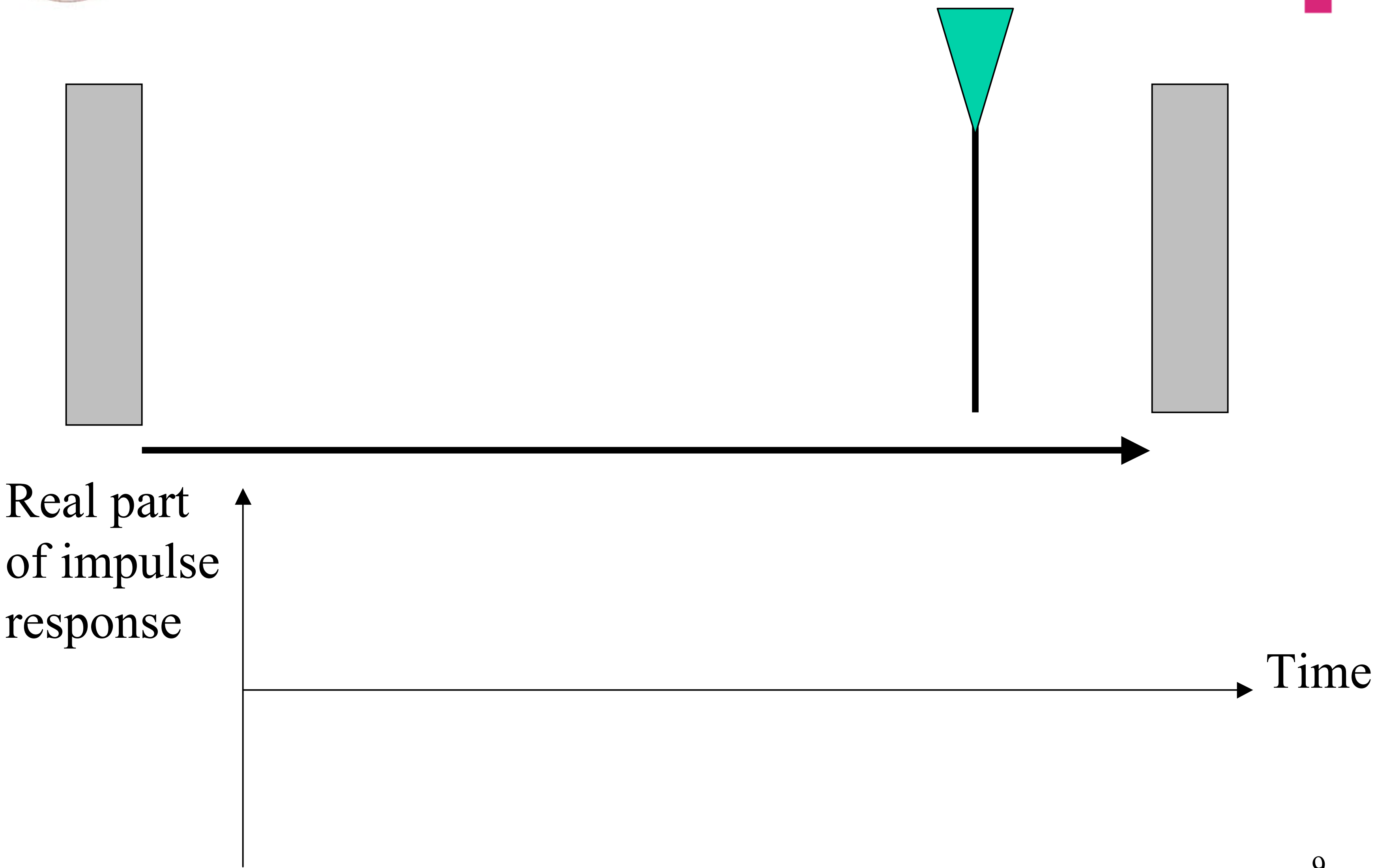
  - In a static fashion to “gather” more of the signal: optimal ways of combining the outputs rely on maximum likelihood detection



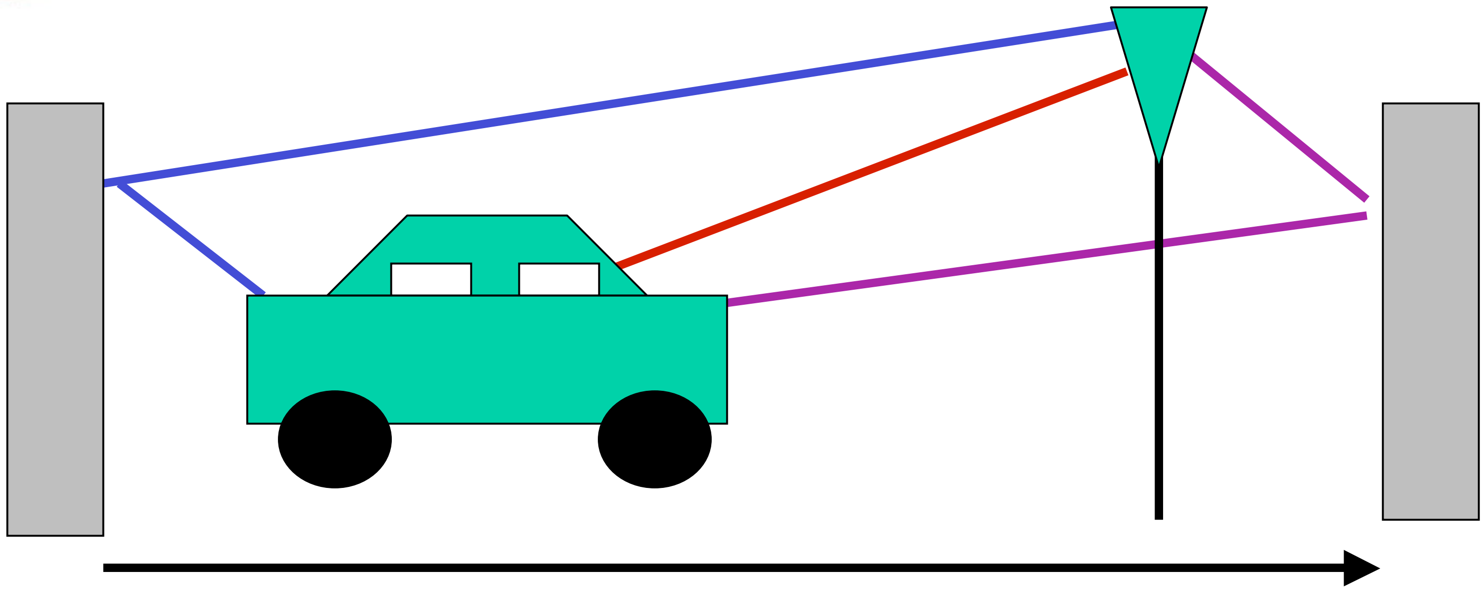
MIMO systems

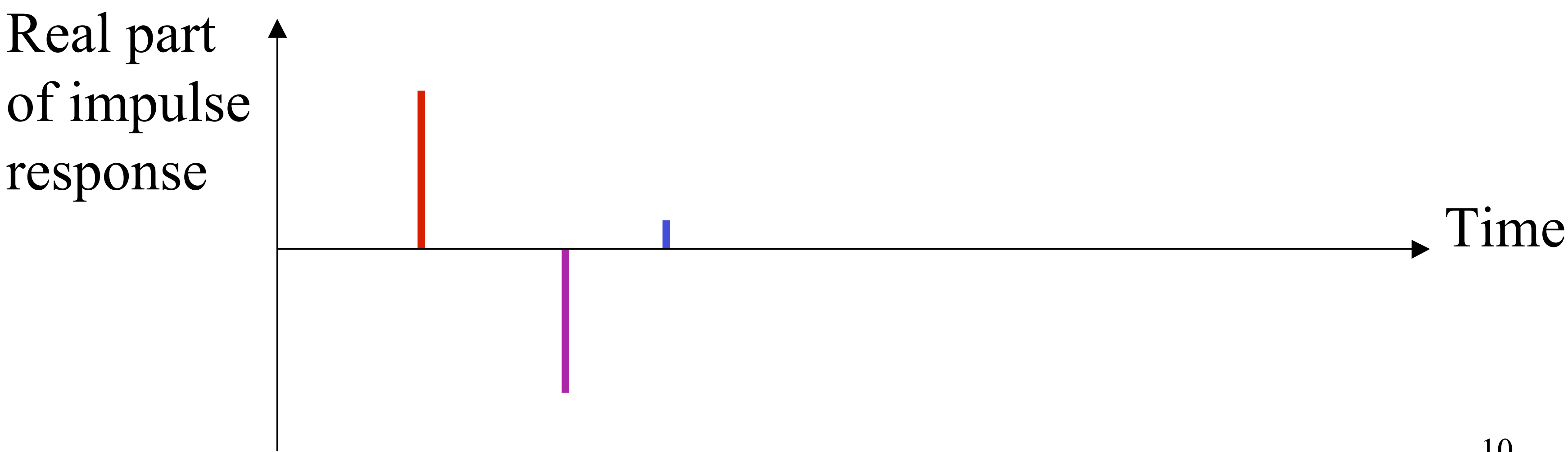
- High SNR case: capacity goes with log(SNR) and min of transmit and receive antennas
- Use of space-time-codes, Alamouti schemes
- Very sensitive to changes in channel and uncertainty in receive channel
- Low SNR case: antennas just help to gather energy, capacity depends only SNR and number of receive antennas\
- Use of impulsive transmission schemes to achieve capacity or near capacity

Wireless Channel Model

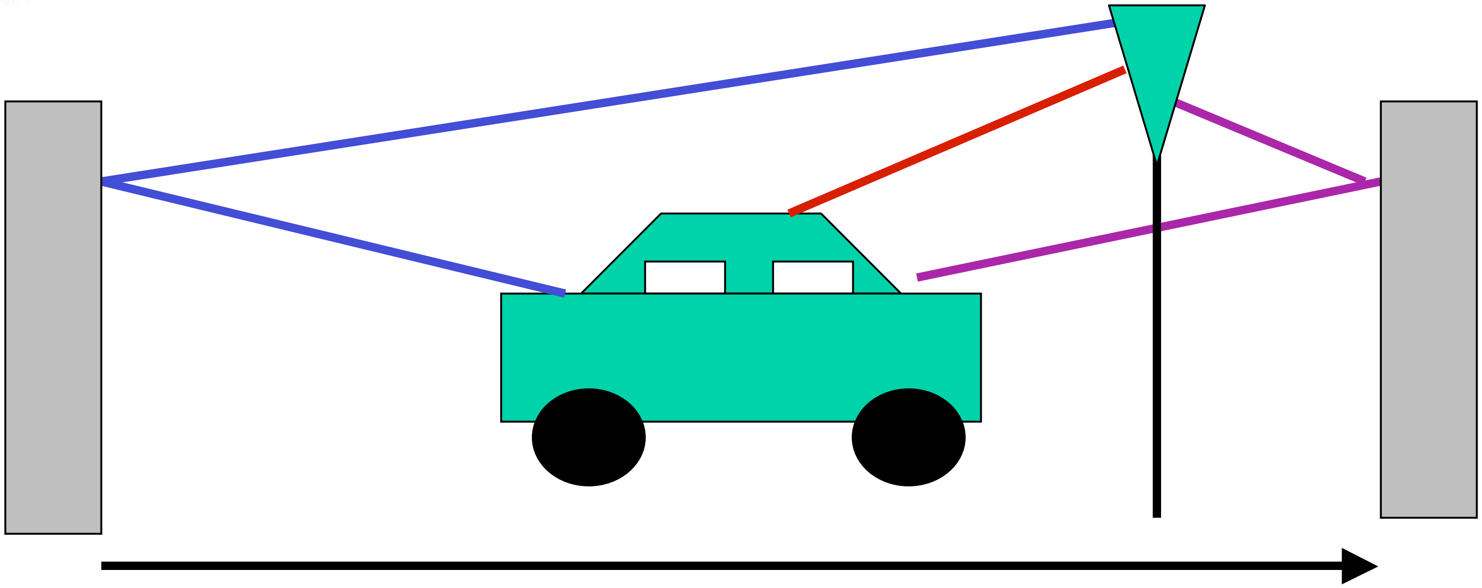


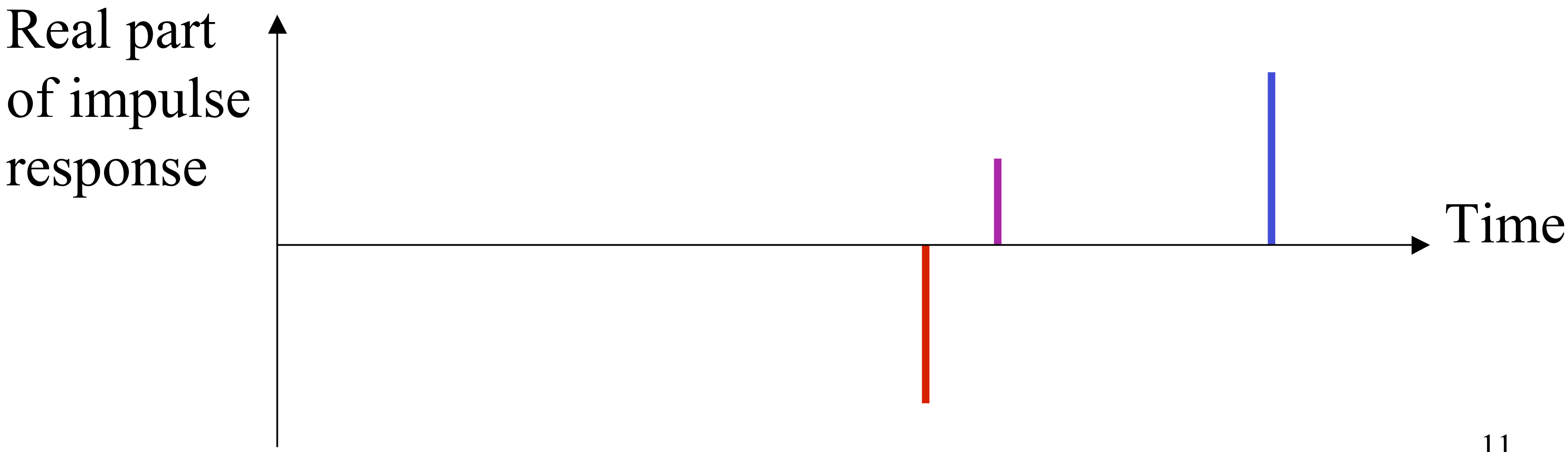
Wireless Channel Model





Wireless Channel Model





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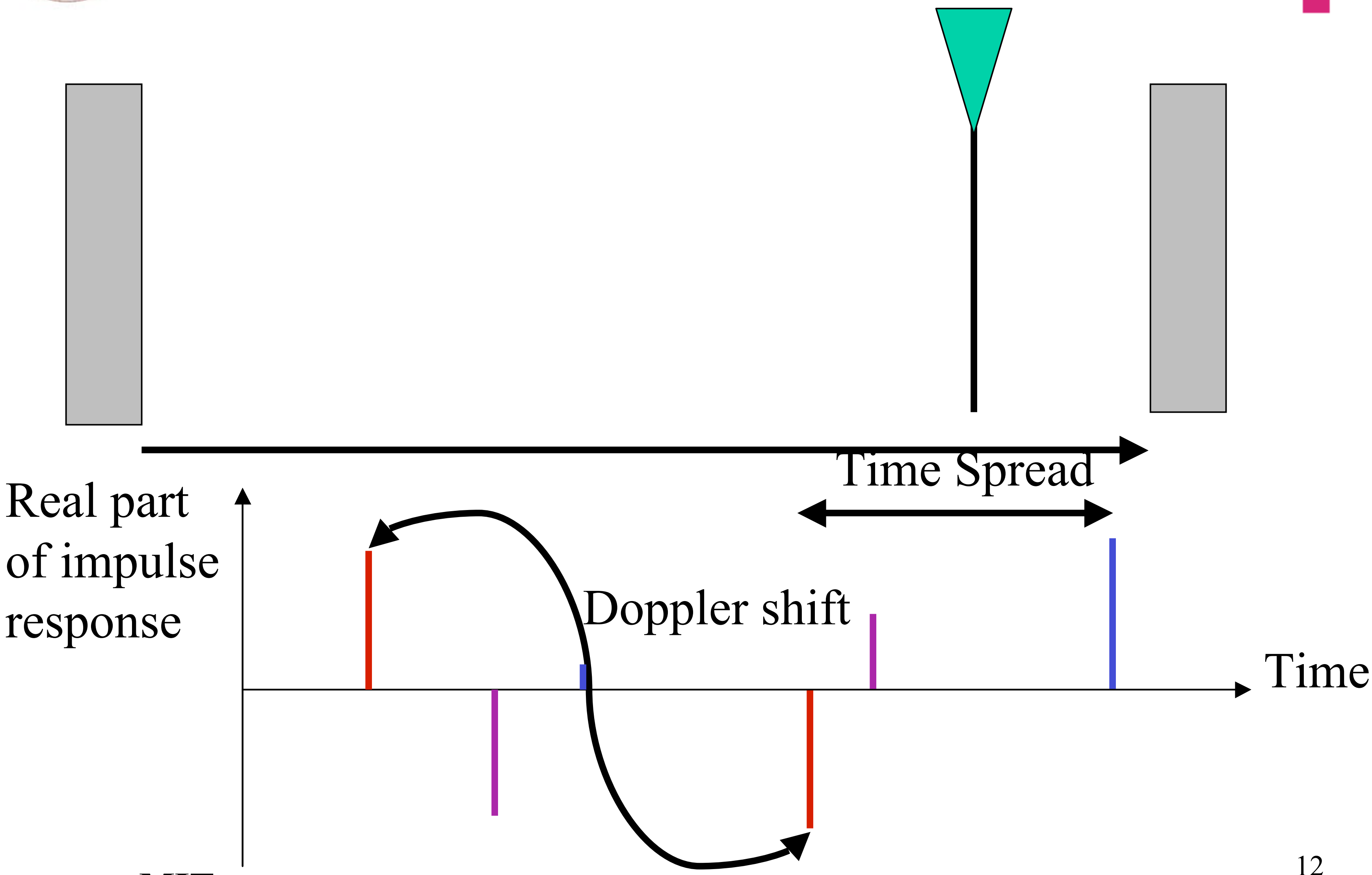
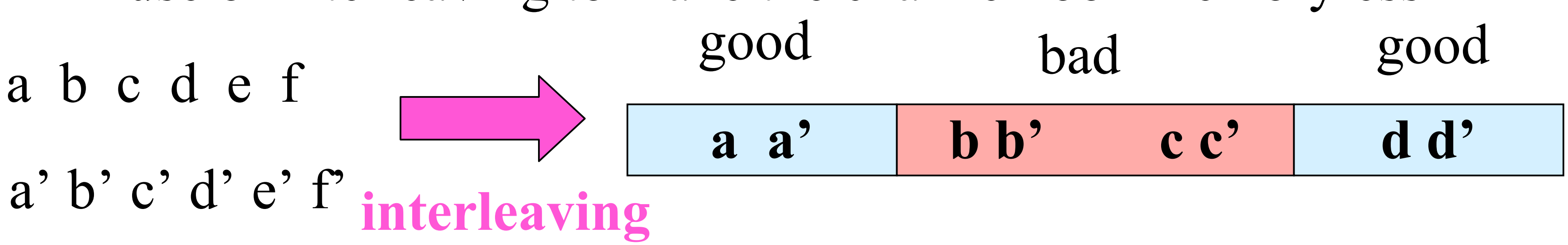


Variations in time and frequency

- The channel roughly changes across time and frequency
- In time, the time for change is roughly given by Tc, the coherence time
- The coherence time is generally taken to be the inverse of the Doppler spread, which is proportional to the speed of the mobile with respect to the obstacle and to the carrier frequency
- In frequency, the bandwidth for change is roughly given by Fc, the coherence bandwidth
- The coherence bandwidth is generally taken to the inverse of the time spread
- Most of the channels for wireless applications are of the underspread type, which means that TcFc >> 1

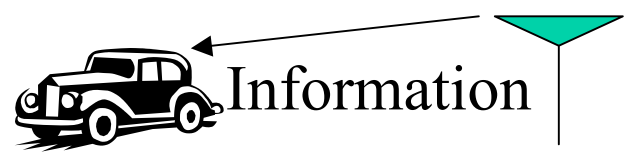
Implications of variations

- Variations occur and lead to fades
- It is difficult to transmit during fades in time or in frequency
- Therefore we try to achieve "diversity" in time and in frequency
- Diversity in frequency may be difficult to achieve because of regulatory issues around spectrum
- Diversity in time can be achieved but at the expense of delay – use of interleaving to make the channel look memoryless

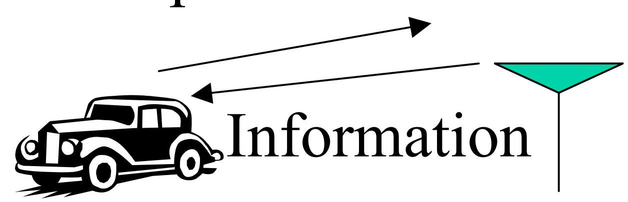


How to adapt to the fades

- Slow fades: due to terrain, shadowing, weather, foliage
- Fast fades: due to short term multipath variations
- What can we adapt for and what should we adapt for?
- Limitation: finite battery energy and power safety constraints
- Two ways of adapting:
  - Open loop: mobile detects a pilot symbol or pilot tone and uses that knowledge to adapt

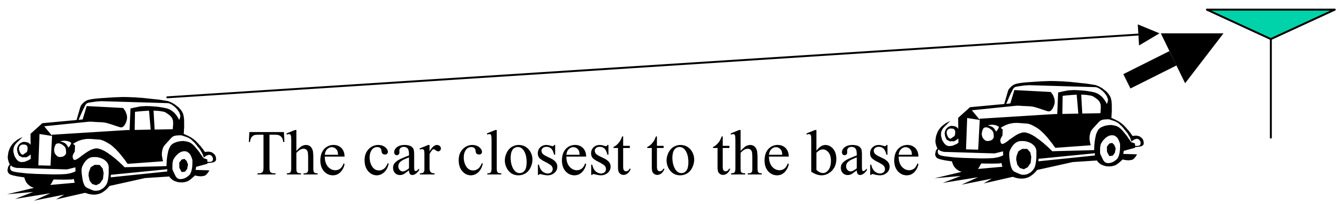


  - Closed loop: base station specifically sends control signals to the mobile, the mobile adapts and the base station detects the adaptation



Adaptation and multiple access

- The near-far effect:

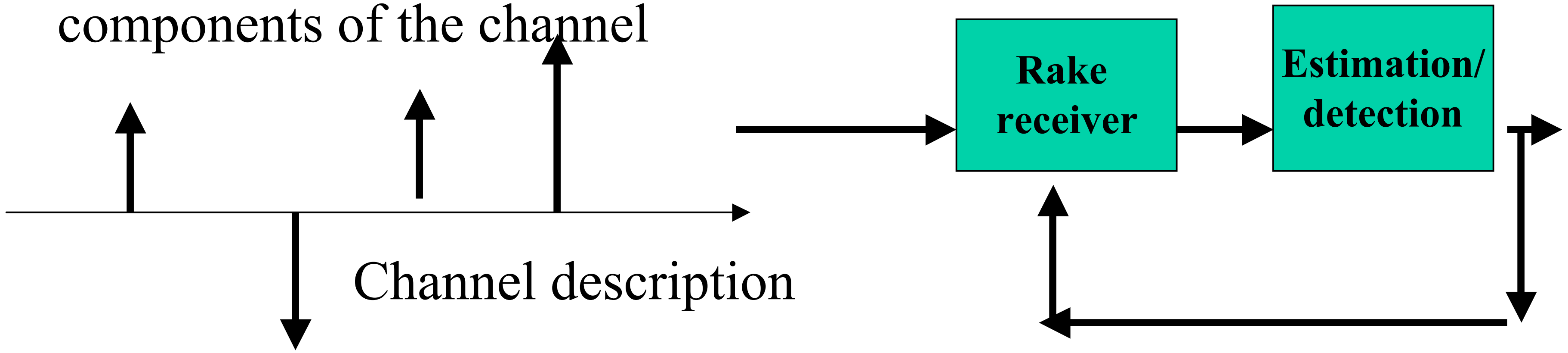


The car closest to the base station overpowers the other car

- In the case of open loop control, a mobile cannot make up for multiple access effects such as the near-far effect
- In the case of closed loop control, the users that are far can increase their power, while the users that are far away can decrease their power
- Can we use power control to make up for fast fades? Tc is about 1/100 s, so would easily require 1000 bits/s

Receivers

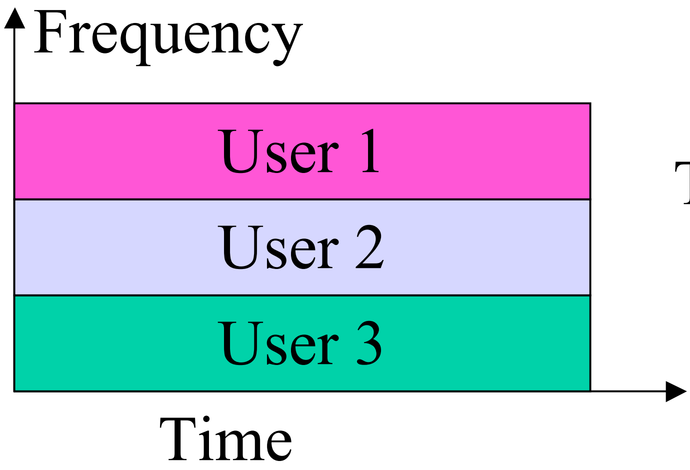
- The receiver must take into account the instantaneous effect of the channel
- Rake receiver is a means of taking into account the main components of the channel



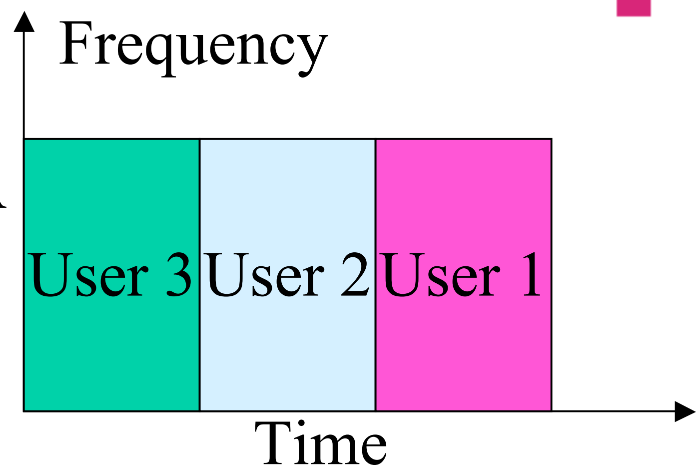
- Channel tap: sample of the channel
- The Rake receiver finds the main non-zero taps (fingers)
- Note: phase is needed to get information beyond the amplitude

How to perform multiple access

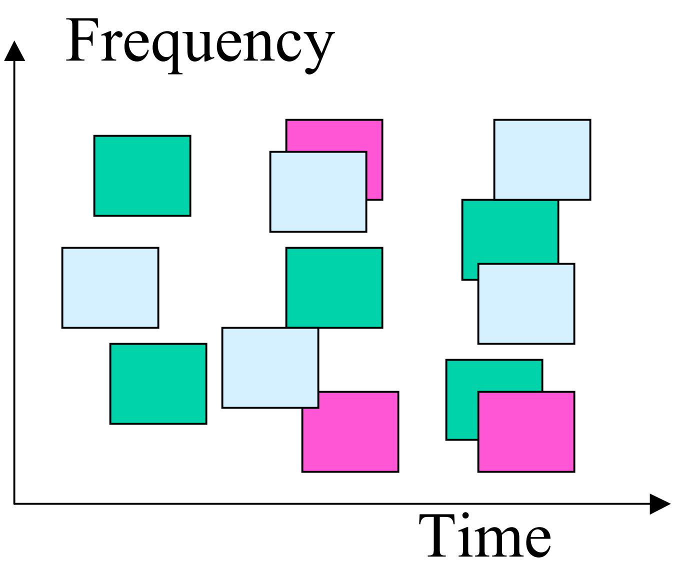
FDMA



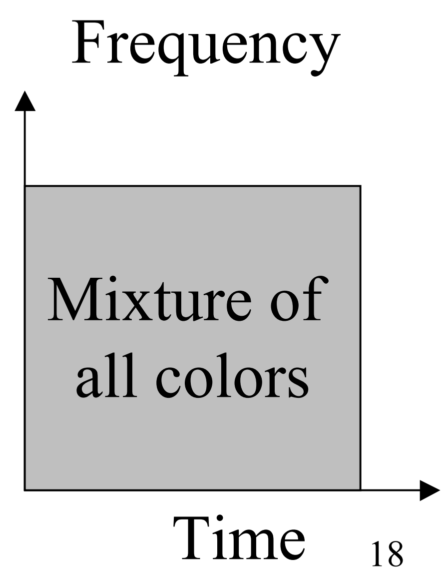
TDMA



Frequency Hopping Spread spectrum

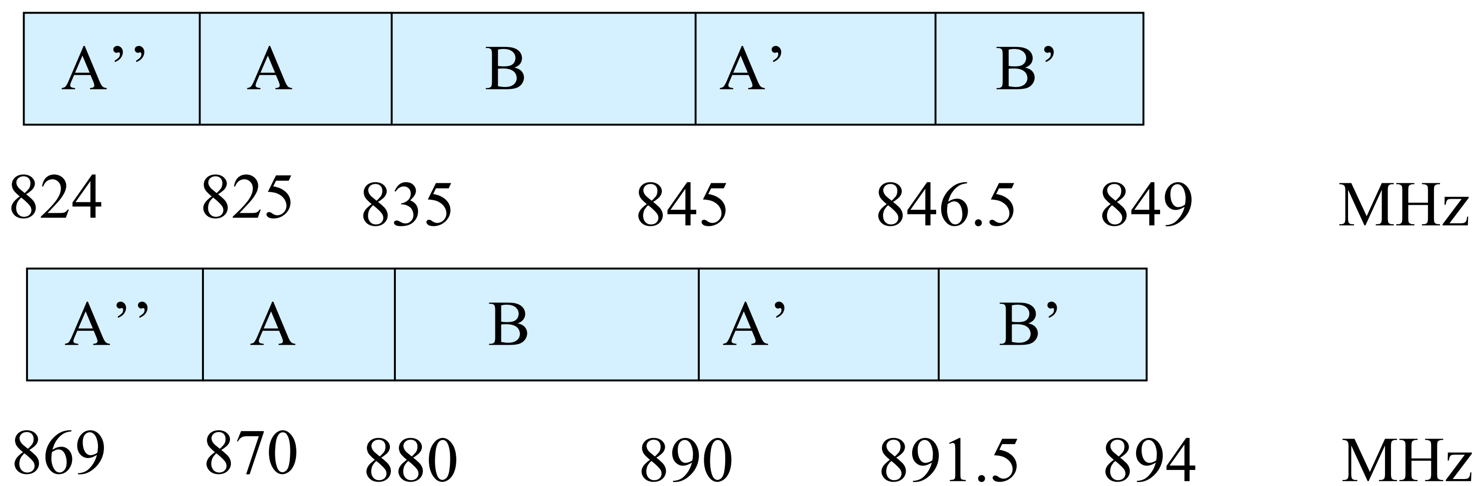


Direct Sequence Spread spectrum



Channels in FDMA

- Channels in each cell
- Each user in a cell is given an uplink channel and a downlink channel
- AMPS: 30 kHz wide
- 1993 old AMPS and NAMPS => IS-91
- Uplink
- Dowlink

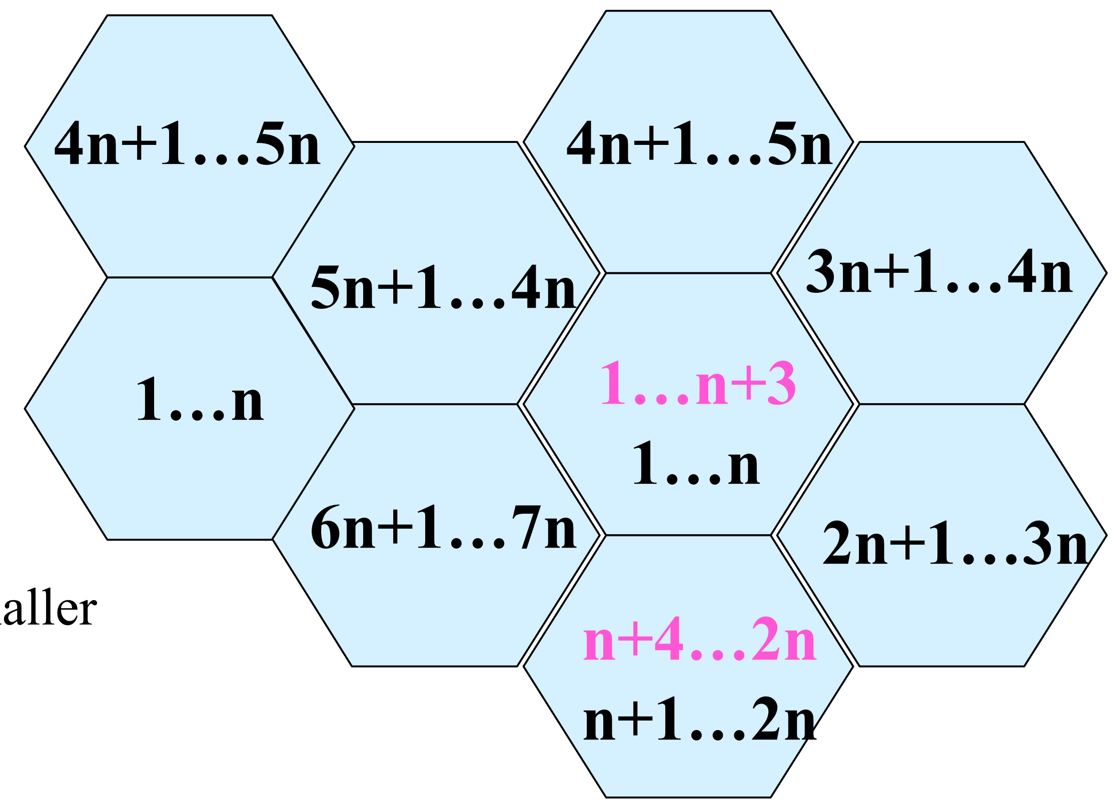


- A channels (channels 1-> 333) competitive provider
- B channels (channels 334 ->666) -> wireline carrier

Managing channels in cells

- Certain cells may have heavier requirements than others at different times
- Standard fixed channel assignment: a channel is used every 7 cells
- Other idea is to **borrow** channels from cells that are less used
- Alternatively, some Channels may be permanently assigned to certain base stations while others are in a shared pool

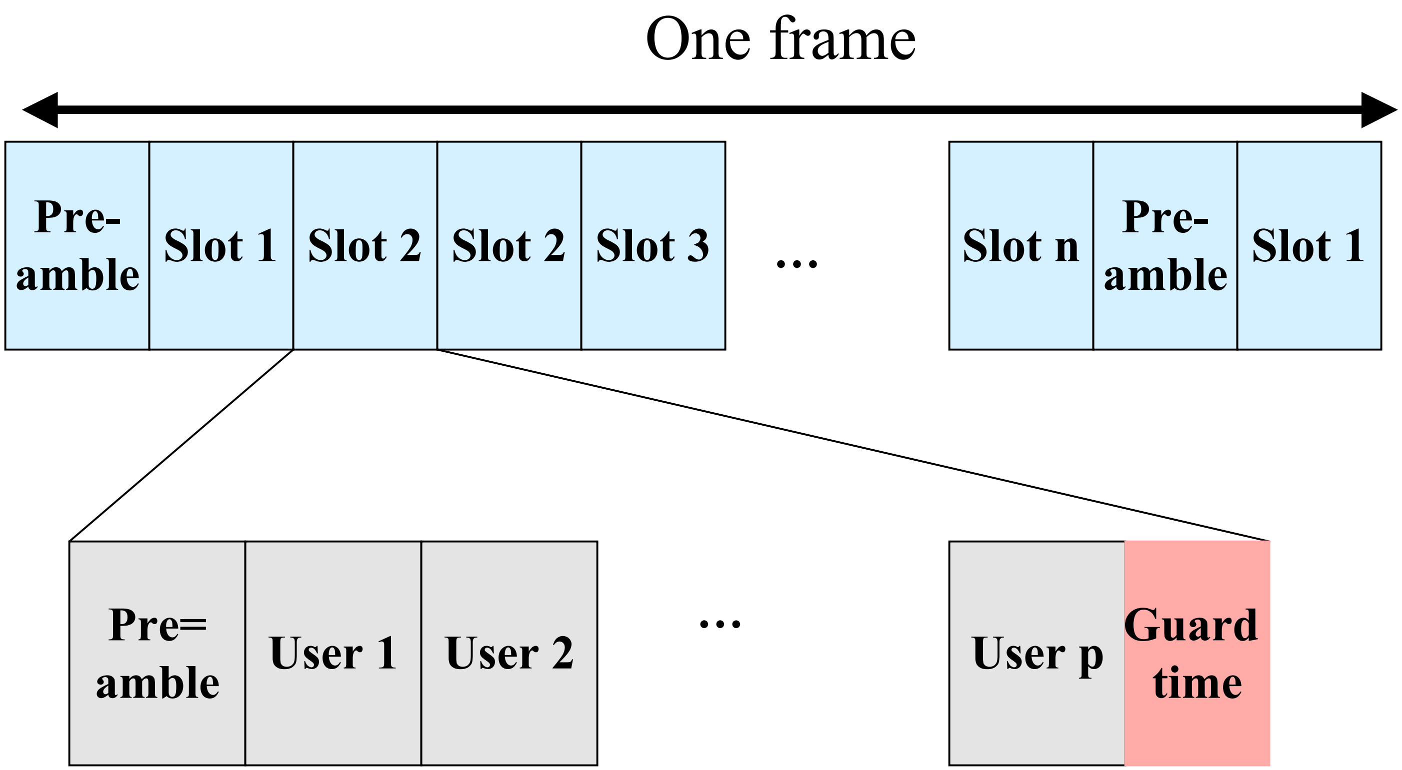
Alternatively – make cells smaller y cell-splitting down to picocells



TDMA

- European GSM (groupe special mobile), IS-54 (US standard), JDC (Japan)
- GSM standardization effort started in 1987, Phase 2 ended in 1995
- Divide a little in frequency, a lot in time
- GSM:
  - Eight channels per carrier with a gross data rate of 22.8 kbps (bit rate of 13 kbps)
  - Frame is 4.6 ms and time slots are 0.575 ms for transmission and reception
  - 200 kHz channel spacing
  - Gaussian minimum shift keying (GMSK)

TDMA


One frame
Pre-amble
Slot 1
Slot 2
Slot 2
Slot 3
…
Slot n
Pre-amble
Slot 1
Pre=amble
User 1
User 2
…
User p
Guard time

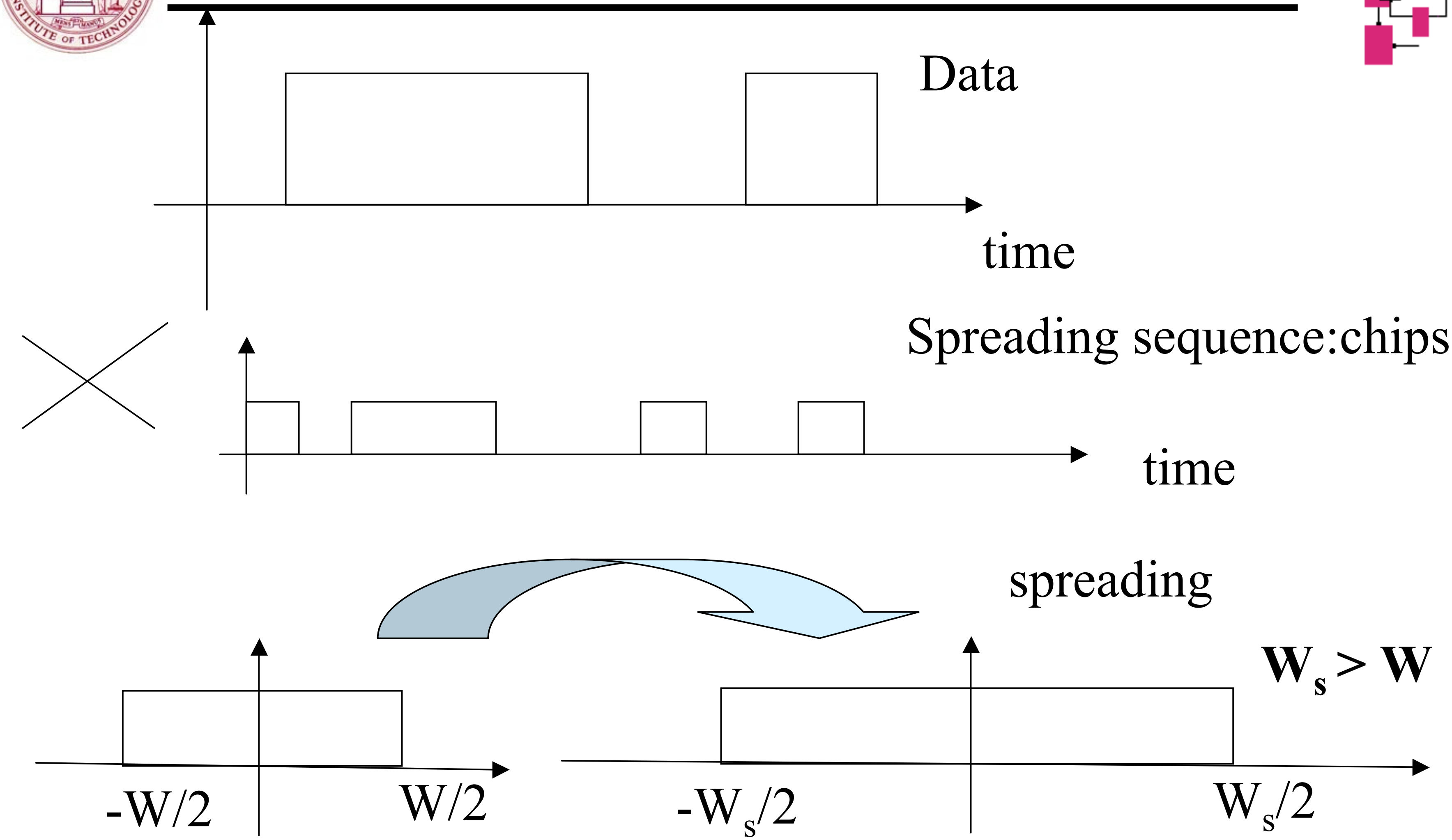
TDMA

- IS-54 keeps the 30 kHz spacing of AMPS
- Each frequency can give 48.6 kbps
- Uses $\pi/4$-differential quadrature phase shift keying at 24.3 kilosymbols/s
- Frame duration is 40 ms
- 6 time slots per frame
- Each time slot carries 260 bits of user information
- Total 395 30 kHz voice channels
- Total 12.5 MHz system bandwidth

CDMA

- Code division multiple access
- Roots are in military applications:
  - Anti-jam
  - Low-probability of intercept
- Frequency hop:
  - Slow: hop every few bits
  - Fast: hop every bit or faster
  - Relatively expensive because of tuning
- Direct sequence:
  - Use a spreading sequence to allow al users to share the bandwidth at all times

DS-CDMA



Spreading gain = chip rate/data rate

IS-95

- Chip rate 1.2288 Mcps
- Modulation is QPSK on forward. OQPSK on rverse
- Filtered bandwidth in uplink or downlink is 1.23 MHz
- 63 Walsh codes per link for forward
- Convolutional coding with Viterbi decoding
- Interleaving with 20 ms span
- Main mode is 9600 bps (also available as 14,400 bps)
- Available in the 90 MHz range and the PCS 2 GHz range
- Reverse and forward links are separated by 45 MHz in the former and 80 MHz in the latter

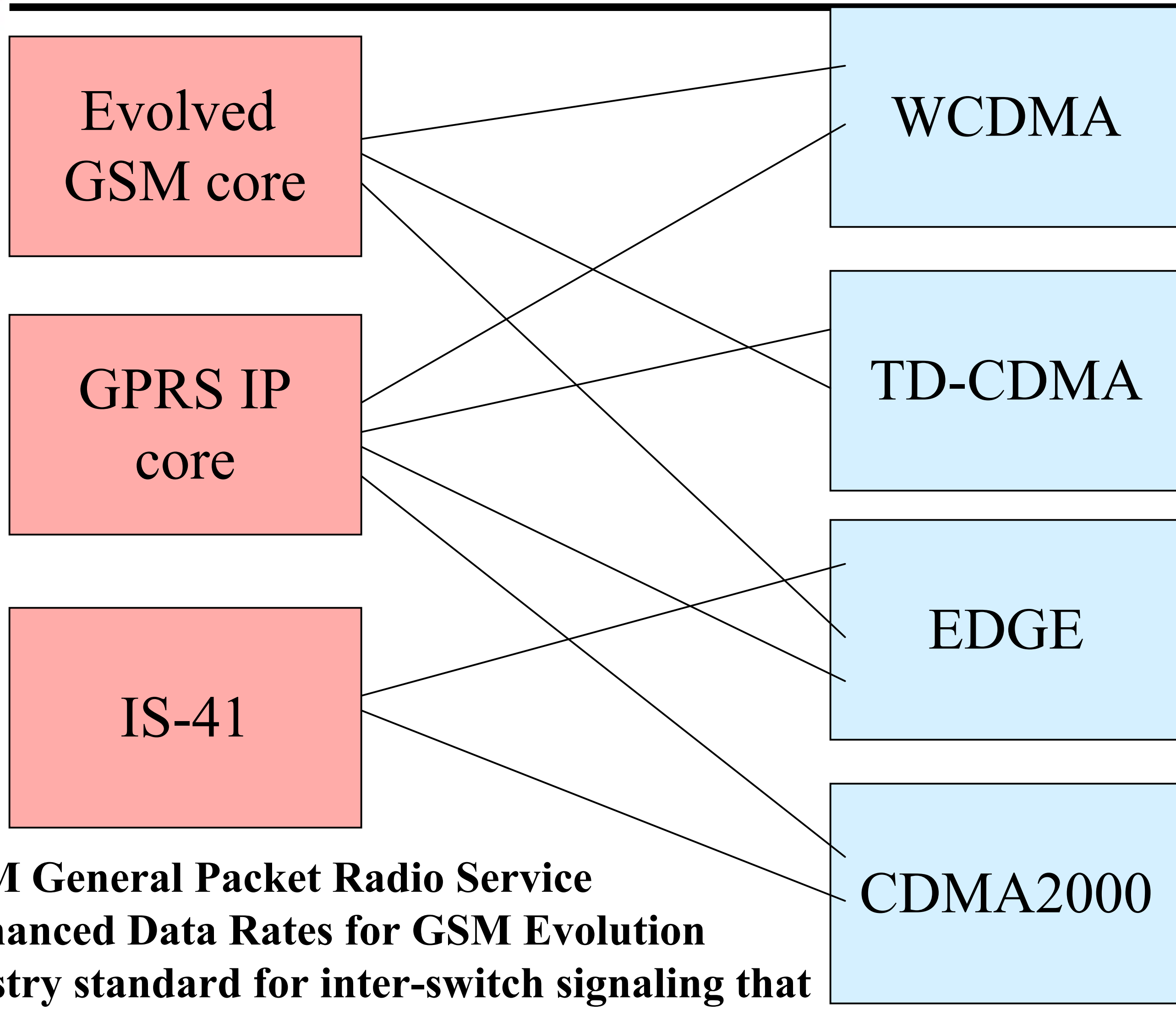
CDMA2000

- 3-G system, generated in accordance with the recommendations of the International Mobile Telecommunications (IMT)-2000 of the ITU (International Telecommunications Union)
- Main features:
  - Channel sizes of 1,3 , 6, 9 and 12 1.25 MHz
  - Advanced antenna technology support
  - Greater possible cell sites, up to megacells (>35 km in radius), down to indoor.indoor picocells (<50m)
  - Allows voice services
  - End-user data services, packet data service node (PDSN) to support Intenet/intranet data connectivity
- Corresponding Universal wireless communications (UWC) is IS-136

Third generation

- Loose partnership for standardization is the Third Generation Partnership Project (3GPP)
- Predominantly Wideband-CDMA (W-CDMA)
- DOCOMO W-CDMA, UTRA (W-CDMA and T-CDMA) (UMTS terrestrial radio access) (UMTS= Universal mobile telecommunications system), EDGE (enhanced data rates for GSM evolution), IS-136 (digital AMPS, yielding up to 2 Mbps using TDMA technology close to EDGE)
- 4.096 Mcps for DOCOMO, 3.84 for UMTS
- UTRA not synchronized base station
- Frame lengths: 10 ms for both
- For comparison CDMA200:
  - 3.6864 Mcps
  - Synchronized base station
  - 20 ms frame length

New services to core network connection



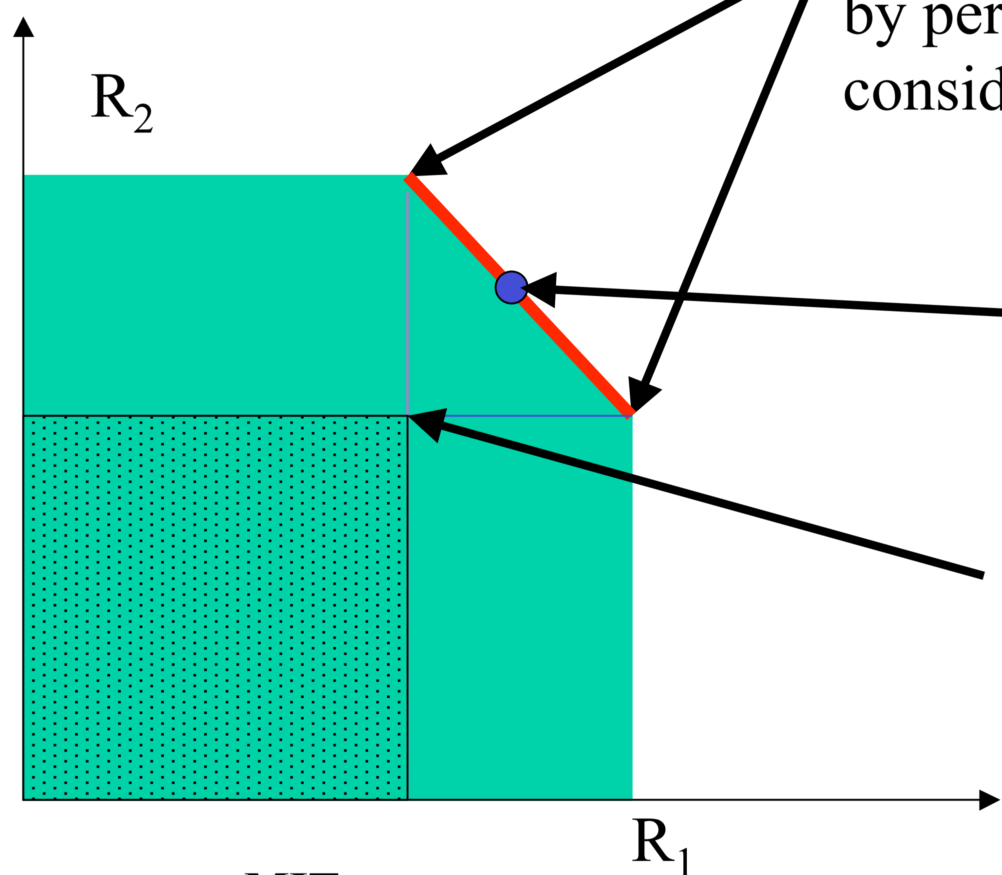
GPRS: GSM General Packet Radio Service
EDGE: Enhanced Data Rates for GSM Evolution
IS-41: industry standard for inter-switch signaling that allows validation of wireless calls and call completion in out-of-area markets

Performance comparison

- Garg and Wilkes: ratio of number of mobile users $\frac{N_{\text{CDMA}}}{N_{\text{TDMA}}} = 1.7$
- Viterbi: Erlang capacity with imperfect power control (3-sector per station), CDMA has a factor 6 improvement
- How to reconcile the different numbers?
- Becomes very implementation specific and highly reliant on the channel model.

Multiple access

The Cover-Wyner rate region



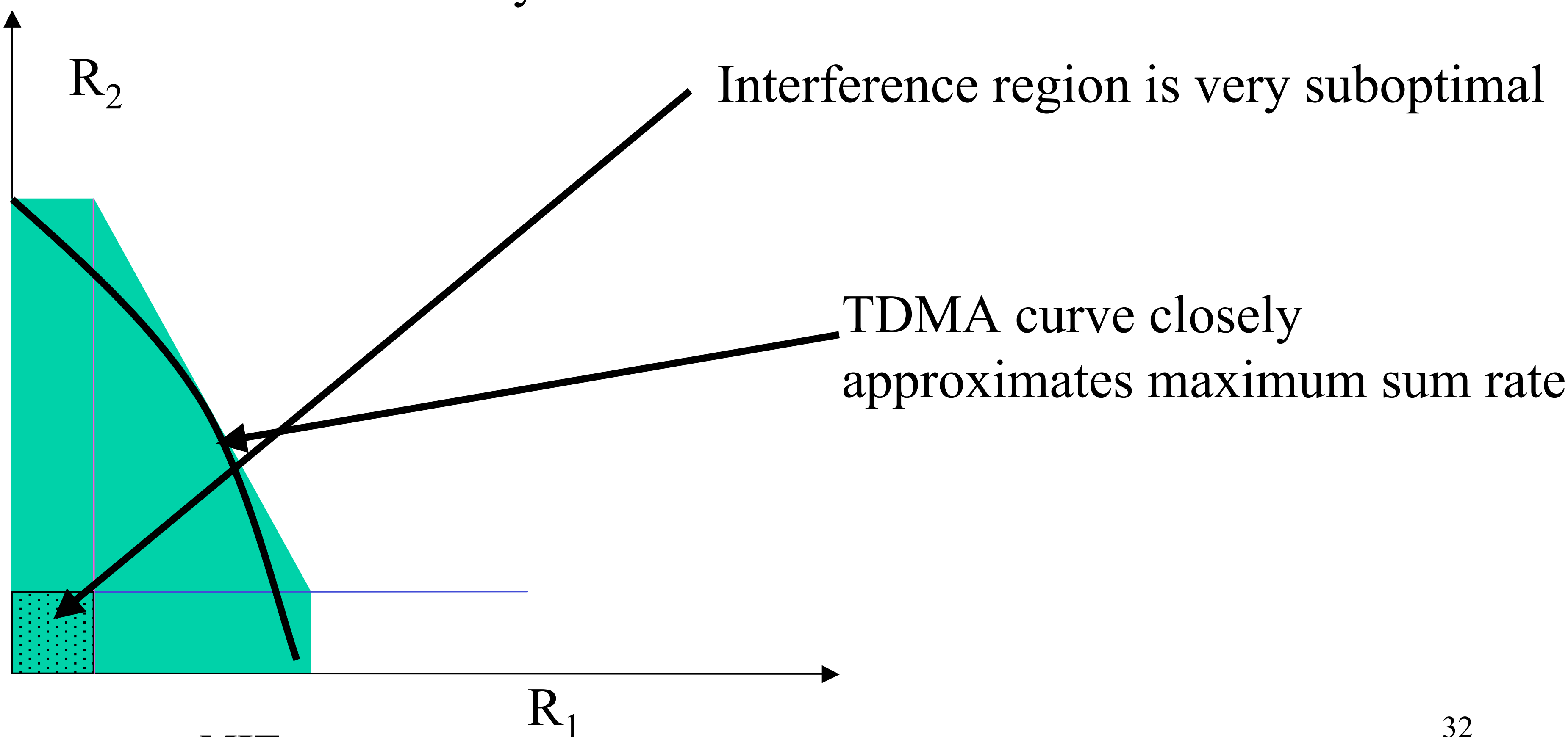
Points are achieved
by performing successive cancellation:
considering one user as noise to the other

Achievable by TDMA
or FDMA
(includes OFDMA)

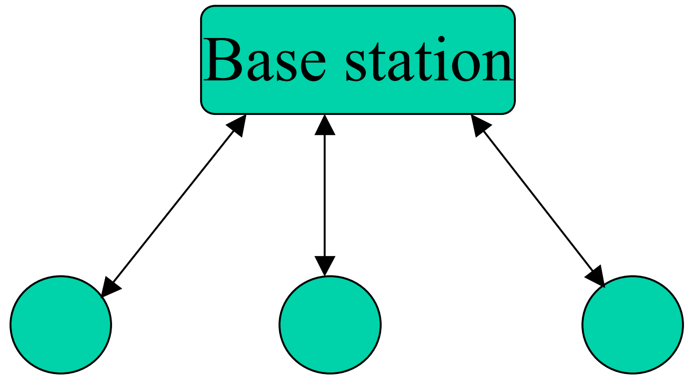
Interference region : rate is given
entirely by SIR
traditional approach of cellular
wireless CDMA

High SNR Case

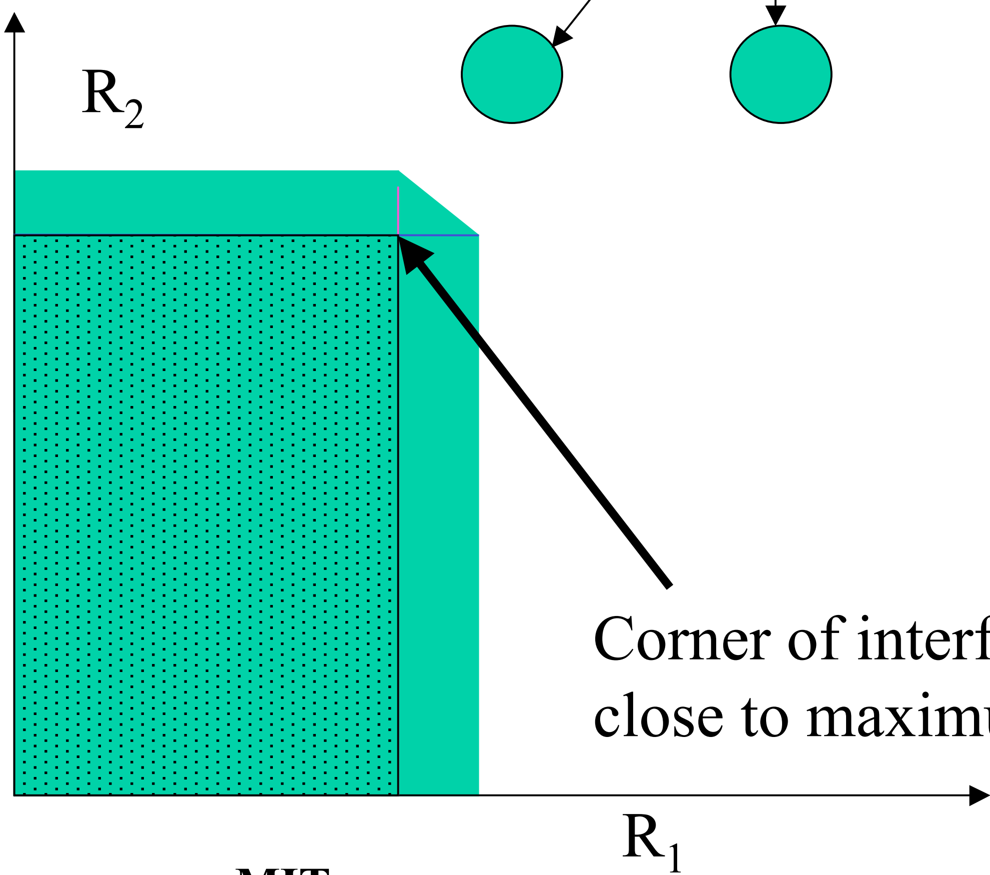
In the case of high SNR, system is quasi-optimal if run as a TDMA system



Low SNR case - Interference



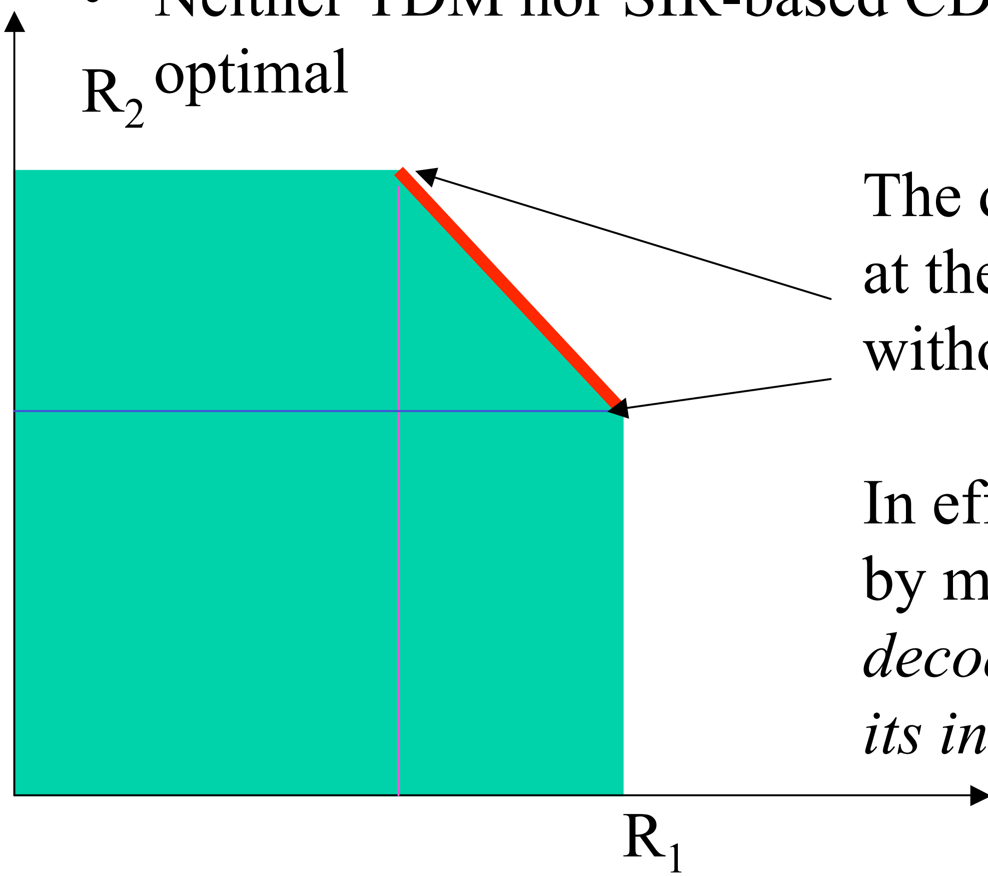
- The users compete for SIR at the base station
- The traditional cellular approach is a max-min approach based on explicit commands using closed-loop control
- No concept of priority, whether permanent or in response to a rapid change of circumstances



Corner of interference region is close to maximum sum rate

Intermediate SNRs

- Neither TDM nor SIR-based CDMA systems are close to optimal



The decoding order changes the rate at the receiver without requiring a change of power

In effect obviates the near-far problem by making use of SIR differences to *decode stronger user first and remove its interference to the other users*

All rates on the maximum sum rate are achievable using rate-splitting

Overview of UWB

- Wireless communications over broad band have been evolving rapidly
- Quest: uncoordinated, cheap access to large amounts of bandwidth for many users
- What do theoretical limits tell us about how possible this is?
- Topics:
  - Effectiveness of different spreading techniques - CDMA, FH, PPM, flash signaling
  - When happens when we are not bandwidth limited?
  - Can we find simple schemes that successfully approximate the infinite bandwidth results?
  - Can we have uncoordinated multiple access?

Spreading

- DS-CDMA (direct sequence code division multiple access) has gained considerable commercial importance
- Spread in frequency by transforming bits into a series of chips
- Every user appears as noise to all other users, good LPI
- Why not simply extend this to higher bandwidths?
- **Does not scale when channel decorrelates in time and frequency** (Medard and Gallager, 1997, 2002, Telatar and Tse 1999, Hajek and Subramanian, 1999, 2002)
- Intuitive justification - cannot track the channel well enough to make reliable decisions because there is not enough energy in any portion of the spectrum

Pulse-position modulation (PPM)

- Spread-spectrum multiple-access wireless system
- Time-hopping baseband signal comprised of very short pulses - occupies frequency band from near-DC to several GHz,
- Low power-spectral density
- Interference to other narrow-band systems should be low (although very poor from the point of view of peak interference)
- Appears to be sub-optimal from the point of view of approaching capacity - it is limited theoretically by the time spread, so may not be useful for very wide bands
- Not very LPI

Frequency hopping

- Robust to fades by changing frequencies
- Does not suffer from channel tracking issues of DS-CDMA because there is enough energy transmitted in a single portion of the spectrum to identify the channel
- Not generally used in commercial systems, except as some extra diversity added onto other systems
- Somewhat LPI

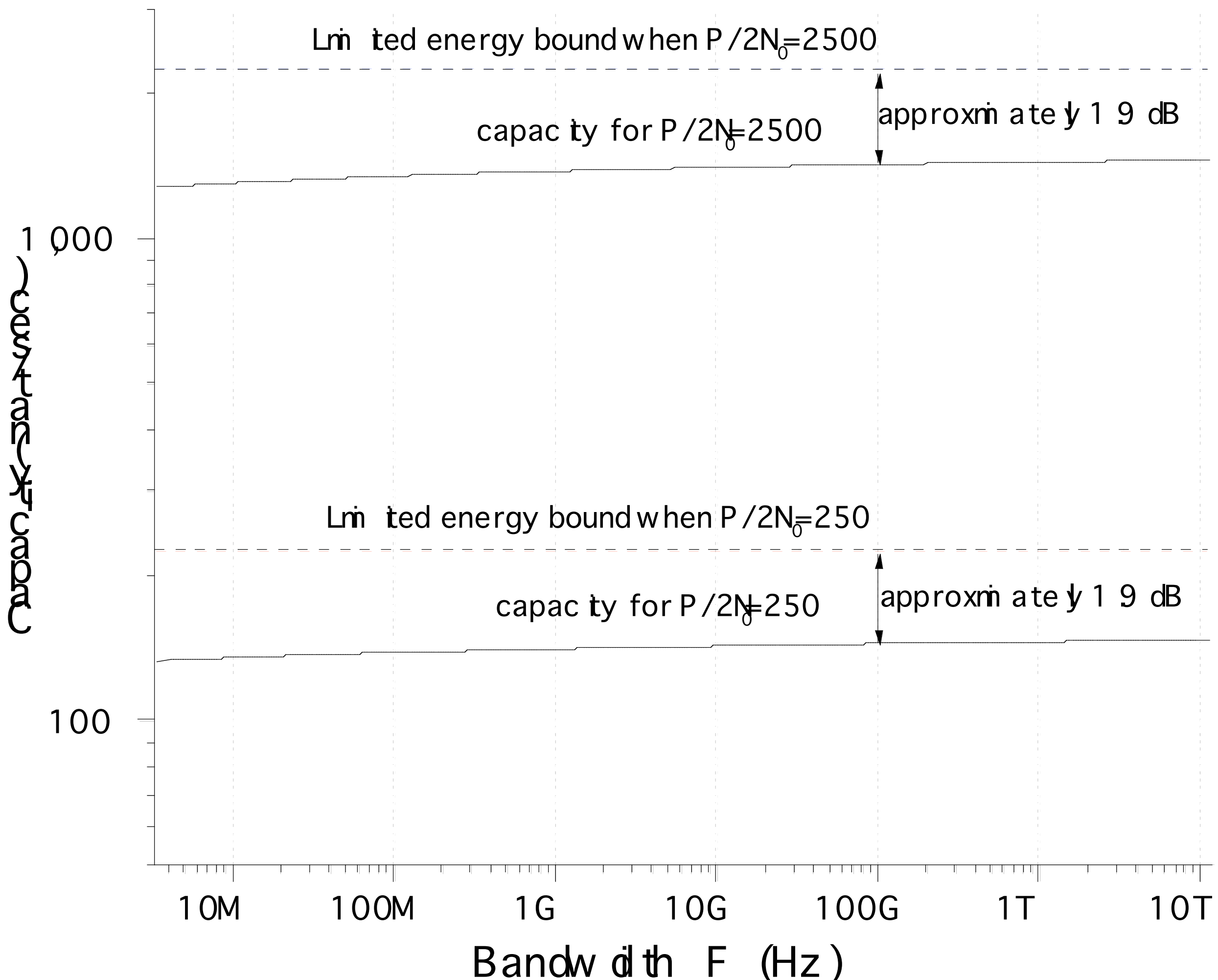
What if we had unlimited bandwidth?

- Capacity of infinite-bandwidth multipath fading channel is equal to the capacity of the infinite-bandwidth channel with noise only
- Capacity can be achieved using frequency-shift keying with non-coherent detection by transmitting at a low duty cycle - ``peaky" or flash signaling (looks similar to FH)
- How does the probability of error decay to zero as bandwidth approaches infinity for rates under capacity?
- Very slowly if we want to approach capacity (bandwidth must grow rapidly to achieve low probability of error if we are close to capacity)
- Other drawback- huge peak energy

Can we approach the infinite bandwidth limit with finite bandwidth?

- Use FSK that is somewhat impulsive and also use it over more than a single tone at a time
- Code over the tones that are used, rather than a single tone - thus allowing a reduction in peak energy
- Gets close to capacity for large bandwidths where DS-CDMA or PPM may no longer be effective
- Gracefully goes from energy-limited to bandwidth-limited regime
- Joint work with Cheng Luo and Lizhong Zheng

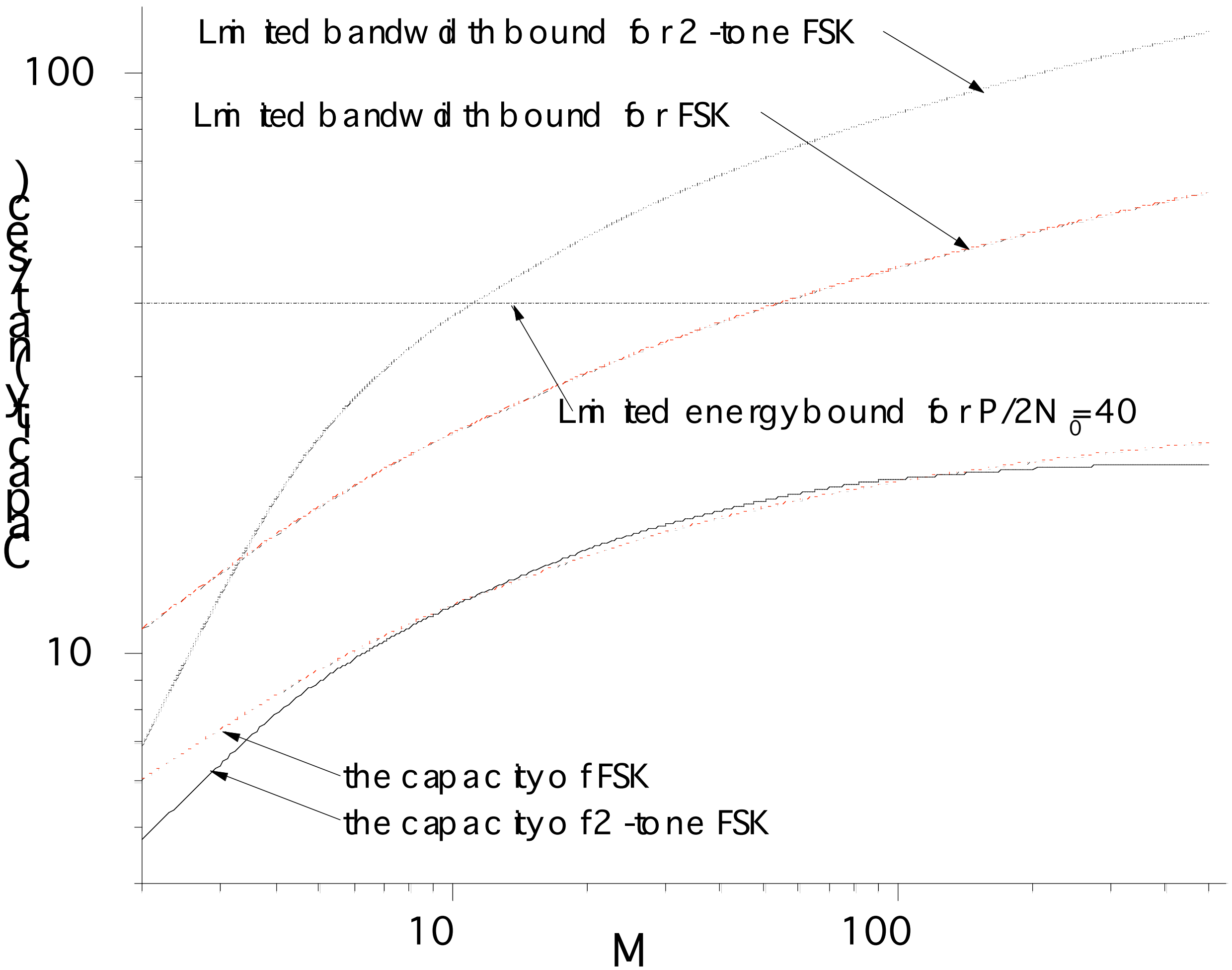
Capacity vs. bandwidth



$T_s = 10\ \mu s$

$T_d = 1\ \mu s$

Capacity vs. M = number of coherence bands



$T_s = 0.1$ s
$T_d = 1$ μs
$P/2N_0 = 40$

Wireless data and networks

- Wireless LANs (WLANs):
- Main standards efforts:
  - IEEE 802.11
  - High-Performance Radio Local Area Network (HIPERLAN)
  - Wireless Information Networks Forum (WINForum)
  - IEEE 802.16
- General issues: packetized access for wireless
- How do interleaving and higher probability of packet loss affect buffering, window sizes and end-to-end protocols

802.11

- MAC for peer-to-peer and peer-to-centralized communications using DSSS and FHSS for radio and infrared
- 2.4-2.4835 band, over more than 80 MHz
- Allows for 1 Mbps or 2 Mbps
- Uses BPSK or QPSK modulation for for DSSS and Gaussian FSK for FHSS
- For DSSS, 5 overlapping bands of 26 MHz each
- For FHSS, 79 sub-bands, each 1 MHz wide, and 3 patterns of 22 hop
- CSMA/CA
- Maximum power of 1 W

More wireless networks

- HIPERLAN:
  - emanates from ETSI (European Telecommunications Standards Institute)through technical subcommittee RES 10
  - Two bands 5.12-5.30 GHz and 17.1 –17.3 GHz
  - Rates of 500-1000 Mbps per user for total of about 20 Mbps
- WINforum:
  - For WLAN and wireless private branch exchange
  - Short bursts, quick release of medium
  - Asynchronous bands of 50 KHz to 10 MHz, isochronous bands of 1.25 MHz

Bluetooth

- Born in 1994, when Ericsson looked for alternatives for interfaces between mobile phones and accessories
- The name: Harald Blatand - Danish King who united Denmark and Norway in the Xth century
- Since 1998, Bluetooth Special Interest Group has spearheaded the specification (First one released in July 1999)
- Low-cost applications – about $ 5 each
- Ranges of up to 10 m, 20 m and 100 m
- Need to have networking ability as well as point-to-point
- Need to be able to carry voice and data
- Low power requirements:
  - Class 1 100 mW (20 dBm)
  - Class 2 2.5 mW (4 dBm)
  - Class 3 1 mW (0dBm)

Frequency hopping

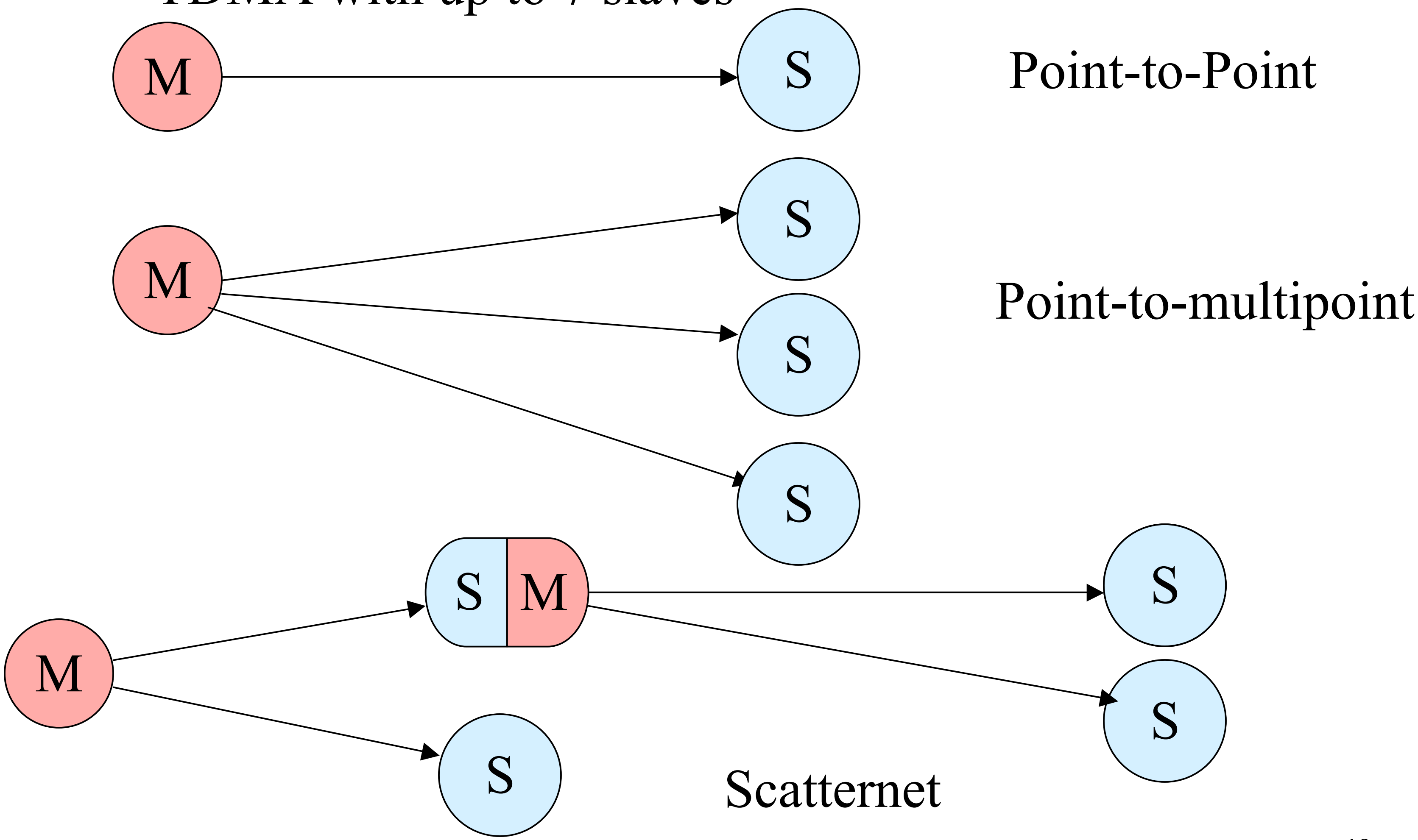
- 2.4 GHz operation: Industrial, Scientific and Medical (ISM) band – a very polluted band
- The AJ properties of spread-spectrum are well suited to this environment
- 1 MHz-spaced channels, each signaling at 1 Mbaud per second, using GFSK (1Mb/s)
- Frequency hops between packets
- Slots are 635 microseconds and packets last 1, 3 or 5 slots

Packets

- Two types of packets: SCO (synchronous Connection Oriented) for voice and ACL (Asynchronous Connectionless) for data
- ACL: has 72 bit access code, 54-bit packet header and 16-bit CRC
- Largest packet size is 5 lots (DH5) with 2712 bits of data, rest overhead
- Largest full duplex data rate is using DH-5 packets in each direction – 433.9 kbps in each direction (for comparison, MP3 is about 128 kb/s)
- SCO gives 64 kbps - same as GSM

Networking aspects of Bluetooth

Master determines FH sequence and performs TDMA with up to 7 slaves

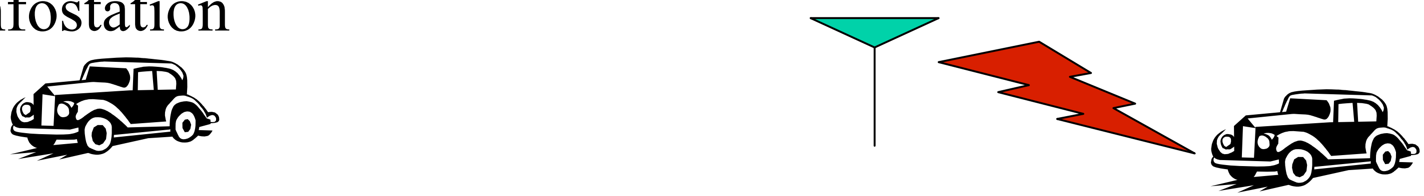


802.16

- Wireless MAN task group
- Task group 1: looking at for Fixed Broadband Wireless Access Systems for 10-66 GHz – 802.16
- Task group 3 amends the above as MAC Modifications and Additional Physical Layer for 2-11 GHz –802.16a
- Task group 4 amends 802-16b Modifications and Additional Physical Layer for License-Exempt Frequencies – AKA the wireless human (?!)
- Issues – as we go up in carrier frequency, propagation worsens, also underspread assumption begins to hold less

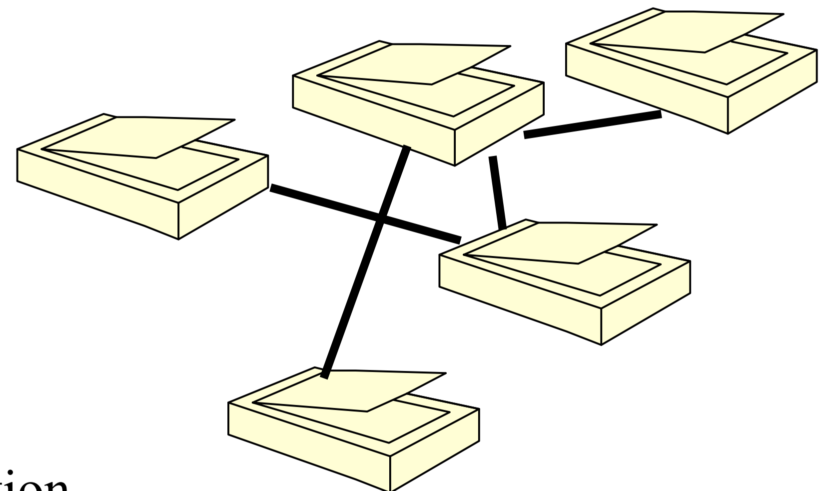
New directions in networking

- Since physical channel limitations are one of the major challenges of wireless communications and since data is the main engine of growth for data, use channel when it is good
- Infostation concept: do data transfer when one is quite close to infostation
- Good for data ,where BER is important but delay is not – bad for voice where delay is important but BER is less
- Problem- data has to get there eventually, dealing with time outs and possible high interference when several users use the infostation



Ad Hoc Networks

- Networks that are possibly self-organizing, in which there are networking components beyond a single wireless link

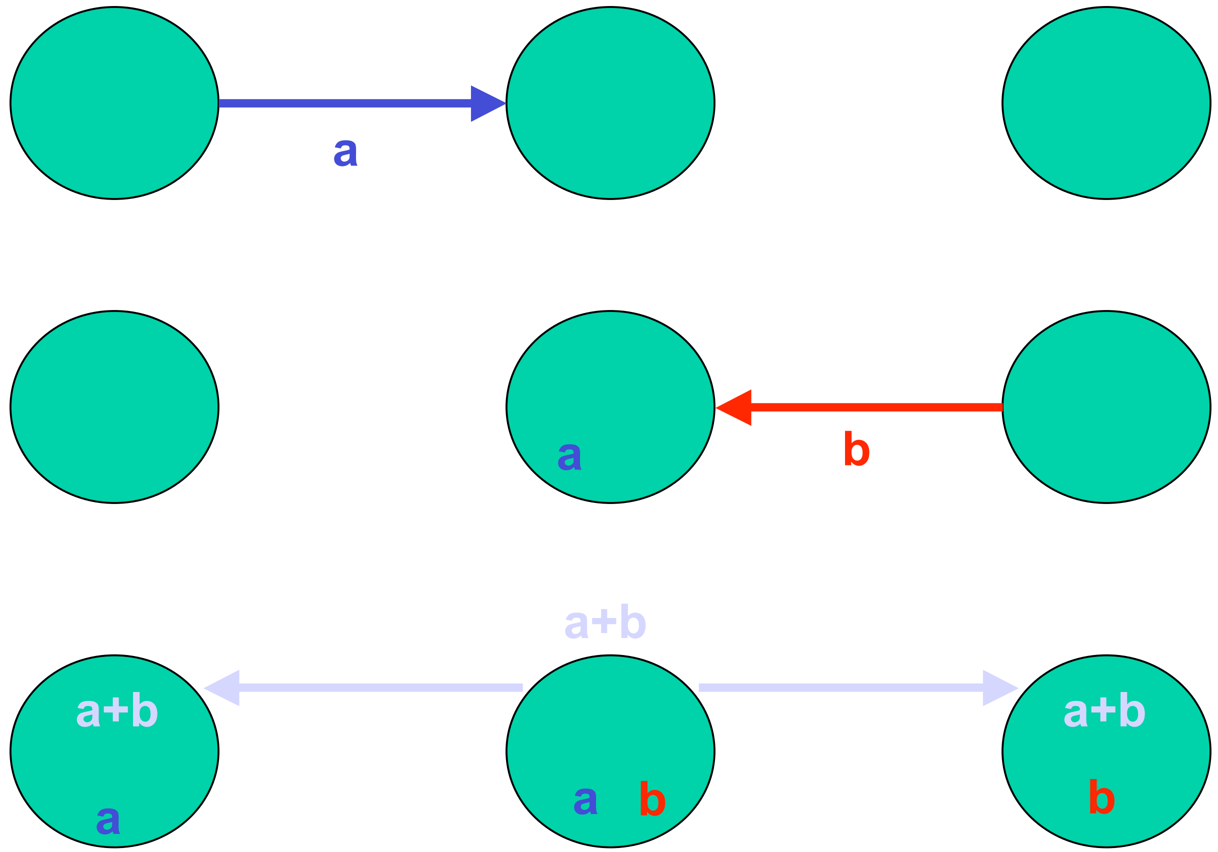


- Issues:
  - Organization
  - Power consumption
  - Fairness
  - Security
- Related issues: networks of low power sensors

Ad-hoc networks

- Scaling laws - Gupta and Kumar
- $\theta(n)$ bit.m/s for certain types of networks if there is enough receiver complexity
- $\theta(\sqrt{n})$ bit.m/s with reduced complexity, giving only $\theta(1/\sqrt{(n \log n)})$ bit.m/s for a node to a random other node
- Mobility helps, by allowing transmission at propitious times - Grossglauser and Tse : long-term throughout can be kept constant in the face of a growing number of users, albeit at the cost of extra delay

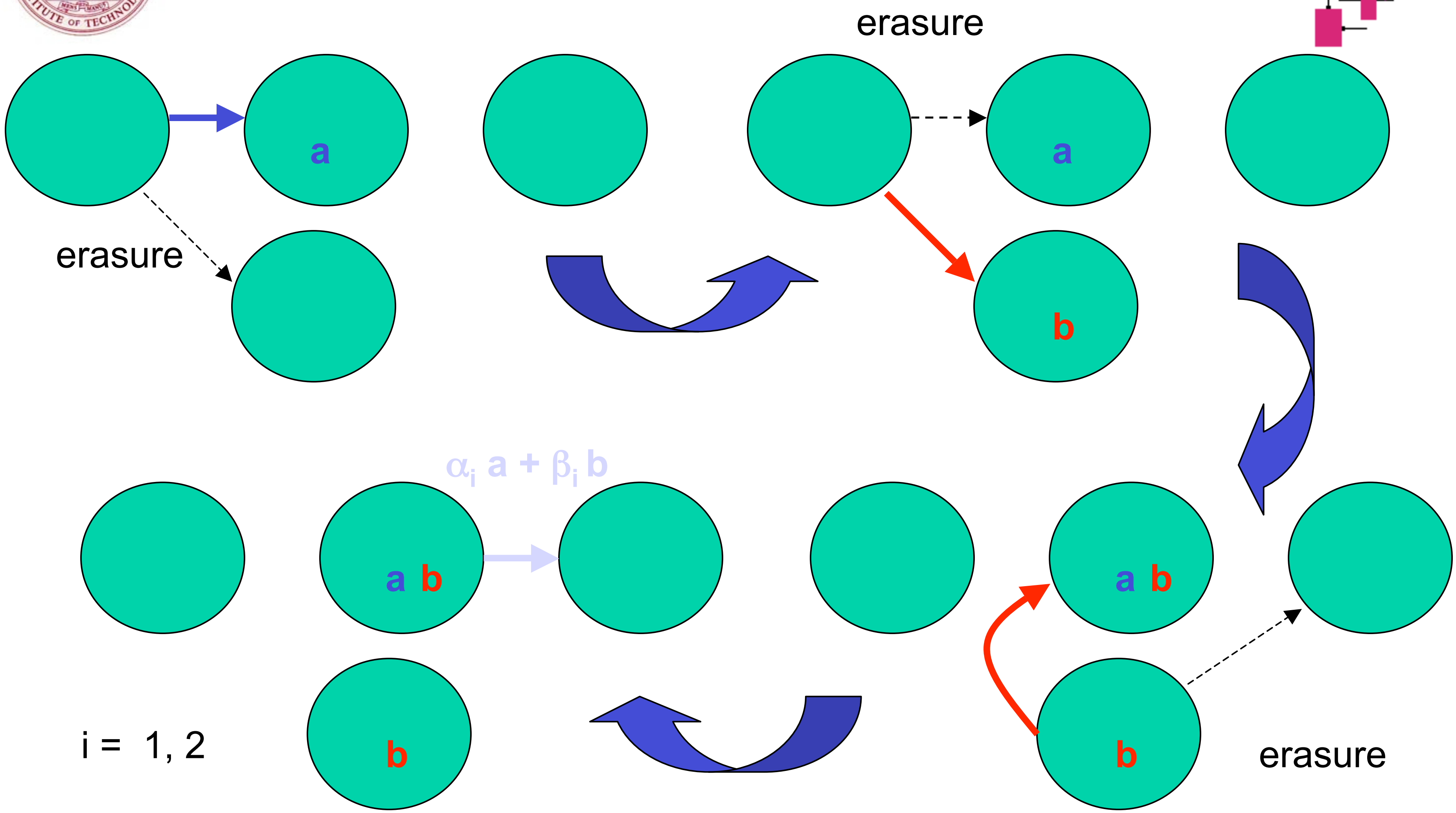
Network coding



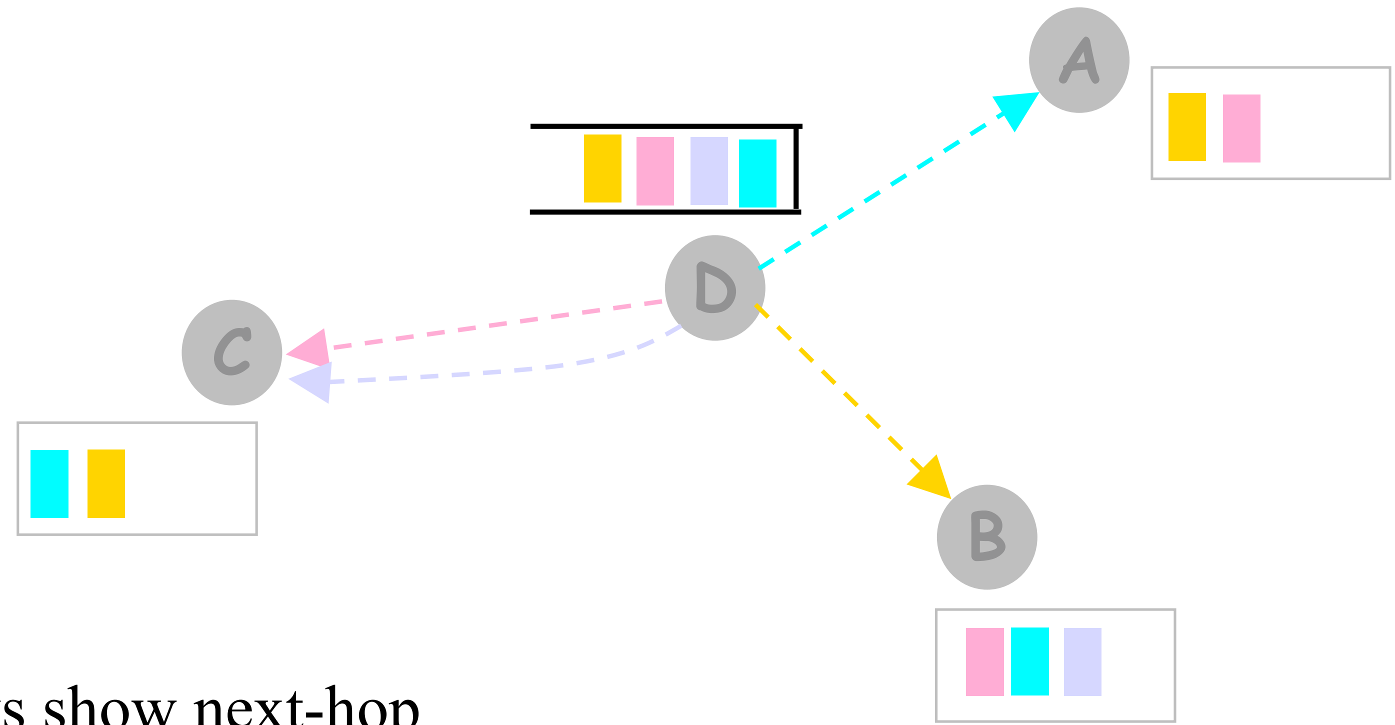
Networking coding in the presence of impairments

- What occurs when transmissions are corrupted or missing?
- Example: a is missing, so that a+b alone is received, which yields nonsense
- When all received packets are relevant (multicast case), simply collect degrees of freedom until a sufficient number has been accumulated
- How does this concord with protocols, say TCP?
  - TCP repeats information packet by packet until it is received – it is in effect a very constrained case of a length one (or a few) packet(s) repetition network code with no intermediate coding
  - Hop-by-hop acknowledgement is a constrained length one packet repetition code with intermediate coding
- **Network coding is a logical step in erasure reliability for networks**

Network coding with erasures



X-OR – opportunistic local coding

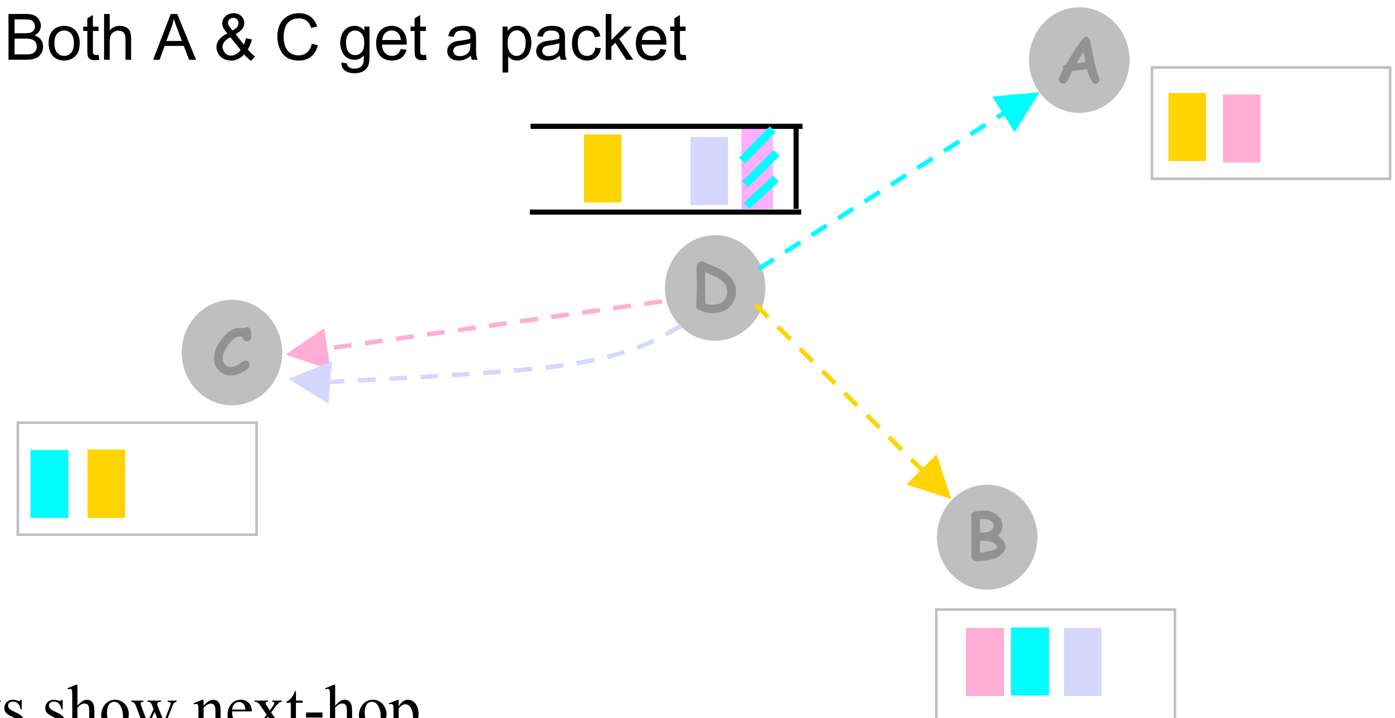


Arrows show next-hop

X-OR – opportunistic local coding

OK Coding

Both A & C get a packet

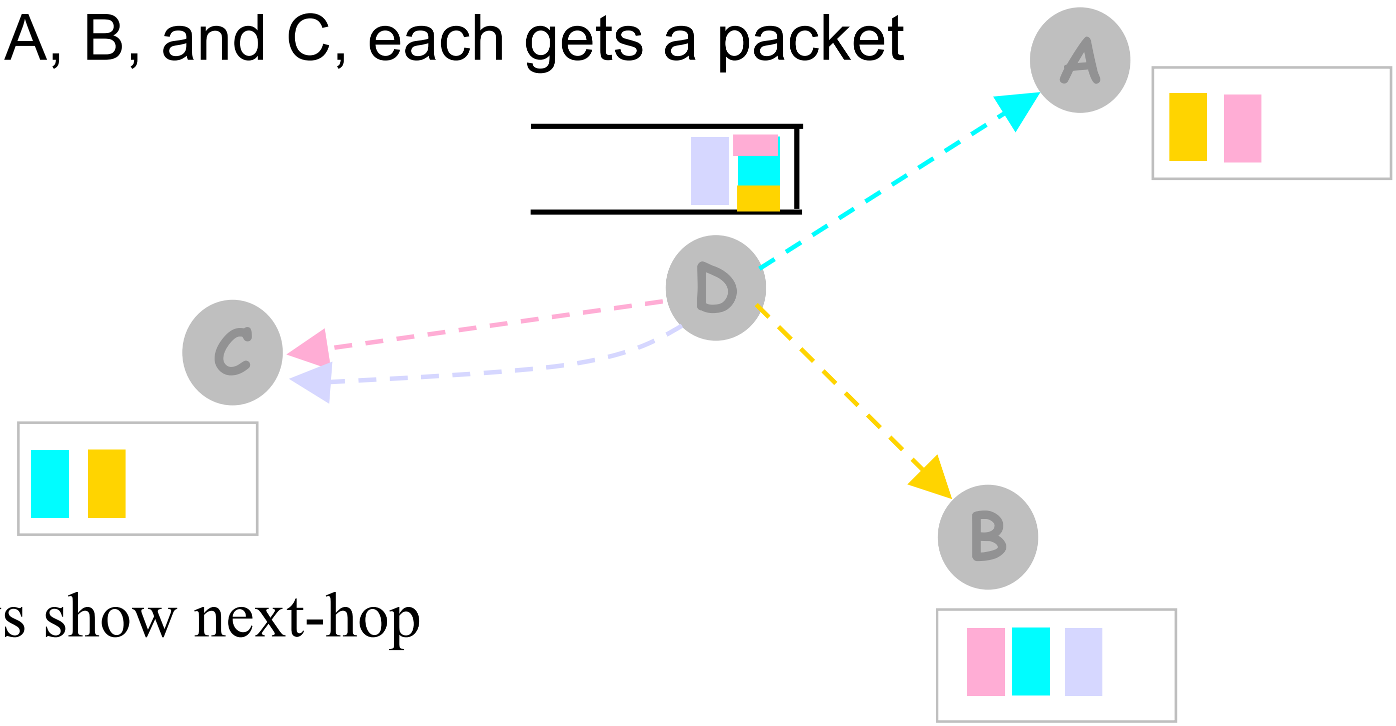


Arrows show next-hop

X-OR – opportunistic local coding

Best Coding

A, B, and C, each gets a packet

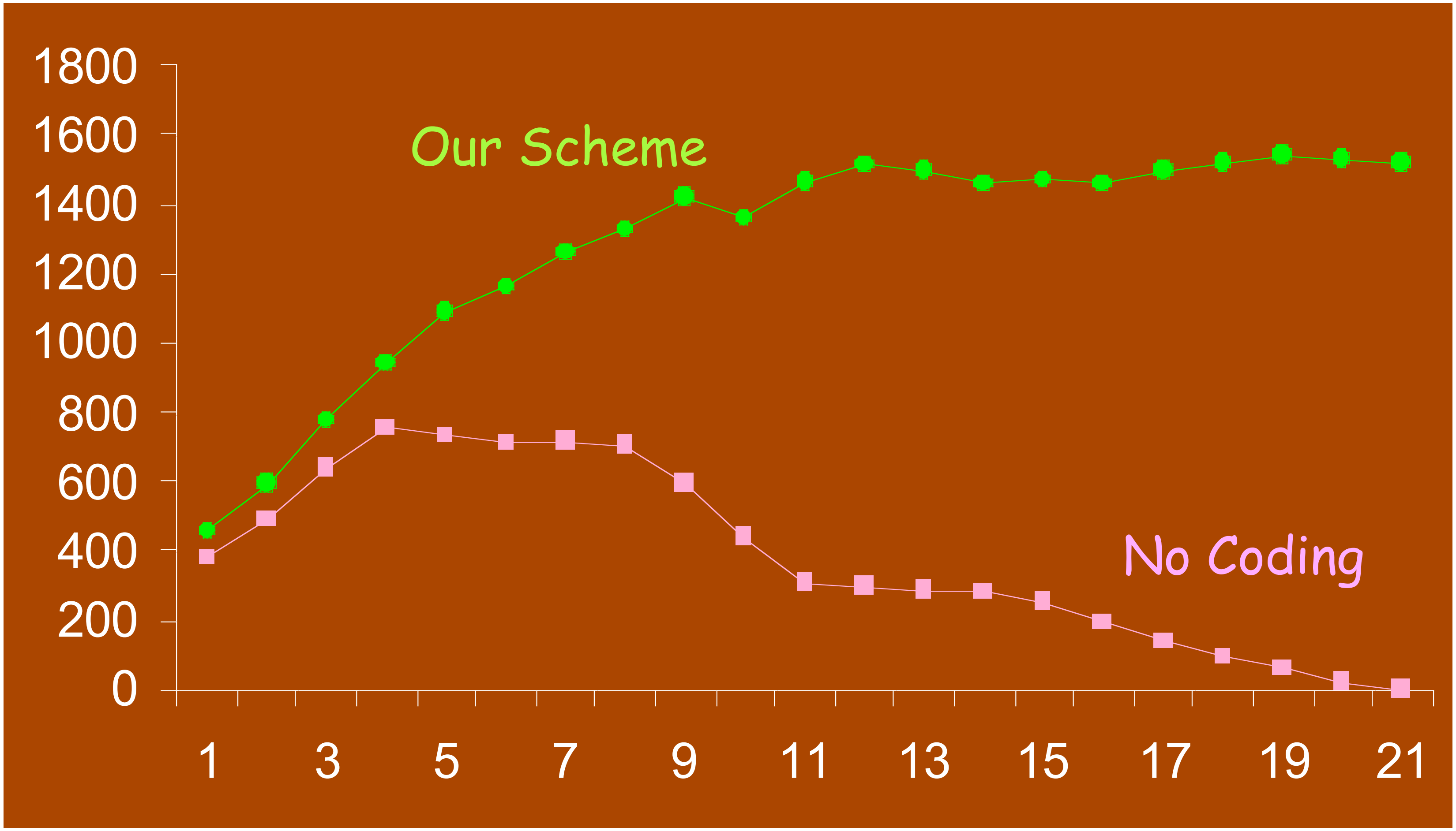


Arrows show next-hop

To XOR *n* packets, each next-hop should have the *n-1* packets encoded with the packet it wants

Opportunistic network coding vs. traditional routing in 802-11

Net. Throughput (KB/s)

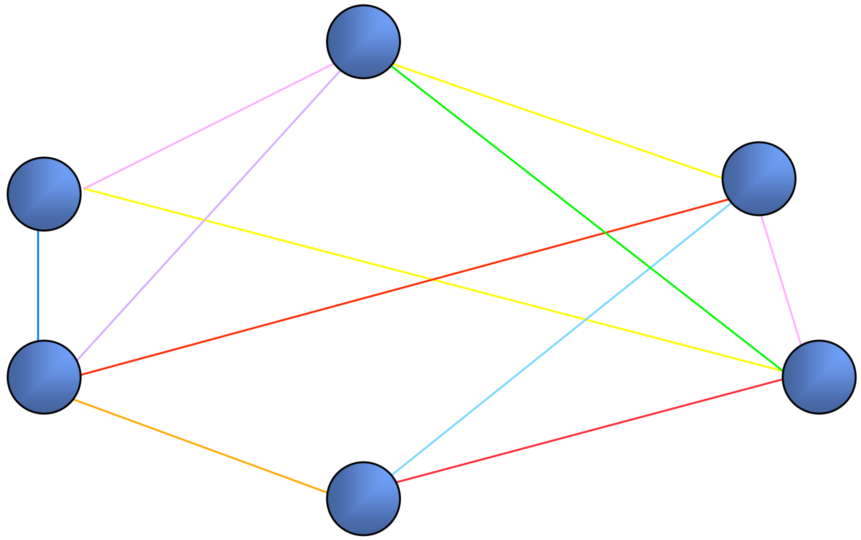


Number of flows in experiment

[Katabi et al. 05]

New areas in wireless

- Several active areas of research:
  - Ultra-wideband systems
  - Software-defined radios
  - Mobility management
  - Network coding



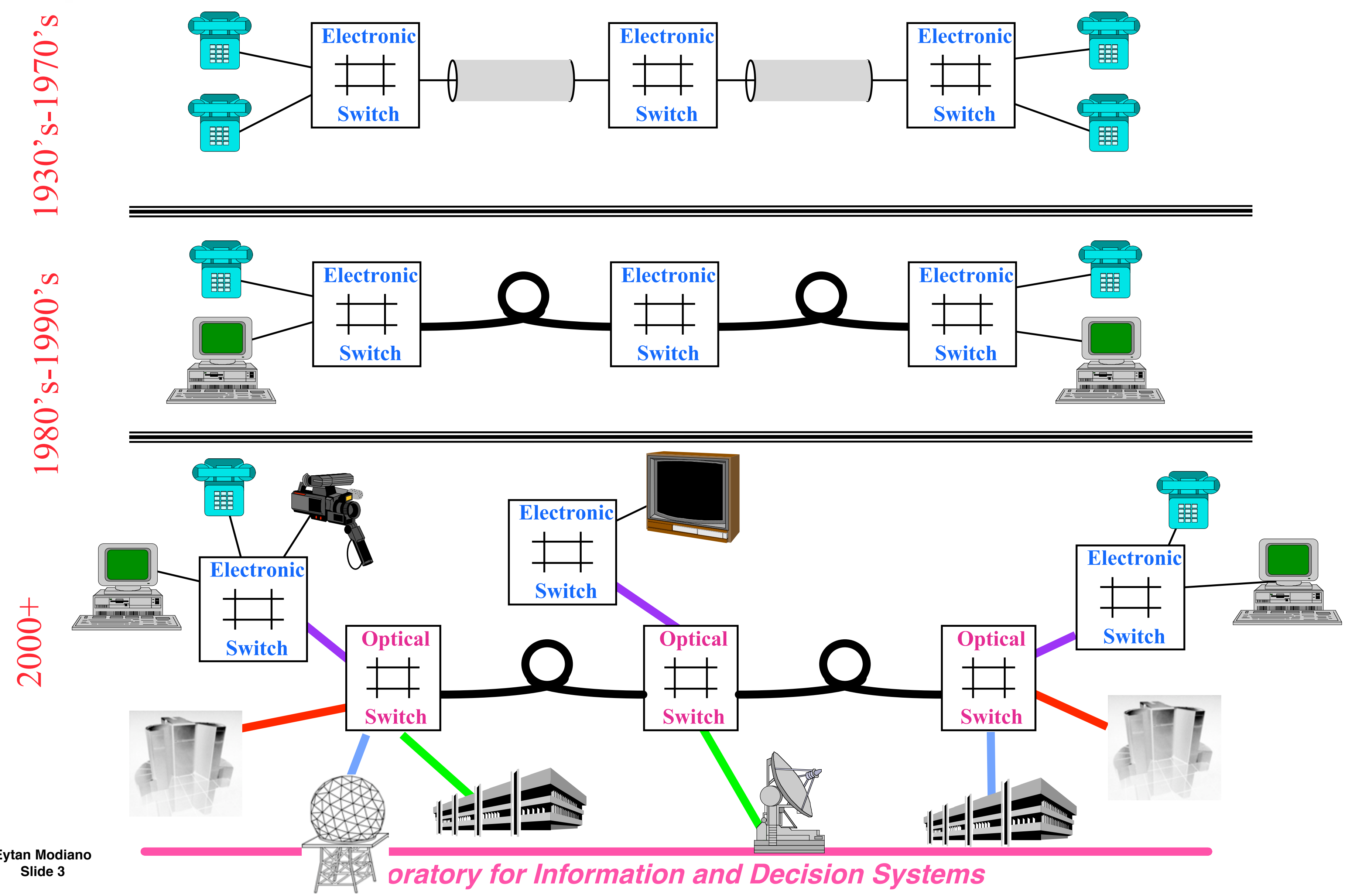
Optical Networks
and
Wavelength Division Multiplexing (WDM)

Eytan Modiano

Outline

- Introduction
  - SONET
  - WDM
- All optical networks
  - LANs
  - WANs
- Hybrid optical-electronic networks
  - IP over WDM
  - Protection
  - Topology design

Communications Evolution



Synchronous Optical Network (SONET)

- **Standard family of interfaces for optical fiber links**
  - **Line speeds**

    n x 51.84 Mbps

    n=1,3,12,48,192, 768

  - **TDMA frame structure**

    125 μsec frames

  - **Multiplexing**

    Basic unit is 64 kbps circuit for digitized voice

  - **Protection schemes**

    Ring topologies

SONET Line Rates

LIDS

Backbone Speeds

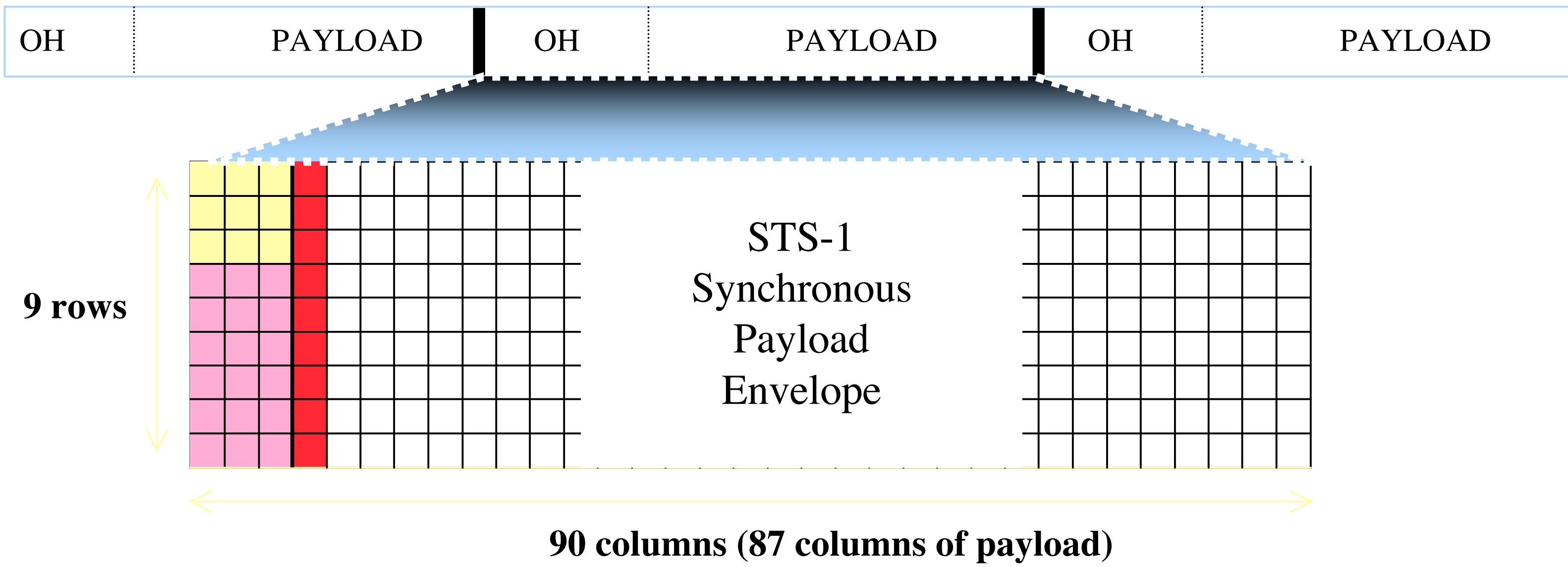
Fiber Optic Signal OC Level	Synchronous Transport Signal STS Level	Synchronous Transport Mode STM Level	Line Rate	Equivalent Channels		
				DS0 (64 KBPS)	DS1 (1.54 Mbps)	DS3 (44.74 Mbps)
OC1	STS-1		51.84 Mbps	672	28	1
OC3	STS-3	STM-1	155.52 Mbps	2016	84	3
OC12	STS-12	STM-4	622.08 Mbps	8064	336	12
OC48	STS-48	STM-16	2488.320 Mbps	32256	1344	48
OC-192	STS-192	STM-64	9953.280 Mbps	129024	5376	192
OC-768	**STS-768**	**STM-256**	**39813.12 Mbps**	**516096**	**21504**	**768**

1995

2000

Multiplexing Frame Format

810 bytes x 8000 frame/sec x 8 bits = 51,840,000 bits

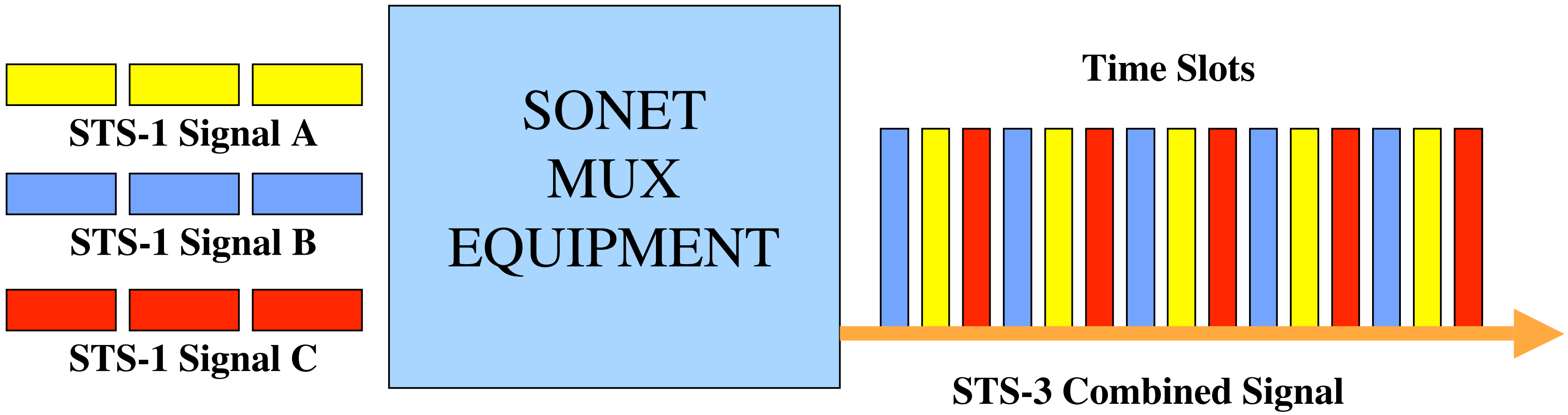


3 columns of transport overhead:

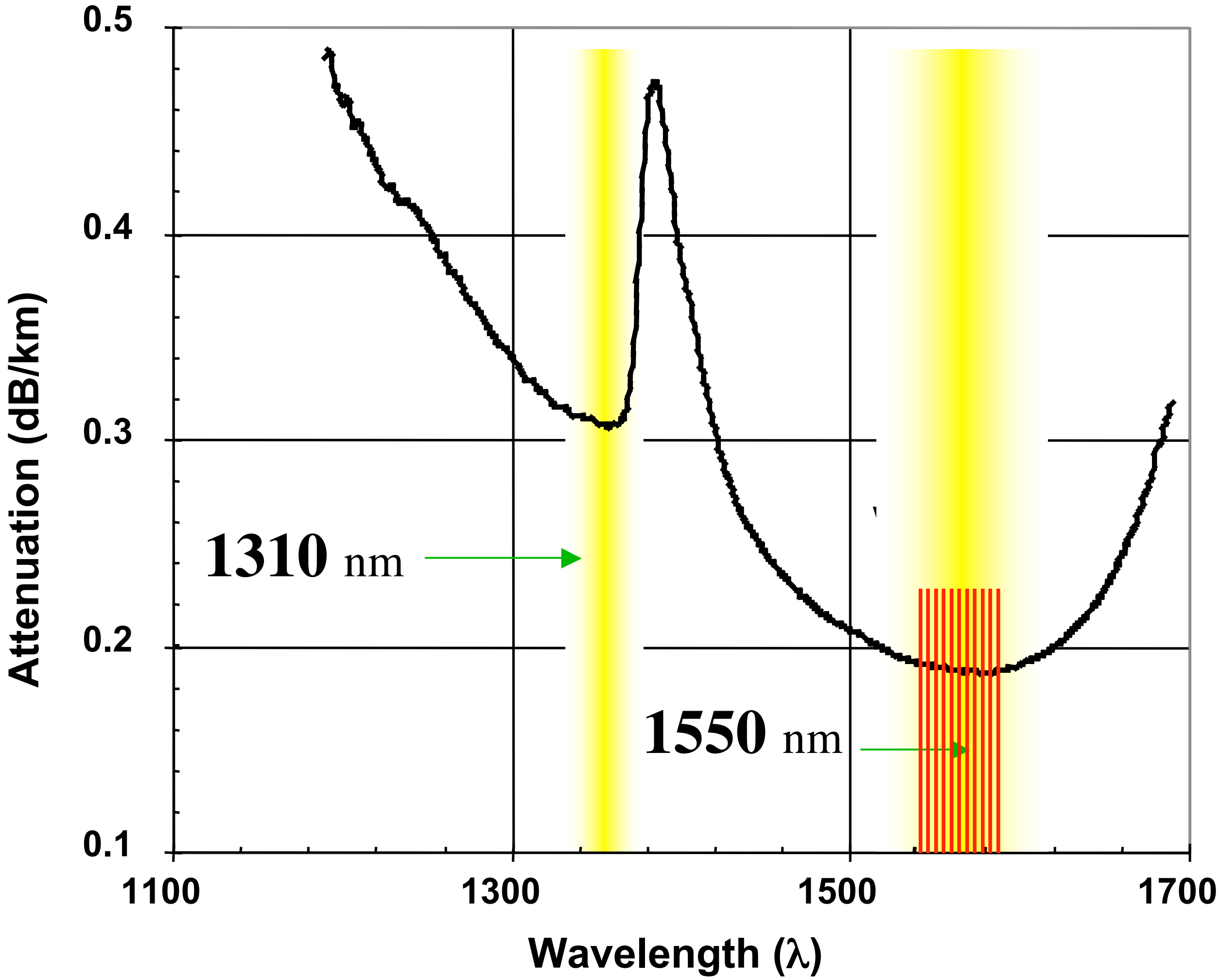
Section overhead **Path overhead** **Line overhead**

STS-1 Multiplexing

3 x 51.840 Mb/s = 3 x STS1 = STS-3 = 155.520 Mb/s (OC-3)



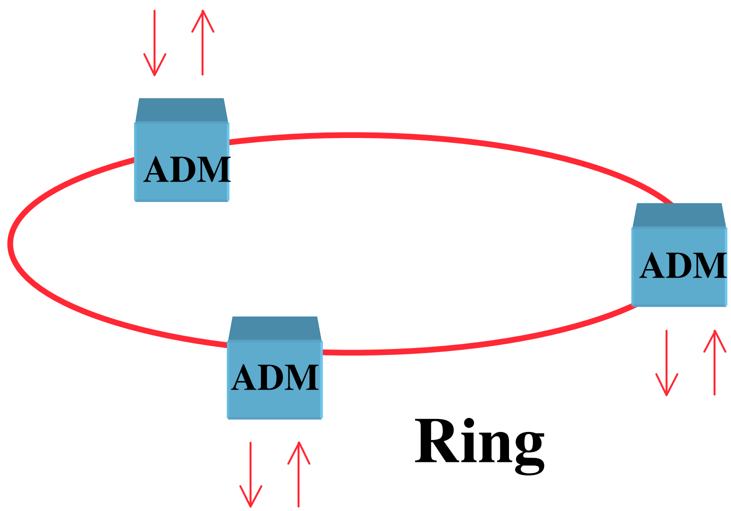
Transmission medium (Low Loss Windows)

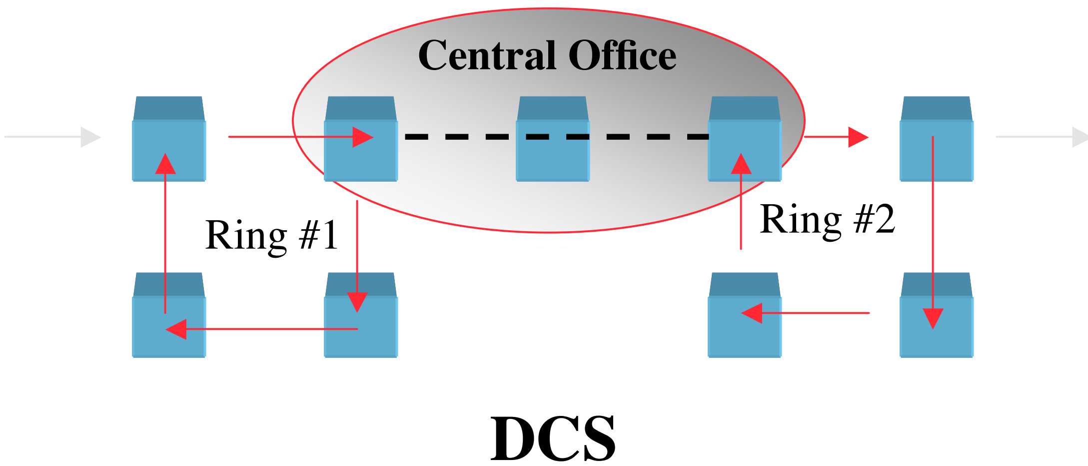


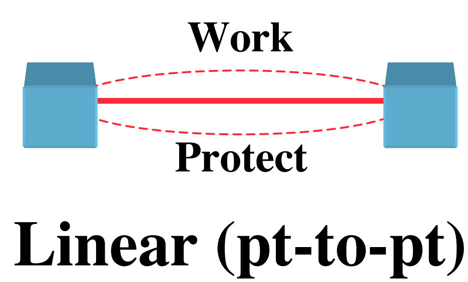
Network Elements and Topologies

LIDS

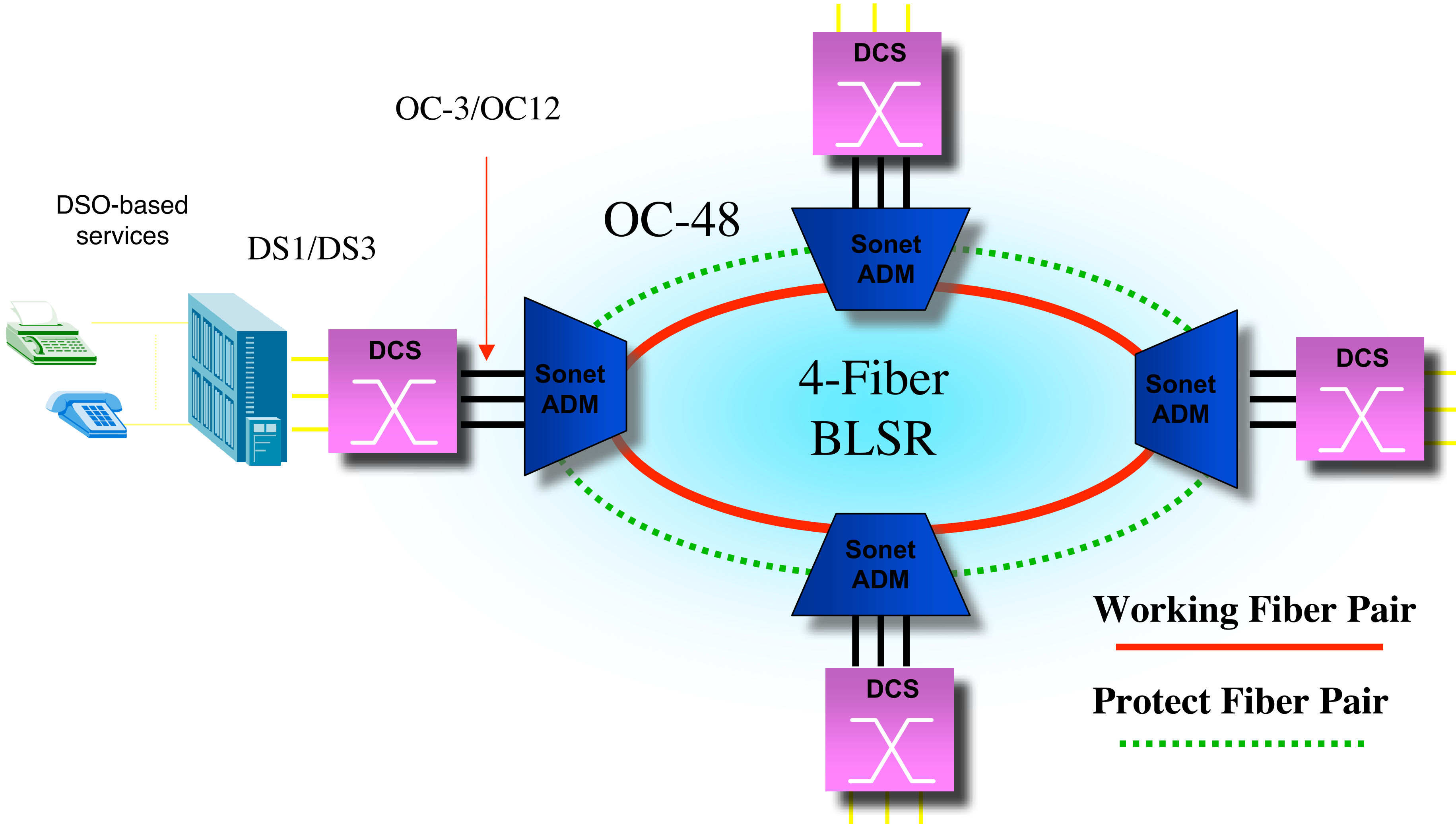
- Add Drop Multiplexers (ADMS)
  - (De) multiplex lower rate circuits into higher rate stream
- Digital Cross-connects (DCS)
  - Switch traffic streams



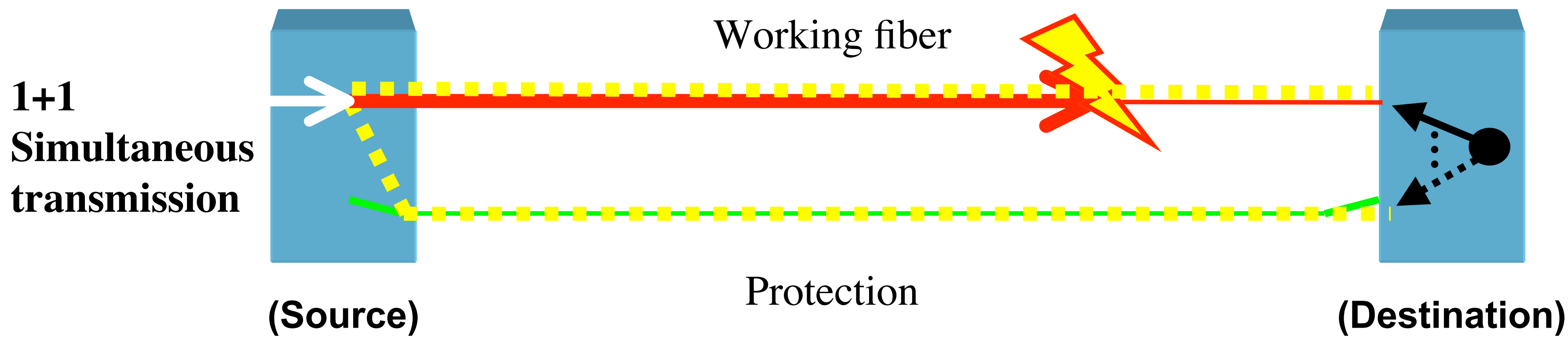


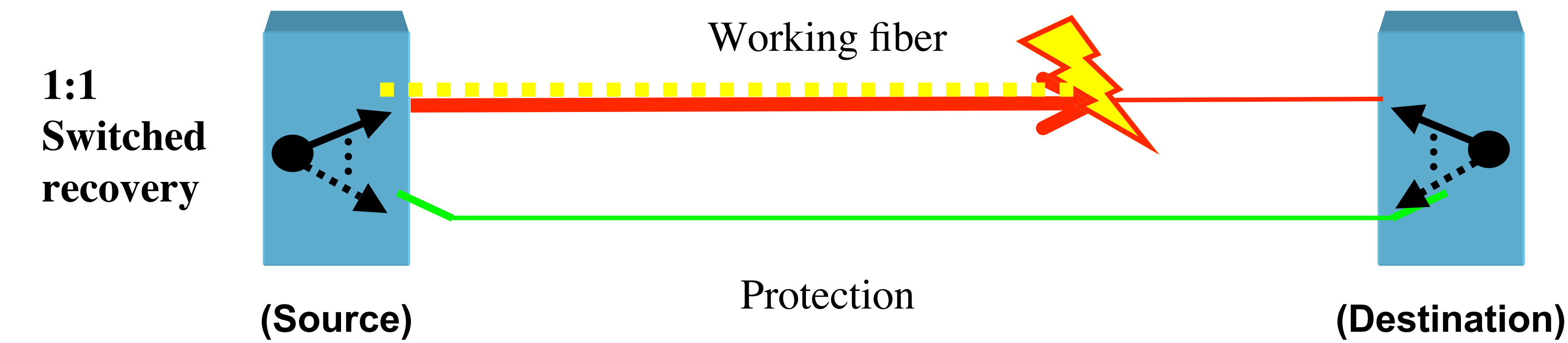


Traditional SONET Ring Architecture



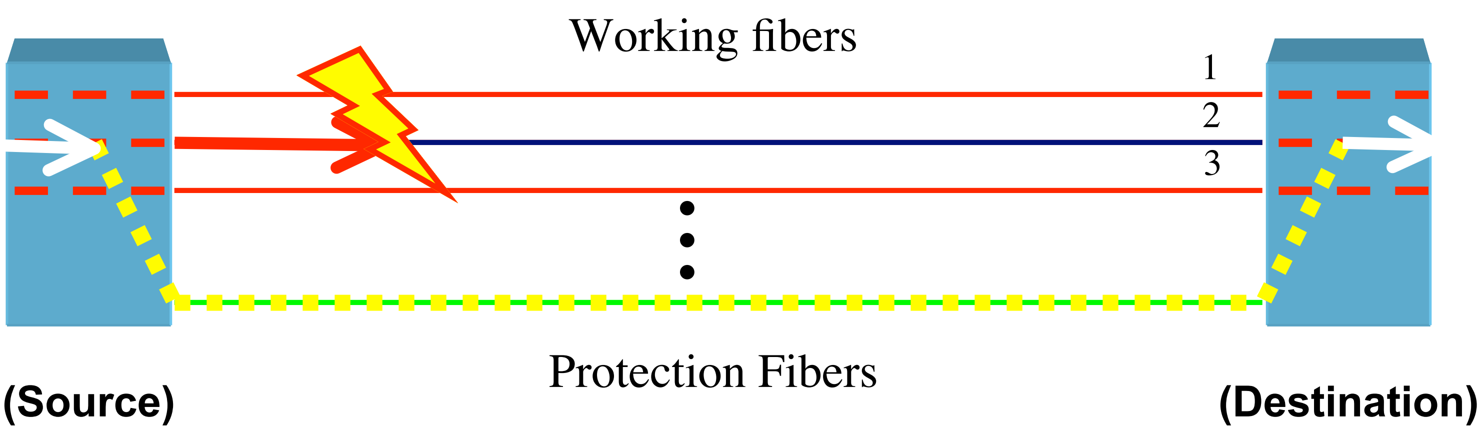
Link protection schemes





50 % bandwidth inefficiency

Protection Schemes: 1:n

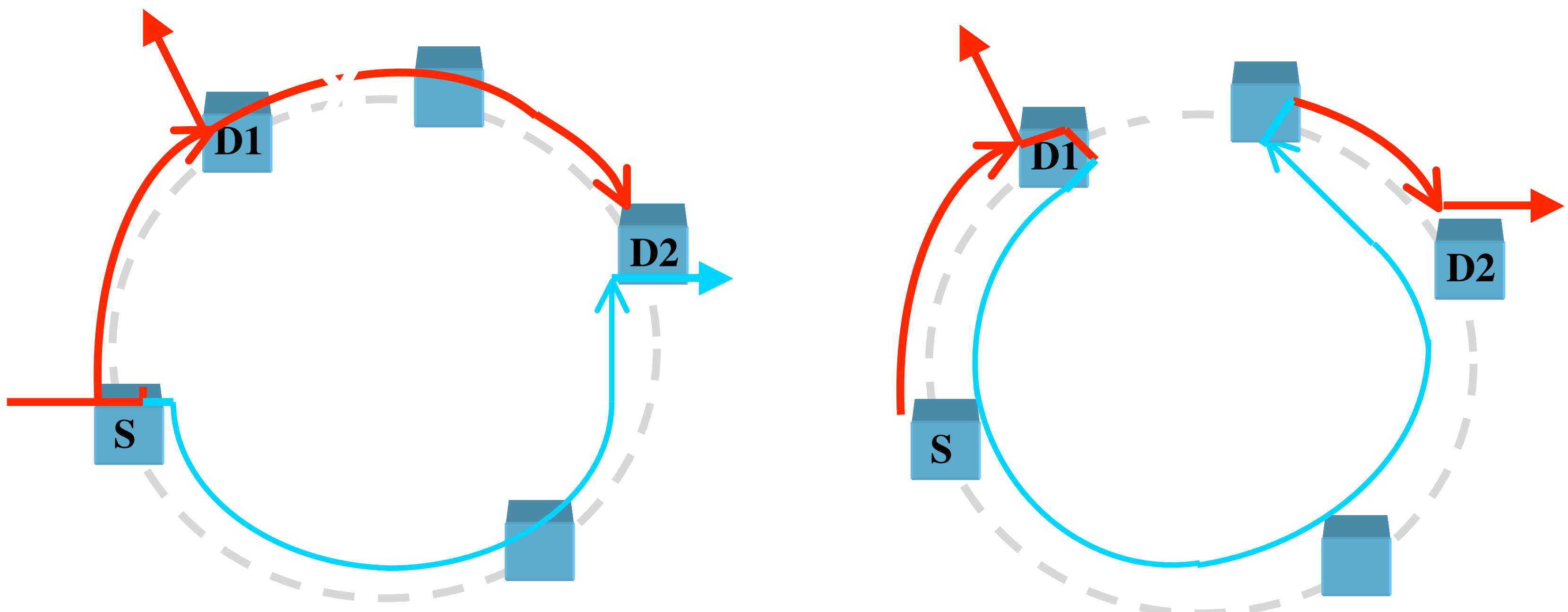


1:n Protection Switching

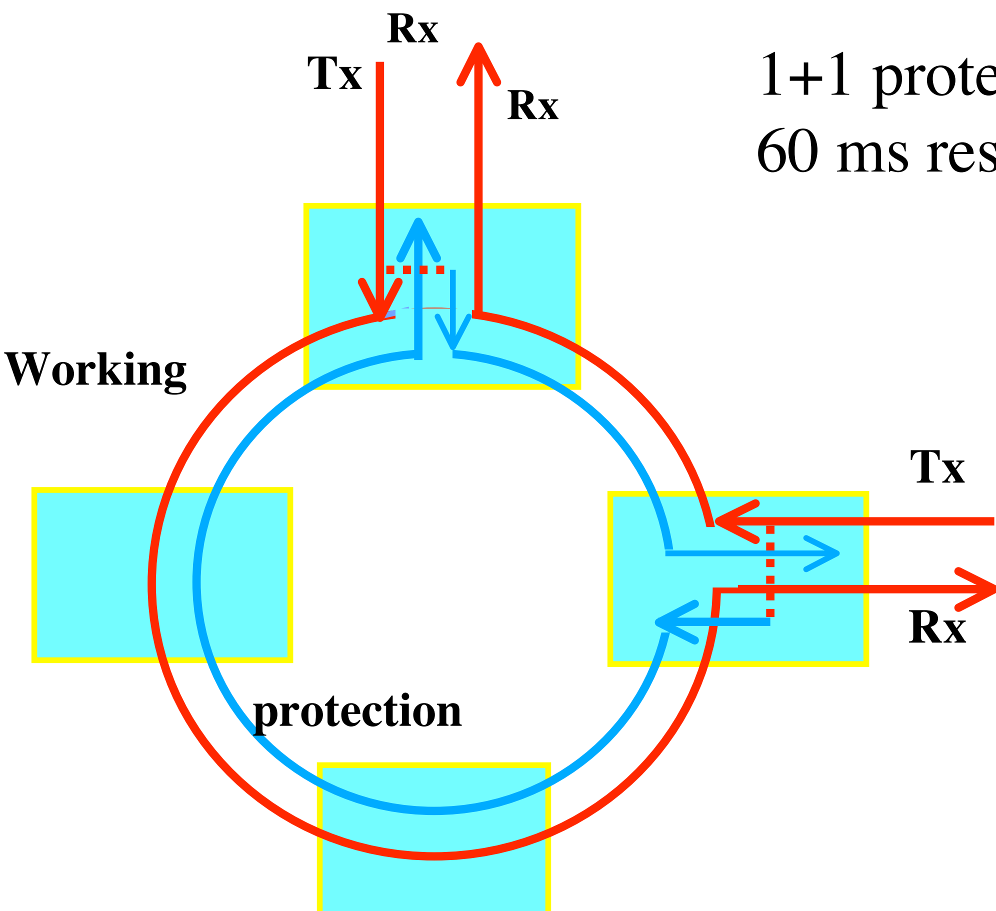
Path vs. line protection

Path Protection

Line Protection (Loopback)



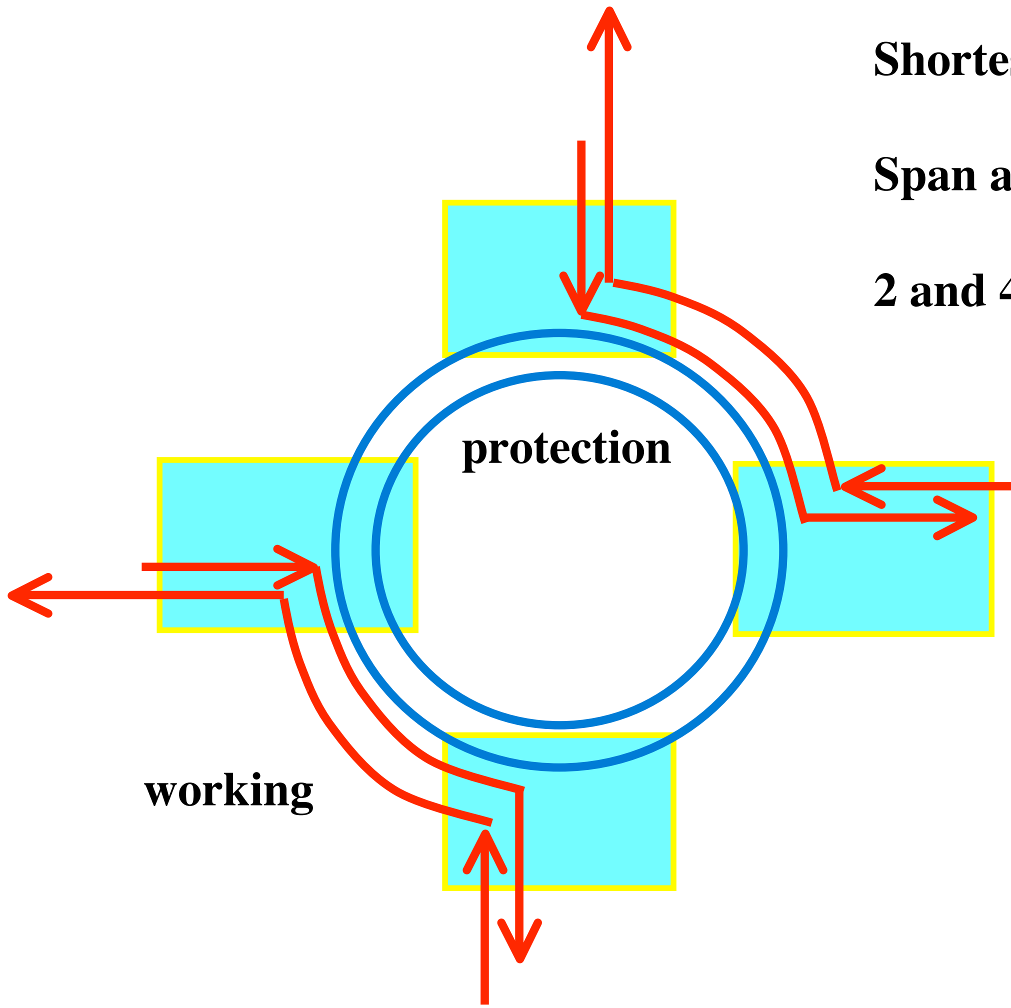
Protection Schemes: UPSR



1+1 protection
60 ms restoration time

Unidirectional/Path Switched Ring (UPSR)

Protection Schemes: BLSR



Shortest path routing

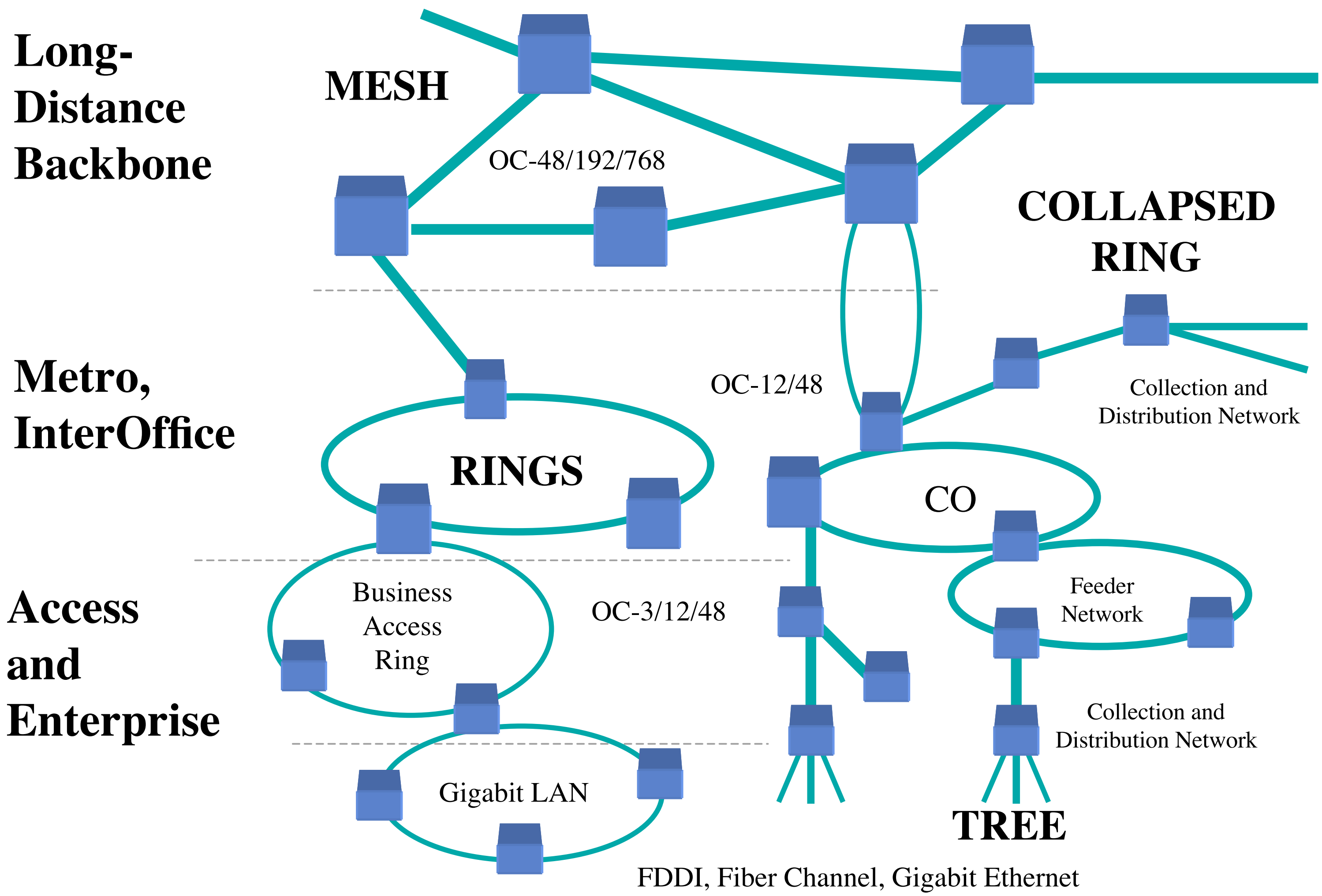
Span and path protection

2 and 4 fibers

Bidirectional/Line Switched Ring (BLSR)

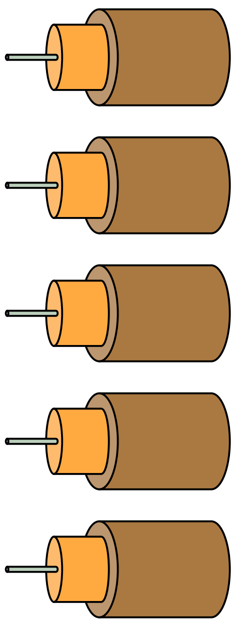
Architectures and Topologies

LIDS

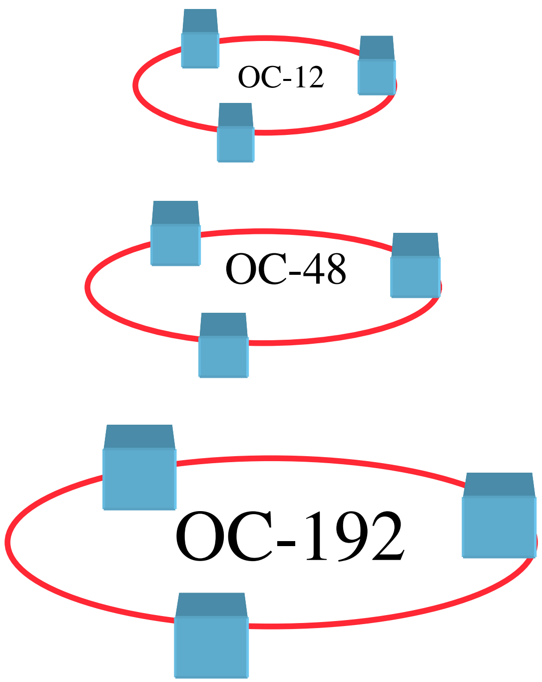


Scaling Options

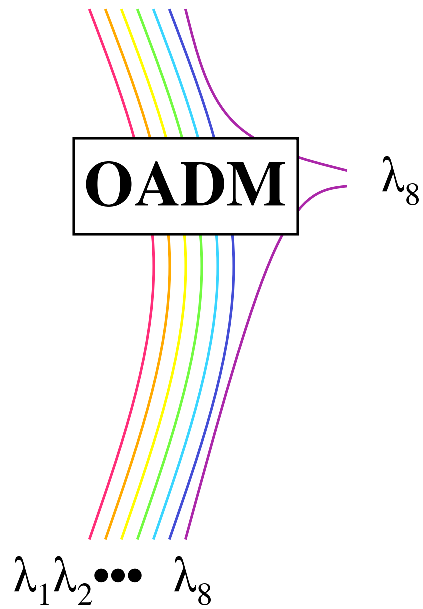
Option 1: Overbuild Fiber



Option 2: Upgrade SONET

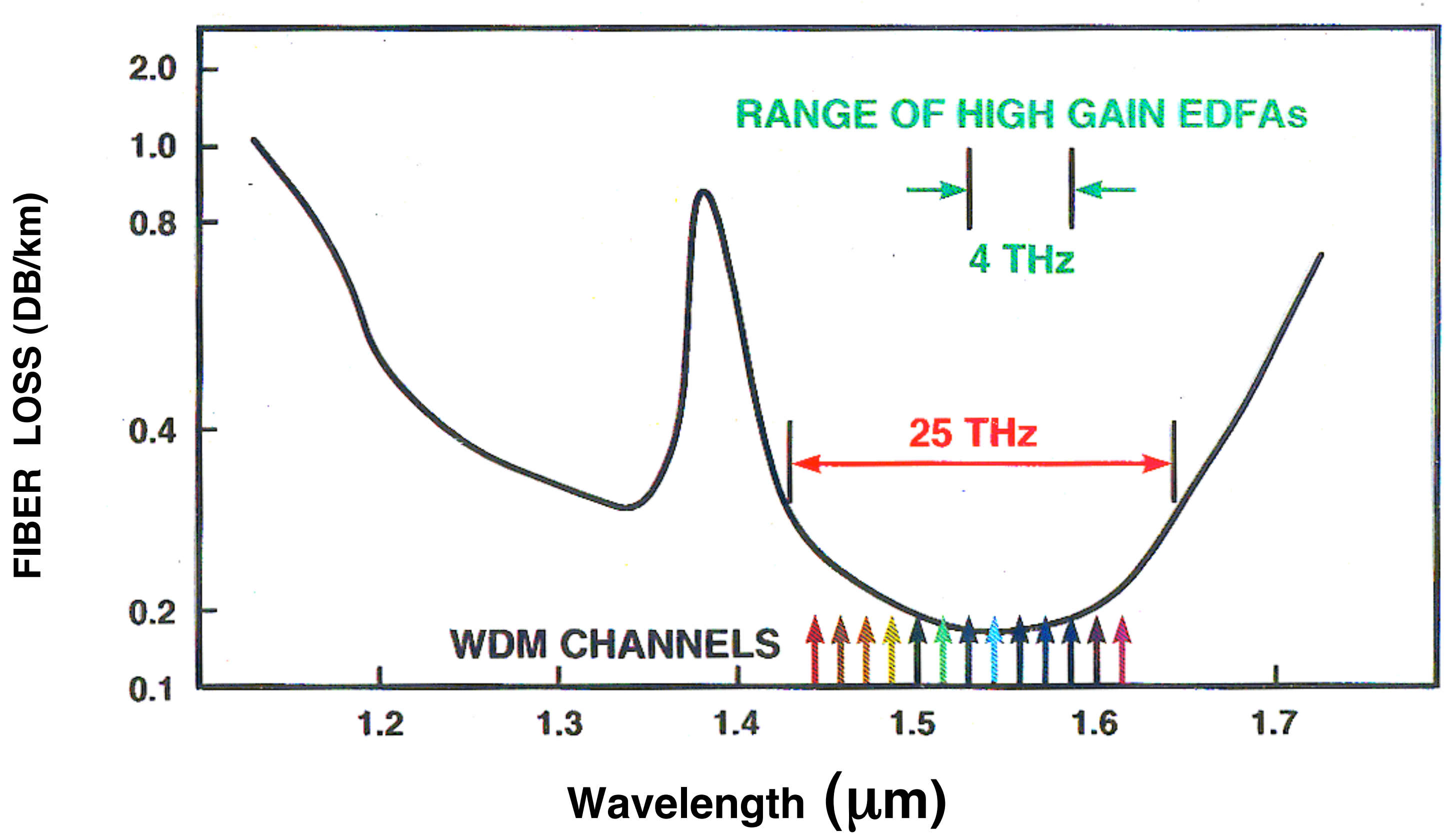


Option 3: Introduce DWDM

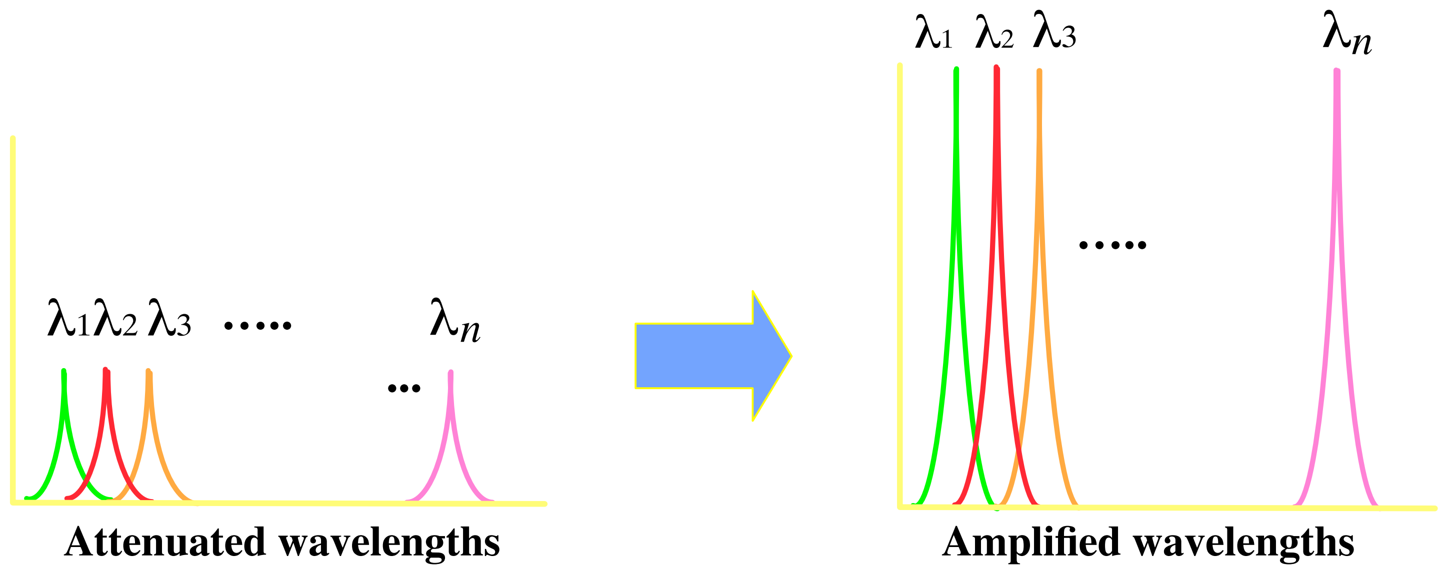


WAVELENGTH DIVISIION MULTIPLEXING

- EXPLOITS
  - ENORMOUS BANDWITH OF SILICA FIBER
  - HIGH-GAIN WIDEBAND OPTICAL AMPLIFIERS



Optical Amplifiers



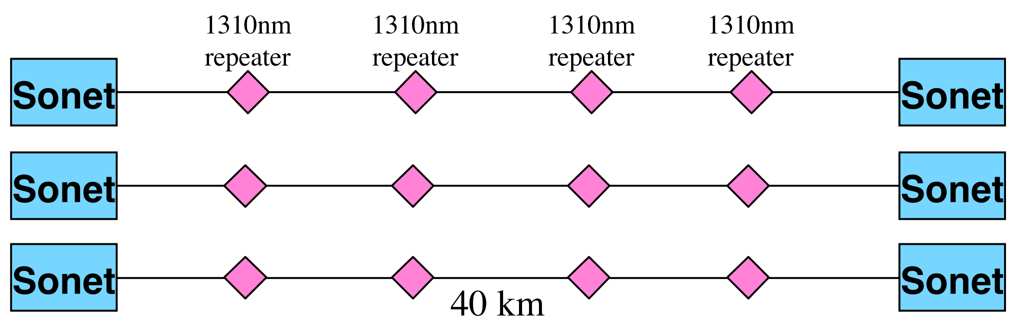
- No O/E, E/O conversion
- Greater bandwidth than electronic repeaters
- Transparent to bit rates
- Transparent to modulation formats
- Simultaneous regeneration of multiple WDM signals
- Low noise, high gain

WDM Benefits

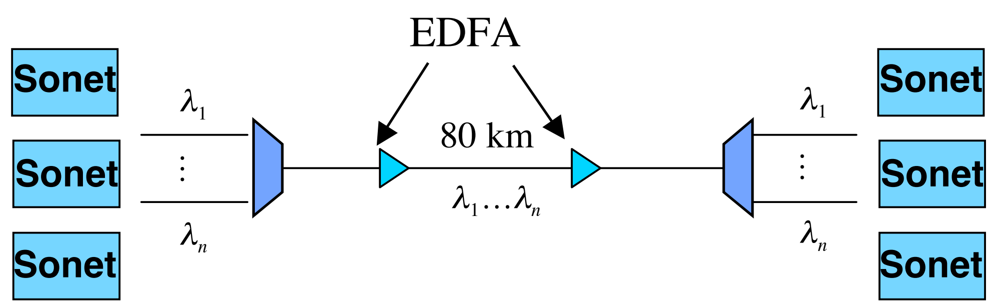
- Increases bandwidth capacity of fiber
- Addresses fiber exhaust in long-haul routes
- Reduces transmission costs
- Improves performance
- Enhances protection (virtual and physical)
- Enables rapid service deployment
- Reduces network elements

SONET over WDM

Before



After



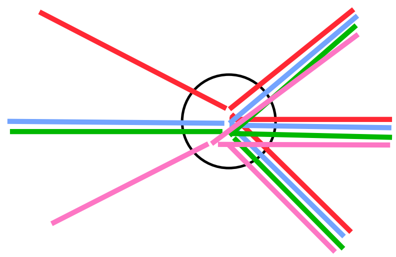
All optical WDM networks

- Network elements
  - Broadcast star
  - Wavelength router
  - Frequency selective switch
  - Wavelength converters

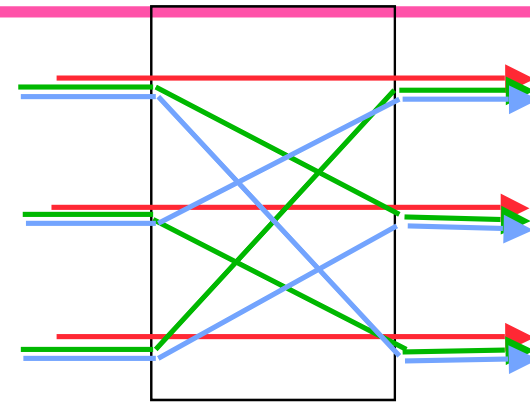
- WDM LANs
  - Passive networks
  - Broadcast star based

- WDM WANs
  - Hierarchical architectures
  - Wavelength assignment
  - Wavelength conversion

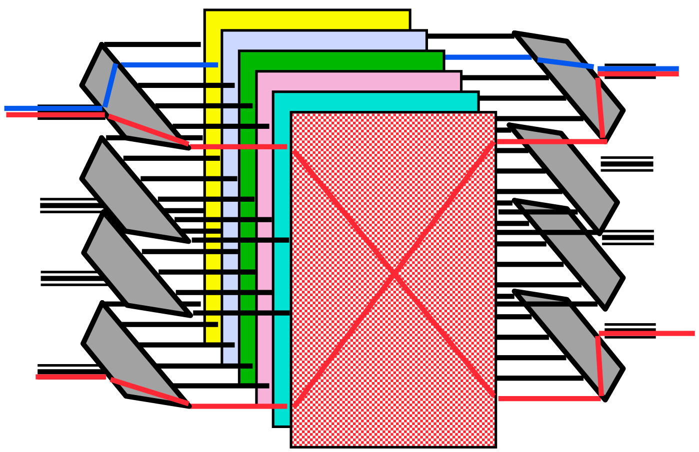
COMMON ALL-OPTICAL NODES



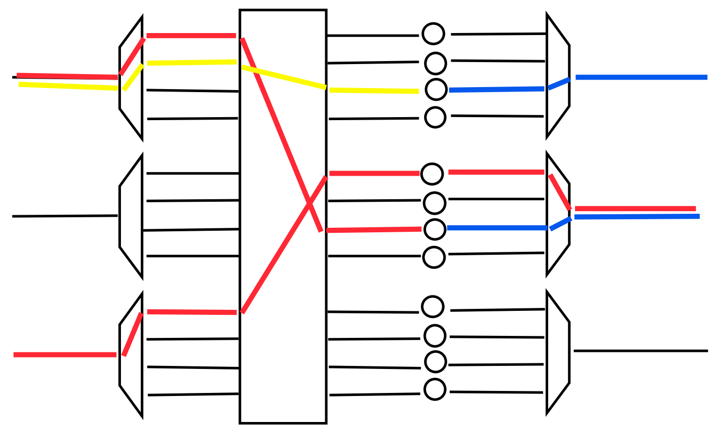
BROADCAST STAR
(PASSIVE)



WAVELENGTH ROUTER
(PASSIVE)

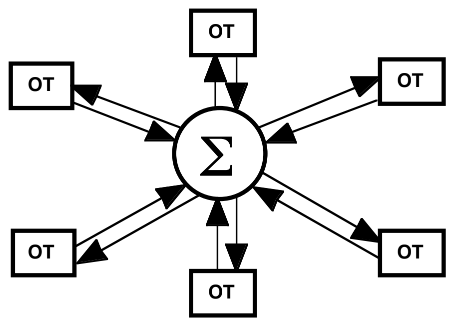


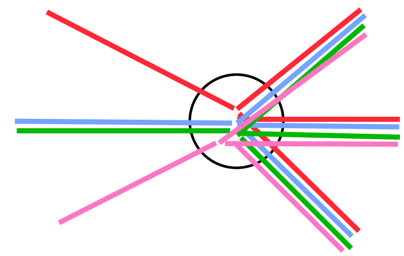
FREQUENCY SELECTIVE SWITCH
(CONFIGURABLE)



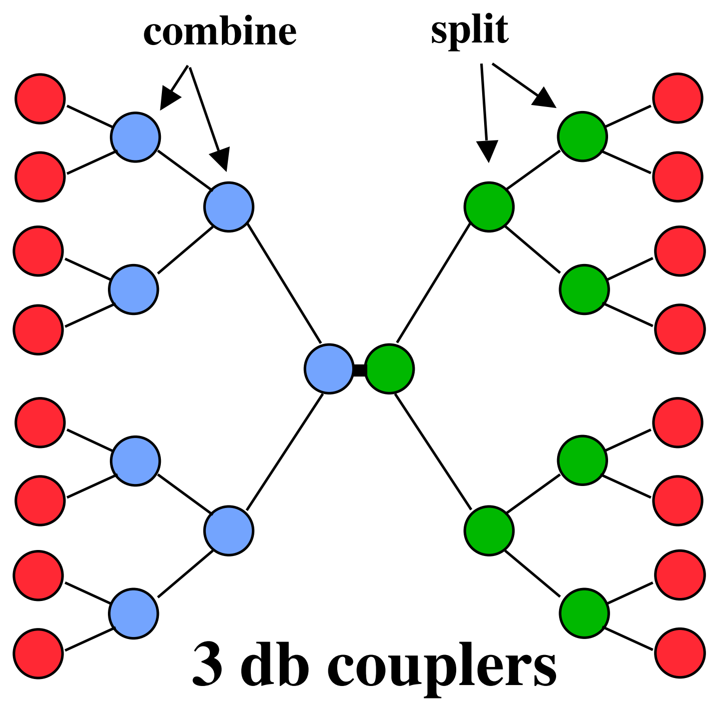
FREQUENCY SELECTIVE SWITCH
WITH WAVELENGTH CHANGERS
(CONFIGURABLE)

Broadcast star (passive)

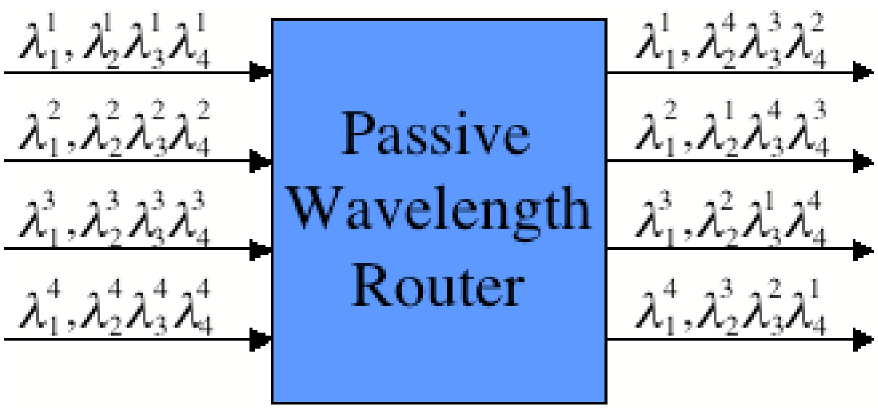


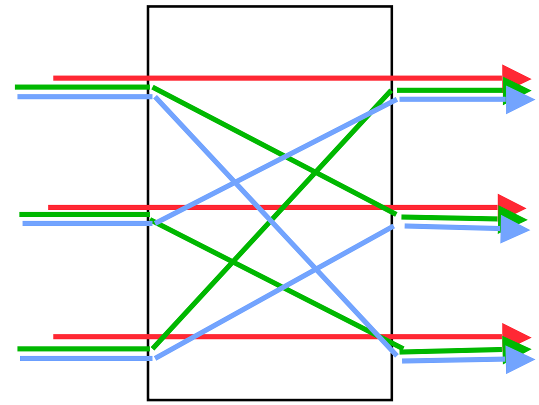


- Each output contains all inputs
- High loss
  - 3 db per stage
  - Log N stages
- No frequency reuse
  - Only one user per wavelength
- Cheap and simple
- Support W connections



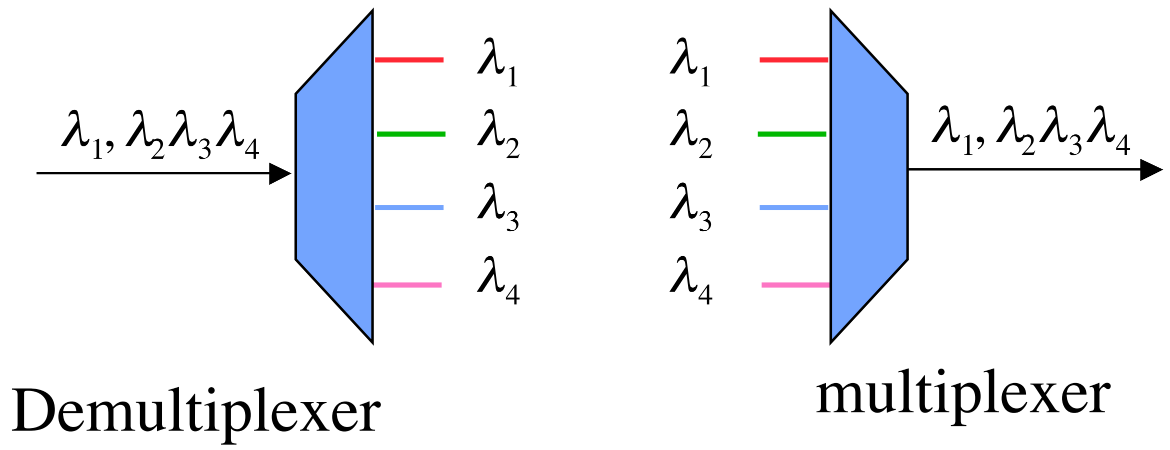
Wavelength Router





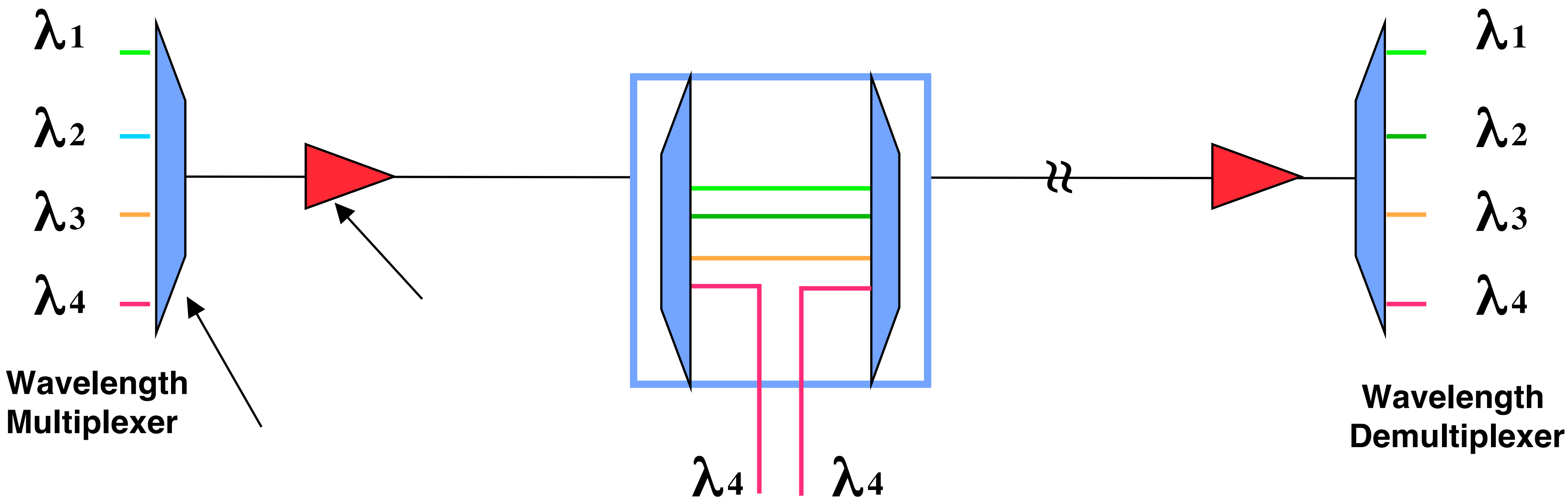
- **Complete frequency reuse**
  - **Each input can use all wavelengths without interference**
  - **Can support N^2 connections**
- **Passive device**
  - **All connections are static**
  - **Exactly one wavelength connecting an input-output pair**

Multiplexers and De-multiplexers



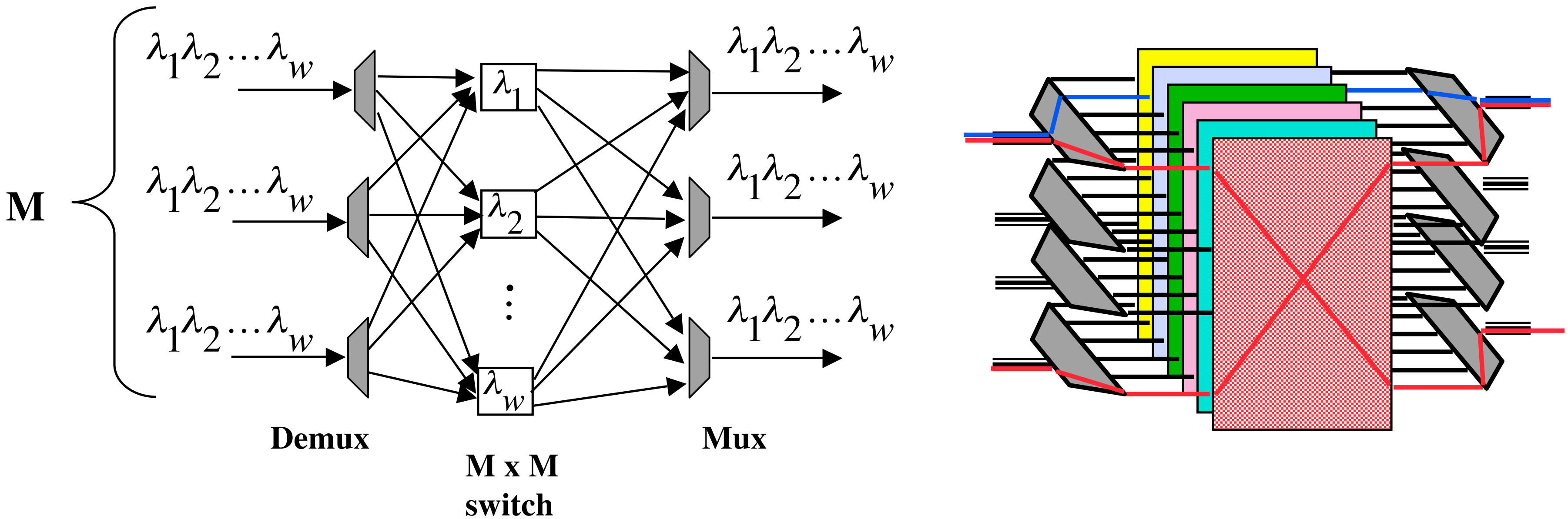
- **Multiplexer**
  - **Single output of a router**
- **Demultiplexer**
  - **Single input to router**

Optical Add/Drop Multiplexers (ADM)



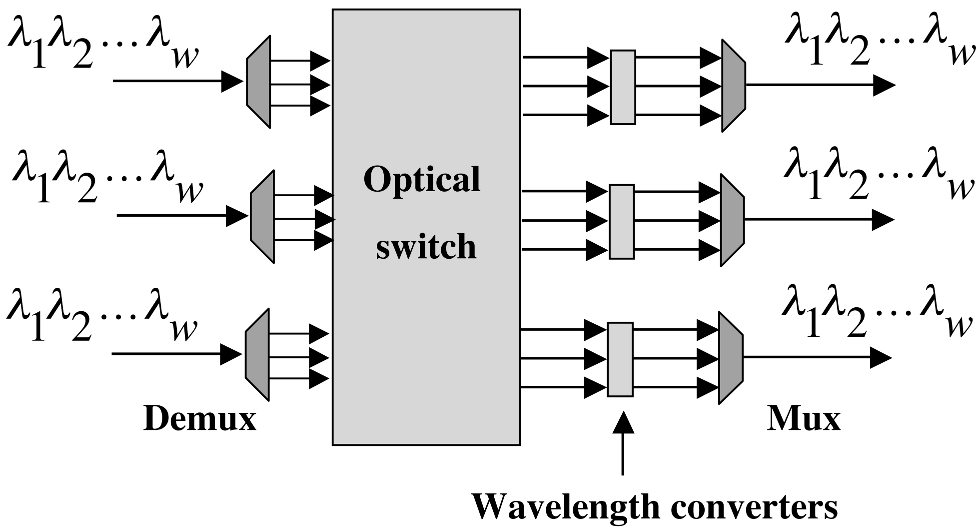
- An ADM can be used to “drop” one or more wavelengths at a node
  - One input fiber and one output fiber plus local “drop” fibers
  - can be either static or configurable
  - Usually limited number of wavelengths
  - Loss proportional to number of wavelengths that can be dropped at a node

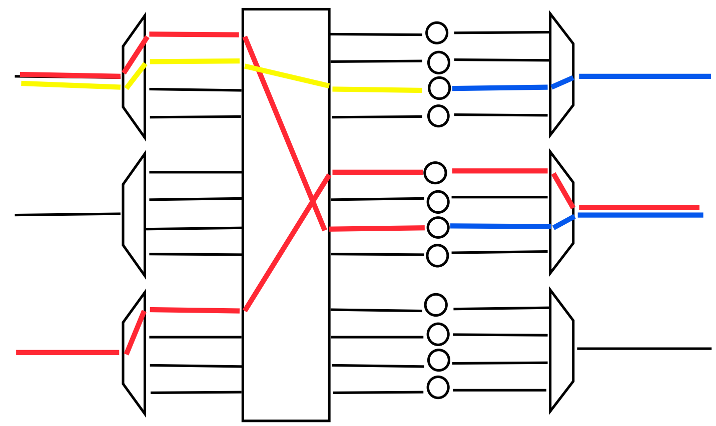
Frequency Selective Switch



- M input and M output fibers
- Any wavelength can be switched from any input fiber to any output fiber
- Expensive device that offers a lot of configurability
  - Switch times depend on implementation but are typically in the few ms range

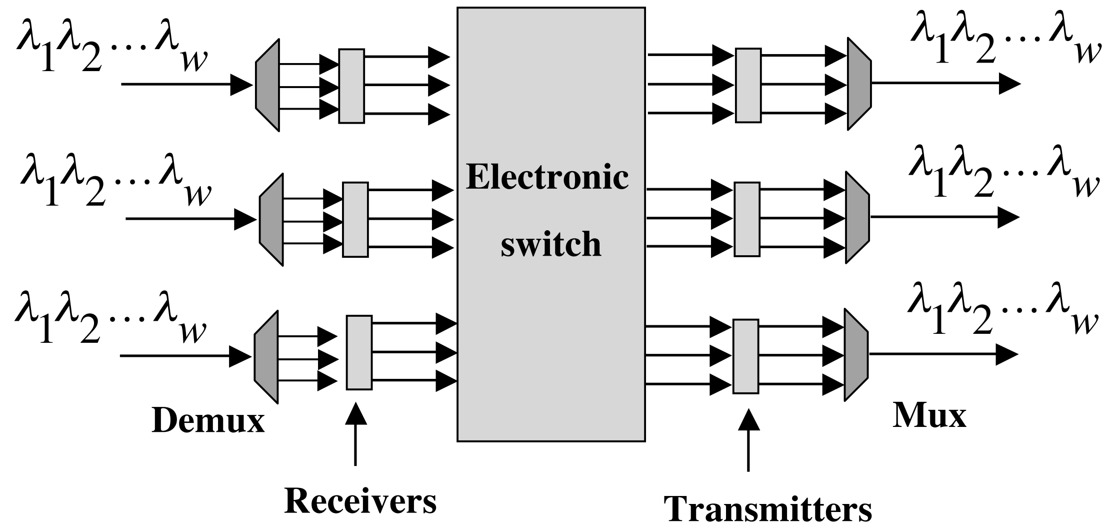
Frequency selective switch with wavelength conversion





- Wavelength conversion offers the maximum flexibility
- Optical wavelength conversion not a mature technology
- Electronic conversion is possible but very expensive
  - Essentially requires a transceiver

FSS using an electronic cross-connect

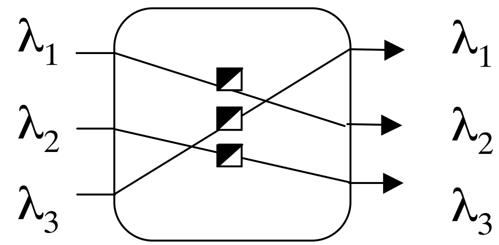


- Electronic cross-connects are less expensive
  - Limited size
  - Not all optical
  - Not bit rate transparent (OC-48)
  - Most of the cost is in the transceivers
- Most practical implementation
  - Implemented on an ASIC
  - No need for optical wavelength conversion
  - Very fast switching times

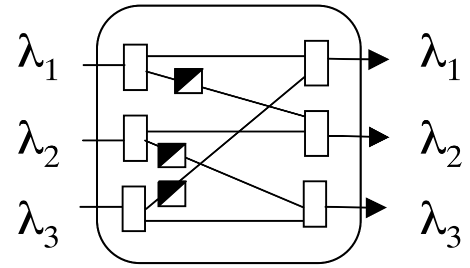
Wavelength Conversion

- **Fixed conversion**
  - Convert from one wavelength to another
  - Maybe useful for integrating different networks
- **Limited conversion**
  - Provides conversion to a limited set of wavelengths
  - Drivers: cost and technology
    - Limited range conversion
- **Full conversion**
  - Maximum flexibility
  - Costly
  - Optical to electronic to optical is probably the most practical implementation

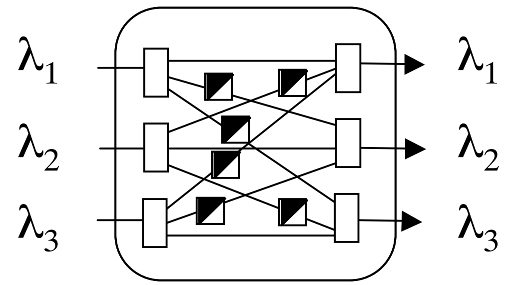
Fixed Wavelength conversion



Limited Wavelength conversion



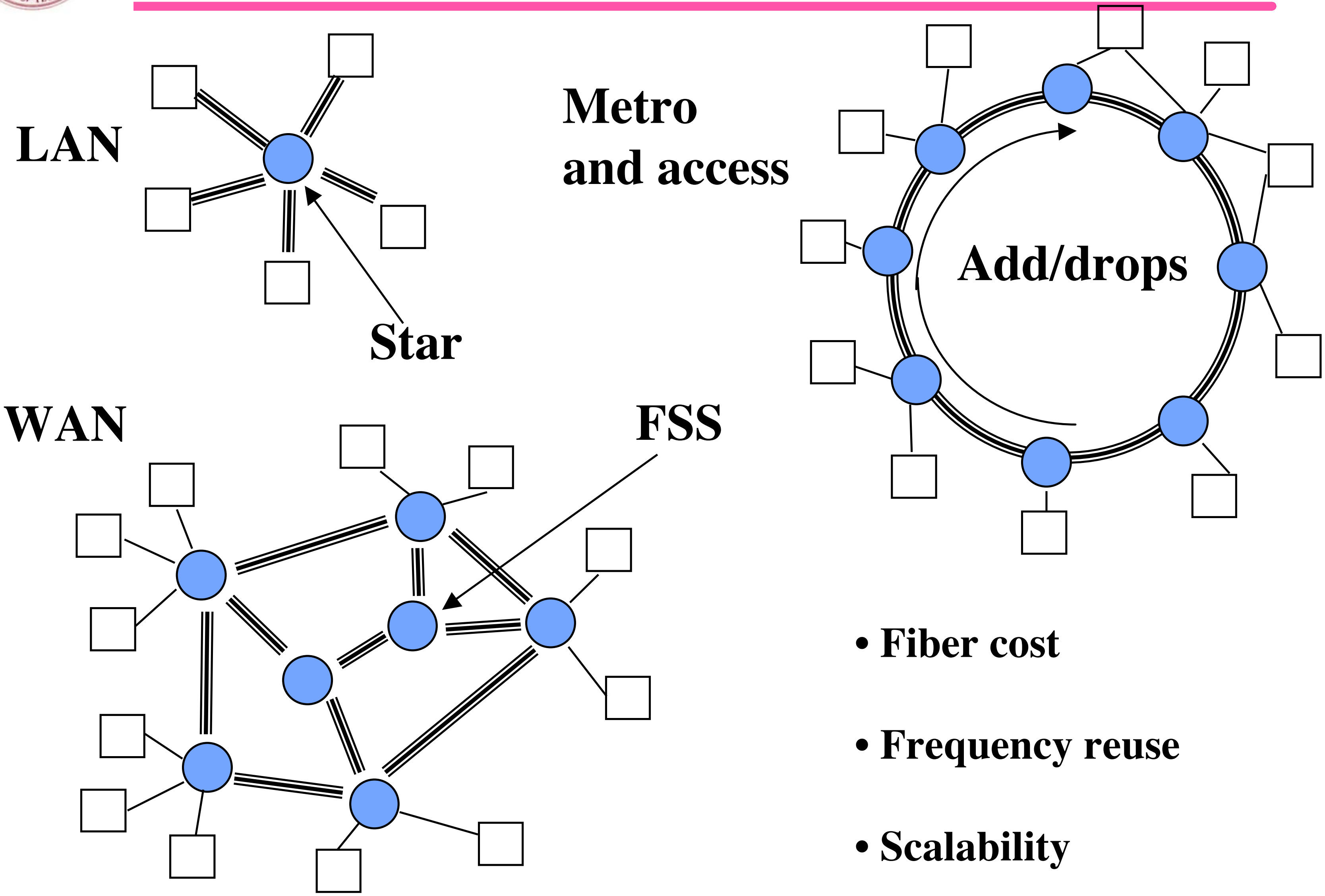
Full Wavelength conversion



WDM ALL-OPTICAL NETWORKS

- Low Loss / Huge Bandwidth
- Transparency (rate, modulation, protocol)
- Future Proofing
- Multiple Protocols
- Electronic Bottleneck
- All-Optical nodes potentially cheaper than high capacity electronic nodes

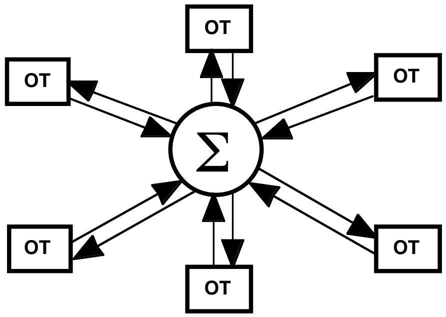
Possible all-optical topologies

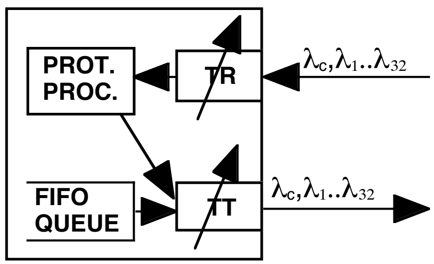


- Fiber cost
- Frequency reuse
- Scalability

WDM LAN

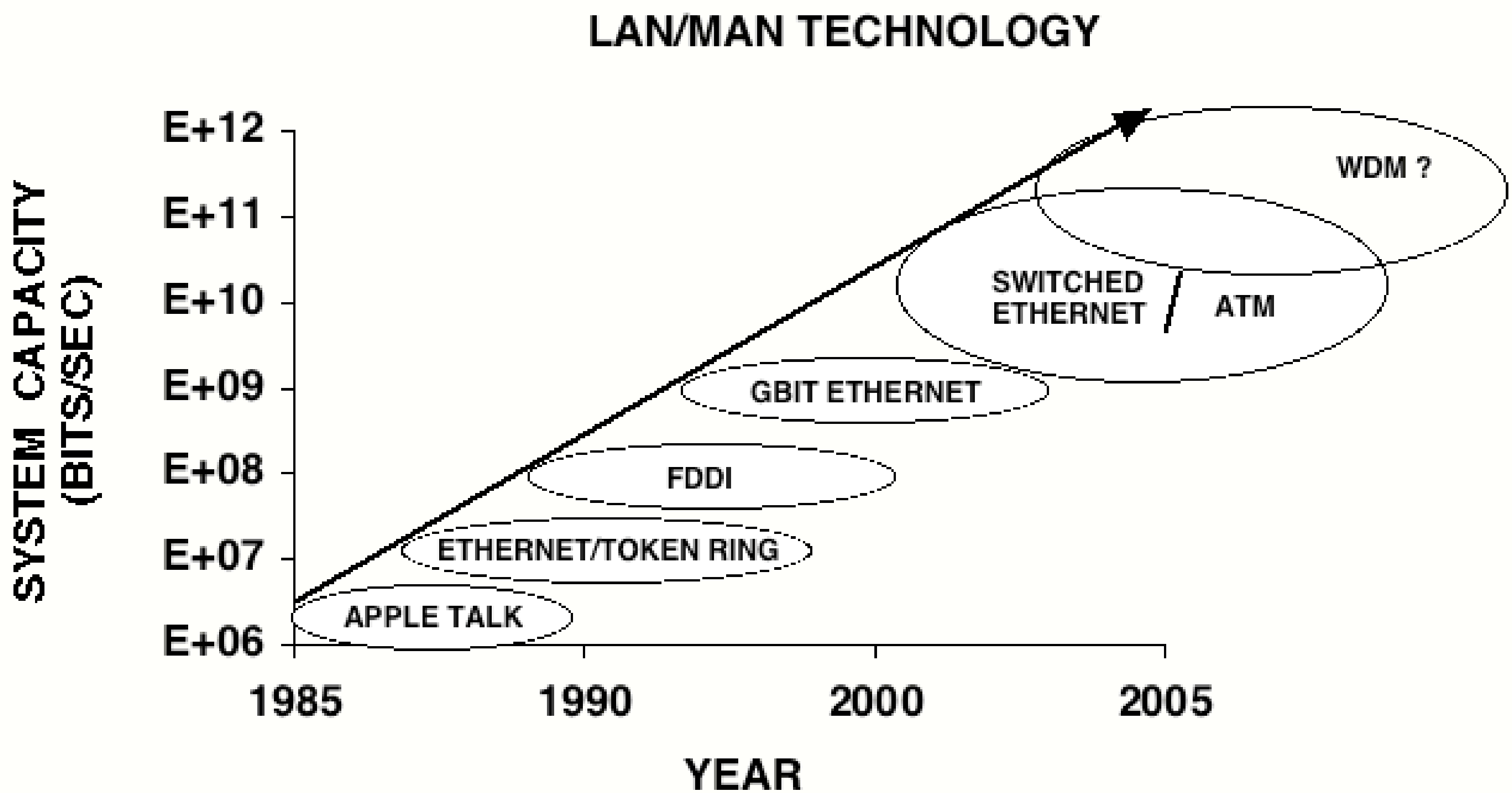
- **Passive star topology**
  - Low cost
  - Broadcast medium
- **Scalability issues**
  - With broadcast star if two users transmit on the same wavelength their transmissions interfere (collisions)
  - A circuit switched network limits the number of connections to the number of wavelengths
  - A packet switched system can support virtually an unlimited number of connections (MAC)
  - Need MAC protocol to coordinate transmissions across wavelengths



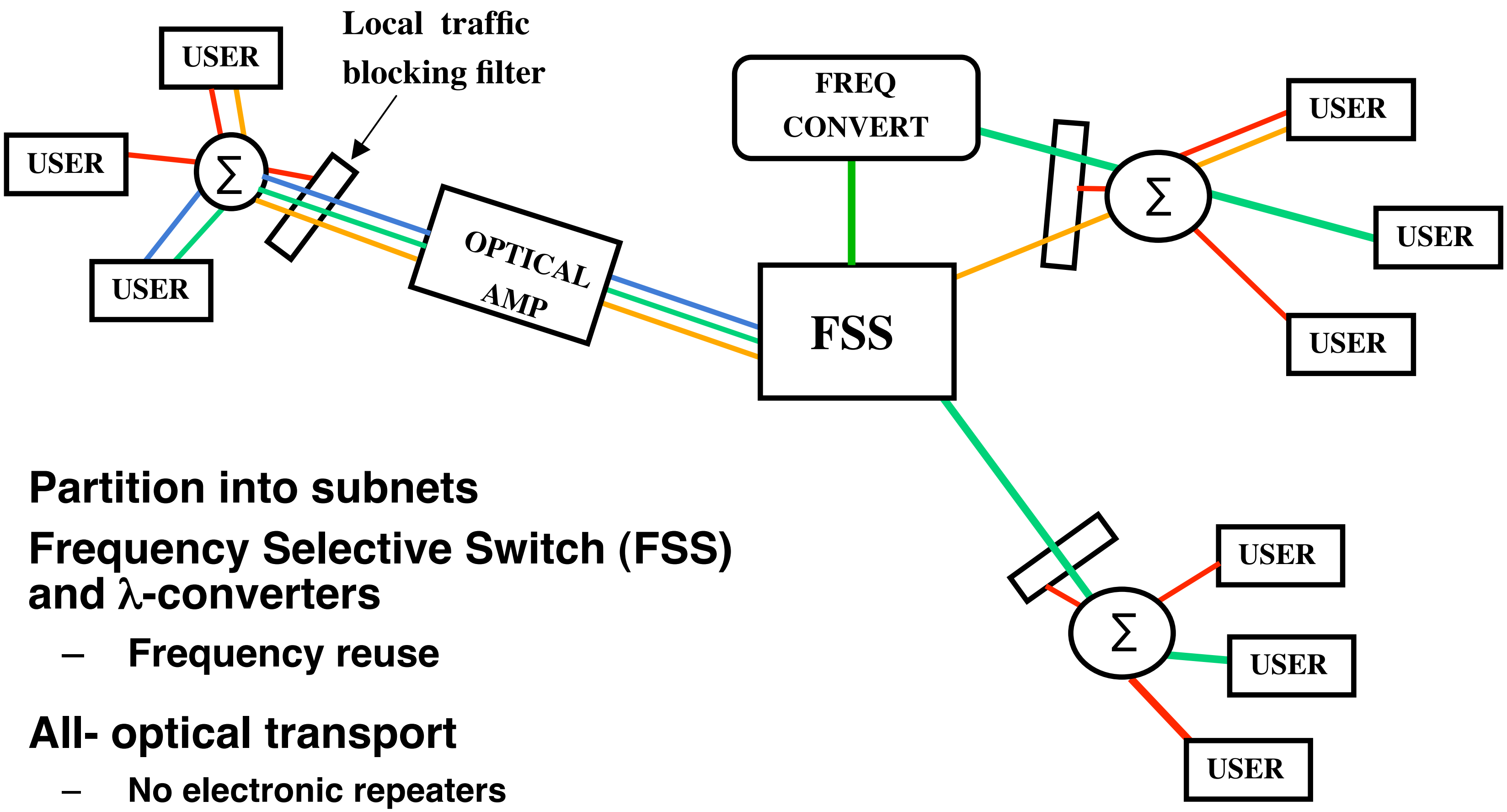


THE EVOLUTION OF LAN/MAN TECHNOLOGY

LIDS

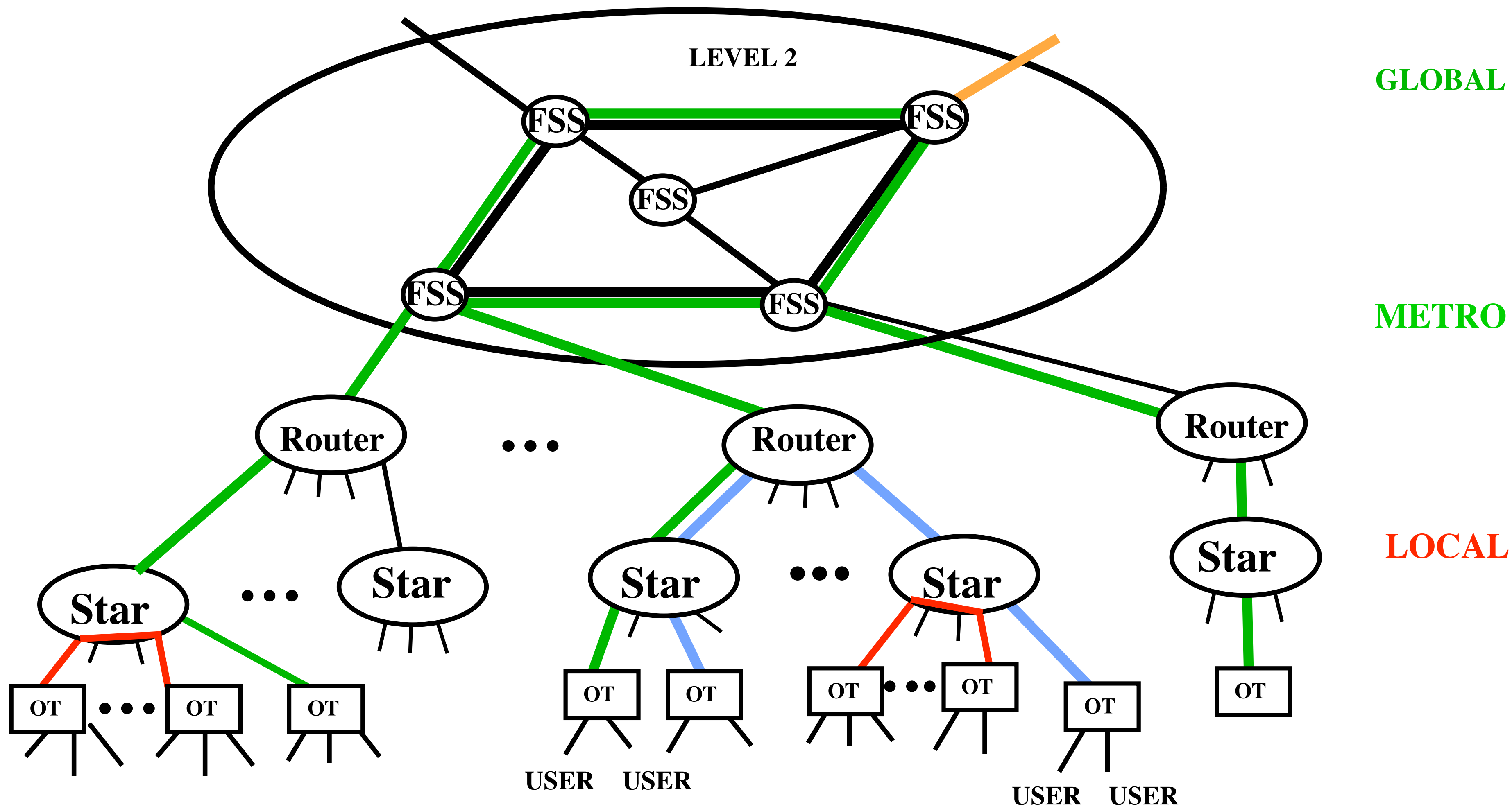


Partitioned WDM network

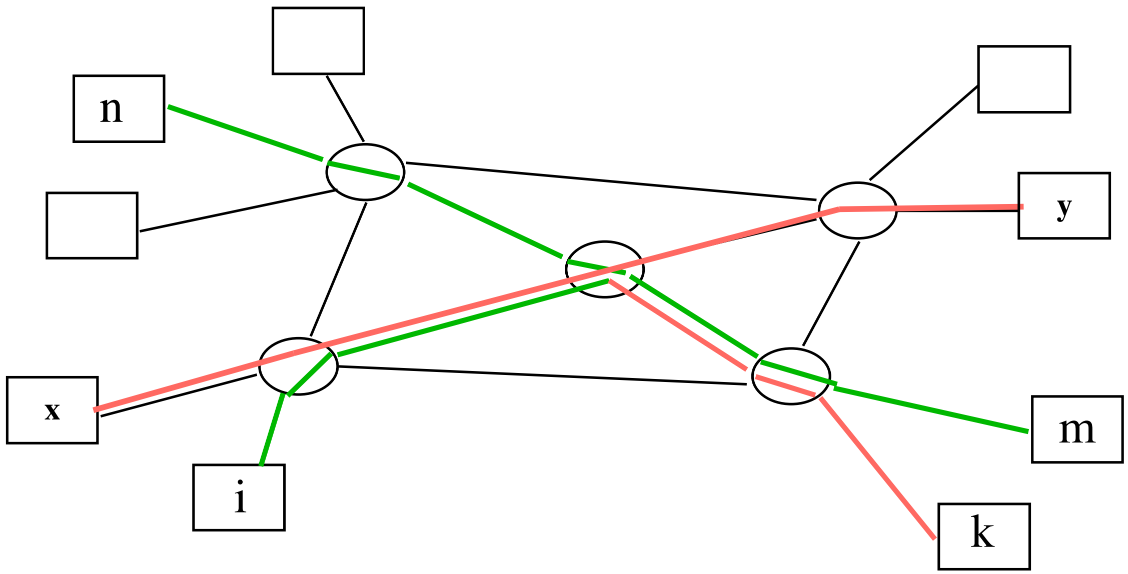


- Partition into subnets
- Frequency Selective Switch (FSS) and λ-converters
  - Frequency reuse
- All- optical transport
  - No electronic repeaters
  - Optical amplifiers

Hierarchical All-optical Network (AON)



Resolving Wavelength Conflicts



- **Approaches**
  - **Use wavelength converters**
    - **Everywhere or at select nodes**
  - **Wavelength assignment algorithm**
    - **Cleverly assign wavelengths to reduce conflicts**

Wavelength Changing Gain

- $$\text{Gain} = \frac{\text{Offered load (with } \lambda\text{–changers)}}{\text{Offered load (without } \lambda\text{–changers)}}$$

  For same blocking probability $p_b = 0, 10^{-6}..10^{-3}$

- Important factors

  – H = Path length in hops

    Large *H* increases need for wavelength changers

  – L = Interference length (average length of an interfering call)

    Large *L* reduces benefit of wavelength changers

  – d = number of fibers per link

    Large d reduces benefit of wavelength changers

Simple Analysis (Independence Approximation)

- Assume each wavelength is used on a link with probability p
  - Independent from link to link and wavelength to wavelength
  - approximation
- Consider a call of length H

- Without wavelength changers,
  - Pb = Pr(every wavelength is used on some link)

    $= [1 - P(\text{wavelength is not used on any link})]^W$

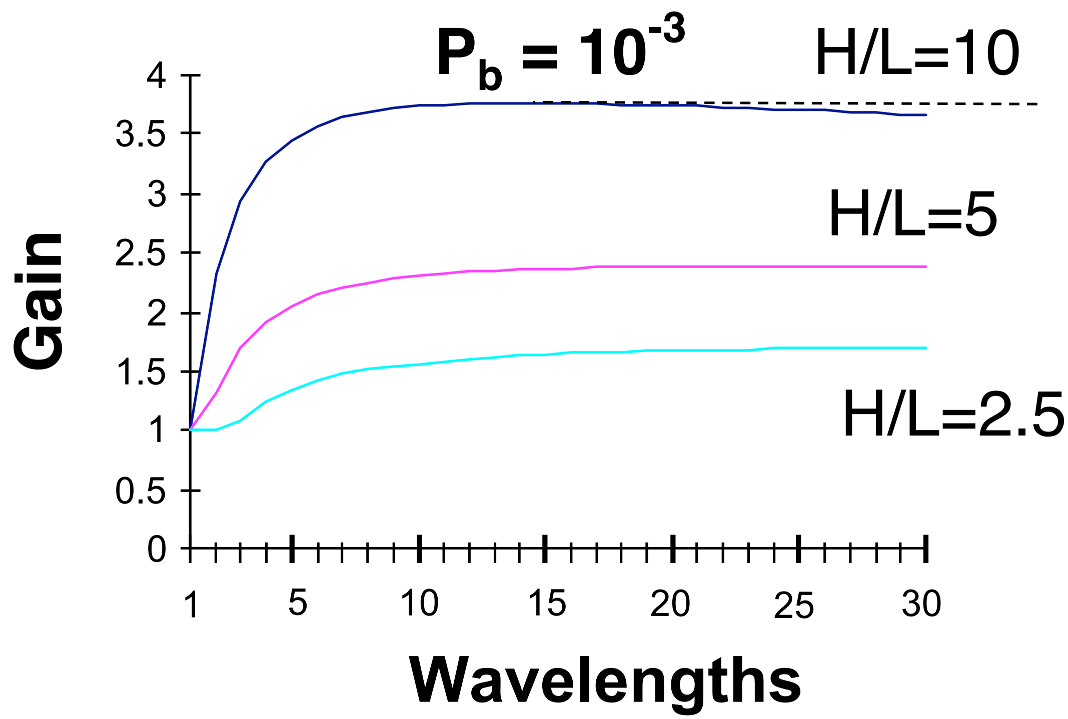
    $= [1-(1-p)^H]^W$

- With wavelength changers,
  - Pb = 1 - Pr(every link has at least one unused wavelength)

    $= 1 - (1-p^W)^H$

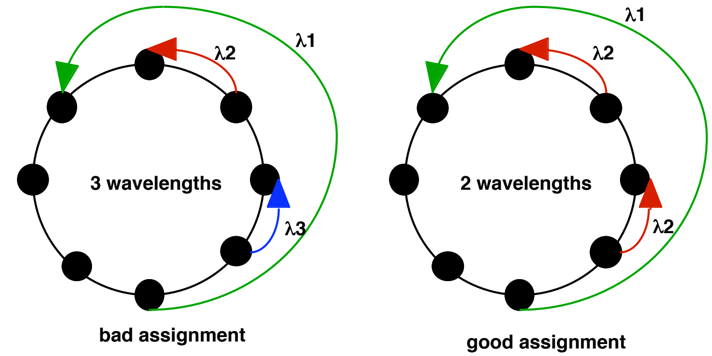
- Analysis can be extended to include multiple fibers and account for interference length

Wavelength Changing Gain



- **Comparison to Random Wavelength Assignment**
- **d = 1 fiber per link, Poisson traffic**

Wavelength Assignment Algorithms

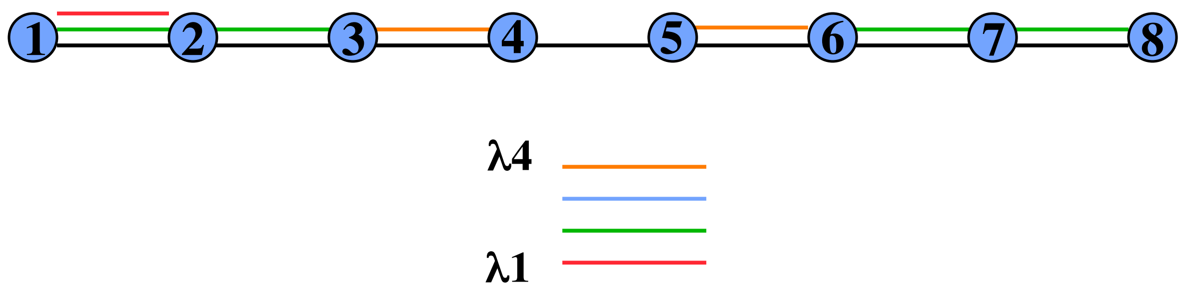


Let Ω = candidate wavelengths

RANDOM: **pick $f \,\varepsilon\, \Omega$ uniformly randomly**

- FIRST FIT: **pick lowest number $f \,\varepsilon\, \Omega$**
- MOST USED: **pick $f \,\varepsilon\, \Omega$ used on the most links**
- LEAST LOADED ROUTING: **pick $f \,\varepsilon\, \Omega$ with least congested link along call path**
- MAX_SUM (MΣ): **pick $f \,\varepsilon\, \Omega$ which maximizes remaining excess capacity**

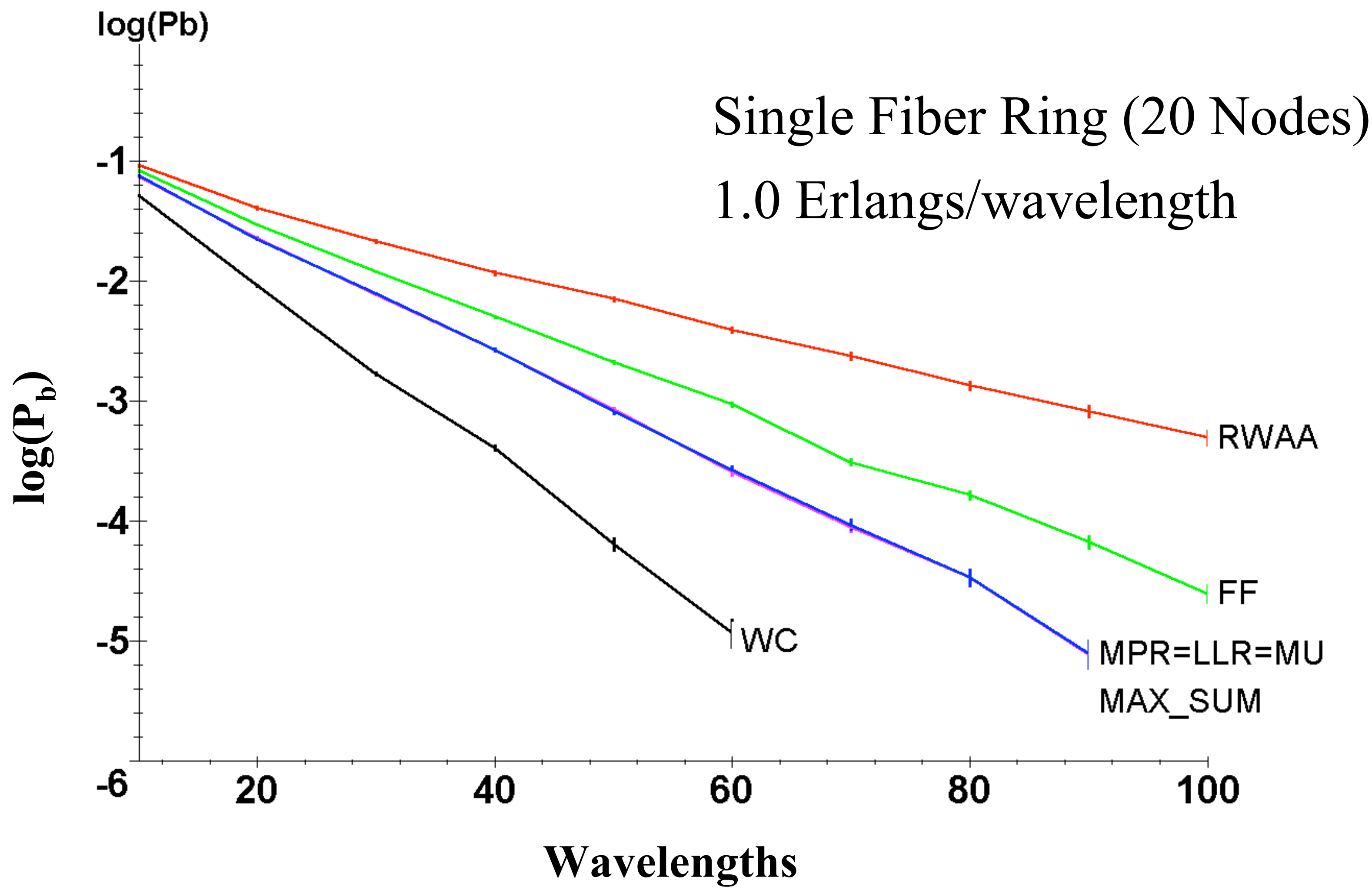
Example



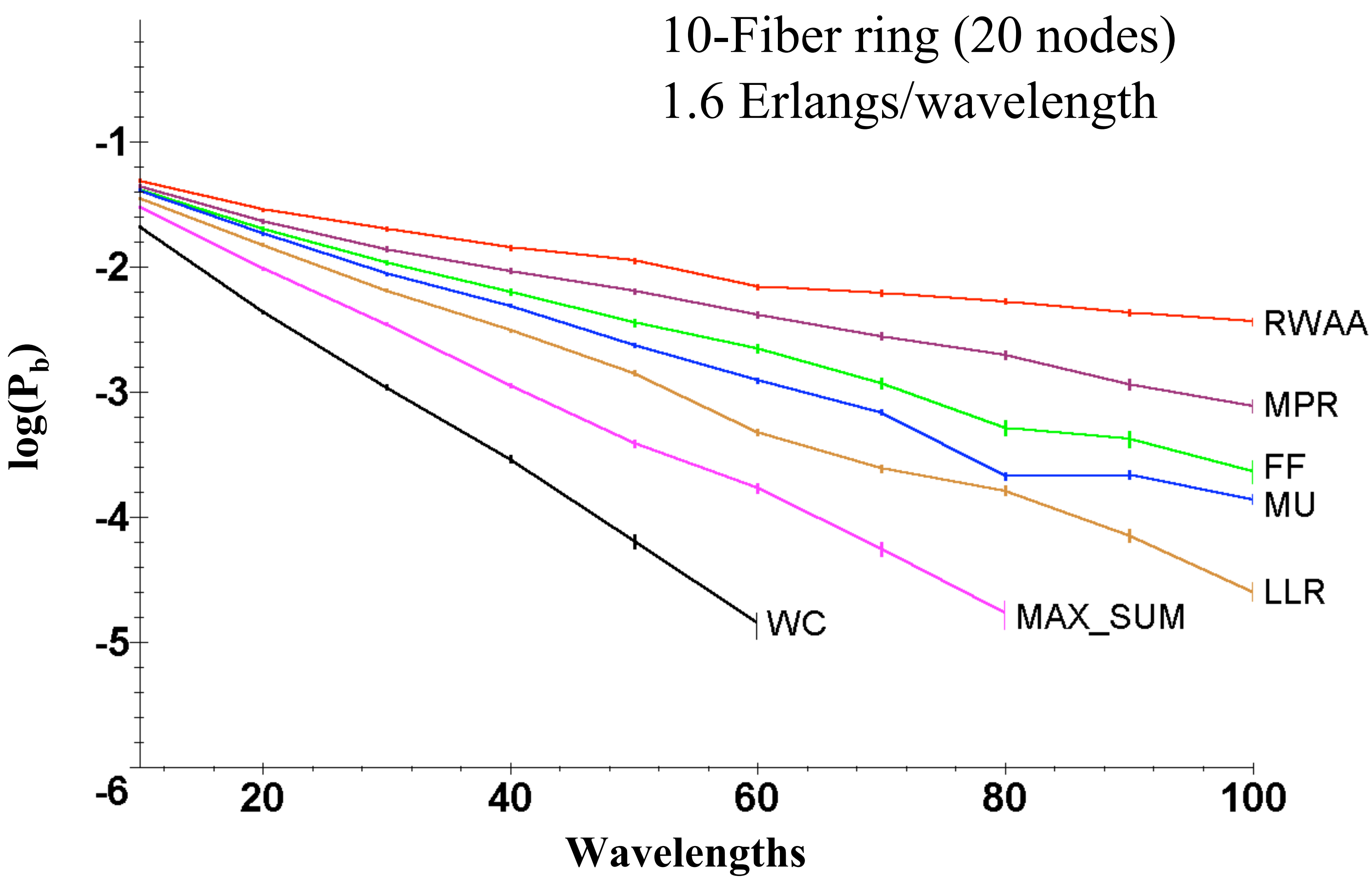
- New call between 4 and 5
  - All wavelengths are available
  - First Fit (FF) would select λ1 (red)
  - Most used would select λ2 (green)
  - Max sum would select λ4 (orange)
    - Disrupt the smallest number of potential future calls
  - Random may choose say blue…

Wavelength assignment performance

LIDS



Wavelength assignment performance

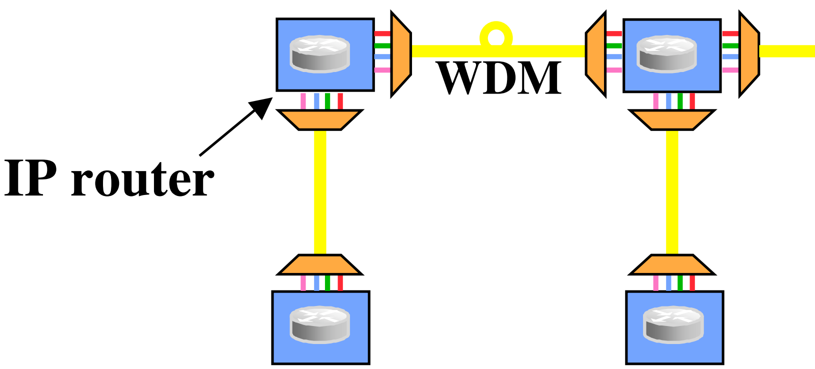


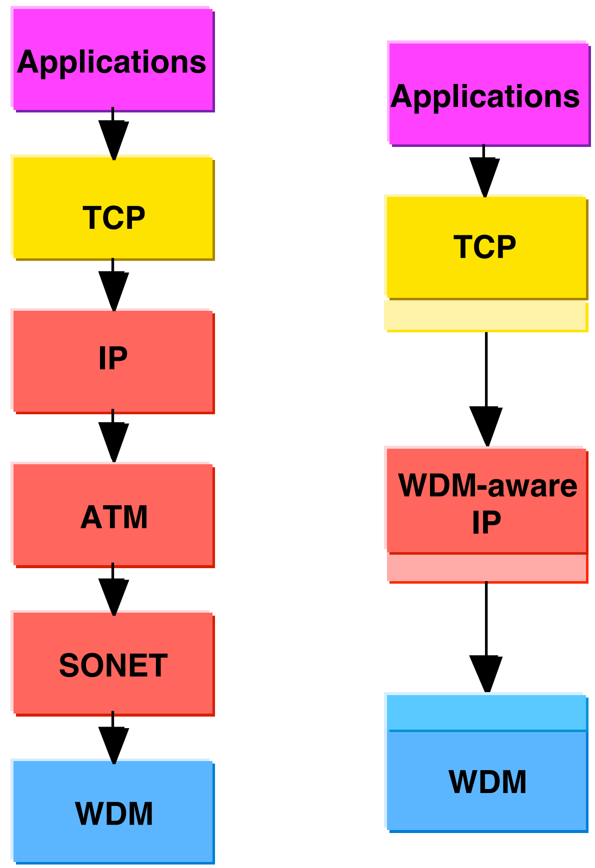
Status of Optical Networks

- All-optical networks are primarily in experimental test-beds
- WDM commercial marketplace is very active
  - Point to point WDM systems for backbone networks
    - Systems with up-to 80 wavelengths
  - WDM rings for access networks
  - WDM being used as a "physical" layer only
    - Network layer functions are done in electronic domain
    - E.g., IP/SONET/WDM
- Hybrid electronic/optical networks appear to be the way to go
  - IP over WDM

IP-over-WDM

- Networks use many layers
  - Inefficient, expensive
- Goal: reduced protocol stack
  - Eliminate electronic layers
  - Preserve functionality
- Joint design of electronic and optical layers
  - Virtual topology design
  - Traffic grooming
  - Optical layer protection





Optical layer protection

- Protection is needed to recover from fiber cuts, equipment failures, etc.
- Some protection is usually provided at higher layers
  - E.g., SONET loop-back
- So, why provide optical layer protection?
  - Sometimes higher layer protection is limited (e.g., IP)
  - Optical protection can be much faster
  - Optical layer protection can be more efficient
    - Restoring a single fiber cut is easier than 40 SONET rings
    - Once restored optically, SONET can protect from more failures
  - Also, SONET is mainly used for its protection capability so if we can provide protection at the optical layer we can eliminate SONET equipment

Optical protection mechanisms

- **Path protection**
  - Restore a lightpath using an alternative route from the source to the destination
    - Wavelength by wavelength
- **Line protection**
  - Restore all lightpaths on a failed link simultaneously by finding a bypass for that link (loop-back)

- **In rings techniques such as 1+1,1:1,1:n still apply**

- **In a mesh protection is more complicated**
  - Path protection requires finding diverse routes
  - Line protection requires finding ring covers
  - Sharing protection resources
    - Establish backup paths in such a way that minimizes network resources
    - If two lightpaths share a common fiber they cannot share protection capacity

Limitations of optical layer protection

LIDS

- Cannot recover from electronic failures (e.g., line card)
- Added overhead
  - As much as 50% for 1:1 schemes
  - This overhead is on top of whatever overhead is used by the higher layer

    For example, SONET uses an additional 50%

- Compatibility with higher layer protection mechanism
  - SONET must recover from a fault in 60 ms
  - SONET starts to responds after 2.5 ms of disconnect

    Can the optical layer recover before SONET detects a failure?

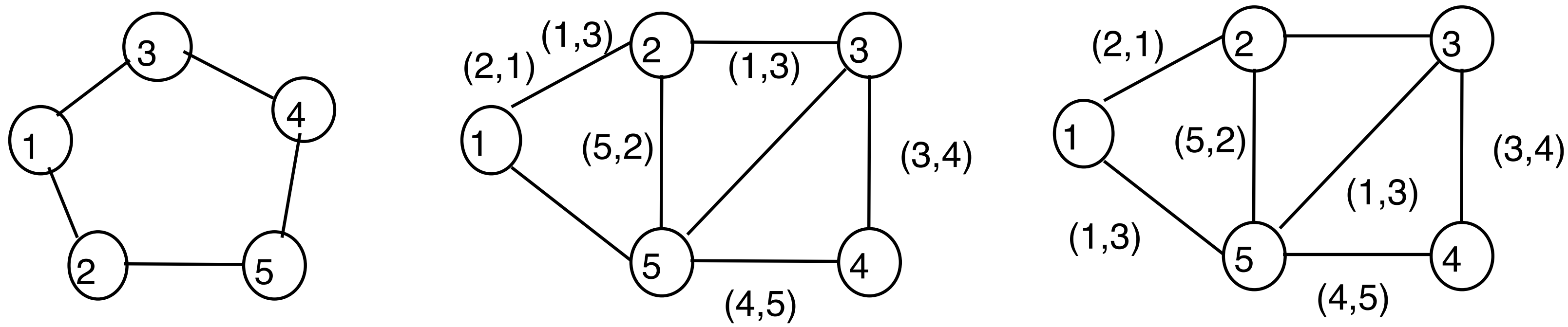
- Joint design of optical and electronic protection mechanisms

Joint design of electronic and optical protection (example)

LIDS

Logical topology

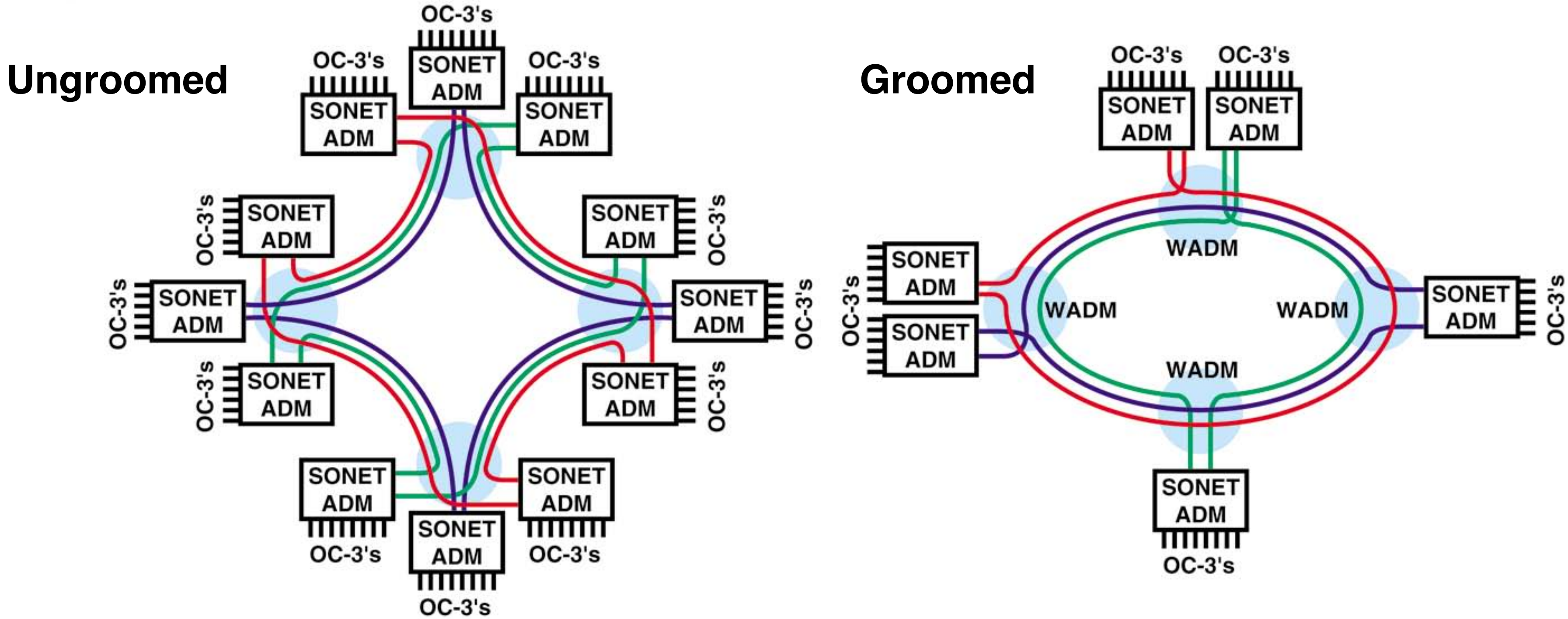
Physical topology



Bad **Good**

- **How do we route the logical topology on the physical topology so that we can keep the logical topology protected ?**
  - **Logical connections are lightpaths that can be routed in many ways on the physical topology**
  - **Some lightpaths may share a physical link in which case the failure of that physical link would cause the failure of multiple logical links**
    - **For rings (e.g., SONET) this would leave the network disconnected**
  - **Need to embed the logical topology onto the physical topology to maintain the protection capability of the logical topology**

SONET/WDM network design



- **Groom traffic onto wavelengths in order to minimize amount of electronic equipment**
  - "Drop" only those wavelengths that have traffic for that node
  - Assigns traffic to wavelengths to minimize the number of wavelengths that must be dropped at each node
    - E.g., minimize number of SONET ADMs
  - Similar problem in the design of an IP/WDM network (minimize ports)

SONET Example

- **Traffic grooming in a SONET ring network**
  - Each wavelength can be used to support an OC-48 SONET ring
  - 16 OC-3 circuits on each OC-48 circuit
  - Each time a wavelength is dropped at a node a SONET ADM is needed
  - Assign OC-3 circuits onto OC-48 rings using the minimum number of ADMs

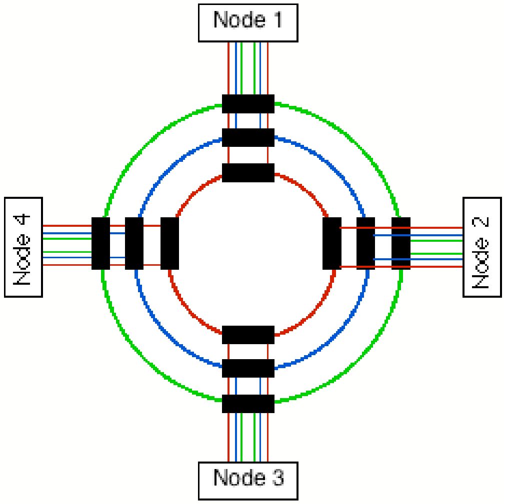
- **Simple example:**
  - Unidirectional ring with 4 nodes
  - 8 OC-3's between each pair of nodes
  - traffic load:

    6 node pairs
    8 OC-3's between each pair
    Total load = 48 OC-3's
    ➔ 3 full OC-48 rings

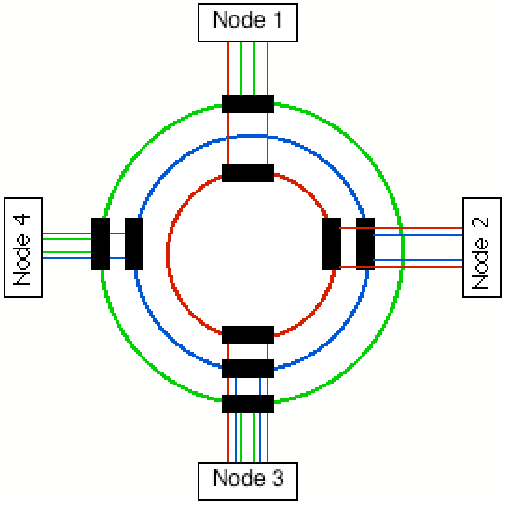
  - Each ring can support traffic between two node pairs

Example, continued

- **Assignment #1**
  - λ1: 1-2, 3-4
  - λ2: 1-3, 2-4
  - λ3: 1-4, 2-3
  - 12 ADMs needed
    (n1 = n2 = n3 = n4 = 3)



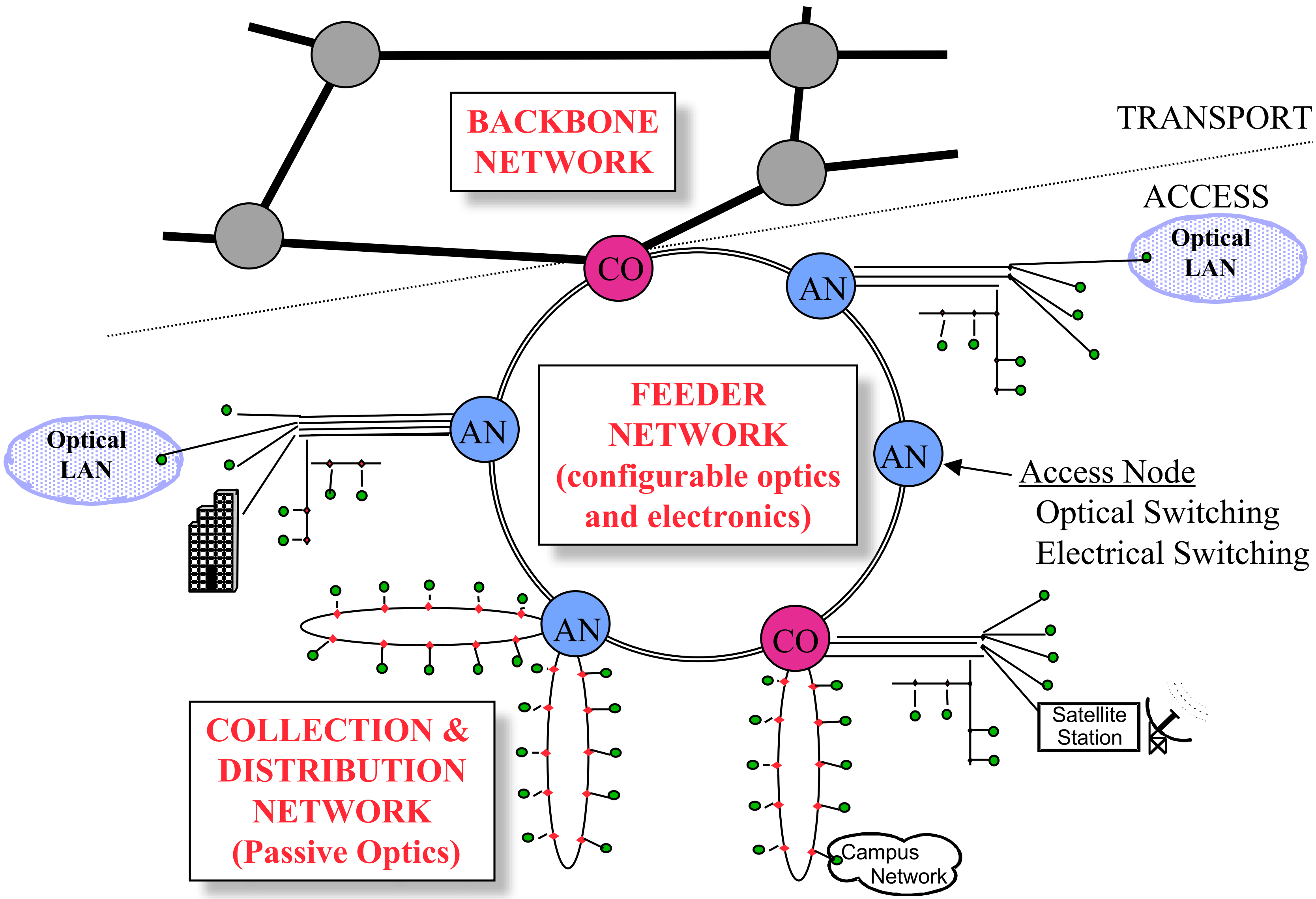
- **Assignment #2**
  - λ1: 1-2, 1-3
  - λ2: 2-3, 2-4
  - λ3: 1-4, 3-4
  - 9 ADMs needed
    (n1 = n2 = n4 = 2, n3=3)



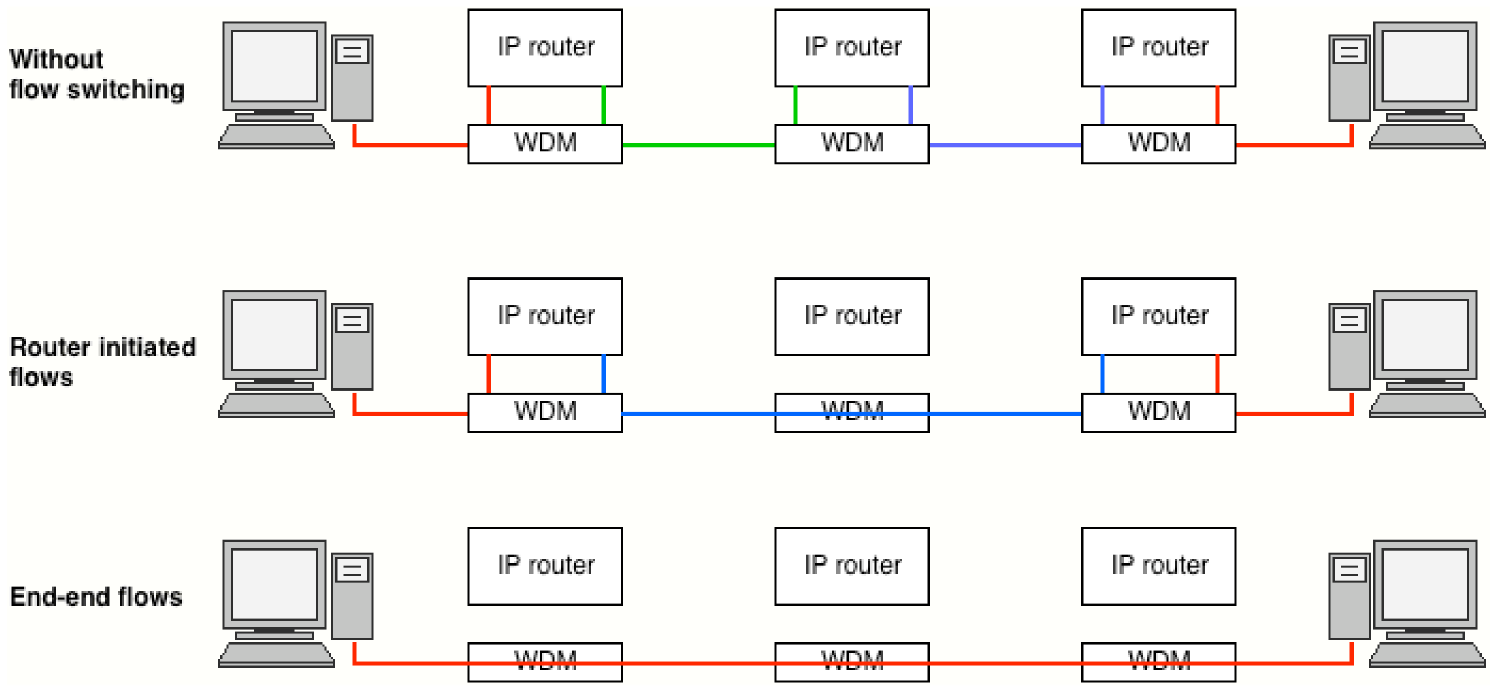
Future Trends

- Optical access
- Optical flow switching
- Logical topology (IP) reconfiguration
- All-optical packet switching

Access Network Architecture

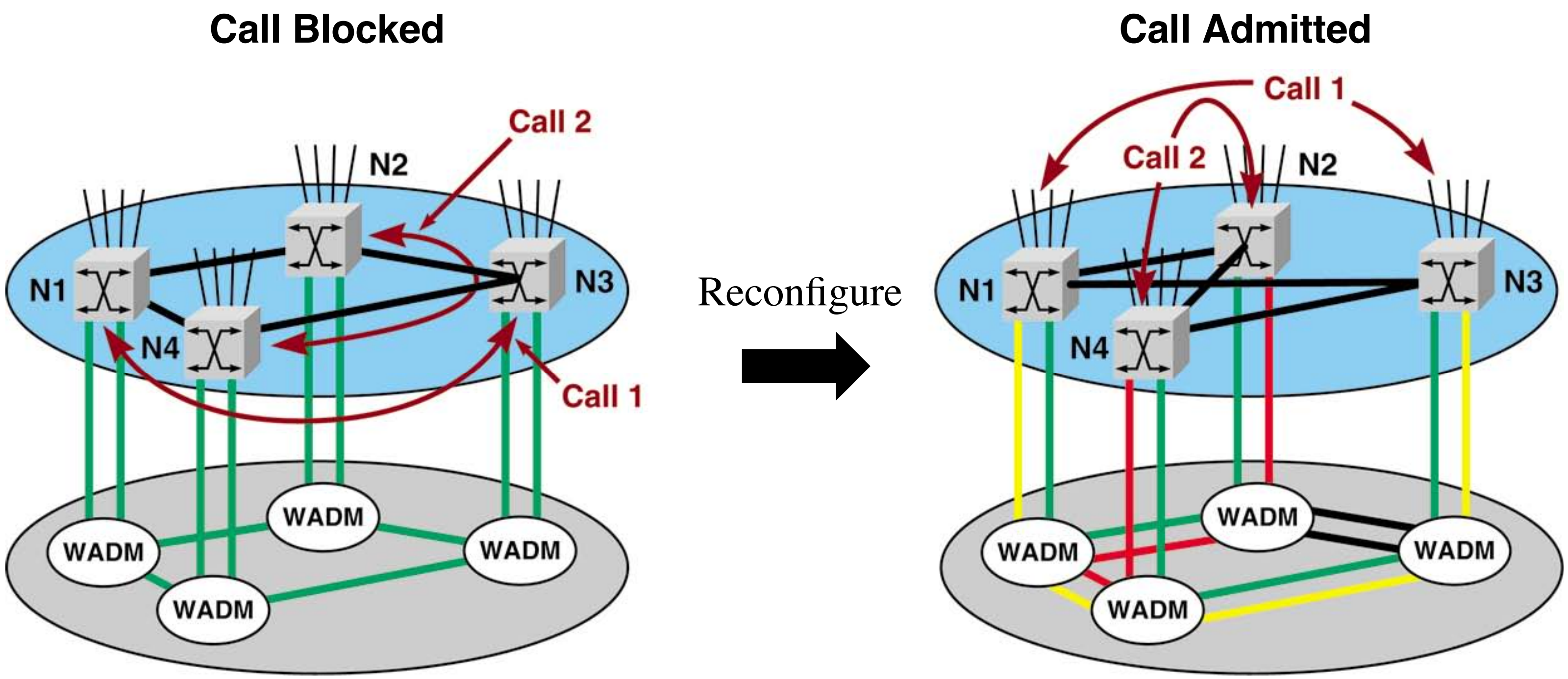


Optical flow switching



- **Optical flow switching reduces the amount of electronic processing by switching long sessions at the WDM layer**
  - **Lower costs, reduced delays, increased switch capacity**
  - **Today: IP over ATM (e.g., IP switching, tag switching, MPLS)**
    - **dynamically set-up new ATM VC's to switch a long IP session**
    - **Future: IP directly over WDM**
    - **dynamically configure new lightpaths to optically switch a long session**

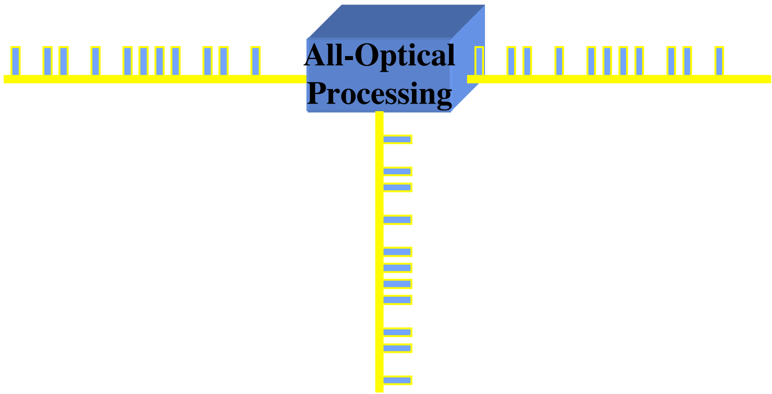
Topology Reconfiguration



- Reconfigure the electronic topology in response to changes in traffic conditions
  - Electronic switches are connected using lightpaths
  - Lightpaths can be dynamically rearranged using WADMs

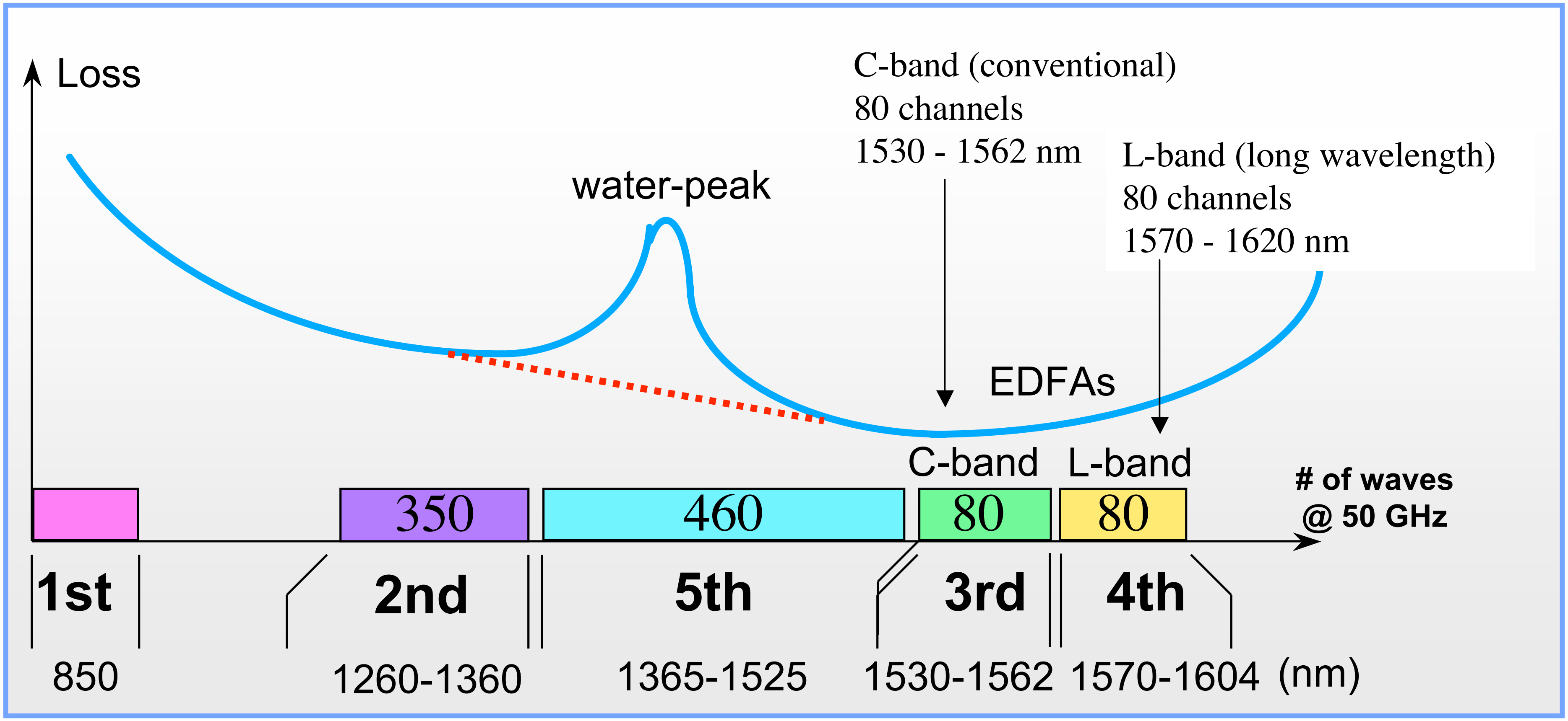
Optical packet switched networks

- Wide area WDM networks are circuit (wavelength) switched
  - Limits scalability
- Packet switching is needed for scalable optical networks
- In the LAN we saw that packet switching can be accomplished using a MAC protocol
  - Requires fast tunable transceivers
  - This approach does not easily scale to wide areas
    - High latency
    - Broadcast
- Optical packet switching is needed for all-optical WANs
  - Header processing
  - Packet routing
  - Optical buffers



- Do we really need all optical??

Opening Up New Wavelength Bands



WDM Network Evolution

Early-Mid '90s		Late '90s - Early '00s		Early '00s
LINEAR	→	RINGS	→	MESHES

Early '90s — 400 GHz ←→

Mid '90s — 200 GHz ←→

Late '90s — 100 GHz ←→

Late '90s — 50 GHz ←→

Late '90s — Fixed add/drops ←→

Early '00s — Configurable add/drops ←→

Early '00s — Configurable switches ←→

Wavelength changers

Select References

- R. Ramaswami and K. N. Sivarajan, Optical Networks, Morgan Kaufmann, 1998
- B. Mukherjee, Optical Communication Networks, McGraw-Hill, 1997
- B. Mukherjee, WDM based Local Lightwave Networks, IEEE Network, May, 1992
- E. Modiano, WDM based Packet Networks, IEEE Communications Magazine, March, 1999
- V.W.S. Chan, et. al. "Architectures and Technologies for High-Speed Optical Data Networks," IEEE Journal of Lightwave Technology, December 1998.