Internet access and backbone technology

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Key objectives

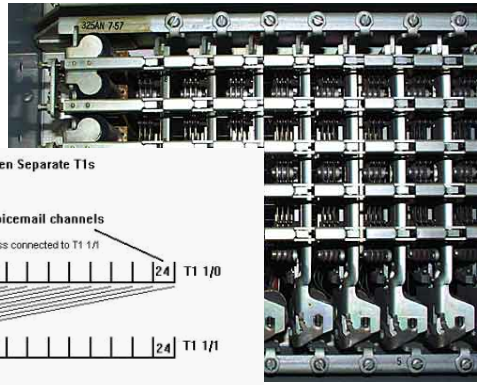
- Fundamental models for communication
- How are bits switched?
- How does a large router work internally?
- What are the limits to communication capacity?
- How do DSL and cable modems work?

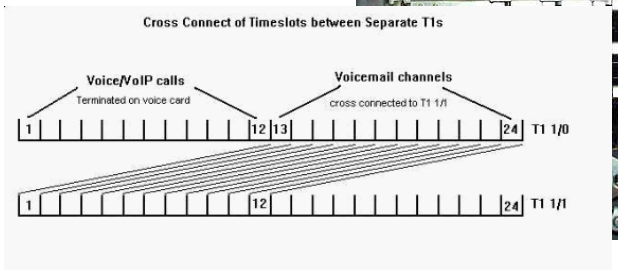
Overview

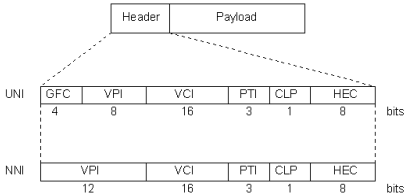
- Physical layer for CS majors
  - modulation
  - spectral efficiency
- Residential last-mile technologies
  - DSL
  - Cable (DOCSIS)
  - Residential fiber
- Backbone networks
- Wireless networks

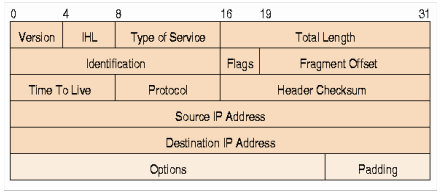
Circuits, VCs and packets

	Circuits	virtual circuits	packets
Resources	copper circuit (space) time	switching capacity (maybe)	none (except with resource reservation)
Information unit	bit, byte	cell, frame	packet
Routing	switched (e.g., timeslot 15 to timeslot 13)	VC identifier (switch-local)	IP address (network-global)
Examples	phone, ISDN, X.21	ATM, MPLS	IP, Ethernet



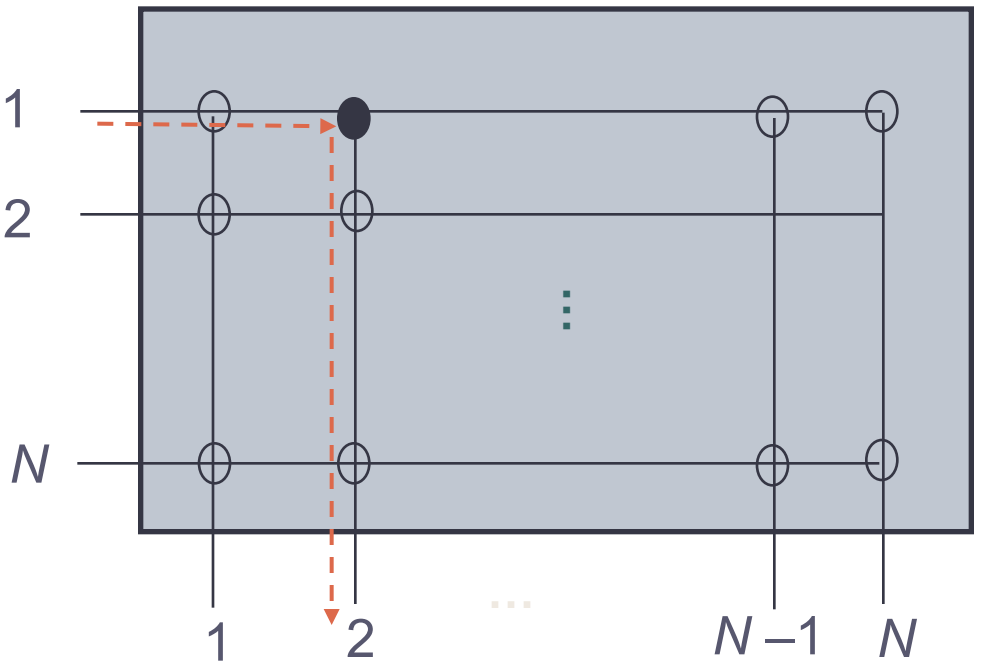






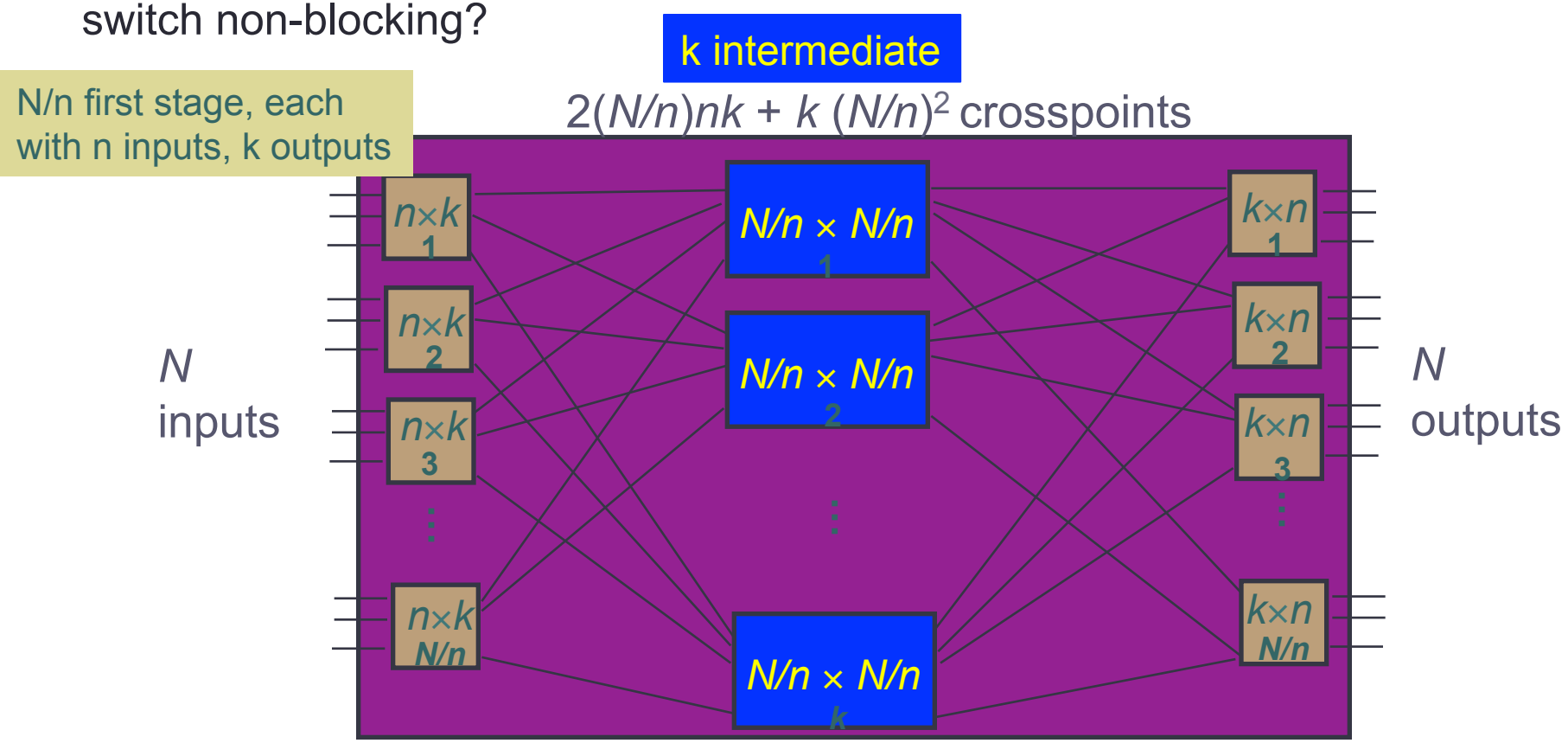
Circuit switching: crossbar space switch

- *N* x *N* array of crosspoints
- Connect an input to an output by closing a crosspoint
- Non-blocking: Any input can connect to idle output
- Complexity: N^2 crosspoints



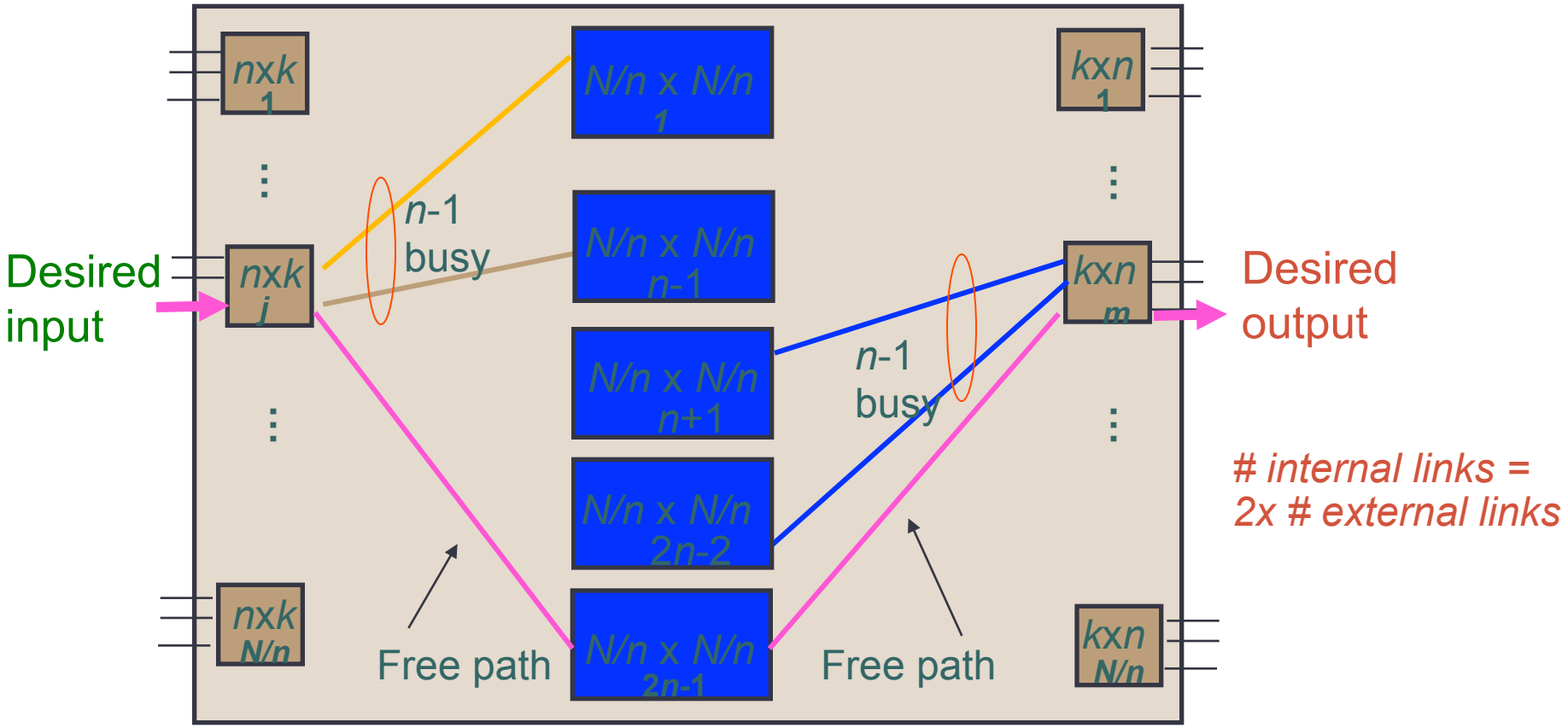
CS: multistage space switch

- Large switch built from multiple stages of small switches
- *n* inputs to a first-stage switch share *k* paths through intermediate crossbar switches
- Larger *k* (more intermediate switches) means more paths to output
- In 1950s, Clos asked, "How many intermediate switches required to make switch non-blocking?

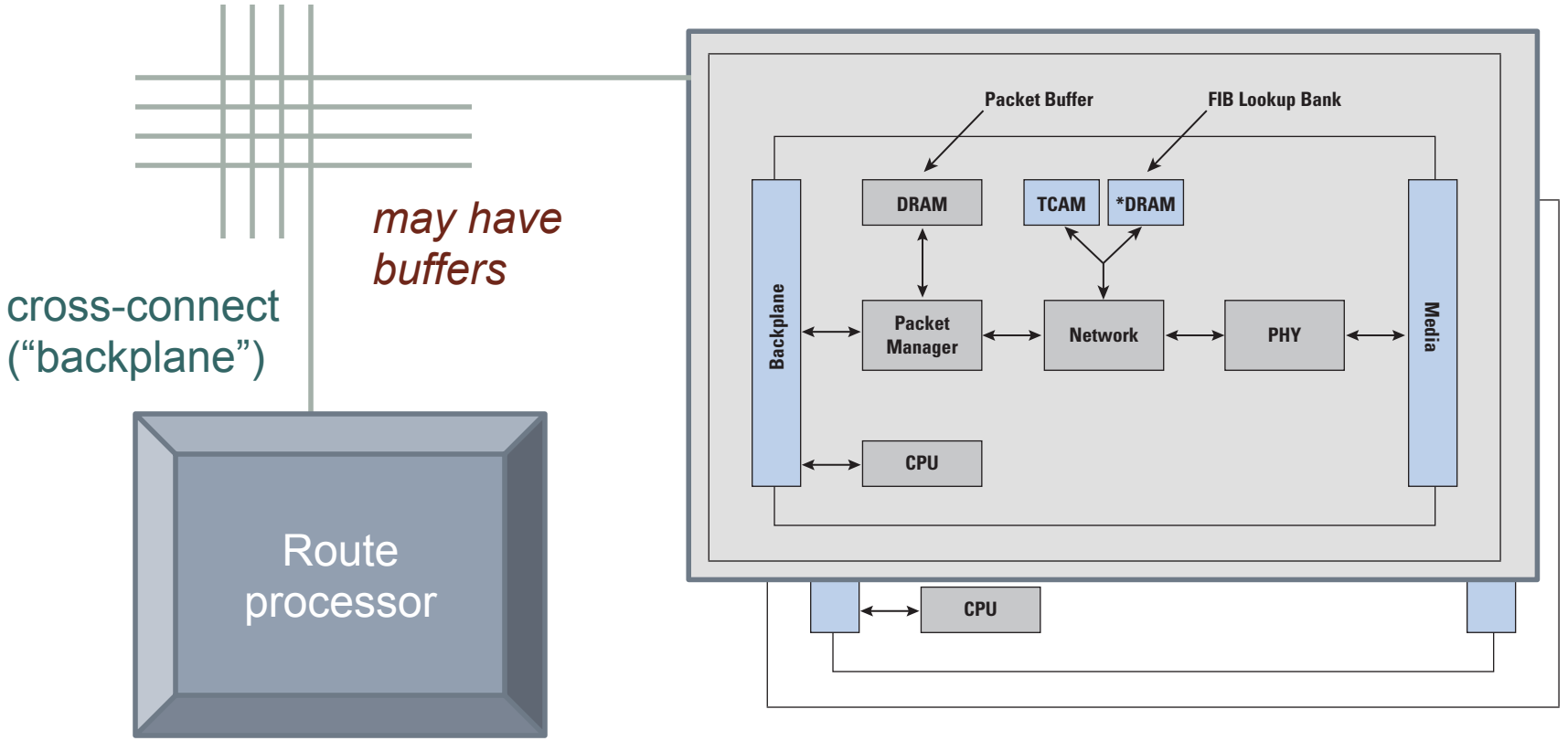


CS: Clos Non-Blocking Condition: *k=2n-1*

- Request connection from last input to input switch j to last output in output switch m
- Worst Case: All other inputs have seized top *n-1* middle switches AND all other outputs have seized next n-1 middle switches
- If ***k=2n-1***, there is another path left to connect desired input to desired output



Backbone router



TCAM = ternary content addressable memory

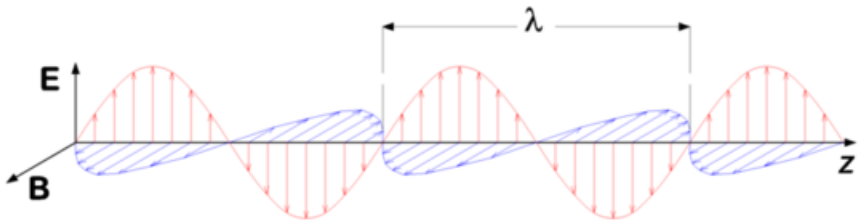
Example: Cisco CRS-1

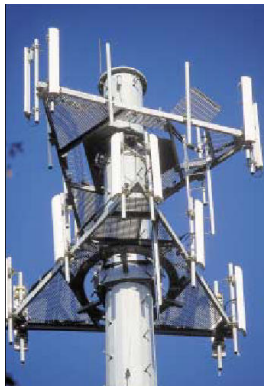
Physical media: capacity

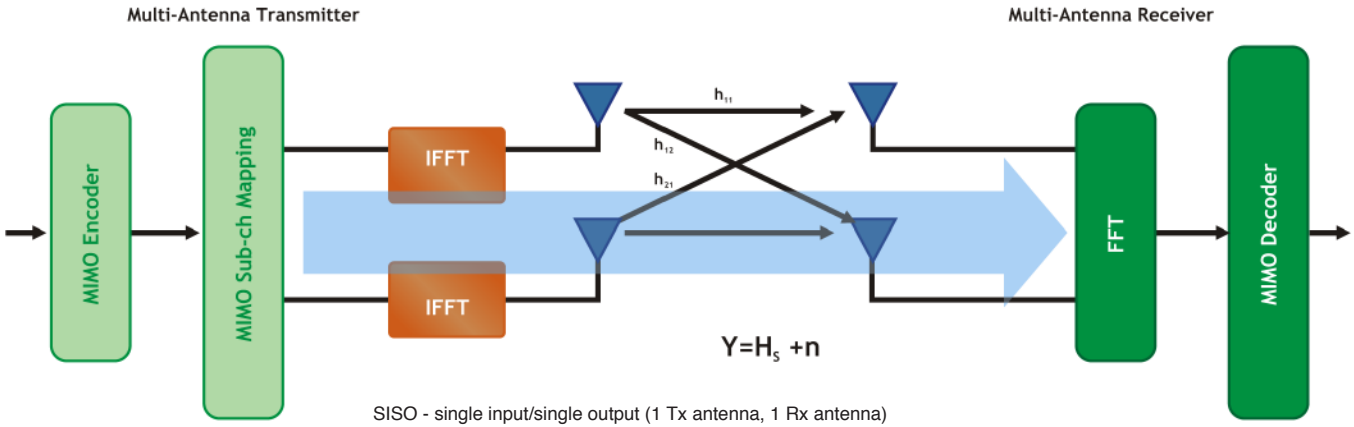
- Capacity has theoretical limit
  - Shannon's Law: capacity limit given by
  - C = *B* $\log_2$ (1 + S/N) with spectral bandwidth *B*
  - E.g., phone has *B* = 3000 Hz, S/N = 35 dB, *C* = 34.8 kb/s
  - dB = $10 \log_{10} S/N$
  - E.g., 25 dB = $10^{2.5} = 316$
- Speed has physical limits: *c* in free space, 0.66 *c* in fiber

Bypassing Shannon

- Multiple channels
  - polarization
- Spatial re-use
  - directional antennas (120^{o} “sectors”)
  - smaller cell sizes
    - macro, micro, femto, … cells





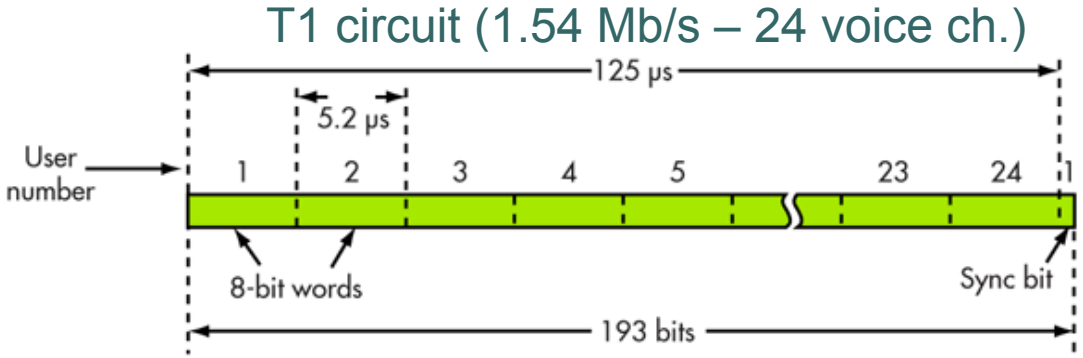


SISO - single input/single output (1 Tx antenna, 1 Rx antenna)
SIMO - single input/multiple output (1 Tx antenna, multiple Rx antenna)
MISO - multiple input, single output (multiple Tx antenna, 1 Rx antenna)
MIMO - multiple input/multiple output (multiple TX antenna, multiple Rx antenna)

Figure 4 MIMO

Multiplexing

- Time
  - TDxxx
  - typically, “time slots”
- Frequency
  - one signal → one frequency
  - multiple frequencies → OFDM
    - e.g., DSL, LTE, 802.11a/n, …
- Phase (time-shift)



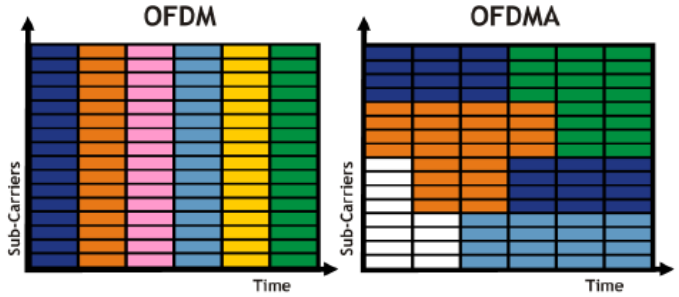
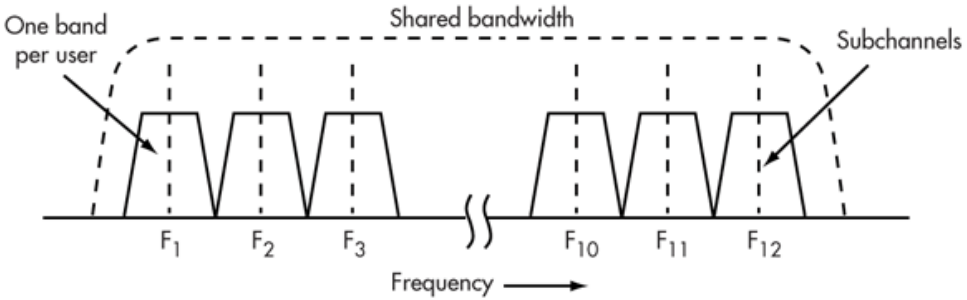


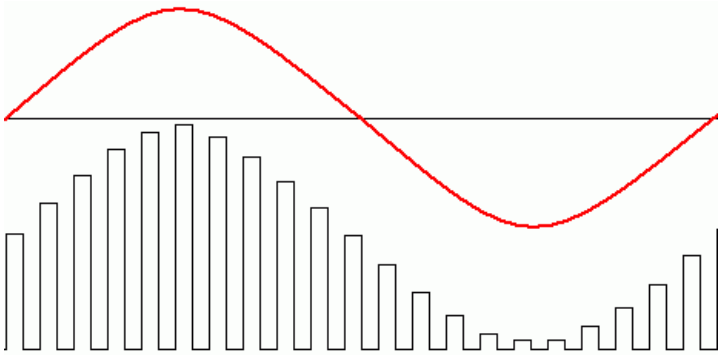
Figure 2 OFDM vs. OFDMA. Each color represents a burst of user data. In a given period, OFDMA allows users to share the available bandwidth.



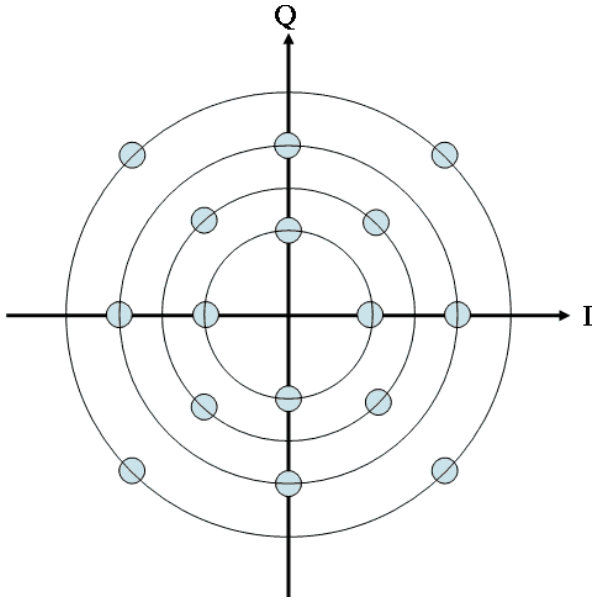
Mapping bits to symbol

symbol rate vs. bit rate

Amplitude



Phase (+ amplitude)



Spectral efficiency

Medium	Spectrum	Data rate	b/Hz
Modem (V.92)	3,100 Hz	56 kb/s	18.1
2G cellular (GSM)	0.2 MHz		0.52
LTE	20 MHz	326 Mb/s	<16.3
ADSL downlink	0.962	12 Mb/s	12.5
WiFi 802.11 a/g	20 MHz	< 54 Mb/s	< 2.7
WiFi 802.11 n	20 MHz	< 144 Mb/s	< 7.2

Broadband

- What (is Broadband Internet Access)?
  - FCC: was >200 kb/s or 4 Mb/s down & 1 Mb/s up
    - now 25 Mb/s down/3 Mb/s up
  - NTIA: >768 kb/s downstream/200 kb/s upstream
  - YouTube recommendation: >500 kb/s
  - Multimedia: >10 Mb/s downstream
    - Unicast/broadcast
- Where?
  - Rural: Low density (<100 pop/km^2)
    - Minimize fixed infrastructure cost
  - Urban: High density (>1000 pop/km^2; >10,000 in cities)
    - Maximize Mb/s/km^2

Cost for providing access