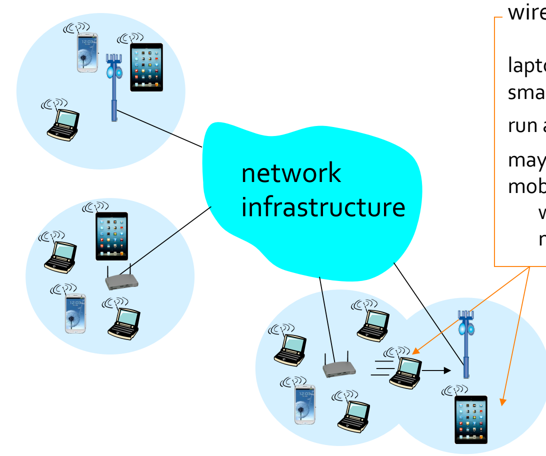
eecs489 COMPUTER NETWORKS

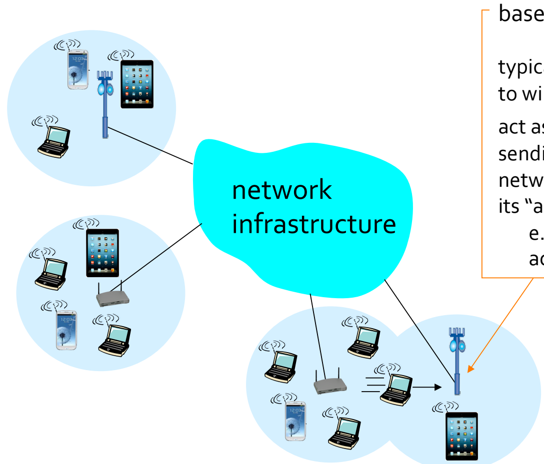
Lecture 38:
Wireless Standards, Network Architectures, and Modulation Schemes

Elements of a Wireless Network



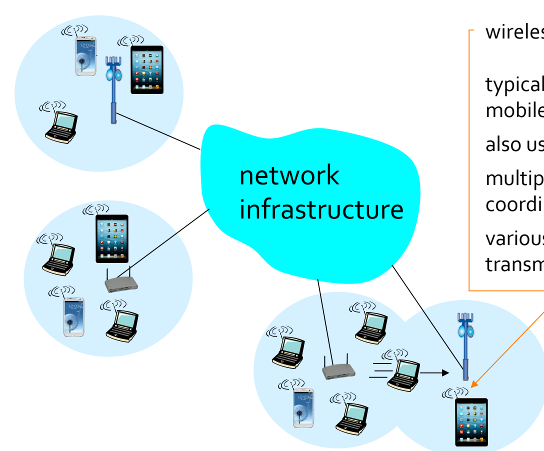
wireless hosts
- laptop, tablet, smartphone
- run applications
- may be stationary (non-mobile) or mobile
  - wireless does not always mean mobility, could be just nomadic

Elements of a Wireless Network



base station
- typically connected to wired network
- act as relay - responsible for sending packets between wired network and wireless host(s) in its "area"
  - e.g., cell towers, 802.11 access points

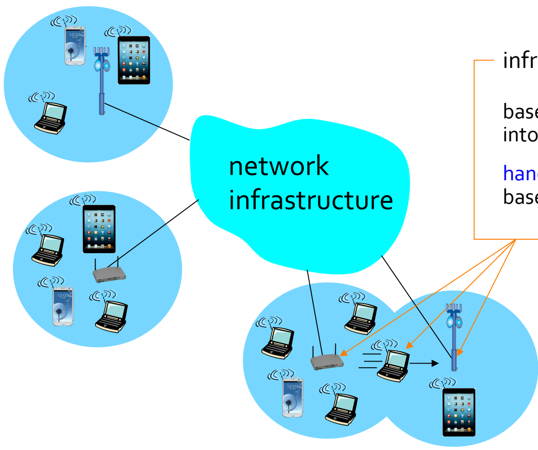
Elements of a Wireless Network



wireless link
- typically used to connect mobile(s) to base station
- also used as backbone link
- multiple access protocol coordinates link access
- various data rates, transmission distance

down- or forward-link (↓): base station to wireless host
up- or reverse-link (↑): wireless host to base station

Mode of Operation

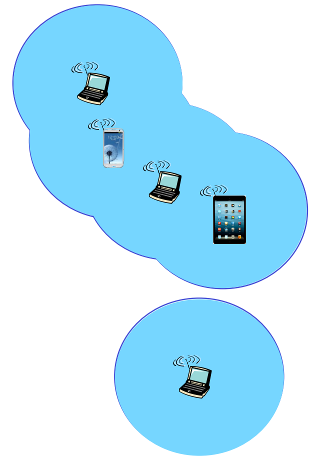


infrastructure mode

base station connects mobiles into wired network

handoff: mobile changing base station

Mode of Operation



ad hoc mode

no base stations

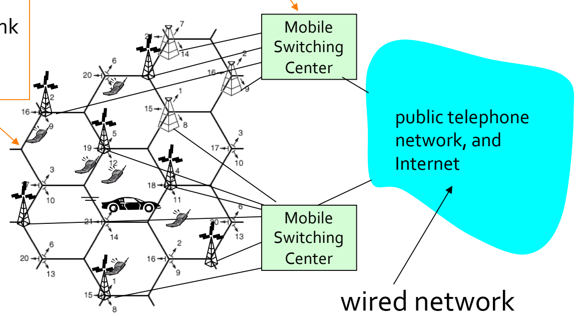
nodes can only transmit to other nodes within link coverage

nodes organize themselves into a network: route among themselves

Cellular Network Architecture

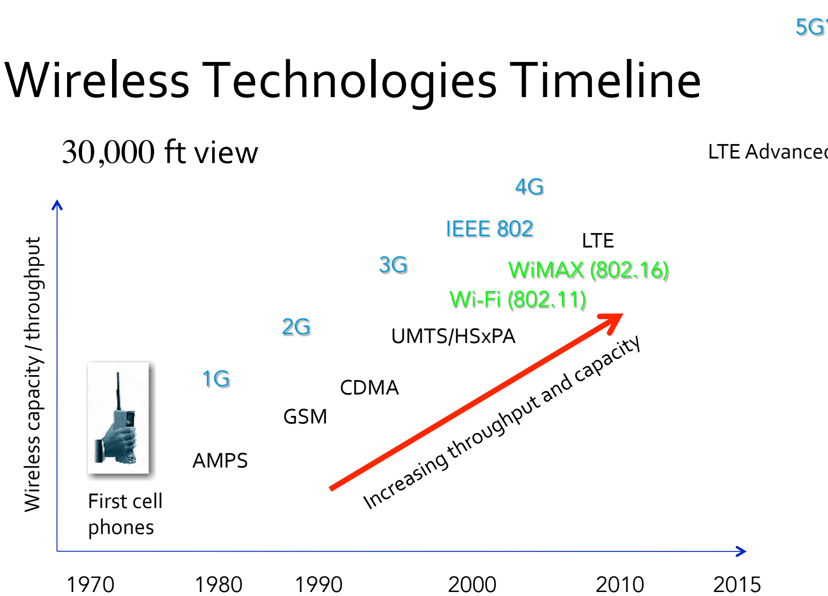
cell
- covers geographical region
- base station (BS) analogous to 802.11 access point (AP)
- mobile users attach to network through BS
- air interface: physical and link layer protocol between mobile and BS

MSC
- connects base stations to wide area net
- manages call setup
- handles mobility



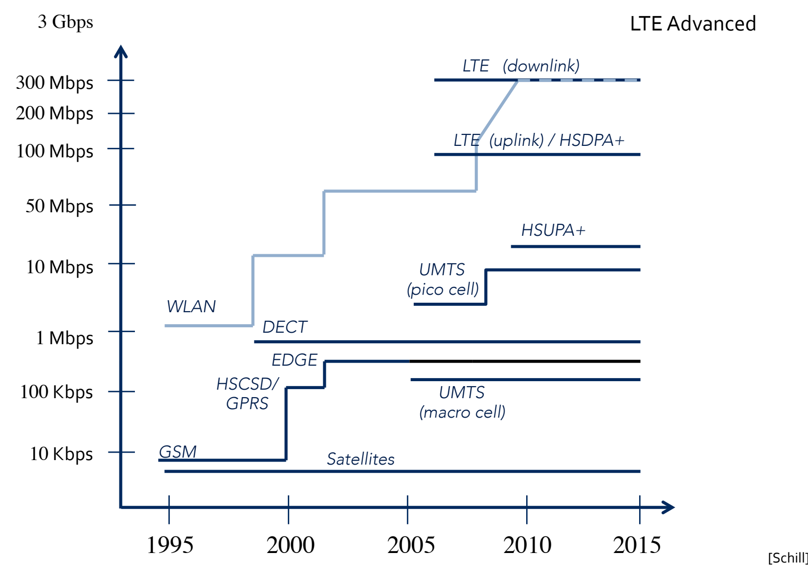
Wireless Technologies Timeline

30,000 ft view



[Mlinarsky, Turner]

Corresponding Data Rates



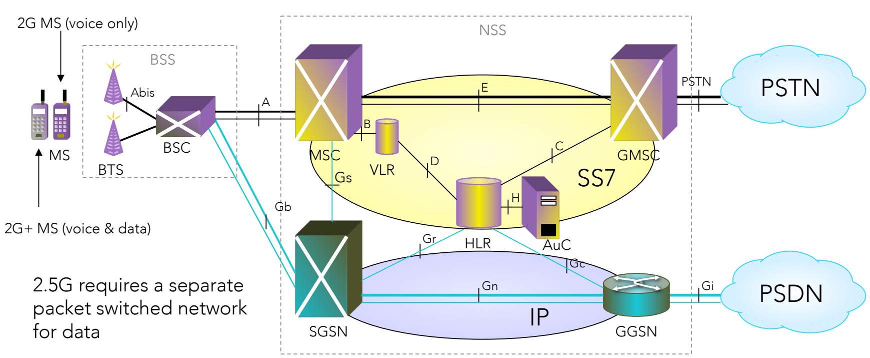
[Schill]

Cellular Network Standards

Range: < 2-8 km
Speed: < 250 km/h

	Standard	Modulation	Data rate (avg) in Kbps, K^2=M	Multiple Access
1G	AMPS	FM	-	FDMA
2G	GSM	GMSK	9.6-14.4	TDMA
	GPRS	GMSK	115 (20-30)	
	EDGE	8PSK	384 (100-130)	
	EDGE Evolution	16QAM/32QAM	1.89K (400)	
	IS-136	DQPSK	9.6	
	IS-95 (cdmaOne)	QPSK/OQPSK	9.6	CDMA
	cdma2000 1xRTT	QPSK	114 (50-70)	
3G	cdma2000 1xEVDO (Rel 0)	QPSK/8PSK/16QAM	2K/150 (500/80)	CDMA w/ TDM
	cdma2000 1xEVDO rev A		3K/1.8K (700/350)	
	WCDMA/UMTS	QPSK/BPSK	2K (220-320)	CDMA
	UMTS HSPA	64QAM/16QAM+MIMO	28K/11K (500-1K)	
	UMTS HSPA+	64QAM/64QAM+MIMO	336K/72K (14K)	
	UMTS LTE	QPSK/QAM/OFDM+MIMO	73K-300K/36-75K	OFDMA
	WiMAX Rel 1 (802.16e)	OFDM+MIMO	128K/56K	SOFDMA
4G	WiMAX Rel. 2 (802.16m)	OFDM+MIMO	100K	SOFDMA
	LTE-Advanced	OFDM+MIMO	1M/375-568K	SC-FDMA

GSM (2G) and GPRS (2.5G) Network Architecture



2.5G requires a separate packet switched network for data

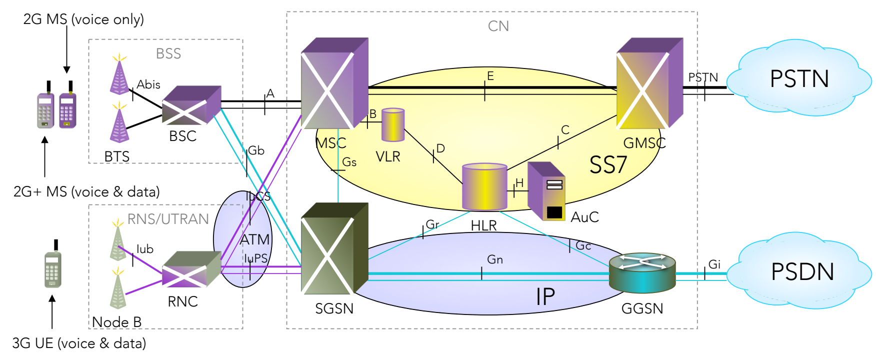
BSS — Base Station System
BTS — Base Transceiver Station
BSC — Base Station Controller
MS — Mobile Station

NSS — Network Sub-System
MSC — Mobile-service Switching Controller
VLR — Visitor Location Register
HLR — Home Location Register
AuC — Authentication Server
GMSC — Gateway MSC

SGSN — Serving GPRS Support Node
GGSN — Gateway GPRS Support Node

[Turner&Orange]

UMTS (R99) Network Architecture



BSS — Base Station System
BTS — Base Transceiver Station
BSC — Base Station Controller
MS — Mobile Station

CN — Core Network
MSC — Mobile-service Switching Controller
VLR — Visitor Location Register
HLR — Home Location Register
AuC — Authentication Server
GMSC — Gateway MSC

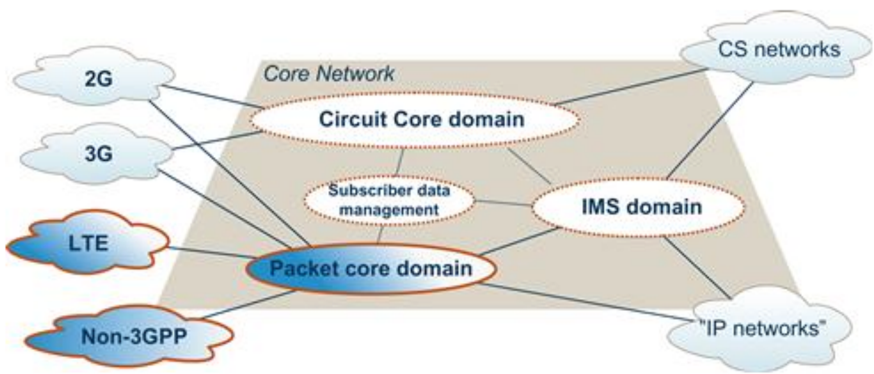
SGSN — Serving GPRS Support Node
GGSN — Gateway GPRS Support Node

RNS — Radio Network System
UTRAN — UMTS Terrestrial Radio Access Network
RNC — Radio Network Controller
UE — User Equipment

UMTS — Universal Mobile Telecommunication System

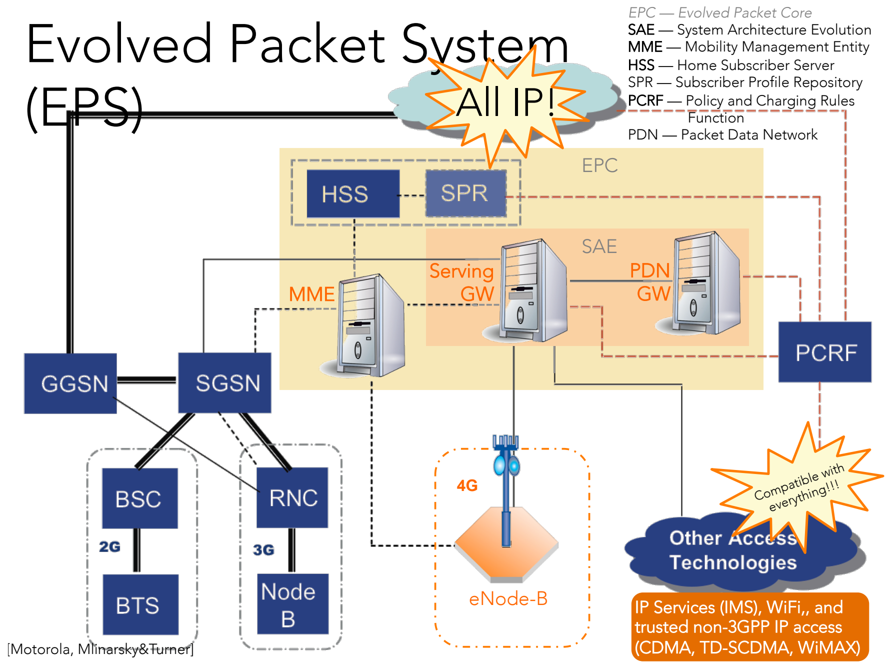
[Turner&Orange]

Overall 3GPP Network Architecture



[Olsson et al.]

Evolved Packet System (EPS)



[Motorola, Mlinarsky&Turner]

RF Spectrum

Band	Uplink	Downlink	Total FDD	Comments
800 MHz	832-862	791-821	2 x 30 MHz	established or new
900 MHz	880-915	925-960	2 x 35 MHz	originally GSM, recently UMTS
1800 MHz	1710-1785	1805-1880	2 x 75 MHz	GSM
2100 MHz	1920-1980	2110-2170	2 x 60 MHz	original UMTS
2600 MHz	2500-2570	2620-2690	2 x 70 MHz	LTE

Why are 800, 1800 and 2600 bands popular?

IEEE Wireless 802.1x Standards

Standard	Year	Frequency Band (GHz)	Air Interface	Mbps (actual)	Range (m)	Speed
802.11	1987 (started) 1997 (standard)	2.4	DS-SS/DBPSK DS-SS/DQPSK	1 2		walking
802.11b (WiFi)	1999		CCK-BPSK CCK-QPSK	5.5 11 (5)	< 30/300 (outdoors)	
802.11a	1999	5	OFDM/24QAM	54 (27)	< 10/100	
802.11g	2003	2.4	OFDM/64QAM	1-54 (22)	< 30/300	
802.11n	2010 (est)	2.4 and 5	64QAM+MIMO	300 (144)	< 10/100	
802.11ac	12/2013	5	256QAM+MUMIMO	1.3K		
802.11ad (WiGig, Wireless USB)	12/2012	2.4, 5, and 60	MIMO	7K	LoS	
802.15.1 (Bluetooth)	1994 (started) 1999 (standard)	2.4	TDM-FHSS	.721-4	< 10 m	N/A
802.16a (Line Of Sight)	2001	10-66	OFDM QPSK 16QAM 64QAM	4-70 (1-4)	< 50 km	
802.16d (Non LOS)	2003	2-11			< 6-10 km	
802.16e (Mobile WiMAX, S. Korea WiBro)	2005, 2009	2.3, 2.5, 3.3, 3.5	ScalableOFDMA +MIMO		< 1-5 km	< 120 km/h
802.16m (WiMAX II)	2011	2.3, 2.5, 3.3, 3.5	ScalableOFDMA +MIMO	100 mobile 1K fixed	< 50 km	

802.15: Personal Area Network

Replacement for cables (mouse, keyboard, headphones)

Ad hoc: no infrastructure

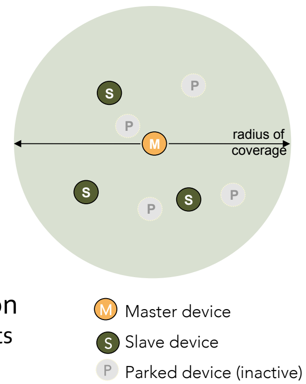
Less than 10 m diameter

Master/slaves:

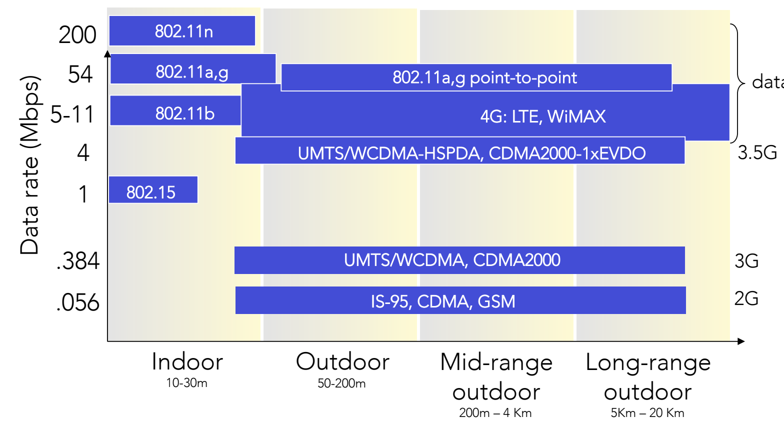
- slaves request permission to send (to master)
- master grants requests

802.15: evolved from Bluetooth specification

- a bluetooth network (piconet) supports 2-7 gadgets
- each gadget given a 12-bit address
- supports gadget authentication and data encryption
- uses frequency hopping spread spectrum (signal occupies different frequencies, in a given pattern and duration, as transmission progresses)
- uses FEC, CRC, and ARQ



Characteristics of Selected Wireless Link Standards



Internet Protocol Stack

application: supporting network applications

- HTTP, SMTP, FTP, etc.

transport: endhost-endhost data transfer

- TCP, UDP

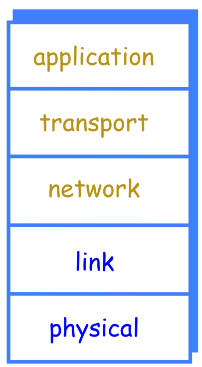
network: routing of datagrams from source to destination

- IP, routing protocols

link: data transfer between neighboring network elements: multiple access control

- Ethernet, WiFi

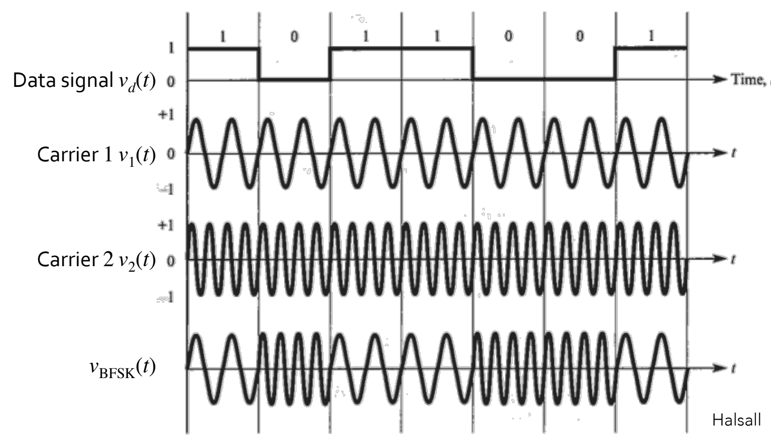
physical: modulation methods, bits in the air



air interface

Frequency-Shift Keying

Binary Frequency-Shift Keying (BFSK): uses 2 fixed-amplitude (A) carrier signals, different in frequency (f), to represent 1 and 0



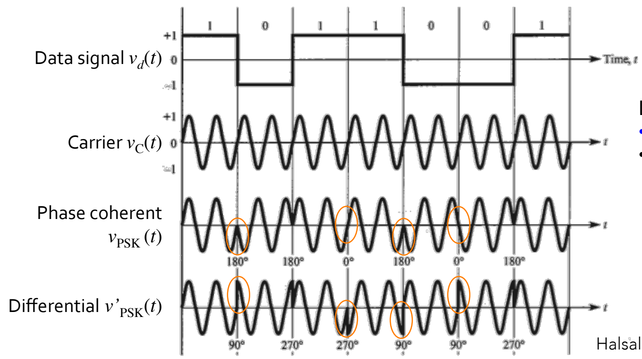
Halsall

Phase-Shift Keying

Phase shift occurs at each bit transition

Binary Phase-Shift Keying (BPSK): A and f are fixed, 1 and 0 are different phases (φ) of the signal, e.g., start at $180^\circ = 0$, at $0^\circ = 1$

Differential Phase-Shift Keying (DPSK): phase difference is relative to previous bit, e.g., signal shifted by $90^\circ = 0$, by $270^\circ = 1$



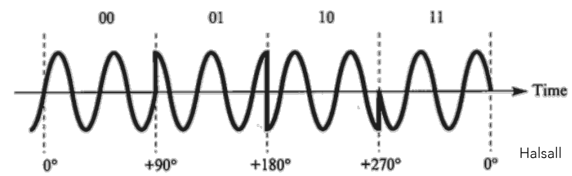
DPSK:
- simpler to implement
- but more prone to errors

Halsall

M-ary Phase-Shift Keying

We're not limited to using only 2 phases

Quadrature Phase-Shift Keying (QPSK): each phase of the signal represents 2 bits, giving 4 values



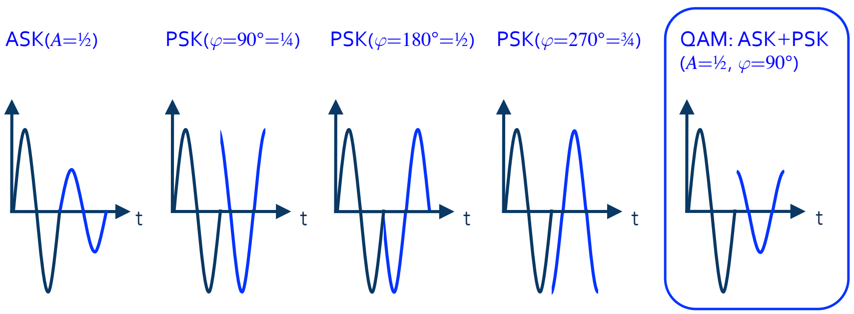
Halsall

- 8PSK: each phase represents 3 bits, giving 8 values
- reducing phase differences makes the signal more prone to noise and interference

Differential QPSK (DQPSK): phase difference is relative to previous bit

Amplitude+Phase Shift Keying

Quadrature* Amplitude Modulation (QAM):
- uses amplitude, in addition to phase, for bit encoding
- a combination of Amplitude Shift Keying (ASK) and Phase Shift Keying (PSK) used to encode/represent multiple bits



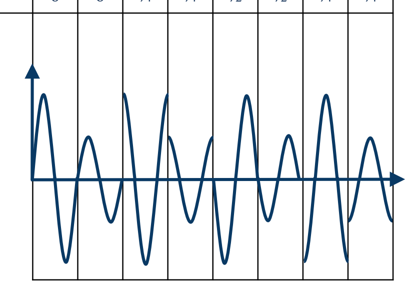
* The "quadrature" in the name refers to the use of "in quadrature" component signal

[Schill]

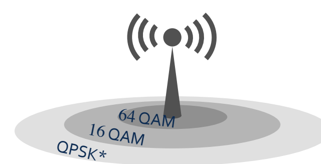
kQAM

Example: 8QAM, 3 bits/symbol (8 codable states)

Bit value	000	001	010	011	100	101	110	111
amplitude (A)	1	½	1	½	1	½	1	½
phase shift (φ)	0	0	¼	¼	½	½	¾	¾



16QAM: 4 bits/symbol
- more states, more sensitive to interference



* Quadrature Phase-Shift Keying $=$ 4QAM (no info from amplitude)

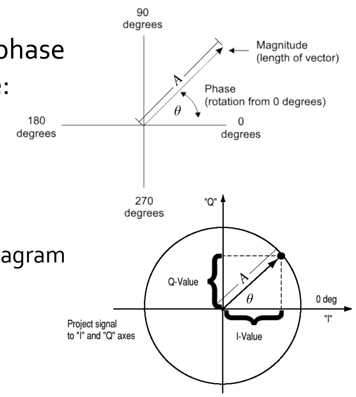
[Fujitsu, Schill]

Polar and I/Q Representation

Difficult to modulate amplitude and phase simultaneously and separately, e.g., phase change can cause amplitude modulation and vice versa

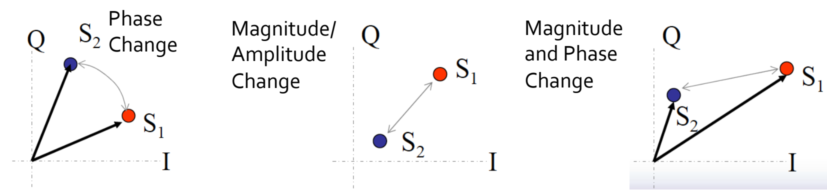
Easier to represent the amplitude and phase of signal as a vector in polar coordinate:

- the 0^o-axis is called the "in-phase" (I) axis
- the 90^o-axis is orthogonal or "in quadrature" (Q) to the I axis
- projections of the signal vector on these axes is a rectangular representation of the polar diagram
- I-value: $A \cos \theta$
- Q-value: $A \sin \theta$

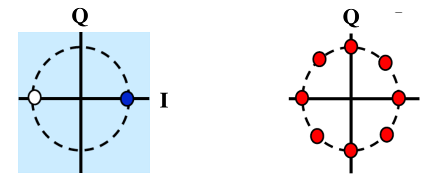


[HP, Cisco]

Signal Changes on the I/Q Plane



Constellation diagrams:



BPSK 8PSK

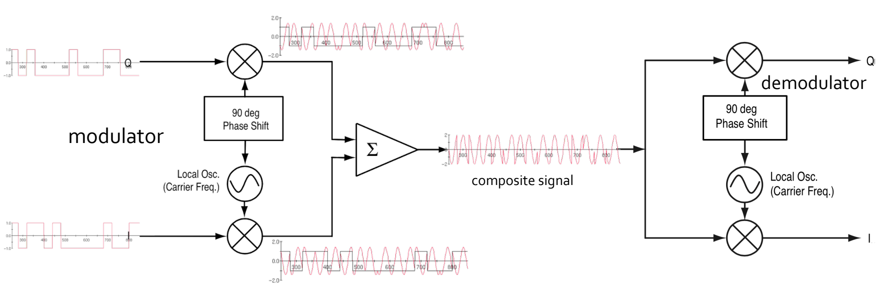
[Donadio, Keithley]

I/Q Signal Modulation

Data in the modulator is separated into 2 channels I and Q

- each channel modulates a carrier
- the two carriers have the same frequency and amplitude but the phase is offset by 90^o ("in quadrature")

The two components are summed in a modulator circuit and transmitted as one composite signal

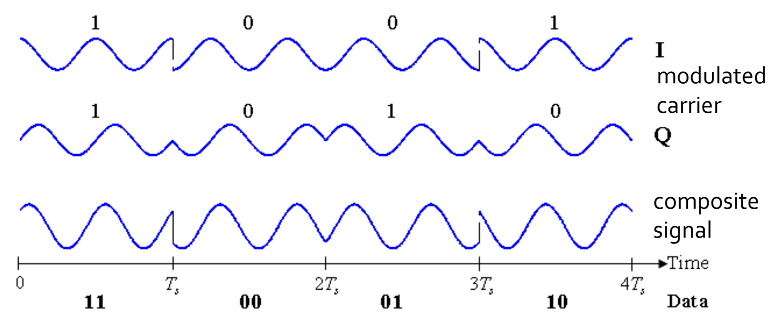


[Langton, HP, Cisco, wikipedia]

Polar and I/Q Representation

The I and Q signals are two independent components of the signal, changing one doesn't change the other

Signals that are in quadrature do not interfere with each other



[HP, Cisco, wikipedia]

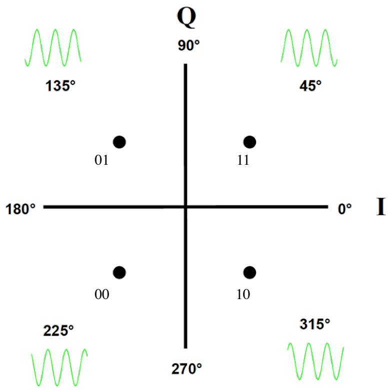
QPSK on the I/Q Plane

The 4 values of QPSK can be represented on the I/Q plane :

- with phases 45°, 135°, 225°, and 315°
- theoretical bandwidth efficiency: 2 bits/sec/Hz

QPSK constellation:

Symbol Transmitted	Carrier Phase	Carrier Amplitude
00	225°	1.0
01	135°	1.0
10	315°	1.0
11	45°	1.0



[Cisco]

16QAM

As with QPSK, data is split into I and Q channels, but each channel can take on 2 phases and 2 amplitude values!

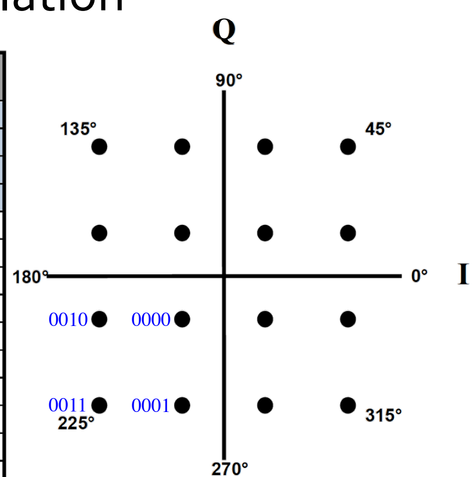
Four I values and four Q values: 4 bits per symbol, $2^4 = 16$ states

Two bits are routed to each channel simultaneously, which are added and applied to the carriers

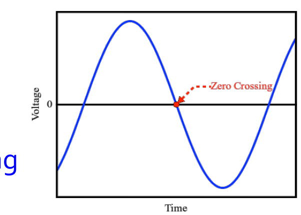
Theoretical bandwidth efficiency: 4 bits/sec/Hz

16QAM Constellation

Symbol Transmitted	Carrier Phase	Carrier Amplitude
0000	225°	0.33
0001	255°	0.75
0010	195°	0.75
0011	225°	1.0
0100	135°	0.33
0101	105°	0.75
0110	165°	0.75
0111	135°	1.0
1000	315°	0.33
1001	285°	0.75
1010	345°	0.75
1011	315°	1.0
1100	45°	0.33
1101	75°	0.75
1110	15°	0.75
1111	45°	1.0



Zero Crossing



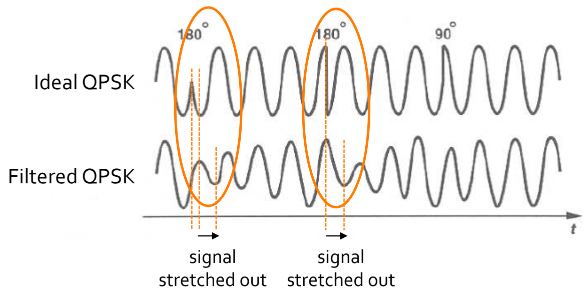
At 0, there's no voltage present:

- when signal is amplified, zero crossing causes artifacts (e.g., audio clicks) in the non-zero part of the output signal when gain is abruptly switched between gain settings
- when signal is filtered, voltage needs time to ramp up/down, zero crossing causes amplitude change
- in graphics rendering, zero crossing shows up as black lines
- in image processing, zero crossing usually marks boundary/edge of features ⇒ don't want extraneous zero crossings

[wikipedia]

QPSK and Zero Crossing

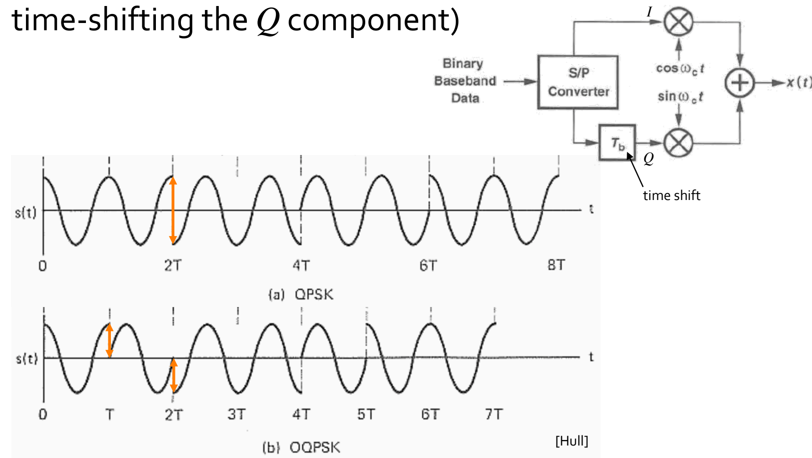
In QPSK, carrier signal can phase shift by 180^o, encountering zero crossing, causing carrier amplitude change when filtered or amplified



[Donadio]

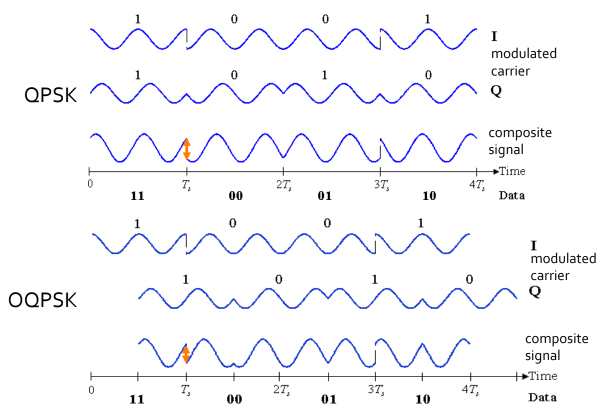
OQPSK

Offset QPSK (OQPSK) a.k.a. Staggered QPSK (SQPSK): limit phase shift to 90^o every half-symbol time (T) (by time-shifting the Q component)



QPSK vs. OQPSK

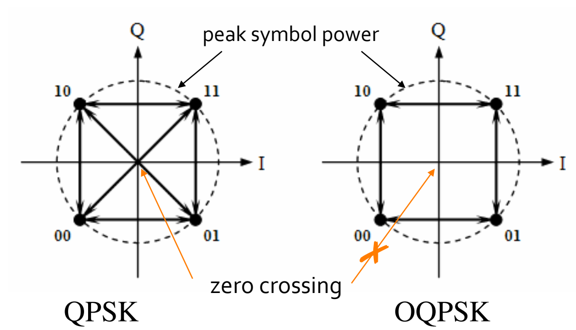
Offset QPSK (OQPSK) a.k.a. Staggered QPSK (SQPSK): limit phase shift to 90^o every half-symbol time (T) (by time-shifting the Q component)



[wikipedia]

QPSK vs. OQPSK

QPSK can phase shift by 180^o, whereas OQPSK is limited to 90^o per half symbol time

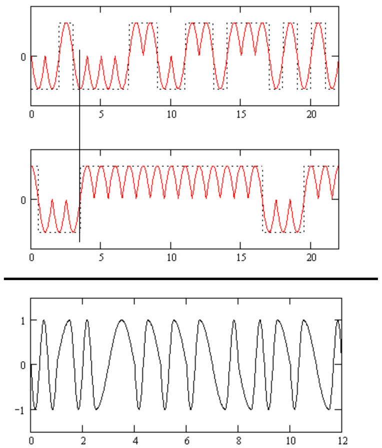


[Donadio]

GMSK

Minimum Shift Keying (MSK):
OQPSK with half-cycle sinusoid component signal, instead of rectangular pulse, to make the phase change linear

- result turns out to be equivalent to FSK with only 1 bit/symbol



Gaussian MSK (GMSK):
MSK output passed through a Gaussian filter, resulting in narrower bandwidth requirement; used in GSM

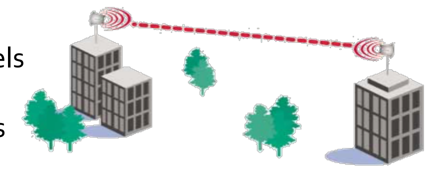
[Langton, HP]

Wireless Link Characteristics

Differences from wired link ….

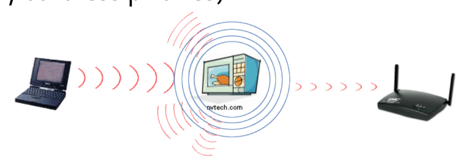
Decreasing signal strength:

- radio signal disperses as it travels greater distances
- and attenuates as it propagates through matter (path loss)



Interference from other sources

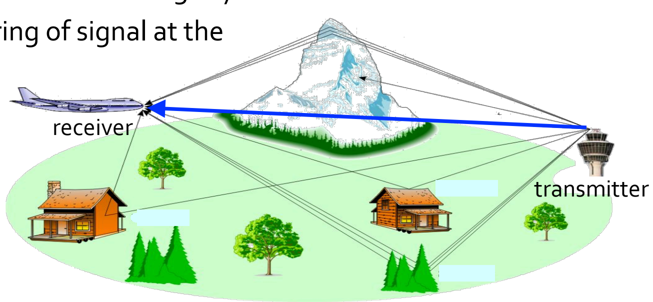
- standardized wireless network frequencies (e.g., 2.4 GHz) shared by other devices (e.g., cordless phones)
- electromagnetic noise (e.g., microwave oven, motors) interferes as well



Wireless Link Characteristics

Multi-path propagation

- radio signal reflects off objects, walls, ground
- taking many paths of different path lengths, arriving at destination at slightly different times
- causing blurring of signal at the receiver



make communication across (even a point to point) wireless link much more "difficult"

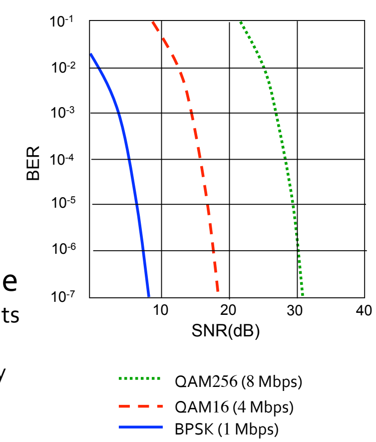
Wireless Link Characteristics

Given air interface: increased power → increased SNR → decreased BER

- SNR: signal-to-noise ratio
- BER: bit error rate

Fundamental trade-off:
energy-saving vs. rate vs. range

- given SNR: choose air interface that meets BER requirement at highest throughput
  - SNR may change with mobility: dynamically adapt the air interface to compensate (modulation technique, rate)
  - all the latest standards have rate adaptation, including 802.11, 802.16, and LTE



Dealing with Bit Errors

Wired vs. wireless links

- wired: most loss is due to congestion
- wireless: higher, time-varying bit-error rate

Dealing with high wireless bit-error rates

- sender could increase transmission power
  - requires more energy (bad for battery-powered hosts), and
  - creates more interference with other senders
- stronger error detection and recovery
  - more powerful error detection/correction codes
  - link-layer retransmission of corrupted frames

Many TCP alternatives/extensions for wireless

- e.g., TCP Westwood uses an Explicit Loss Notification (ELN) bit

Multi-antenna (MIMO)

With bandwidth reaching Shannon's limit, future gain in bandwidth will come from smarter antenna use:

Beamforming (a.k.a., smart antenna/adaptive antenna system (AAS)): generate interfering patterns from multiple antennae such that the intended signal is strengthened, in the direction intended (Cf. noise cancellation headphones)

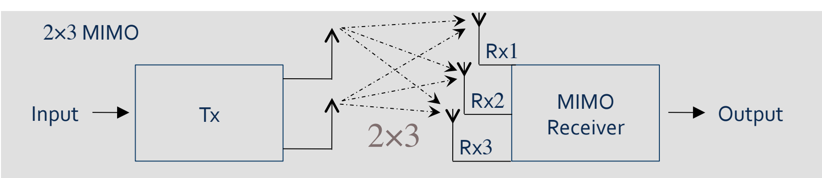
Spatial multiplexing: organized data into spatial streams that are transmitted simultaneously, on the same frequency, using multiple antennae; streams received over multiple antennae and separated using various detection algorithms

- increase in spectral efficiency (and resulting data rate) and quality of transmission

MIMO Antenna Technique

MIMO: Multi-Input/Multi-Output

- there's a propagation path between each transmit (Tx) and receive (Rx) antenna (a "MIMO path")
- $N \times M$ MIMO (e.g., 4×4, 2×2, 2×3)
  - N transmit antennas
  - M receive antennas
  - total of $N \times M$ paths
- MIMO transmission increases throughput by beam forming, error correction across Tx antennae, signal interpolation across Rx antennae, network coding across multiple hosts (co-MIMO)



[Mlinarsky&Turner, Schill]