Lecture 6

Network Deployment (2)

Basics of Transmission Schemes (1)

Capacity Expansion

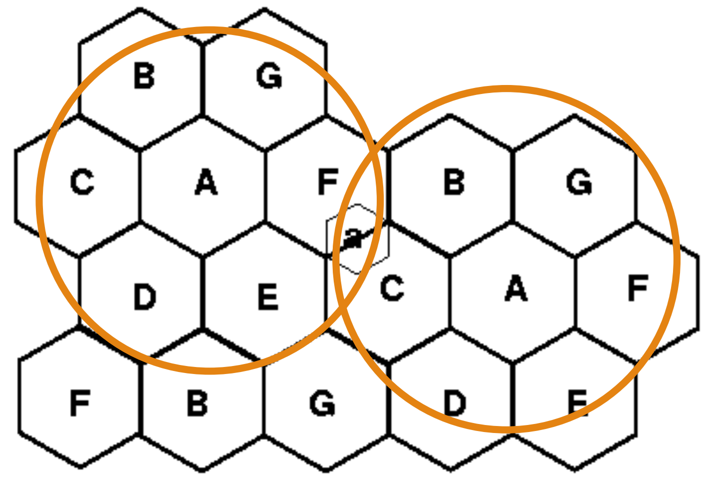
- Main investment in deploying a cellular network is the cost of infrastructure, land, base station equipment, switches installation, interconnection, etc.
- Income is proportional to subscriber base
- Initial installment may not be able to support increasing subscriber demand
- How can capacity be increased without replicating deployment?

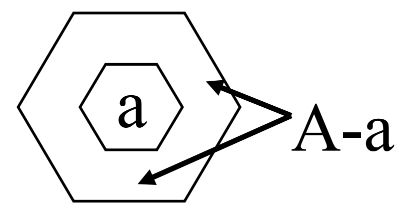
Techniques to expand capacity

- Additional spectrum
  - Very hard to obtain – also expensive
  - 1900 MHz bands for PCS; 700 MHz bands from TV
- Architectural approaches
  - Cell splitting
  - Cell sectorization
  - Reuse partitioning
  - Lee’s microcell zone technique
- Changing to digital – TDMA or CDMA
- Dynamic channel allocation

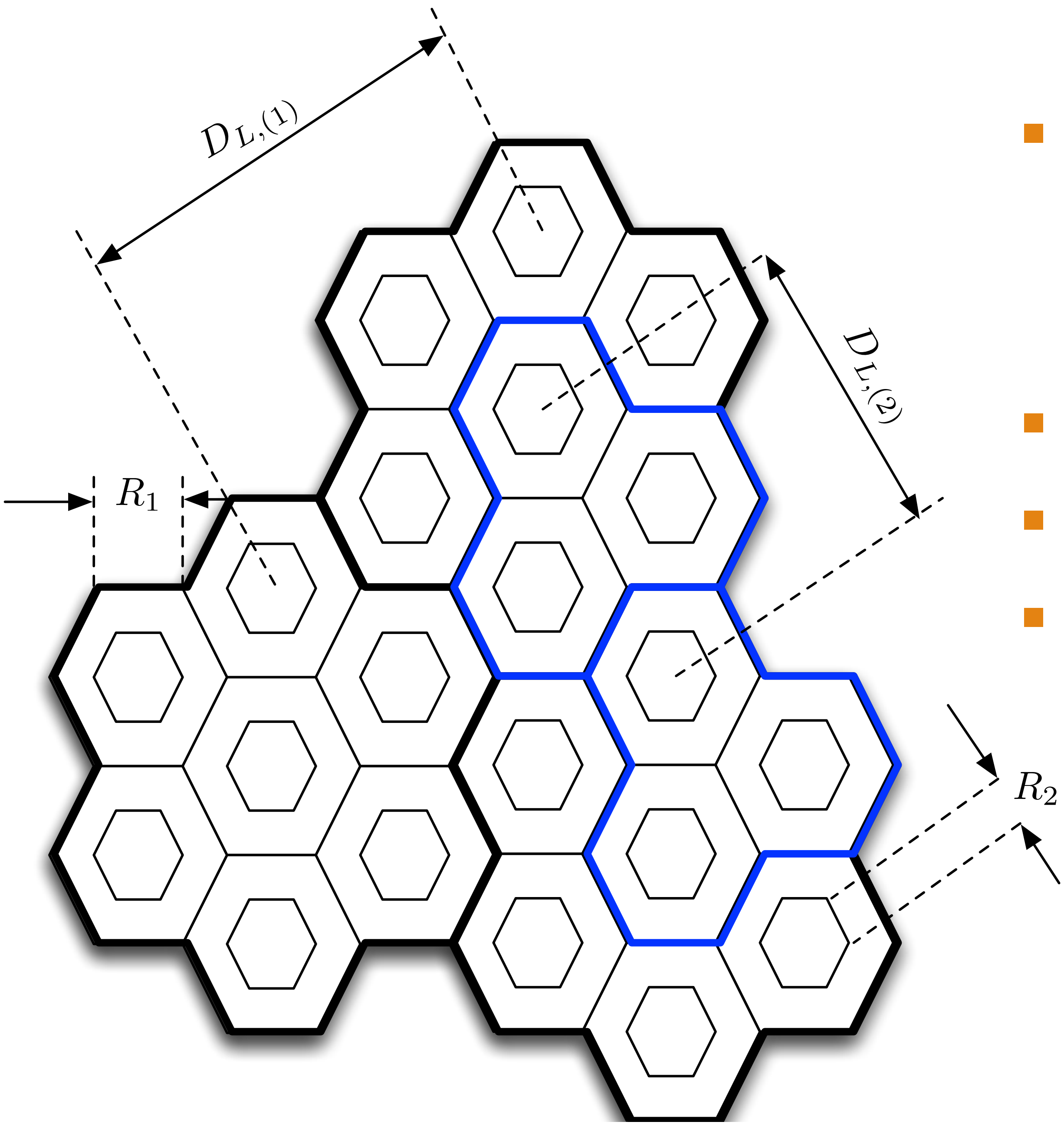
Cell Splitting

- Hotspots are created in certain areas
- Introduce a smaller cell of half the size midway between two co-channel cells
- Interference problems
- Channels must be split between the larger and smaller cells





The Overlaid Cell Concept

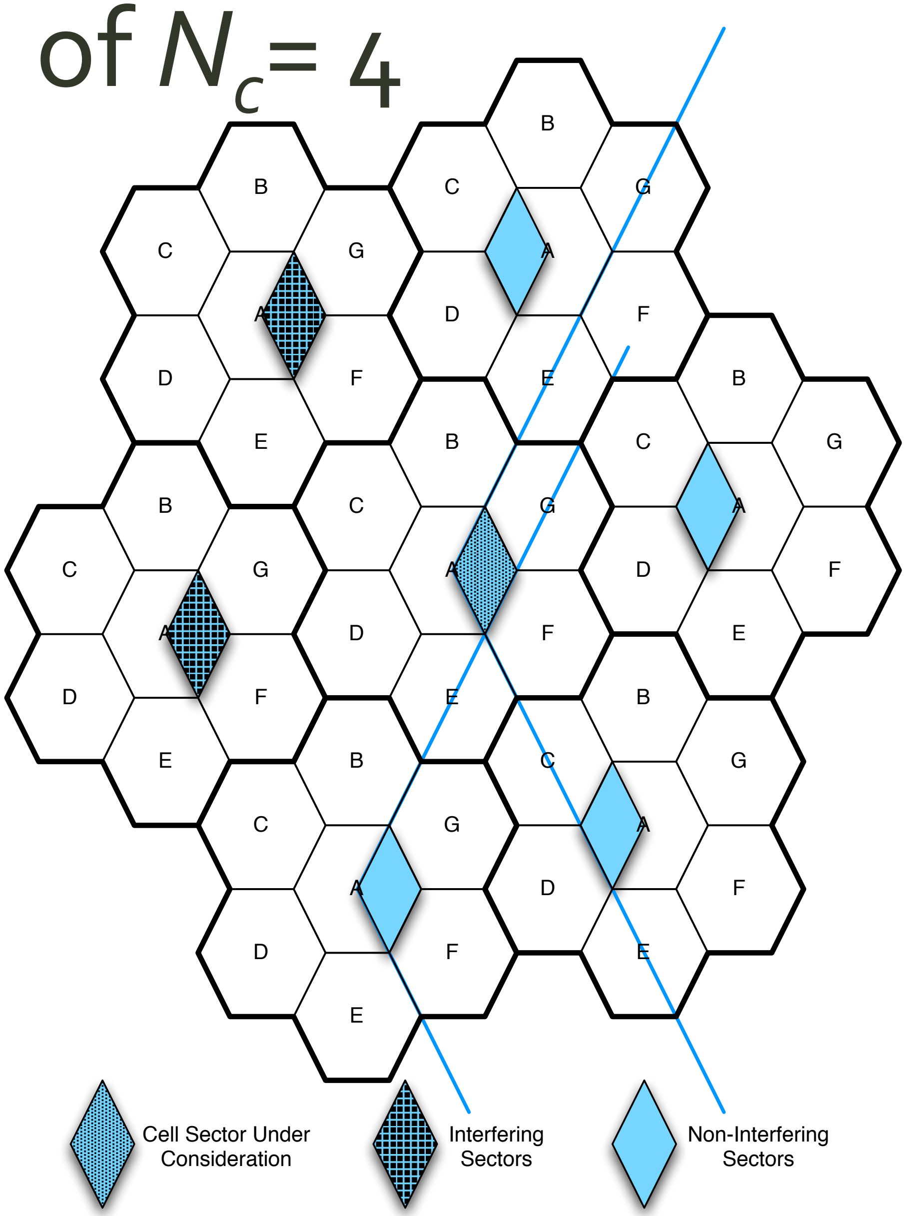


- Channels are divided between a larger macro-cell that co-exists with a smaller micro-cell that is completely contained within the macro-cell
- D_2/R_2 is larger than D_1/R_1
- Split-band analog systems
- Reuse partitioning
  - Used in LTE (Revisit)

Cell Sectoring

- Use directional antennas to reduce interference
- Radio propagation is focused in certain directions
  - Antenna coverage is restricted to part of a cell called a sector
- By reducing interference, the cluster size can be reduced (J_s is reduced, and so we can reduce N_c)

Three-sector cells and a cluster size of $N_c = 4$



- 120º directional antennas are employed
- Channels allocated to a cell are further divided into three parts
- Without directional antennas, S_r = 13.8 dB which is inadequate
- With directional antennas, S_r = 18.5 dB

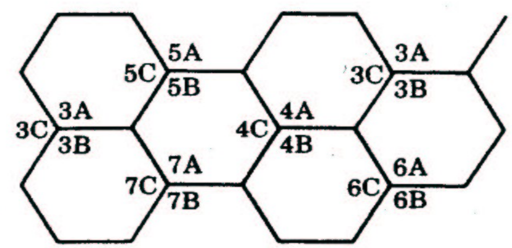
$$S_r \approx \frac{R^{-4}}{J_s D^{-4}} = \frac{R^{-4}}{2D^{-4}} = \frac{1}{2}\left(\frac{D}{R}\right)^4 = \frac{9}{2}N_c^2$$

Sectored Frequency Planning

- Example: Allocate frequencies for an AMPS operator in cellular B-block who uses a 7 cell frequency reuse pattern with 3 sectors per cell
- Use a Frequency Chart – available from FCC web site
  - Groups frequencies into 21 categories Cells 1-7 and sectors A-B-C in each cell

Block B

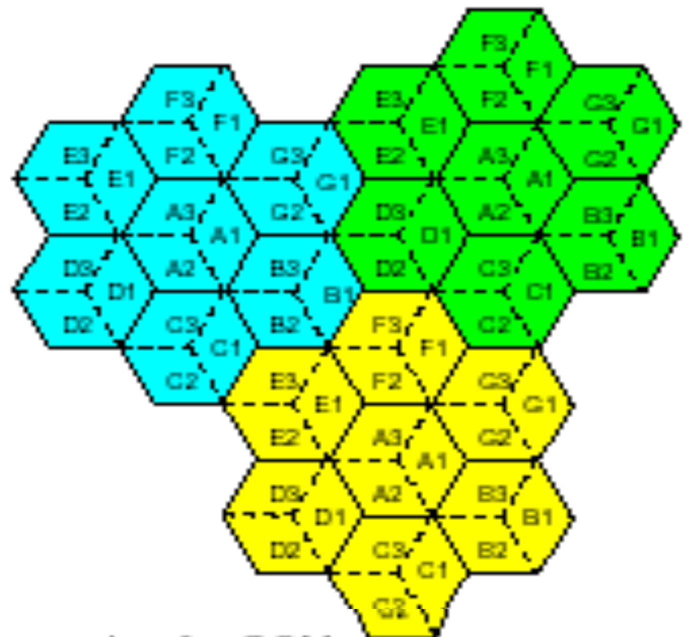
1A	2A	3A	4A	5A	6A	7A	1B	2B	3B	4B	5B	6B	7B	1C	2C	3C	4C	5C	6C	7C
334	**335**	**336**	**337**	**338**	**339**	**340**	**341**	**342**	**343**	**344**	**345**	**346**	**347**	**348**	**349**	**350**	**351**	**352**	**353**	**354**
355	356	357	358	359	360	361														375
376	377	378	379	380	381	382														396
397	398	399	400	401	402	403														417
418	419	420	421	422	423	424														438
439	440	441	442	443	444	445														459
460	461	462	463	464	465	466														480
481	482	483	484	485	486	487														501
502	503	504	505	506	507	508														522
523	524	525	526	527	528	529														543
544	545	546	547	548	549	550														564
565	566	567	568	569	570	571														585
586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606
607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627
628	628	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648
649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	717	718	719
720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740
741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761
762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782
783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799				



*Boldface numbers indicate 21 control channels for Block A and Block B respectively.

Sectored Frequency Planning

- Example: Allocate frequencies for a GSM operator in U.S. PCS B-block who uses a 7 cell frequency reuse pattern with 3 sectors per cell
- Use a Frequency Chart – available from FCC web site
- Groups frequencies into 21 categories Cells A-G and sectors 1-3 in each cell



Frequency Chart . 612-685 represent B-block frequencies for GSM

A1	B1	C1	D1	E1	F1	G1	A2	B2	C2	D2	E2	F2	G2	A3	B3	C3	D3	E3	F3	G3
612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	628	629	630	631	632
633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653
654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674
675	676	677	678	679	680	681	682	683	684	685										

Summary: Cell sectoring

- The cluster size can be reduced by employing directional antennas
- The capacity increase is 1.67 times for N = 4 and 2.3 times for N = 3 compared to N = 7
- Sectoring is better than splitting
  - No new base station has to be set up
  - No new planning efforts are needed to maintain interference levels
- Sectoring leads to handoff between sectors which increases signaling load and some loss of call quality
- A cell cannot be ideally sectored and the signal to interference values obtained here are optimistic

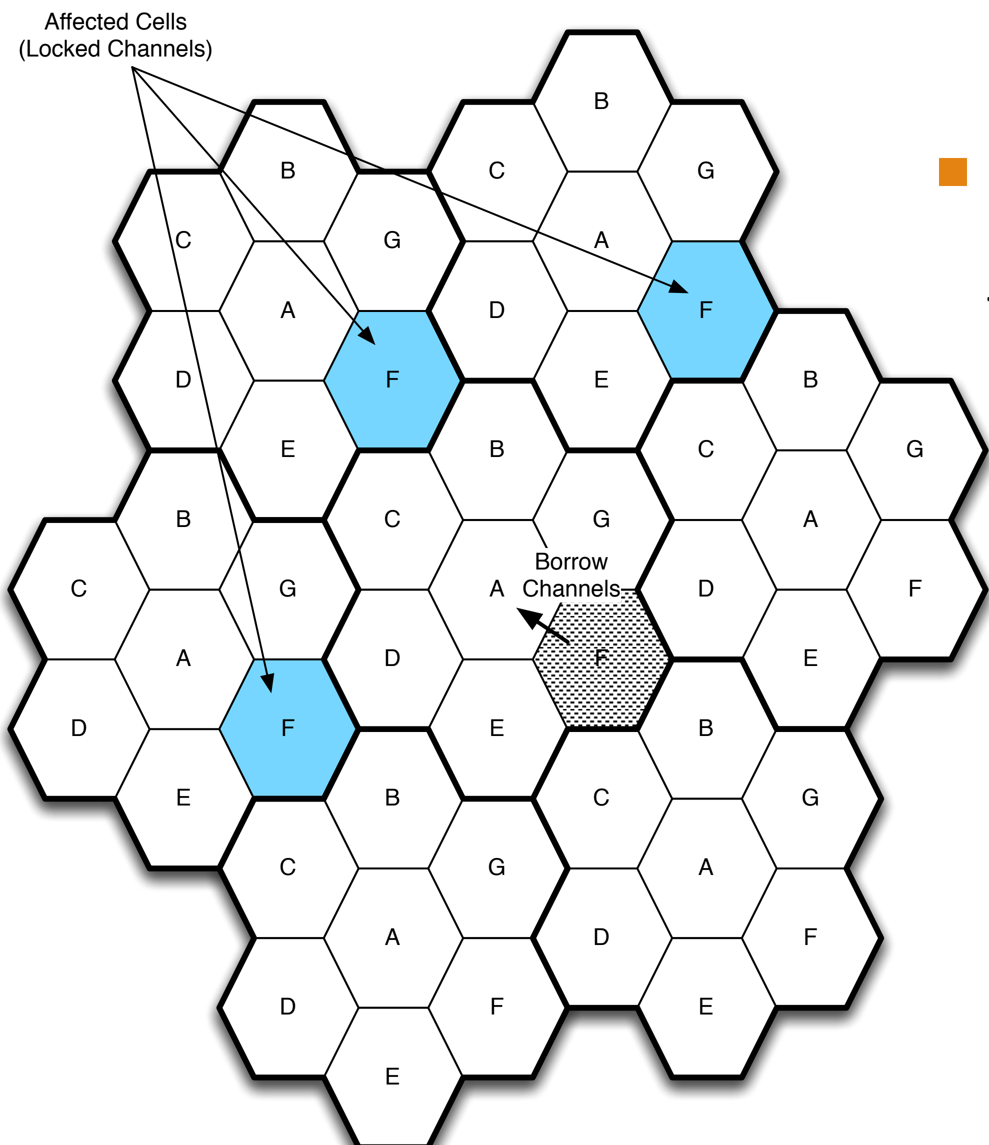
Channel Allocation Techniques

- Idea:
  - During the day on weekdays, downtown areas have a lot of demand for wireless channels
  - In weekends and evenings, suburban areas have a larger demand and downtown areas have very little demand
  - Instead of allocating channels statically to cells, allocate channels ***on demand*** while maintaining signal-to-interference ratio requirements
- The (voice) user does not care how the channels are allocated as long as
  - He/she gets access to the channel whenever required
  - The quality of the signal is acceptable

Channel Allocation Techniques (2)

- Fixed channel allocation (FCA)
  - Channel borrowing
- Dynamic channel allocation (DCA)
  - Centralized DCA
  - Distributed DCA
    - Cell-based
    - Measurement-based
- Hybrid channel allocation (HCA)

Channel borrowing



- Idea: Borrow channels from low loaded cells and return them whenever required
  - Temporary channel borrowing
    - Return channel after call is completed
    - Locks channel in co-channel cells
  - Static channel borrowing
    - Distribute channels non-uniformly but change them in a predictable way

Dynamic Channel Allocation

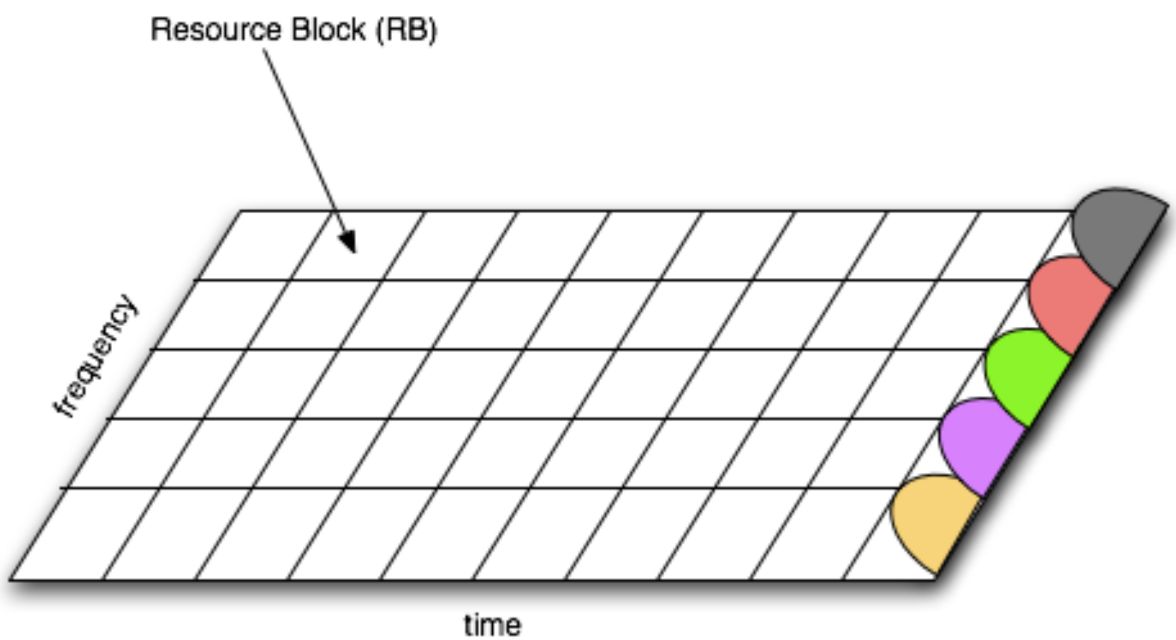
- All channels are placed in a pool
  - When a new call comes in, a channel is selected based on the overall SIR in the cell
  - Selection of the channel in this way is costly
    - Needs a search and computation of SIR values
- Centralized
  - A central entity selects channels for use and returns it to the pool after completion of calls
- Distributed
  - Base stations locally compute the channels that can be used
    - Cell-based – BSs communicate with each other on the wired backbone to determine the best way to select channels
    - Measurement-based – BSs measure RSS or receive RSS reports from MSs that they use in their decisions

Comparison of FCA and DCA

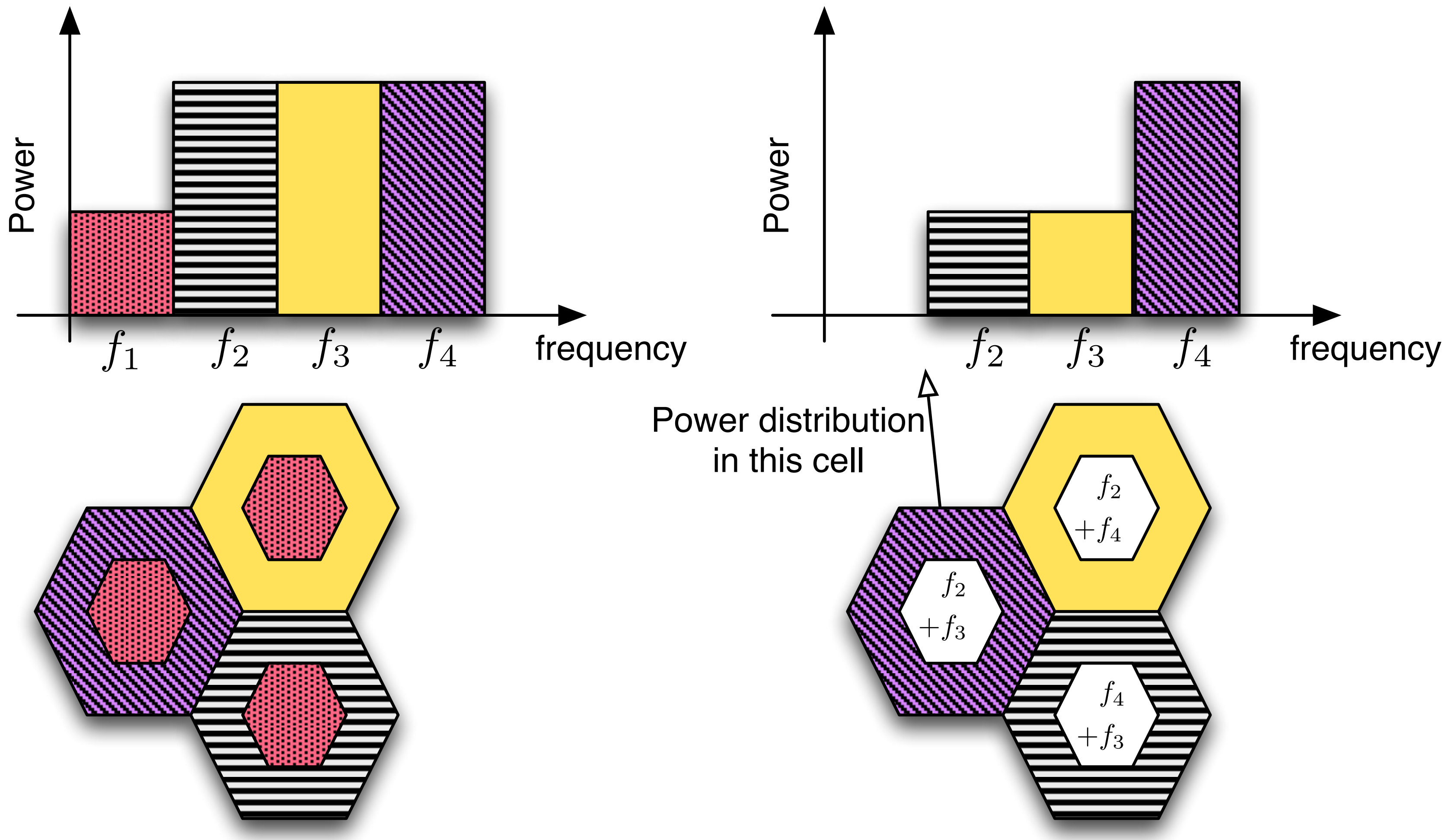
Attribute	Fixed Channel Allocation	Dynamic Channel Allocation
Traffic Load	Better under heavy traffic load	Better under light/moderate traffic load
Flexibility in channel allocation	Low	High
Reusability of channels	Maximum possible	Limited
Temporal and spatial changes	Very sensitive	Insensitive
Grade of service	Fluctuating	Stable
Forced Call Termination	Large probability	Low/moderate probability
Suitability of cell size	Macro-cellular	Micro-cellular
Radio equipment	Covers only the channels allocated to the cell	Has to cover all possible channels that could be assigned to the cell
Computational effort	Low	High
Call set up delay	Low	Moderate/High
Implementation complexity	Low	Moderate/High
Frequency planning	Laborious and complex	None
Signaling load	Low	Moderate/High
Control	Centralized	Centralized, decentralized or distributed

Interference Management in LTE-OFDMA

- Borrows ideas from *Reuse Partitioning* and *Dynamic Channel Allocation*
- Aims for a frequency reuse of 1
  - Sub-carriers and "resource blocks" (RBs) may not be universally reused
- Base stations talk with each other to manage interference and also scheduling RBs to users



Strict and Soft Fractional Frequency Reuse in LTE



(a) Strict FFR with reuse of 3+1

(b) Soft FFR with reuse of 3

Femtocells

- Initial Idea
  - Coverage challenged areas with good Internet connectivity
- Progressive Benefits
  - High spectrum efficiencies
    - Typically indoor!
    - High data rates are possible
  - Reducing subscriber churn
  - Reducing CAPEX and OPEX costs for service providers
    - Backhaul capacity and capital expenditures are reduced

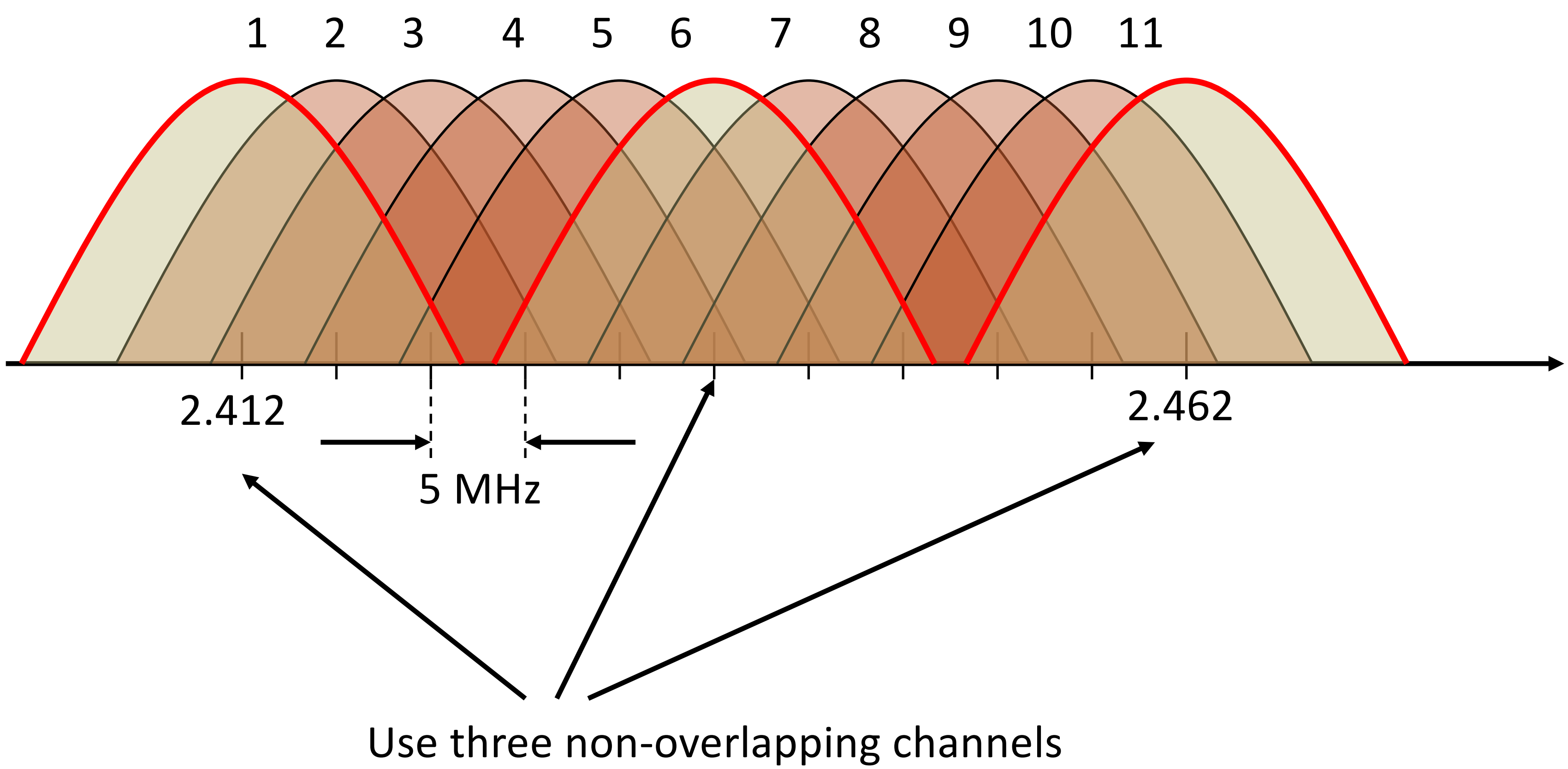
Issues with Femtocell deployment

- Femtocell base station cannot transmit at high power nor at low power
  - Should not swamp users that do not belong to femtocell
  - Should not deny coverage to someone who installs the femtocell
- Femtocell base station reception has to be dynamic
  - A mobile that is near should not swamp it because of its minimum transmit power
  - A mobile far away should not be forced to transmit at high power to reach the femtocell
    - This may interfere with transmissions in a macrocell

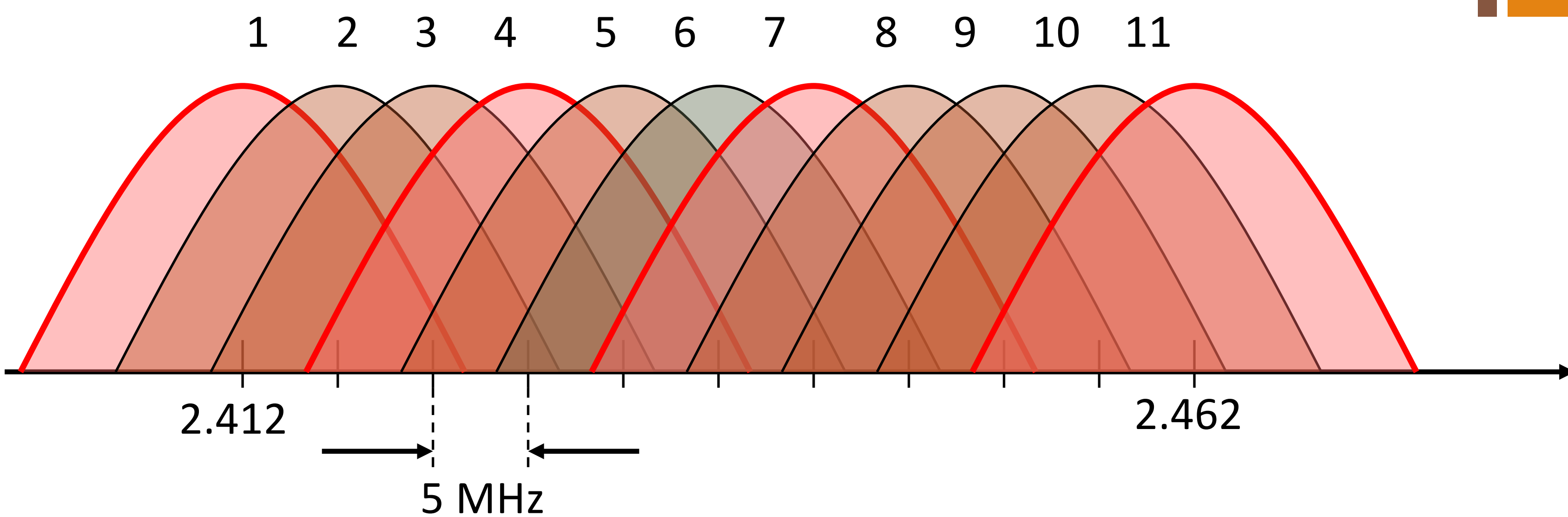
+ Design Issues in Local Area Wireless Data

- IEEE 802.11
  - Initial deployments were based on the 915 MHz bands
    - There was only one channel
  - In the 2.4 GHz bands
    - There are three non-overlapping channels → frequency reuse is possible
    - Thresholds!
  - In the 5 GHz bands, there are eleven non-overlapping channels
- Three dimensional planning is required
  - Antenna patterns and building architecture
- There are three levels of transmit power at the AP
  - Not clear what can be done at the MS

Overlapping channels in the 802.11 specifications



Using overlapping channels

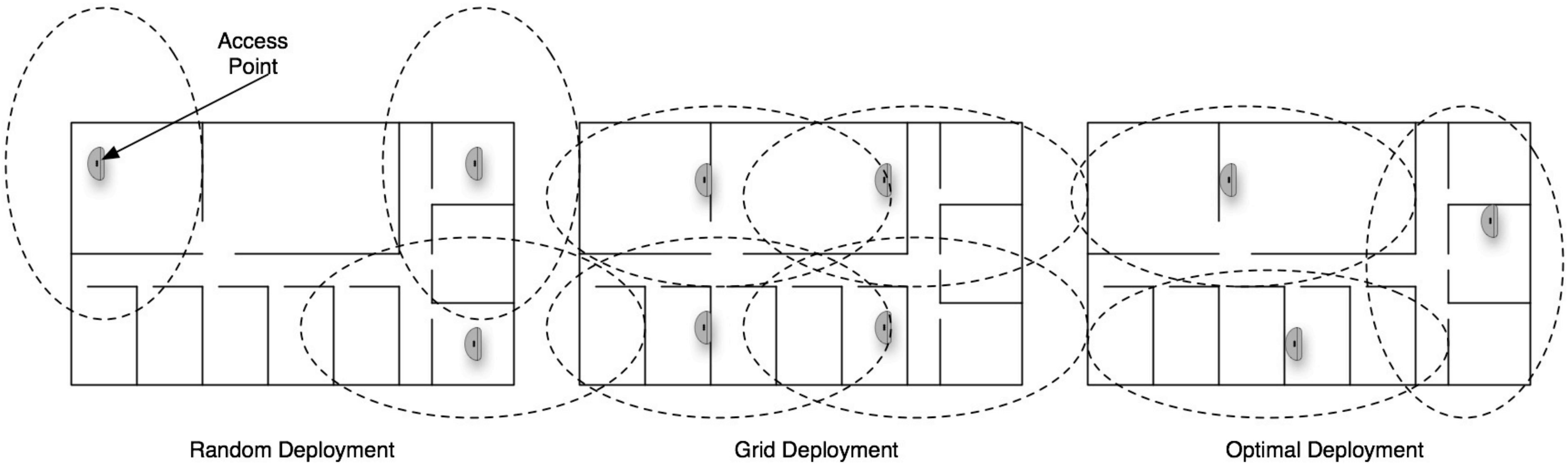


- It is possible to use Channels 1, 4, 7 and 11 instead of 1, 6 and 11
  - There is a drop in throughput
  - There are some results of actual performance but they are inconclusive
- It is not clear whether the drop in throughput is due to backoff or packet loss

SIRs in 802.11 WLANs (@2Mbps)

- Reports of measurements and models of 802.11 RSS and throughputs are vendor specific
  - One report says that a minimum SIR of 15 dB is required for good throughput
  - Used UDP streams and estimated the SIR using a path loss model
  - Throughput falls from 1.8 Mbps to 1 Mbps as the SIR reduces from 15 dB to 10 dB
  - Reuse issues are then simulated
  - Unlike voice, data is bursty – so the design and deployment issues are different
    - Most real deployments design the network for coverage rather than specific QoS goals

WLAN Deployment Methods



- Random deployment by users
- Arrange access points in a grid
- Optimally place access points for coverage/interference

Coexistence?

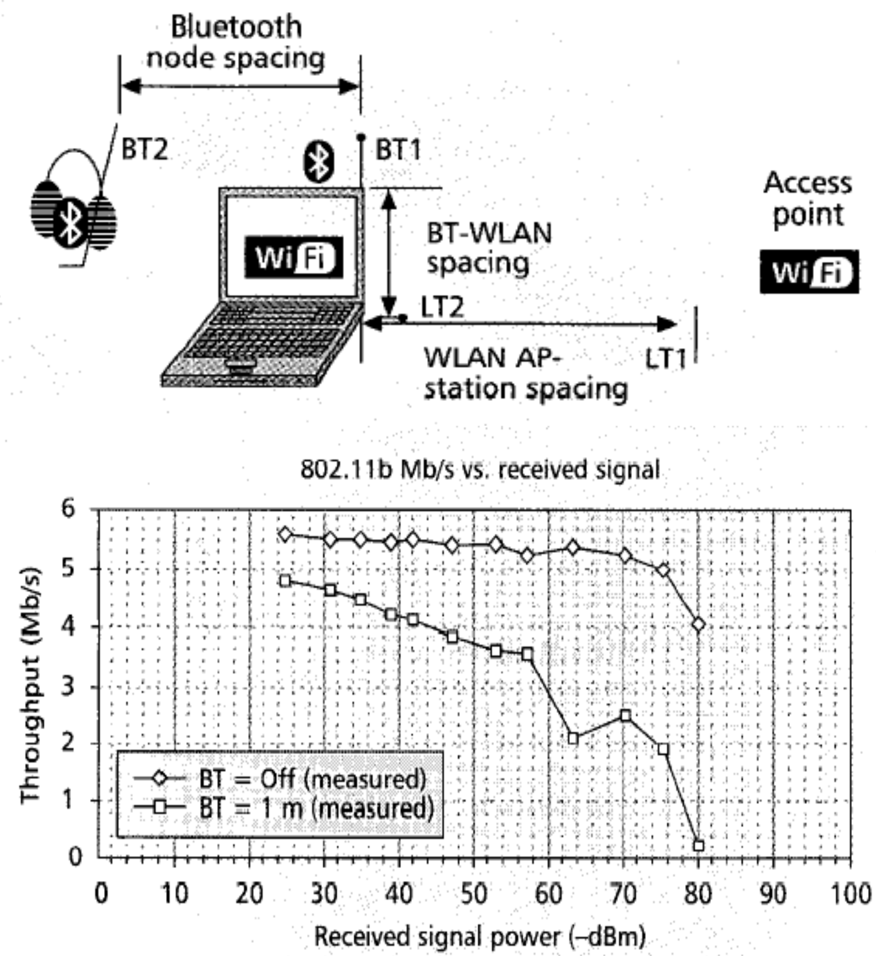
- Interference
  - Two wireless technologies interfere if co-location causes significant performance degradation
- Coexistence
  - Two wireless technologies coexist if there is no significant impact on the performance
- Interoperable
  - Devices belonging to two different wireless technologies are interoperable if they can communicate and exchange data between them

Coexistence between HomeRF and IEEE 802.11

- HomeRF uses very slow frequency hopping
  - 50 hops/s – frame is 20 ms long
  - Compare with Bluetooth – 1600 hops/s and 625 μs
  - Also operates in the 2.4 GHz bands
- Experiments on studying the impact of HomeRF on 802.11 throughput
  - HomeRF is very detrimental to 802.11 throughput
  - HomeRF is an “interference”

Bluetooth and 802.11 (1)

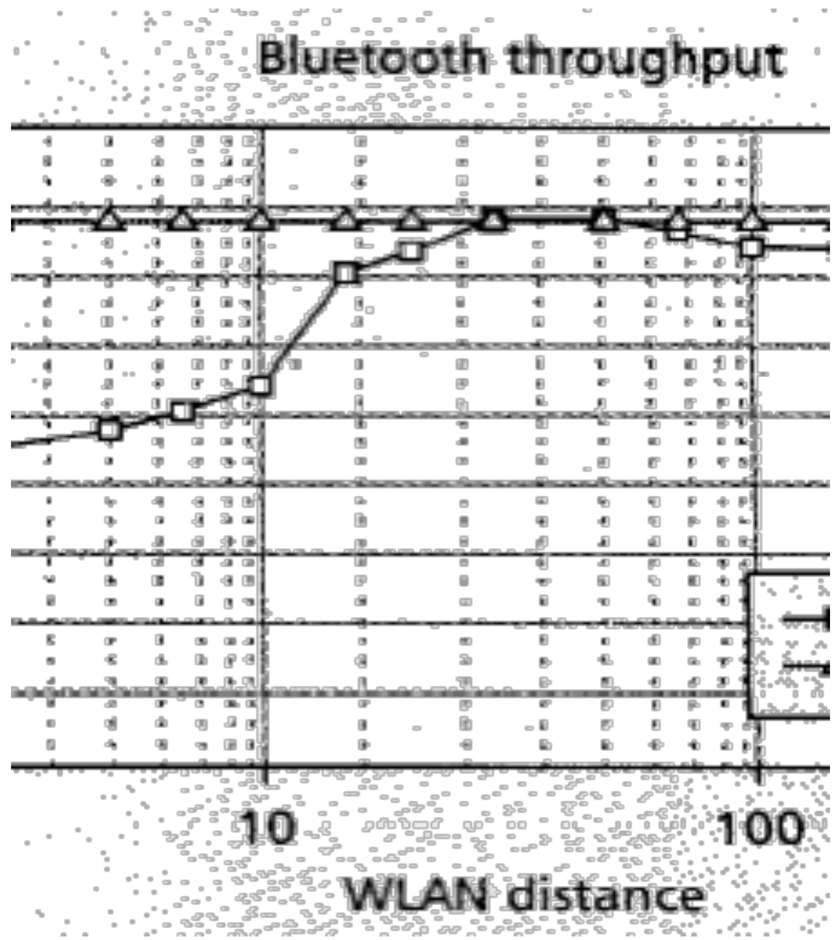
- Impact of BT on 802.11
  - At large RSS, the throughput is fairly good
  - As the RSS falls, the throughput falls drastically
  - BT causes substantial interference, but there is some kind of capture when the RSS is good



Source: J. Lansford et al., *IEEE Network*, September 2001

Bluetooth and IEEE 802.11 (2)

- Impact of IEEE 802.11 on BT
  - 802.11 signal is like a wideband jammer
  - As the RSS from the AP falls, the throughput improves
  - As the RSS from the AP increases, voice packets are dropped randomly
  - The transition occurs suddenly
- Short ACKs are less likely to cause errors than long frames



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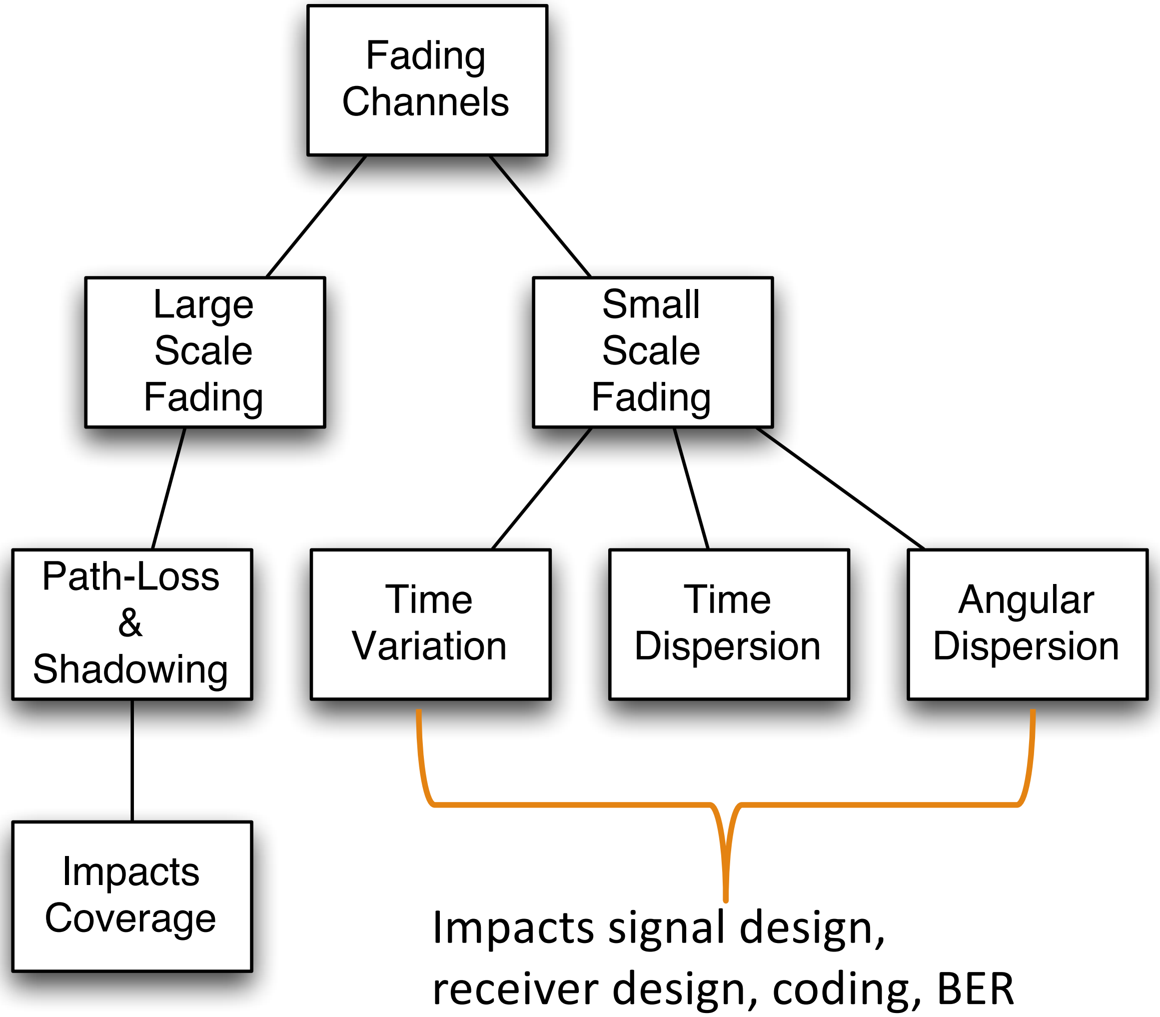
Communication Issues and Radio Propagation



Before we get into small-scale fading…

- What is the best we can do when there is *NO* fading?
- What are the tradeoffs between bit errors, power, noise, and bandwidth?

Digital Modulation (Revisited)

- Changing the parameters of a sinusoid is called “shift keying” if information is digital
- Types
  - Amplitude-shift keying (ASK)
    - Amplitude difference of carrier
  - Frequency-shift keying (FSK)
    - Frequency difference near carrier frequency
  - Phase-shift keying (PSK)
    - Phase of carrier signal shifted
  - Quadrature amplitude modulation (QAM)
    - Both amplitude and phase of the carrier carry data
- Bits/Symbol
  - Binary (one bit in one symbol => two symbols)
  - M-ary ($\log_2 M$ bits in one symbol => M symbols)

Binary Amplitude-Shift Keying

- Idea
  - One binary digit represented by the presence of the carrier, at constant amplitude
  - The other binary digit is represented by the absence of the carrier

$$s(t) = \begin{cases} 0:\ 0, & 0 \le t \le T \\ 1:\ A\cos(2\pi f_2 t), & 0 \le t \le T \end{cases}$$

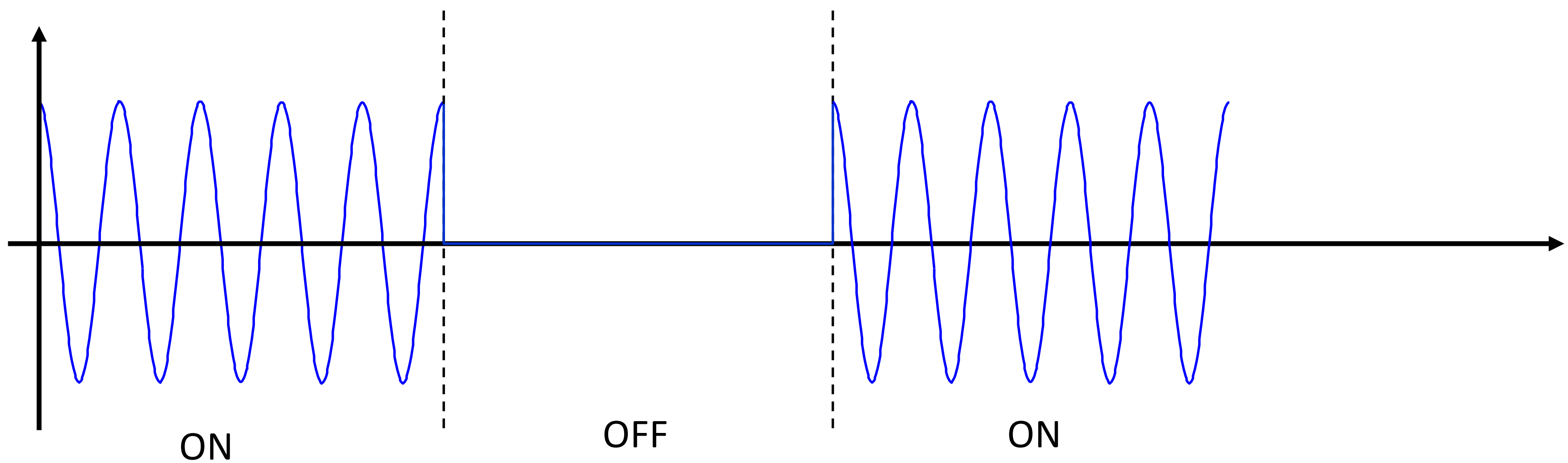
- Remarks:
  - The carrier signal is $A\cos(2\pi f_c t)$
  - The symbol duration is T seconds
- Also called On-Off keying or OOK

Average Power in Signal = $A^2/4$

Average Energy per bit $E_b = A^2T/4$

Amplitude-Shift Keying

- Susceptible to sudden gain changes
- Inefficient modulation technique (what do we mean by this?)
- Used on voice-grade lines up to 1200 bps
- Used to transmit digital data over optical fiber and in IR systems



Binary Frequency-Shift Keying (BFSK)

- Two binary digits represented by two different frequencies near the carrier frequency

$$s(t) = \begin{cases} 0\colon\ A\cos(2\pi f_1 t), & 0 \le t \le T \\ 1\colon\ A\cos(2\pi f_2 t), & 0 \le t \le T \end{cases}$$

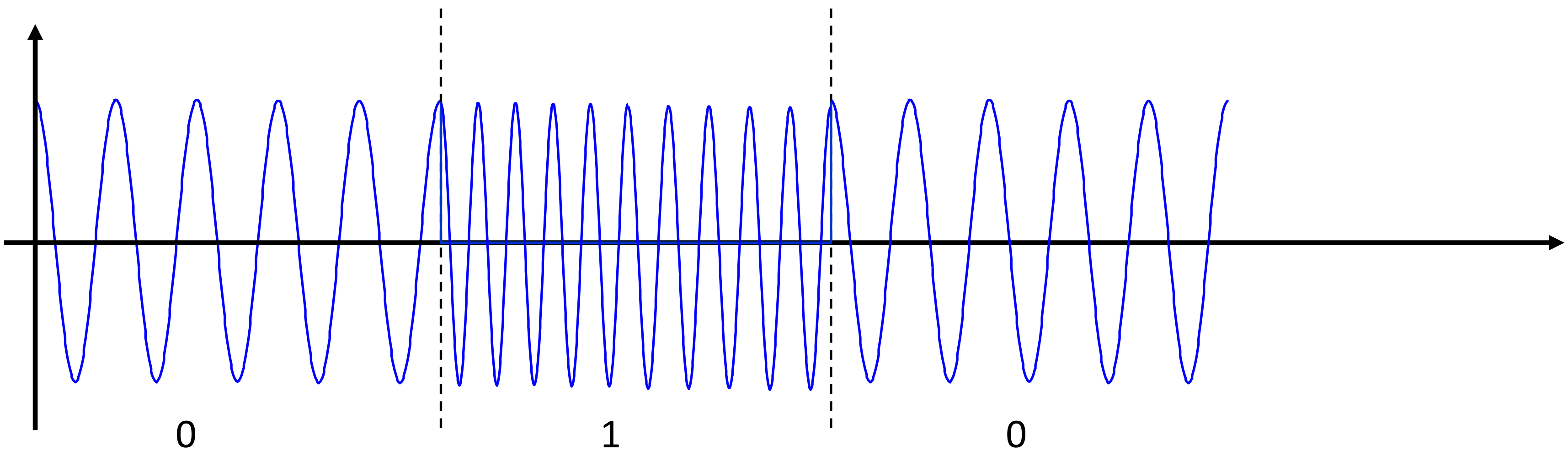
- f_1 and f_2 are offset from carrier frequency f_c by equal but opposite amounts

Average Power in Signal = $A^2/2$

$E_b = A^2T/2$

Frequency-Shift Keying (FSK)

- Less susceptible to error than ASK
- On voice-grade lines, used up to 1200bps
- Used for high-frequency (3 to 30 MHz) radio transmission
- Can be used at higher frequencies on LANs that use coaxial cable



Binary Phase-Shift Keying (PSK)

- Uses two phases to represent binary digits

$$s(t) = \begin{cases} 0: \; A\cos(2\pi f_c t), & 0 \le t \le T \\ 1: \; A\cos(2\pi f_c t + \pi), & 0 \le t \le T \end{cases}$$

  - OR

$$s(t) = \begin{cases} 0: \; A\cos(2\pi f_c t), & 0 \le t \le T \\ 1: \; -A\cos(2\pi f_c t), & 0 \le t \le T \end{cases}$$

- We revisit BPSK later

Average Power in Signal = $A^2/2$

$E_b = A^2T/2$

M-ary Modulation Schemes

- M-ary => M symbols
  - The symbols are $\alpha_1, \alpha_2, \ldots, \alpha_M$
- Each symbol carries $k = \log_2 M$ bits
  - Example: M = 4 => the symbols are α_1, α_2, α_3, α_4
  - Let $\alpha_1 = 00$, $\alpha_2 = 01$, $\alpha_3 = 10$, and $\alpha_4 = 11$
  - We have $k = 2$ bits/symbol
- The symbols can once again be represented by the amplitude, phase, or frequency of the carrier

+ Example: 4-ASK

Average Power in Signal = $7A^2/4$

$E_b = 7A^2T/8$

- In 4-ASK, we need 4 different amplitudes of the carrier to represent 4 symbols
- Let the amplitudes be 0,1,2 and 3
- The symbols will be:

$$s(t) = \begin{cases} \alpha_0 \rightarrow 00: & 0, 0 \le t \le T \\ \alpha_1 \rightarrow 01: & \cos(2\pi f_c t), 0 \le t \le T \\ \alpha_2 \rightarrow 11: & 2\cos(2\pi f_c t), 0 \le t \le T \\ \alpha_3 \rightarrow 10: & 3\cos(2\pi f_c t), 0 \le t \le T \end{cases}$$

More on M-ary modulation

- M-ASK (also called PAM) is not common
- More common are
  - MPSK – There are *M* phases of the carrier to represent the *M* symbols
  - MFSK – There are *M* frequencies around f_c to represent the *M* symbols
- Quadrature amplitude modulation (QAM)
  - Uses a combination of amplitude and phase
  - M-QAM

Advanced Modulation Schemes

- Variations on ASK, FSK and PSK possible
- Attempt to improve performance
  - Increase data for a fixed bandwidth
  - Remove requirement for phase synchronization
    - Differential modulation and detection
  - Improve BER performance
- Main schemes for wireless systems are based on FSK and PSK because they are more robust to noise

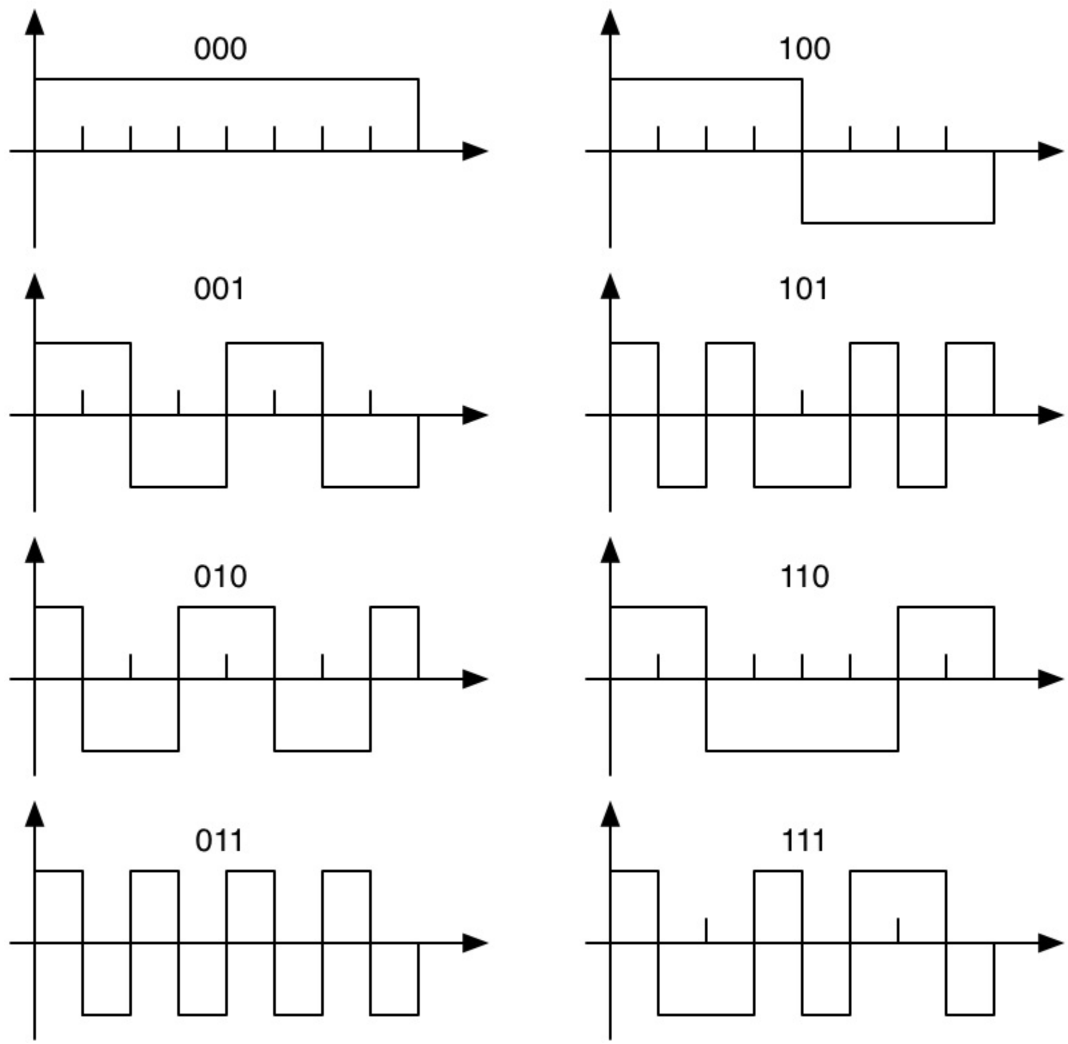
Orthogonal signaling with codes

What is orthogonality?

Show in time and frequency

Show in space

Bandwidth



Modulation schemes used in wireless networks

- GMSK
  - GSM, CDPD, Mobitex, GPRS, HIPERLAN/1
- $\pi/4$ – DQPSK
  - Tetra, IS-136
- OQPSK
  - IS-95, cdma2000
- FSK
  - ARDIS, 802.11 FHSS, Bluetooth
- BPSK, QPSK, 16-QAM, 64-QAM
  - HIPERLAN/2, IEEE 802.11a (with OFDM), LTE
- BPSK, QPSK
  - IS-95, IEEE 802.11 (with DSSS)
- Pulse Position Modulation
  - IEEE 802.11 IR
- Orthogonal Modulation
  - IS-95, cdma2000

Communication Issues

- Noise (unwanted interfering signals) is not necessarily additive, white or Gaussian
  - Examples: Inter-symbol interference (ISI), Adjacent channel interference (ACI), Co-channel interference (CCI)
  - In CDMA interference from users etc.
- Noise affects the Bit Error Rate (BER)
  - Fraction of bits that are inverted at the receiver
- Also, the radio channel has multiplicative components that degrade the performance
  - The behavior of the radio channel can increase ISI, reduce the signal strength, and increase the bit error rate

Performance in General

- What determines how successful a receiver will be in interpreting an incoming signal?
  - Signal-to-noise ratio => power
  - Data rate
  - Bandwidth
- Typical trends
  - An increase in data rate increases bit error rate
  - An increase in SNR decreases bit error rate
  - An increase in bandwidth allows an increase in data rate
- In mobile wireless systems both bandwidth and power are in short supply

Wireless Performance Considerations

- In wireless communications, the primary issues are
  - Spectrum
  - Power
  - Effects of the radio channel
- When we look at modulation schemes, we are interested in the following
  - **Performance in AWGN channels**
    - **Provides a baseline performance**
  - Performance in multipath fading channels
    - Expected performance in realistic channels
  - Bandwidth efficiency
  - Cost and complexity

Performance in AWGN Channels

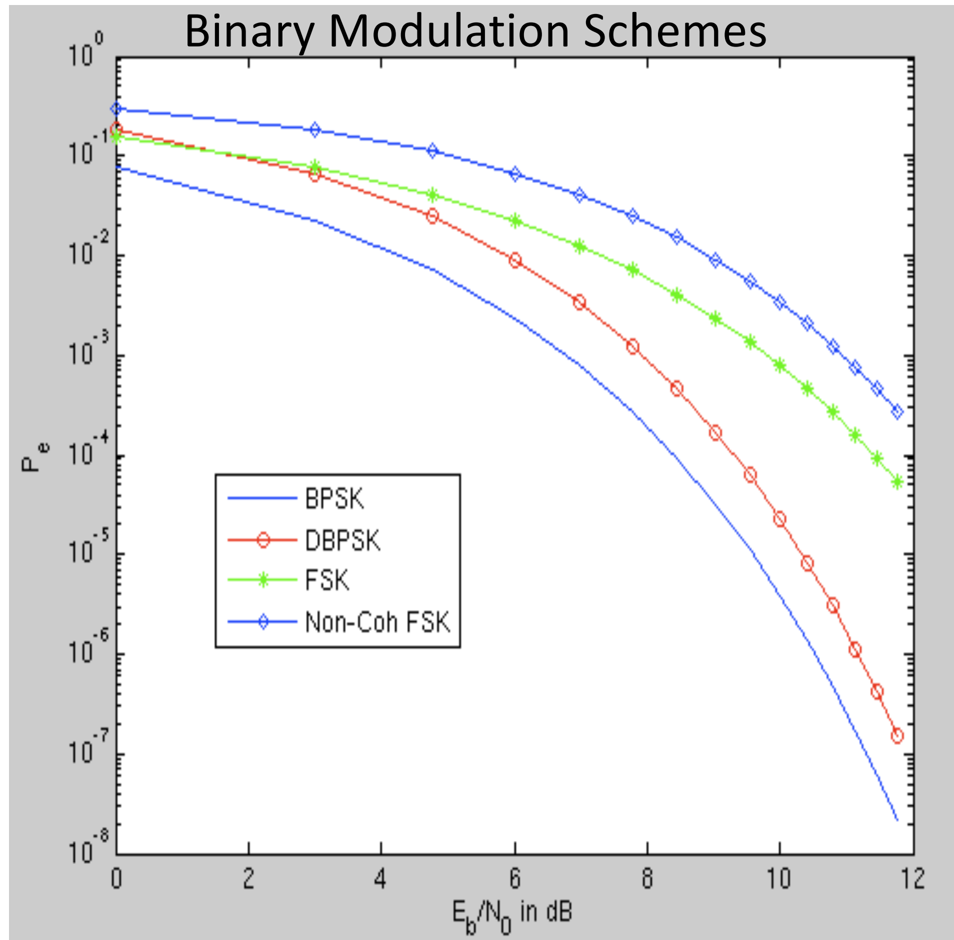
- Suppose the communications channel is only affected by AWGN (thermal noise)
  - This is the most ideal conditions you may get
  - Similar to a wire
- Provides a benchmark or baseline performance
  - Can get some insight into whether one modulation scheme is better than another
- Ideally we want
  - Very low bit error rates at small signal-to-noise ratio
  - Ensures we can conserve battery power by transmitting at low powers
  - Yet the information can be recovered reliably

Bit Error Rate or BER is a function of

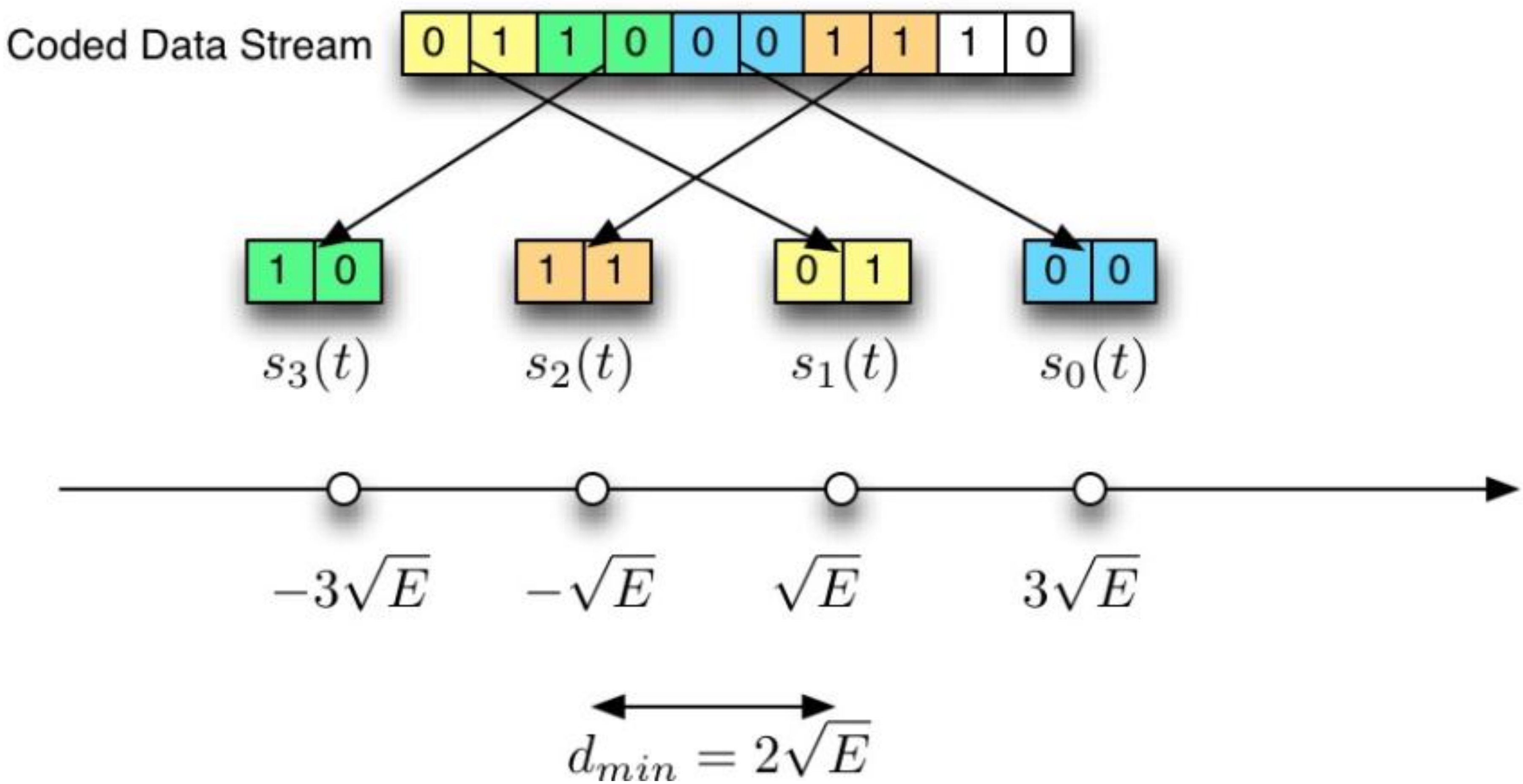
$$\frac{E_b}{N_0} = \gamma_b$$

+ Performance in AWGN channels (2)

- AWGN = Additive White Gaussian Noise
  - This has a "flat" noise spectrum with average power spectral density of N_0
- The probability of bit error (bit error rate) is measured as a function of ratio of the "energy per bit" – E_b to the average noise PSD value
  - BER or P_e variation with E_b/N_0
  - E_b/N_0 is a measure of the "power requirements"
- Tradeoffs!

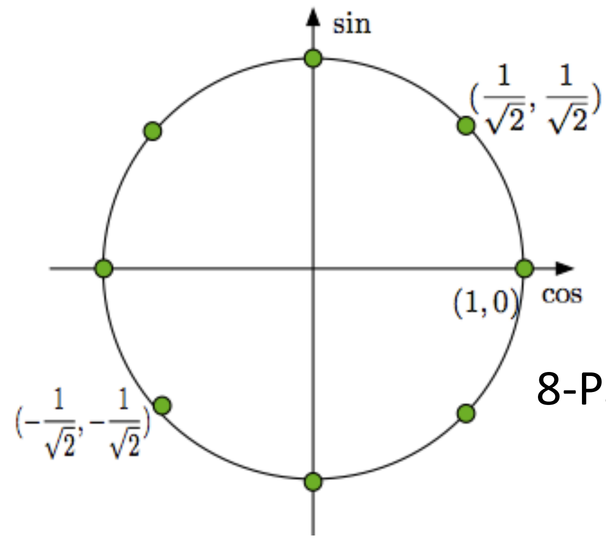


Signal Constellation (1)

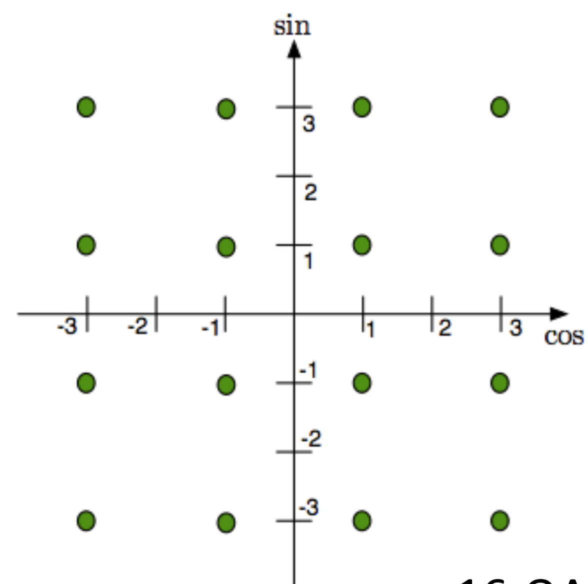


Signal Constellation (2)

- Given any modulation scheme, it is possible to obtain its signal constellation.
  - Represent each possible signal as a vector in a Euclidean space.
- In symbol detection – decode incoming signal as closest symbol in the signal constellation space
- If we know the signal constellation, we can estimate the performance in terms of the probability of symbol error given the noise parameters
- Probability of error depends on the minimum distance between the constellation points

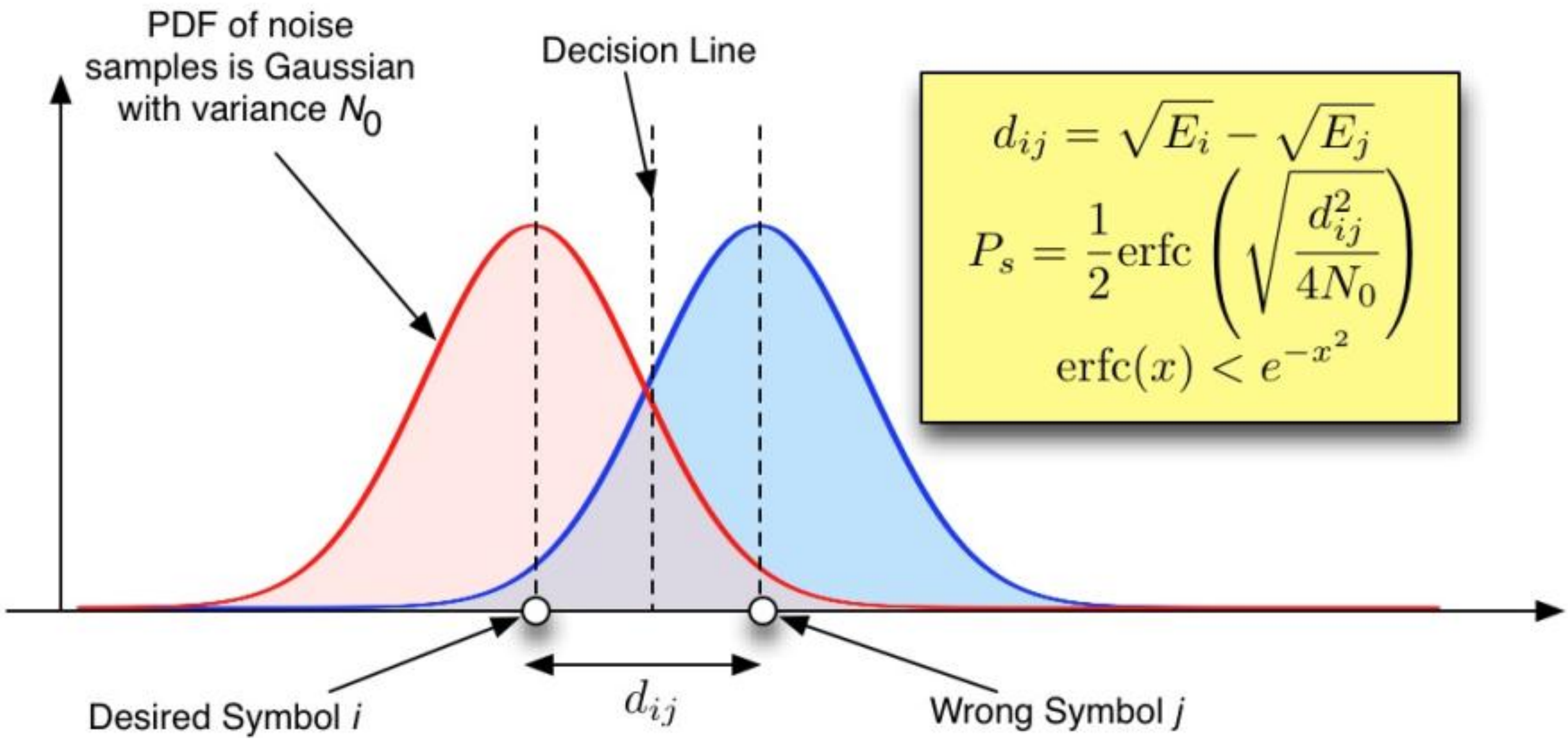


8-PSK

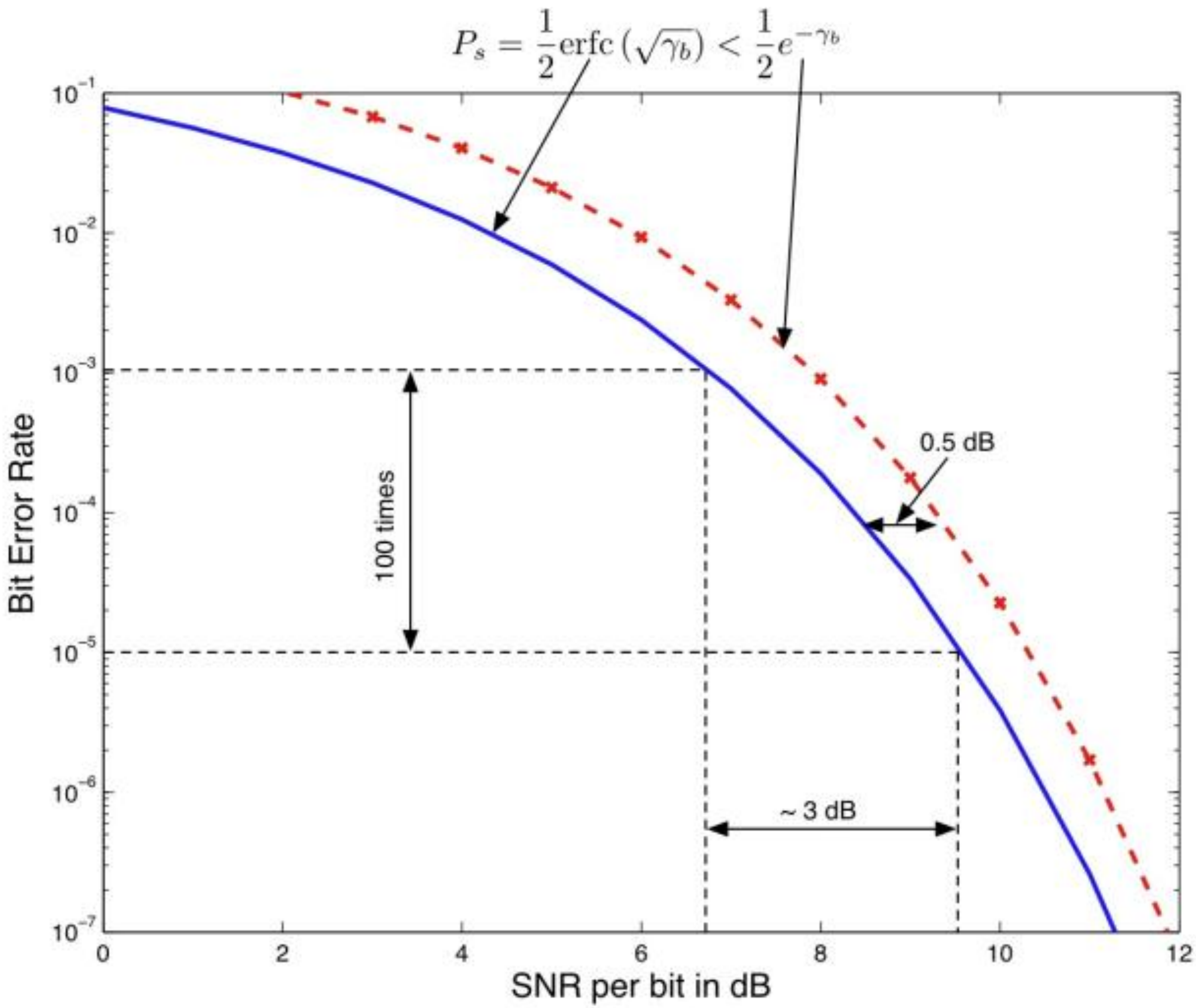


16-QAM

Probability of Error



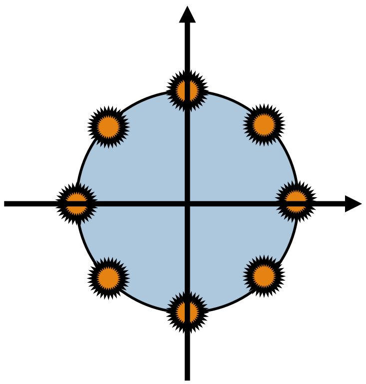
Performance in AWGN(2)

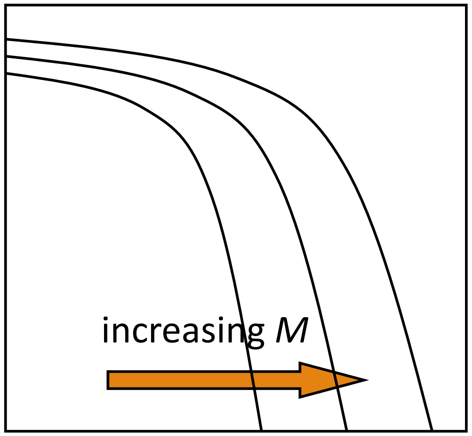


M-ary modulation schemes

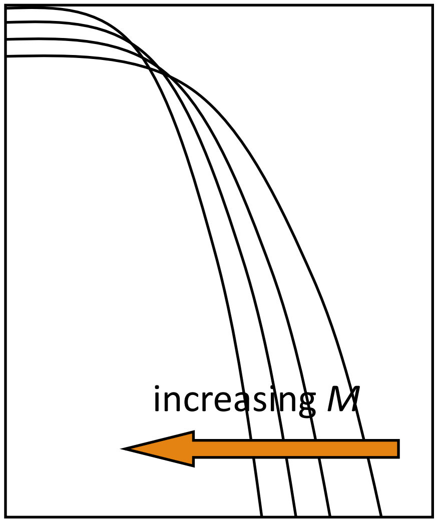
- Bits per symbol = $\log_2 M$
- Phase shift keying
  - Signal points are on a circle
  - More bits/sec/Hz but larger P_e for given E_b/N_0
- Orthogonal keying
  - M-dimensional constellation
    - FSK
    - Pulse position modulation
    - Orthogonal keying/signaling
  - Less bits/sec/Hz but much smaller P_e for given E_b/N_0
- QAM
  - Works mostly like PSK

phase shift keying or QAM





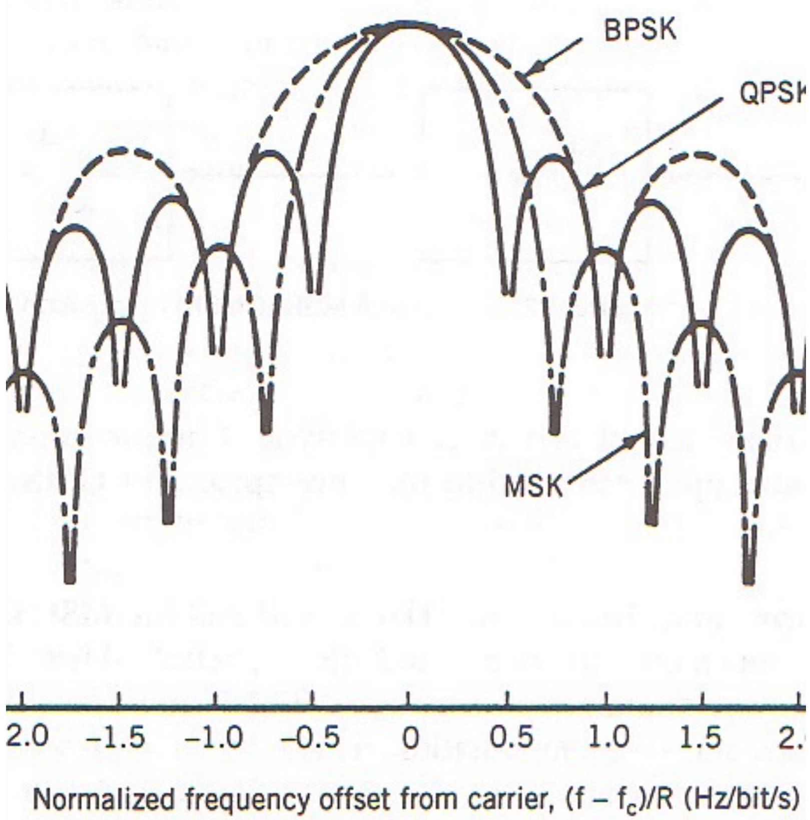
orthogonal keying

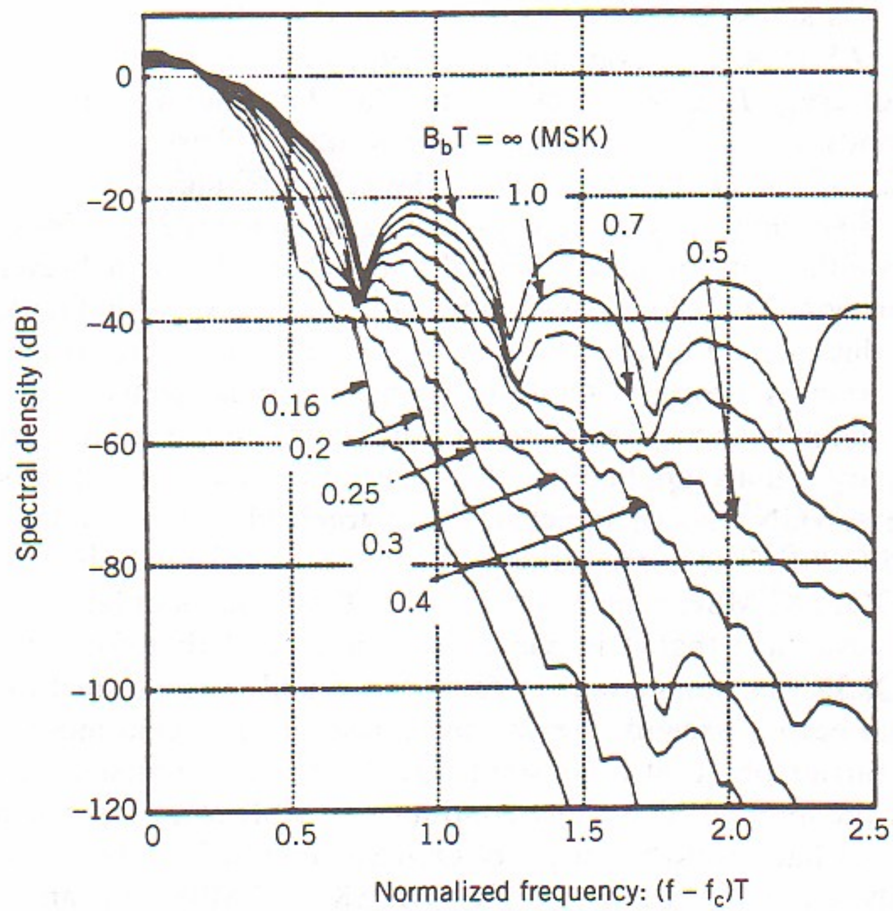


Bandwidth Efficiency and Complexity

- Bandwidth efficiency (related to spectral efficiency)
  - For a given bit error rate what is the required bandwidth for a specified data rate?
    - Recall discussion of capacity
    - Example – At a BER of 10^{-5}, BPSK requires 2 MHz for a data rate of 2 Mbps
  - Ideally our goal is to stuff as many bits as possible in a given bandwidth
  - Bandwidth (spectrum) efficiency is measured in terms of the data rate supported over a given bandwidth
  - Units: bits/sec/Hz.
- Cost/Complexity
  - In achieving good performance and bandwidth efficiency, the modulation scheme should not be too expensive or complex to implement
  - Circuitry should be simple to implement and inexpensive (e.g. detection, amplifiers)

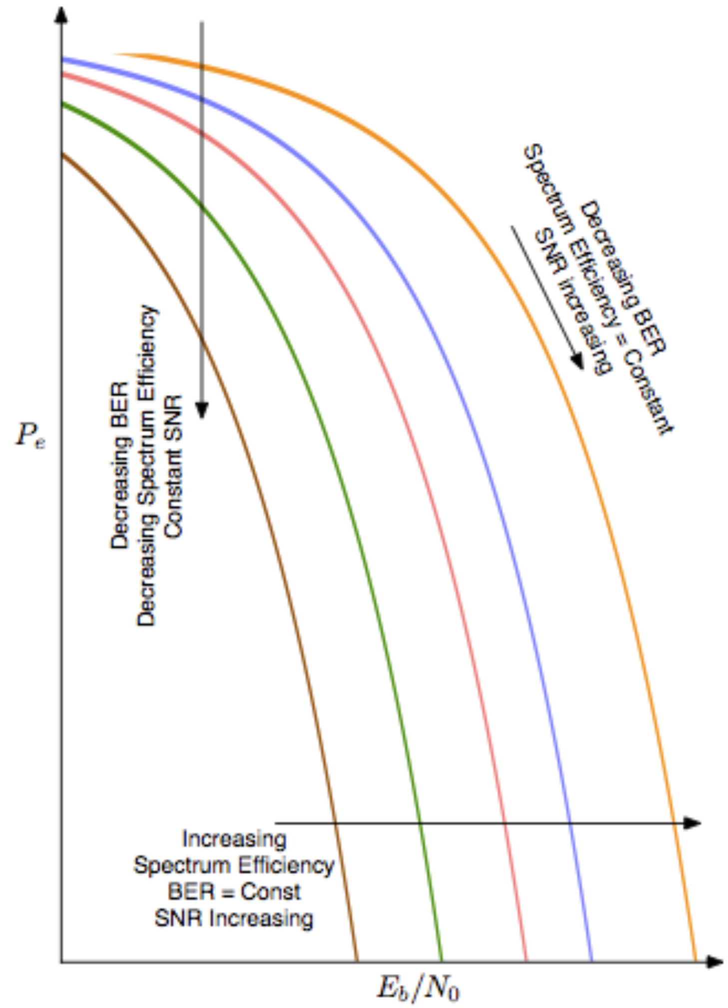
Bandwidth of modulation schemes





Tradeoffs between BER, power and bandwidth

- (1) Trade BER performance for power – fixed data rate
- (2) Trade data rate for power – fixed BER
- (3) Trade BER for data rate – fixed power



Next Week

- Small Scale Fading