Cellular Communications Tutorial

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The Cellular Concept

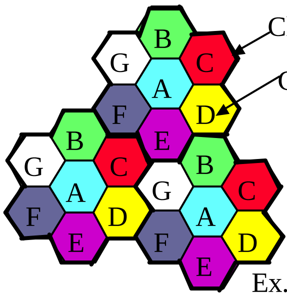
- High capacity with limited radio spectrum
  - Fixed number of channels/cluster which can be used over and over again (i.e. GSM has 25 MHz/200kHz/ channel = 125 max channels per cluster)
  - Increase capacity by:
    - decreasing cell size, with corresponding reduction in transmitter power (to keep co-channel interference low)
    - increase number of cells for a given cluster size N (therefore number of clusters goes up and increases capacity)
- Goal: Increase capacity while minimizing interference

In 1970 Bell had a mobile system in NYC with a single high power transmitter; it could only support **12 simultaneous** calls! => Cellular concept was major breakthrough in solving spectral congestion and user capacity constraints.

Key => Frequency Reuse (use lower power transmitters per cell and shrink cell size, so that frequencies can be reused more often)

Frequency Reuse

- Key Concept
  - Allows same carrier frequencies to be reused
  - Trade-off: cost ($) and complexity of managing more and more base stations goes up with capacity increase



Cluster with size N=7 cells; M = # of clusters

Cell (k = # of channels/cell)

$\boxed{C(apacity) = MkN = MS}$

Ex.: GSM - 125 ch/cluster/7 ≈ k = 17-18 ch/cell
C (3 clusters) = 3*125 = 375 total radio channels

In high density areas, the required reduction in cell size is the reason for the emergence of micro and pico base stations. The only other solution to increase capacity is to use another frequency band; this is done in GSM where in Europe the main band is from 890-960MHz and another band is from 1710-1880 MHz.

Using a separate frequency band is a form of FDD (Frequency Division Duplexing).

Real cells are not perfectly hexagonal, but rather depend on the surface contour.

Typical cluster sizes are 4, 7, 12. If the cluster size is reduced while maintaining the same cell size, capacity increases.

Small cluster size indicates that co-channels are much closer together => higher co-channel interference for fixed transmitter power.

Larger cluster size indicates that co-channels are farther away, I.e. the ratio between the distance to co-channel cells and the cell radius is large.

Interference - Co-Channel

- Co-Channel Interference (CCI)
  - Two cells that use the same frequency need to be separated far enough to keep the Carrier to Co-Channel Interference, C/I_{cc}, ratio at acceptable levels (ex.: AMPS $C/I_{cc} > 18$ dB)
  - With hexagonal cells C/I_{cc} can be approximated by:

$$\frac{C}{I_{cc}} = \frac{(D/R)^n}{6} = \frac{\left(\sqrt{3N}\right)^n}{6}$$

n = path loss exponent (typically 2-4 in urban areas)
N = cluster size (typically 7 or 12)
D = distance to center of nearest co-channel cells
R = cell radius

  - Ex.: AMPS C/I_{cc} = 18 dB, n=4 => N=6.49 => Actual N=7

Interference is a major bottleneck in increasing capacity and is often responsible for dropped calls. In practice, the transmitters of competing cellular providers are often a significant source of out-of-band interference, since competitors locate their base stations in close proximity to one another to provide similar coverage areas.

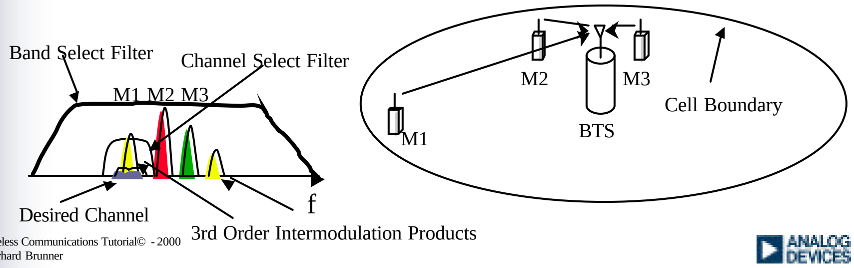
Frequency Reuse implies that in a given coverage area there are several cells that use the same carrier frequencies. These cells are called *co-channel* cells, and the interference between signals from these cells is called ***co-channel interference***.

The actual C/I_{cc} ratio is determined through subjective test to determine acceptable voice quality and BER; i.e. for AMPS this was determined to be 18 dB through field trials.

The C/I_{cc} equation in slide is an approximation that assumes hexagonal cells and that only the 6 nearest co-channel cells are producing interference at equal levels at the central cell.

Interference - Adjacent Channel

- Adjacent Channel Interference (ACI)
  - Imperfect Rx filters allow nearby frequencies into passband
  - with perfectly linear receiver only co-channel interference would be present. However, non-linearities in Rx components cause M2 to show up in M1 spectrum
  - This is called the Near-Far Effect



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ACI - due to poor out-of-band (channel) suppression of adjacent transmitters

The main reason why ACI is such a big problem, is that it results in two major issues:

1) Desensitization (also called Blocking) due to compressive nature of non-linear elements. *One* large interferer together with a very small desired signal causes the *small signal* gain to go to zero, and therefore ***blocks*** the desired small signal since it doesn't experience any gain.

2) Intermodulation - caused by 3rd order linearities in the Rx components. This is shown in the above slide, where M2 and M3 cause intermodulation distortion which effects reception of M1.

Note: If M2 is VERY large compared to M1 and M3, then the latter two will be ***blocked***. If however, M2 and M3 are approximately the same and significantly below the 1dB compression point of the receiver, then intermodulation distortion may cause the M1 signal to be swamped (see slide).

Interference (cont.)

- Power Control
  - In practical cellular systems, Tx power levels of mobiles are constantly monitored and adjusted (this is where ***log-amps [AD830x]*** and ***RMS-DC [AD8361]*** are being used)
  - Dramatically reduces C/I on *reverse channel* (from mobile to BTS); plus prolongs battery life
  - Especially important in IS-95 CDMA

CDMA - all signals are noise-like and occupy the same band, therefore it is extremely critical to make sure that all signals have the same power level at the BTS. If one mobile signal is allowed to become about 10 dB larger then all the others, then that mobile will *swamp* all other signals and effectively block their calls.

Handoff

- The cellular structure mandates ***handoff*** of a mobile from the BTS in one cell to the BTS in another cell.
- Handoff from BTS1 to BTS2 is done by Mobile Switching Center (MSC)
- If adjacent cells do not have the same frequency => channel must change - ***hard handoff***
- In IS-95 CDMA; all cells use the same channel in every cell. => only serving BTS needs to be changed - ***soft handoff***

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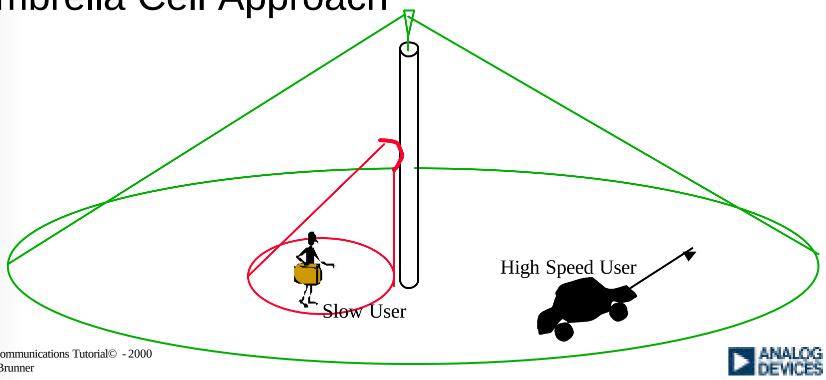
Hard handoff - in channelized wireless systems (TDMA, FDMA) different radio channels are assigned during a handoff.

Soft handoff - in IS-95 (Qualcomm CDMA), spread spectrum mobiles share the **same** channel in every cell, therefore, the term handoff does not mean a physical change in the assigned channel, but rather that a different BTS handles the radio communication task.

Handoff (cont.)

- Handoffs should be as infrequent as possible and be imperceptible to the users
  - High speed (car) users have priority over slow (pedestrian) users
- Umbrella Cell Approach



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Umbrella Cell Approach

This approach minimizes handoffs for high speed users and provides additional microcell channels for slow users => increased capacity.

Because of physical constraints, a fully separate tower for the microcell is not constructed, but rather an antenna is located on the same tower as the macro BTS.

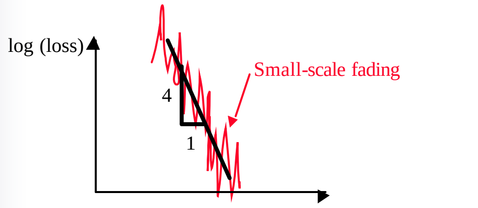
Handoff (cont.)

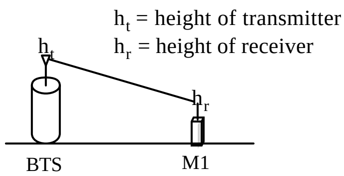
- **Mobile Assisted Handoff (MAHO)**
  - Every mobile measures received power from surrounding base stations and continually reports levels to the serving base station
  - Handoff is initiated when Rx power of other than serving BTS is higher by a certain level and time
  - Handoff requires continuous RSSI measurement of all channels

MAHO is another case for which power measurement is required, in addition to power control for interference reasons.

Fading

- Large-Scale (Average) Fading
  - This type of fading is due to the attenuation of the signal as the mobile moves further away from the base station
  - In free space signal attenuation is $\propto 1/d^2$ (20 dB/dec), however, in real situations due to ground reflection, the attenuation is $\propto 1/d^4$ (40dB/dec) for $d >> \sqrt{h_t h_r}$





Note: The attenuation rates are all in the far field of the antenna. For practical purposes, no mobile can get close enough to the base station or even to another mobile to ever be in the near field. The far field is determined by the Fraunhofer distance:

$$d_f = \frac{2D^2}{l}$$

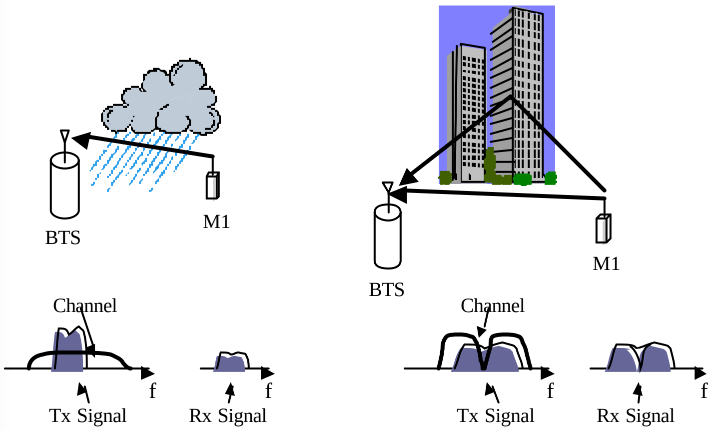
$$l = \frac{c}{f}$$

where **c** = speed of light (300 km/s), l = wavelength, **D** = largest physical linear dimension of transmitter antenna aperture. For example, assuming D=1m, and f=900MHz, d_f=6m; since most base station towers are at least 20m high to get reasonable coverage, the mobiles will always be in the far field.

Note: As an example, to show what separation d needs to be for the signal to be attenuated by 40 dB/dec, let's assume that h_t = 50m and h_r =1.5m, then d >> 8.7m. So after a "few hundred" meters, one can safely assume an attenuation of 40 dB/dec.

Multipath Fading

- Flat vs Frequency Selective Fading



During flat fading the signal is only attenuated; while during frequency selective fading the signal is distorted. Frequency selective fading is most common in mobile environments.

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Flat Fading: This is a non-frequency dependent attenuation of the transmitted signal and typically occurs during periods of heavy rain particularly at higher microwave frequencies (> 3 GHz). Therefore most mobile systems tend to not experience flat fading since the RF carrier frequencies are mostly below 3 GHz.

Flat fading channels are also known as **amplitude varying channels**. Typically flat fading channels cause deep fades and may require 20-30 dB more transmitter power to achieve low bit error rates.

A flat fading event reduces the C/N (SNR) and therefore is equivalent to a rise of the noise floor.

Frequency Selective Fading: If the channel has a constant gain and linear phase response over a bandwidth that is smaller than the transmitted signal bandwidth, then the received signal will experience frequency selective fading. This type of fading is more pronounced for lower RF carrier frequencies and therefore is the dominant fading for mobile systems.

This type of fading is the **predominant** fading mechanism in a **mobile environment**, compared to **flat, slow**, and **fast fading**.

Multipath Fading (cont.)

- Fast vs Slow Fading
  - Both types of fading are due to ***Doppler frequency shifts*** because the mobile is moving
- Fast Fading Channel:
  - Channel impulse response changes rapidly within one symbol duration (time selective fading causes frequency dispersion)
- Slow Fading Channel:
  - Channel impulse response changes slowly over a few symbol durations

Due to the relative movement between the base station and mobile, the different multipath waves experience different Doppler frequency shifts.

Fast Fading:

Practically only occurs for very low data rates, because the Doppler frequency spread is in the range of only a few hundred Hz for even the fastest moving vehicles like trains or cars.

Slow Fading:

This type of fading could look like a flat fading incident if the movement of the mobile is very slow.

Summary:

Multipath leads to **time dispersion** (pulse distortion) and **frequency selective fading**, while **Dopper spreading** leads to **frequency dispersion** and **time selective fading**. The two propagation mechanisms are independent of each other.

Even though there exist models for the various forms of signal fading, in actual practice, field measurements will have to be taken to provide parameters for system simulations and for cell design. Much of the work is still empirical.

Flat fading generates an even distribution of errors, while **multipath fading** generates bursts of errors.

Multipath Fading Solutions

- Frequency Diversity
  - Multiple carrier frequencies are used since fading is less likely to occur at two frequencies with “sufficient” spacing
- Space (Antenna) Diversity
  - Separate antennas that are separated more than 1/2 of a carrier wavelength (practical only in point-to-point radios)
- Polarization Diversity
  - Horizontal and vertical polarization between mobile and BTS is uncorrelated
  - At most two diversity branches, BUT antennas can be co-located
- Time Diversity
  - Is a form of data redundancy; data is transmitted more than once (overhead reduces data rate though)
  - CDMA RAKE receiver is an implementation of time diversity

RAKE receiver - CDMA spreading codes are designed to provide low correlation between successive chips (transmit “bit” rate). Thus if the multipath components are delayed by more than one chip period, they appear like uncorrelated noise at a CDMA receiver. By using multiple receivers (correlators), one can detect separate multipath components and weight them such that the strongest multipath component is selected while correlator outputs corrupted by fading can be weighted such that they are discounted in the overall sum of received signals.

Note that the RAKE receiver is a form of phased array.

Multipath Fading Solutions (cont.)

- Interleaving or Direct Sequence Spread Spectrum
  - Data gets scrambled before transmitting; it is a form of time diversity (no overhead, but some latency due to processing time)
- Adaptive Equalizer
  - Especially important at higher modulations like 16 or 64 QAM

Interleaving and Direct Sequence Spread Spectrum (DSSS)

DSSS can be thought of as a form of interleaving, i.e. the transmit data stream is scrambled. As pointed out earlier in the presentation, frequency selective fading (FSF) is the biggest problem for a narrow band signal. The reason why FSF is such a big problem, is that it creates a null in the transmitted signal band or amplitude slope across the band. As a percentage of signal BW, this null can be quite large and therefore destroy the signal such that little or no data can be recovered at the receiver. However, if the same data is scrambled or "chipped" as in DSSS, then the transmit BW of the signal goes up and consequently the same FSF event will destroy a smaller percentage of the signal BW and cause less errors.

Equalization - if multipath is fixed with time it can be effectively countered by adaptive equalization. This is may be the case for a slow moving mobile, like for a pedestrian.

Multiple Access - Transmission Modes

- **Simplex**
  - Transmission possible only in one direction (i.e. paging)
- **Half-Duplex**
  - Two-way communications, but only one channel for Rx and Tx (i.e. walkie-talkie, only one person can speak at a time - “Over”)
- **Full-Duplex**
  - Simultaneous two-way communications (i.e. cordless phone)
  - ***Frequency Division Duplex*** (**FDD**) or ***Time Division Duplex*** (**TDD**) are used to provide full-duplex service

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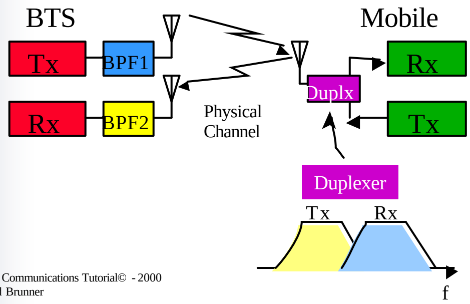
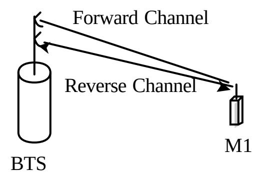
FDD

- BTS: typically separate Tx and Rx antennas
- Mobile: one antenna + duplexer
- Pair of simplex radio channels ***separated in frequency*** define the full-duplex logical channel (“Dual Radio Pipe”)
- Analog and Digital Radios can use FDD





Duplexer Problems :

Duplexer power loss typically 2-3 dB, therefore up to half the power out of the mobile PA will be lost at the antenna!

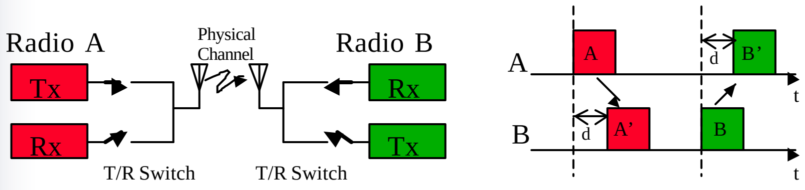
The same 3 dB duplexer loss increases the NF by 3 dB in the receiver of the mobile.

Typical attenuation between Rx and Tx of duplexer is about 50 dB, thus the strong Tx signal will leak into the receive band. However, in most systems the Tx and Rx time slots are offset in time, which significantly relaxes PA leakage into the receive band and corresponding desensitization of the LNA.

Consequently, the main reasons that duplexers are used, is that they are small and relatively cheap.

TDD

- Shares a ***single radio channel*** in time (“Single Radio Pipe”)
- Pair of simplex channels ***separated in time*** define the full-duplex logical channel
- ***Only*** possible for Digital Radio
- Tx data rate typically >> user data rate



d - Physical channel propagation delay

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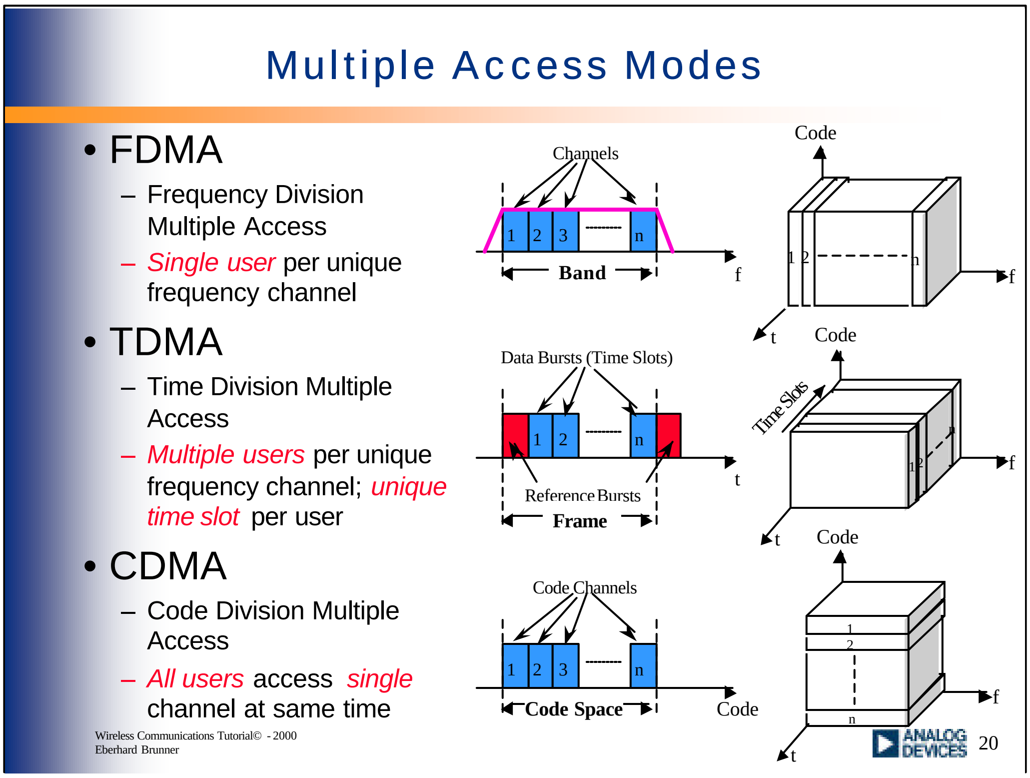


FDMA

Analogy: A room full of people where pairs are talking in ***different pitches.***

FDMA is the simplest to understand; each allocated frequency channel is a dedicated communication "***pipe***" from user ***A*** to user ***B***. No data buffering needed as in TDMA, since the connection is ***on*** for all time. This is the ***only*** way to make a full-duplex analog radio!

TDMA

Analogy: A room full of people where pairs are talking and only ***one pair at a time*** is allowed to speak.

Requires data buffering since each user only gets to transmit every n-th time. This is also the reason why the individual time slots are called ***data bursts***! It also means that the data rate during a transmit burst is n-times higher than the user data rate.

Note also, that the base station has to ***continually*** process data at the n-times user data rate! This is one of the factors that makes BTS design more demanding then mobile design in a TDMA system.

CDMA

Analogy: A room full of people where pairs are talking in ***different languages***.

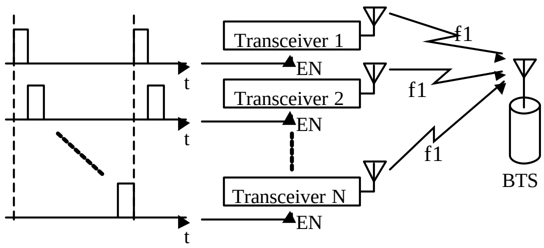
Objective is to transmit signals from multiple users in the ***same frequency band at the same time***. Looking at it from the FDMA and TDMA perspective this means that we only have ***one*** channel. The way different users get differentiated in CDMA is through different codes that multiply the actual data. In essence each mobile gets assigned a personal key for the length of the connection. The number of different keys (codes) determines the number of users that can be accommodated. Theoretically, this means that an infinite number of users could share the channel, however, as the number of users goes up, the average signal level goes up (each user transmitting generates a noise like signal) and eventually no one can "hear". In the analogy this means that too many people are in the room and it just gets too loud.

FDMA

- Carries only one phone circuit at a time per channel
- BW tends to be narrow since only one circuit per carrier (channel)
- Continuous transmission scheme
- Requires tight RF filtering to minimize adjacent channel interference
- Idle channels are wasted resource

TDMA

- Shares a single carrier frequency with several users
- Non-overlapping time slots
- Data transmission is in bursts
- Lower power because transmitter can be turned off, between bursts
- Handoff is simpler, since mobile can listen during idle time slots
- No duplexer needed
- High synch overhead



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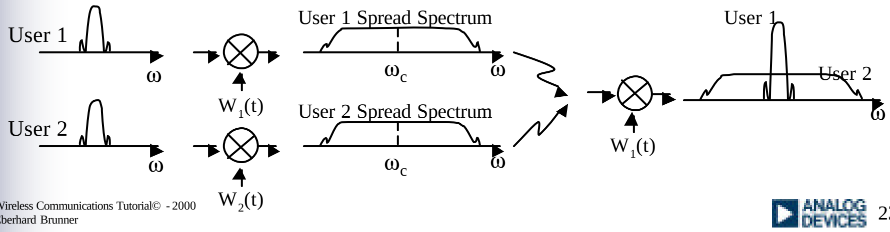
High synchronization overhead due to burst transmission; during each transmission, the receivers need to be synchronized for each data burst. In addition, guard slots are necessary to separate users, and this causes TDMA to have larger overheads than FDMA.

CDMA

- Provides immunity to multipath
- Power control essential to avoid *near-far* problem
- Soft capacity limit
- Soft handoff
- Self-Jamming
- CDMA is very bandwidth inefficient for a single user, however in a multiple user environment it becomes very efficient because of shared spectrum



Power Control: the strongest received signal at BTS will *capture* the BTS demodulator, unless power control makes sure that all mobiles signals arrive with equal power at the BTS. Out-of-cell mobiles that are not under control of the receiving BTS still can cause problems.

Soft Capacity Limit: Increasing the # of users in a CDMA system raises the noise floor in a linear manner. Therefore, there is no absolute limit on the # of users. Rather the system performance degrades equally for all users as the number of users increases, and improves equally as the number of users decreases.

Soft Handoff: CDMA uses co-channel cells, thus it can provide macroscopic spatial diversity to provide soft handoff. Soft handoff is possible because the MSC can monitor a user from two or more base stations simultaneously. The MSC may choose the best version of the signal at any time without switching frequencies.

Self-Jamming: Arises from the fact that codes are not perfectly orthogonal, hence during despreading of a particular code, non-zero contributions arise from transmissions of other users.

Multiple Access Comparison

Generation	Cellular System	Multiple Access Techniques
1G	Advanced Mobile Phone System (AMPS)	FDMA/FDD
2G	US Digital Cellular (USDC, NADC)	TDMA/FDD
2G	Japanese Digital Cellular (PDC, JDC)	TDMA/FDD
2G	Digital European Cordless Telephone (DECT)	FDMA/TDD
2G	GSM	TDMA/FDD
2G	US Narrow band spread spectrum (IS-95)	CDMA/FDD
3G	EDGE	TDMA/FDD
3G	UMTS - WCDMA	CDMA/FDD

Major Wireless Standards Summary

Generation	1G	2G						
Standard Name	AMPS	NADC (IS-54)	GSM	PDC (JDC)	CDMA (IS-95)	DECT	DCS1800	PHS
Multiple Access/ Duplexing	FDMA/FDD	TDMA/FDMA/ FDD	TDMA/FDMA/ FDD	TDMA/FDMA/ FDD	CDMA/FDD	FDMA/TDMA/ TDD	TDMA/FDMA/ FDD	TDMA/FDMA/ TDD
Frequency Bands (MHz)	824-849 (R) 869-894 (F)	824-849 (R) 869-894 (F)	890-915 (R) 935-960 (F)	810-826/1429-1453 (R) 940-956/1477-1501 (F)	824-849 (R) 869-894 (F)	1880-1900 (10 ch)	1710-1785 (R) 1805-1880 (F)	1895-1906.1
Number of Carriers	833	833	125	1600 (?)	5 (A) 6 (B) 11 (Total)	10	375	37
Carrier Spacing/ Ch. BW (kHz)	30	30	200	25	1250	1728	200	300
Traffic Channels per Carrier	1	3 (Full-Rate) 6 (Half-Rate)	8	3 (Full-Rate) 6 (Half-Rate)	Up to 62; typ. 55	12	8	4
Total Voice Channels	832	2500 (F-R) 5000 (H-R)	1000	3000	682	120	3000	148
Modulation	Analog FM	$\pi/4$ DQPSK	GMSK (BT=0.3)	$\pi/4$ DQPSK	OQPSK (R) QPSK (F)	GFSK	GMSK (BT=0.3)	$\pi/4$ QPSK
User Data Rate (kbps)	10	48.6	270.833	42	9.6 14.4	1152	270.833	384
Chip Rate (Mcps)	---	---	---	---	1.288	---	---	---

CDMA (IS-95) - Total channels is limited by the number of unique PN sequences on the forward link (64; 62 max usable voice channels) per cell, however, capacity can be increased by reducing cell size and increasing number of cells. Also in principle, the number if PN codes could be increased to increase the number of users.

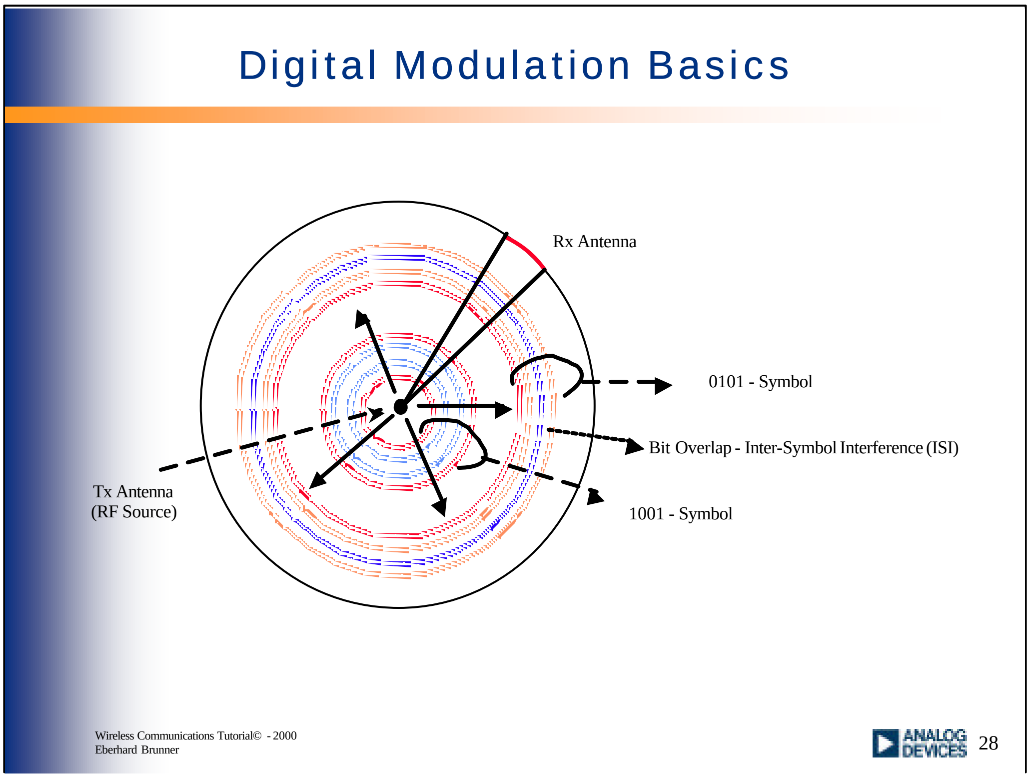
Modulation Basics

- Why ***modulation***?
  - allows multiple information sources to use common channel; i.e. ***simultaneous transmission of multiple signals***
  - the size of the radiating element has to be a significant fraction of the wavelength of the signal; i.e. the antenna can be smaller at higher frequencies
  - FCC (or equivalent in other countries) says which part of spectrum can be used
- The inverse of modulation is ***demodulation*** or ***detection***

Without modulation, only one baseband signal could be transmitted within a given location. An analogy is a room full of people, where only one person can talk at a time. A form of modulation would be for different groups that want to communicate to use different languages.

Types of Modulation

- There are only three types of analog modulation:
  - Amplitude Modulation (AM)
  - Frequency Modulation (FM)
  - Phase Modulation (PM)
- Digital equivalents:
  - Amplitude Shift Keying (ASK)
  - Frequency Shift Keying (FSK)
  - Phase Shift Keying (PSK)
- Digital Only
  - m-ary Modulation like m-PSK, QAM, and multi-carrier (m-FSK) where symbols may be represented by different carriers (i.e. xDSL)
  - Direct Sequence Spread Spectrum



Analogy: Imagine a circular fountain with a raised middle section (a little hill). In the middle of the hill is a well from which water comes continuously. The water runs down the hill on all sides equally towards the edges of the fountain. Now imagine that there are two people: one in the middle of the fountain right by the well (person A), and another at the edge of the fountain (person B). The one in the middle wants to send a message to the one on the edge. He drops red and blue ink in the water; red represents a '1' and blue represents a '0'. Both have agreed on a code beforehand, i.e. 5 bits are used to represent all the letters of the alphabet.

Therefore as A drops alternating red and blue ink in the water, B will observe what arrives at the edge of the fountain (a small part of the total color that was dropped in by A) and can decode what A sent. Assuming, of course, that the colors have not dispersed so completely that B can't tell which color was sent. Of course, if B would have some color detection device that can determine what color was dropped in the water even when he can't see it anymore, then he could still decode As message even in a fountain with larger diameter.

This analogy is equivalent to the following in a digital radio: water - RF carrier; red and blue color - positive and negative pulses which modulate RF carrier; central well with water flowing in all directions - omni-directional antenna; color detection device of B - LNA.

Modems

- Overall performance depends on modulator and demodulator together (***Modems***) and what type of channel is used
- Important aspects of Modulation Scheme
  - C/N required for given BER and bandwidth (***digital modems only***)
  - How effectively is channel capacity used
  - Required bandwidth (***spectral (bandwidth) efficiency***)
  - Determines type of power amplifier used (linear or nonlinear; ***power efficiency***)

Digital Modulation

- Why ***Quadrature Modulation***?
  - Because for a given channel bandwidth, an I/Q modulated signal allows ***higher data rates*** depending on the ***number of bits/symbol***
  - The above implies higher spectral efficiency

$$Symbol\ Rate = Bit\ Rate / n \qquad \text{n = number of bits per symbol}$$
$$n = \log_2(m) \quad \text{bits/symbol;} \qquad \text{m = states per symbol}$$

    - Ex.: 16 QAM => n=4, bit rate = 2 Mbps, => symbol rate = 500 kHz
- Cost
  - More complicated modems
  - Requires higher C/N ratio
  - Spectral (bandwidth) efficiency - => Power Efficiency

Channel Capacity

- Shannon's Channel Capacity Theorem

$$C = B \cdot \log_2\left(1 + \frac{S}{N}\right) \quad \text{in bps;} \quad \text{upper theoretical limit}$$

$$h_B = \frac{R}{B} \quad \text{in bps/Hz;} \quad \text{Spectral (bandwidth) efficiency}$$

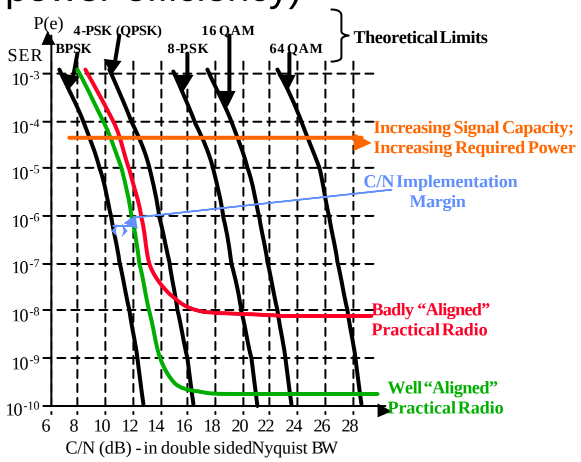
- This theorem determines the theoretical limit on channel capacity for a given bandwidth (B) and signal-to-noise ratio (S/N)

Digital Modulation Scheme Choice

- What determines the choice of a digital modulation scheme in a system?
  - Low BER at low SNR
  - Performs well in multipath and fading conditions (low sensitivity to interference)
  - Occupies minimum bandwidth (best bandwidth efficiency)
  - Uses least amount of power (best power efficiency)
  - Low sensitivity to timing jitter (i.e. good decision thresholds)
  - Easy and cost-effective to implement

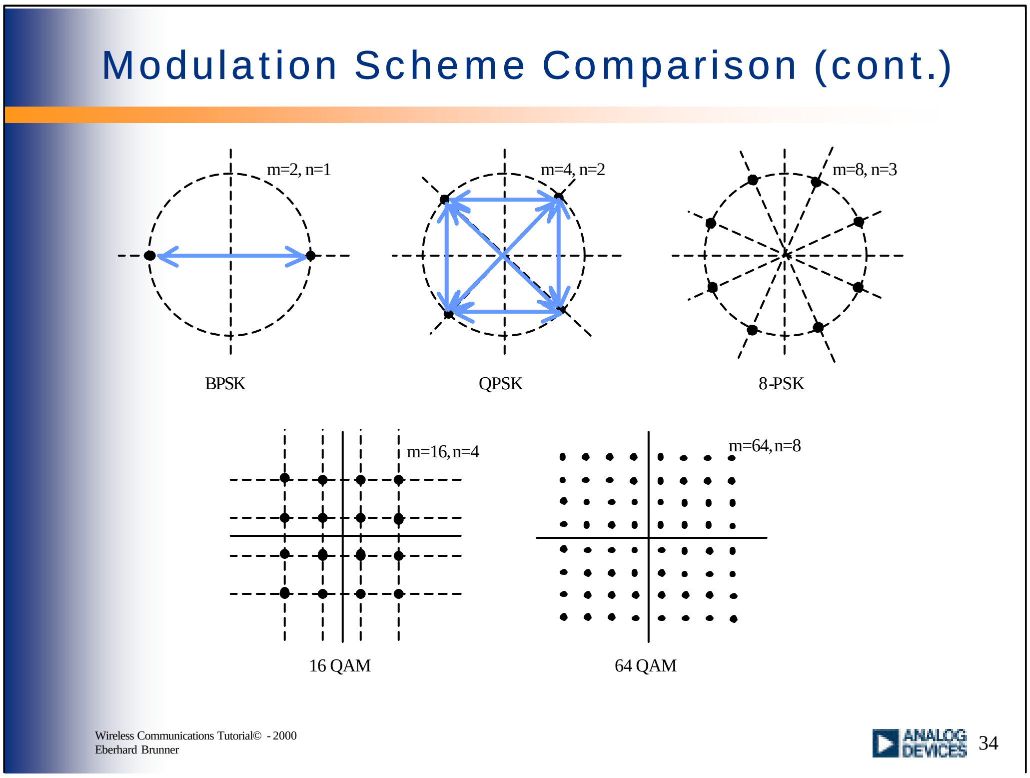
Modulation Scheme Comparison

- For increasing signal capacity (i.e. higher data rate), a higher C/N is required at the receiver (i.e. lower power efficiency)



C/N Implementation Margin comes from the summation of all the imperfections in a radio system. The smaller it is, the better, since one gets closer to the ideal radio system for a given chosen modulation.

In general one can say: the more complex the modulation, the larger the implementation margin will be. Or a corollary: the more complex the modulation, the more difficult it is to get to the theoretical C/N curve.



The blue arrows indicate possible phase transitions. Note that 180° phase changes (through center of constellation in QPSK case) cause the envelope of the RF carrier waveform to go to zero for an instant. Also the instantaneous phase transitions result in a very wide bandwidth signal, normally the signal will need to be filtered (i.e. raised cosine) to suppress the sidelobes of the sin(x)/x response due to the digital BB square waves. However, the filtering causes a non-constant amplitude of the QPSK signal. This now requires a ***linear power amplifier***, while for the unfiltered QPSK signal a ***nonlinear power amplifier*** would have sufficed. This is an example of the trade-off between ***spectral and power efficiency***.

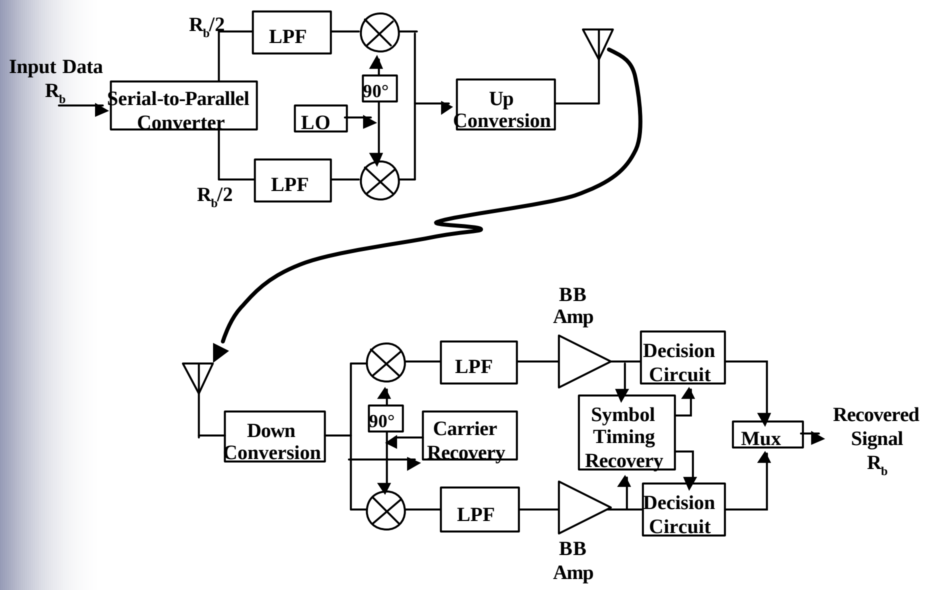
Furthermore, if the required linear PA is not perfect, the non-linearity causes the spectrum to widen again - this is called ***spectral re-growth***. The effect of this is an increase in ***adjacent channel power*** which causes ACI in a neighboring channel.

One modified version of the QPSK modulation that avoids 180° phase changes is the $\pi/4$-QPSK modulation; it has at most 135° phase changes. Therefore, a less linear (i.e. more efficient) PA can be used.

Another class of modulation schemes that is even more power efficient than the QPSK family are MSK (Minimum Shift Keying) signals. However, MSK signals require larger bandwidths than QPSK waveforms. But they belong to the class of constant envelope modulations which allow the use of highly efficient, non-linear Class C power amplifiers. GMSK is one popular example of this class of modulation schemes.

NOTE: To increase the data rate for a fixed channel BW in a system like GSM, requires that the modulation needs to be changed; i.e. the constant envelope of GMSK won't hold anymore. From the discussion above it should be obvious that now ***linear PAs are required***!!! Therefore in the move from GSM to GSM EDGE, parts that can be helpful in ***PA linearization***, like the ***AD8302, AD8347, AD8313*** are in high demand.

QPSK Communication Example



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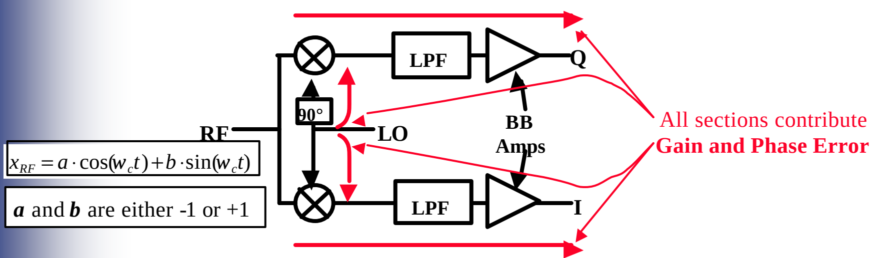
Note that in this example no assumptions are made on the implementation of the I/Q modulator and demodulator, i.e. if they are implemented in analog or digital.

How this partitioning is done is a matter of transceiver architecture (heterodyne, homodyne, IF sampling, etc.).

I/Q Mismatch



$$x_{LO,I}(t) = 2 \cdot (1 + \frac{e}{2}) \cdot \cos(w_c t + \frac{q}{2})$$

$$x_{LO,Q}(t) = 2 \cdot (1 - \frac{e}{2}) \cdot \sin(w_c t - \frac{q}{2})$$

Note: All gain and phase errors are assumed to be introduced by the LO paths.
The factor of ***2*** is introduced to simplify results.

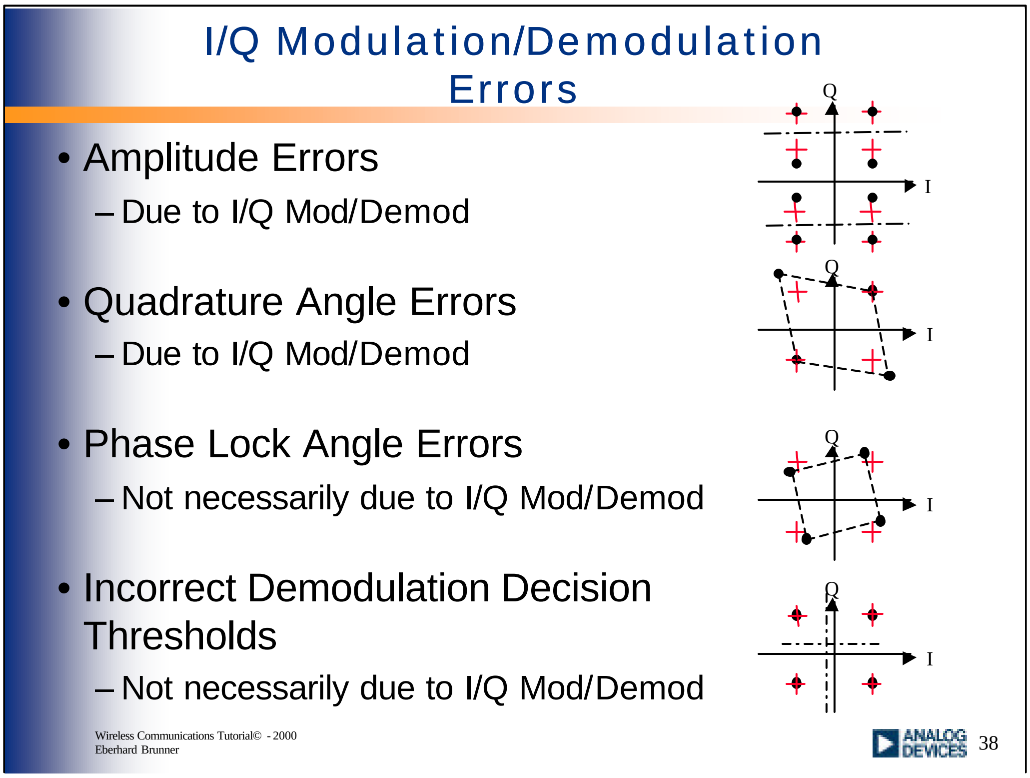
$$x_{BB,I}(t) = a \cdot (1 + \frac{e}{2}) \cdot \cos\frac{q}{2} - b \cdot (1 + \frac{e}{2}) \cdot \sin\frac{q}{2}$$

$$x_{BB,Q}(t) = -a \cdot (1 - \frac{e}{2}) \cdot \sin\frac{q}{2} + b \cdot (1 - \frac{e}{2}) \cdot \cos\frac{q}{2}$$

Note that the above equation for the RF signal is technically not totally correct since ***a*** and ***b*** are really functions of time. However, at the sampling instance the value of ***a*** and ***b*** are ideally -1 or +1. This allows the BB equations to be simpler and to observe the effects of modulator imperfections, rather than sampling misalignment (could be due to timing jitter).

Key Specs for I/Q Demodulator

- Noise Figure
- P1dB
- IIP2 and IIP3
- Offset
- Gain Imbalance and Phase Error (I/Q Mismatch)
- LO Leakage (to RF input and I/Q baseband outputs)
- LO Power needed for specified performance
- Conversion Gain (and how it is partitioned)
- Gain Flatness (over signal bandwidth)
- Group Delay Flatness
- Baseband Bandwidth



Amplitude Errors

- Non-equal amplitude values (could be due to gain error, in which case the constellation looks "squashed" but symmetric)

- Unequal I/Q levels

- Non-linear modulation of I/Q carriers

Quadrature Angle Errors

Errors due to I/Q carriers not being at exactly 90º; the result is a constellation diagram that is trapezoidal or rhombic in shape

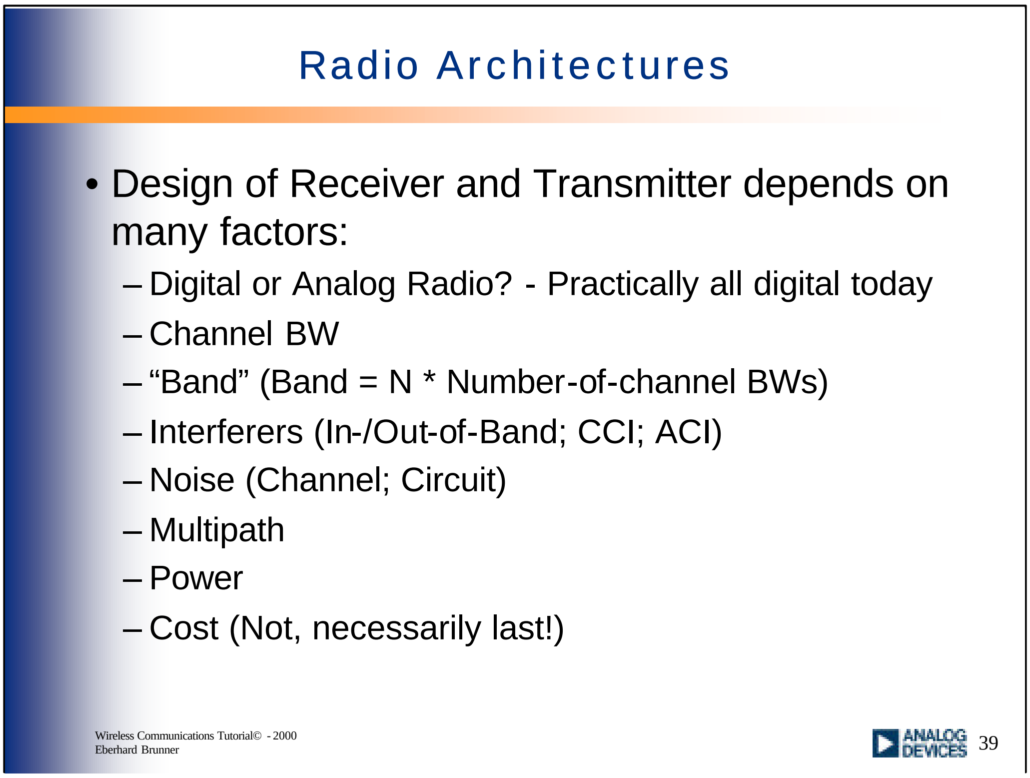
Phase Lock Angle Errors

Recovered carrier is not correctly phased with incoming signal, resulting in rotated constellation

Incorrect Demodulation Decision Thresholds

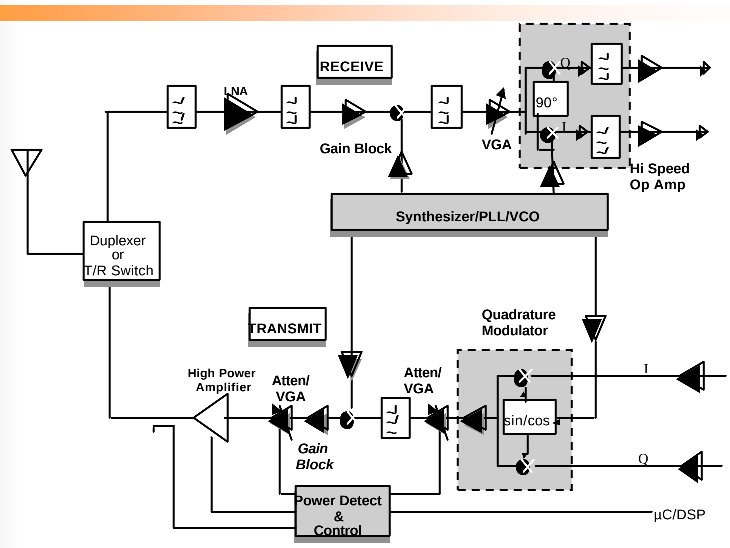
Similar in effect to amplitude errors in the modulator; end result is a reduced margin between state value and decision threshold

Note: The constellation is perhaps the most useful of all the digital radio measurements since all the possible radio impairments can be observed!



Band/Channel - i.e. GSM has two 25 MHz bands (890-915MHz, reverse link, mobile to BTS; 935-960 MHz, forward link, BTS to mobile) with 200 kHz channels

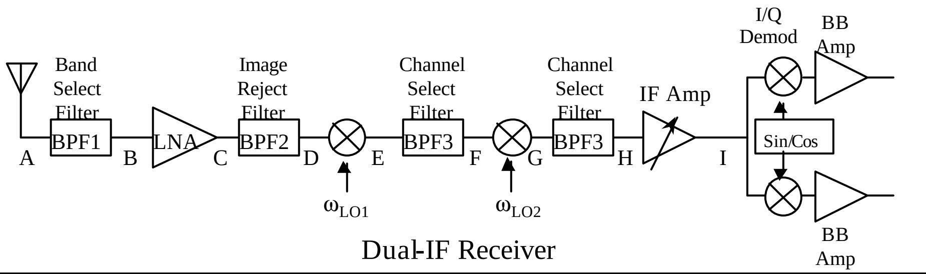
Representative Transceiver



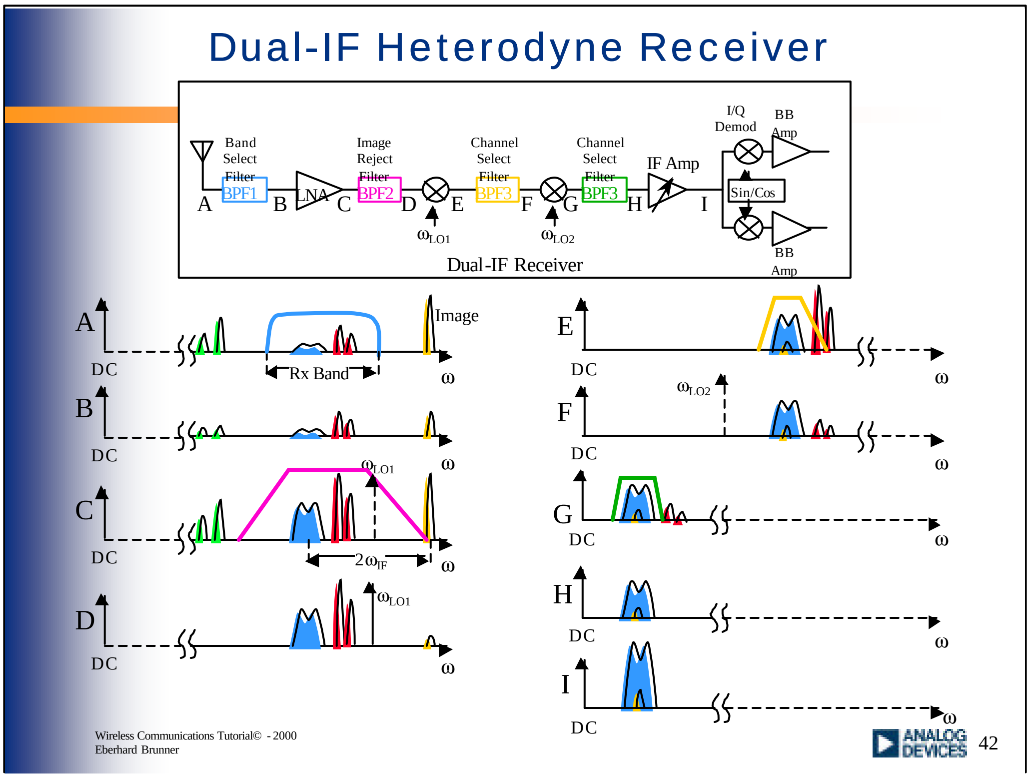
Generic Diagram - no presumptions are made on type of architecture yet, i.e. IF sampling, analog I/Q, etc.

Receivers - Heterodyne

– ***Heterodyne*** (Hetero - other, another; Dyne - to mix)
- Single- or “Multi”-IF (Super Heterodyne) Topology
- Advantageous for narrow-band signals
- Allows use of ***standard IFs*** (cheap filters)
- Requires frequency synthesizer at ω_{LO1} to get to common IF
- ω_{LO2} can be a fixed frequency if ω_{LO1} does channel selection
- I/Q demodulator not very demanding; can be done digitally



Dual-IF Receiver



This slide shows how a desired signal (blue) is extracted from large interferers even though its signal level is much smaller compared to the interferers. The letters A-I show the signal at various stages in the receiver.

At the antenna (A), it is difficult to achieve high-Q filters because of the required ratio of signal BW to RF carrier. I.e. for a 30 kHz AMPS channel at 900 MHz, with 60 dB rejection at 45 kHz offset, the Q would have to be on the order of 10^7, a value difficult to achieve even in SAW filters. Note also that high-Q filters tend to have higher loss which directly translates to higher Noise Figure. This is especially critical in receivers. Therefore BPF1 tends to be a ***band select filter*** which is quite broad band with relatively low Q. In the case of AMPS, this filter has a BW of about 25 MHz.

BPF1 attenuates out-of-band interferers somewhat. A LNA then amplifies the signals (B,C).

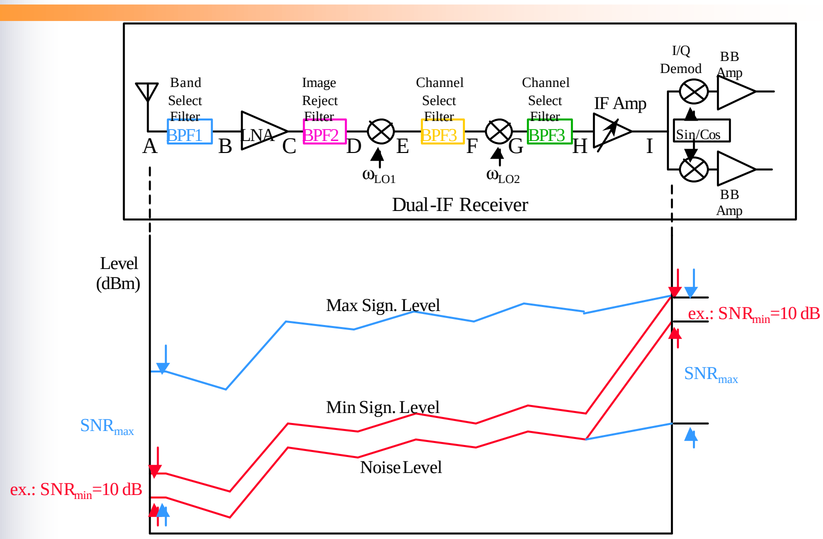
BPF2 is an image-reject filter which eliminates the “yellow” interferer at the image frequency. Simple mixers don’t preserve amplitude and phase information (unless they are four-quadrant multipliers - they have noise and conversion gain problems; or ***image reject mixers***), thus the output of the mixer can’t distinguish between $\cos(\omega_1 - \omega_2)$ and $\cos(\omega_2 - \omega_1)$ and both will fall on top of each other at the IF frequency. It is assumed that one of the two signals is the desired frequency and the other the image. If now the image signal is much larger than the desired signal, unless some image rejection is performed, it will swamp the desired signal at IF. After this corruption, the desired signal can not be recovered!

BPF3 is the first channel select filter, which rejects the close-in interferers. These are most likely other users in a cellular system. In the above diagram, a two-step down conversion is shown. However, after the first mix-down, there are many options: second-step as shown; digital sub-sampling; etc.

In the above example, the second mix-down uses ***low-side injection*** (LO below signal frequency). BPF4 is a second channel-select filter that removes the remaining part of the close-in interferers.

The main advantage of multiple down-conversions is that all the filter can be relatively simple with low insertion loss and low Q.

Signal Level Diagram Example



NOTE: Due to action of AGC in IF Amp, the noise ***appears*** to rise when input signal level drops! This might be due to a fading event, for example.

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This diagram shows what the effect of the various elements in the signal chain does to the signal-to-noise ratio. It is assumed here that all BPFs have some loss (decrease in curves), all mixers, and of course amplifiers, have gain (increase in curves).

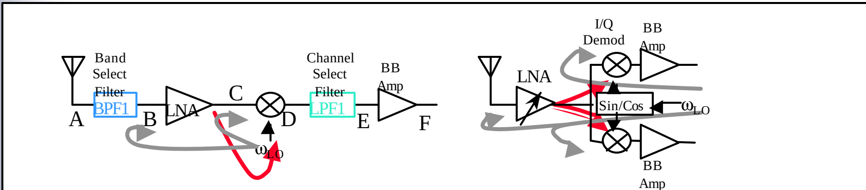
In the diagram above it is also assumed that the gains and losses for all elements except for the IF VGA are fixed. This, however, may not always be true, often the variable gain is distributed across the chain, starting at the LNA. This allows for a better adjustment of the trade-off between SNR and distortion/linearity for each element in the chain.

Furthermore, the Noise Figure (NF) of the LNA is assumed to dominate the signal chain because the SNR (distance between signal and noise levels) is shown as constant throughout the signal chain. If the LNA however would have to little gain, then the NFs of the latter elements might become significant and the SNR would change as one moved from antenna to I/Q demodulator.

Receivers - Homodyne

– *Homodyne (Zero-IF)*

- $f_{LO} = f_{RF}$
- No Image because $\omega_{IF} = 0$; no image filter required
- No IF Channel Select (SAW) Filter needed
- Rejection of out-of-channel interferers can be difficult
- DC Offsets are ***key problem***
  - Self-mixing (gray arrows) due to LO leakage
  - Interferer leakage (red arrows)
- I/Q demodulator ***has to be analog***! Matching is key issue



Simple Homodyne Receiver (Double-sideband AM only)

I/Q Homodyne Receiver (Frequency and Phase Modulated Signals)

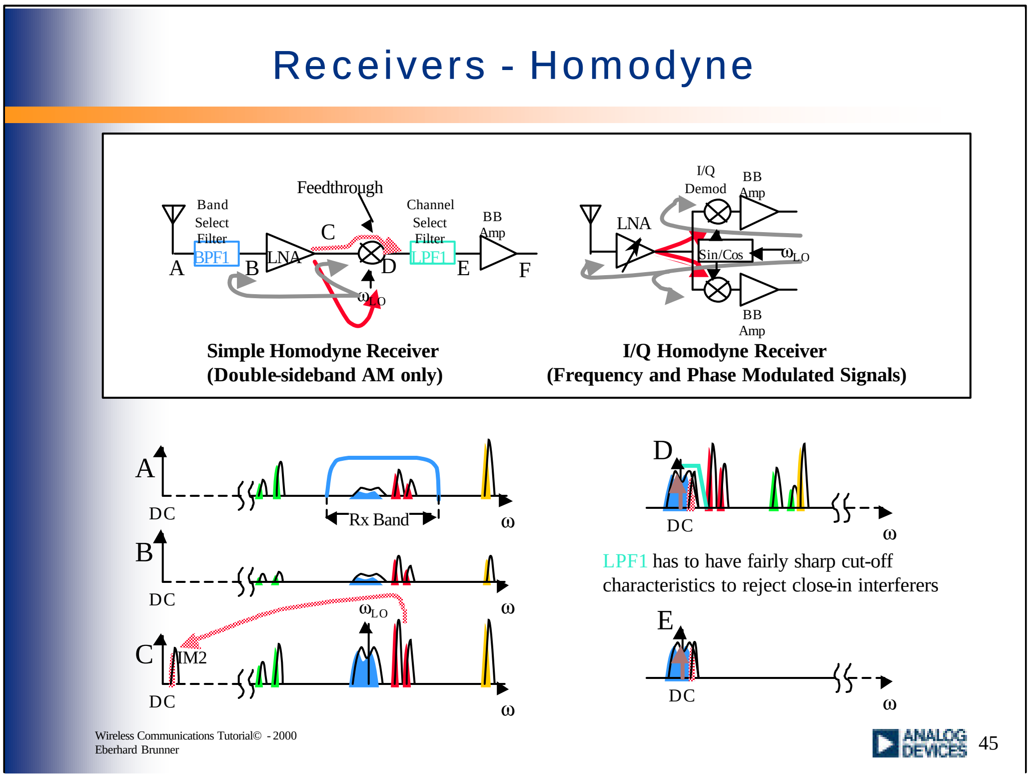
When compared to the heterodyne architecture the homodyne receiver is much simpler at first sight. However, it has some major design issues that need to be overcome. The biggest problem is any offset generated by either self-mixing and/or interferer leakage plus any other DC offsets generated after the mixers in both the Simple and I/Q Homodyne receiver.

Typical gains from points A to F are on the order of 80-100 dB to amplify the small input signals to a level that can be digitized by an ADC. Of this gain about 20-30 dB of gain are due to the LNA/mixer combination.

Ex.: LO level at mixer port 0 dBm; leakage of LO to point B is -60 dB; then offset due to self-mixing at output of mixer is about -30 dBm (~7mVrms in 50 Ohm). If we now assume that there is another 60 dB of gain AFTER the mixer, then expected DC value at point F would be 7V!!! This clearly could swamp any signal.

A further even more severe problem with self-mixing can be leakage to the antenna. In that case the LO signal will get radiated and can reflect back from moving objects; now the offset becomes ***time varying*** and may be impossible to distinguish it from the signal. Note that the amount of ***in-band*** LO radiation at the antenna is specified by an agency like the FCC; typical values are in the -50 to -80 dBm range.

Clearly self-mixing, leakage to the antenna, and interferer leakage ought to be reduced at all costs. Furthermore, some means of ***offset cancellation*** is required in homodyne receivers.



Even-Order Distortion: This can be a serious problem in homodyne receivers as shown in this slide. If, for example, the LNA exhibits even-order distortion (characterized by IP2) and the mixer has some leakage from the RF to the IF port, then a signal can appear in the baseband that can't be eliminated.

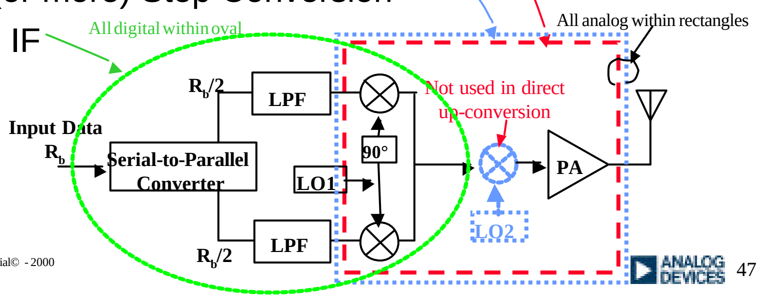
The mixer could of course also exhibit even-order distortion.

Receivers - Homodyne Offset Solutions

- Two practical solutions for the offset problem exist
  - DC-free coding
    - the baseband signal has very little energy at DC
    - especially useful for wideband signals
  - Offset Cancellation in Idle Time Slots
    - this works only in TDMA systems where time between consecutive TDMA bursts can be used to perform offset cancellation
    - Problem: Interferers may be stored along with offsets

Transmitters

- Transmitters perform
  - Modulation
  - Up-Conversion
  - Power Amplification
- Tx architectures are only found in a few forms
  - Direct (Up-) Conversion
  - Two- (or more) Step Conversion
  - Digital IF



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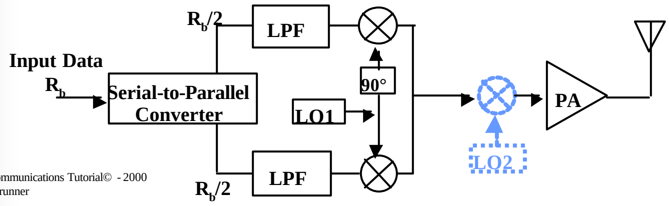
Typically the LPFs (pulse shaping filters) in the above diagram are done digitally because they would be bulky in the analog domain, and even more so it would be difficult to provide the exact pulse shape needed to minimize ISI and/or limit the signal bandwidth.

Transmitter - Direct Up-Conversion

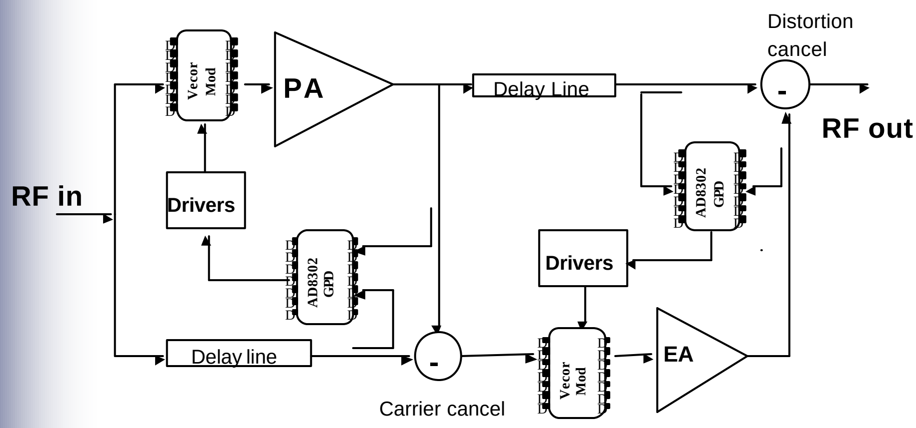
- $f_{LO} = f_{RF}$
- I/Q Mismatch leads to ***cross-talk*** between the two data streams
  - A measure of this is ***unwanted sideband suppression***; ideally only one sideband should be present at the I/Q modulator output
  - Sideband suppression should be typically better than 30 dB to minimize cross-talk
- PA Leakage can cause ***VCO pulling***
- Once BB signal is up-converted, filtering of noise and in-band spurious signals is essentially impossible



Power Amplifier Issues

- PA/Antenna Interface
  - FDD: PA output must pass through duplexer; typical duplexer loss = 2-3 dB => 30-50% of PA power is ***lost*** in duplexer!
  - TDD: Switches only have typical losses of 0.5-1 dB, this yields a ***substantially*** higher power efficiency

PA Feedforward Linearization



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