83080 Receiver Architectures and Synchronization
in Digital Communications

Practical RF Architectures for GSM and WCDMA Mobile Terminals

Mobile Generations

- 1st generation systems, analog
  - NMT, AMPS, TACS
- 2nd generation systems, digital
  - GSM, IS-136 TDMA, IS-95 CDMA, PDC
- 3rd generation systems, digital wide band
  - WCDMA standards have been prepared by ETSI (Europe), ARIB (Japan), TIA (USA),...
  - 3GPP[1] is a joint project that combines all proposals into one standard
  - Harmonized standard includes three modes
    - Direct sequence mode based on 3GPP (UTRA[2]/FDD)
    - Multi carrier mode based on CDMA2000 (USA proposal)
    - TDD mode based on 3GPP (UTRA/TDD)

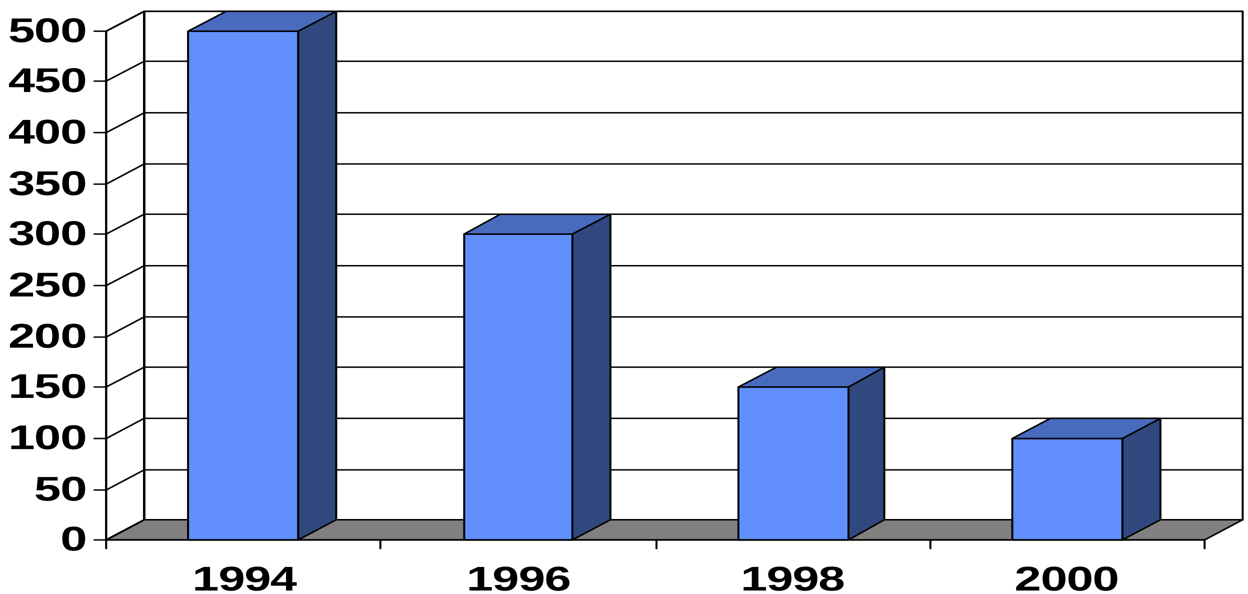
1) 3GPP = 3rd Generation Partnership Project

2) UTRA = Universal Terrestrial Radio Access

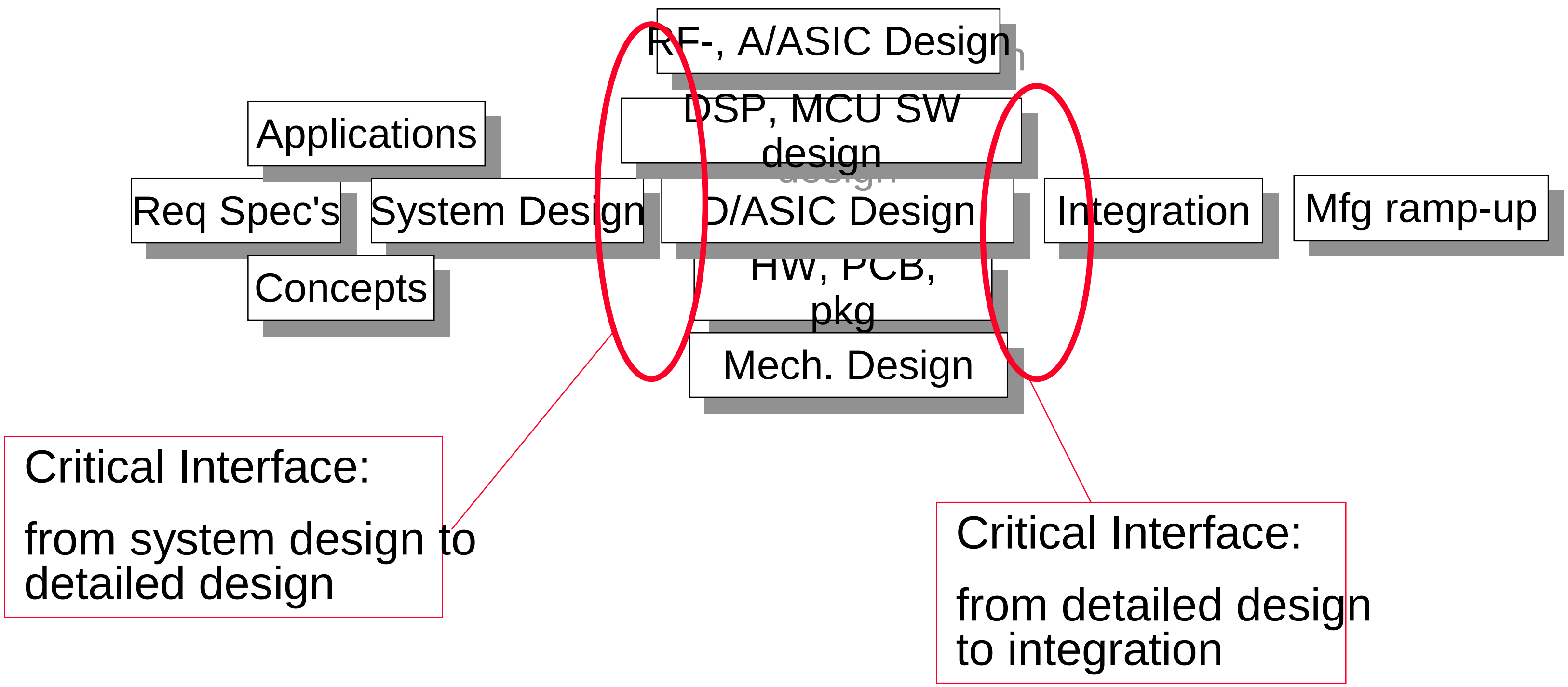
Main Drivers for RF Architecture Design

- Cost, Size, Power consumption
- System complexity, time to market

Component count in GSM RF



Design Process - time to market



GSM Specifications for Receiver

- Bad frame indication performance
- Sensitivity
- Usable receiver input level range
- Co - channel rejection
- Adjacent channel rejection (selectivity)
- Intermodulation rejection
- Blocking and spurious response
- AM suppression

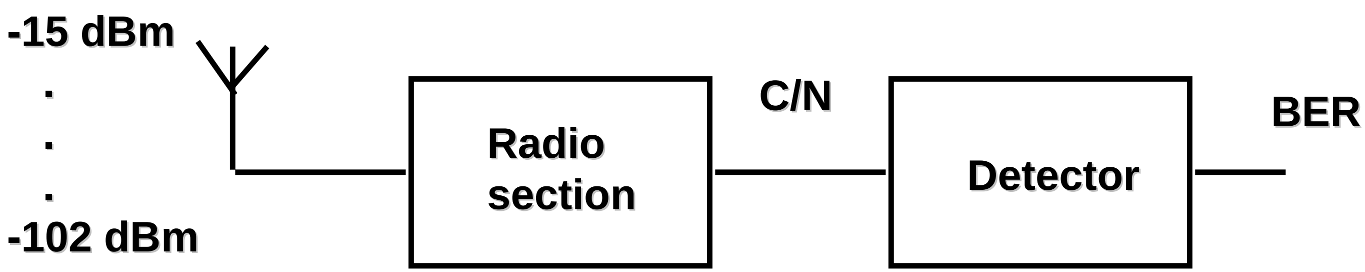
Example of sensitivity specification

Table 1: Reference sensitivity performance

GSM 900						
Type of channel		Propagation conditions				
		static	TU50 (no FH)	TU50 (ideal FH)	RA250 (no FH)	HT100 (no FH)
FACCH/H	(FER)	0.1 %	6.9 %	6.9 %	5.7 %	10.0 %
FACCH/F	(FER)	0.1 %	8.0 %	3.8 %	3.4 %	6.3 %
SDCCH	(FER)	0.1 %	13 %	8 %	8 %	12 %
RACH	(FER)	0.5 %	13 %	13 %	12 %	13 %
SCH	(FER)	1 %	16 %	16 %	15 %	16 %
TCH/F9.6 & H4.8	(BER)	10^{-5}	0.5 %	0.4 %	0.1 %	0.7 %
TCH/F4.8	(BER)	-	10^{-4}	10^{-4}	10^{-4}	10^{-4}
TCH/F2.4	(BER)	-	$2\ 10^{-4}$	10^{-5}	10^{-5}	10^{-5}
TCH/H2.4	(BER)	-	10^{-4}	10^{-4}	10^{-4}	10^{-4}
TCH/FS	(FER)	0.1α %	6α %	3α %	2α %	7α %
	class Ib (RBER)	0.4/α %	0.4/α %	0.3/α %	0.2/α %	0.5/α %
	class II (RBER)	2 %	8 %	8 %	7 %	9 %
TCH/HS	(FER)	0.025 %	4.1 %	4.1 %	4.1 %	4.5 %
	class Ib (RBER, BFI=0)	0.001 %	0.36 %	0.36 %	0.28 %	0.56 %
	class II (RBER, BFI=0)	0.72 %	6.9 %	6.9 %	6.8 %	7.6 %
	(UFR)	0.048 %	5.6 %	5.6 %	5.0 %	7.5 %
class Ib (RBER,(BFI or UFI)=0)		0.001 %	0.24 %	0.24 %	0.21 %	0.32 %
	(EVSIDR)	0.06 %	6.8 %	6.8 %	6.0 %	9.2 %
	(RBER, SID=2 and (BFI or UFI)=0)	0.001 %	0.01 %	0.01 %	0.01 %	0.02 %
	(ESIDR)	0.01 %	3.0 %	3.0 %	3.2 %	3.4 %
	(RBER, SID=1 or SID=2)	0.003 %	0.3 %	0.3 %	0.21 %	0.42 %

How to convert system specifications to RF design parameters ?

- From the bit error rate (BER) requirement of the whole phone we can derive secondary specifications for the radio section (Gain, Signal to Noise ratio, Linearity)
- System specification and detector implementation define the required S/N ratio
- GSM needs 8…9 dB S/N (number includes some implementation margin 2…3 dB)



Sensitivity

Signal must be 9 dB above noise floor, so requirement for receiver noise figure (NF) is

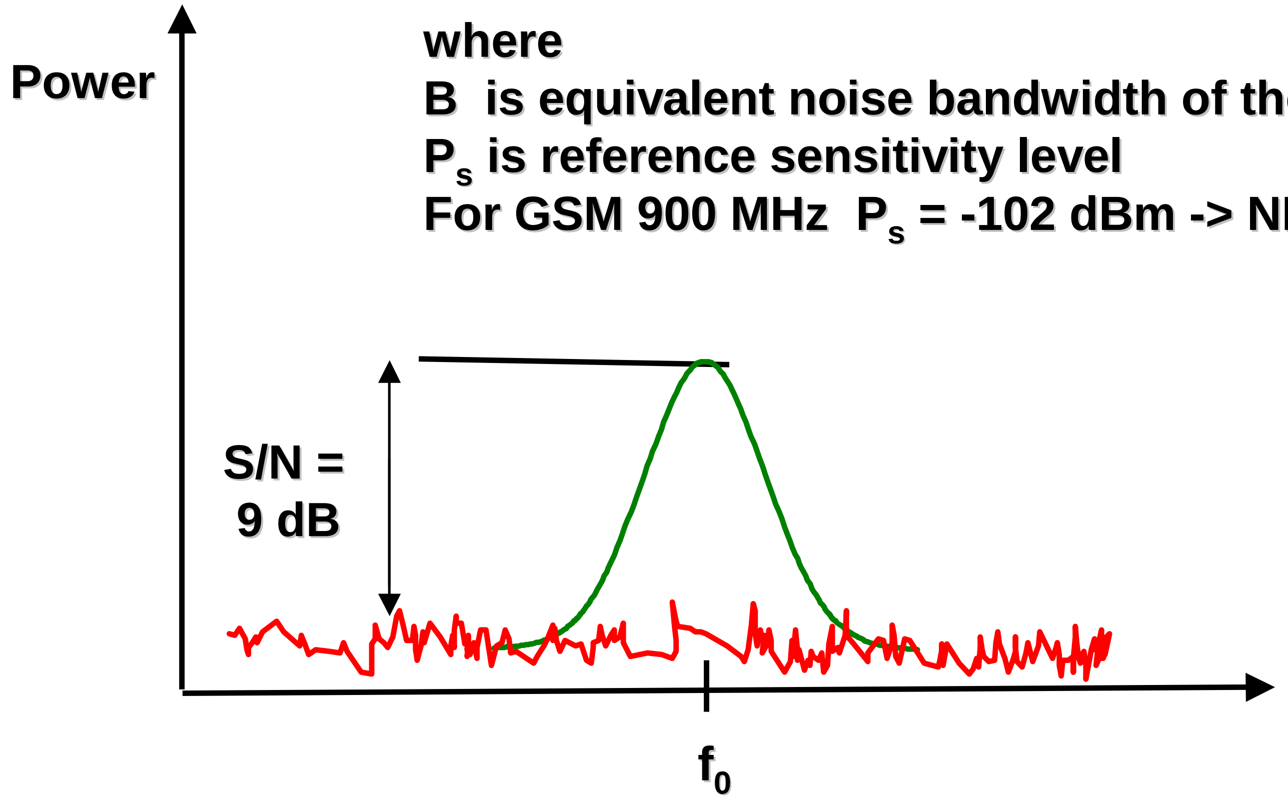
$$NF = P_s + 174\ \text{dBm} - 10 \log B - S/N$$

where

B is equivalent noise bandwidth of the receiver

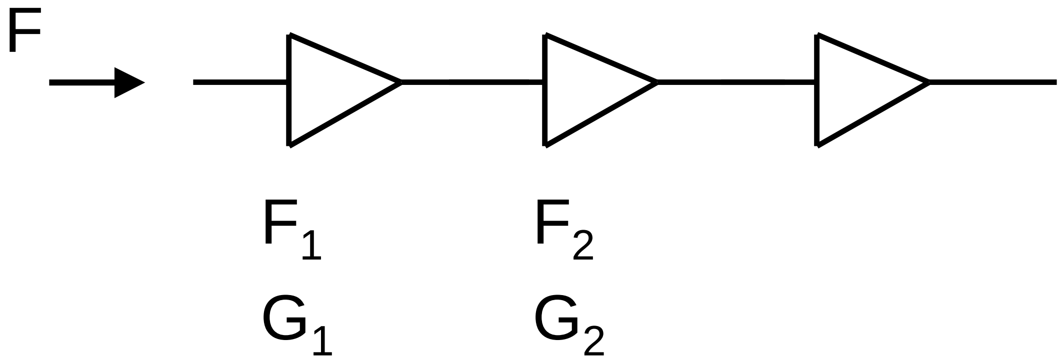
P_s is reference sensitivity level

For GSM 900 MHz P_s = -102 dBm -> NF = 10 dB



Sensitivity and Selectivity

- Cascaded noise figure
  - NF = 10 log F, where NF is noise figure and F is noise factor
  - $F = F_1 + (F_2-1)/G_1 + (F_3-1)/G_1G_2 + \ldots + (F_n-1)/ G_1G_2\ldots G_{n-1}$
- RF section must have enough gain to provide adequate signal level for A/D converter
- Minimum input level is -102 dBm -> 1.8 uV @ 50 ohm. If we need for example 100 mV at A/D converter input, voltage gain needs to be 20 log(100mV/1.8uV) = 95 dB



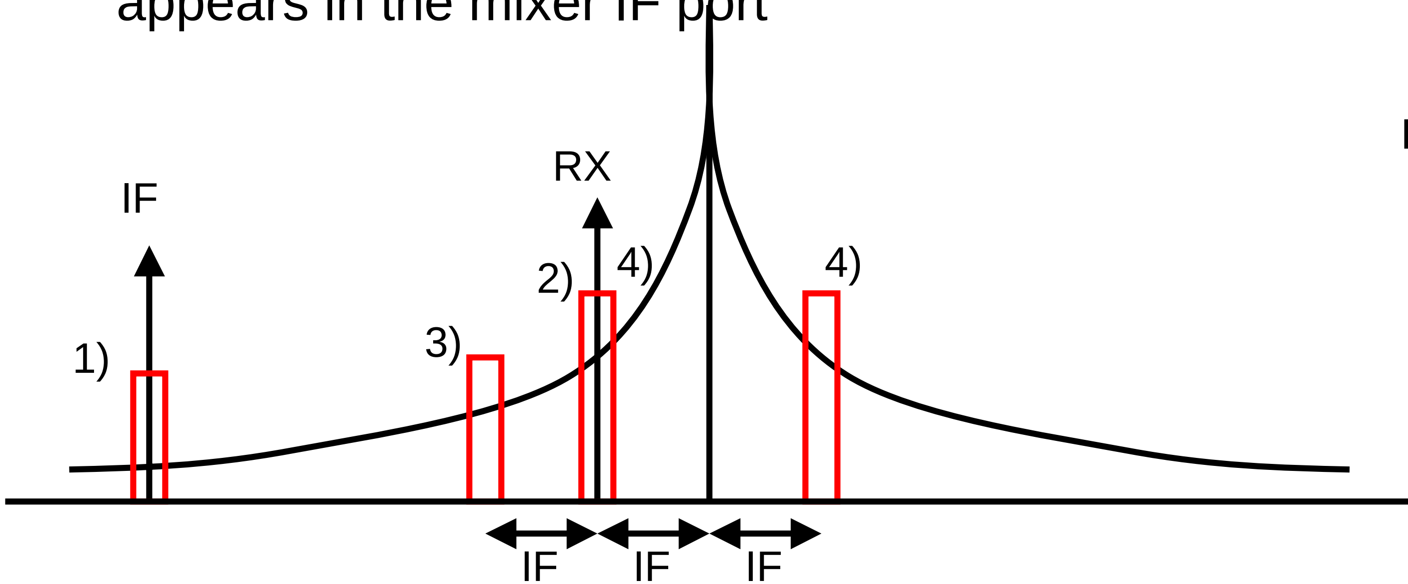
Selectivity

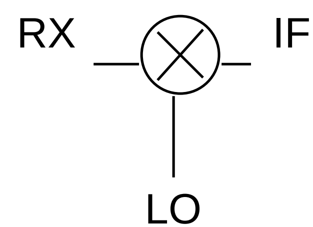
- Before detector interfering signals need to be filtered so that S/N is adequate
- This attenuation is split between IF filter, analog BB filter and digital filter after A/D
- Digital filtering at baseband would be cost effective but then A/D coverter must be able to handle wider dynamic range (typical A/D resolution 10…12 bits)
- Distribution of gain and selectivity affects also linearity requirement of the analog part
- If interfering signal is for example -43 dBm -> 5 mV @ 50 ohm and we amplify that 95 dB the signal level would be 280 V !

Microsoft Excel Worksheet

Phase Noise

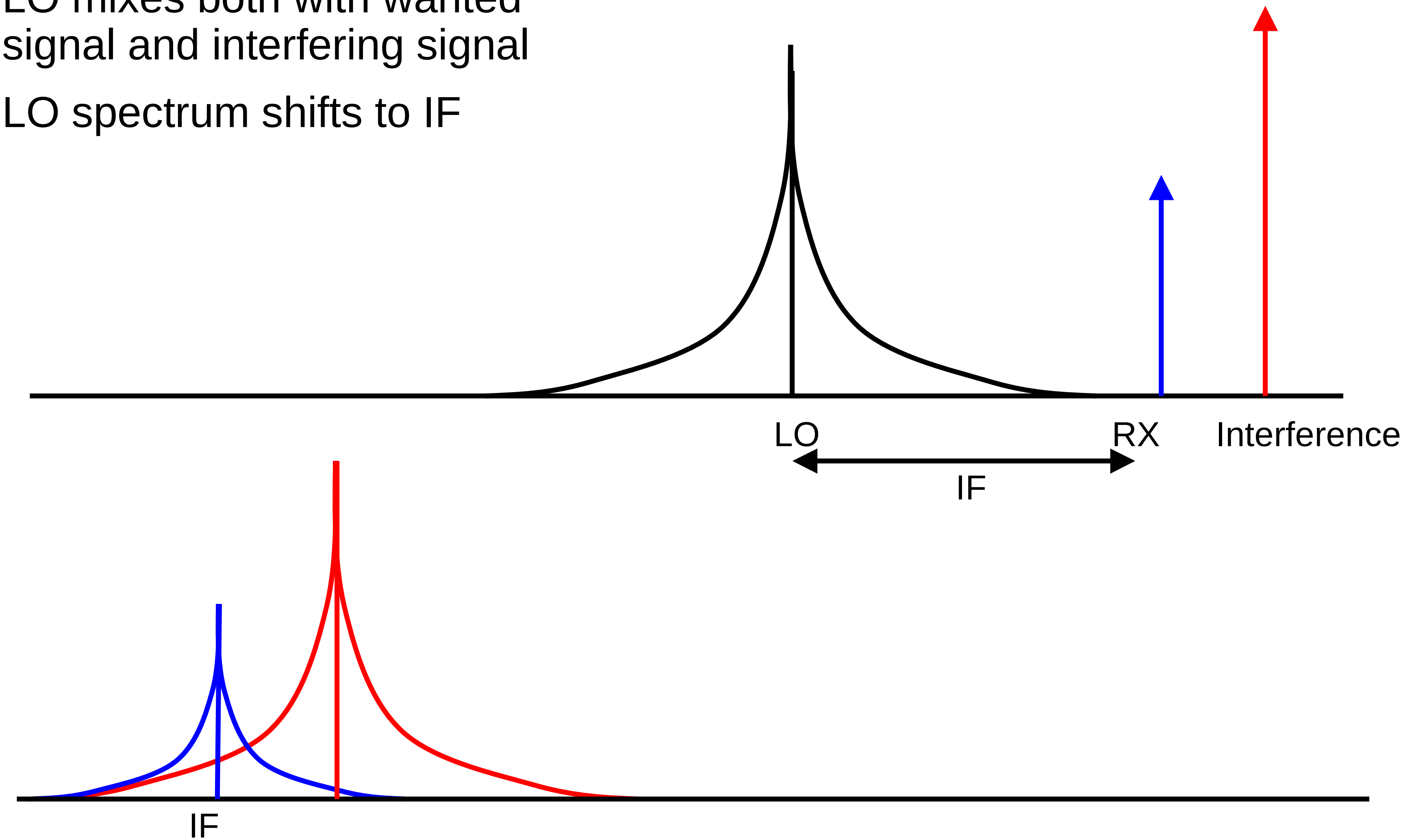
- Local oscillator (LO) phase noise has effect both on sensitivity and selectivity
- Phase noise may pass through mixer and degrade sensitivity different ways
  1) Noise at IF leaks directly into mixer IF port
  2) Noise at RF leaks directly into mixer RF port
  3) Noise at the distance of IF from the RX-frequency mixes with RX and appears in the mixer IF port
  4) Noise at the distance of IF from the LO-frequency mixes with LO and appears in the mixer IF port





Phase noise

- LO mixes both with wanted signal and interfering signal
- LO spectrum shifts to IF



Phase noise

- Usually selectivity sets most difficult requirement for VCO phase noise
- Example GSM 900 MHz handportable:
  - wanted signal -102 dBm + 3 dB = -99 dBm
  - blocking signal -43 dBm @ 600 kHz offset
  - typical values S/N = 9 dB, noise BW = 200 kHz
  - Phase noise = -99 - (-43) - 10 log 200000 - 9 = -118 dBc/Hz (600 kHz)

Receiver Architectures

- Heterodyne
  + flexibility, achievable component specifications
  + standard components available
  - spurious responses
- IF Sampling
  + no need for I/Q mixer
  - requires better A/D converter
- Homodyne (direct conversion)
  + simplest architecture
  + no IF filters, advantage especially in multiband/multisystem phones
  - very difficult to implement

GSM Receiver Principles

- GMSK modulation has no AM component that carries information
- However the equalizer requires real time amplitude information to be able to correct the multipath propagation

→ Most common solution is linear receiver that provides in-phase (I) and quadrature (Q) signals for the baseband

→ Non linear (limiting) receiver possible, if it can provide amplitude information for the equalizer

Limiting Receiver in GSM

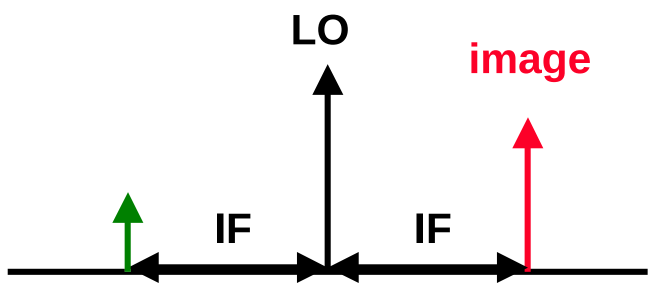
- Relaxes AGC and A/D requirements
- High level interferers must be low enough before limiter -> requires good IF filters
- Can handle fast amplitude changes without saturation

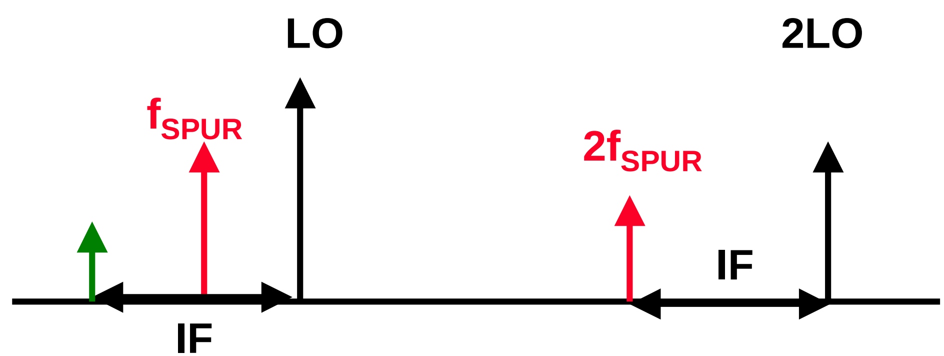
Spurious response rejection

- Mixing products in nonlinear circuits can cause spurious responses if they fall at IF or RX frequency
- Usually low order products are the most important
- Some examples of spurious responses in superheterodyne receiver with high side LO injection

Image: $f_{SPUR} - f_{LO} = f_{IF}$

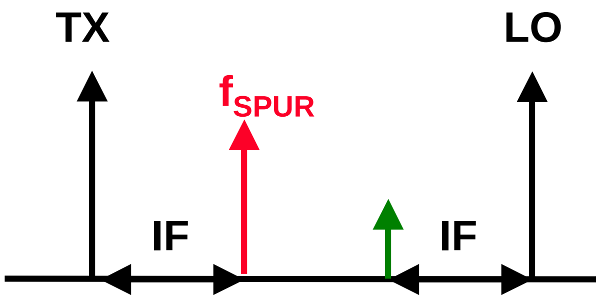
Half IF: $2f_{LO} - 2f_{SPUR} = f_{IF}$

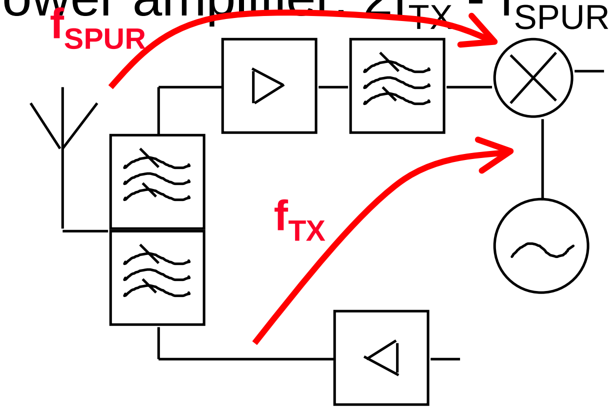


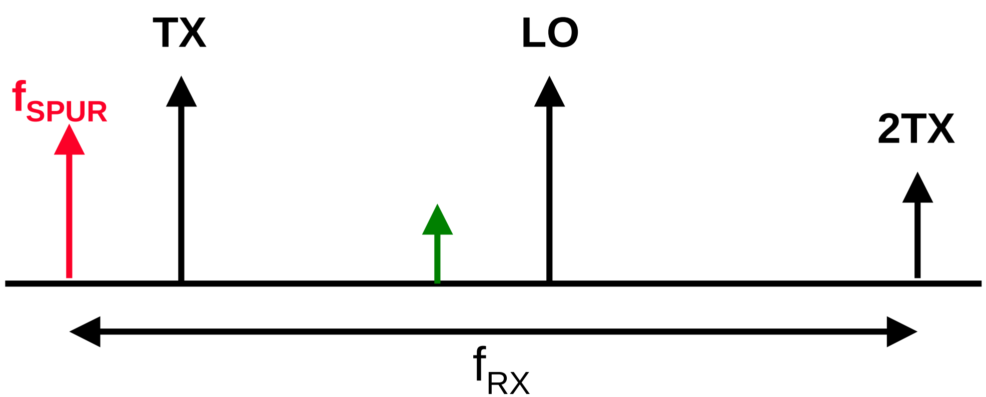


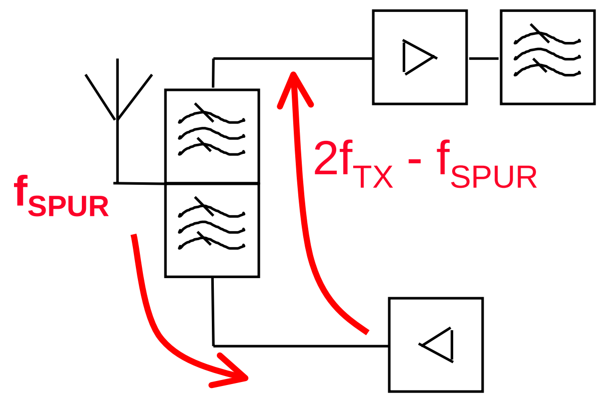
Spurious response rejection

- In full duplex systems the high level TX signal causes more spurious responses
- If TX leaks to RX mixer it mixes directly with spurious signal: $f_{SPUR} - f_{TX} = f_{IF}$
- Mixing can also take place in power amplifier: $2f_{TX} - f_{SPUR} = f_{RX}$







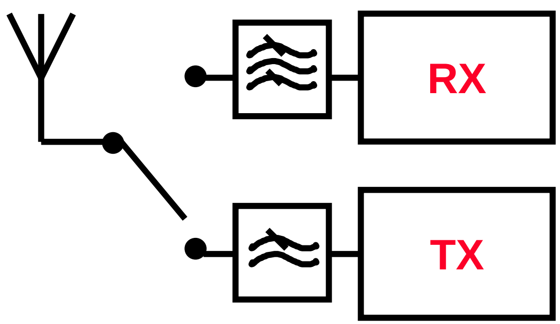


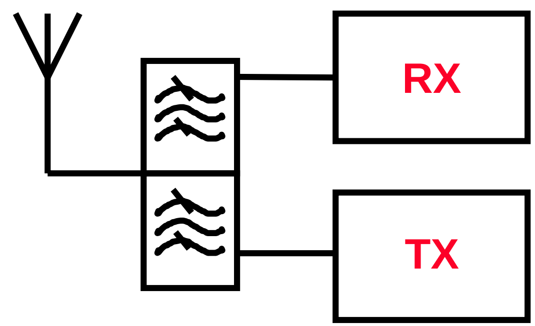
Choosing IF frequency

- Spurious response requirements
  - Image should be at relatively quiet band
  - Usually IF/2 spurious should not be in RX band -> first IF > 2 * operating band
  - TX + IF should not fall in RX band (on the other hand we can use TX+ IF = RX)
- IF filter availability, size and cost
  - 71 MHz is most popular GSM IF at the moment
  - Higher frequency SAW filter is smaller but stopband attenuation is not as good
- LO frequency
  - lower frequency is slightly easier to implement. On the other hand in mobile TX band is below RX and LO may be too close to TX band with low side injection
- Amount of oscillators
  - Use same oscillator for RX and TX if possible
  - harmonics of the oscillators should not fall in RX band

Duplexing Techniques

- Uplink and downlink signals can be separated using different frequency or different time slot
- RX and TX use same frequency but different time slot
- -> Time Division Duplex (TDD)
- RX and TX are on simultaneously but use different frequency
- -> Frequency Division Duplex (FDD)
- GSM can use either switch or duplexer
- WCDMA must use a duplexer (option for TDD in the spec.)





Duplexing Issues

- Using a duplex filter in GSM may be feasible if RF archtecture is such that also TX needs good filtering
- If a simple high pass filter is adquate in TX, lower cost and size can be achieved with a switch and separate filters
- Typically swithch and filters are combined in a ceramic module
- In GSM system receive and transmit functions occur in different time slots
  → Isolation between TX and RX is not a concern
    - High level circuit integration possible
    - Common blocks for RX and TX possible, e.g. synthesizer (frequency can be shifted between RX and TX time slots)
    - Less spurious responses in the RX

Automatic Gain Control (AGC)

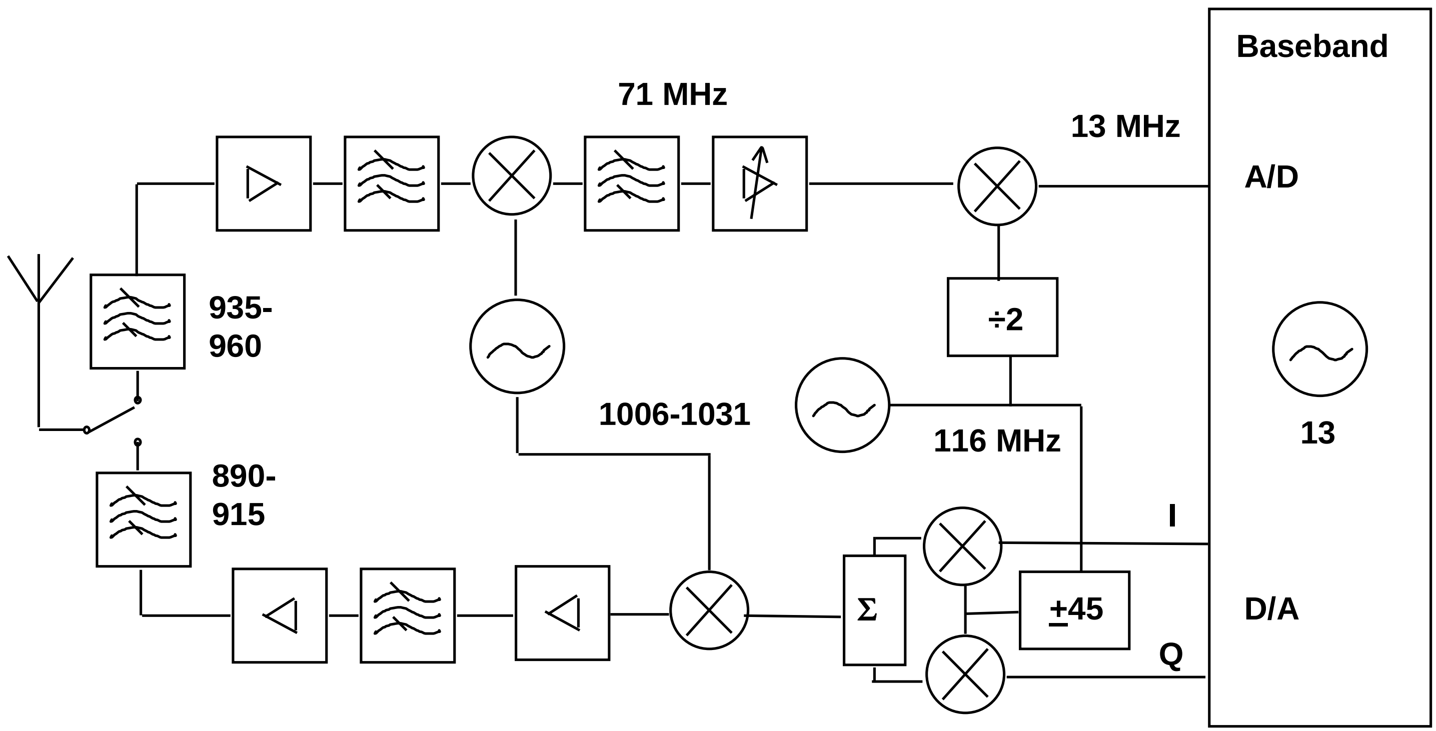
- With AGC the average signal level at the A/D converter input is kept almost constant
  - Trade off between AGC and A/D converter dynamic range
- In GSM phone reports received signal strength and $\pm$1 dB relative measurement accuracy is required from -110 dBm to -48 dBm
- In IS-95 CDMA the TX power must follow received signal strength: Pout = -Pin -76 dBm at the input range -104 dBm to -25 dBm (open loop power control, accuracy requirement $\pm$9.5 dB)
- In CDMA RX and TX gain controls should have similar temperature behavior

AGC Implementation

- Accuracy and temperature compensation are easier to implement at IF and baseband
- By adjusting front-end gain, AGC also provides a measure against intermodulation distortion at high signal levels
- Often AGC is split between front-end and IF, for example 20…30 dB step in front-end and 60…80 dB at IF

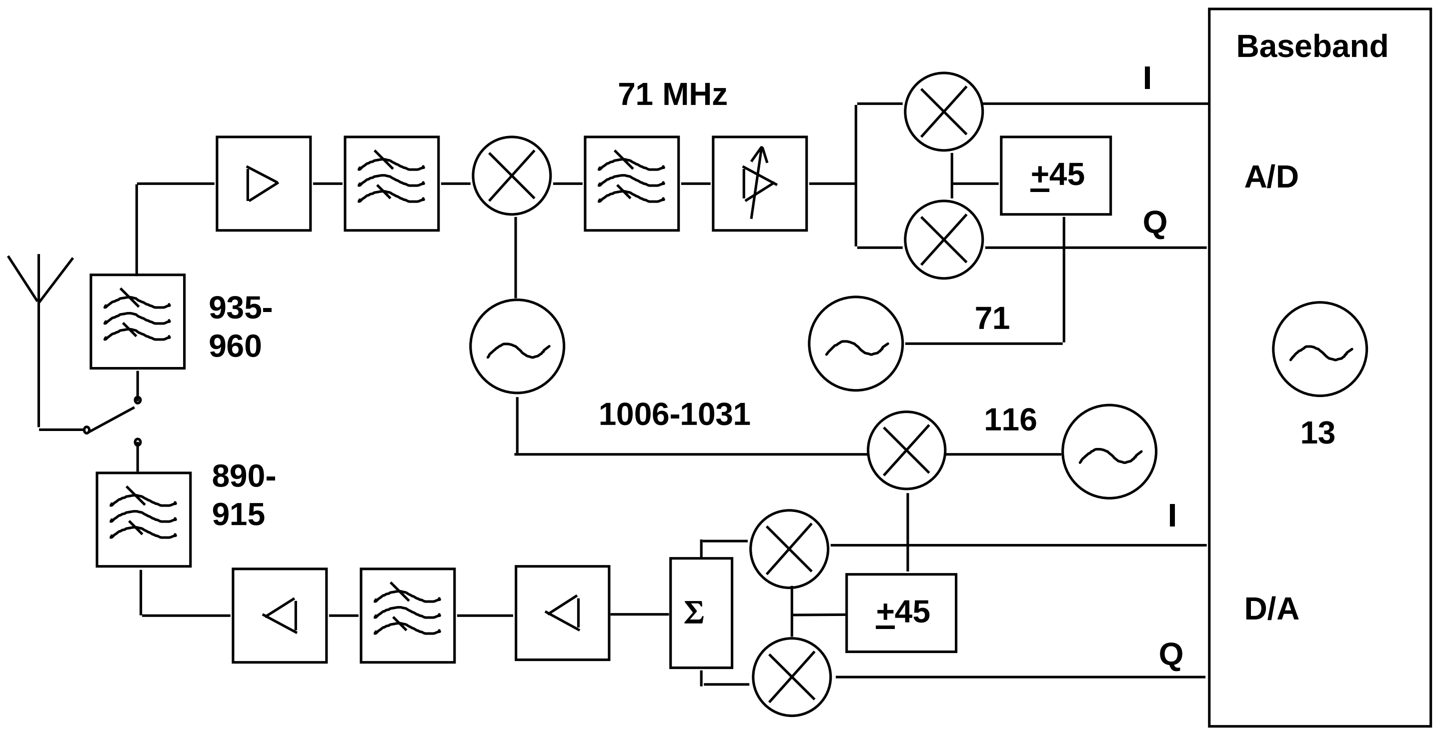
Example of a GSM Block Diagram

Superheterodyne with IF sampling GSM 900 MHz

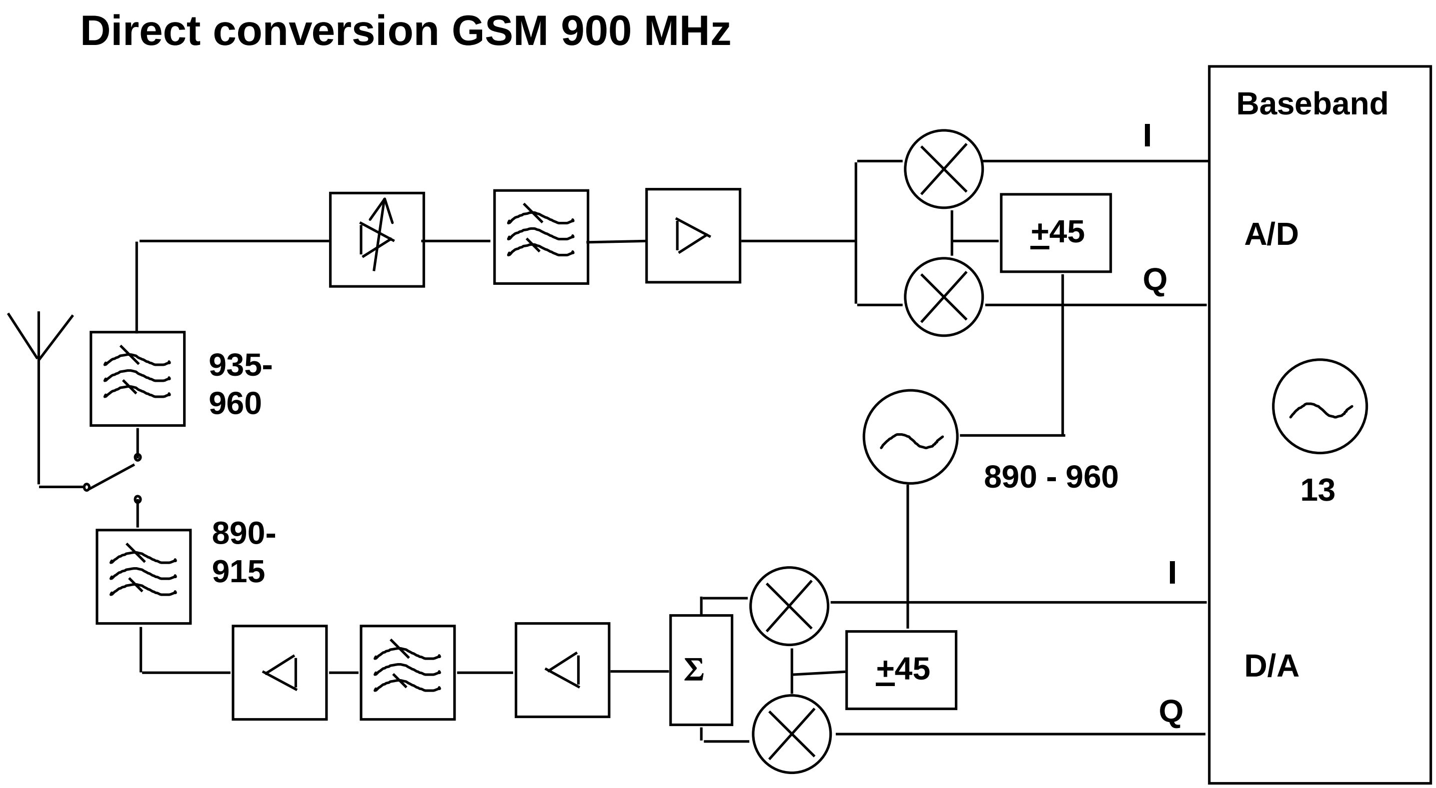


Example of a GSM Block Diagram

Superheterodyne GSM 900 MHz

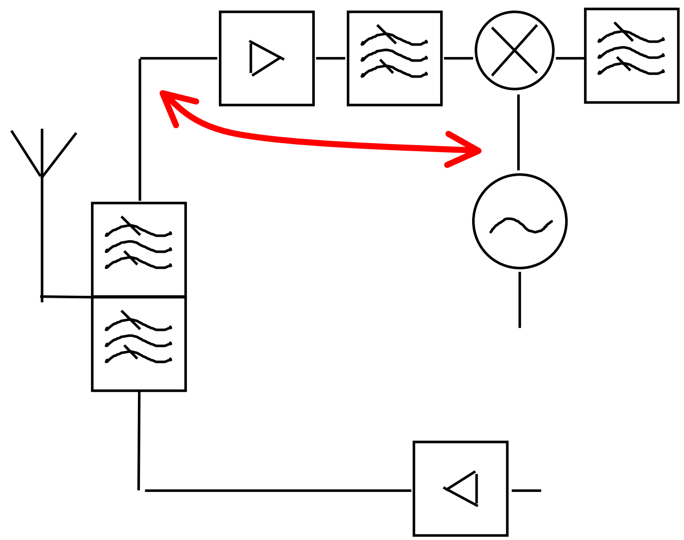


Example of a GSM Block Diagram



Direct Conversion Implementation

- LO leakage to the RX input causes DC-offset
- LO leakage can not be filtered out and it may cause too high spurious emissions (limit in GSM specification is -57 dBm)
- High level interference signals can couple to LO an cause LO pulling
- RF part must be very linear because strong adjacent channel signals are not filtered out until baseband
- To meet all requirements mixer linearity and balance are essential



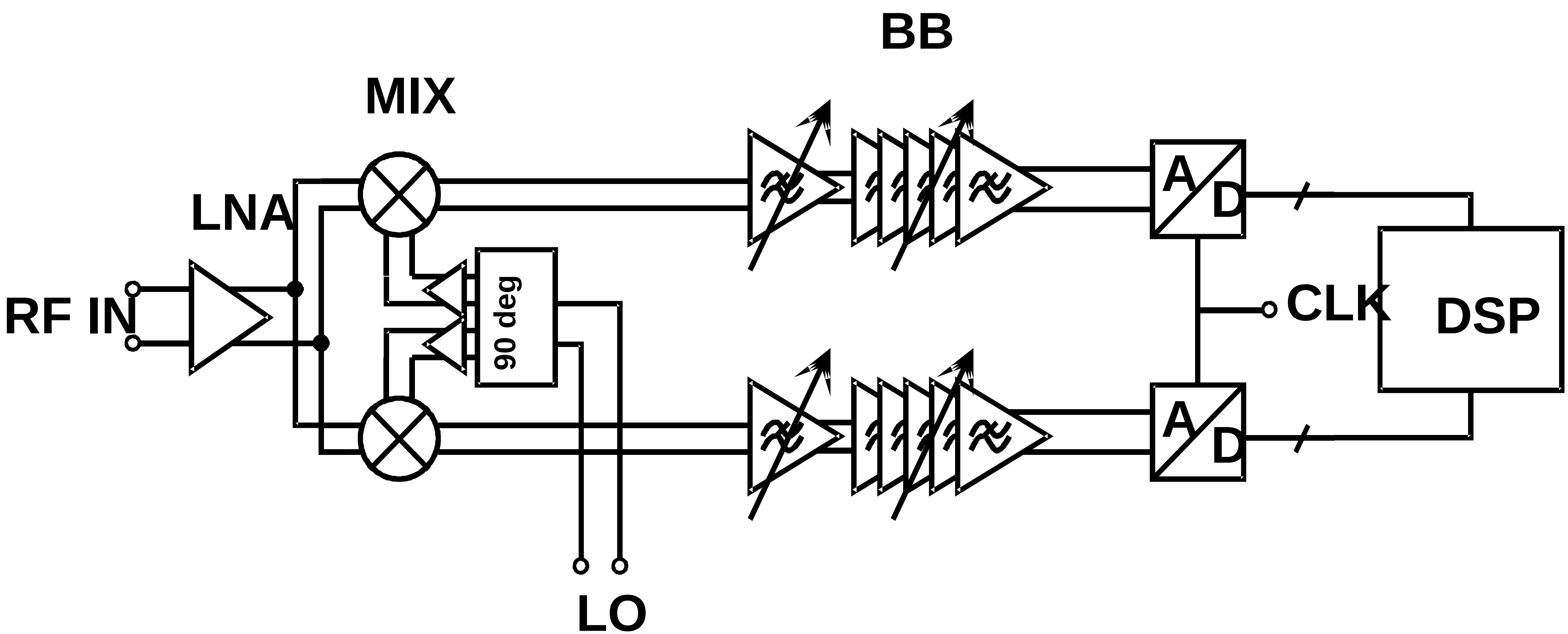
Direct Conversion Implementation

- Can be much larger than a weak signal
- DC offset is first measured without signal before RX burst
- This information is then used to cancel offset just before detection

- Direct conversion implemented in GSM by Alcatel and Nokia
- RFIC vendors are developing direct conversion chipsets (Analog Devices)

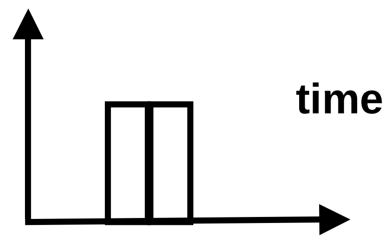
Direct Conversion Implementation

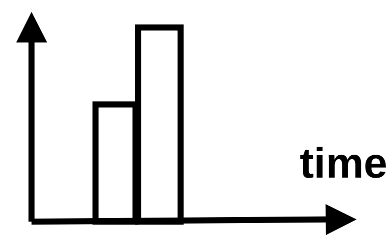
- Balanced circuits and double LO frequency reduce interference coupling



GSM Data Services, HSCSD and GPRS

- HSCSD & GPRS
  - HSCSD = High Speed Circuit Switched Data
  - GPRS = General Packet Radio Service
  - Different coding 9.6 kbit/s -> 14.4 kbit/s
  - More slots, for example 2 slots -> 28.8 kbit/s
  - Dynamic use of slots in GPRS
  - In multislot case receiver has less time to change channel -> synthesizer must be faster
  - Adjacent slots may have different amplitude -> more dynamic range needed because gain control has no time to adapt

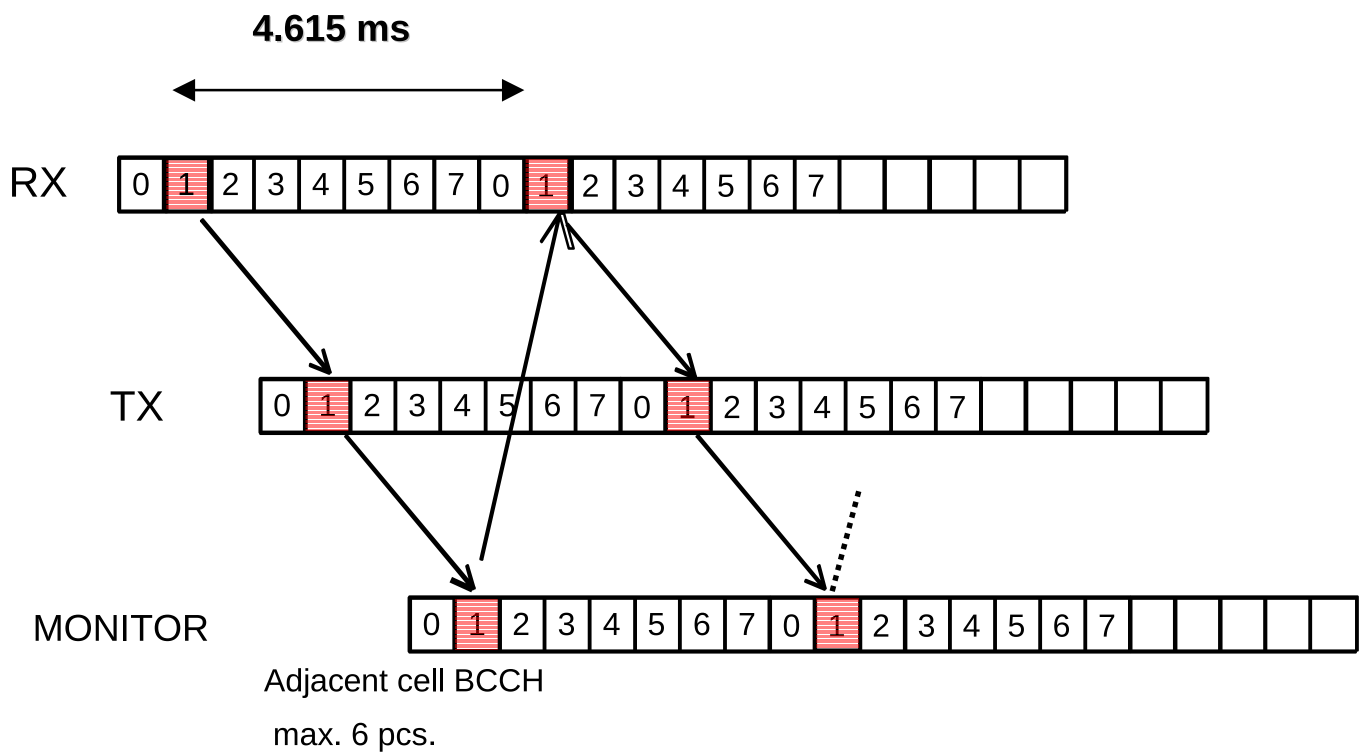




GSM Data Services, EDGE

- In EDGE also modulation changes GMSK -> 8PSK
- Not constant amplitude anymore, only linear receiver possible
- EDGE has several coding schemes and fastest data speeds can only be achieved with very good signal to noise conditions
- Theoretical maximum 69 kbit/s per timeslot
- AGC gain distribution important
  - LNA gain step should not be used as low levels as in basic GSM

GSM Radio Access in the Time Domain

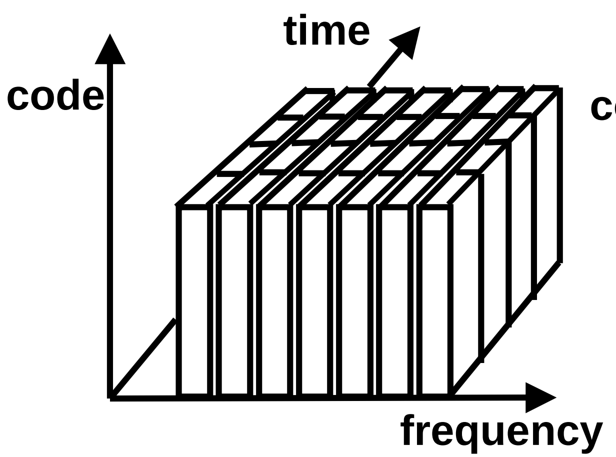


HSCSD RF

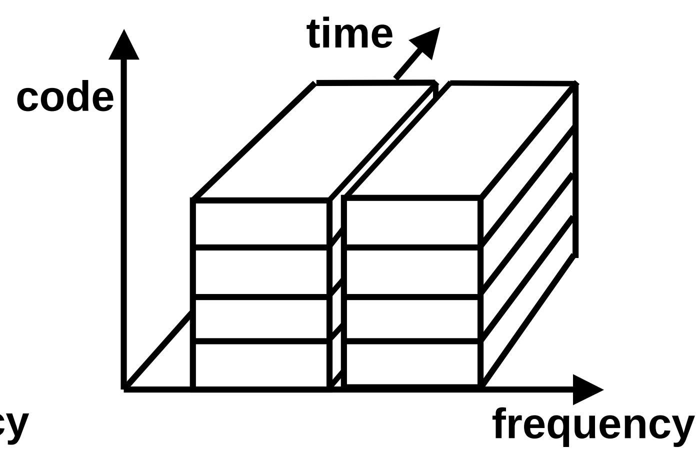
- 2 + 2 slots or 3 +1 slots still leave some settling time between the slots
- In dual slot operation with maximum timing advance the time between RX and TX slots is 577 μs - 233 μs = 344 μs
- It becomes difficult to achieve this with conventional synthesizer
  - Separate synthesizers for RX and TX
  - Fractional-N synthesizer
  - Use double frequency (synthesizer step 400kHz) and divide for LO
- 3 + 3 slots and higher the RX and TX overlap and whole RF system design must be different including two synthesizers, duplex filter and high isolation between TX and RX

Spread-Spectrum Basics

- Spectrum is spread using a code that is independent of the information signal
- Bandwidth used in spread spectrum transmission is typically at least 100 times wider than the information signal bandwidth
- WCDMA uses direct sequence spreading where a pseudo-random code is directly combined to the signal
- Users are separated by different codes
- Bits in the spreading code are called chips



GSM



WCDMA

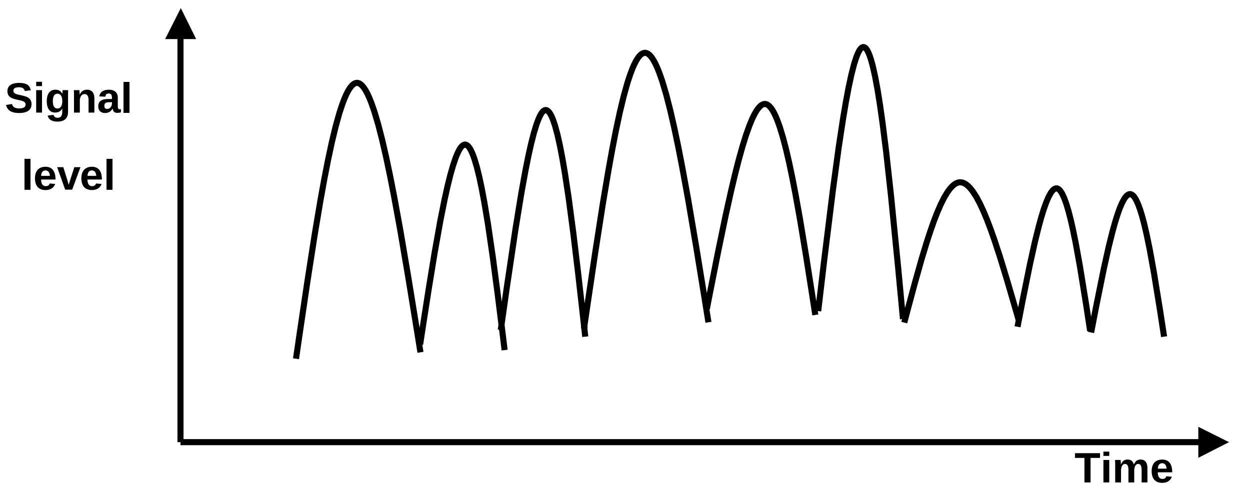
Mobile Radio Channel

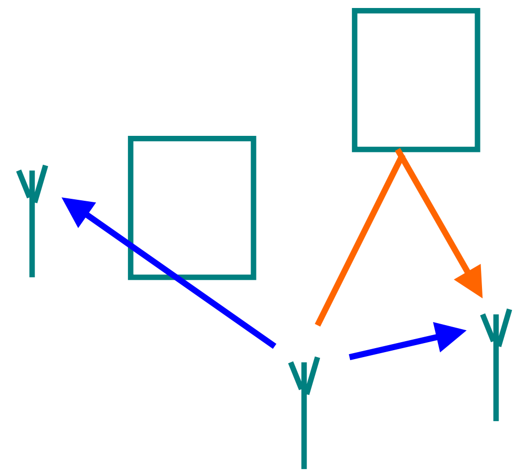
Multipath propagation (frequency selective fading)

Shadowing

Doppler shift

linear time-variant channel





Mobile Receiver

- In GSM training sequence is used to estimate the impulse response of the radio channel
- This information is necessary to equalize the user bits on a burst by burst basis
- CDMA chip rate is typically greater than flat fading BW of the channel and multipath components appear like uncorrelated noise -> no equalizer is needed
- RAKE receiver combines time shifted versions of the original signal
  - One finger is assigned for the direct signal, another for the reflected signal
- Fingers in RAKE receiver can also be used for soft handoff
  - One finger is assigned for new base station while another still listens the old BS
- RAKE receiver in implemented in digital baseband and it does not require any special functionality in RF part -> Receiver can be implemented with similar blocks as current GSM receiver

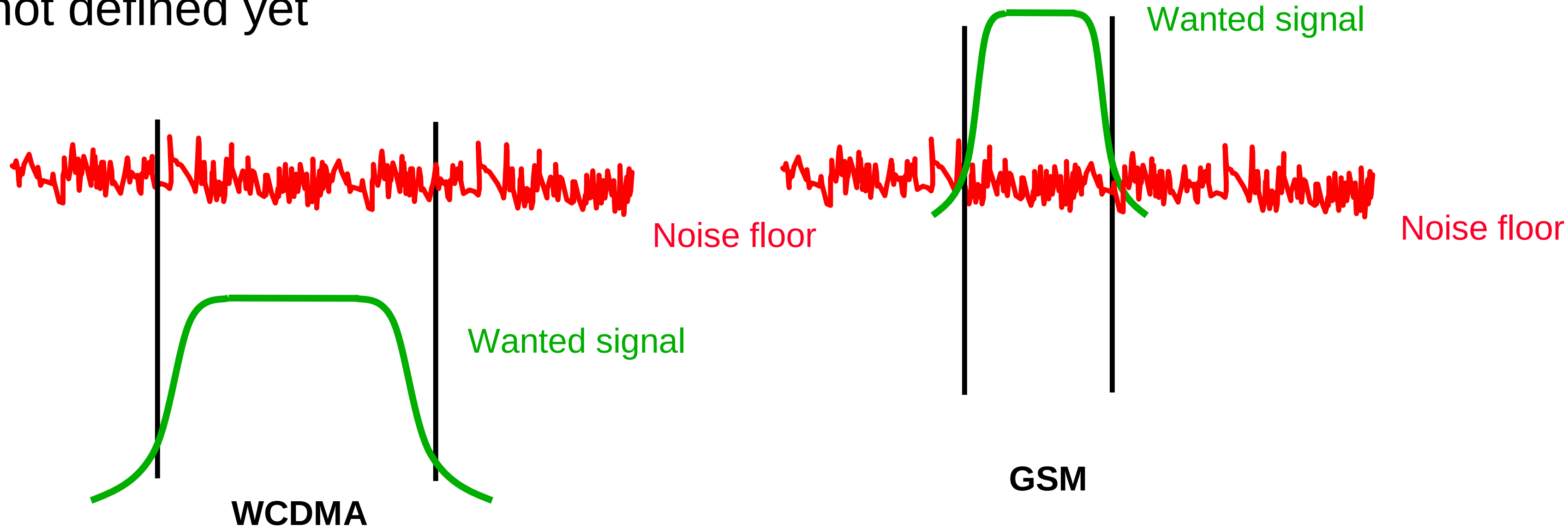
CDMA System Parameters

- IS-95 CDMA
  - Frequency bands
    - Cellular band (AMPS): TX 824…849, RX 869…894 MHz
    - PCS1900: TX 1850...1910, RX 1930...1990 MHz
  - Carrier spacing 1.25 MHz, 64 Walsh codes
  - Chip rate 1.2288 Mchip/s

- WCDMA
  - Frequency bands
    - UTRA FDD (Europe & Asia): TX 1920…1980 MHz , RX 2110…2170 MHz
  - Carrier spacing 5.00 MHz
  - Chip rate 3.84 Mchips/s (first proposal 4.096 Mchips/s)

Receiver requirements

- Sensitivity requirement is -117 dBm @ 12.2 kbps user data rate
- Changing user bit rate changes processing gain (PG) and also sensitivity level
- PG = 10 log (3.84Mcps/user symbol rate)
- Selectivity requirement is defined as RX filter attenuation at adjacent channel compared to wanted channel, spec is 33 dB, interferer crest factor not defined yet

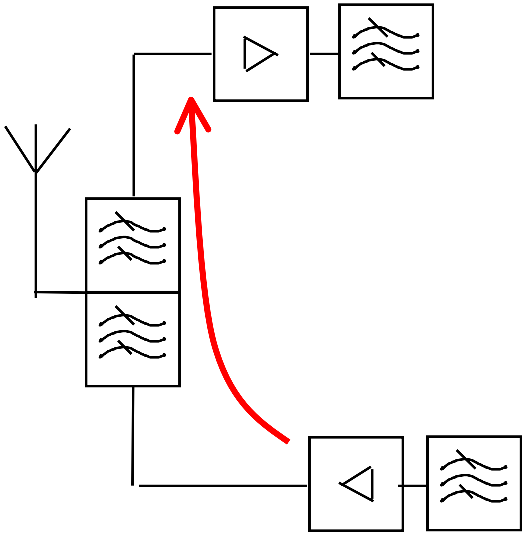


RX Design issues

- Full duplex operation
  - TX noise at RX band must be attenuated
  - A good duplexer is relatively large and expensive component
- High chiprate
  - Wide BW in baseband -> higher current consumption
  - Wide band IF filters -> higher loss

WCDMA RX Design Issues

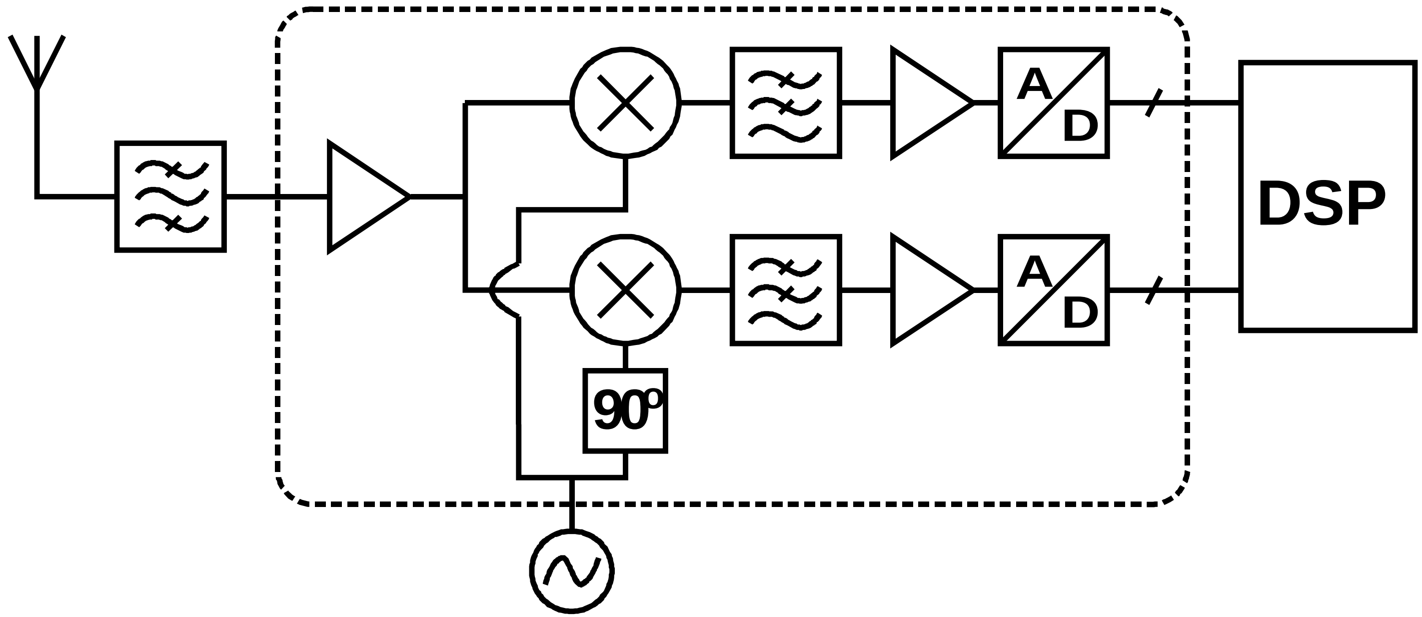
- Linear modulation -> limitting receiver not possible
- In full duplex system TX noise at RX band may desense receiver
  - If we require that TX is not decreasing RX sensitivity, noise at RX input must below thermal noise floor (-174 dBm/Hz)
  - Even if TX chain is relatively low noise, about 40 dB attenuation is needed in duplexer
- Wider band compared to GSM increases slightly filter losses and current consumption



Variable duplex separation

- In WCDMA specification there is an option to use variable duplex separation
- This means that receiver and transmitter channels can be selected freely and distance between RX and TX center frequency is variable
- In current situation where operators have only two or three channels this option is not useful but if more spectrum becomes available it makes spectrum allocation more flexible
- In superheterodyne receive variable duplex separation increases number of spurious responses dramatically and makes the calculation complex
- With direct conversion architecture independent RX and TX frequencies are relatively easy to implement

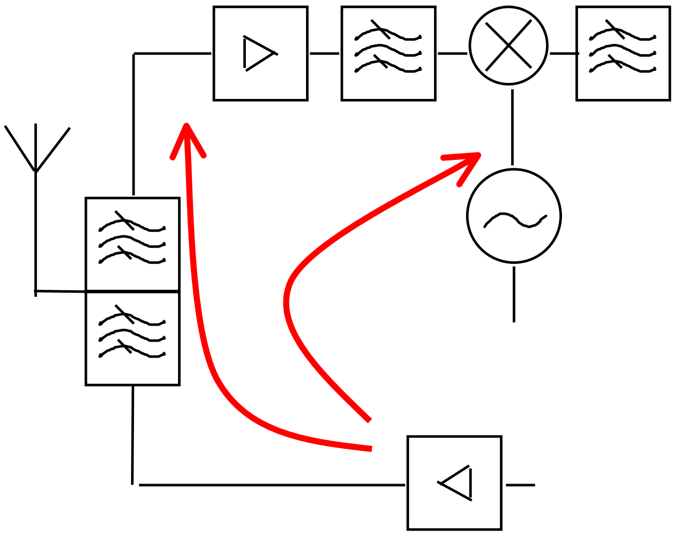
Direct Conversion Receiver in WCDMA



- Integration level
- Image suppression
- DC offsets
- Envelope distortion
- Flicker noise

Direct conversion problems in CDMA

- No idle time slots for cancellation
- Highpass filtering possible (dc block in the signal path or servo feedback)
  - Slow transients
  - Large component values
- Long-term average subtracted from signal
  - DSP controls analog offset
- Digital methods
  - Typically for offsets 10-50 % depending on algorithm
- Own TX interference
  - Leakage through duplex filter and to RX VCO
  - TX modulation at mixer output
  - Double VCO frequency *f*=4 GHz and differential circuits reduce coupling



NOKIA

WCDMA & Direct Conversion

- Envelope distortion
  - 2nd-order nonlinearity
  - BALANCING
  - Mixer and first stages of baseband critical
  - Interference sources: all radio channels containing AM
    - Variable (non-constant) envelope in digital modulation
      - QPSK, QAM
    - TDMA (GSM)
    - TDD (WCDMA)

WCDMA & Direct Conversion

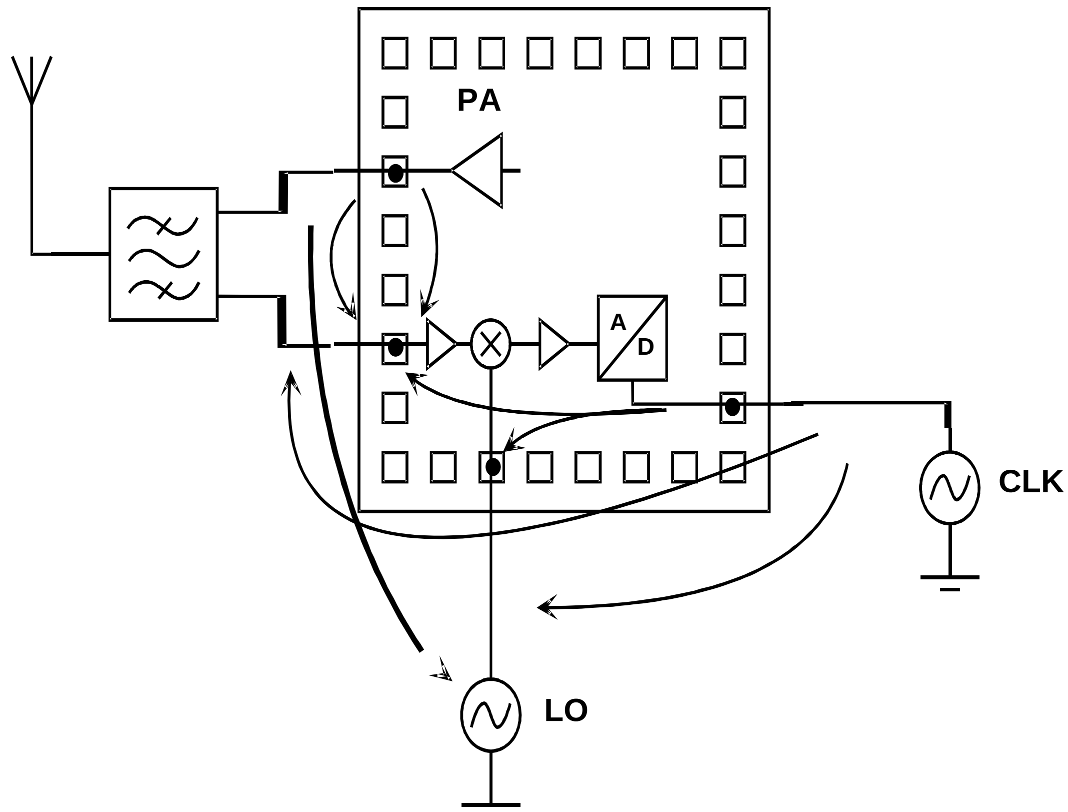
- Analog baseband processing
  - Mixer is a part of the demodulator
    - I/Q balance
  - Offsets
  - Gain control
    - Time constant critical inside offset compensation loop
    - Techniques to maintain the same offset with different gain values
  - Flicker noise
    - Critical in direct conversion
    - Linearity & power consumption limits gain at RF
    - Smaller relative contribution in wide-band system

Integrating WCDMA Receiver

- Most functions can already be integarated
- Most difficult blocks are
  - Front end RF filters
  - Tank circuit in VCO
  - Reference oscillator, at least crystal is external
- Small size & smaller parasitics
- Better matching
- Low cost in mass production

Single-Chip Integration

- High-speed clock and digital signals on the same chip with RX front-end
- Coupling through substrate and interconnections
- Transmitter power and noise on RX band
- Differential RF
- Double VCO frequency



Component Technologies

- RF part of a GSM phone includes typically following blocks
  - One RF ASIC including RX, synthesizer(s) and TX
  - Power amplifier
  - VCO module
  - TCXO module
  - Front end switch
  - SAW filters (RX front end filter may be on the switch module)
  - Some passive components

- In WCDMA RX and TX are likely to be on separate chips

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Component Technologies, RFIC

- BiCMOS process is most suitable for RF ASIC design
  - Good RF performance
  - Easy to implement control logic and digital part in synthesizer
- SiGe option increases f_t
  - Main advantage of higher speed process is lower power consumption
- Packages are typically ball grid arrays (BGA) with pin count up to 100

- Power amplifier technologies
  - HBT GaAs (most popular today)
  - Silicon MOS
  - GaAs FET
  - Silicon bipolar
  - InP and InGaP are promising some performance improvement over GaAs HBT

Component Technologies, Filters and Switches

- Filter technology has been changing from ceramic to surface acustic wave (SAW)
- Bulk Acoustic Wave (BAW) filters would give even smaller size and some integration possibilities
- BAW technology is more difficult to implement than SAW beacause also material thickness should be controlled extremely accurately
- Switches are used in front end so performance is very important because it directly effects the total receiver performance
- GaAs FET and pin diode switches are used today
- Micromechanical Switches (MEMS) would improve both insertion loss and isolation performance dramatically
- MEMS linearity is also superior compared to electrical switches
- Problems today are reliability and high control voltages

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Receiver Components

- Typical IF filter specifications

	900 MHz GSM	800 MHz CDMA	1900 MHz CDMA
Center freq.	71 MHz	85 MHz	210 MHz
Bandwidth	200 kHz	1.25 MHz	1.25 MHz
Insertion loss	7 dB	12 dB	9 dB
Attn @ 600kHz	30 dB		
Attn @ 900kHz		35 dB	
Attn @ 1.25MHz			33 dB

Statistical Analysis

- Because manufacturing volumes are high receiver architecture must be robust and tolerate some component variation
- If daily production is for example 10000 phones and yield is 90% it means that there is 1000 phones to be fixed
- As a rule of thumb most parameters need 2…3 dB marginal. For example if sensitivity limit is -102 dBm, design target should be around -105 dBm
- To avoid unneccessary high margins receiver chain should be analysed with some statistical method (Monte Carlo Analysis)

Power Consumption

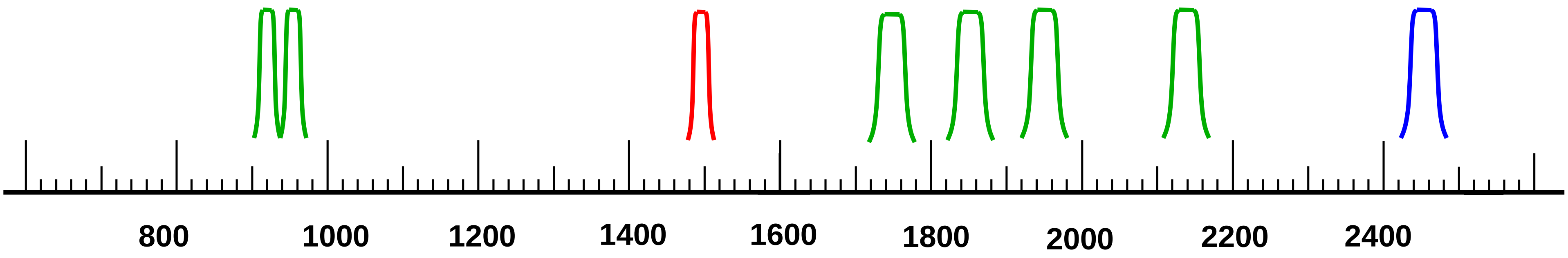
- Power consumption of the amplifiers and mixers depend on the intermodulation requirements
- For example a typical LNA with 18 dB gain and below 2 dB noise figure can be easily designed to take only a few milliwatts of power if there is no IIP3 requirement
- Typical GSM LNA with the same specification and -5 dBm IIP3 takes over 10 mW
- To achieve low power most gain should be after selectivity filters, but high selectivity filters increase cost
- In VCO low phase noise requirement means usually more power consumption because resonance circuit power should be high

Power consumption, Superhet vs. Direct Conversion

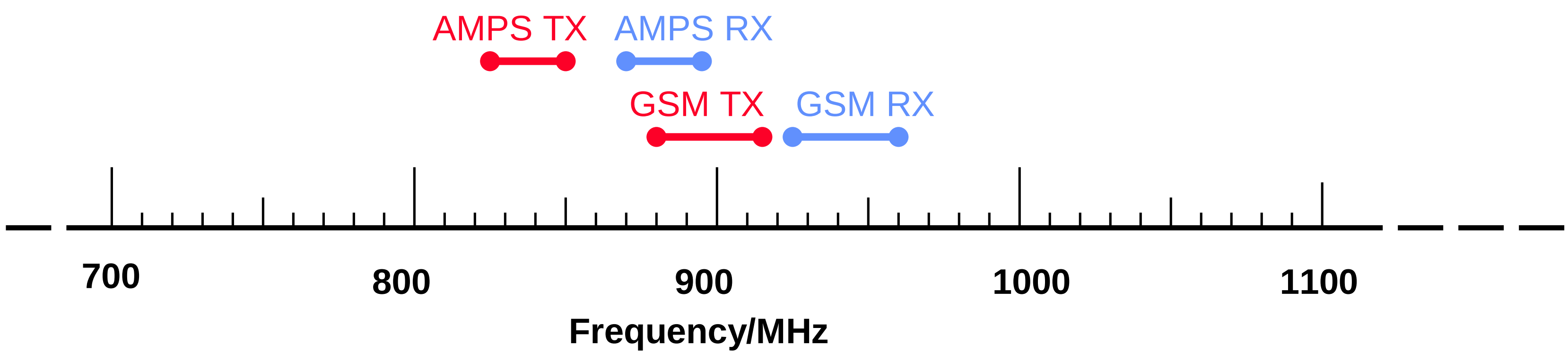
- Sometimes it claimed that direct conversion receiver consumes more power than superheterodyne receiver
- Claim is true if good IF filters are used in superhet and most gain is after that filtering
- However situation is reverse if we compare receivers with same size and cost
- To get direct conversion size and cost with superheterodyne receiver, very small and cheap IF filters must be used and then current is higher to achieve linearity
- So the practical implementation affects power consumption more than the receiver principle

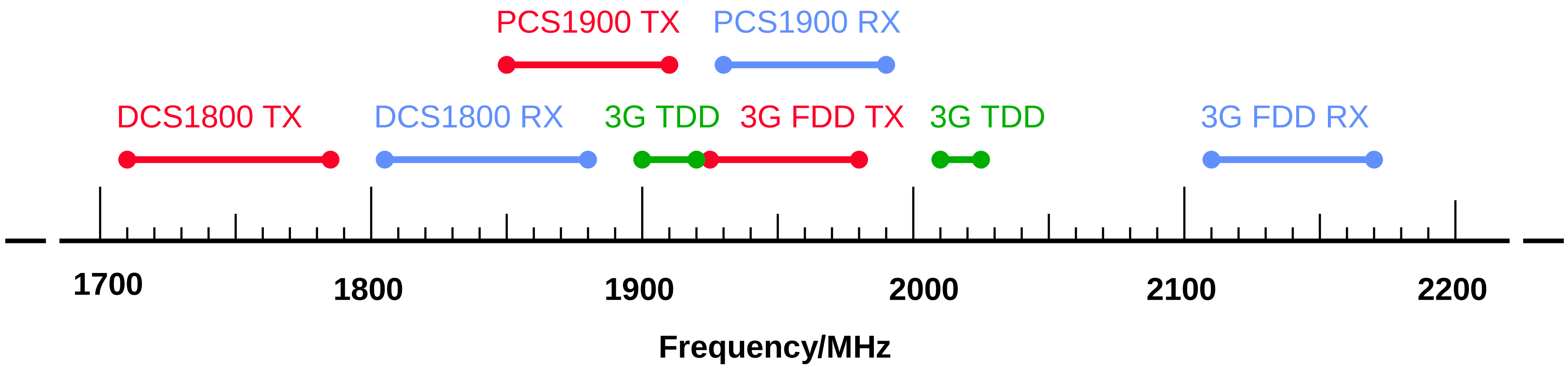
Multiband

- Most new products today are dualband
  - 900/1800 in GSM and 800/1900 in US-systems
- With WCDMA and extra RF features like Bluetooth and GPS we may see up to five frequency bands in the same phone
- Multiple switchable filters are costly and take a lot of space in multiband RF
- Direct conversion architecture is optimal for multimode RF engines
- Multicarrier proposals coming (CDMA2000, multicarrier EDGE?)
- Also antenna design will be very challenging in multiband phones



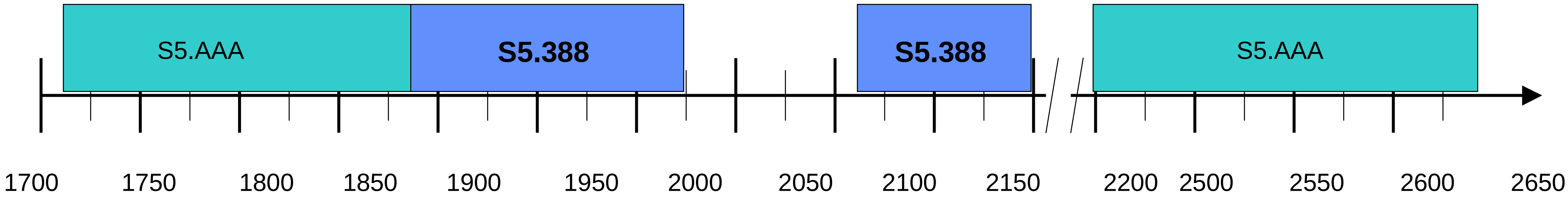
Frequency bands



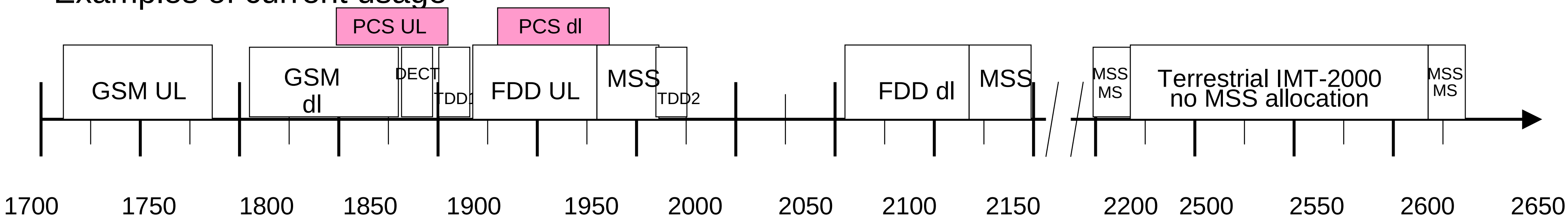


Proposed framework for global implementation of IMT-2000 in the 2GHz frequency range

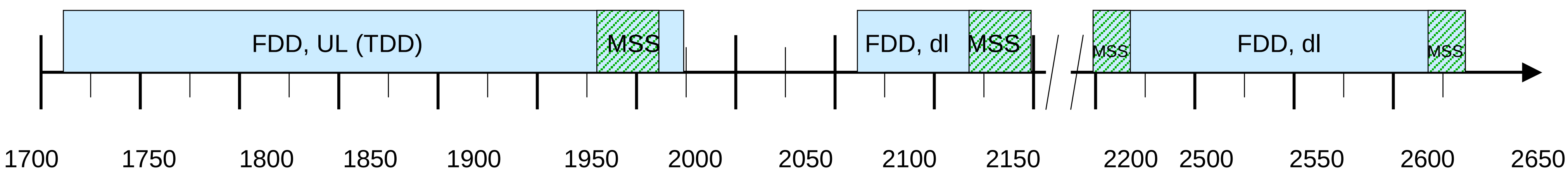
ITU identifications



Examples of current usage



Proposal for the long term objective:



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References

- WCDMA specification work
  - http://www.3gpp.org/
- APLAC info from HUT (e.g. manuals)
  - http://www.aplac.hut.fi/aplac/

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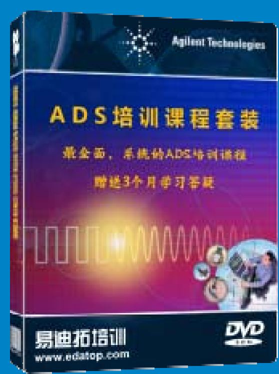

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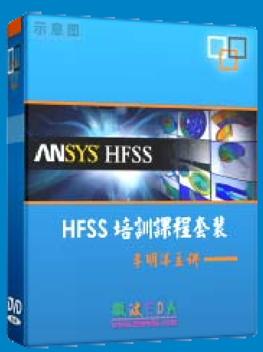

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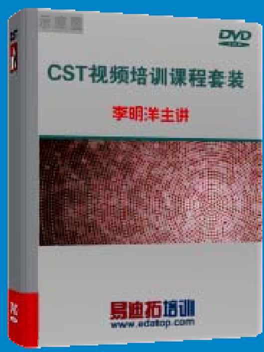

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