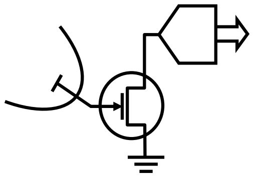
Politecnico di Torino
ICT School

Telecommunication Electronics

A1 - Radio systems architecture

» Basic radio systems
» Image rejection
» Digital and SW radio
» Functional units



Lesson A1: radio system architectures

- Basic radio systems architectures
  - Heterodyne
  - The image problem
  - Image rejection techniques
  - Digital radio
  - Software defined radio
- Transmitter block diagram
  - Heterodyne
  - Direct synthesis
- Identification of functional modules → this lessons
- Description of functional modules → next lessons

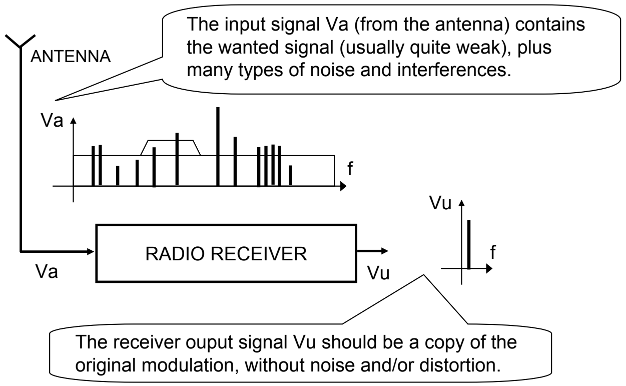
This lesson describes architectures for radio receivers and transmitters, and point outs some specific problems, such as rejection of image frequency and channel separation. The basic architecture here presented is heterodyne, based on frequency translation.

As for any electronic systems, a radio receiver (or transmitter) can use analog or digital signals and circuits. Digital circuits are more easy to design, reliable, and digital fabrication technology can be less expensive, therefore current design emphasis is towards digital techniques. Also radio systems move from analog to digital; the process is still on the way and the lesson presents benefits and critical issues.

The lesson follows a top down approach (like other parts ot his course): first step is description of function (high level block diagram), then the analysis moves down to more detailed descriptions: low level block diagrams, and finally circuit schematics, with selection or design of each device. There is always a separation between WHAT to do (the specification, the user view of the systems), and HOW the task is accomplished (the circuit details).

This architecture description identifies the various functional units, which are presented and analyzed in detail in the following lessons.

Expectations from a radio receiver



A radio receiver can be seen as a system which converts RF signals (Va in the diagram), collected by an antenna, and extract the information contained in one of the “channels” (e.g. a radio station), converted to a suitable representation (e.g. an electric signal Vu, able to drive earphones or other transducers).

The useful signal/station is usually embedded in a variety of other signals, originated by other channels, interferences (EMI), and noise. The receiver must have some SELECTIVITY to isolate the required signal, and TUNING capability to select different channels. Before the output, information is extracted from RF signal by a DEMODULATOR.

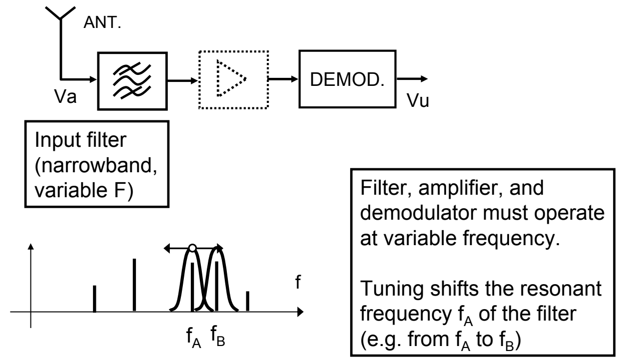
The electrical signals collected by the antenna may have very low levels (down to few microV), or – in the case of nearby transmitters – medium levels (such as a few hundred mV). In both cases they must be amplified to the power level useful to drive transducers.

The functions required to the system are therefore

- TUNING & SELECTIVITY (for channel separation),
- AMPLIFICATION (to increase power towards output transducer)
- DEMODULATION (information recovery)

They can be applied also in a different sequence.

Elementary receiver



The block diagram shows the most simple architecture for a receiver:

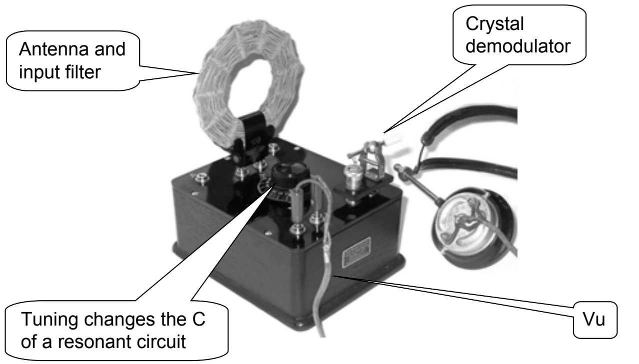
- the antenna, which collects RF signals (the desired signal is RFa in the following)
- a band-pass filter, to isolate the “good” channel RFa,
- a demodulator, to get the baseband signal from AM, FM...

The amplifier (middle block) is useful but at this point can be considered optional.

To select different channel we must shift the response of the band-pass (e.g. using a resonant circuit, tuned by changing one of the L or C reactive parameters).

To get good channel separation (selectivity, ability to listen only a specific station), the input pass-band filter needs steep frequency response (high Q). This is not easy to achieve, especially if we consider also the tuning requirement.

The crystal receiver



From http://www.antiqueradios.com

This is an example of radio system based on the previous architecture: a “Galena” receiver.

Galena is a natural mineral form of lead sulfide, which allows to build point-contact diodes, and in turn AM demodulators.

The antenna is a coil, which is also part of the RF band-pass resonant circuit. Tuning is achieved by changing C through a variable capacitor.

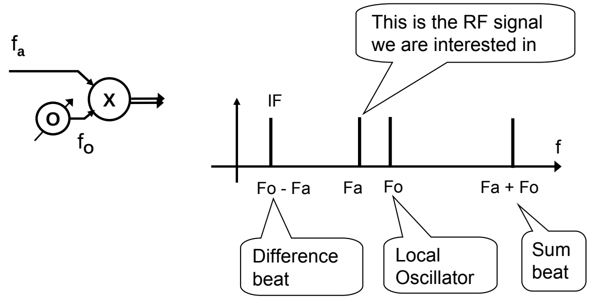
This device can operate as AM receiver in LW, MW, and SW ranges.

There is no amplifier, so the output power comes directly from RF signal: the receiver can drive anly earphones, and requires high power (or quite close) transmitters.

Since no power supply is needed, the system remains always operational, without need for batteries or other power source. This radio architecture is now used in passive RF ID, which get operating power from the RF signal.

Beats

- If we multiply two sine signals, the output is sum and difference beats
  - Werner’s formulae ….



The slide is a refresh on what happens when we multiply two sine signals, with frequencies respectively fa and fo.

In the time domain we can use Werner’s formula:

sin(fa t) sin(fo t) = .5 [cos(fa + fo)t + cos(fa - fo)t]

In the frequency domain the output includes two terms:

- a sum beat, with frequency fs = fa + fo,
- a difference beat with frequency fd = fo – fa.

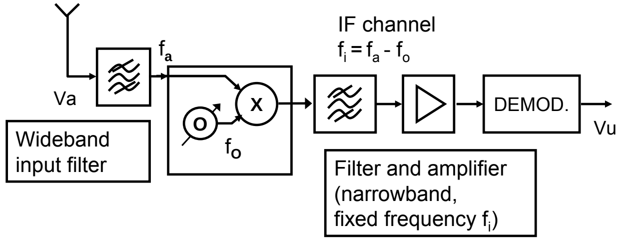
Mixing can be seen as a translation of Fa to a+fo and to fo-fa. If we multiply a signal with spectrum X(f) by a sinewave with frequency fo, the spectrum is translated to X(f+fo) and X(f-fo).

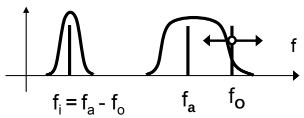
This technique can be applied to a radio receiver, where fa is the RFa signal from the antenna, and fo comes from a local oscillator LO.

Fa is translated to the difference and sum positions.

Fa can be any signal (instead of a simple sine-wave), its spectrum wil be translated to positions corresponding to sum and difference beats.

The heterodyne receiver





The input signal is shifted to a fixed frequency $f_i = f_a - f_o$. Tuning shifts the frequency f_O of the local oscillator

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In this diagram the RF signal from the antenna is filtered (wideband input filter) to remove outband noise, then multiplied by the Local Oscillator signal Fo; this causes a shift in the frequency domain to the sum and difference beat positions.

The IF channel band-pass filter isolates the difference beat (at frequency Fi), which is then amplified and demodulated. The received signal is therefore the part of RF spectrum at Fa=Fo-Fi. Only this signal can go through the IF filter.

To receive another channel, the system moves the frequency of the local oscillator to a new value Fo', and the mixer brings to IF the RF signal Fa' = Fo'+Fi.

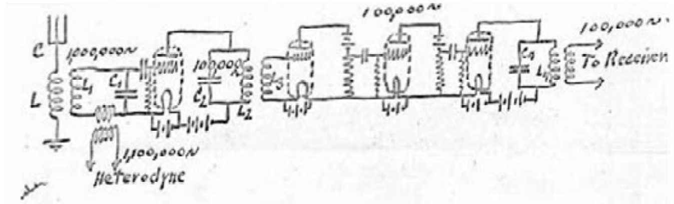
Channel separation is performed by the IF filter; which operates at fixed frequency, and can be quite narrow.

This is a HETERODYNE receiver.

In the heterodyne receiver one of the beat (usually the difference) is filtered, amplified, and demodulated in the IF chain. All the units after the mixer (the IF chain) operate at fixed frequency, which makes possible to get better parameters, especially in the filters.

Not so new …

- Armstrong original drawing: 1 MHz RF to 100 kHz IF (D. Marsh: "Direct conversion receivers…." edn europe, Oct.2000)



- Reginald Fessenden (1901): from the Greek heteros (other) and dynamis (force).

(from http://www.antiqueradios.com/superhet/)

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The principle of heterodyne (or use of beats) is well known; the slide shows the schematic diagram of an heterodyne receiver with electronic tubes (triodes).

The first triode receives at the input the sun of the antenna signal and local oscillator (through the transformer). Due to nonlinearity of the active device, the output includes product terms.

Benefits of heterodyne receivers

- Channel isolation achieved by fixed-frequency IF filter
  - No need for tunable narrowband filter
- Tuning achieved by shifting the LO frequency
  - Possible to cover wide frequency range
- Amplifiers and demodulator operate at fixed IF
  - Narrowband circuits more easy to design and test
- But …
  - Fi = Fo – Fa or Fb – Fo
  - both Fa and Fb enter the IF chain

→ image frequency problem

Benefits of heterodyne receivers:

- Channel isolation is achieved by fixed-frequency IF filter; it can have high Q and narrowband response

- Tuning is achieved by shifting the LO frequency; that removes tunable high Q circuits, and makes possible to cover a wide frequency range.

- Amplifiers and demodulator operate at fixed frequency (IF); such narrowband circuits are more easy to design and test.

Main problem of heterodyne receivers

- the same value of IF can be achieved as Fi = Fo – Fa or Fb – Fo:

Two RF signals Fa and Fb are both moved to the IF frequency and enter the IF chain. The unwanted one (Fb) is the IMAGE frequency.

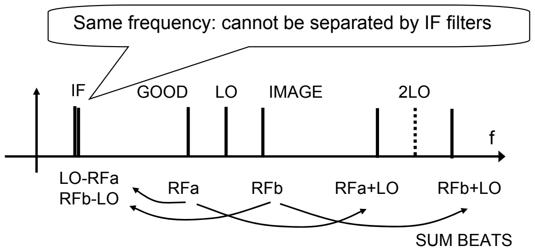
Most part of variations in basic heterodyne architecture are introduced to handle the image problem.

Lesson A1: radio system architectures

- Heterodyne receivers
- The image problem
- Dual conversion receivers
- Complex mixer & I/Q processing
- Digital receivers
- Software Defined Radio
- Examples

The image frequency

- The mixer generates sum and difference beats
  - Sum beats can be easily filtered
- good (RFa) and image (RFb) both folded to IF



The mixer brings to the same IF frequency two RF signals, RFa and RFb, with frequency respectively:

fa = fo – fi, and fb = fi – fo.

The unwanted signal is called IMAGE (can be seen as the image of the good one, mirrored on the LO frequency). The image could come from other transmitters, and can be stronger than the useful signal, causing

- Interference (high noise)

- Blocking (drive LNA/mixer into saturation)

Since in the IF chain image and good signal are on the same frequency range, they cannot be separated by filtering. Removing the image is the major problem in the heterodyne receivers, and can be accomplished in several ways:

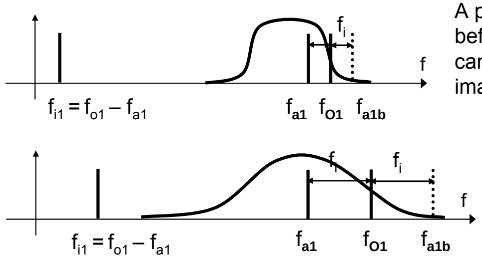
- Filters (on RF, before the mixer)

- Multiple-conversion

- Image rejection mixers

- Zero-IF architectures

Remove the image by RF filtering



A passband filter before the mixer can remove the image f_{a1b}.

With high IF, the image f_{a1b} is more far away, and the filter can be less steep.

A pass-band filter on RF before the mixer can remove the image. The RF filter bandwidth must cover all the input frequency range of the receiver

High attenuation requires steep filters (with high Q); a high IF frequency increases the distance between Fa and Fb, making less hard the RF filter requirements.

Numeric example:

RF Input channel: 2.5 GHz

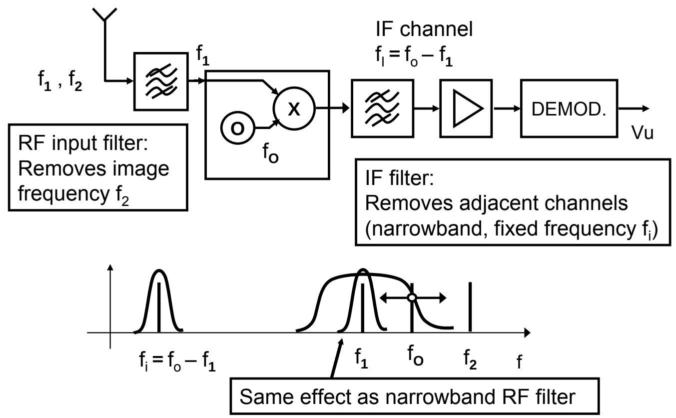
IF channel: 1 MHz

LO frequency:	2.5 GHz + 1 MHz = 2,501 MHz
Image at:	2.502 GHz
Q of RF image removal filter:	2,500/2 = 1250 !!! → difficult tio get

IF channel: 10 MHz

LO frequency:	2.5 GHz + 10 MHz = 2,510 MHz
Image at:	2.52 GHz
Q of RF image removal filter:	2,500/20 = 125 → rasonable

Filters in the heterodyne receiver



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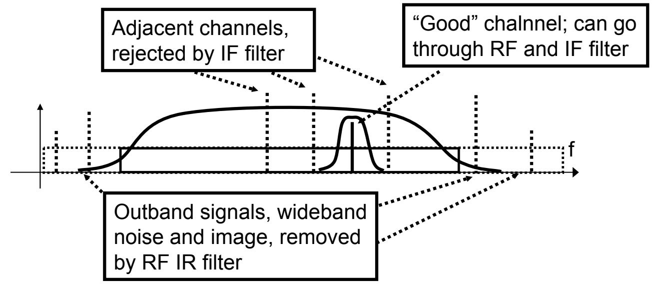
The RF input filter (band-pass, wide) removes noise and interferers outside the band used by all received channels; all channels are still present at mixer input.

The mixer translates the spectrum of the set of channels, to bring the desired channel to the IF frequency. At this point it is pass-band filtered and isolated from other channels. Tuning, that is channel separation, is achieved by moving the LO frequency Fo.

Noise and IF filters



IF filter must have tightly controlled transfer function

Difficult to get high Q filters at high IF

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The effect of frequency translation and IF filtering is like placing a narrow band-pass filter (IF bandwidth) on the RF signal. When LO is moved, the effect is the same as a tunable band-pass with a high Q.

The main benefit is that IF filters operate at fixed frequency, and can comply more tight specification (higher Q, better controlled shape).

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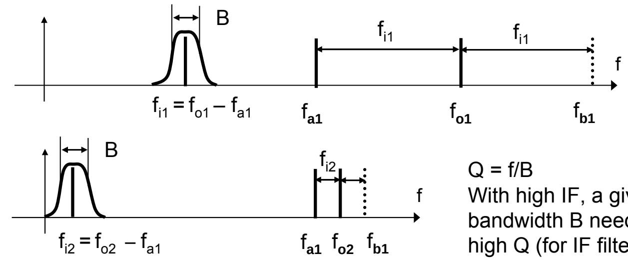
high or low IF frequency?



$Q = f/B$
With high IF, a given bandwidth B needs high Q (for IF filter)

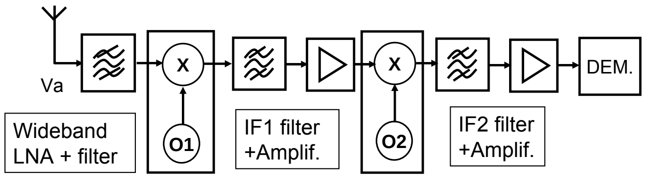
The IF channel is moved to a lower frequency with a second beat: from fi1 to fi2. Since fi2 is lower, the same bandwidth B can be achieved with lower Q

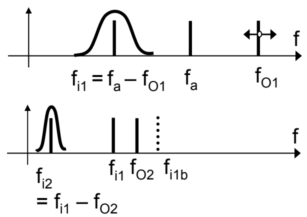
With high IF image frequencies are more far from the “good” signal (the actual distance is 2 Fi).

On the other hand, a low IF can achieve channel separation with lower Q IF filters.

A structure which brings together the benefits of high IF (image rejection) and low IF (channel isolation) is the double conversion heterodyne.

Dual-conversion heterodyne receiver





High first IF (IF1)
→ easy image removal Low second IF (IF2)
→ Simple channel filter

Tuning by shifting O1 or O2

IF1 image risk on IF2 (f_{i1b})!

Dual frequency conversion joins the benefits of high and low IF:

- easy image removal, thanks to higher separation of image from good signal.

- Good channel isolation, thanks to narrow bandwidth of the IF2 filter.

Dual conversion releases the specification of RF and IF1 filters.

RF filter removes images & wideband noise

BW and Q related with 1st IF frequency

High IF → wide RF filter (image is 2 x IF away)

First IF (High): reduces noise and far interferers (other channels)

Second IF (low):

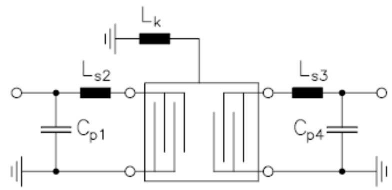
- Further noise rejection

- Remove adjacent channels (narrowband IF filter)

Tuning can be achieved by shifting either local oscillator (O1 or O2).

Mechanical filters

- Quartz lattice filters
  - Combination of high-Q resonators
- Surface Acoustic Waves (SAW)



Good band-pass filters are expensive & bulky, and achieving a specified shape can be difficult. Available technologies include

-LC resonators (Q is limited by losses)

-Mechanical resonators (SAW, Ceramic, Quartz)

Best performance can be obtained with mechanical resonators. They are based on piezoelectric materials, and exploit mechanical resonance

Electrical signals are converted to a mechanical wave which travels across a piezoelectric crystal or ceramic. The wave propagates across the device with minimum attenuation at the mechanical resonant frequency, and at the other end is converted back to an electrical signal.

SAWs use ceramic materials, less expensive then quartz lattice.

(RF filters for the cellular phone use this technology).

Lesson A1: radio system architectures

- Heterodyne receivers
- The image problem
- Dual conversion receivers
- Complex mixer & I/Q processing
- Digital receivers
- Software Defined Radio
- Examples

Complex mixers: SSB

- Werner's formulae:
  - sin a x sin b = ½ (cos(a-b) - cos(a+b)) → A
  - sin a x cos b = ½ (sin(a-b) + sin(a+b))
  - cos a x cos b = ½ (cos(a-b) + cos(a+b)) → B
- Single Side Band beat: A + B = cos(a-b)
  - No filter
  - Only difference product term
  - No sum term
  - In TX chain: generation of SSB signals

Another approach to image frequency removal is based on I/Q processing. The starting point is again Werner's formulae:

1.sin f1 cos f2 = ½ [sin(f1 - f2) + sin(f1 + f2)]

2.cos f1 cos f2 = ½ [cos(f1 - f2) + cos(f1 + f2)]

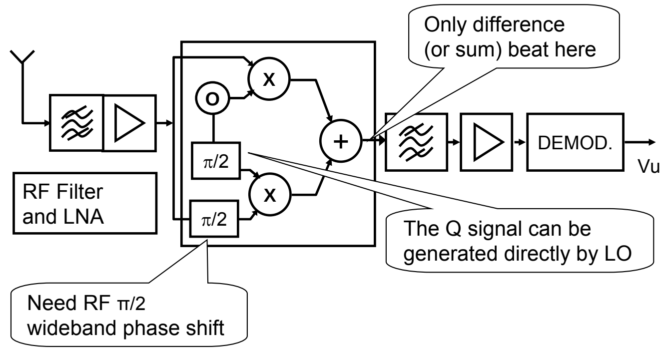
3.sin f1 sin f2 = ½ [cos(f1 - f2) - cos(f1 + f2)]

Adding 2 and 3 we obtain:

cos f1 cos f2 + sin f1 sin f2 = cos(f1 - f2)

Since it operates using In-Phase (I) and Quadrature (Q) components (the sine and the cosine), this is a first example of I/Q signal processing.

I/Q mixer in receivers



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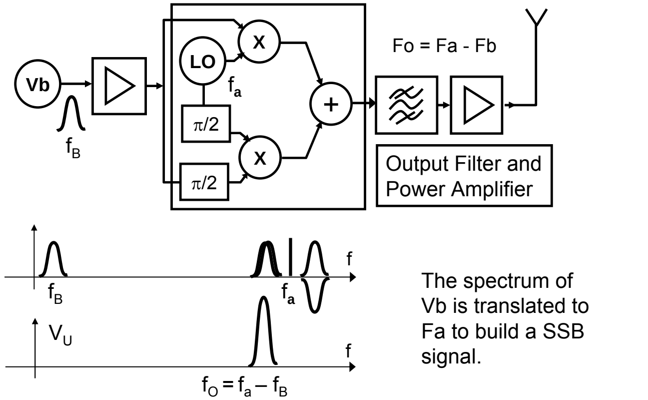
This technique can be used in receivers to get from the mixer only difference (or sum) beat.

In a receiver the I/Q mixer alone brings little benefit, since the difference and sum beats have wide separation, and can be easily isolated by filters in the IF chain (which must have narrowband band-pass for channel separation).

Benefits can come from the separate I/Q processing, as described in the next section.

Single Side Band (SSB) transmitter



The spectrum of Vb is translated to Fa to build a SSB signal.

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A more interesting application is in SSB transmitters. A standard AM signal includes the carrier and two sidebands; since each sideband carries all information, higher efficiency is achieved by keeping only one of the sidebands. The benefits are

- No power wasted for useless signals
- Less spectrum occupation.

The sidebands can be isolated by filters, which should be quite complex and expensive. A more convenient solution is to use I/Q frequency translation, with cancelation of one sideband.

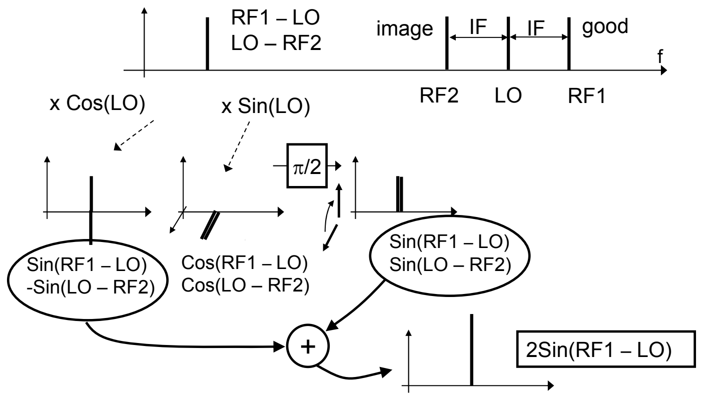
To achieve good cancelation, tigth gain and phase rotation matching between the two mixing paths is required. The technique is known since a long time, but it was used only in professional equipment, with individual trimming to match I/Q path parameters. With the improvements in RF IC technology, it is now used directly inside integrated systems without trimming.

Another critical point are phase shifters. For the local oscillator (LO) it is possible to design circuits which directly generate sine and cosine at the same frequency (DDS, Lesson B6). On the RF path we need a wideband phase shifter, which must comply high precision requirements for cancellation.

Complex mixers: image rejection

- Werner's formulae:
  - sin a x sin b = ½ (cos(a-b) - cos(a+b)) → A
  - sin a x cos b = ½ (sin(a-b) + sin(a+b))
  - cos a x cos b = ½ (cos(a-b) + cos(a+b)) → B
- Single Side Band beat: A + B = cos(a-b)
  - The same technique is used in
- Image rejection mixer
  - No image components
  - No need for filter (but needs phase shifters)

Image rejection mixer



Besides generating SSB signals, I/Q signal processing can be used to cancel the image signals in a receivers.

The diagram in the slide refers only to difference beats (sum beats can be easily removed by filters).

1): two mixers multiply RF signal respectively by LO I (sine) and Q (cosine) components. The RF signal includes RFa (good signal) and RFb (unwanted image).

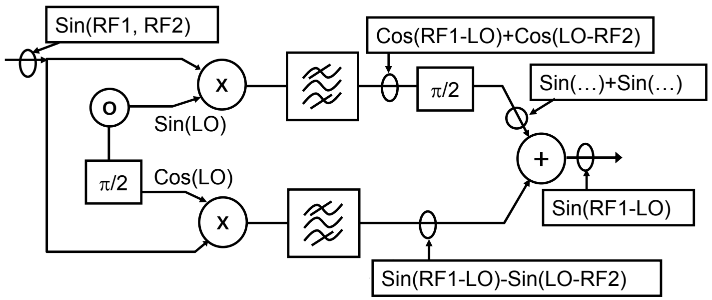
After each mixer the IF signal includes both RFa (the "good" one) and RFb (the image), overlapped to the same frequency. Due to the use of I/Q LO signal, the phases are different in the two branches.

2) A π/2 phase shift is applied to one channel; it generates image components with opposite polarity in the two channels.

3) the two channels are added; only RFa beat (the good signal) survives.

Image cancellation with this technique requires precise matching of mixer transfer function (Gain, Phase rotation).

Hartley image rejection



IF π/2 phase shift (narrowband) No RF2 in IF

The operations above described can be achieved with this structure (Hartley image rejection mixer).

Critical issues are:

- Phase shifters. A first one can be embedded in the LO; the second operates on fixed frequency (narrowband).

- Channel balance to achieve cancelation (gain and phase)

In summary, the main benefit of image rejection mixers is the removal of complex RF and IF band-pass filters.

The drawback is the need for tight balancing of gain and phase shift, to achieve good cancellation.

This in turn requires good “analog” technology.

Receiver with image rejection mixer

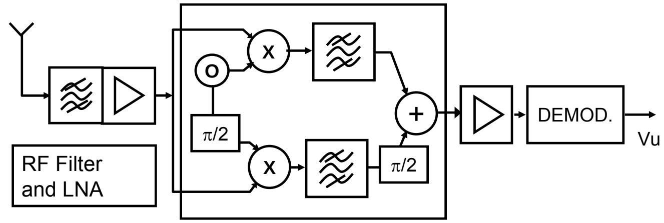


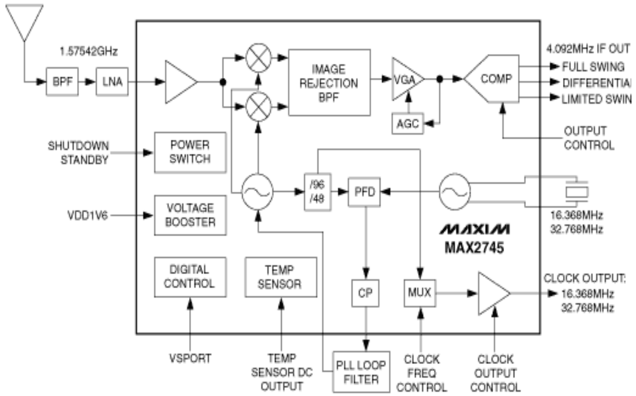
Image rejection mixer
IF π/2 phase shift (narrowband)
LO phase shift with digital techniques

The image rejection I/Q mixer is here used in the receiver chain, after RF filter and LNA.

Compared with single-branch mixer, this technique releases the requirements on RF input filter.

With dual conversion receivers, the I/Q image cancellation can occur at the first or second IF conversion.

Receiver with image reject mixer



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Example of complete radio chain in a commercial IC (GPS receiver).

In this diagram we can recognize several elements of an I/Q receiver.

-The PLL loop for the LO

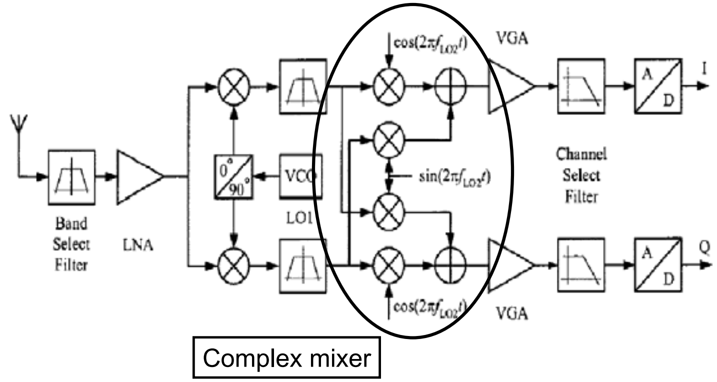
-The VCO with direct sin/cos outputs

-The image rejection unit

-A Variable Gain Amplifier (controlled by the AGC unit)

-Image rejection uses the I/Q Hartley structure.

Weaver image rejection



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The diagram represents another technique for image rejection.

Here the circuit generated I and Q IF components.

Indicating the π/2 rotation with the j operator, and considering input signal decomposed in I and Q components (a + jb), the circuit multiplies this signal with the LO, expressed as (c + jd).

$(a + jb) \times (c + jd) = (ac-bd) + j\,(bc+ad) = I + jQ$,

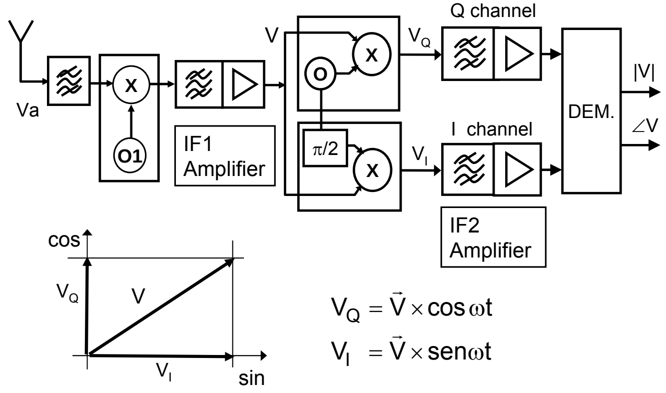
With:

$I = ac - bd$

$Q = bc + ad$

This structure is a COMPLEX MIXER.

I-Q channels



$$V_Q = \vec{V} \times \cos \omega t$$

$$V_I = \vec{V} \times \mathrm{sen} \omega t$$

The receiver may use I/Q demodulation, to keep amplitude and phase information.

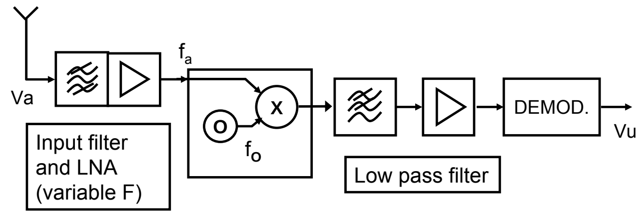
I and Q components can be obtained multiplying the received signal by sine and cosine references.

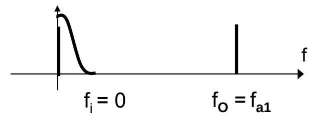
The signal is decomposed in I and Q components (at IF2 in this example).

The I/Q demodulator can compute |V| and ∠V.

This technique is used for complex phase/amplitude modulations.

Zero- IF (or low-IF) receiver





Received signal at f_a directly moved to baseband

Lowpass filter in IF channel

The heterodyne moves the signal spectrum to IF, usually lower than RF; Zero-IF receivers apply the same principle, but move the signal spectrum to DC (LO has the same frequency as the desired channel). This is called Zero IF (ZIF).

The main benefit of ZIF comes from using low-pass IF filters, with:

- Better control of shape: changing IF bandwidth requires only to change the cutoff frequency of the LPF.

- A LPF is more easy to design and build than band-pass inside an IC, making the architecture suitable for SOC.

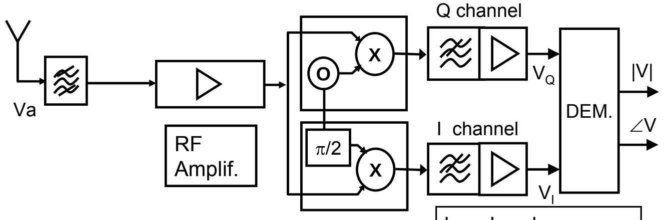
Critical issues in ZIF architectures are:

- Offset (DC is a signal): high-pass filters (to remove offset and DC unbalances) are not allowed.

- LO to RF leakage in the mixer: causes a DC beat, which cannot be isolated from actual RF (overlapped on the same frequency band).

- Image is the same signal spectrum flipped on the frequency axis, and cannot be removed by filters; image cancelation by I/Q processing becomes mandatory.

ZIF with I-Q channels



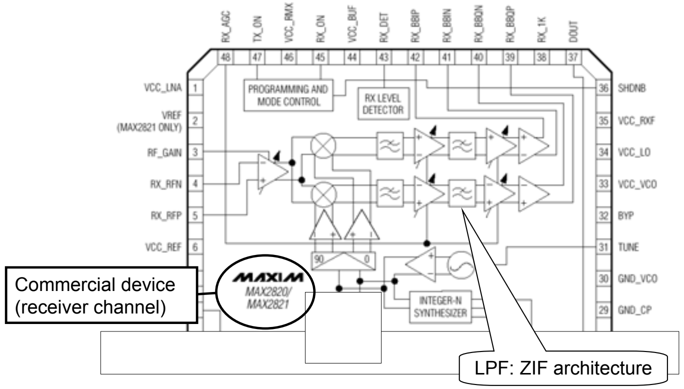
The signal is decomposed in I and Q components directly at RF

ZIF radio architectures are widely used inside ICs, mainly because low-pass filters are more easy to design and build than band-pass.

Offset and balance must be tightly controlled, therefore these circuits use differential signaling and structures.

ZIF radio systems can be recognized by the low-pass filters in the IF chain (instead of the usual band-pass).

Example of ZIF with I-Q channels



In this diagram (commercial device MAX2820) we can recognize:

- the fully differential structure, from RF to outputs
- a Variable Gain Amplifier (VGA) at RF front-end, with external control
- a PLL-based LO (frequency synthesizer)
- the I/Q mixer
- a phase shifter for the LO
- LPF in the IF chain (meaning it is a ZIF system)
- Variable gain IF amplifiers

Lesson A1: radio system architectures

- Heterodyne receivers
- The image problem
- Dual conversion receivers
- Complex mixer & I/Q processing
- Digital receivers
- Software Defined Radio
- Examples

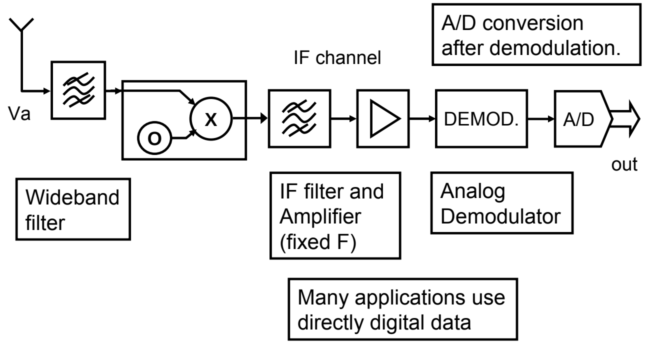
All the system previously analyzed are based on analog building blocks (filters, amplifiers, mixer, local oscillator).

The same function can be obtained also with digital circuits, which give benefits in terms of design ease, fabrication cost, and flexibility.

Moving from analog to Digital requires an Analog-to-Digital converter (ADC) somewhere along the receiver chain. The ADC position defines the boundary between analog and digital processing: all units before the ADC operate on analog signals, the ones after it process digital samples.

The various positions correspond to different tradeoff between complexity, performance, power consumption. This section describes the various choices for moving from the analog structures to digital ones, discussing the respective benefit and drawbacks.

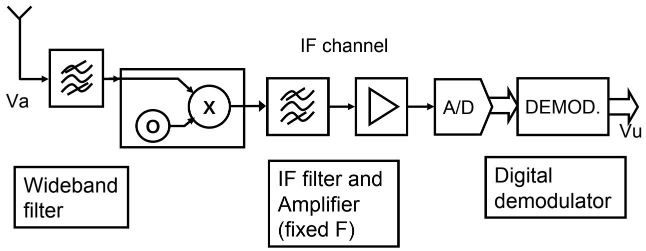
First step towards digital radio



A first choice is to place the ADC at the end ot the receiver chain, after the demodulator. On demodulated signal represented by numeric samples, it is possible to apply error correction, encryption or other functions that can be easily implemented on digital signals.

Carrying out similar operations with analog circuitry if not impossible; just more complex and expensive, due to signal degratation caused by noise intrinsically added at each analog processing step.

More digital - 2



The digital demodulator can use complex algorithms
The same HW support different types of modulation
The A/D converter must operate at high frequency

A second choice is to place the A/D converter at the end of the IF chain, between the IF output amplifier and the demodulator.

The ADC will operate on IF band, requiring higher sampling rate than in the previous case.

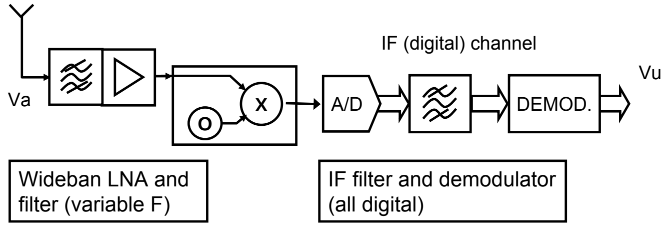
The digital demodulator provides high versatility; it can handle complex modulations, and use proprietary demodulation schemes in software, achieving improved noise immunity and robustness.

The same hardware can operate on different modulation schemes (provider they require the same processing till IF).

Different information (e.g., voice, data, video) can be easily muxed and demuxed.

Since digital processing can be carried out by a processor (microP or DSP) with SW defined algorithm, this can be seen as a first step towards software radio.

More digital - 3



The digital IF filter increases the computational load, but allows to modify the IF parameters in the SW

The next step is to place the A/D converter at the input of the IF chain, just after the mixer.

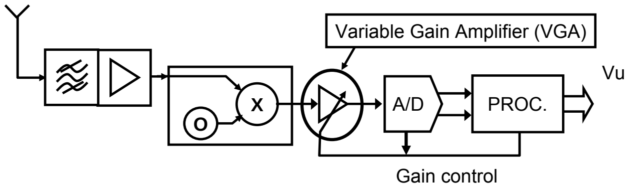
The ADC operating requirements are the same, but now the digital processor must carry out also digital filtering functions.

Again, the main benefit is increased flexibility in the IF filter: a digital filter is more easy to build (and modify) than an analog one. Frequency and shape changes require just reprogramming (in the processor SW or of a FPGA).

This structure requires more computational power than the previous ones, which in turns means more energy from the power supply.

How many bits do we need ?

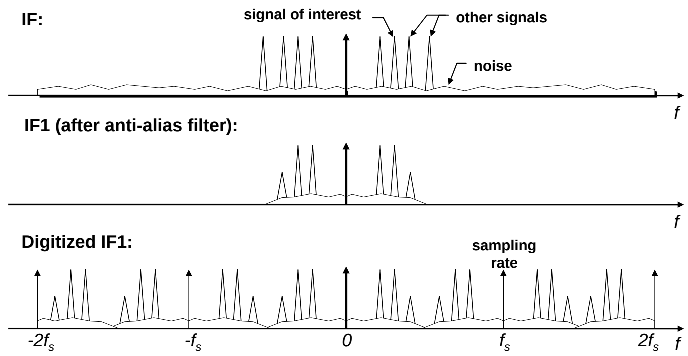
- RF signals have wide dynamic (µV…V)
- Nonlinearity → distorsion, intermodulation, …
- Two approaches:
  - Many bits /12, 14, … →high power & cost
  - AGC with analog or digital control loop



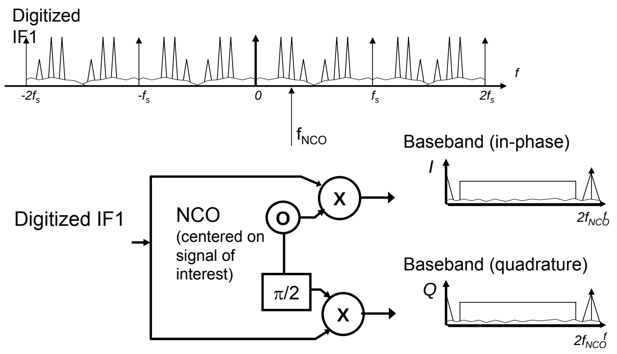
A key parameter in complex digital processing (such as filters) is the resolution (or precision) of the computation (the number of bits). To get a high resolution the ADC must provide a high number of usable bits, over all possible signal values.

Instead of using wide dynamic ADCs, some systems use variable gain amplifiers (VGA) before the ADC. Gain is controlled by feedback from the ADC output; as it approaches full scale, the gain is reduced.

IF Digitization

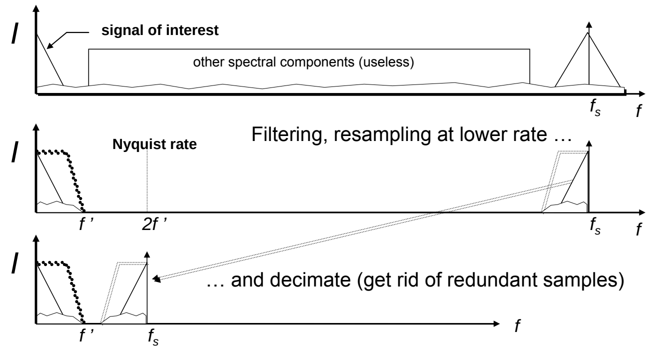


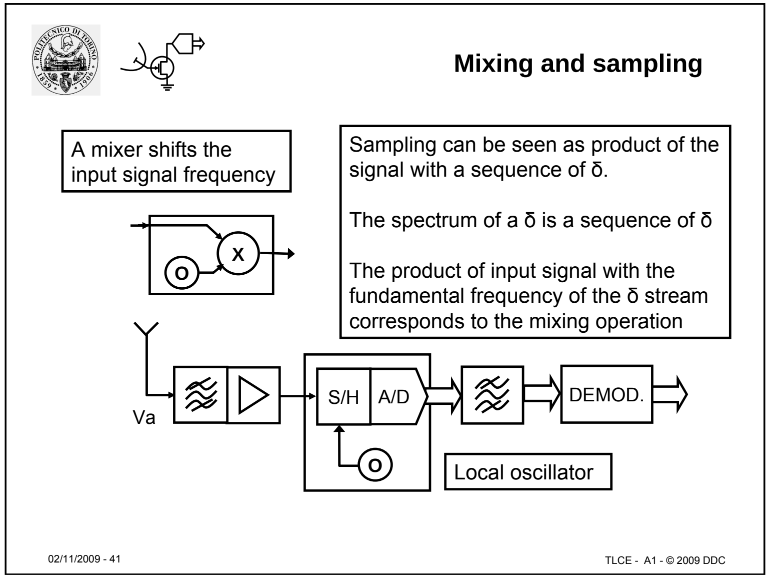
I-Q IF digitization



Oversampling, filtering and decimation

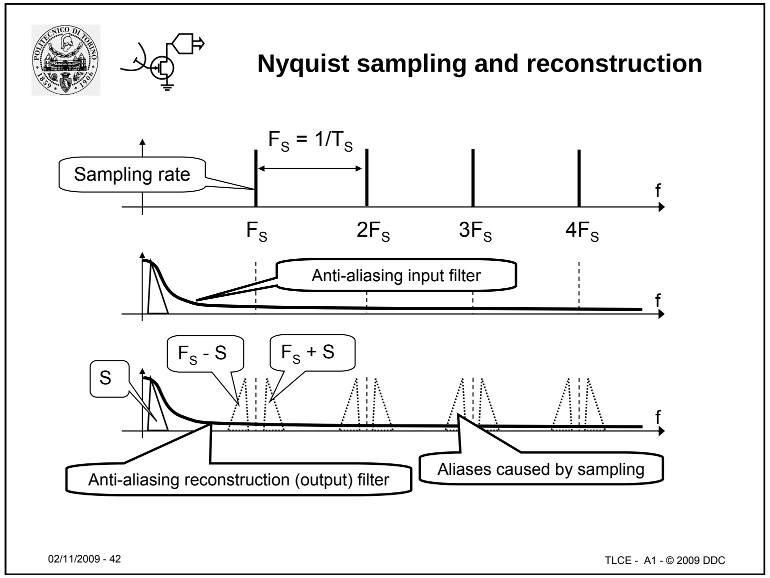
Baseband (or IF2 – one component):





Sampling corresponds to multiplying a signal by a sequence of pulses, spaced by the sampling interval Ts. The spectrum of a sequence of deltas is a sequence of delta (in the frequency domain), spaced by the sampling rate Fs = 1/Ts.

The sampling therefore can be seen as multiplying a signal by a set of sine waves, corresponding to the various lines of the spectrum of deltas. The product of the signal by the fundaments sampling rate Fs corresponds to mixing the signal with Fs. Only the X(t) x Fs beat can go trough the IF filter; all other products with higher order harmonics are filtered out.

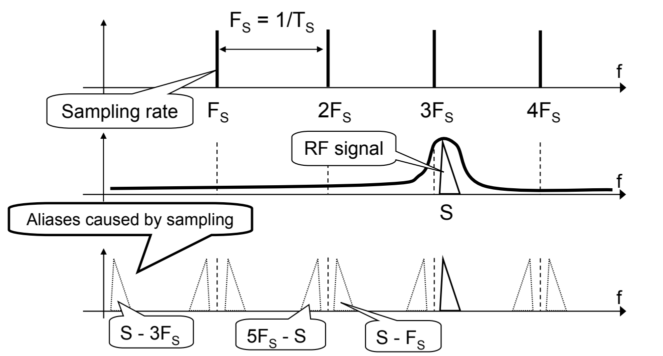


The slide shows the effect of sampling on signal spectrum. Compliance with the Nyquist-Shannon rule (Fs > 2 Fb) guarantees that aliases are not overlapped, and the original signal can be recovered by low-pass filter.

If the only spectral range interesting for the radio elaboration is the one near to 3Fs, where Fs is defined as:

Fs = 1/Ts, and Ts is the sample time.

Frequency translation by subsampling



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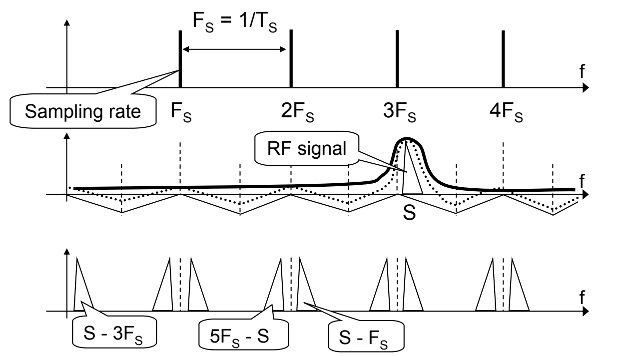
Now the sampled signal has a spectrum just above 3Fs, with a bandwidth Fb. Sampling at Fs rate creates the set of aliases. If the bandwidth Fb is < Fs/2, these aliases are not overlapped.

One of them (S – 3 Fs in this example), is moved to baseband.

The sampling process can be seen as frequency conversion. Sampling at a rate lower than the carrier causes a frequency translation of signal spectrum. If the Nyquist rule is fulfilled, the various aliases are separated, and one of them (usually baseband) can be isolated.

The ADC sampling rate is related to signal bandwidth, but sampling is affected by a jitter (noise in the time domain, which moves the actual sampling instant). The time precision of the sampling circuit (sampling jitter) is related to carrier frequency.

Subsampling and spectrum folding



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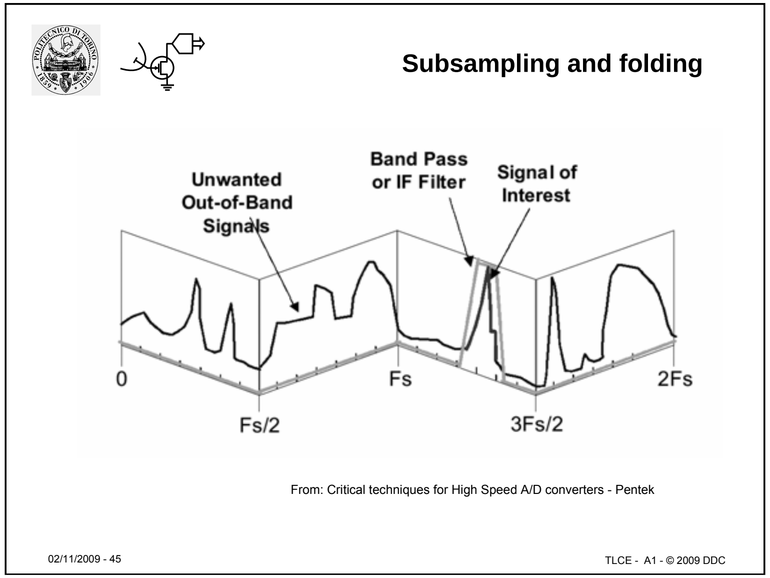
The generation of aliases can be represented with a folding process. The spectrum is drawn on a strip of paper, which is folded at Fs/2, Fs, and multiples of Fs/2. The signals present in each fold are copied (by the sampling) to all other segments.

This is SPECTRUM FOLDING.

Folding shows how a spectrum S is moved to baseband by sampling.

To avoid aliasing, the sampling rate must be higher than twice the signal bandwidth (foa any position of the carrier).

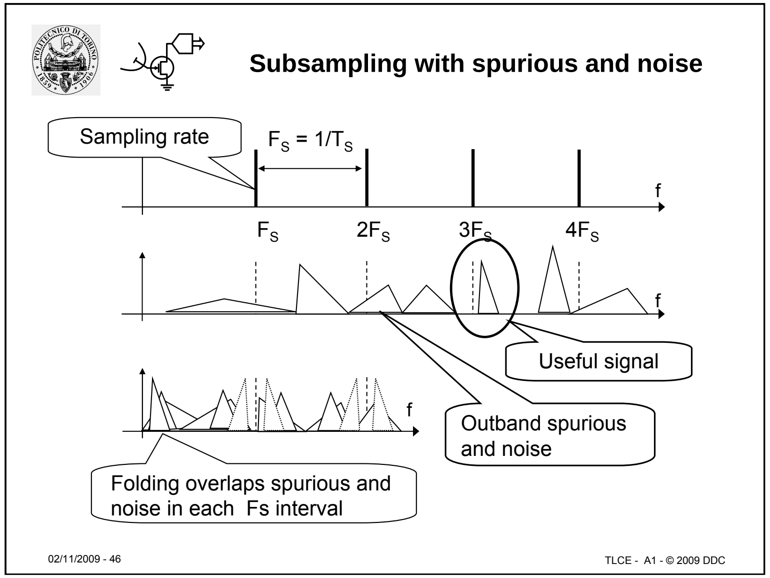


Spectrum folding overlaps several parts of the spectrum; to keep (in each fold) only the useful signal, this must be filtered (pass-band) to eliminate/reduce outband noise and interferers. Here we have the filtering effect: by filtering, so isolating the set of the

The sampling rate is related with the bandwidth (set of channels). After the ADC, filtering and channel separation is carried out by digital processing.

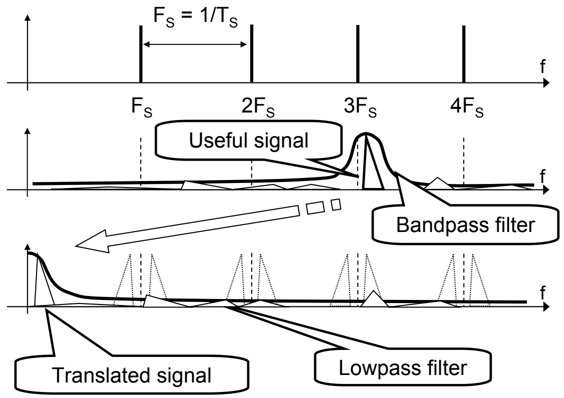
Example:

The set of channels has a bandwidth large 300 MHz, must be sampled at least at 600 MHz. The individual channels are isolated after ADC by digital filtering.



Subsampling unfiltered signals brings to overlapping of various spectrum segments. Outband signals become inband noise, which cannot be isolated later

Subsampling and filtering



The RF signal must be filtered before the sampling.

Sampling rate must be higher than twice the bandwidth (to keep aliases separated).

Further narrowband filtering (e.g. for channel separation) can be carried out in the digital part.

Subsampling and sampling jitter

- Sampling rate depends on signal bandwidth
  - Subsampling receivers use less power
- Sampling jitter depends on carrier
  - Amplitude error = (time jitter) x (slew rate)
    Slew rate = V x ω(carrier)
  - Phase error in I/Q chains
- Sampling jitter is a critical parameter
- Need for
  - low jitter sampling clock
  - high-speed Sample/Hold circuits (low aperture jitter)

The main idea for a radio system is to go digital as soon as possible.

The radiofrequency filter must be large enough to keep all channels; professional receivers have many filters, to divide the RF in several bands with better SNR.

Sampling rate depends of RF filter bandwidth; the aliases generated by sampling must not overlap.

Sampling occurs with a time error, called aperture jitter (Tja). The errors in sampling time become amplitude errors through the signal slew rate. Allowed sampling jitter depends on signal frequency (not bandwidth !).

Numeric example:

RF band: 820 – 880 MHz BW = 60 MHz

Suitable sampling rate: 200 Ms/s

Evaluation of sampling jitter at 850 MHz (sampling jitter error Ej):

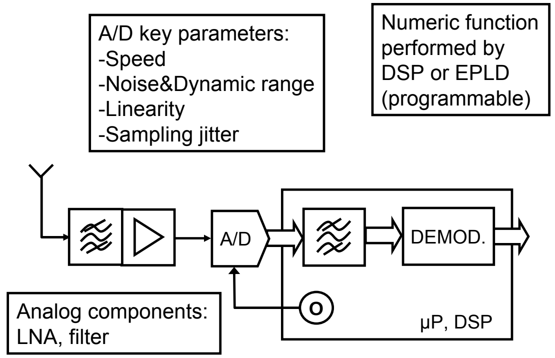
Ej = Tja x SR = Tja x om V

Percentage error, for full scale signal: Ejp =

Lesson A1: radio system architectures

- Heterodyne receivers
- The image problem
- Dual conversion receivers
- Complex mixer & I/Q processing
- Digital receivers
- Software Defined Radio
- Examples

SDR: Software Defined Radio



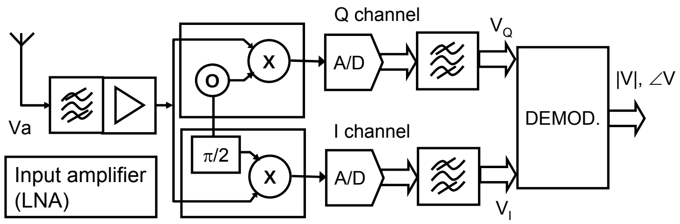
The block diagram in the slide shows a radio system where all functions (besides RF filter and amplifier) are carried out by digital units, after the ADC.

When the digital processing is carried out by microprocessors or DSPs, the functions are casted in the SW. This creates the term “SW radio”.

The actual meaning is “almost all digital”, including the LO (as NCO).

Systems which operates at 2.5 GHz with ZIF architecture are commercially available.

I/Q software defined radio



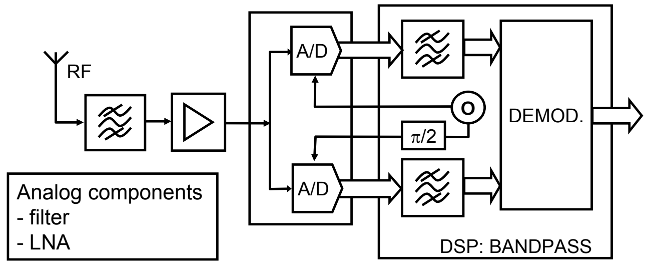
Signal decomposed in I-Q components, fed to the digital demodulator

The slide shows a digital I/Q radio system.

This architecture keeps phase information, thanks to the I/ channels. This is mandatory for some numeric modulations. I/Q processing allows image cancellation, and tolerates carrier frequency shift.

Since IF filtering and demodulation are carried out in the digital part, this can be seen as a “universal” radio systems, which can operate on several modulation types (for RF signals compatible with the input front-end).

Direct sampling I-Q SDR



Universal radio HW:
Can change frequency, modulation, application (GSM, GPS, UMTS, …)

O = RF + IF
IF processing
Bandpass filter

Same principle (all digital processing) with direct sampling.

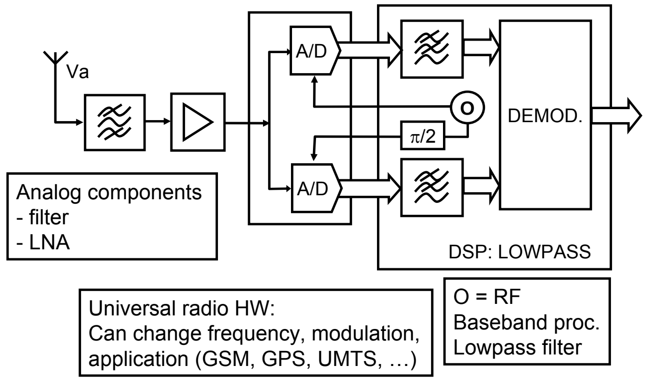
Down conversion carried out by sampling, without mixer.

Image cancellation uses I/Q processing

Sampling rate is related with RF bandwidth

Sampling jitter is related with carrier frequency.

ZIF I/Q



This is the same structure as in previous slide, but here the RF is moved directly to baseband (DC): we get a Zero IF (ZIF) system.

Main benefit: the IF chain filter is low-pass instead of band-pass.

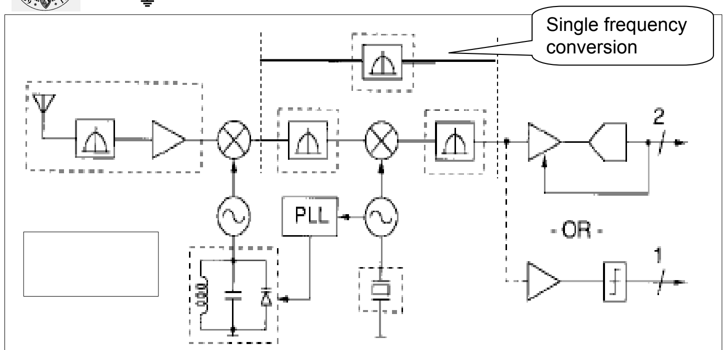
Problems: DC offset & drift cannot be separated from useful signals.

With ZIF images are overlapped with useful signal; I/Q processing is mandatory to remove images.

Lesson A1: radio system architectures

- Heterodyne receivers
- The image problem
- Dual conversion receivers
- Complex mixer & I/Q processing
- Digital receivers
- Software Defined Radio
- Examples

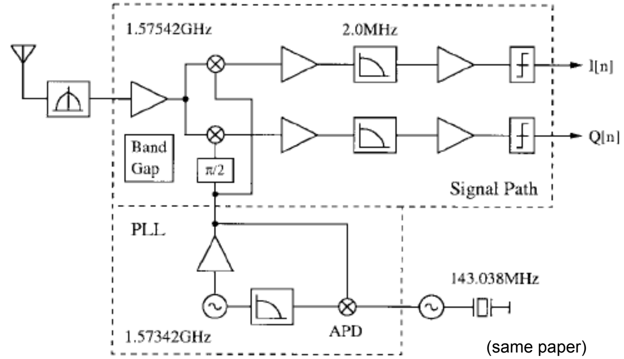
Positioning RX – dual conversion



IEEE JSSC, VOL. 33, NO. 12, Dec. 1998
Thomas H. Lee: A 115-mW, 0.5- m CMOS GPS Receiver with Wide Dynamic-Range Active Filters

LO1 and LO2 from the same reference with a PLL synthesizer
Low resolution ADC (2 bits), but with VGA to increase the dynamic range.

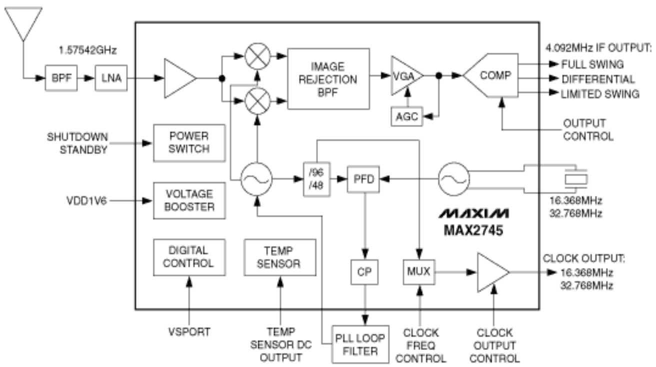
Positioning Receivers – I/Q ZIF



(same paper)

A I/Q structure with direct conversion (ZIF).
IF Filters become low-pass.

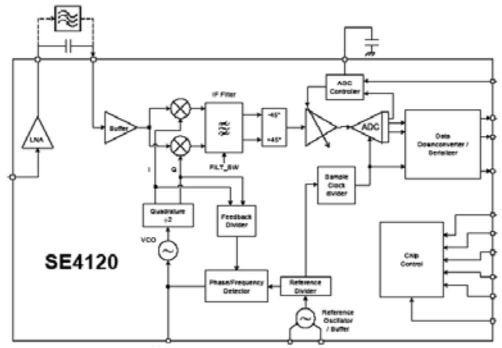
Positioning RX – image reject mixer



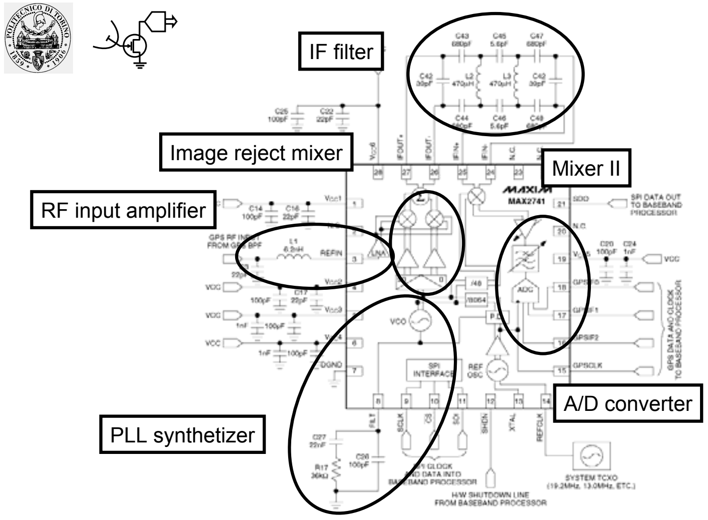
Block diagram of a commercial IC, where it is possible to recognize
- I/Q architecture (not a ZIF, since the IF filters are bandpass)
- VGA controlled by an AGC circuit
- I/Q Local Oscillator

Example: IC for GPS + Galileo

Sept 2006



…. world's first Galileo-ready receiver for mass market consumer electronics.



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The transmitter chain

- Conventional
  - Generate carrier
  - Modulate
  - Filter and Amplify (PA)
- Reverse heterodyne receiver chain
  - Generate baseband modulated signal
  - Filter and translate to RF
  - Filter and amplify (PA)
- Next
  - Direct generation of RF (high speed DAC)
  - Filter and amplify

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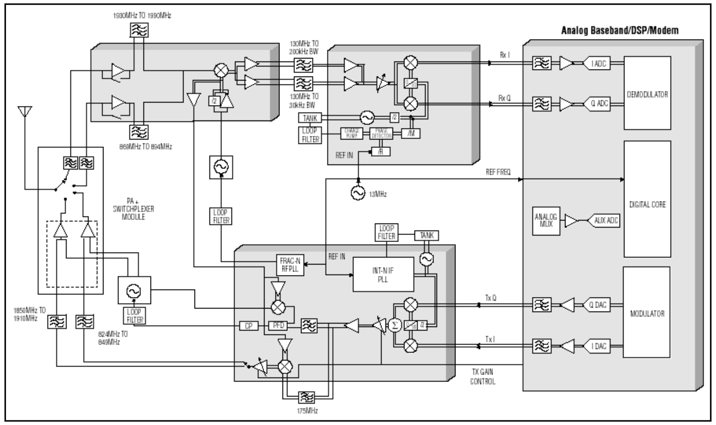
Up to now we have seen radio architectures for radio receivers; transmitters can use the same approaches, that is:

- spectrum shift with heterodyne

- ZIF

- digital signal generation and processing

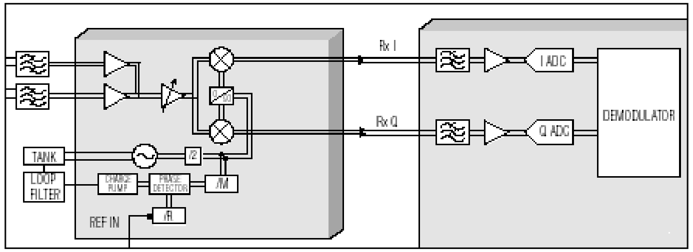
Complete RTX structure



Details of receiver I/Q chain

Section of the receiver chain:
- filters, amplifiers, PLL, mixer
- A/D converters
- Numeric demodulator

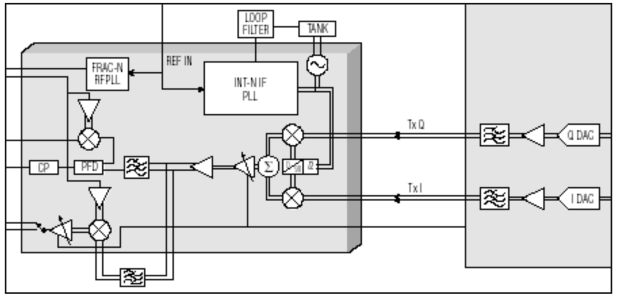
Signal flow



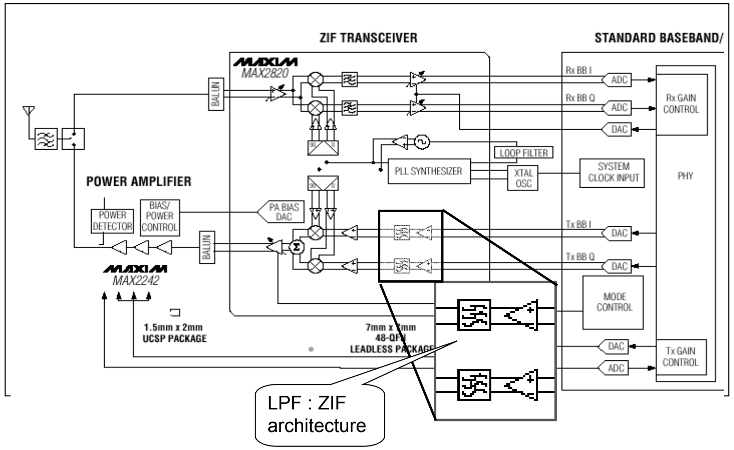
I/Q transmitter structure

Section of the transmission chain:
- D/A converters,
- amplifiers, filters
- PLL, mixer,

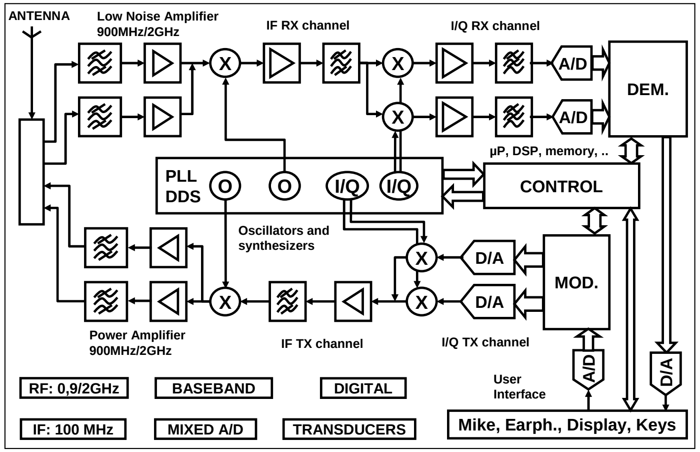
Signal flow



Example of ZIF transceiver



Reference block diagram



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Basic blocks of RTX (next lessons)

- LNA (Low Noise Amplifiers)
- PA (Power Amplifier)
- MIXER
- AGC, RSSI (Received Signal Strength Indicator)
- PLL (Phase Lock Loops) or
  DDS (Direct Digital Synthesizers)
- A/D and D/A converters
- Signal conditioning (anti-alias filters, S/H)
- Not here: Filters, tuned circuit, Digital processing, …

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Lesson A1 – final test

- Which are the benefits of heterodyne receivers?
- Explain the image frequency problem.
- Which filter is used for channel separation?
- Why some receivers use dual conversion?
- Which techniques are used for image rejection?
- What do AGC and VGA mean ?
- Describe the architecture of a SW radio.
- Which is the minimum sampling rate (Fs) for a signal with 2.5 GHz carrier, and a bandwidth of 2 MHz ?

Next lesson (A2)

- Transistor amplifiers
  - Basic circuit, Linear transistor model, Biasing
  - Small signal analysis, Frequency response
- Design of amplifiers
  - Specifications, Design sequence
- Lab experience 1:
  - Transistor amplifier, small signal (linear model)
- Lab experience 2:
  - Transistor amplifier, large signal (nonlinear model)
- Text reference
  - Transistor circuits 1.1, 1.2