

# Radio-communications architectures

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## 1. Introduction

Wireless communications, i.e. radio-communications, are widely used for our different daily needs. Examples are numerous and standard names like BLUETOOTH, WiFi, WiMAX, UMTS, GSM and, more recently, LTE are well-known [Baudoin et al. 2007]. General applications in the RFID or UWB contexts are the subject of many papers. This chapter presents radio-frequency (RF) communication systems architecture for mobile, wireless local area networks (WLAN) and connectivity terminals. An important aspect of today's applications is the data rate increase, especially in connectivity standards like WiFi and WiMAX, because the user demands high Quality of Service (QoS). To increase the data rate we tend to use wideband or multi-standard architecture. The concept of software radio includes a self-reconfigurable radio link and is described here on its RF aspects. The term multi-radio is preferred. This chapter focuses on the transmitter, yet some considerations about the receiver are given. An important aspect of the architecture is that a transceiver is built with respect to the radio-communications signals. We classify them in section 2 by differentiating Continuous Wave (CW) and Impulse Radio (IR) systems. Section 3 is the technical background one has to consider for actual applications. Section 4 summarizes state-of-the-art high data rate architectures and the latest research in multi-radio systems. In section 5, IR architectures for Ultra Wide Band (UWB) systems complete this overview; we will also underline the coexistence and compatibility challenges between CW and IR systems.

## 2. Transceiver aspects for radio-communications

### 2.1 Radio communications signals

Radio-communications applications deal with communicating and non-communicating links with their different parameters. People expect high quality from their different services (QoS) whatever the telecommunications system used. For example, voice (low data rate) or visio-phone and multimedia download (high data rate) are assumed to be present on the new generation mobile phone. This reveals the co-existence and interaction goals between mobile communication systems (GSM, GSM EDGE, UMTS...) and connectivity standards (BLUETOOTH, WiFi, WiMAX...) [Baudoin et al., 2007]. Thanks to Impulse Radio

Ultra Wide Band (IR-UWB), other fields of interest such as Radio Frequency Identification (RFID) and localization systems are examples of where radio-communications transceivers are currently being designed. Each kind of application can be classified by the resulting radio signals emitted/received. Determining factors are (i) the use of power efficient or spectrum efficient modulation schemes, (ii) the frequency and type of carrier signal used: Continuous Wave (CW) or Impulse Radio (IR) based signals and (iii) the data rate needed (defining a major subdivision of CW based systems). Depending on the choice of the factors involved, the design faced by the RF architect can be varied and challenging. We differentiate three types of cases in this chapter, as illustrated in Fig. 1.

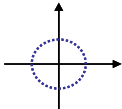
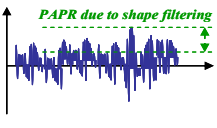
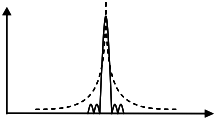
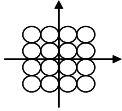

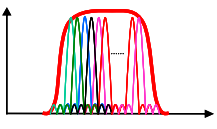
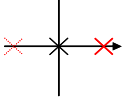
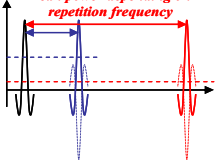
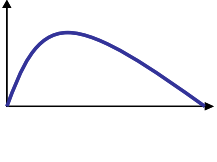
		<i>Typical Modulation Scheme</i>	<i>Time signal (with shaping filter for CW)</i>	<i>Frequency spectrum</i>	<i>PROS.</i>
<b>CW</b>	<b>NB-CW</b>				<b>Power efficient</b>
	<b>WB-CW</b>				<b>Spectrum efficient</b>
<b>IR</b>	<b>IR-UWB</b>				<b>Power saving Spread spectrum</b>

Fig. 1. Main types of radio-communications signals

1) NarrowBand CW (NB-CW) systems, like GSM (GMSK), EDGE (D-QPSK), BLUETOOTH, RFID tags, etc... These systems are often power efficient modulation schemes (EDGE is an exception) because these applications use a low data rate transfer. Major problems of the NB-CW architecture involve with the coexistence and the signal protection against interferers or blocking signals. Some spread-spectrum techniques are often added to improve the communication range (frequency-hopping in the case of BLUETOOTH). The NB-CW case is also considered to be the classic radio communications link and reference system because it corresponds to the popular AM/FM radio broadcasts. NB-CW systems are often considered as using constant envelope signals. This could be true only if FSK modulation schemes are performed, but it is also possible to use x-QAM low symbol rate modulations (EDGE). Additionally, the shaping filter (root raised cosine filter) implies amplitude variations (non-constant envelope) even on FSK modulated signals (GSM).

2) WideBand CW (WB-CW) systems, like: UMTS (W-CDMA), WiMAX (OFDM enhanced), LTE (OFDM based), WiFi (OFDM), UWB (OFDM version)... These systems correspond to high data rate transfer, often for multimedia applications. We can see an increasing need in this field of interest due to the large number of new standards which can be found. Due to the bandwidth limitations for each standard, the modulation scheme is often spectrum efficient (x-QAM) and the use of multi-carrier transmission is usually performed, e.g., OFDM or MC-CDMA. Since there are high amplitude variations of such signals, the transceiver architecture is designed in function with the unavoidable non-linear effects (NL) caused by the power amplification block. Emitting a high PAPR (Peak to Average Power Ratio) has always been a well-known transmitter challenge. The linearization of such a transmitter is mandatory and will be discussed in part 3. WB-CW transceivers also need a wideband design for all of its key elements: antennas, LNA (Low Noise amplifier), HPA (High Power Amplifier) and mixers. This often results in lower performance of the above-mentioned blocks than for NB-CW systems.

3) IR-UWB systems such as UWB localization systems, RFID-UWB... These systems are special because they are based on (one of the) spread spectrum techniques in order to protect the information. The idea is to spread the information in frequency while lowering the emitted power. The use of UWB (3.1-10.6 GHz in the USA) was highly discussed in order to evaluate its co-existence with NB-CW and WB-CW. What is important here is how the power amplification is processed differently for this type of communication. An average power is defined in function of the Pulse Repetition Frequency (PRF), given by the specifications of the IR-UWB standard. For a fixed emitted power: the shorter the pulse, the higher the instantaneous power and bandwidth. Transceivers for these signals are based on impulse generators and energy detectors or correlation receivers, see section 5.

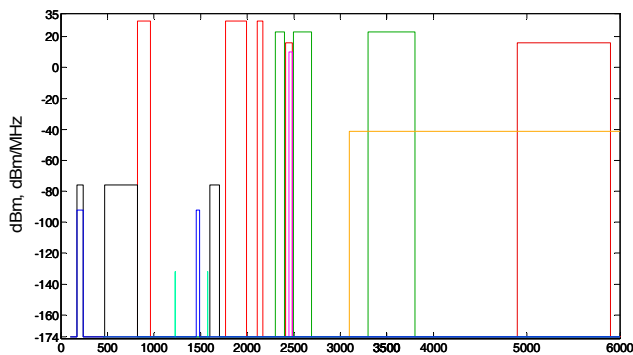


Fig. 2. Telecommunications spectrum sharing and power limitations up to 6 GHz

The three types described can represent every kind of radio-communications signal. The characteristics which have an impact on the architecture are mainly the centre frequency (choice of the technology) and bandwidth (circuits' topologies and performance limitations), and also the PAPR for CW signals. Fig. 2 qualitatively summarizes the power limitations and frequency specifications for some telecommunications standards up to 6 GHz: cellular, WiMAX, WiFi, Bluetooth, UWB and DVB-H. The goal of RF architecture is to emit and receive such signals with no alteration of the information (no constellation distortion for CW). Designing the architecture implies other considerations such as noise, linearity, efficiency and

systems co-existence and immunity. The receiver part of a transceiver has to correctly identify information without adding too much noise, even when high power unwanted signals are close (in the frequency domain). The transmitter part has to linearly amplify the signal in order to emit as far as possible, respecting the standard power limitations (spectrum mask) for co-existence. Architectures for NB-CW, WB-CW and IR-UWB use some basic elements (blocks) that will be described in the next sub-section. Multi-radio is interpreted as a possible reconfigurable architecture for most of the signals presented (mainly NB-CW and WB-CW). This helps drive improvements on classic structures.

**2.2 Basic elements and their imperfections**

Transceiver architectures for radio-communications signals is defined from the Digital to Analog Converter (DACs, in the baseband section) to the transmitter (Tx) antenna and, respectively, from the receiving (Rx) antenna to the Analog to Digital Converter (ADCs). Each of the Tx and Rx sections deal with unavoidable tradeoffs such as linearity/efficiency (Tx), noise/gain (Rx). Other transceivers in the spectrum vicinity are supposed to correctly receive (co-existence) and/or emit their signals (immunity) without lowering QoS. The basic functions (blocks) in radio-communications are conversion (digital/analog), high frequency transposition and modulation, filtering, power or low noise amplification and radiation/sensing (Tx/Rx antenna). Here, we are describing a system and how it relates to these blocks in radio-communications architecture. We will focus on their imperfections and their impact on the system performance (noise, spectrum distortion...). Sometimes, for CW standards, the influence of noise or spectral re-growths is quantified by certain criteria such as the EVM and/or the ACPR as defined in Fig. 3 [Baudoin et al., 2007][Villegas et al., 2007].

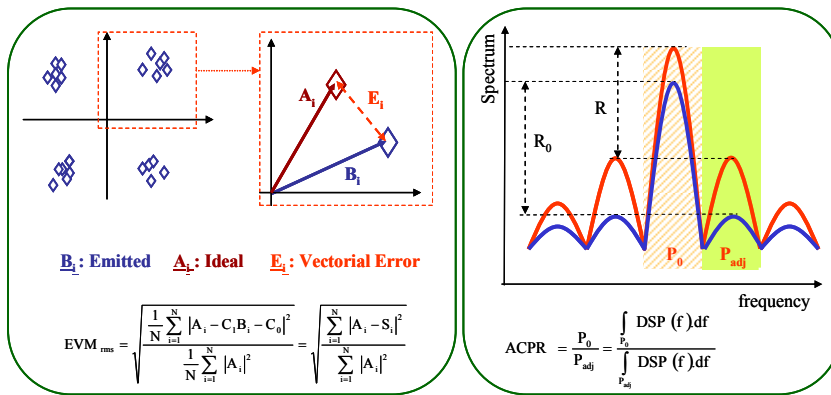


Fig. 3. EVM and ACPR definitions

- DACs and ADCs will not be presented in details because their performance in terms of bandwidth (up to 100 MHz) and resolution (up to 16 bits) is almost sufficient for today's radio-communications signals. The main limitations are the current consumption of fast converters and the difficulty in designing near-GHz Sigma Delta ( $\Sigma\Delta$ ) encoders, often in the context of polar transmitters as is presented in section 4. It should be noticed that for WB-CW signals, the bandwidth limitation is the criterion of choice and a source of important spectrum degradation (approximated qualitatively by a windowing effect).

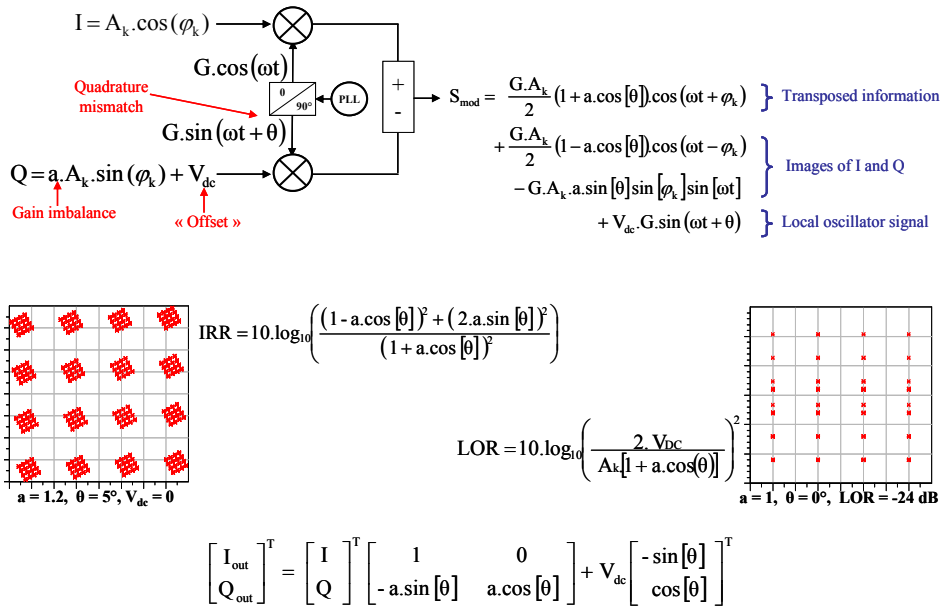


Fig. 4. IQ modulator equations and the effects of its imperfections

- The IQ modulator is the block providing the transposition of the information at high frequency (up-converter) or at baseband/intermediate frequency (down-converter). We describe the case of the up-converter for simplicity. It needs the baseband information components I and Q (I and Q channels) and a carrier frequency signal, provided by a frequency synthesizer. Key components are the non-linear multipliers provided thanks to passive (PIN diodes...) or active circuits (Gilbert cell...). Every component should be carefully designed with regards to the synthesizer frequency value. Moreover, the noise added by the multipliers will be impossible to filter. The main difficulty for the modulator is the perfect matching between I and Q paths. As is reported in Fig. 4 (at one fixed frequency), gain and phase imbalances ( $a$  and  $\theta$ ) create unwanted images of the information. Also the presence of an offset  $V_{DC}$  can create the emission of the synthesized carrier frequency (called Local Oscillator, LO). All of these imperfections result in the distortion of the information and are quantified by the  $IRR$  and  $LOR$  power ratio (the actual performance is in the range of -50 dB). These imperfections are not seen on the spectrum because their equivalent added noise is inside the main lobe. The biggest challenge concerns the modulation of wideband signals because it is hard for the modulator to perform and to be frequency independent (over the entire bandwidth). An example of this can be seen in the conversion gain (ratio between the RF output power and the baseband input power). A variation of this gain produces an unwanted AM on the emitted signal and can distort the information. Another problem is the image frequency. This effect is due to the multiplication of signals in a modulator. A multiplication of harmonic signals results in two signals whose frequencies are, respectively, the sum and the difference of the input frequencies. This duality is mathematically illustrated and discussed for the case of the receiver in Fig. 16, section 3. At the outgoing emission, an image is created at RF and

increases the EVM. At the reception (only for heterodyne architectures), an image frequency different from RF can be sensed and interpreted as unwanted information which increases the EVM, too. This is illustrated in section 3.3 with the presentation of the Hartley and Weaver image rejection receiver architectures for NB-CW. To conclude, the effects of the IQ modulator imperfections are: non-linearities, noise and the possibility of image frequencies. Selective filtering and stable reference signals are needed to improve the system (easier for NB-CW than for WB-CW).

- Frequency synthesizers are blocks which produce a stable reference signal for transposition. RF architectures need flexibility and stability in the choice of their reference frequency. It is usually not possible to provide this simultaneously with a simple oscillator circuit such as Quartz (stable), SAWR... The stabilization and synthesis by a Phase Lock Loop (PLL) is usually necessary. The PLL is a looped system whose different designs will not be discussed here, only its system's characteristics, which are reported in Fig. 5. The worst imperfection of the PLL is its phase noise. An example of the resulting phase noise profile of a synthesizer is illustrated in Fig. 5 (N=1). The different transfer functions of each noise of the sub-blocks are reported in the same figure. The great challenge of the PLL is to keep the stability performance of the synthesized signals for different values of N. It is also possible to modulate the signal in frequency by directly adding the baseband information on the Voltage Controlled Oscillator (VCO) input. This is called an "over the loop" modulation. For CW systems, synthesizers are used to produce the different Local Oscillators (LOs) needed for transposition(s) and for channel selection (fine tuning of the LO value). PLL can be used to transpose the information, but only for angular modulations schemes: PM, PSK, FSK or FM. This is not usually used for constant envelope WB-CW signals for noise and stability reasons.

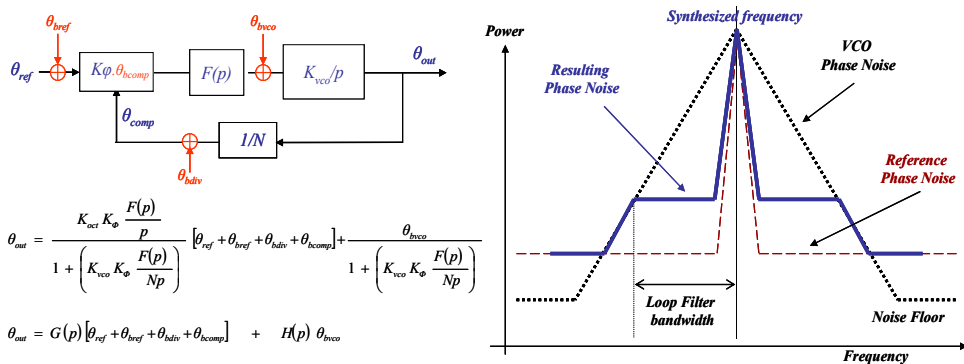


Fig. 5. PLL functional blocks and frequency synthesizer phase noise

- RF filters are essential in communications chains for information selectivity (interferences, noise, image-filtering for example). They are used at emission (limiting spectral re-growths), reception (rejecting unwanted signals) and for channel selection (high selectivity for discrimination and for image rejection). Their system characteristics are well-known: attenuation/rejection, selectivity, ripple, group delay... Different technologies are used depending on the frequency, implying different sources of imperfections.

At GHz frequencies, LC filtering is preferred for its low noise property but the components' sensitivity (especially for integrated technology) implies low order filters. For higher selectivity, active or high speed digital filters can be used, but often need a frequency transposition section due to the circuit bandwidth and the sampling rate limitations. Moreover, these filters consume power and add much noise (circuit or quantification).

Whatever the technology used, the wider the bandwidth the higher the ripple (oscillation of the transfer function). This ripple problem introduces an unwanted amplitude variation. In order to reduce this, the order is increased as much as possible and some prototype functions like Butterworth or Cauer are chosen for the design. Attenuation in the rejection band is worst in these cases. Additionally, the group delay of the filter is mandatory for non-distortion of the information. For NB-CW, it is usually not a problem but the phase response has to be linear for WB-CW and IR-UWB systems. In the case of a multi-band system, being linear in each sub-band is sufficient. These remarks point out that filters for WB-CW are more difficult to design than filters for NB-CW due to the performance limitations over the bandwidth.

To conclude, the RF filters imperfections are modeled by their noise factors (noise added, distortions and non constant group delays), insertion losses (due to the ripples and mismatches) and selectivity (finite attenuation of unwanted frequencies).

- Power Amplifiers (PA) in RF architectures are designed to linearly amplify radio-communication signals with the highest efficiency possible and with the lowest spectrum re-growths or added noise (see spectrum mask/ACPR and EVM criteria to respect). Since the active components of the amplifier are operating at maximum power, non-linear (NL) compression/conversion and memory effects are unavoidable (Fig. 6). The PA design, identified as "class of operation", impacts the performances [Villegas et al., 2007][Diet et al., 2004-2007]. Efficiency and linearity of the PA are mandatory for NB-CW and WB-CW architecture because the signal is transmitting information continuously. Low efficiency reduces battery lifetime and increases the dissipated power and the temperature of the circuit. Low linearity affects the quality of the signal. For IR-UWB systems, only peak performances in time are needed (see section 5). We are focusing upon the PA impact on the architecture in the case of the CW system. The most difficult case is for WB-CW due to the bandwidth, and the usual high PAPR of chosen modulation schemes (high data rate). A PA class of operation is determined by the hypothesis of transistor saturation (current source or switch). There are two families of PA classes: the switched mode (SW) and the continuous wave (CW) or biased mode. The different load-lines are illustrated in Fig. 6 (right).

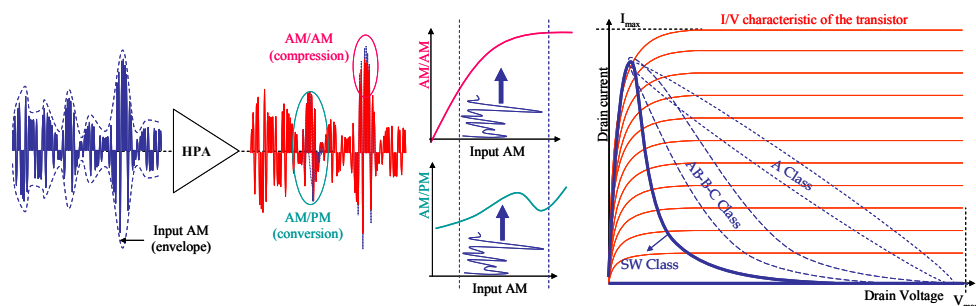


Fig. 6. AM/AM, AM/PM effects (without memory effects) and PA class load-lines

Due to the need of polarization, CW classes (namely A, B, AB and C) present lower efficiency than SW classes (D, S, E and F). SW classes need a switching of the transistor and cannot reproduce an amplitude modulation for that reason. Their linearity is also worse than in CW classes because of this switching operation. Moreover, it is possible to restore the amplitude information by adjusting the voltage supply. This is theoretically linear in the case of SW classes and there is a tracking effect for CW classes. For AM signals the average efficiency will rely on the statistical properties of the signal itself. Additionally, it is important to consider that efficiency is given as a peak value for CW classes. An improvement in efficiency is gained if saturation/clipping on the peak values is introduced in order to increase the average power of the output signal for the same power dissipated by the amplifier. WB-CW signals for high data rate applications present such a high PAPR that the amplification by a CW class PA requires a power back off (very low efficiency) or a linearization technique to reduce the NL effects of compression (AM/AM) and conversion (AM/PM), see Fig. 6. Techniques which are interesting for the designer in the case of wideband and high PAPR signal are those providing the highest efficiency of the entire architecture including the PA (see section 3). Polynomial modeling of the AM/AM can be done by the PA response to 1 or 2 frequency signals, called 1 or 2 tons. These indicators are the 1 dB compression point (P1dB) and the 3<sup>rd</sup> order Interception Point (IP3), as defined in Fig. 7.

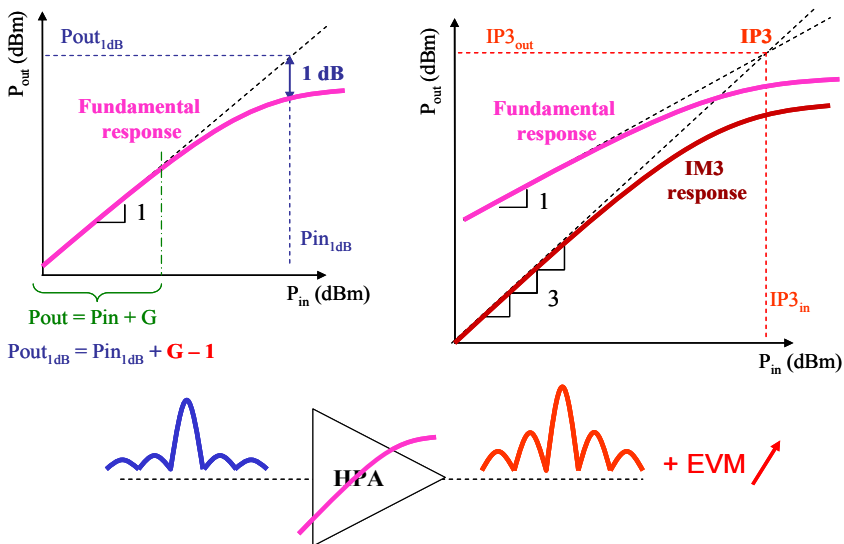


Fig. 7. Compression effect modeling for 1 ton (P1dB) and 2 tons (IP3)

These are considered to illustrate the main PA imperfections. AM/AM and AM/PM measurements, when it is possible to take them, can be the best way of characterizing the effects of the PA on the architecture: EVM and noise factor increase and spectral re-growths (ACPR, spectrum mask). In CW systems, the PA has to amplify modulated signals (a sum of several tons). For NB-CW signals, the PA behavior is well-characterized by the P1dB and the input power is usually set at this value for the linearity/efficiency trade-off (if the PAPR is not too high). In the case of WB-CW, the IP3 is a good representation of NL effects on the



spectrum if the frequency separation of the two tons is coherent with the modulated bandwidth (symbol rate frequency). Moreover, the conversion effects are, by far, more complex to analyze. It is almost impossible to determine an equivalent of the P1dB or the IP3 for AM/PM. This relies upon the influence of transistor technology. For wideband and high PAPR signals, the conversion effect increases the EVM significantly and often destroys the information.

SW classes are based on the hypothesis that the transistor switches perfectly (no power dissipated). The filtering is mandatory in RF applications, except if the SW PA is dedicated to the amplification of a square signal (class D). The load-line of every SW PA class tends to be that of an ideal switch, which is impossible in practice due to the physical realities of the transistor (resistive and capacitive output effects). Although the switching cannot be perfect, SW classes present higher efficiency than CW classes, see the 100% efficiency class E PA [Sokal & Sokal, 1975][Raab et al., 2003][Diet et al., 2008]. Moreover, they are used for AM signals only with a recombination process: supply modulation or amplification of an envelope coded signal (PWM,  $\Sigma\Delta$ ) [Robert et al., 2009][Suarez et al., 2008]. Using supply modulation creates NL effects of compression and conversion on the output signal. These effects are named Vdd/AM and Vdd/PM [Diet et al., 2004]. For new RF architectures, high efficiency (SW) classes are preferred due to their high efficiency, but the challenge then shifts to the linearity of the amplified signals. Whatever the CW system is, NL effects of the PA are unavoidable and are sources of important imperfections (i.e., loss of linearity). In the case of high PAPR signals, a correction or a modification of the architecture is needed, as is presented in the following section.

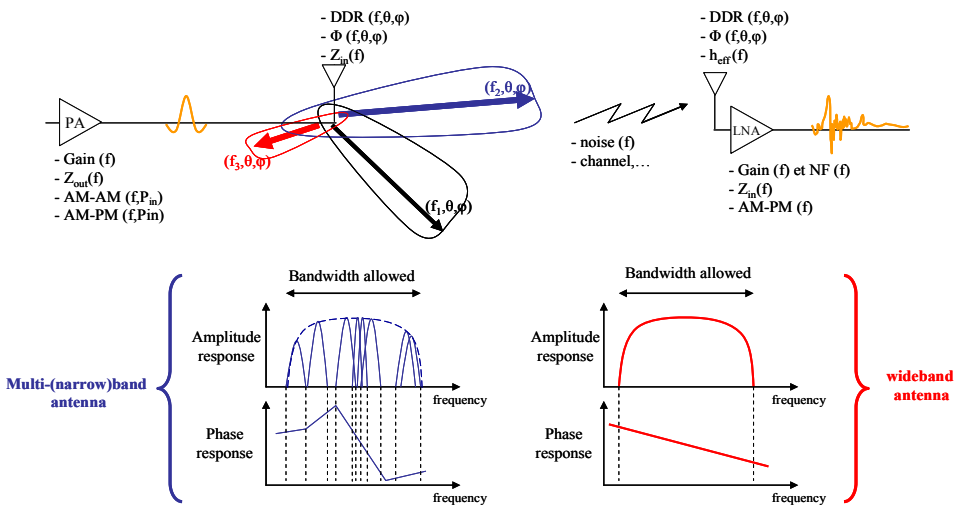


Fig. 8. Antenna system characteristics in radio-communications

- Antenna characteristics from a “system” point of view are reciprocal interfaces between electrical and radiated signals. Depending on the application, antennas have to be adapted to their environment (omni-directivity of their radiation pattern, polarization...). Fig. 8 summarizes the different system parameters of an antenna that can influence the

performance of the radio-communications link: spatial and frequency variations of the radiation pattern, bandwidth limitations and phase distortion. Some of the imperfections are equivalent to those of the filter, but they depend on the signal direction and the channel. For wideband systems, i.e. WB-CW and IR-UWB, the use of a UWB antenna is mandatory for keeping the phase information unaltered [Schantz, 2005]. For NB-CW and separated multi-band signals using a wide bandwidth (see Fig. 8), the use of a multi-band antenna is sufficient. The latter can present phase linearity only for used sub-bands [Diet et al., 2006]. To conclude, the communications channel composed of the emitting and receiving antennas and the propagation channel is the source of amplitude and phase distortion, with a statistical dependence on time and space. Noise is added and the techniques of signal protection and antenna diversity (e.g., MIMO) are exploited as much as possible to improve the system's range.

### 3. Architecture basics

RF architectures are adapted to radio-communications signals and provide emission and reception. Linearity improvements are needed when power amplification NAs can destroy the information. This section first focuses on the transmitter section where different major modifications are described. We especially focus on CW systems because of their important challenges about efficiency and linearity.

#### 3.1 Classic architectures for RF transmitters

Radio-communications architecture is composed of the above-mentioned blocks in section 2 and provides the emission and reception of the signal. There exist three kinds of basic architectures, the classic ones, designed for NB-CW systems (the oldest application of which is radio broadcasting): homodyne, heterodyne and PLL modulated.

- The homodyne architecture means that the I and Q signals (the information after DACs) is transposed directly from baseband to RF see Fig. 9. If the modulation scheme is not x-QAM, there is only one frequency transposition in the transmitter. This type of architecture is the simplest combination of function blocks and theoretically requires the minimum number of components.

If the signal is transposed directly to RF, the frequency synthesizer output is at the same frequency value, and so is the HPA and the antenna. In a compact system (mobile phones for example), the spatial proximity is the cause of unavoidable coupling between the synthesizer, the HPA and the antenna. This problem of electromagnetic coupling (EMC, EM Compatibility) is that it highly distorts the signal (EVM increase). EMC effects can be reduced by circuit spatial optimization, when possible, and more efficiently with a shielding of the considered block (LO, HPA). Additionally, a ground plane acting as a reflector can be added between the antenna and these elements (HPA and/or LO synthesizer) to reduce the amount of radiated waves toward the circuit. Choosing the homodyne structure results from multiple trade-offs concerning the EVM, the simplicity and the size of the system.

- The heterodyne architecture, as represented in Fig. 9, means that the frequency transposition is achieved in two or more steps. In fact, heterodyne means that the frequency synthesizers are not at RF values. Any combination is possible, but for a minimum use of components only two transpositions are usually performed. As the frequencies are different, the coupling effect is highly reduced in this architecture. In heterodyne structures,

there are more components than in homodyne ones (with at least one filter and one additional mixer) and imperfection sources are added. For example, the phase noise is a function of the number of synthesizers. An additional mixer also means the possibility of an image frequency that can distort the emitted information if the intermediate frequency (IF) filter is not selective enough. This IF filter is traditionally an external SAW one (because of its selectivity). This increases the cost and complexity of building this system. An advantage of the heterodyne architecture is that the need of frequency flexibility for channel selection can be more easily achieved with two synthesizers than with one (homodyne case).

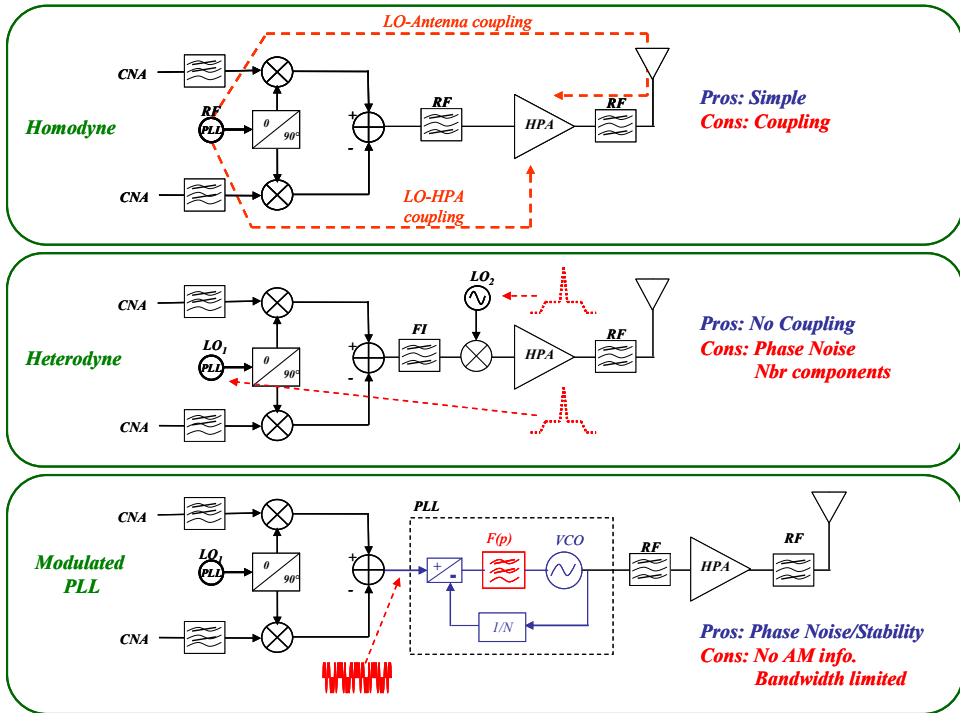


Fig. 9. Classic architectures for RF transmitters

- Architectures using modulated PLL can benefit from PLL advantages. This corresponds to the direct modulation of a synthesizer (with  $N=1$ ). The signal of a PLL is stable and its noise profile depends on the loop filter bandwidth. It is possible to modulate the PLL by introducing small variations of the reference frequency which will be stabilised by the loop reaction. This is called a modulation “in the loop” and is used for narrow-bandwidth modulations (low symbol rate). On the contrary, the input voltage of the VCO can be directly modulated to produce a wider bandwidth modulation (modulation “over the loop”) but this could affect the stability of the PLL. As is understood here, only angular modulations are possible with modulated PLL architectures. If the signal to transmit has AM information, this latter should be reintroduced after the PLL. To conclude, architectures using modulated PLL are very interesting with regards to their noise property (less noise

than an IQ modulator) and their design for non-constant envelope signals implies some important modifications of the architecture.

The classic architectures presented are widely used for NB-CW signals. While the efficiency and linearity of the transmitter is not significantly affected, these well-known structures are preferred for their simplicity. In the case of WB-CW systems, the bandwidth and the probable increase of the PAPR (due to high data rate) lower the performance of such architectures. For power amplification in particular, high PAPR values of OFDM and other multi-carrier signals cause such compression and distortion/conversion effects that the information cannot be interpreted at reception. Additionally, standard limitations are, by far, not respected. The first choice is to perform a PA back-off, but this drives it to unacceptably low values for the architecture efficiency. To achieve a linear transmitter, linearization techniques are provided. The next sub-section is dedicated to their descriptions.

### 3.2 Linearization techniques for the transmitter

Wireless communications require highly efficient and compact transceivers, whatever the signal characteristics are. Transmitter architecture, at worst, must meet design constraints of: providing high efficiency and linearity for a wideband and high PAPR signal (or high dynamic). Power amplification of WB-CW multi-carrier signals (WiFi, WiMAX, LTE...) introduces crippling Non-Linearities (NLs) in amplitude and in phase in the communication system. The linearization of such this kind of transmitter is mandatory. Identifying a type of architecture for such signals requires a careful study of linearization techniques and their performance. A linearization technique is beneficial only if it provides linearity with the maximum efficiency possible. There are several linearization techniques, depending on the PAPR of the signal, the added complexity and the increase in size and consumption of the system that can be accepted by the RF designers [Villegas et al., 2007]. Many criteria characterize the technique used: static/dynamic processing, adaptability, frequency (digital, baseband, IF or RF), correction of memory effects, complexity, stability, resulting efficiency, size increase... Herein, we basically classify these techniques in three types: (i) correction techniques, (ii) anticipation of NLs and (iii) those based on a decomposition and recombination of the signal, often dedicated to wideband signals.

Examples of correction techniques are (A) feed-back, (B) feed-forward and the anticipated technique of (C) pre-distortion, illustrated in Fig. 10. Their point in common is to modify the modulated signal as close as possible to the PA (before or after). The architecture considerations here, do not include the modulator nor the baseband signal processing. To linearize, we need a carefully selected NL model of the PA (Volterra series, Wiener or Saleh model...). Adaptability to the signal amplitude can be introduced in order to compensate for the model's lack of accuracy and the PA memory effects (a temperature influence can be considered) [Baudoin et al., 2007]. Each structure contains a major defect. (A) Feed-back reduces the gain of the amplification and introduces a bandwidth limitation due to the transfer function of the loop (stability and dynamic response). The feed-back can be performed on the amplitude (Polar feed-back) or on I and Q quadrature components of the signal (Cartesian feed-back) and both are dedicated to narrowband signals. (B) Feed-forward requires a significant increase in signal processing and RF blocks in the transmitter, with the hypothesis of a precise matching between NLs and reconstructed transfer functions. The improvement in linearity will be costly in terms of consumption and size

(integration criterion). The advantages are stability and the possibility to process wideband signals. The most interesting of the three techniques is (C) pre-distortion because of its flexibility: the anticipation can be done in the digital part and, by doing so, can provide adaptability of the technique if using a feed-back loop (with an additional DAC). The digital pre-distortion represents an additional and non-negligible consumption of a Digital Signal Processor (DSP) and often requires a look-up table [Jardin & Baudoin, 2007]. The signal is widened in frequency because of the non-linear law of the pre-distorter (as for NL effects of compression on the spectrum), requiring baseband and RF parts to be wideband designed. Interesting improvements of pre-distortion have been made with OFDM WB-CW signals in [Baudoin et al., 2007] [Jardin & Baudoin, 2007].

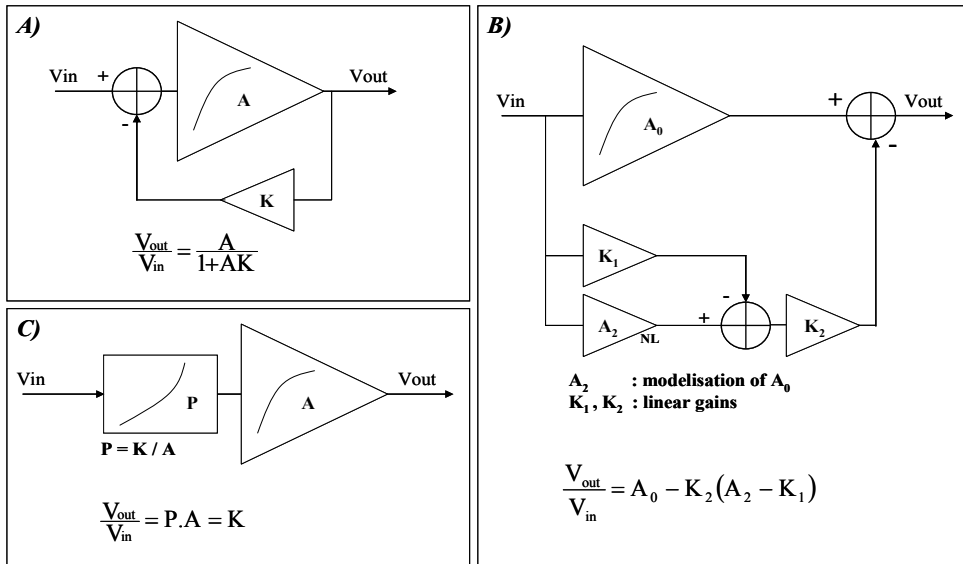


Fig. 10. Correction (A and B) and anticipation (C) linearization techniques

Other techniques presented are based on a vectorial decomposition of the signal. The goal is to drive high efficiency switched mode RF PAs with constant envelope (constant power) signals, avoiding AM/AM and AM/PM [Raab et al., 2003] [Diet et al., 2003-2004]. These techniques are used when NL effects are so great that feed-back or pre-distortion cannot sufficiently improve the linearity. We can consider the problem of linearization in the communication chain from the digital part to the antenna (front end). This drives one to completely modify the architecture and its elements' specifications in baseband, IF/RF and power RF. After the amplification of constant envelope parts of the signals, the challenge is to reintroduce the variable envelope information with lower NLs than in a direct amplification case, keeping high efficiency of the architecture. Basic examples of these techniques are the LINC (LInearization with Non-linear Components) and the EER (Envelope Elimination and Restoration) methods (and their recent evolutions) [Cox, 1974] [Kahn, 1952] [Baudoin et al., 2003-2007] [Diet et al., 2004] [Suarez et al., 2008].

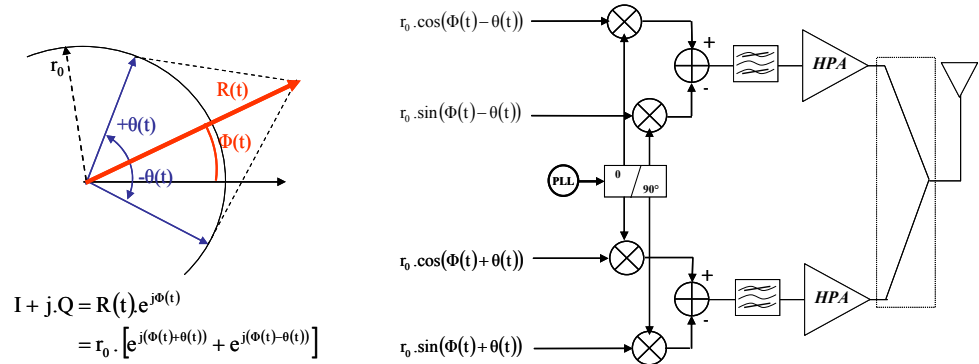


Fig. 11. LINC decomposition and recombination at RF power amplification

The LINC principle relies on a decomposition of the modulated signal into two constant envelope signals as is shown in Fig. 11. The decomposition can be computed by a Digital Signal Processor (DSP) or by combining two VCOs in quadrature PLL configuration: CALLUM. This latter configuration is an interesting architecture but presents the possibility of instability and additional manufacturing costs. The amplification of the two constant envelope signals implies the design of two identical HPAs at RF frequency, and this often causes signal distortion due to imbalance mismatches. Also the HPA must be wideband because the signal decomposition is a non-linear process (widening of the spectrum), and the phase modulation index is increased. Whatever the decomposition technique is (LINC/CALLUM), the problem is that the efficiency is directly determined by the recombination step: a sum of the powers. It is very difficult to avoid losses at RF while designing a RF power combiner.

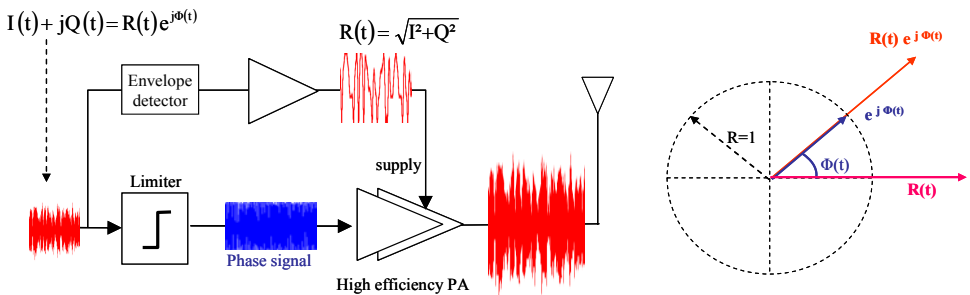


Fig. 12. Principle of the EER technique [Kahn, 1952]

Another decomposition technique was proposed by Kahn in 1952 and this is basically an amplitude and phase separation technique (polar): Envelope Elimination and Restoration (EER). This method was first proposed for AM signals as represented in Fig. 12. The advantage of EER is that it drives the RF PA with a constant envelope modulated signal (carrying the phase information), enabling the use of a SW high efficiency amplifier [Raab et al. 2003] [Sokal & Sokal, 1975] [Diet et al., 2005-2008]. The difficulty is to reintroduce the amplitude information linearly using the variations of the PA voltage supply. This implies a

power amplification of the envelope signal at a frequency equal to the symbol rate (lower than RF). The recombination can be done with a SW class PA because the output voltage is linearly dependant on the voltage supply for this PA mode. Two difficulties are to be considered in such a linearization technique: (i) synchronization between the phase and the amplitude information and (ii) linear and efficient amplification of the amplitude before the recombination (directly impacting the overall efficiency), as reported in [Diet, 2003-2005]. Recently, a lot of work has been done on the EER based architectures, often named as “polar” ones [Nielsen & Larsen, 2007] [Choi et al., 2007] [Suarez et al., 2008] [Diet et al., 2008-2009]. The generation of the amplitude and phase components can be expected to be done digitally thanks to the power of DSPs, as is shown in Fig. 13. As was previously discussed in [Diet et al., 2003], the bandwidths of the envelope and phase signals are widened due to NL processing and make it necessary to design the circuit for three to four times the symbol rate (as for LINC or any other NL decomposition). Fortunately, a clipping in frequency and on the envelope is possible, increasing the EVM and ACPR under acceptable levels. These polar architectures are suited for new high data rate standards where efficiency of the emitter and linearization are mandatory. Also, the multi-standard and multi-radio concepts have helped polar architectures to evolve in multiple ways. For example, recombination on the PA’s input signal is possible because the amplitude information can modulate the phase signal (RF) and can be restored by the band-pass shape function of the following blocks: PA + emission filter + antenna. The emitted spectrum is the criterion of quality to be considered carefully, because the PWM or  $\Sigma\Delta$  envelope coding are the source of useless and crippling spectral re-growths. The efficiency is also penalized by the power amplification of such frequency components, but this is counter-balanced by the advantages of high flexibility of this architecture [Robert et al. 2009]. The digitally controlled PA and the mixed-mode digital to RF converter are key parameters in the evolution of these polar architectures [Suarez et al., 2008] [Robert et al., 2009] [Diet et al., 2008].

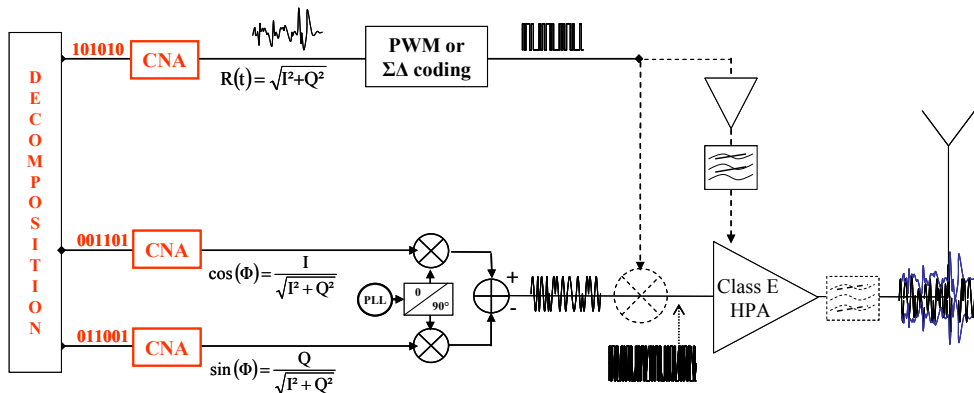


Fig. 13. Recent improvements of EER/polar architectures for wideband OFDM signals

We have presented the main linearization techniques. Actual needs, in terms of transmitter linearity and efficiency for high data rate applications, have caused the RF designer to consider RF architectures based on combined techniques. For example, digital pre-distortion is an improvement on polar based architectures, as is shown in section 4. Another example

is described in [Diet et al., 2008] where a combination of cascaded EER and LINC techniques can theoretically provide an architecture which cancels the PAPR influence, see Fig. 14.

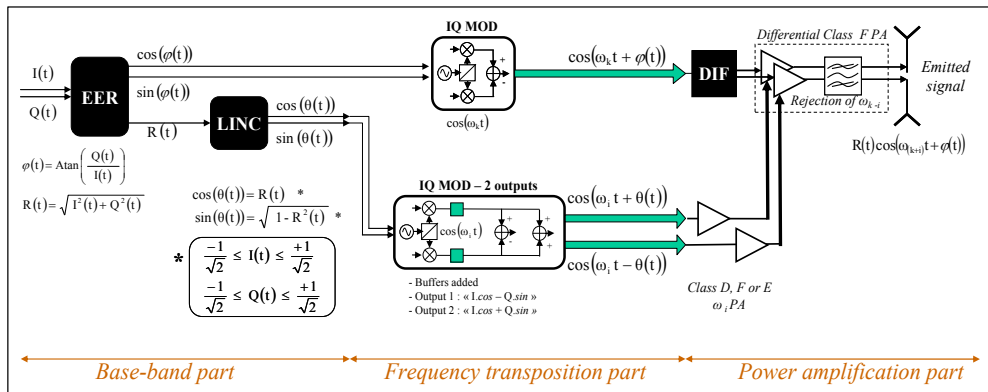


Fig. 14. EER-LINC method for high PAPR signals

This architecture needs some new components (e.g., a balanced switched PA with frequency transposition). This also represents an increase in complexity, but proposes new ways to improve WB-CW signals transmitters. In EER-LINC, the envelope information is converted to two angular modulated signals. The RF balanced PA (also called differential PA) is in SW class and is supply-modulated with the two above-mentioned signals. The fact that the PA is differentially supplied allows for the combining operation and a transposition at the same time (due to the multiplication). As the antenna is supposed to be differential, there is no balun after the PA.

This review of linearization techniques reveals that the different parts of an efficient and linear transmitter cannot be designed separately: baseband, frequency transposition and power amplification (and antenna for wideband systems). The modification of the architecture for global performance improvements must be done, considering each block's impact, digital or analog (and their imperfections). To conclude this theoretical sub-section, linearized architectures are mandatory for the major part of actual and future CW systems, which are WB-CW (high data rate). The highest performance can be reached if a combination of different techniques is exploited: pre-distortion and EER seem to be the most popular.

### 3.3 Receiver architectures

The challenges of the receiver architectures are the noise level, the presence of other channels and blocking/interference signals. This is summarized by the immunity and the coexistence of the standards, illustrated in Fig. 15.

The information received is at such a low level that other RF emissions can mask it. It is easily possible to saturate the receiver if a signal is too strong in the vicinity of the spectrum. Other characteristics of the receiver are its sensitivity and selectivity. The sensitivity is the lowest level of power that can be received and demodulated correctly (providing a Bit Error Rate sufficient for interpretation). This latter, is altered by the total amount of noise added by the receiver itself. The noise factor (F) expresses an equivalent of a white Gaussian noise



addition, for each block. It is possible to compute the global noise factor for the receiver thanks to Friis formula, see Fig. 15. This formula shows that amplifying the signal as close as possible to the antenna, at the front-end, is better for minimizing the total added noise. This is the goal of the Low Noise Amplifier (LNA) whose design is optimized for noise and not for gain or output power performance. Unfortunately, the presence of high power signals (blocking) often implies starting the reception chain with a selective band-pass filter, as is reported for the Rx architectures in Fig. 15. At this point, the signal bandwidth is another limiting factor for the design of the receiver because it directly impacts the reception filter design and the LNA. The selectivity and sensitivity performance are also affected. At reception, the decrease in the signal quality is expressed by the EVM and the BER. This degradation results from the noise in the system (noise factor) but other imperfections are due to the architecture design: block interactions, CEM, image frequency and so on. In digital radio-communications, the channel coding (block and convolution types) improves the robustness of the system against the noise, but this point will not be developed here.

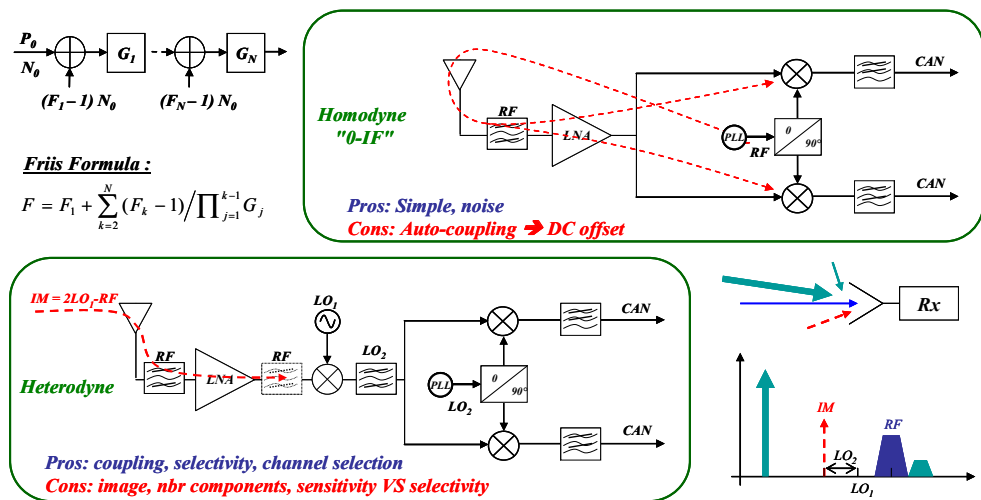


Fig. 15. Considerations for receiver architectures

The topic of this sub-section is to present the main types of receiver architectures. As there is no PA NL effects (Tx architecture), there is no need for linearization techniques. If the receiver is saturated, it suffices to reduce the gain of the LNA (if possible) or to attenuate the signal (back-off). The basic receiver structures are similar to that of the classic transmitter structures, that is to say homodyne and heterodyne types as represented in Fig. 15.

- Homodyne receivers are composed of a direct IQ demodulator which comes after the LNA. RF filters, before and after the LNA, tend to avoid a masking effect by other signals received. The filter technology for RF is subject to a trade-off between the selectivity and the losses, which increase the noise factor of the filter. Swapping the LNA and the RF filter in the receiver chain creates a limitation of the received band. This is set in function with disturbing signals and the resulting noise factor (sensitivity). This architecture is simple, as it requires few components, and theoretically limits the total amount of noise added. The

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