RF BASICS

Low Power RF

Texas Instruments

Abstract

This presentation gives an introduction to wireless RF systems. The presentation gives an overview of an complete RF system as well as a introduction to the different building blocks in an wireless RF system. Important parameters such as sensitivity, selectivity, output power, modulation, link budget etc. are discussed in detail. Finally, compliance to frequency regulations around the world is discussed.

Outline

- Overview of an RF System
  - Transceiver
  - System on Chip
  - Balun
  - Antenna
- Important Parameters in an RF system
  - Link Budget
  - Sensitivity
  - Selectivity
  - Output power
  - Modulation
- Extending the Range
- Frequency Regulations
- Summary

Agenda

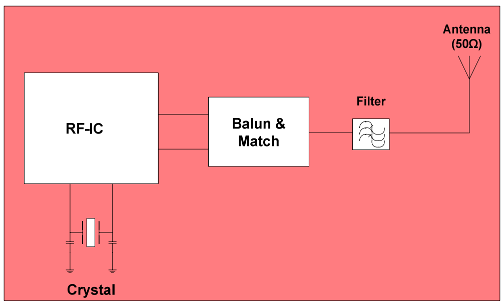
I will start by introducing...

Overview of an RF system

In this section of the presentation we will give an overview of an RF system

Basic Building Blocks of an RF System

- RF-IC
  - Transmitter
  - Transceiver
  - System-on-Chip (SoC)
- Crystal
  - Reference frequency for the LO and the carrier frequency
- Balun
  - Balanced to unbalanced
  - Converts a differential signal to a single-ended signal or vice versa
- Impedance Matching
- Filter
  - Used if needed to pass regulatory requirements/ improve selectivity
- Antenna



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•RF-IC. Several factors should be considered when chosing which RF-IC to use.

•Available board space -> SoC (transceiver with integrated microcontroller) or two chip solution

•One or two way protocol -> Transmitter or tranceiver

•Required range -> Operating frequency

•Where is the product going to be sold. The frequency bands that can be used for SRD and ISM band devices differ around the world -> Operating frequecny

•Standard or propriatary system -> IEEE 15.4 compliant radio or propriatary radio

•Choise of crystal.

•Price vs. Accuracy (Using inaccurate crystals will require larger RX bandwidth to compensate for frequency drift. Larger RX bandwidth results in more noise in the receiver chain and thus reduced sensitivity, but accurate crystals are expensive.

•Load capasitance

•Frequency

•See data sheet for requirements

•Balun, Matching and Filter

•The reference design shows how the balun, matching and filter should be implemented.

•Texas Instruments provides a reference design for all Chipcon products. We recommend that you always copy this part of the circuit exactly from our reference design to ensure optimum performance. Note that the internal amplifier has to match at both the fundamental and also at the harmonics of the fundamental.

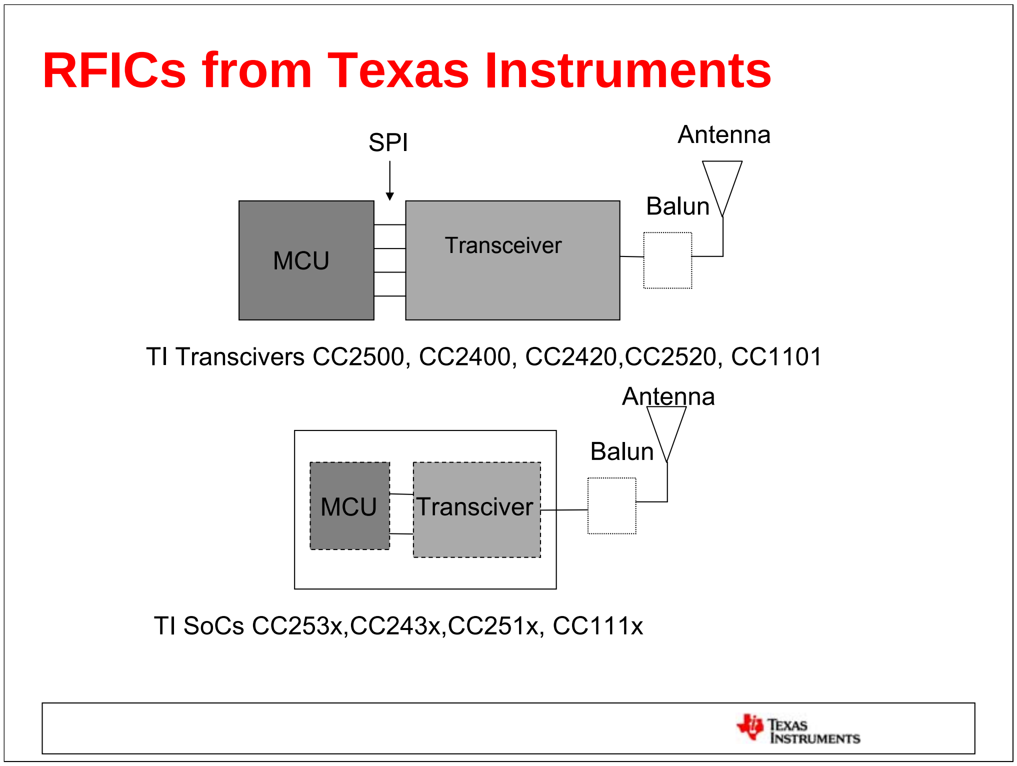
•Antenna

•The antenna is VERY important if long range is important

•Mainly three different antenna types are being used, chip antenna, PCB antenna and whip antenna

•Several antenna reference designs can be found on www.ti.com/lpw

•Designing good antennas can be difficult. It is therefore recommended to contact an antenna expert if a custom antenna design is needed.



Transciver + MCU vs SoC

Our chips starting with CC1xxx is sub-GHz covering most of the intresting bands in the Sub-GHz. The lowest frequency convered is 315-915 MHz. Our chips starting with CC2xxx cover the 2.4 GHz band. Hence, we choosing our RFIC the operating frequecy is an important parameter. Another parameter which affects the choise of RFIC is if you will have a a standard or propriatary system. We have radios that is IEEE 802.15.4 compliant and we have radios sutible for propriatary system.

Transciver

The TI trancivers is more than an upconverter. The RF transceiver fromTI is integrated with extensive hardware support for packet handling, data buffering, burst transmissions, clear channel assessment, link quality indication, and wake-on-radio.The main operating parameters and the 64-byte transmit/receive FIFOs can be controlled via an SPI interface. In a typical system, the transciver will be used together with a microcontroller and a few additional passive components.

Transmitter

We are also offering different transmitters. They can be intresting to use in a one way protocol. Hence, one or two way protocol -> Transmitter or tranceiver

TI SoCs

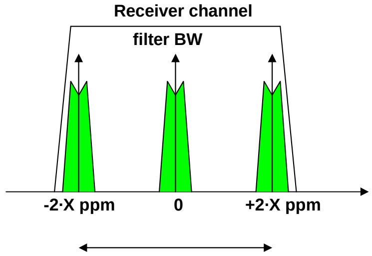
TI SoCs a true low-cost system-on-chips (SoC) designed for lowpower wireless applications. The similar Radio as the RF-transceivers and combine it with an industry-standard enhanced 8051 (TI have a CC430 which integrate MSP core) MCU and programmable flash memory and RAM, and many other powerful features. Our SoCs is well suited for systems where low power consumption is required. This is ensured by several advanced low-power operating modes. Our chips ending with 1 such as CC2431,CC2511 have added USB interface. Interfacing to a PC using the USB interface is quick and easy, and the high data rate (12 Mbps) of the USB interface avoids the bottlenecks of RS-232 or low-speed USB interfaces.

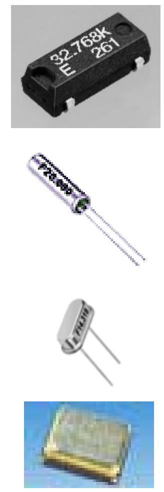
Pros and cons

- •Available board space
- •Flexibillity
- •Need a more power full MCU?

Crystals

- Provides reference frequency for Local Oscillator (LO) and the carrier frequency
- Important characteristics:
  - Price, often a price vs. performance trade-off
  - Size
  - Tolerance[ppm], both initial spread, ageing and over temperature





Crystals

Choise of crystal.

•Price vs. Accuracy (Using inaccurate crystals will require larger RX bandwidth to compensate for frequency drift. Larger RX bandwidth results in more noise in the receiver chain and thus reduced sensitivity, but accurate crystals are expensive.

•Load capasitance

•Frequency

•See data sheet for requirements

•For transciver 26 MHz crystal.

• SoC with USB usually have a 48 MHz crystal.

• The SoC can also have a 32 kHz crystal for sleep.

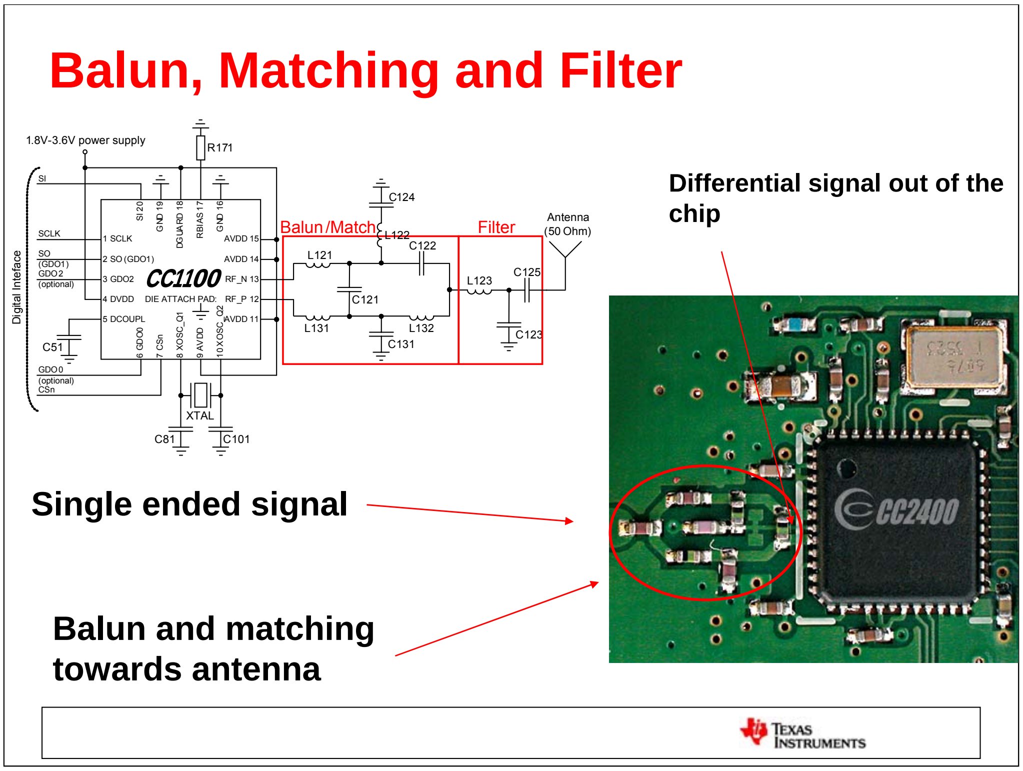
Comment on Crystal accuracy vs performance of the receiver:

•Wider RX filter BW means reduced sensitivity and close-in selectivity

•Wider RX filter BW also means that temperature compensation might not neccessary

•Wider receiver filter bandwidth allows cheaper (i.e. less accurate) crystal to be used

Note: for true narrowband systems (ARIB and ETSI) the crystal accuracy is set by regulations (±4 ppm and ±5.7/2.8 ppm respectively)



Balun, Matching and Filter

Balun

•The chip have differential RFinputs/Outputs.

•Normally, an antenna is single-ended and have an impedance of 50 Ohm.

•The Balun is used to make the to make the differential signal to single-ended our vice versa.(Balun is short for Balanced to unbalanced)

Matching

•With a matching network we convert the optimal load impedance looking into the chip to 50 Ohm (most antennas are 50 Ohm) looking into the antenna. If it is properly matched no reflection.

•Frequencies are very high here so the even the wave properties of the signals have to be taken into account. (Reflections)

•Wrong matching decreases the output power and the receiver sensitivity.

Filter

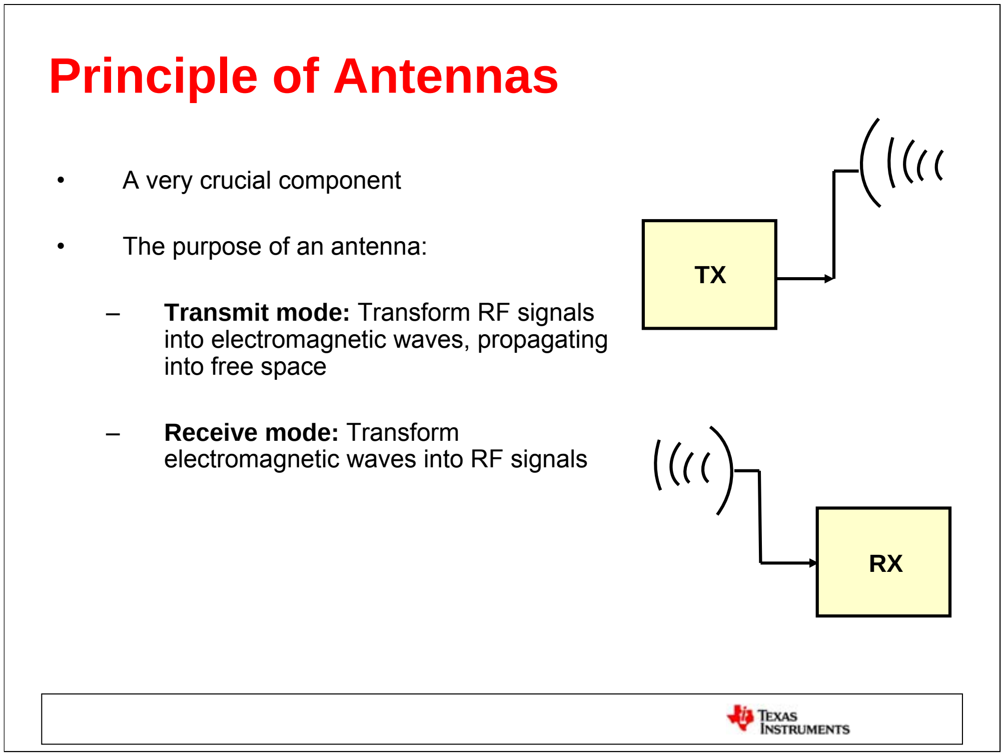
The filter is used to filter out spurious emissions and especially the harmonics when the transmitter is transmitting.

The frequency regulations worldwide have requirements of spurious emissions.

Finally

The reference design shows how the balun, matching and filter should be implemented.

Texas Instruments provides a reference design for all Chipcon products. We recommend that you always copy this part of the circuit exactly from our reference design to ensure optimum performance. Note that the internal amplifier has to match at both the fundamental and also at the harmonics of the fundamental. TI engineers have spent a lot of time to optimizing the design over temperature, supply voltage e.t.c



Principle of the antenna

•Crucial component. Huge effect of the overall performance for an RF system.

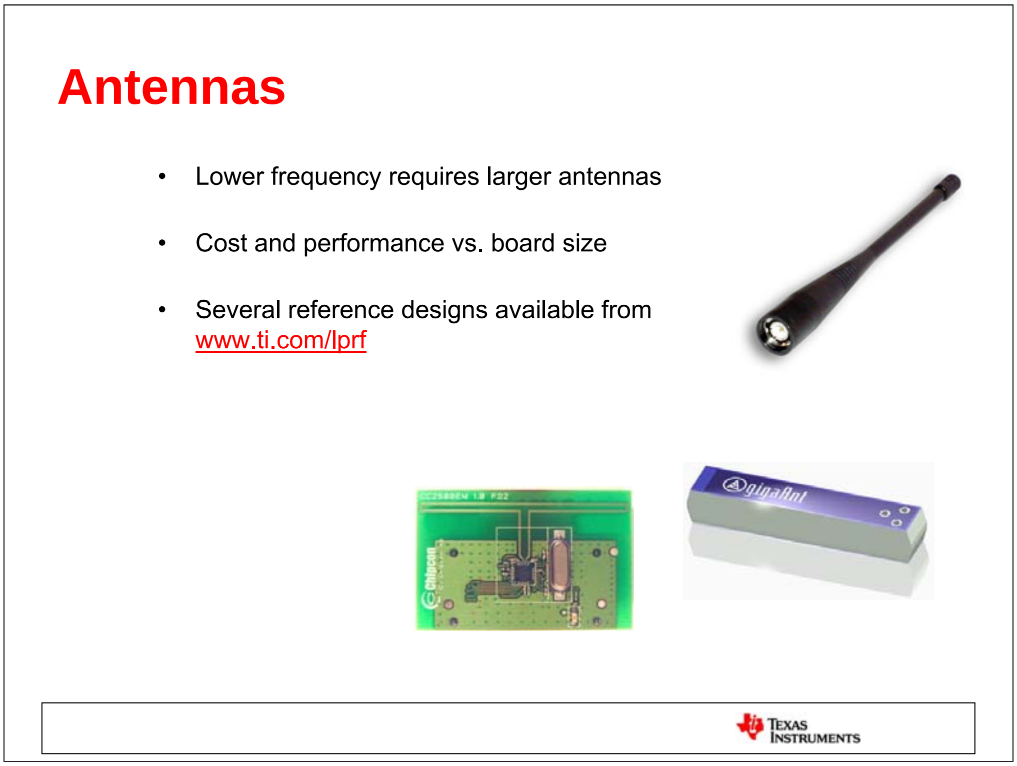
•The purpose of an antenna:

- **Transmit mode:** Transform RF signals into electromagnetic waves, propagating into free space
- **Receive mode:** Transform electromagnetic waves into RF signals
- Regulatory issues will also be affected by the antenna since radiated testing is often required.
- Antennas are reciprocal and have therefore the same performance in RX as TX.

Important parameters of an antenna (to mention a few)

•Directivity, Gain, Polarization, Impedance and Bandwidth (do not go into details).

•**High gain** is not necessarily a good thing. It depends on the application and what factor that are causing the high gain. High gain is desirable for an RF system with fixed positioning of both receiving and transmitting antennas. Thus the antennas can be positioned with the optimum direction pointed towards each other. For mobile systems it is usually better to have an antenna which spreads the radiated power in a more omnidirectional manner. This will ensure that the performance of the system is not heavily affected by the positioning of the devices. Gain is usually referred to an isotropic antenna and usually with the designation dBi. An isotropic antenna is a theoretical antenna that radiates equally in all directions. Gain in an antenna must not be related to gain from an amplifier. An antenna has not the capability to amplify the RF signal, but it can focus the energy in a specific direction and thus increase the gain. It can be compared to a flashlight were you always have the same amount of light, but it is possible to focus it to form a narrow beam. Thus you get a more intense light in a smaller area. Since antenna gain is often only given for the maximum direction it is important to also look at the radiation patter or an average gain number when evaluating an antenna.



Antennas

•Generally more space available makes it easier to implement an efficient antenna.

•The antenna size is often dependant of the wave length. For example, there are many quarter wave length antennas and half wave length antennas. Hence, a lower frequency gives a larger antenna.

•Several reference designs on our webpage. Both designs with chip antenna as well as PCB antennas. The **AN058 – Antenna Selection Guide** (swra161.htm) gives a good overview of the available reference designs on our home page.

Antenna in slides

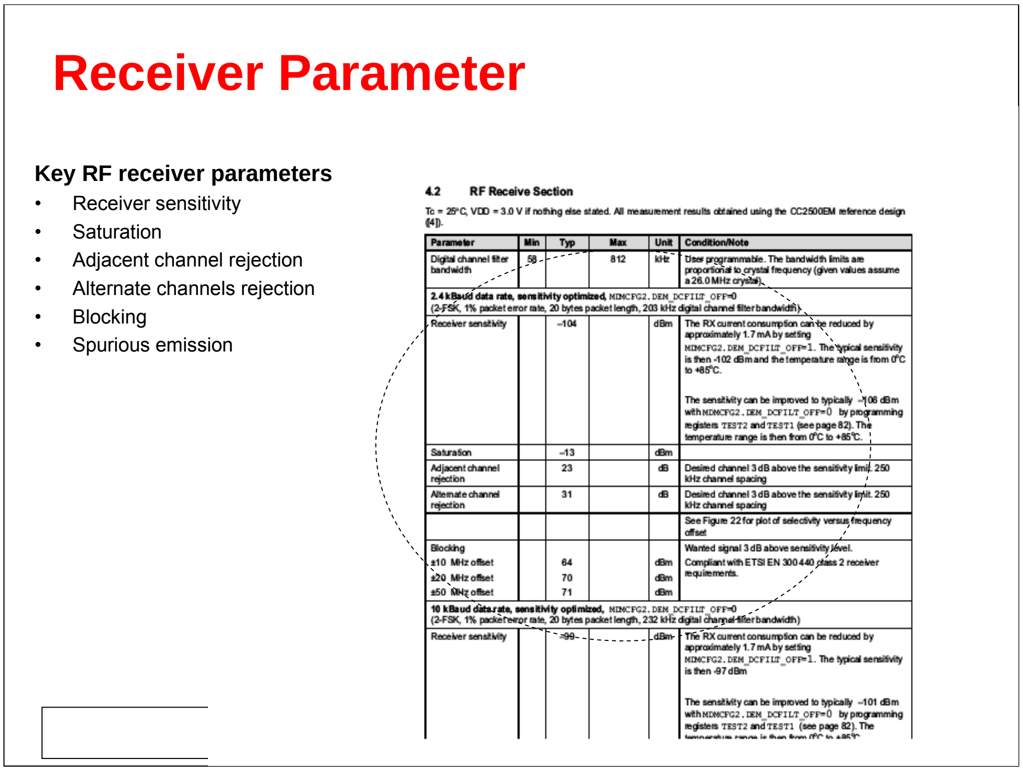
•**PCB antenna.** Designing a PCB antenna is a difficult task and requires EM simulation tools. Such simulation tools are very expensive and it is not straight forward to configure them to perform accurate simulation. It is therefore recommended to make a copy of one of the antenna reference design available from www.ti.com/lprf. Also note that this is a differential antenna shown here. Hence, the Balun is note needed. Differential antennas is normally larger and can be more difficult to design.

•**Chip antenna.** Smallest size. If the available board space is limited a chip antenna could be a good solution. Especially at frequencies below 1 GHz chip antennas could be a good choice to obtain compact solutions.

•**Whip antenna.** Expensive large, omi-directional good performance.

Important RF Parameters

In this section of the lecture we will focus on some imporant parameter.



4.2 RF Receive Section

Tc = 25°C, VDD = 3.0 V if nothing else stated. All measurement results obtained using the CC2500EM reference design ([4]).

Parameter	Min	Typ	Max	Unit	Condition/Note
Digital channel filter bandwidth	58		812	kHz	User programmable. The bandwidth limits are proportional to crystal frequency (given values assume a 26.0 MHz crystal).
2.4 kBaud data rate, sensitivity optimized, MDMCFG2.DEM_DCFILT_OFF=0 (2-FSK, 1% packet error rate, 20 bytes packet length, 203 kHz digital channel filter bandwidth)					
Receiver sensitivity		–104		dBm	The RX current consumption can be reduced by approximately 1.7 mA by setting MDMCFG2.DEM_DCFILT_OFF=1. The typical sensitivity is then -102 dBm and the temperature range is from 0°C to +85°C. The sensitivity can be improved to typically –106 dBm with MDMCFG2.DEM_DCFILT_OFF=0 by programming registers TEST2 and TEST1 (see page 82). The temperature range is then from 0°C to +85°C.
Saturation		–13		dBm	
Adjacent channel rejection		23		dB	Desired channel 3 dB above the sensitivity limit. 250 kHz channel spacing
Alternate channel rejection		31		dB	Desired channel 3 dB above the sensitivity limit. 250 kHz channel spacing
					See Figure 22 for plot of selectivity versus frequency offset
Blocking ±10 MHz offset ±20 MHz offset ±50 MHz offset		 64 70 71		 dBm dBm dBm	Wanted signal 3 dB above sensitivity level. Compliant with ETSI EN 300 440 class 2 receiver requirements.
10 kBaud data rate, sensitivity optimized, MDMCFG2.DEM_DCFILT_OFF=0 (2-FSK, 1% packet error rate, 20 bytes packet length, 232 kHz digital channel filter bandwidth)					
Receiver sensitivity		–99		dBm	The RX current consumption can be reduced by approximately 1.7 mA by setting MDMCFG2.DEM_DCFILT_OFF=1. The typical sensitivity is then -97 dBm The sensitivity can be improved to typically –101 dBm with MDMCFG2.DEM_DCFILT_OFF=0 by programming registers TEST2 and TEST1 (see page 82). The temperature range is then from 0°C to +85°C.

Key RF receiver parameters

The plot is taken from the CC2500 data sheet. All parameter are tested at a given datarate and carrier frequency. Moreover, for some of our chips it is possible by change register settings for example increase the receiver sensitivty at the expense of power consumption.

•Receiver sensitivity

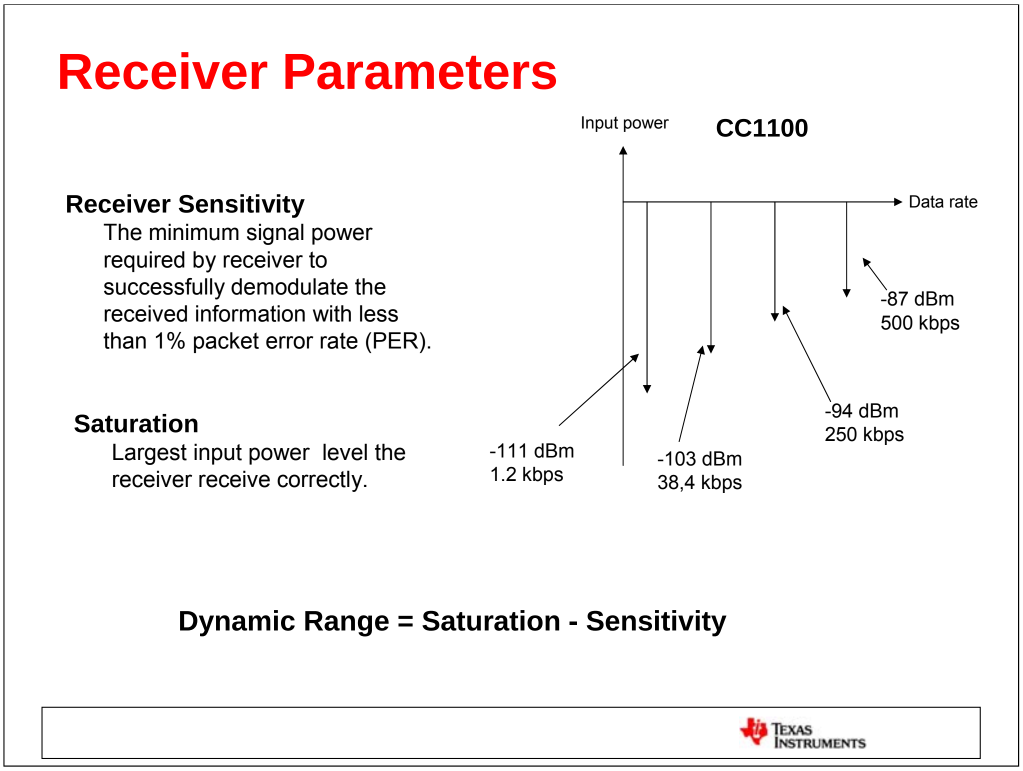
•Saturation

•Adjacent channel rejetions

•Alterenate channels rejection

•Blocking

•Spurious emission (Can be intresting because some (ETSI) regulations specifies maximum emission in RX)



Receiver sensitivity

Signal/Noise (S/N)-ratio is the ratio of received signal power to noise power. Receivers need a required S/N level to be able to demodulate the received signal. Sensitivity is the signal ratio required to successfully demodulate a received signal when only thermal noise is present.

Figure to the right shows the receiver sensitivity for different datarate for the CC1100. Hence, increasing the data rate of course degrades the performance.

Sensivity can be improved by narrowing the receiver bandwidth as this reduces noise coming into the receiver. However, the datarate affects the bandwidth of the signal. Data sent with high datarates therefore requires larger RX filter bandwidth to fit the signal. A narrow RX filter bandwidth also demands good frequency control and therefore a more expensive crystal. The RX filter bandwidth further affects the blocking and and selectivity properties. Larger bandwidth reduces the blocking and selectivity performance.

Saturation

Largest input power possible for the receiver. What usually happens is the input amplifier goes into saturation. Note: that the saturation and the largest input level the receiver can tolerate before it breaks down is different.

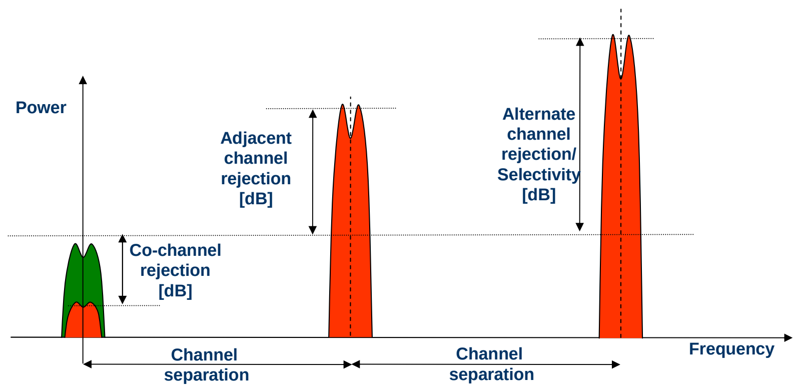
Dynamic Range

The Dynamic range of an receiver is descirbed by ”Dynamic range=Saturation – sensitivity”.

Selectivity / Channel Rejection

- Gives a measure of how good the receiver is at handling interference

Desired signal / Interferer



Selectivity/Channel Rejection

Due to the world-wide availability of the 2.4GHz ISM band it is getting more crowded day by day (Wi-Fi, Bluetooth, ZigBee, cordless phones, microwave ovens, wireless game pads, toys, PC peripherals, wireless audio devices and many more). How robust a system's link is will therefore be influenced by more than just the sensitivity and the output power. How the system handles interference is getting more and more important for all the frequency bands.

Co-channel rejection is valid for a situation with an interferer at the same frequency as your wanted signal. The green spectrums is your wanted signal. For CC1020, the interferer may be up to 11 dB lower than desired signal without degrading performance.

Adjacent Channel Rejection is a specification that tells us how well our receiver will be perform when there are other transmitters in channels next to your channel. Measure of how close the channels can be spaced.

ACR = interferer level - desired signal level

For CC2420, the signal in the next channel may be 39 dB higher than the desired channel without degrading performance, i.e a jammer in the next channel can be ~7900 times stronger without degradation of the wanted signal.

Selectivity is measured for channels "further out" (alternate channel rejection/ selectivity). Low phase noise and narrow IF bandwith => good ACR.

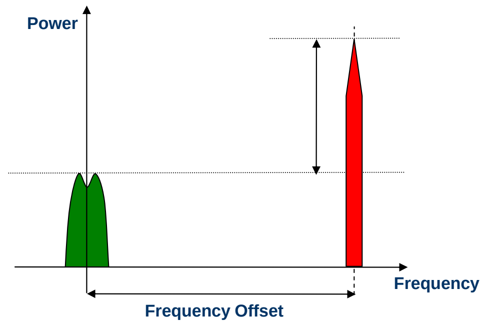
ETSI: Absolute ACP requirement (dBm),

ARIB: Relative (dBc)

Blocking

- Gives a measure of how good the receiver is at handling interference from a source further away in frequency

Desired signal / Interferer



Blocking

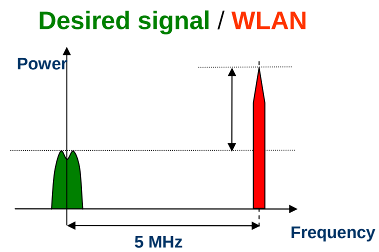
•Similar to channel rejection usuall mesurements with a larger frequency offset of +/- 5 MHz, +/- 10 MHz.

•Usulally when it is measured it is measured using a unmodulated signal as a interferer.

•How good the system is to "ignore" WLAN or any other transmitter is related to the selectivity of the receiver.

We will see an example on next slide.

Receiver Example



	Chip A	Chip B
Sensitivity:	-100 dbm	-97 dBm
Blocking:	27 dB +/- 5 MHz offset	55 dB +/- 5 MHz offset

Case 1:

The power from the WLAN is –80 dBm.
Receiver A can receive a **–100 dBm** signal.
Receiver B can receive a **–97 dBm** signal.

No degradation in receiver sensitivity.

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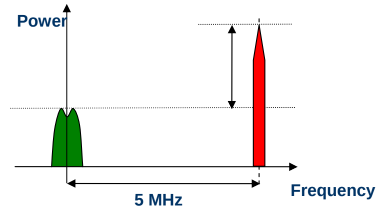
Receiver Example

6 dB theoretically doubles the range.

Case 1: The range of chip A is 1.4x the range of chip B.

Receiver Example 2

Desired signal / WLAN



	Chip A	Chip B
Sensitivity:	-100 dbm	-97 dBm
Blocking:	27 dB +/- 5 MHz offset	55 dB +/- 5 MHz offset

Case 2:

The power from the WLAN is –40 dBm.
Receiver A can receive a -40-27 = **-67 dBm** signal.
Receiver B can receive a -40-55 = **-95 dBm** signal.

Receiver B have 27 dB better receiver sensitivity.

Receiver Example

•Case 2: The range of chip B more than 16x the range of chip A.

•WLAN transmitter can be very close to the reciver. For example in a notebook.

•6 dB theoretically doubles the range.

Transmitter Parameters

Key RF Transmitter parameters

- Output power
- Occupied bandwidth
- Adjacent channel power
- Spurious emission

4.3 RF Transmit Section

Tc = 25°C, VDD = 3.0 V, 0 dBm if nothing else stated. All measurement results obtained using the CC2500EM reference design ([4]).

Parameter	Min	Typ	Max	Unit	Condition/Note
Differential load impedance		80 + j74		Ω	Differential impedance as seen from the RF-port (RF_P and RF_N) towards the antenna. Follow the CC2500EM reference design ([4]) available from the TI website.
Output power, highest setting		+1		dBm	Output power is programmable and full range is available across the entire frequency band. Delivered to a 50 Ω single-ended load via CC2500EM reference design ([4]) RF matching network.
Output power, lowest setting		–30		dBm	Output power is programmable and full range is available across the entire frequency band. Delivered to a 50 Ω single-ended load via CC2500EM reference design ([4]) RF matching network. It is possible to program less than -30 dBm output power, but this is not recommended due to large variation in output power across operating conditions and processing corners for these settings.
Occupied bandwidth (99%)		91		kHz	2.4 kBaud, 38.2 kHz deviation, 2-FSK
		117		kHz	10 kBaud, 38.2 kHz deviation, 2-FSK
		296		kHz	250 kBaud, MSK
		489		kHz	500 kBaud, MSK
Adjacent channel power (ACP)		-28		dBc	2.4 kBaud, 38.2 kHz deviation, 2-FSK, 250 kHz channel spacing
		-27		dBc	10 kBaud, 38.2 kHz deviation, 2-FSK, 250 kHz channel spacing
		-22		dBc	250 kBaud, MSK, 750 kHz channel spacing
		-21		dBc	500 kBaud, MSK, 1 MHz channel spacing
Spurious emissions					
25 MHz – 1 GHz			–36	dBm	
47-74, 87.5-118, 174-230, 470-862 MHz			–54	dBm	
1800-1900 MHz			–47	dBm	Restricted band in Europe
At 2·RF and 3·RF			–41	dBm	Restricted bands in USA
Otherwise above 1 GHz			–30	dBm	
TX latency		8		bit	Serial operation. Time from sampling the data on the transmitter data input pin until it is observed on the RF output ports.

Table 6: RF Transmit Section

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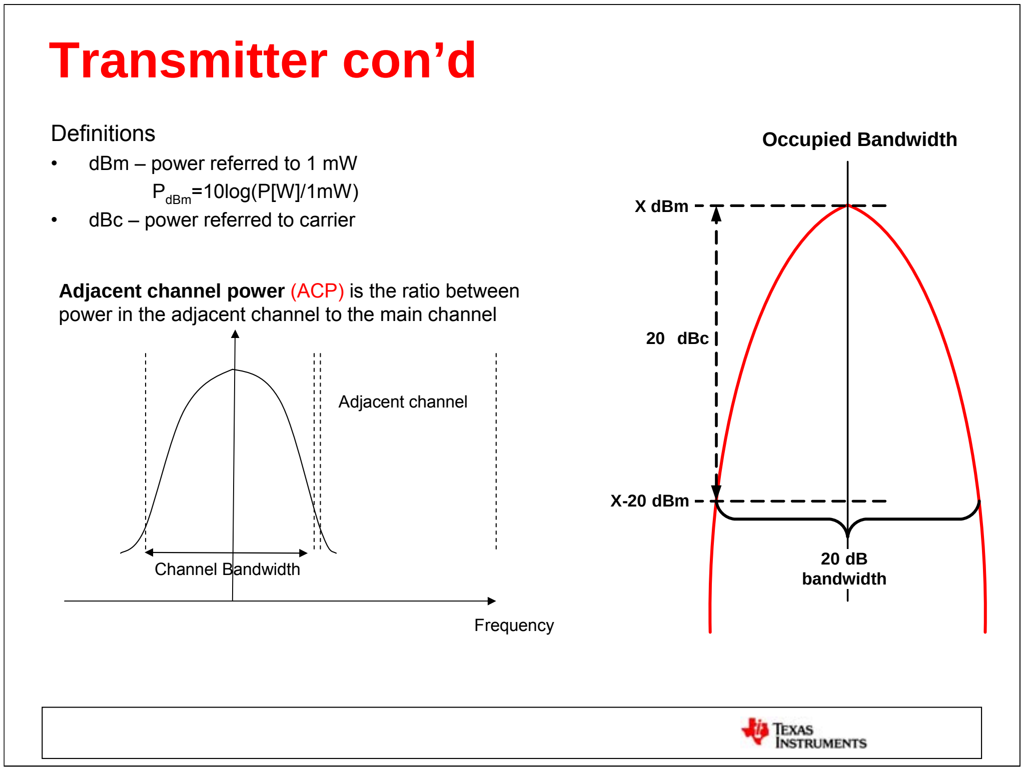
Transmitter Parameter

•Output power

•Occupied bandwidth

•Adjacent channel power

•Spurious emission



Output power

The output power of our chips is programable in steps from -30 dBm to 0 dbm/10 dBm depening of which chip is utilized.

How is dBm related to Watt is shown in equation.

- 30dBm = 1W
- 20dBm = 100mW
- 10dBm = 10mW
- 0dBm = 1mW
- -110 dBm = 1E-11 mW = 0.00001 nW

For a 50 ohm load : -110 dBm is 0.7uV i.e. not much!

dBc

Power referred to carrier i.e., the difference in dB between the carrier and the measured power.

Occupied bandwidth

- The 20 dB bandwidth is a measure of the occupied bandwidth. The measurement.
- Another measurement typ is the 99% occupied bandwidth is is how wide the bandwidth with containing 99% of the energy.
- To measure the 20 dB bandwidth, Find the peak and find the point where you have -20 dBc

Adjacent channel power

- ACPR is ratio between the total power of adjacent channel (intermodulation signal) to the main channel's power (useful signal). Usually measured in dBc.
- Measure the total power in the main channel and the total power in the adjacent channel.
- For TI properaty chips it is specified for different data rates and channel spacings.
- For IEEE 802.15 chips it is of course specified according to the spec.

Modulation Methods

- Starting point:
  - we have a low frequency signal and want to send it at a high frequency
- Modulation: The process of superimposing a low frequency signal onto a high frequency signal
- Three modulation schemes available:
  - **Amplitude Modulation (AM):** the amplitude of the carrier varies in accordance to the information signal
  - **Frequency Modulation (FM):** the frequency of the carrier varies in accordance to the information signal
  - **Phase Modulation (PM):** the phase of the carrier varies in accordance to the information signal

TEXAS INSTRUMENTS

Modulation Methods

Starting point:

we have a low frequency signal and want to send it at a high frequency

Modulation: The process of superimposing a low frequency signal onto a high frequency signal

Three modulation schemes available:

Amplitude Modulation (AM): the amplitude of the carrier varies in accordance to the information signal

Frequency Modulation (FM): the frequency of the carrier varies in accordance to the information signal

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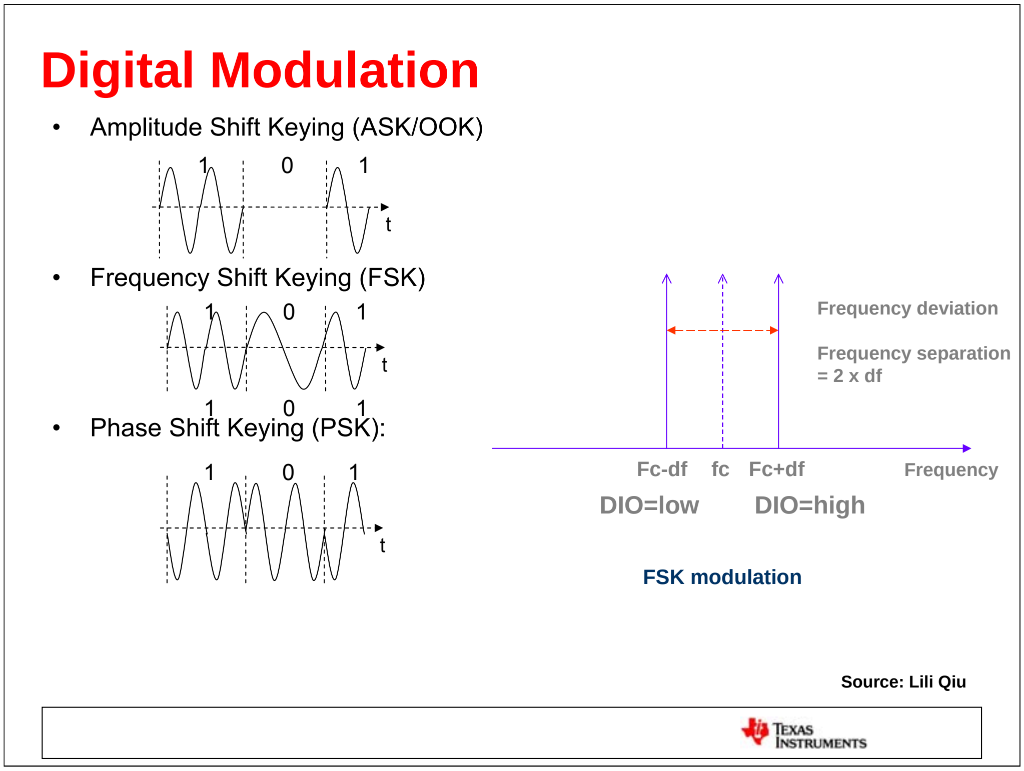


Digital Modulation

Amplitude Shift Keying (ASK/OOK) varies the amplitude of the carrier according to the information signal.

- simple
- duty cycling (gives advantages vs. FCC, allows you to use higher output power)
- lower transmit current
- susceptible to noise
- wide spectrum

Example: Many legacy wireless systems, e.g. AMR and alarm

Frequency Shift Keying (FSK) varies the frequency of the carrier according to the information signal.

- less susceptible to noise
- theoretically requires larger bandwidth/bit than ASK

It is popular in modern systems. Gaussian FSK (GFSK) shapes the information bits before the modulation so it therefore has better spectral density than 2-FSK modulation, i.e. it is more bandwidth efficient.

Figure to the right, shows frequency deviation which is the difference between the carrier frequency and a 0 or 1. The frequency separation is 2x deviation and also the frequency difference between the 0 and 1 signal.

Phase Shift Keying (PSK) varies the phase of the carrier according to the information signal.

- less susceptible to noise
- BPSK (1 bit), QPSK (2 bits per symbol), 8-PSK (3 bits per symbol)
- MSK – Minimum shift keying is also a phase shifting modulation technique (available in some of our chips). Compare to PSK it avoids large phase changes at the end of the symbols i.e., it has a continuous phase shift.
- bandwidth efficient
- Require synchronization in frequency and phase ➔ complicates receivers and transmitter

Example: IEEE 802.15.4 / ZigBee.

How to modulate the signal in a modern transmitter:

- Modern transmitters typically use fractional N synthesizers
- For angle modulation like FSK, MSK, O-QPSK, the synthesizer frequency is adjusted
- For amplitude modulation like OOK and ASK, the amplifier level is adjusted

Spread Spectrum Systems

- 2 types of Spread Spectrum common in ISM bands:
  - Direct Sequence Spread Spectrum (DSSS)
  - Frequency Hopping Spread Spectrum (FHSS)
- Data sent using spread spectrum is intentionally spread over a wide frequency range
- Resistant to noise and interference thus increasing the probability that the signal will be received correctly

Spread Spectrum Systems

You can also use ”smart” protocols to be better suited to handle interference. Spread spectrum makes the signal appear more like noise which will make it more difficult to detect and jam. It is further unlikely to interfere with other signals even if they are transmitted on the same frequency. The use of a spread spectrum technique also increases the amount of output power allowed in the band by regulations authorities. We will have a closer look at this at the end when frequency regulations are discussed.

DSSS:

•Each bit represented by multiple bits using spreading code

•Spreading code spreads signal across wider frequency band and lower peak power

•Good resistance against interferers

FHSS

•Signal broadcast over a seemingly random series of frequencies, adaptive or static.

•Receiver hops between frequencies in sync with transmitter

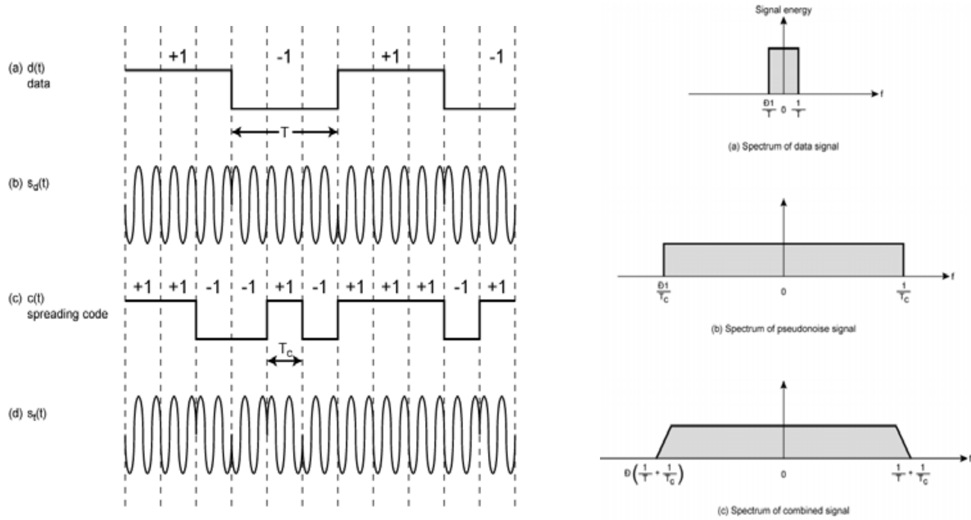
•Jamming on one frequency affects only a few bits

In SS, the radio transceiver spreads a signal’s power over a wider band of frequencies

> The spreading process makes the data signal much less susceptible to noise than conventional radio modulation techniques
>
> Process gain – sacrificing bandwidth to gain signal-to-noise performance

The transmitted signal occupies a bandwidth considerably greater than the minimum necessary to send the information

DSSS – BPSK Example



Source: William Stalling

DSSS – BPSK example

- Each bit represented by multiple bits using spreading code
- Spreading code spreads signal across wider frequency band

(a) The data – spectrum of the data very narrow band

(b) The data are BPSK modulate see the 180 degree phase shifts

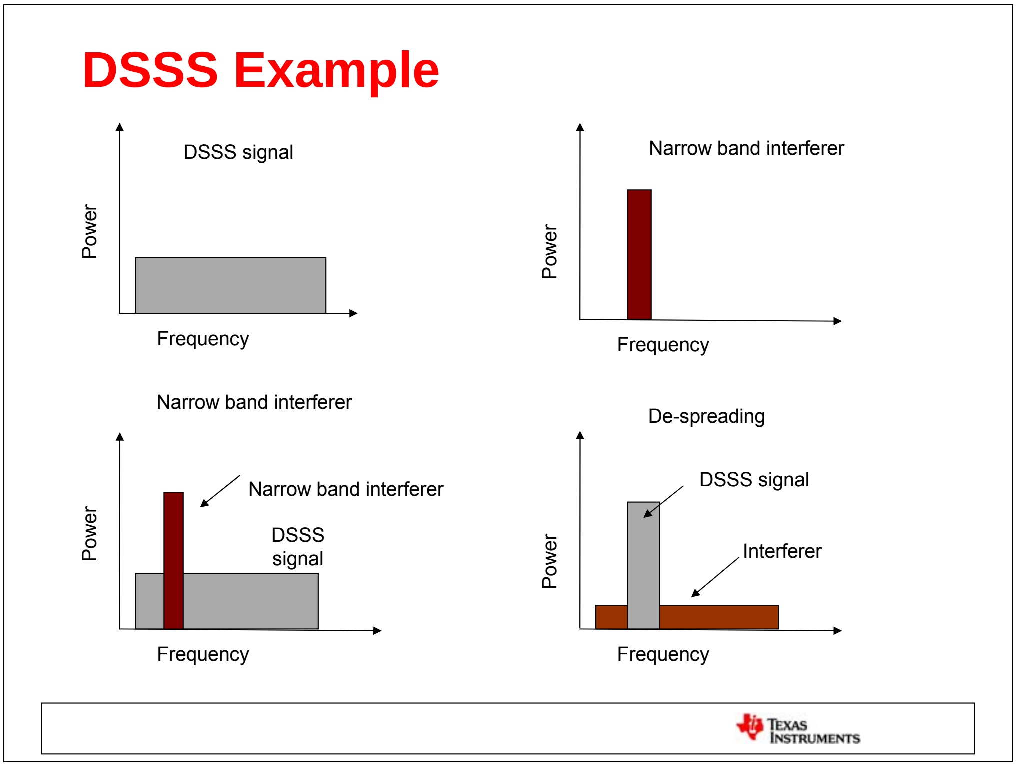
(c) This is the spreading code (higher data rate compared to “data”)– much wider frequency.

(d) Shows the modulated signal multiplied with spreading code.

The spreading process makes the data signal much less susceptible to noise than conventional radio modulation techniques. Process gain – sacrificing bandwidth to gain signal-to-noise performance. The transmitted signal occupies a bandwidth considerably greater than the minimum necessary to send the information

On the receiver side the same process is done in “reverse”. Hence, it is de-spreaded utilizing a predetermined de-spreading code and the data can be “recovered” correctly.

Note: This technique is utilized in IEEE 802.15.4



DSSS Example

Top illustrate the principle and advatange of DSSS:

•Top left – DSSS signal where it have been spread using the spreading code.

•Top right – A narrow band interferer.

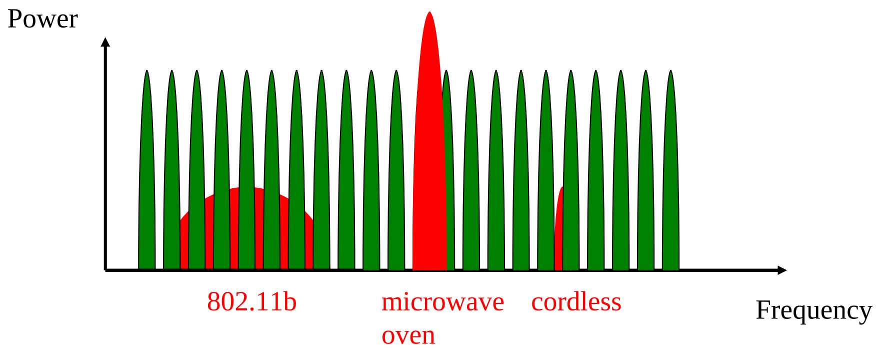
•Bottom left- Noise on top of the DSSS signal.

•Bottom right – The signal after despreading in the receiver.

This makes is possible to detect the correct data.

FHSS - Static Frequency Hopping

- Utilise a predetermined set of frequencies with either a repeating hop pattern or a pseudorandom hop pattern



Source: Eliezer & Michael, TI

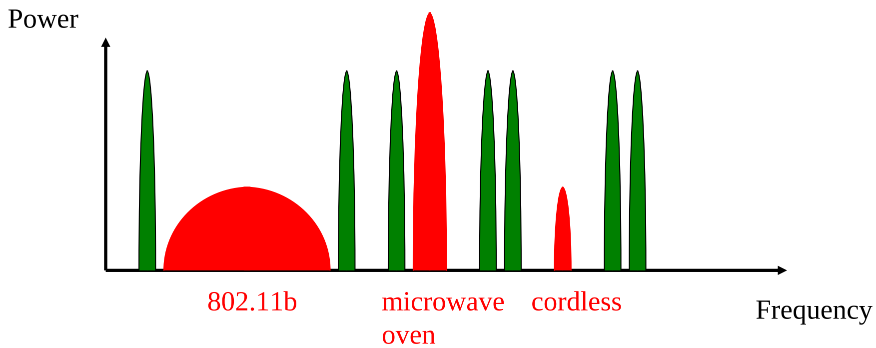
TEXAS INSTRUMENTS

Static Frequency Hopping:

Utilise a pre-determined set of frequencies with either a repeating hop pattern or a pseudorandom hop pattern, e.g. Bluetooth (versions 1.0 and 1.1). Receiver and transmitter must be syncorinzed. Some data with high interference will be corrupted.

Adaptive Frequency Hopping

- Scan the entire frequency band at start-up and restrict usage to frequencies with the lowest energy content.



Source: Eliezer & Michael, TI

Adaptive Frequency Hopping

•Scan the entire frequency band at start-up and restrict usage to frequencies with the lowest energy content.

•This technique is utilized in TIs RadioDesk and Bluetooth 1.2 and 2.0.

•RadioDesk is a protocol developed by TI. It is mainly used in in keyboard/mouse applications.

Extending the Range of an RF system

Extending the Range of an RF system

Link Budget

Link Budget = Output Power + Antenna gain – Sensitivity

Friis equation (Free space loss)

$$P_R = P_T \frac{G_T G_R \lambda^2}{(4\pi)^2 d^n} \qquad n = 2$$

P_R:	Power available from receiving antenna.
P_T:	Power supplied to the transmitting antenna.
G_R:	Gain in receiving antenna
G_T:	Gain in transmitting antenna
λ:	Wavelength λ=c/f, c=speed of light, f=frequency.
d:	Distance [m]
C:	Speed of light in complete vacuum 2.99792458*10^8 [m/s]

TEXAS INSTRUMENTS

Link budget.

•Link budget = Output power + antenna gain– sensitivity.

•Sensitivity is a negative number.

•The gain of the antennas is equal to the gain of the transmitting antenna + gain of the receiving antenna.

•Link budget is equal to how much loss you can have between the transmitter and receiver.

Note: High gain of an antenna is not necessarily a good thing. It depends on the application and what factor that are causing the high gain. High gain is desirable for an RF system with fixed positioning of both receiving and transmitting antennas. Thus the antennas can be positioned with the optimum direction pointed towards each other. For mobile systems it is usually better to have an antenna which spreads the radiated power in a more omnidirectional manner. This will ensure that the performance of the system is not heavily affected by the positioning of the devices. Gain is usually referred to an isotropic antenna and usually with the designation dBi. An isotropic antenna is a theoretical antenna that radiates equally in all directions. Gain in an antenna must not be related to gain from an amplifier. An antenna has not the capability to amplify the RF signal, but it can focus the energy in a specific direction and thus increase the gain. It can be compared to a flashlight were you always have the same amount of light, but it is possible to focus it to form a narrow beam. Thus you get a more intense light in a smaller area. Since antenna gain is often only given for the maximum direction it is important to also look at the radiation patter or an average gain number when evaluating an antenna.

Friis equation (Free space loss)

When discussing range and radio communication Friis Equation relates most system parameters. The equation relates received signal power to supply power to antenna for both transmitter and receiver. The frequency dependent free space loss are also include. However, in real life scenarios the achieved range will differ from the free space loss equations. Especially indoors with "no line of sight" the range will differ a lot from the range expected from the friis formula.

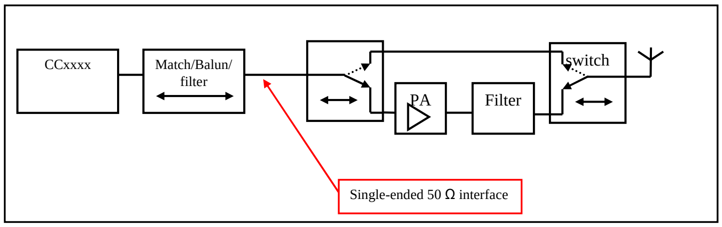
•This equation together with the sensitivity of the receiver determine the free space communication range for a particular radio link.

The Friis equation give us the following relationships.

- Dubble the frequency => Half the range.
- 6 db increased sensitivity or output power => Dubbles the range.
- High gain antenna ca be utilized to increase the range.

Extending the Range

Adding a discrete Power amplifer (PA)



- 50 Ω reference impedance
- Extended range
- The added complexity

Range Extension PA

•Remember our discussion about range and link budget. What could be done to increase the Range? Here is an example of how we can utilize a PA.

An external PA add more external circuitry than the amplifier on its own. An amplifier is an unidirectional component i.e. the received signal cant pass through in the opposite direction. The problem is usually solved by using switches as illustrated. These switches add loss and thereby reduce sensitivity and transmitted power. The reduced sensitivity has to be considered when calculating the total link budget. Some systems use dual antenna to void using the latter switch. Transmitters is also unidirectional devices and additional switches is not required.

Amplifier and switches are generally matched to 50Ω and therefore needs to be connected to into the circuit in 50ohm nodes. 50Ω is the general reference impedance used in most radio circuits. Reference designs usually define inputs and outputs as 50 ohm, this is also valid for LPRF designs. Al instruments used to measure RF circuitry use wideband 50ohm inputs. This load is what is used during characterization and is the preferably the load connected to our reference circuits. Antennas are generally only narrow band 50Ω, this can in some instances introduce some challenges.

Extended range:

Each 6dB output power added by the amplifier doubles range, theoretically.

Advantage:

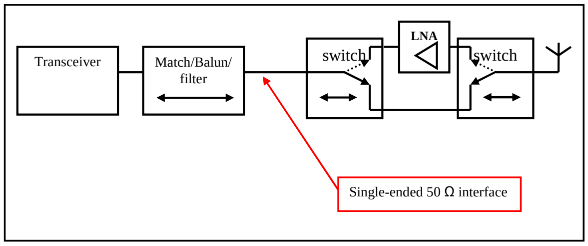
An external PA will increase current consumption however this increase is occurring in TX. The transceiver spend statistical less time TX in compared to other states and RX. Increased current consumption in a seldom occurring state have only minor influence on the total average current.

Disadvantage

Regulation requirements limits the legal transmitted power. Increasing power generally reduce margins to regulatory limits.

Extending the Range

Adding a discrete Low Noise Amplifier (LNA)



$$F_{Total} = F_{LNA} + \frac{F_{CC11XX}}{G_{LNA}}$$

Example

CC11xx approximate NF =11dB
External LNA GAIN G=16dB
LNA NF=2.7dB

→ Total NF=3.3dB
→ Sensitivity improvement (11-3.3)dB=7.67dB
→ this more than doubles original range.

Range extension LNA

Adding an external Low noise amplifier (LNA) require the same considerations as adding an power amplifier.

The range extension is little more cumbersome to calculate. The range extension is dependent on the existing receiver sensitivity and noise figure. CC1100 have typically about 11dB noise figure.
If the example above was implemented for the CC1101operating at 868MHz, 250kbps the sensitivity for CC1101 would be improved from -94dBm standalone operation to +101.7dBm when the receiver and LNA are operated together.

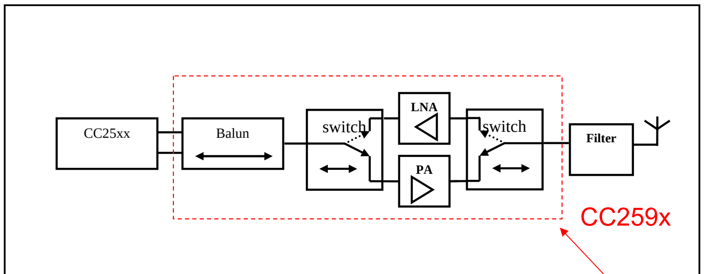
Advantage:
Increase range without increasing transmit power. The solution is often preferred when regulation requirements limits power.

Disadvantage:

Increased current consumption in a mode that both is frequently used and stays active for long durations.
This significantly increasing average total current consumption.

Extending the Range

Add both a Power amplifier and Low Noise amplifier.

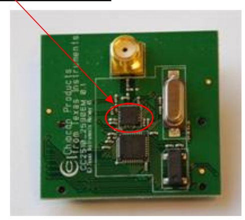


Example CC2430-CC2591EM

Increases the output power to19 dBm

Improves sensitivity by approx. 6 dB

Increased Link budget by 25 dBm



CC2430+CC2591EM

Texas Instruments

Range extension PA & LNA

When LNA and PA are simultaneously used the range extension from each solutions can be added. Significantly increasing range. This solution get both the advantages and the disadvantages from both of the solutions. Combining both the advantages and disadvantages with using a PA and LNA.

We have a chip which we call a range extender

CC259x

The CC259x RF frontend it contains PA, LNA, switches, RF-matching, balun for simple design of high performance wireless applications. It is designed to fit with all our 2.4 GHz chips. We have the CC2590 and CC2591 for different markets. The CC2591 is for the US market and the CC2590 more for the european market.

Example CC2430+2591

CC2430 have typically about 12 dB noise figure. The total noise figure when using the CC2591 with the CC2430 is then 5.8 dB. The sensitivity should therefore be improved from -92dBm to approximately ~98 dBm (sensitivity measured to -98.5 dBm on the CC2430-CC2591EM) which theoretically doubles the original range.

By further adding a PA so that the transmit power increases from 0 dBm to 19 dBm:

Total Link Budget without PA and LNA 92dB

Total Link Budget with PA and LNA 117dB

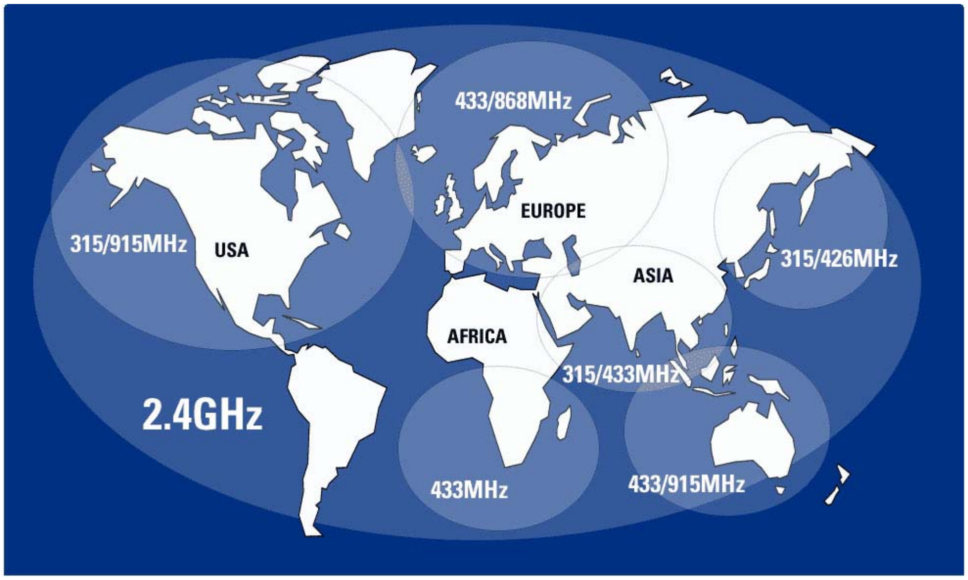
Difference

25dB

This means theoretically more than 16x the range!!

Frequency Regulations

Overview – ISM and SRD bands



Overview – ISM and SRD bands

•2.4 GHz is mainly open for communication in the whole world. Note that there are national differences even for this band. Even if the same frequency band is open for license free communication it might be differences in allowed output power and different limits for spurious emission.

•License free frequency band are often called SRD band and ISM band.

SRD – Short Range Device

ISM – Industrial Science and Medical

For more details on frequence regulations we have some application notes.

Note Ti have Chips cover all frequencies shown in the figure.

AN001 -- SRD regulations for license free transceiver operation
http://www.ti.com/lit/pdf/swra090

AN032 -- 2.4 GHz Regulations
http://www.ti.com/lit/pdf/swra060

ISM-Band and Short Range Device Regulatory Compliance Overview
http://www.ti.com/lit/pdf/swra048

AN50 -- Using the CC1101 in the European 868MHz SRD band
http://www.ti.com/lit/pdf/swra146

Regional Differences

- Europe – ETSI
  - 433/868 MHz
  - 2.4 GHz
- USA – FCC
  - 315/915 MHz
  - 2.4 GHz
- Japan – ARIB
  - 426 MHz
  - 2.4 GHz
- Other National Requirements

Regional Differences

There are different regulatory requirements in different regions. It is important that the product complies with the regulatory limits in all countries it is going to be sold in.

•The Federal Communications Commission (FCC) is responsible for RF regulation in the US.

•European Telecommunications Standards Institute (ETSI) is responsible for RF regulation in Europe.

•Association of Radio Industries and Businesses (ARIB) is responsible for RF regulations in Japan.

It is recommended to do pre-compliance measurements early in the design process to avoid surprises just before releasing a product. Failure to comply with regulatory limits often requires layout changes to resolve the problem which is a time consuming task.

Other countries might follow these standards or have separate requirements. More information about frequency regulations can be found in:

AN001 -- SRD regulations for license free transceiver operation
http://www.ti.com/lit/pdf/swra090

AN032 -- 2.4 GHz Regulations
http://www.ti.com/lit/pdf/swra060

ISM-Band and Short Range Device Regulatory Compliance Overview
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AN50 -- Using the CC1101 in the European 868MHz SRD band
http://www.ti.com/lit/pdf/swra146

FCC example @ 2.4 GHz

FCC - SRD Regulations for the 2400 – 2483.5 MHz band

FCC 15.249, Single channel

FCC 15.247, Spread Spectrum

FHSS - Frequency Hopping Spread Spectrum

Digital Modulation (e.g. DSSS - Direct Sequence Spread Spectrum)

Standard	Relevant Frequency	Radiated Power (EIRP)	Conducted Power	Comment
	2400 – 2483.5 MHz		+30 dBm	Maximum 6 dBi antenna gain
FCC 15.247	Restricted bands defined by 15.205	-41.2 dBm		
	All frequencies not covered in above cells		-20 dBc	

Frequency regulations FCC 2.4 GHZ example.

Narrow band (15.246)

Devices falling under FCC15.249 does not need to have any Spread spectrum technique. However, the maximum output power of -1.2 dBm.

Spread spectrum system (FCC 15.247)

Frequency Hopping Spread Spectrum FHSS and Direct Sequence Spread Spectrum DSSS generally allows higher transmission power than without. FCC Part 15.247 limits the output power to 1 W or +30 dBm when Direct Sequence Spread Spectrum (DSSS) modulation

Frequency Hopping Spread Spectrum (FHSS) with at least 75 hop channels is used

Duty cycled systems

FCC average power over a given time interval. Due to the averaging detector, pulsed transmissions are allowed higher peak fundamental, harmonic and spurious power.

This is a benefit for duty-cycled transmissions. The relaxation factor is 20 log (TX on-time/100 ms) [dB]. A 50 % duty cycle will for example allow for 6 dB higher peak emission than without duty cycling. Notice however that, even when an averaging detector is called for, there is still a limit on emissions measured using a peak detector function with a limit 20 dB above the average limit.

Note when using a PA

When using high output power (external PA), increased filtering is necessary to limit spurs and harmonics. It is therefore important to know the restricted bands in US (FCC 15.205 and 15.209) for high power applications. The strictest limitations to using an external PA are those imposed by the FCC on the frequencies directly adjacent to the upper and lower edges of the 2.4 GHz ISM band. It is also very important to include the antenna in the considerations in US (requirements are given as field strength)!

Comments on ETSI

Up to +20 dBm when spread spectrum is utilized. Etsi also requirements of the emission in receiving mode.

TI reference designs

We test all our reference design against FCC and ETSI compliance.....Hence, coping the reference design is strongly recommended.

Other Resources

- Low Power RF Developer Network
- Engineer-To-Engineer Community

Low Power RF Developer Network:

TI has launched an extensive network of Low-Power RF development partners to help customers speed up their application development. The network consists of recommended companies, RF consultants, and independent design houses that provide a series of hardware module products and design services, including:

•RF circuit, low-power RF and ZigBee™ design services

•Low-power RF and ZigBee module solutions and development tools

•RF certification services and RF circuit manufacturing

http://focus.ti.com/general/docs/staticcontent.tsp?contentId=29028

TI E2E Community:

Here you can freely and openly interact with your peer Engineers, TI Engineers, and other experts in order to ask questions, share knowledge, explore ideas, and help solve problems. This page contains:

•Videos

•Forums (LPRF forum can be found here: http://community.ti.com/forums/default.aspx?GroupID=15

•Blogs

http://community.ti.com/

Summary

- Overview of an RF System
  - Transceiver
  - System on Chip
  - Crystal
  - Balun
  - Antenna
- RF parameters
  - Receiver
    - Sensitivity
    - Selectivity
  - Transmitter
    - Output power
    - ACP
  - Modulation Methods
- Extending the Range
  - Link Budget
  - Power Amplifier
  - Low Noise Amplifier
- Frequency Regulations
  - FCC
  - ETSI
  - ARIB
  - Other national req.

Texas Instruments

Summary

A short summary of what have been presented.

Overview of RF system

•Different ICs from TI transcivers/SOCs

•Which passives needed

•Balun, Why matching is imporatant.

•Crystal tradeoffs.

•Various Antenna such as chip antennas, whip, PCB antennas

Radio range

•Antenna (gain)

•Sensitivity

•Output power

•Radio pollution (selectivity, blocking)

•Modulation techniques (FSK,PSK,ASK)

•Spread spectrum techniques

Extending the Range

•Link budget

•Add PA

•Add LNA

•Add RF frontend (CC259x)

Frequency regulations

•Overview of which frequencies are allowed in different parts of the world.

•Spreading thcniques such as DSSS and FHSS allows higher output powers.

•Important that end product has to be tested and compiant on the market.

Questions?

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