RF Basics, RF for Non-RF Engineers

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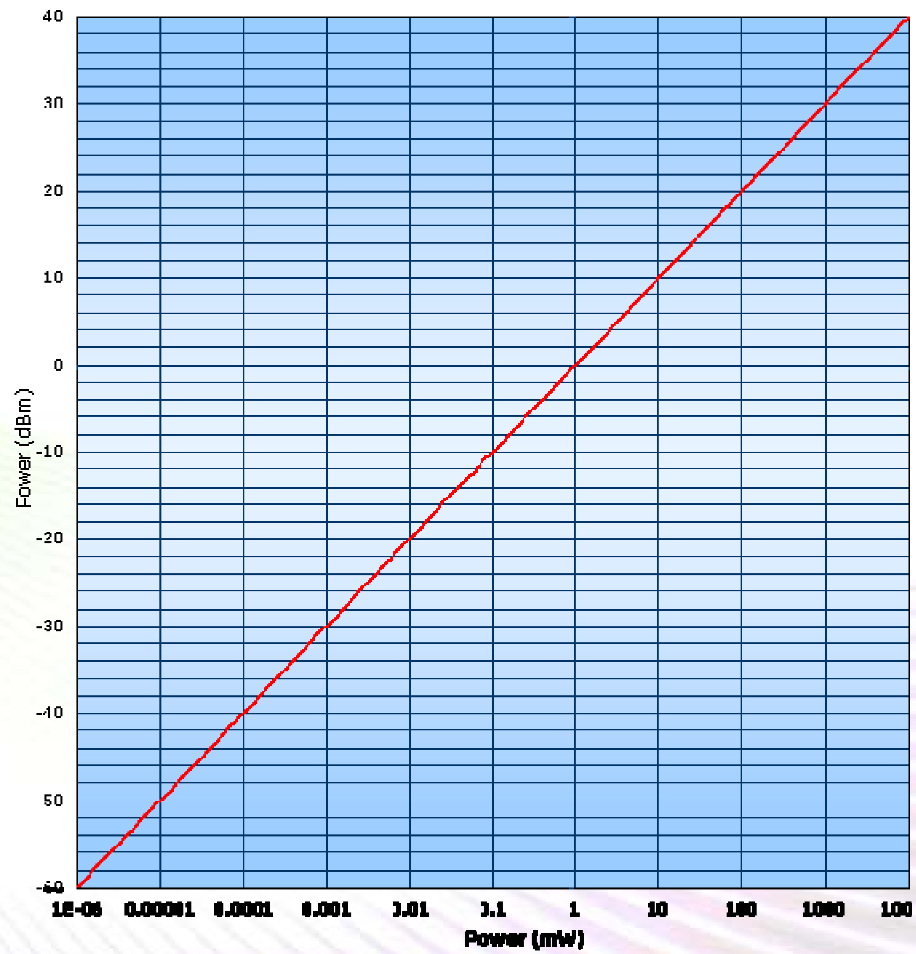
Agenda

- Basics
- Basic Building Blocks of an RF System
- RF Parameters and RF Measurement Equipment
- Support / getting started

Definitions

- **dBm – relative to 1 mW**
- **dBc – relative to carrier**
- **10mW = 10dBm, 0dBm = 1mW**
- **-110dBm = 1E-11mW = 0.00001nW**
- **For a 50 ohm load :**
  -110dBm is 0.7uV,
  i.e. not much!



- **Rule of thumb:**
  - Double the power = 3 dB increase
  - Half the power = 3 dB decrease

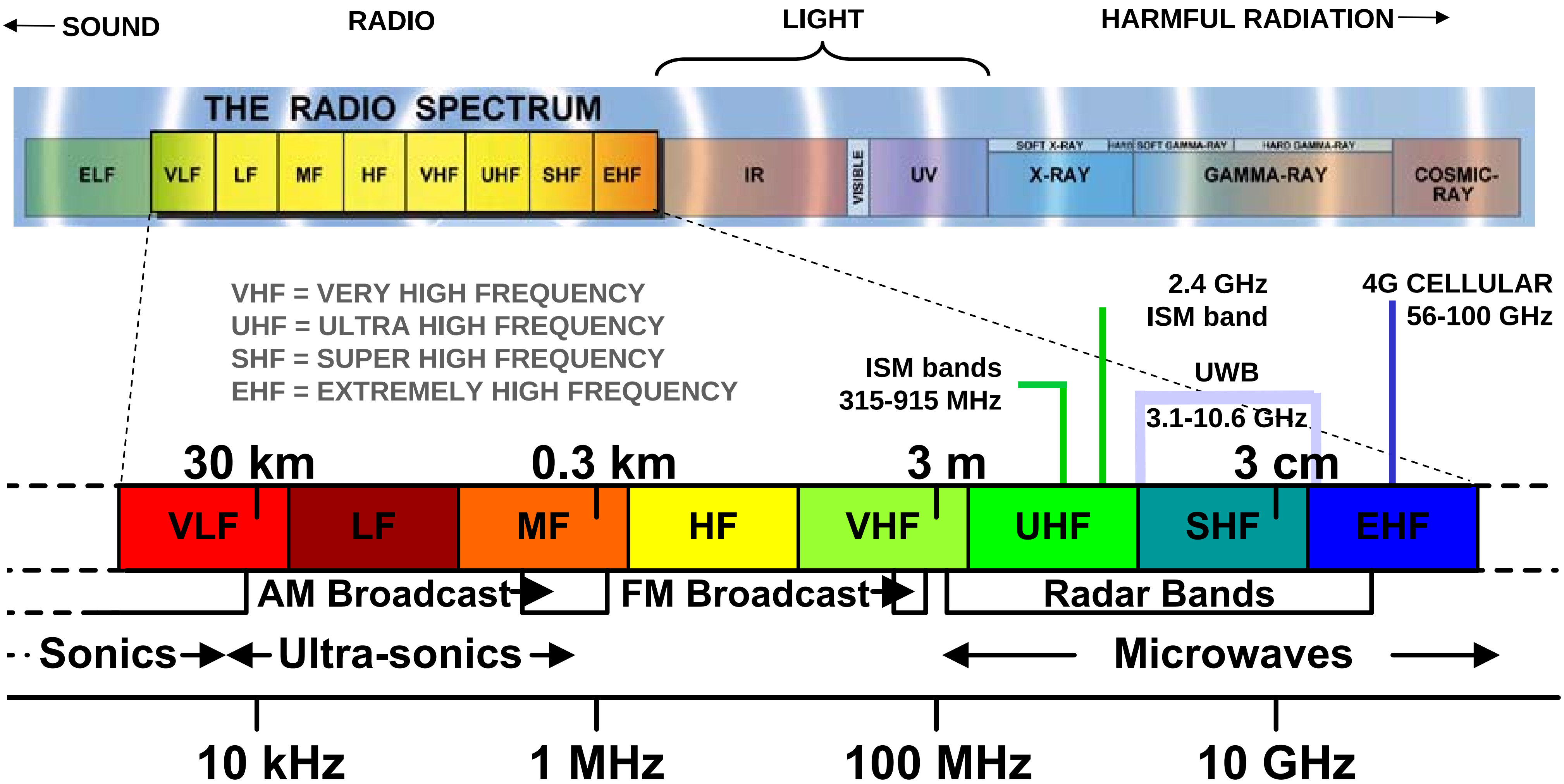
dBm to Watt

- **About dBm and W**

▪ Voltage Ratio	aV = 20 log (P2/P1)	[aV] = dB
▪ Power Ratio	aP = 10 log (P2/P1)	[aP] = dB
▪ Voltage Level	V‘ = 20 log (V/1µV)	[V‘] = dBµV
▪ Power Level	P‘ = 10 log (P/1mW)	[P‘] = dBm

e.g. 25mW max. allowed radiated power in the EU SRD band
>> P‘ = 10 log (25mW/1mW) = 10 * 1,39794 dBm >> 14 dBm

Electromagnetic Spectrum



ISM = Industrial, Scientific and Medical
UWB = Ultra Wide Band

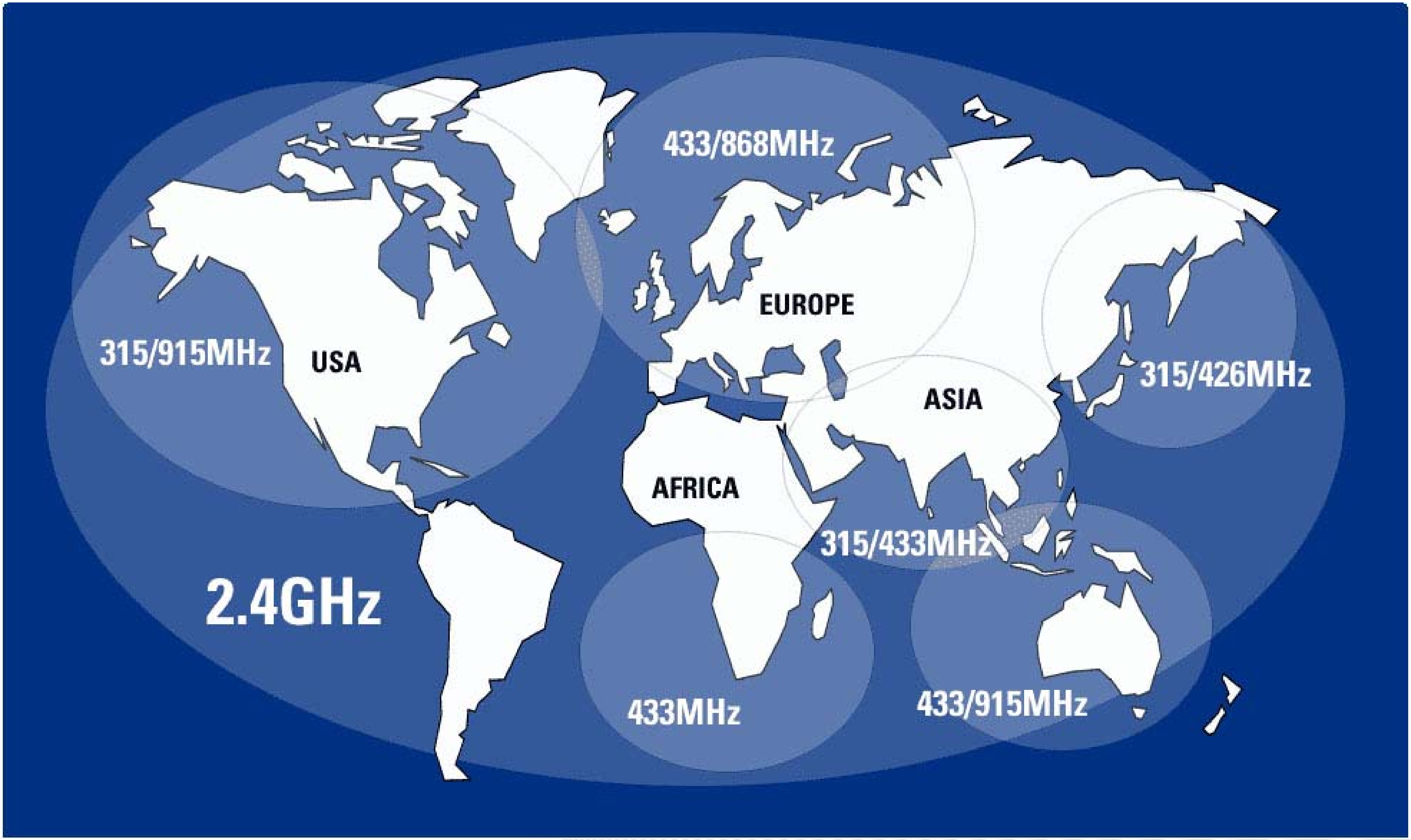
Source: JSC.MIL

Frequency Spectrum Allocation

- **Unlicensed ISM/SRD bands:**
- **USA/Canada:**
  - 260 – 470 MHz (FCC Part 15.231; 15.205)
  - 902 – 928 MHz (FCC Part 15.247; 15.249)
  - 2400 – 2483.5 MHz (FCC Part 15.247; 15.249)
- **Europe:**
  - 433.050 – 434.790 MHz (ETSI EN 300 220)
  - 863.0 – 870.0 MHz (ETSI EN 300 220)
  - 2400 – 2483.5 MHz (ETSI EN 300 440 or ETSI EN 300 328)
- **Japan:**
  - 315 MHz (Ultra low power applications)
  - 426-430, 449, 469 MHz (ARIB STD-T67)
  - 2400 – 2483.5 MHz (ARIB STD-T66)
  - 2471 – 2497 MHz (ARIB RCR STD-33)

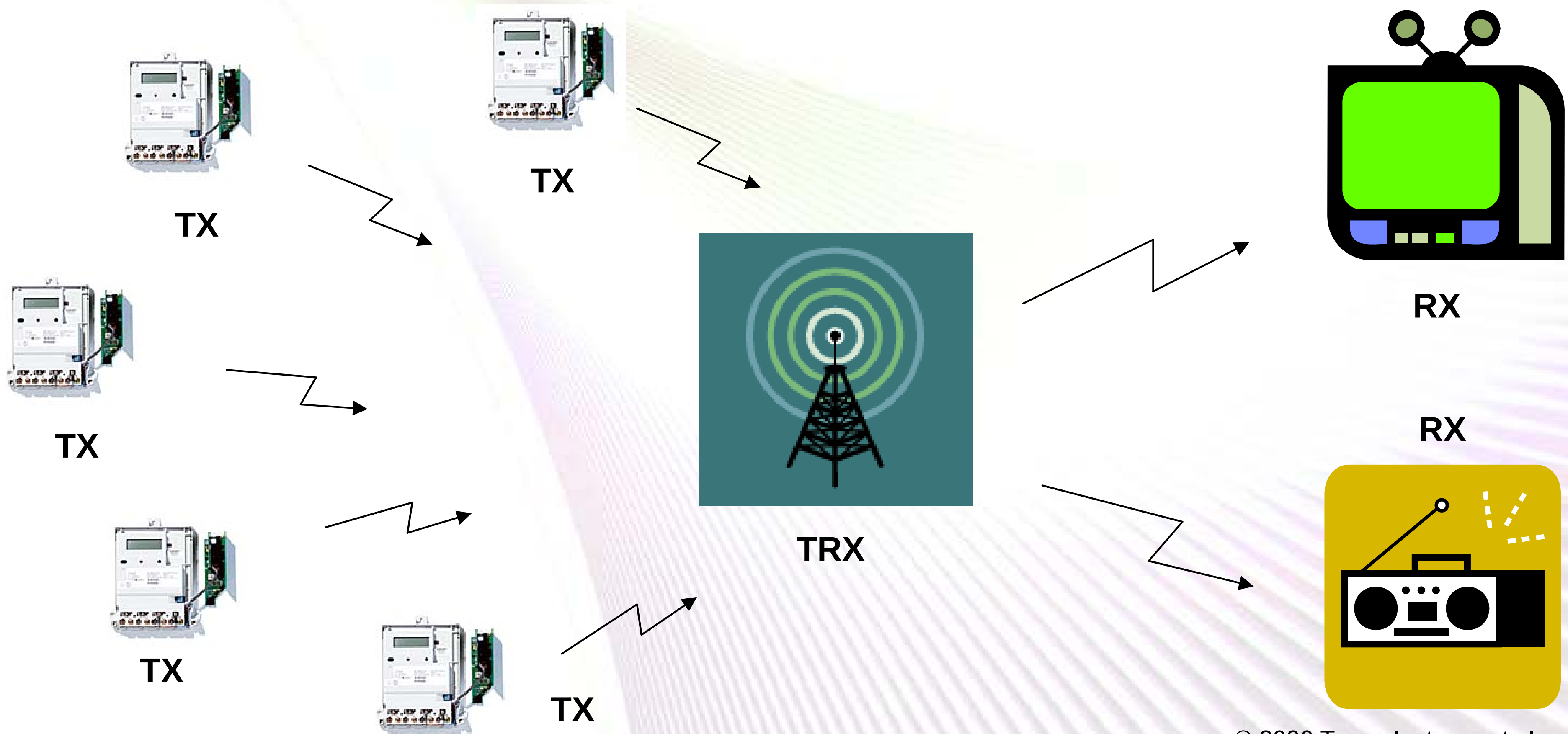
- **ISM** = Industrial, Scientific and Medical
- **SRD** = Short Range Devices

ISM/SRD License-Free Frequency Bands



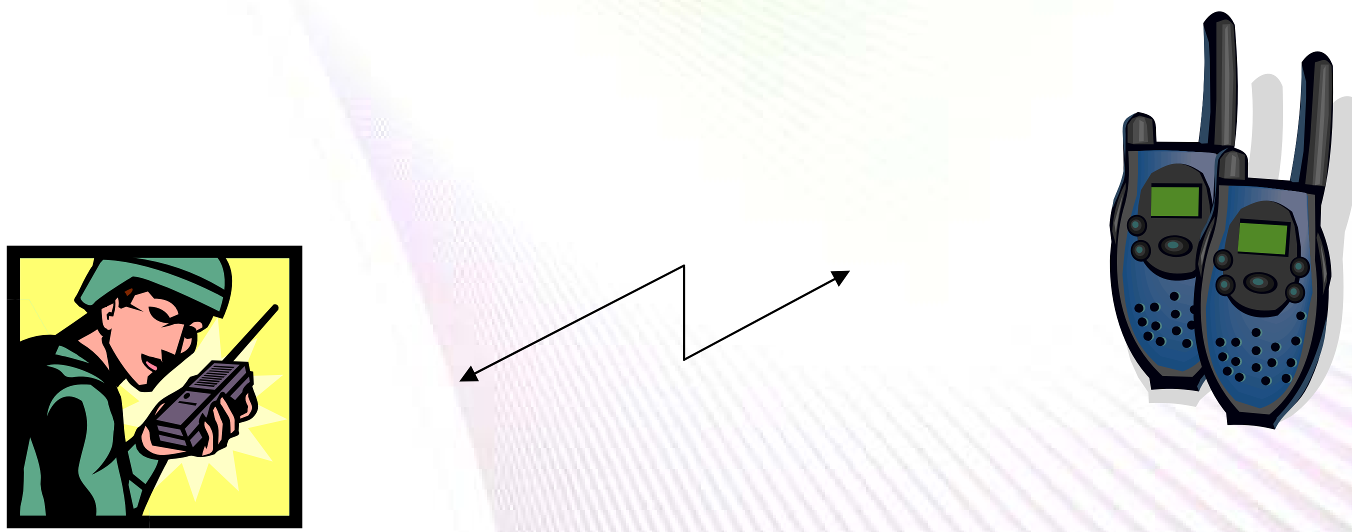
RF Communication Systems

- **Simplex RF System**
  - A radio technology that allows only one-way communication from a transmitter to a receiver
  - Examples: FM radio, Pagers, TV, One-way AMR systems



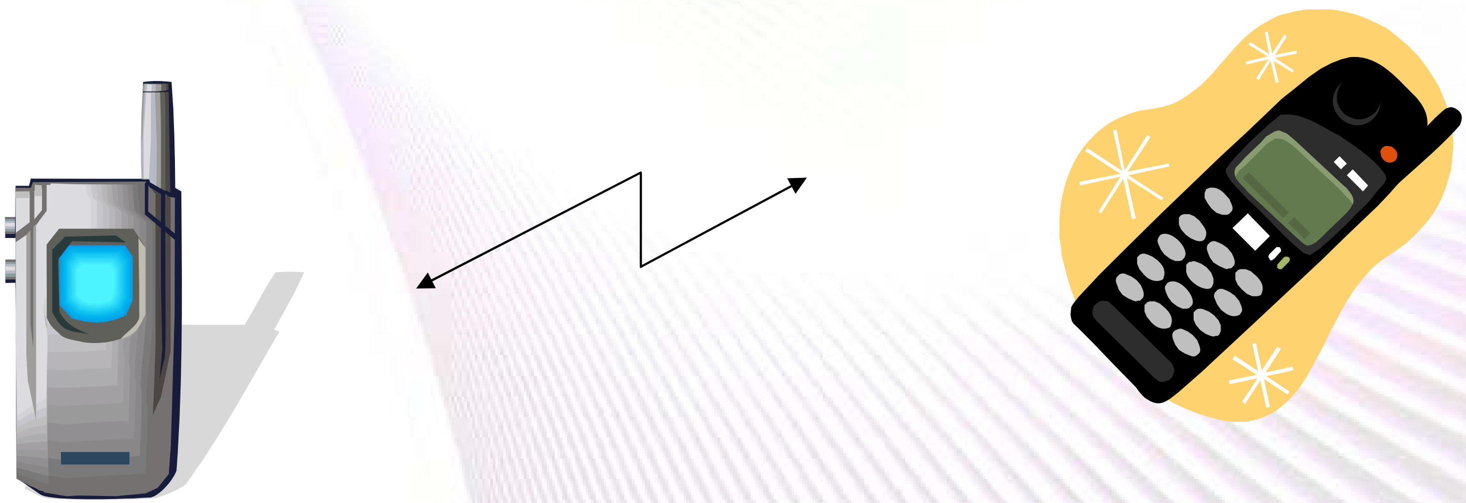
RF Communication Systems

- **Half-duplex RF Systems**
  - Operation mode of a radio communication system in which each end can transmit and receive, but not simultaneously.
  - **Note:** The communication is bidirectional over the same frequency, but unidirectional for the duration of a message. The devices need to be transceivers. Applies to most TDD and TDMA systems.
  - Examples: Walkie-talkie, wireless keyboard mouse



RF Communication Systems

- **Full-duplex RF Systems**
  - Radio systems in which each end can transmit and receive simultaneously
  - Typically two frequencies are used to set up the communication channel. Each frequency is used solely for either transmitting or receiving. Applies to Frequency Division Duplex (FDD) systems.
  - Example: Cellular phones, satellite communication



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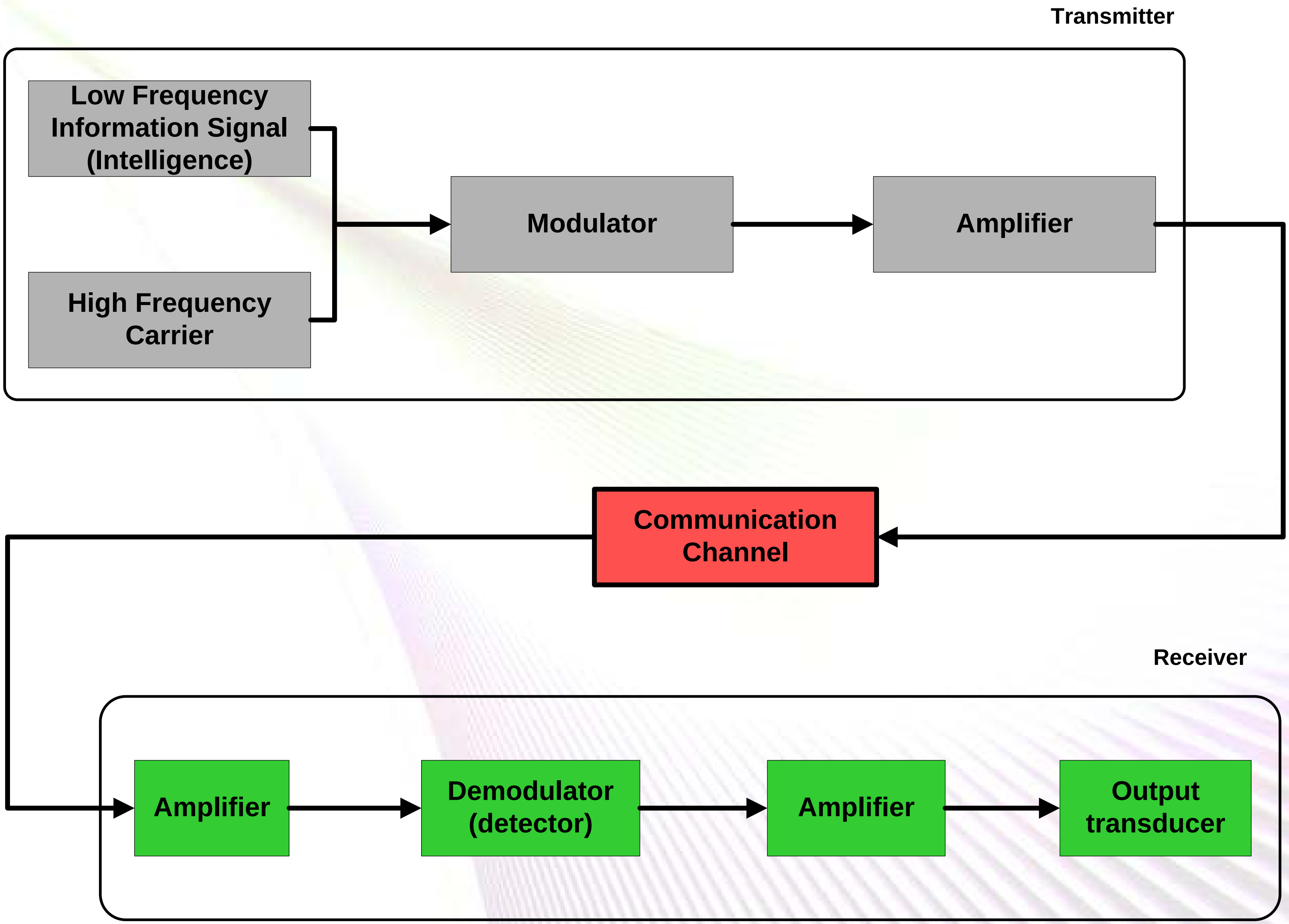
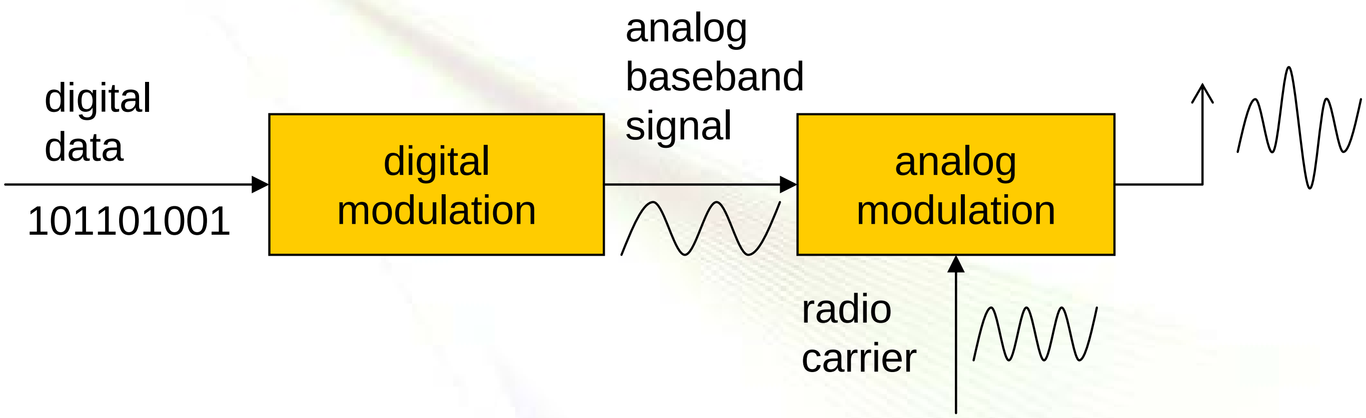
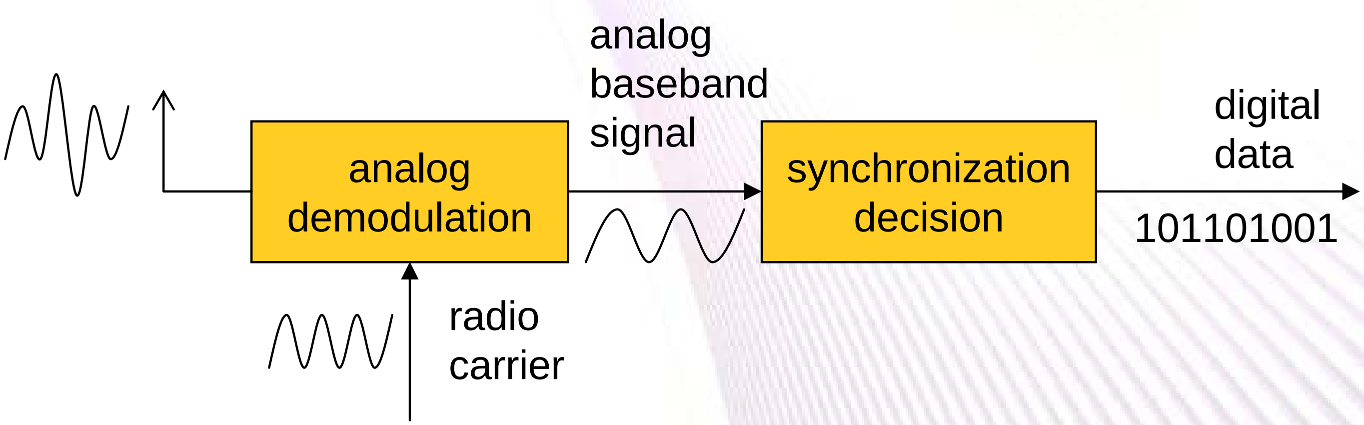
Wireless Communication Systems



Modulation and Demodulation



Radio Transmitter



Radio Receiver

Source: Lili Qiu

Modulation Methods

- **Starting point:**
  we have a low frequency signal and want to send it at a high frequency

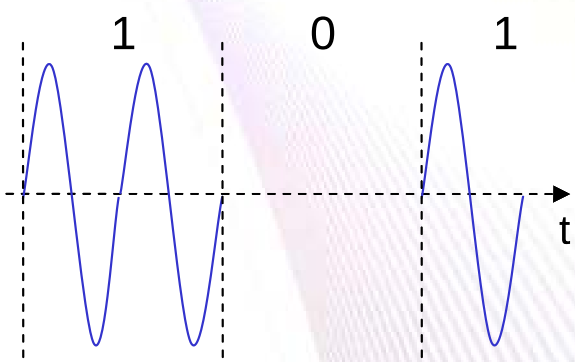
- **Modulation: The process of superimposing a low frequency signal onto a high frequency signal**

- **Three modulation schemes available:**
  1. **Amplitude Modulation (AM):** the amplitude of the carrier varies in accordance to the information signal
  2. **Frequency Modulation (FM):** the frequency of the carrier varies in accordance to the information signal
  3. **Phase Modulation (PM):** the phase of the carrier varies in accordance to the information signal

Digital Modulation

- **Modulation of digital signals is known as Shift Keying**

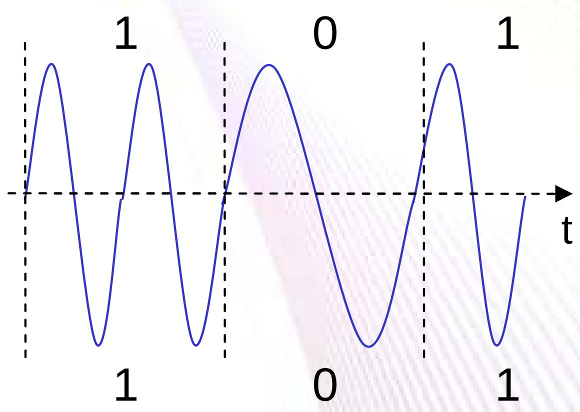
- **Amplitude Shift Keying (ASK):**
  - Pros: simple
  - Cons: susceptible to noise
  - Example: Many legacy wireless systems, e.g. AMR



Source: Lili Qiu

Digital Modulation

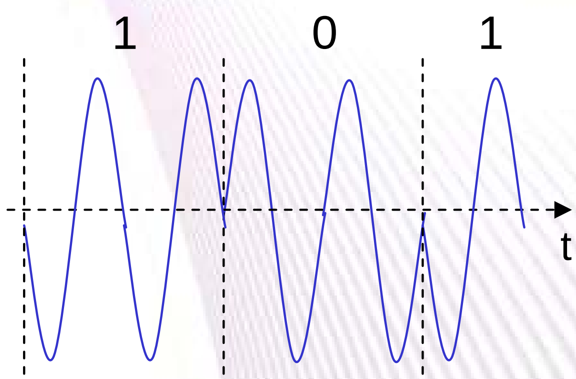
- **Frequency Shift Keying (FSK):**
  - Pros: less susceptible to noise
  - Cons: theoretically requires larger bandwidth/bit than ASK
  - Popular in modern systems
  - Gaussian FSK (GFSK), e.g. used in Bluetooth, has better spectral density than 2-FSK modulation, i.e. more bandwidth efficient



Source: Lili Qiu

Digital Modulation

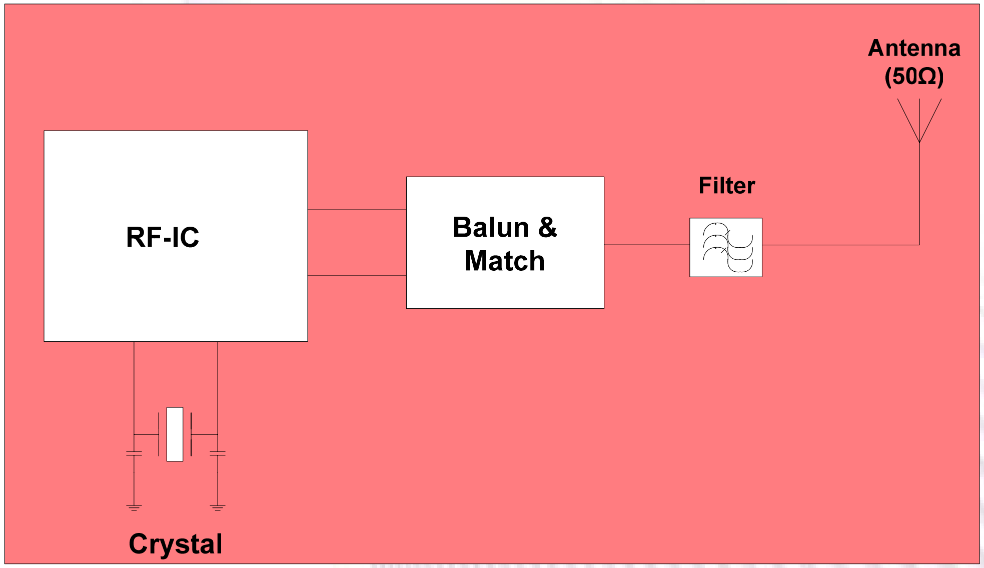
- **Phase Shift Keying (PSK):**
  - Pros:
    - Less susceptible to noise
    - Bandwidth efficient
  - Cons:
    - Require synchronization in frequency and phase ➔ complicates receivers and transmitter
  - Example: IEEE 802.15.4 / ZigBee



Source: Lili Qiu

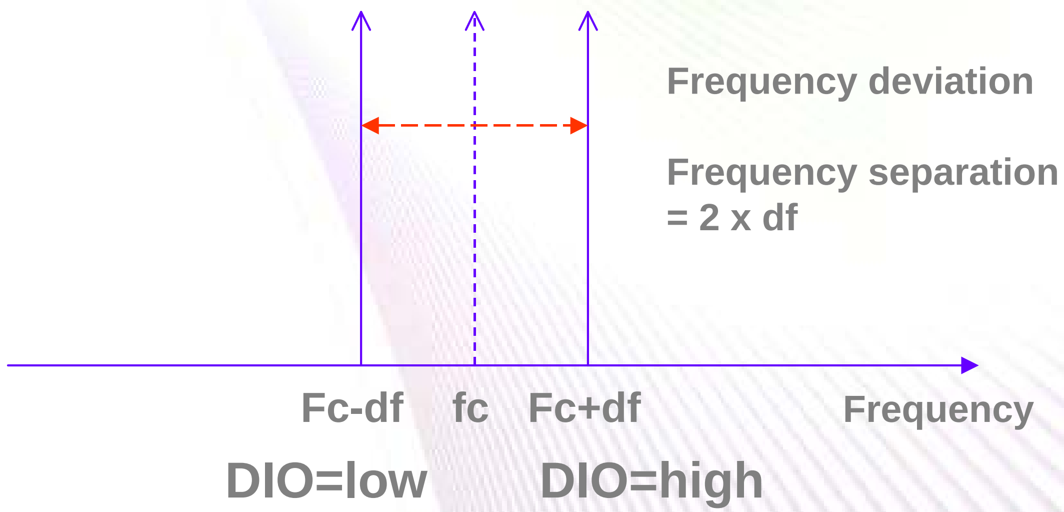
Basic Building Blocks of an RF System

- RF-IC
  - Transmitter
  - Receiver
  - Transceiver
  - System-on-Chip (SoC); typically transceiver with integrated microcontroller
- 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
- Matching
- Filter
  - Used if needed to pass regulatory requirements / improve selectivity
- Antenna



Transmitter

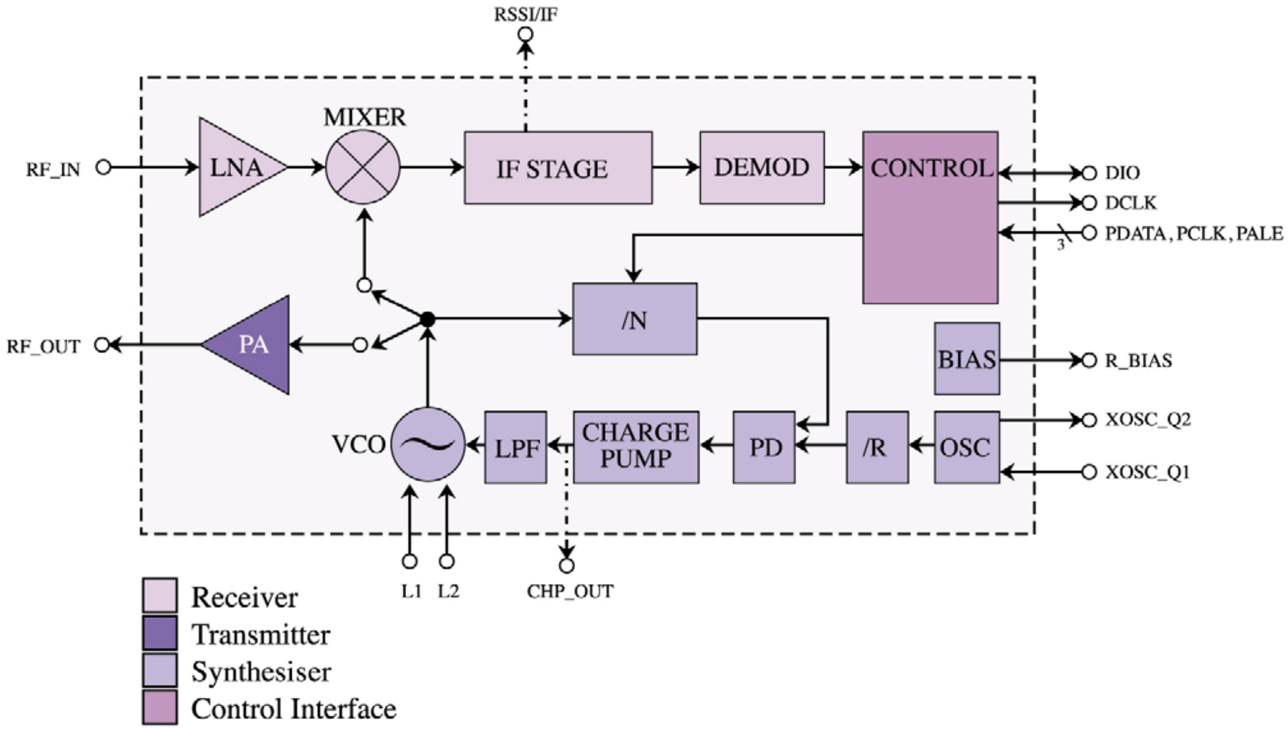
- Modern transmitters typically use fractional-N synthesizers
- For angle modulation like FSK, MSK, O-QPSK, the synthesizer frequency is adjusted
- For amplitude modulation like OOK and ASK, the amplifier level is adjusted



FSK modulation

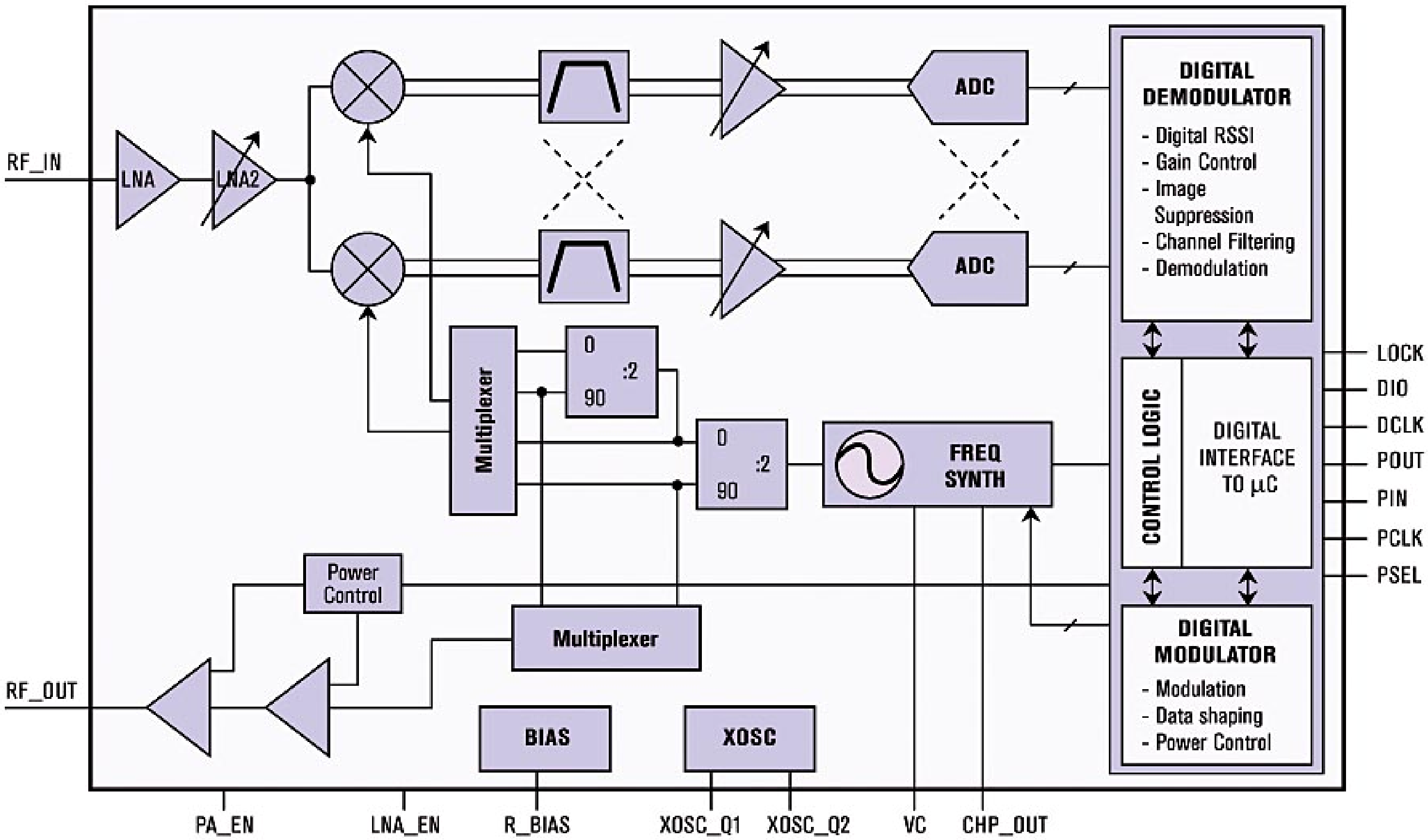
Receiver Architecture

- **Super heterodyne receiver – e.g. CC1000**
  - Converts the incoming signal to an **Intermediate Frequency (IF)** signal and performs:
    1. **Carrier frequency tuning** – selects desired signal
    2. **Filtering** – separates signal from other modulated signals picked up
    3. **Amplification** – compensates for transmission losses in the signal path



Receiver Architecture

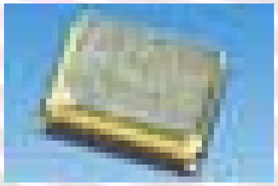
- *Image rejection receiver* ***– e.g. CC1020***
  - *The **image frequency** is an undesired input frequency that is capable of producing the same intermediate frequency (IF) as the desired input frequency produces*



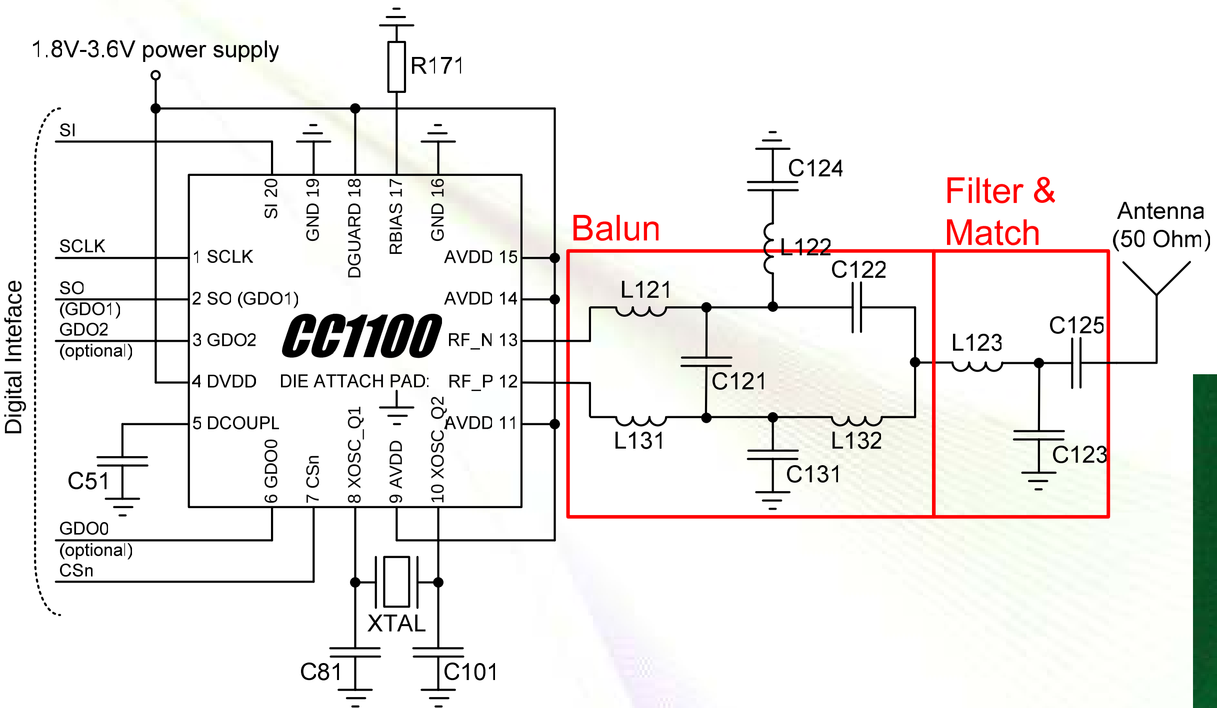
Crystals

- **Provides reference frequency for Local Oscillator (LO) and the carrier frequency**

- **Various types:**
  - Low Power crystals (32.768 kHz)
    - Used with sleep modes on e.g. System-on-Chips
  - Crystals
    - Thru hole
    - Tuning fork
    - SMD
  - Temperature Controlled Crystal Oscillators (TCXO)
    - Temperature stability – some narrowband applications
  - Voltage Controlled Crystal Oscillators (VCXO)
  - Oven Controlled Crystal Oscillators (OCXO)
    - Extremely stable



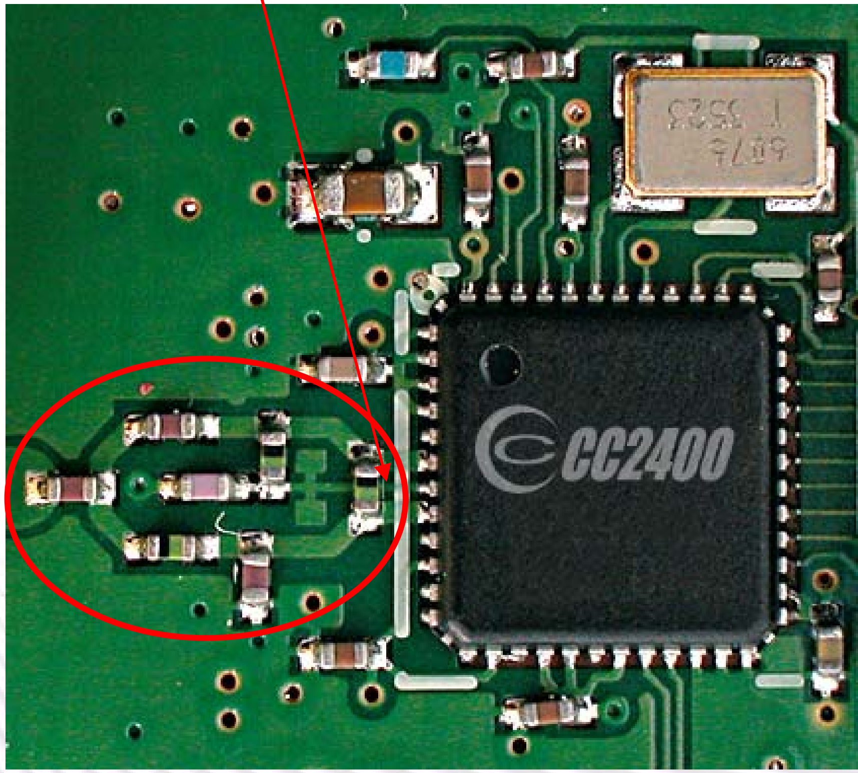
Balun & Matching



Differential signal out of the chip

Single ended signal

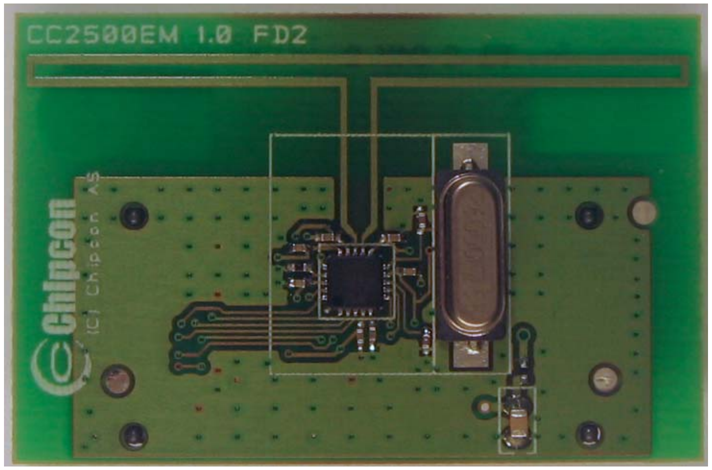
Balun and matching towards antenna



Antennas

Commonly used antennas:

- **PCB antennas**
  - Little extra cost (PCB)
  - Size demanding at low frequencies
  - Good performance possible
  - Complicated to make good designs



- **Whip antennas**
  - Expensive (unless piece of wire)
  - Good performance
  - Hard to fit in may applications

- **Chip antennas**
  - Expensive
  - OK performance

Antennas

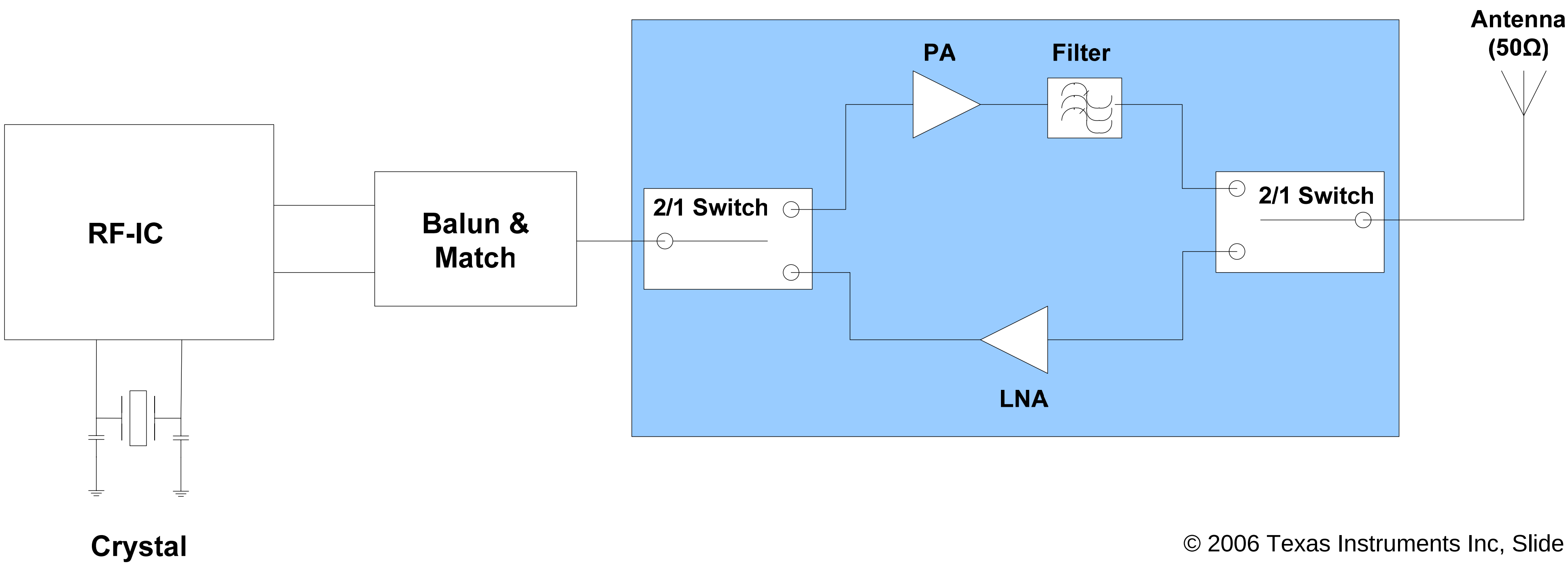
- **The antenna is VERY important if long range is important**

- **A quarter wave antenna is an easy and good solution, but it is not small (433 MHz: 16.4 cm, 868 MHz: 8.2 cm)**
  - You can “curl up” such an antenna and make a helical antenna. This is often a good solution since it utilizes unused volume for a product.

- **If you need long range and have limited space, then talk to an antenna expert !**

Extending the Range of an RF System

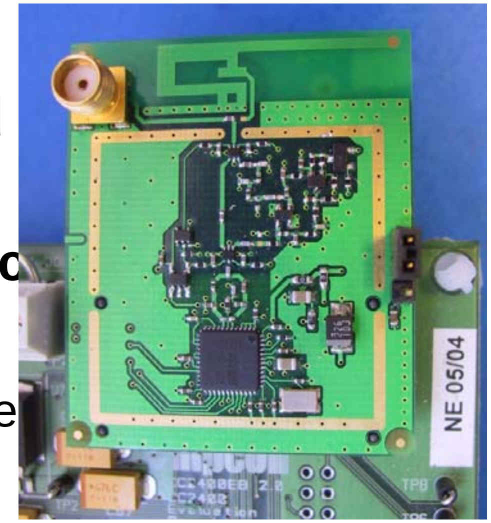
1. **Increase the Output power**
   - Add an external Power Amplifier (PA)
2. **Increase the sensitivity**
   - Add an external Low Noise Amplifier (LNA)
3. **Increase both output power and sensitivity**
   - Add PA and LNA
4. **Use high gain antennas**
   - Regulatory requirements need to be followed

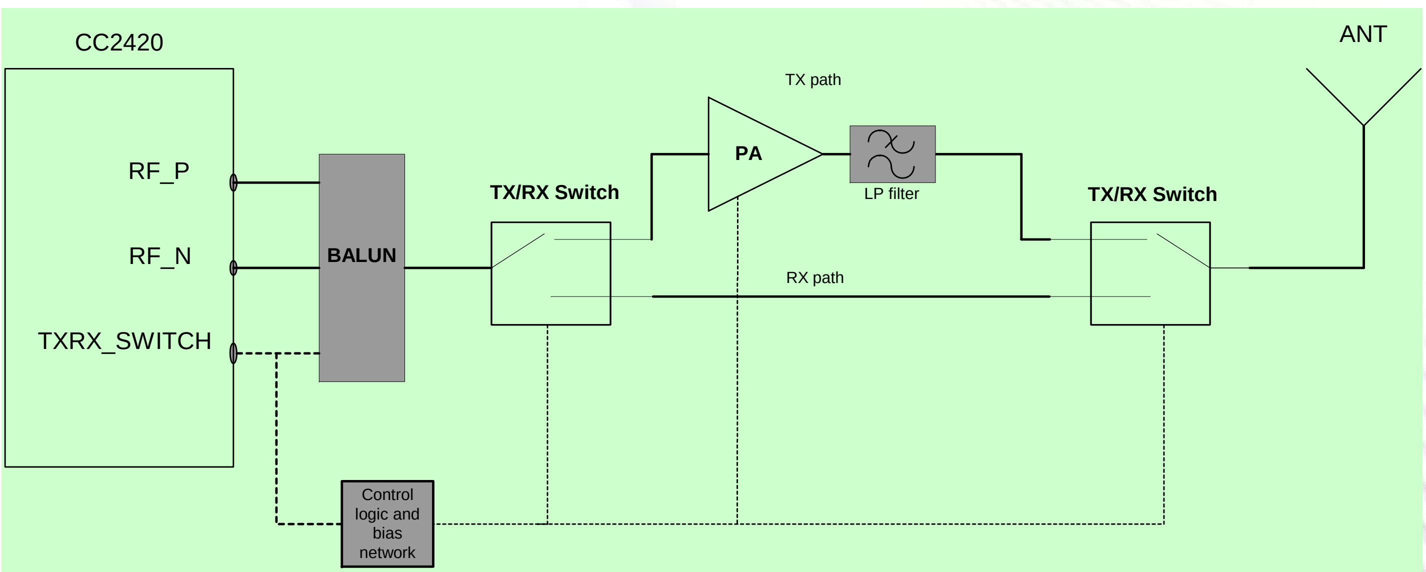


Adding an External PA

CC2420EM PA DESIGN

- **Signal from TXRX_Switch pin level shifted and buffered**
  - Level in TX: 1.8 V, level for RX and all other modes: 0V
- **CMOS and GaAs FET switches assures low RX current c**
- **Simpler control without external LNA**
  - No extra signal is needed from MCU to turn off LNA in low powe





	CC2420EM	CC2420EM w/PA
TX current	17.4 mA	30.8 mA
RX current	19.7 mA	19.7 mA
Output power	0 dBm	9.5 dBm
Sensitivity	-94 dBm	-93.1 dBm
Line of Sight Range	230 meter	580 meter

Radio Range – Free Space Propagation

- **How much loss can we have between TX and RX?**

- **Friis' transmission equation for free space propagation:**

$$P_r = P_t + G_t + G_r + 20\log\left(\frac{\lambda}{4\pi}\right) - 20\log d \quad \text{or} \quad P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2}$$

  - P_t is the transmitted power, P_r is the received power
  - G_t is the transmitter, G_r is the receiver antenna gain
  - Lambda is the wavelength
  - D is the distance between transmitter and receiver, or the range

Radio Range – ”real life”

- **How much loss can we really have TX to RX?**

- **120 dB link budget at 433 MHz gives approximately 2000 meters (Chipcon rule of thumb)**

- **Based on the emperical results above and Friis' equation estimates on real range can be made:**

- **Rule of Thumb:**
  - 6 dB improvement ~ twice the distance
  - Double the frequency ~ half the range
    - 433 MHz longer range than 868 MHz

Radio Range – Important Factors

- **Factors**
  - Antenna (gain, sensitivity to body effects etc.)
  - Sensitivity
  - Output power
  - Radio pollution (selectivity, blocking, IP3)
  - Environment (Line of sight, obstructions, reflections, multipath fading)

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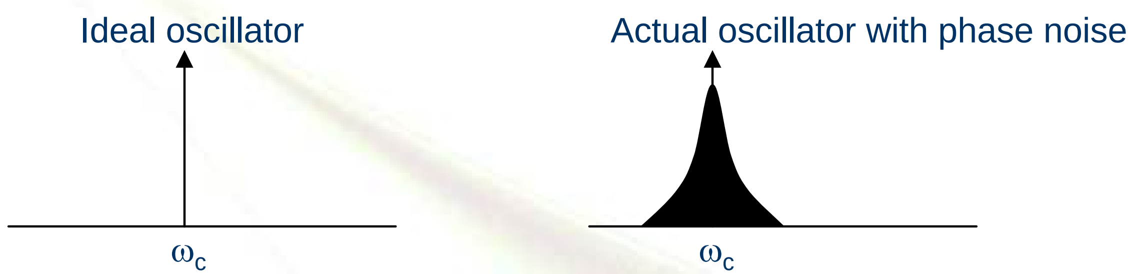
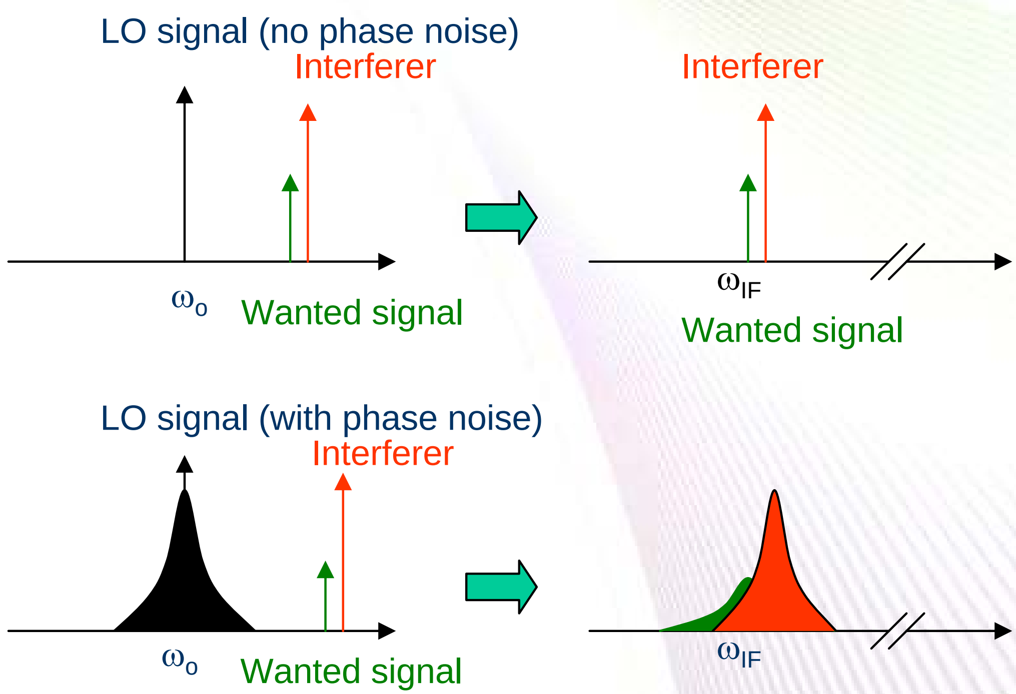
Phase Noise



Down Conversion (receivers):

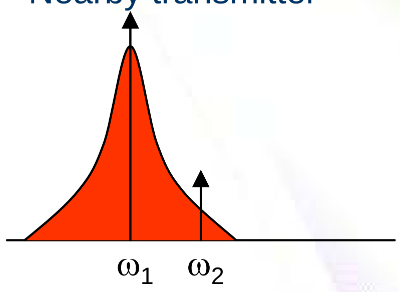


Down-converted bands consist of two overlapping spectra, with the wanted signal suffering from significant noise due to the tail of the interferer

Interferer end up within the IF bandwidth and **cannot** be filtered out

Phase Noise

Transmitters:



Difficult to detect weak signal at ω_2.

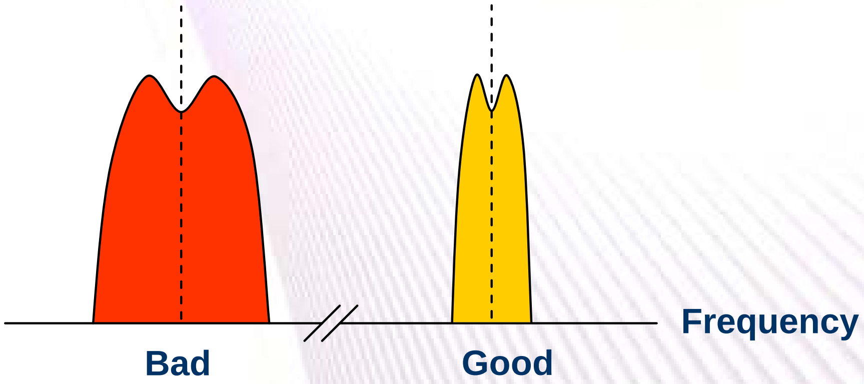
The wanted signal is corrupted by the phase noise tail of the transmitter

- **Phase noise is a key parameter for transceivers**
- **CC1020: -90 dBc/Hz @ 12.5 kHz (narrowband)**

Narrowband Transmitter

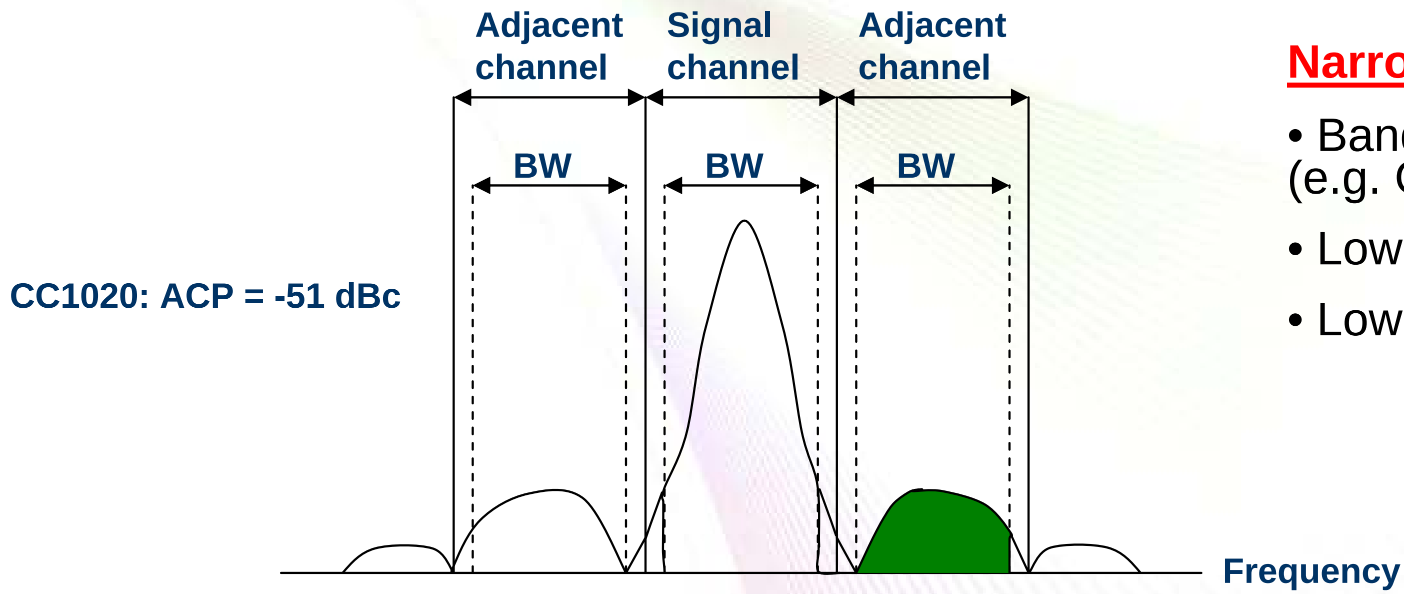
- **How good is the transmitter at making efficient use of the RF spectrum?**

- **OBW = Occupied Band Width**
  - Defined as BW with 99.5% of the total average power (ARIB)
  - For 12.5 kHz channel spacing OBW < 8.5 kHz (ARIB)
  - Measured using built-in function of spectrum analyzer



Narrowband Transmitter

- **ACP = Adjacent Channel Power**
  - 25 kHz channel spacing, 17 kHz BW
  - 12.5 kHz channel spacing, 8.5 kHz BW
  - Measured using built-in function of spectrum analyzer



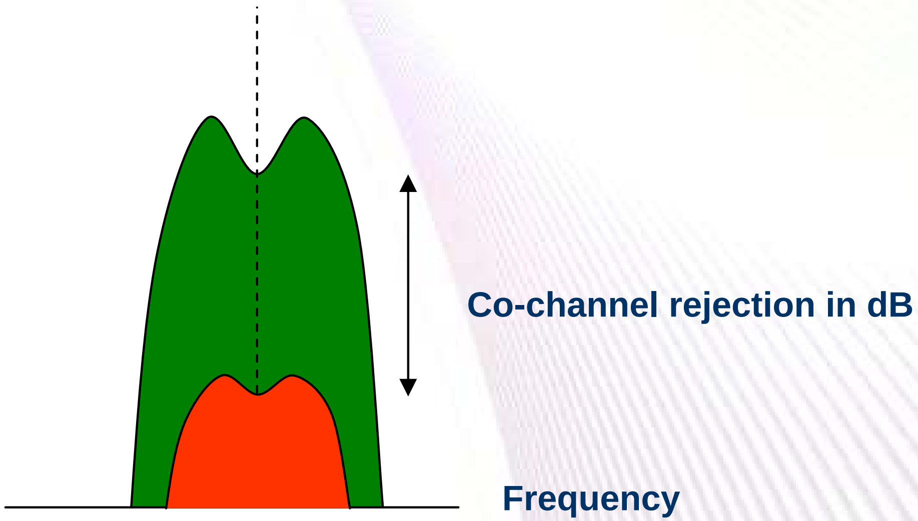
Narrowband characteristics:

- Bandwidth efficient modulation (e.g. GFSK)
- Low data rate
- Low deviation

- **Low phase noise ➡ key parameter for low ACP**
- **ETSI: Absolute ACP requirement (dBm), ARIB: Relative (dBc)**

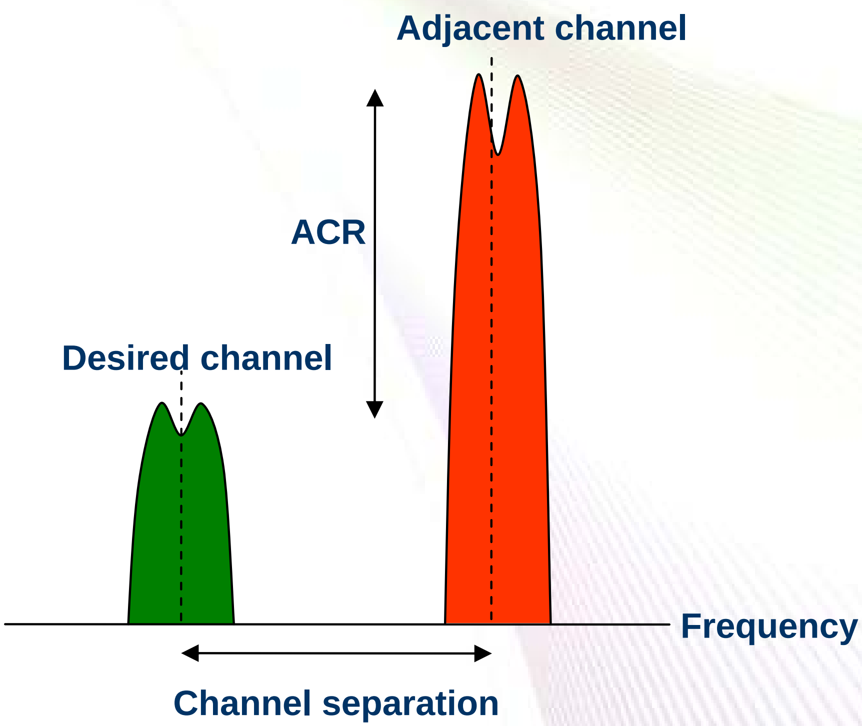
Receiver, Co-channel Rejection

- **How good is the receiver at handling interferers at same frequency?**
- **Co-channel rejection, CC1020/CC1021 : -11dB**
- **Test method: Modulated interferer**
  - Wanted signal 3 dB above sensitivity limit



Receiver Selectivity

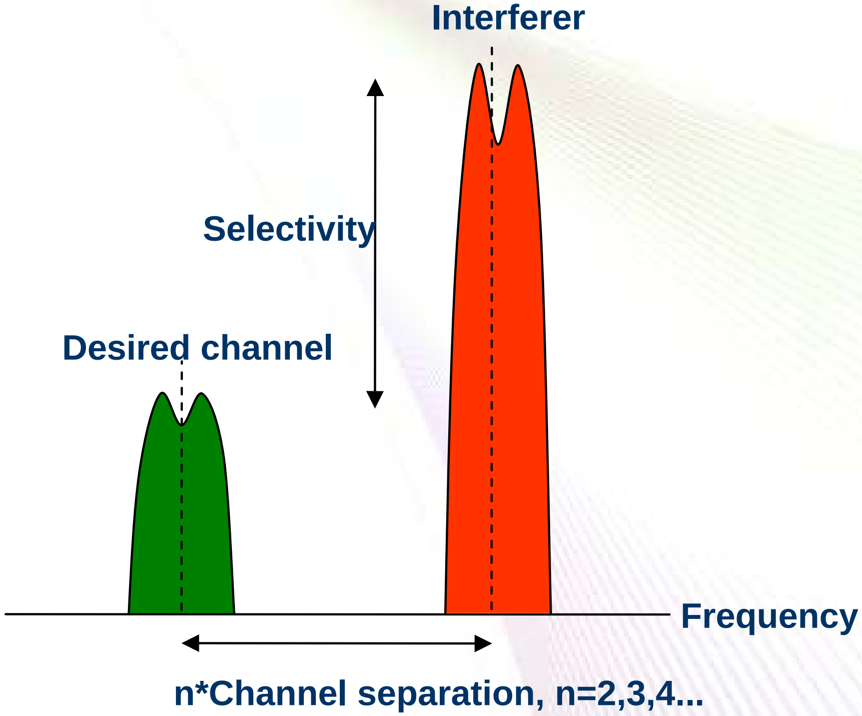
- **ACR = Adjacent Channel Rejection or**
- **ACS = Adjacent Channel Selectivity**



- **CC1020: 32dB @ 12.5 kHz**
- **Test method**
  - Wanted 3dB above sensitivity level
  - Interferer injected in the adjacent channel

Receiver Selectivity

- Selectivity, measured for channels “further out” (alternate channel selectivity)
- Same test method as ACR/ACS



- Low phase noise and narrow IF bandwith
➡ good ACR/ACS

Receiver Selectivity

Selectivity Requirement for different RF standards			
Standard, Ch. Spacing	**Adjacent Channel Rejection**	**Selectivity, other channels**	
ARIB, 12.5 kHz	30 dB (± 12.5kHz)	40 dB for all other channel	
ARIB, 25 kHz	40 dB (± 25kHz)	40 dB for all other channel	
ETSI class 1, 25 kHz	60 dB (± 25 kHz)	84 dB (± 1 MHz)	
Bluetooth, 1 MHz	0 dB (± 1 MHz)	30 dB (± 2 MHz)	40 dB (± 3 MHz)
CC2400, 1 MHz (250kbit/	**12 dB (± 1 MHz)**	**48 dB (± 2 MHz)**	**50 dB (± 3 MHz)**
CC2400, 1 MHz (1Mbit/s)	**0 dB (± 1 MHz)**	**20 dB (± 2 MHz)**	**41dB (± 3 MHz)**
Zigbee (802.15.4), 5 MHz	0 dB (± 5 MHz)	30 dB for all other channels	
CC2420, 5MHz	**39/46 (+ - 5 MHz)**	**53/57 (+ - 10 MHz)**	

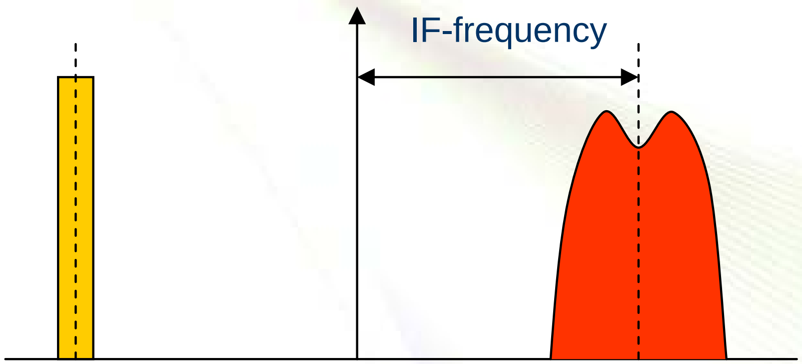
- **CC1020 is ARIB compliant (12.5 and 25 kHz channels)**

Receiver, Blocking/desensitization

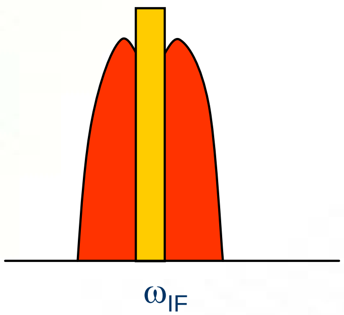
- Blocking/desensitization is a measure of how good a receiver is to reject an interferer "far away" (out of band) from the wanted signal
- Measured the same way as selectivity, but the interfering signal is usually not modulated
- CC1020 performance:
  - 1 MHz 60 dB
  - 2 MHz 70 dB
  - 10 MHZ 78 dB
- Blocking can be further improved with a SAW filter

Image Rejection

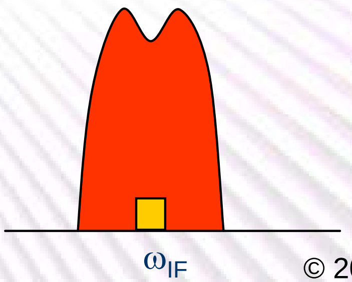
- **Image Rejection**



- ***CC1000***
  - No image rejection



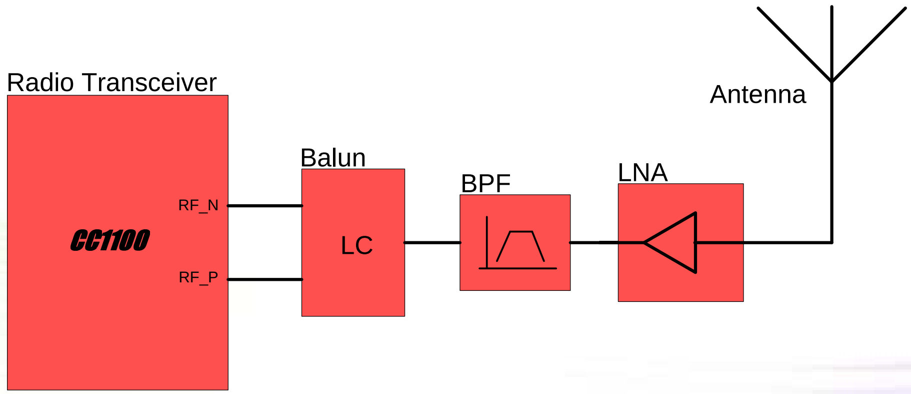
- ***CC1020***
  - Image rejection



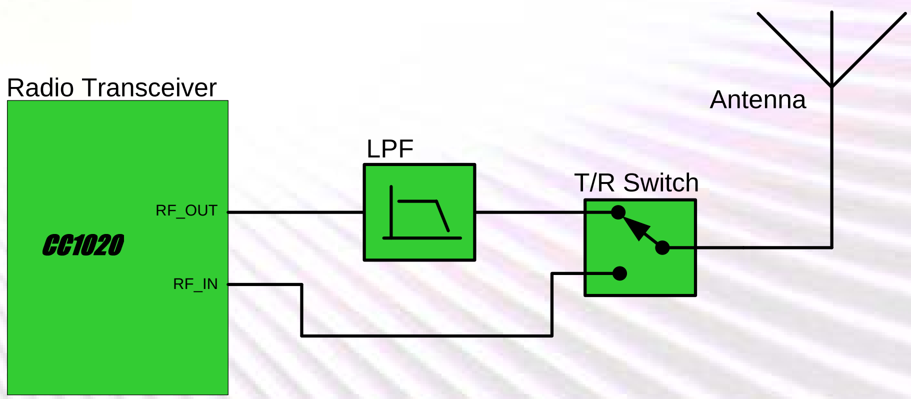
Receiver Sensitivity

- **How to achieve good RF sensitivity?**

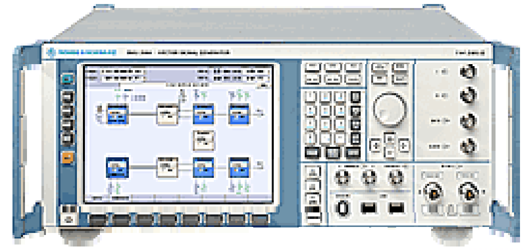
- **Introduce high gain in front of the receiver**
  - External LNA needed
  - Poor linearity (IP3)
  - Poor blocking/selectivity
  - "Removes" the losses in the SAW filter



- **Lower noise bandwidth (narrowband)**
  - Blocking/linearity not changed
  - Good selectivity
  - Good frequency control needed



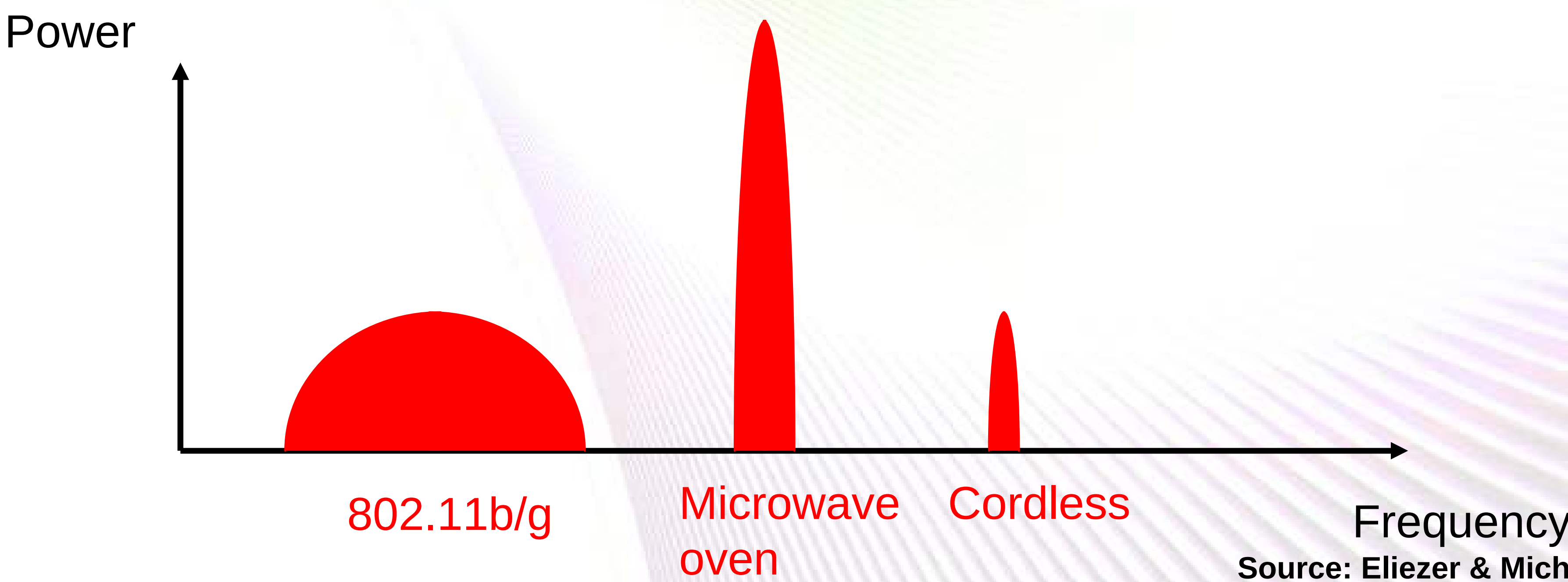
RF Measurement Equipment



- **Vector Network Analyzers**
  - Component Characterisation – insertion loss
  - S-parameters - matching
- **Spectrum Analyzers**
  - Output Power, harmonics, spurious emission
  - Phase Noise
  - ACP
  - OBW
  - Modulation - deviation
- **Signal Generators**
  - Sensitivity (BER option needed)
  - Selectivity/blocking
  - Two-tone measurements – IP3
- **Power Meters**
  - Output Power – calibration
- **Oscilloscopes**
  - Digital signal analysis
- **Function and Arbitrary Waveform Generators**

2.4 GHz ISM-band devices

- **Due to the world-wide availability of the 2.4GHz ISM band it is getting more crowded day by day**
- **Devices such as Wi-Fi, Bluetooth, ZigBee, cordless phones, microwave ovens, wireless game pads, toys, PC peripherals, wireless audio devices and many more occupy the 2.4 GHz frequency band**

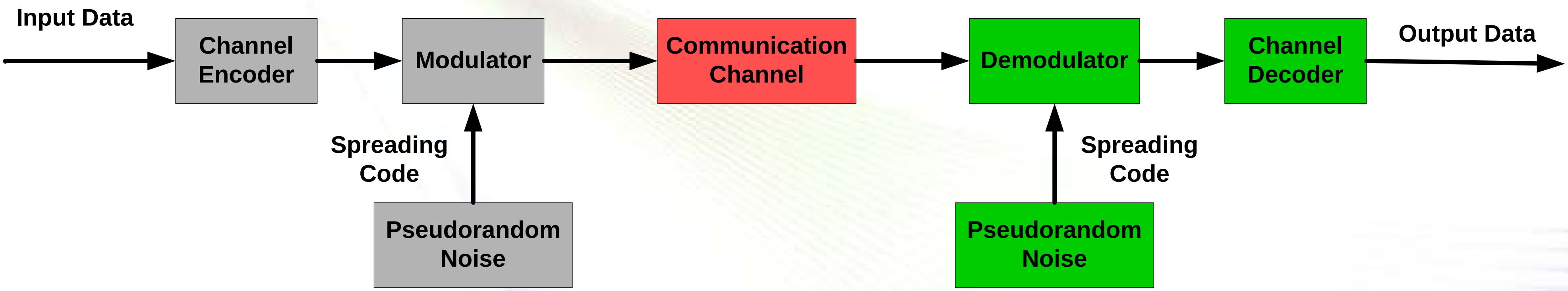


Source: Eliezer & Michael, TI

Spread Spectrum Systems

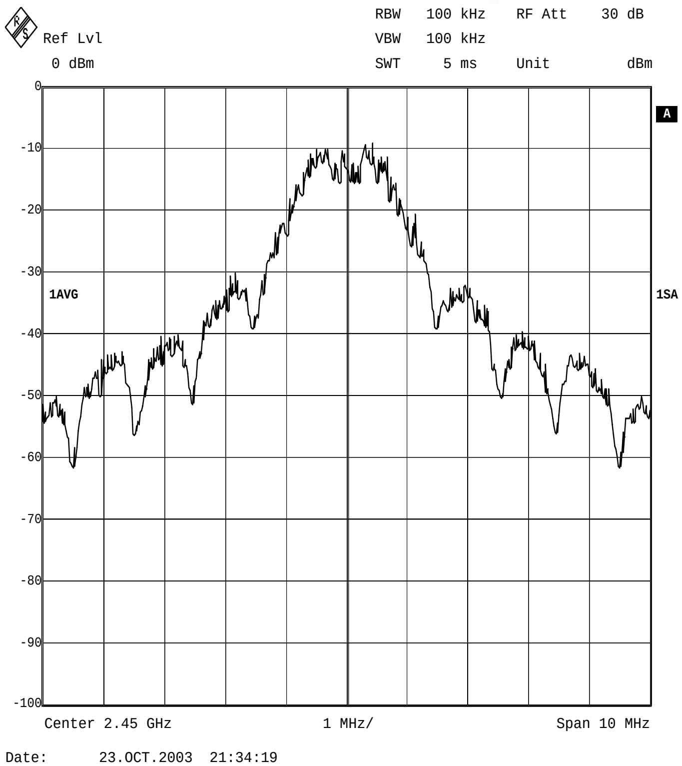
- **Data sent using spread spectrum is intentionally spread over a wide frequency range**
- **Appears as noise, so it is difficult to detect and jam**
- **Resistant to noise and interference thus increasing the probability that the signal will be received correctly**
- **Unlikely to interfere with other signals even if they are transmitted on the same frequency**
- **2 types of Spread Spectrum common in ISM bands:**
  - **Direct Sequence Spread Spectrum (DSSS)**
  - **Frequency Hopping Spread Spectrum (FHSS)**

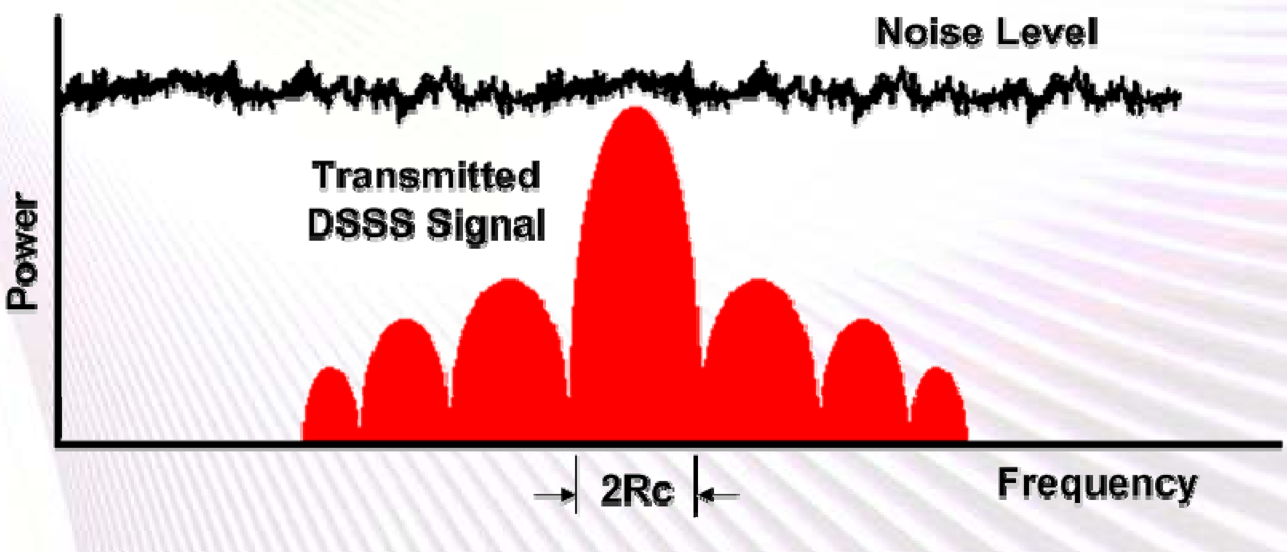
General Model of a Spread Spectrum System



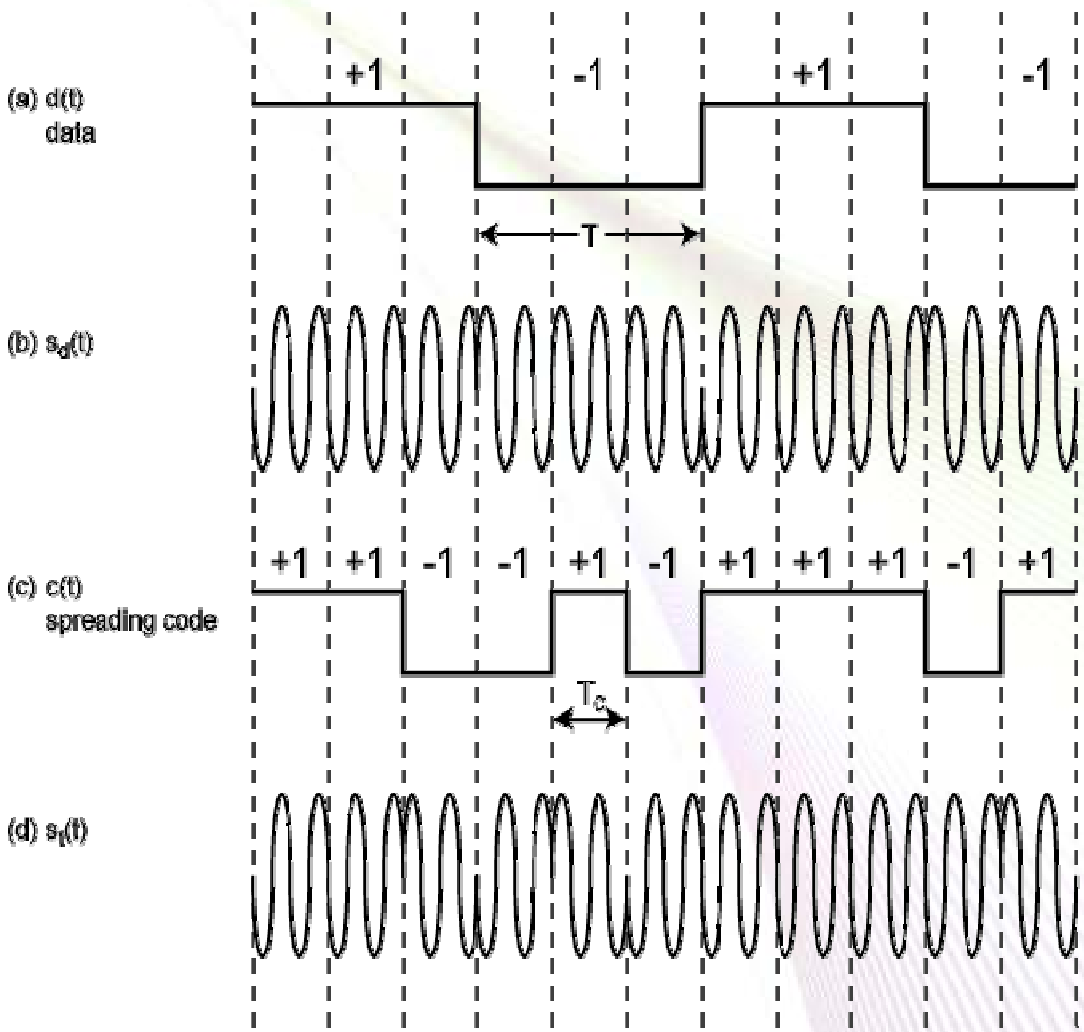
Direct Sequence Spread Spectrum

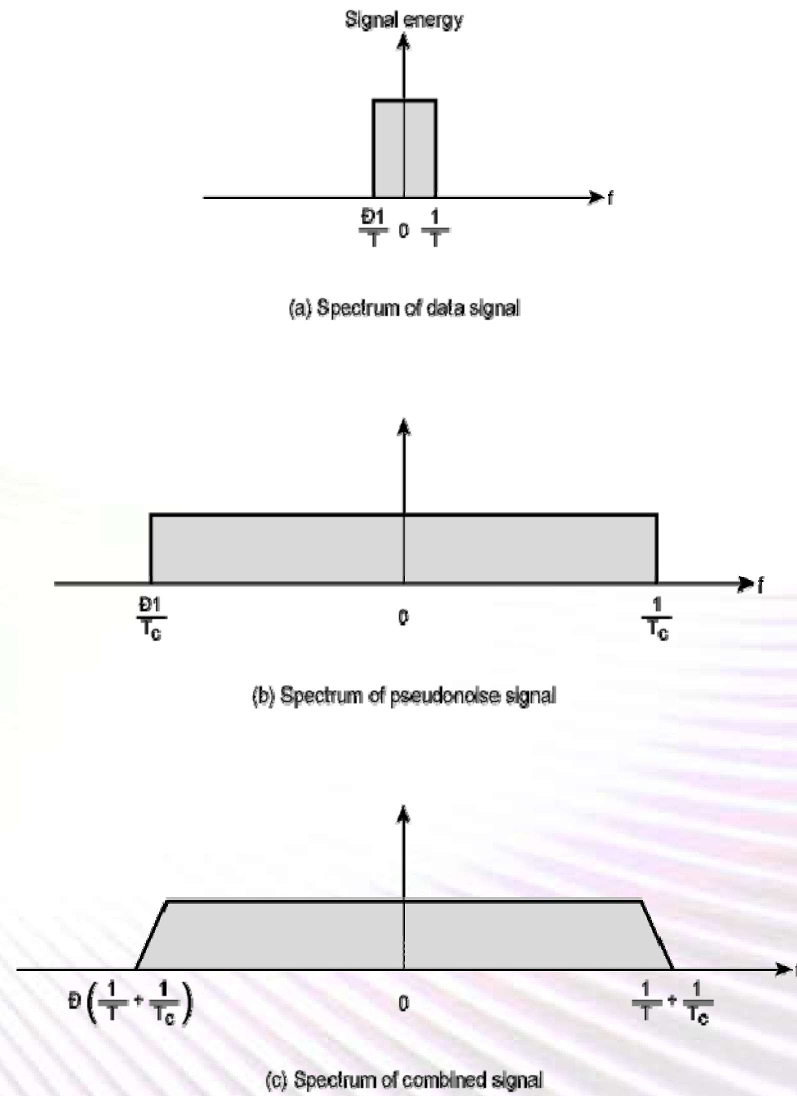
- Each bit represented by multiple bits using spreading code
- Spreading code spreads signal across wider frequency band
- Good resistance against interferers





DSSS – BPSK Example





Source: William Stalling

DSSS Spreading Mechanism

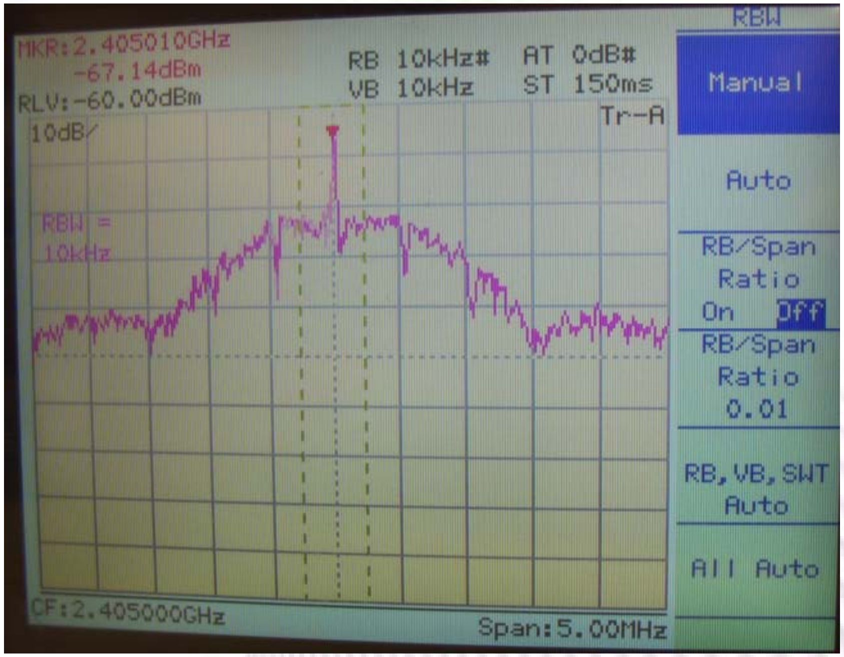
IEEE 802.15.4 (CC2420): 2 Mchips/s -> 250 kbps data rate

- **4 bits (nibble) are coded into 32 chips using a look-up table**
  - RX correlation example:

	Correct chip sequence for nibble = 5:																																
	0	*0*	*1*	*1*	*0*	*1*	*0*	*1*	*0*	*0*	*1*	*0*	*0*	*0*	*1*	*0*	*1*	*1*	*1*	*0*	*1*	*1*	*0*	*1*	*1*	*0*	*0*	*1*	*1*	*1*	*0*	*0*	
	Incoming chip sequence (value is 5, but with 8 faulty chips):																																
	0	**1**	**1**	**1**	**0**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**1**	**1**	**1**	**0**	**0**	
Nibble value	Comparison (XOR) with all possible chip sequences																																*Correlation value*
0	1	1	0	1	1	0	0	1	1	1	0	0	0	0	1	1	0	1	0	1	0	0	1	0	0	0	1	0	1	1	1	0	*18*
1	1	1	1	0	1	1	0	1	1	0	0	1	1	1	0	0	0	0	1	1	0	1	0	1	0	0	1	0	0	0	1	0	*16*
2	0	0	1	0	1	1	1	0	1	1	0	1	1	0	0	1	1	1	0	0	0	0	1	1	0	1	0	1	0	0	1	0	*14*
3	0	0	1	0	0	0	1	0	1	1	1	0	1	1	0	1	1	0	0	1	1	1	0	0	0	0	1	1	0	1	0	1	*12*
4	0	1	0	1	0	0	1	0	0	0	1	0	1	1	1	0	1	1	0	1	1	0	0	1	1	1	0	0	0	0	1	1	*14*
5	0	0	1	1	0	1	0	1	0	0	1	0	0	0	1	0	1	1	1	0	1	1	0	1	1	0	0	1	1	1	0	0	*24*
6	1	1	0	0	0	0	1	1	0	1	0	1	0	0	1	0	0	0	1	0	1	1	1	0	1	1	0	1	1	0	0	1	*16*
7	1	0	0	1	1	1	0	0	0	0	1	1	0	1	0	1	0	0	1	0	0	0	1	0	1	1	1	0	1	1	0	1	*14*
8	1	0	0	0	1	1	0	0	1	0	0	1	0	1	1	0	0	0	0	0	0	1	1	1	0	1	1	1	1	0	1	1	*14*
9	1	0	1	1	1	0	0	0	1	1	0	0	1	0	0	1	0	1	1	0	0	0	0	0	0	1	1	1	0	1	1	1	*16*
10	0	1	1	1	1	0	1	1	1	0	0	0	1	1	0	0	1	0	0	1	0	1	1	0	0	0	0	0	0	1	1	1	*14*
11	0	1	1	1	0	1	1	1	1	0	1	1	1	0	0	0	1	1	0	0	1	0	0	1	0	1	1	0	0	0	0	0	*20*
12	0	0	0	0	0	1	1	1	0	1	1	1	1	0	1	1	1	0	0	0	1	1	0	0	1	0	0	1	0	1	1	0	*14*
13	0	1	1	0	0	0	0	0	0	1	1	1	0	1	1	1	1	0	1	1	1	0	0	0	1	1	0	0	1	0	0	1	*12*
14	1	0	0	1	0	1	1	0	0	0	0	0	0	1	1	1	0	1	1	1	1	0	1	1	1	0	0	0	1	1	0	0	*20*
15	1	1	0	0	1	0	0	1	0	1	1	0	0	0	0	0	0	1	1	1	0	1	1	1	1	0	1	1	1	0	0	0	*18*

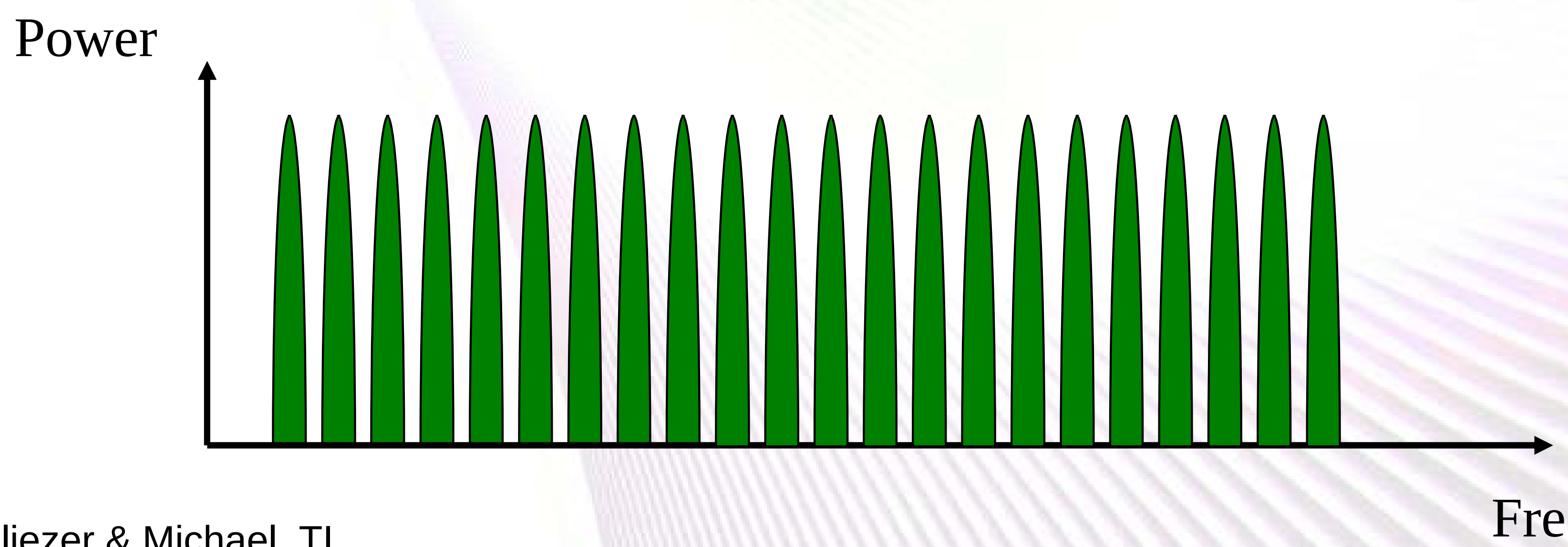
DSSS – Co-existence Performance

- CC2420 - In-band interference
- Power of interferer only 1 dB lower than CC2420 transmitter, NO packet errors
- Narrowband interferer shown as peak in the centre on top of the CC2420 spread spectrum
- A typical FSK receiver requires the desired signal to be 11 dB above interferer



Frequency Hopping Spread Spectrum (FHSS)

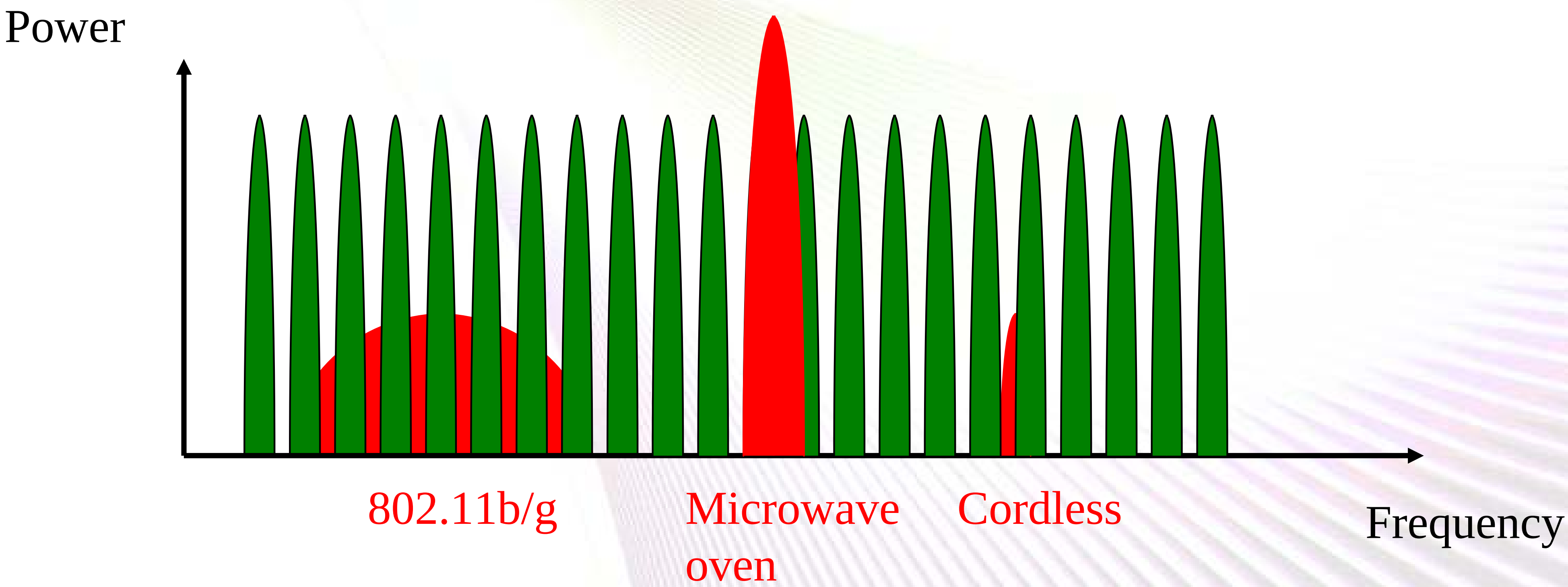
- Signal broadcast over a seemingly random series of frequencies
- Receiver hops between frequencies in sync with transmitter
- Jamming on one frequency affects only a few bits



Source: Eliezer & Michael, TI

2.4 GHz Devices – Static Frequency Hopping

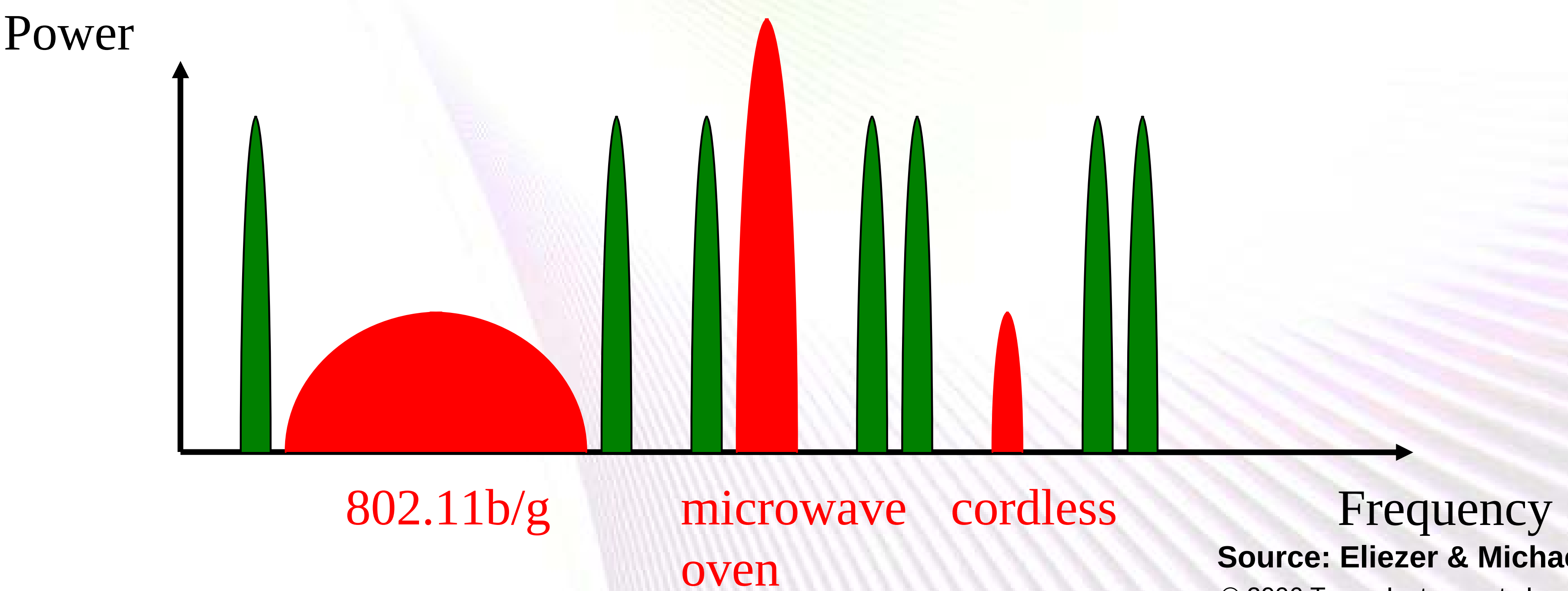
- **Utilise a predetermined set of frequencies with either a repeating hop pattern or a pseudorandom hop pattern, e.g. Bluetooth (versions 1.0 and 1.1)**



Source: Eliezer & Michael, TI

2.4 GHz – Adaptive Frequency Hopping

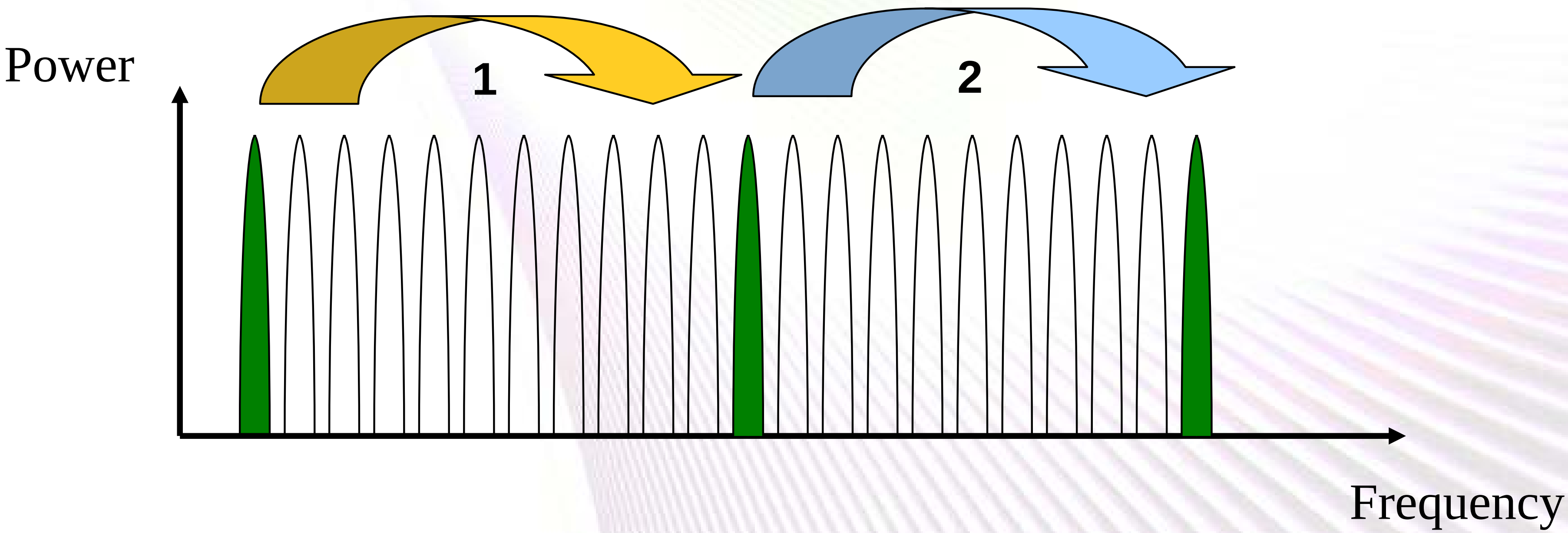
- **Scan the entire frequency band at start-up and restrict usage to frequencies with the lowest energy content. RadioDesk and Bluetooth 1.2 and 2.0 are using AFH.**
- **Substitute frequencies experiencing interference on the fly.**



Source: Eliezer & Michael, TI

Frequency Agility

- **Frequency agility can be considered an extremely slow hopping frequency hopping system**
- **In a frequency agile system the frequency is first changed when the link performance is degraded, i.e. when the Packet Error Rate (PER) exceeds a predetermined threshold**



Agenda

- Basics
- Basic Building Blocks of an RF System
- RF Parameters and RF Measurement Equipment
- Support / getting started

Getting Started

- **Define and specify the product**
  - Following a standard or going proprietary?
  - Power consumption
  - Range and regulatory requirements – frequency of operation
  - Data rate
  - RF protocol
  - SW content
  - Analyse test tool and instrumentation needs
  - Cost
- **Compare different vendors – choose RF-IC & tools**
  - Purchase and evaluate EVMs and required tools
  - What SW examples, application notes and documentation are available?
- **Develop, co-operate or outsource?**
  - Sufficient resources available?
  - Do you have the necessary competence in-house?
  - Compliance testing?

Support

- **Search for the relevant information**
  - Documentation – e.g. data sheets, user guides and application notes
  - Knowledge bases
  - SW examples
- **Contact your local distributor or TI directly:**
  - Internet:
  - TI Low Power Wireless home page:
    - http://www.ti.com/lpw
  - TI MSP430 home page:
    - http://www.ti.com/msp430
  - TI Semiconductor Product Information Center Home Page:
    - http://support.ti.com
  - TI Semiconductor KnowledgeBase Home Page:
    - http://support.ti.com/sc/knowledgebase

Summary

- **RF Basics**
  - Available frequency bands
  - RF communication systems
  - Modulation and demodulation
  - Basic building blocks of an RF system – components
  - Extending range
  - Key RF parameters
  - RF measurement equipment
  - Spread spectrum systems – DSSS / FHSS / Frequency Agility
  - Getting started
  - Support

Thank you for your attention!

Questions?