RF Basics, RF for Non-RF Engineers

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TEXAS INSTRUMENTS

Agenda

- Basics

- Basic Building Blocks of an RF System

- RF Parameters and RF Measurement Equipment

- Support / getting started

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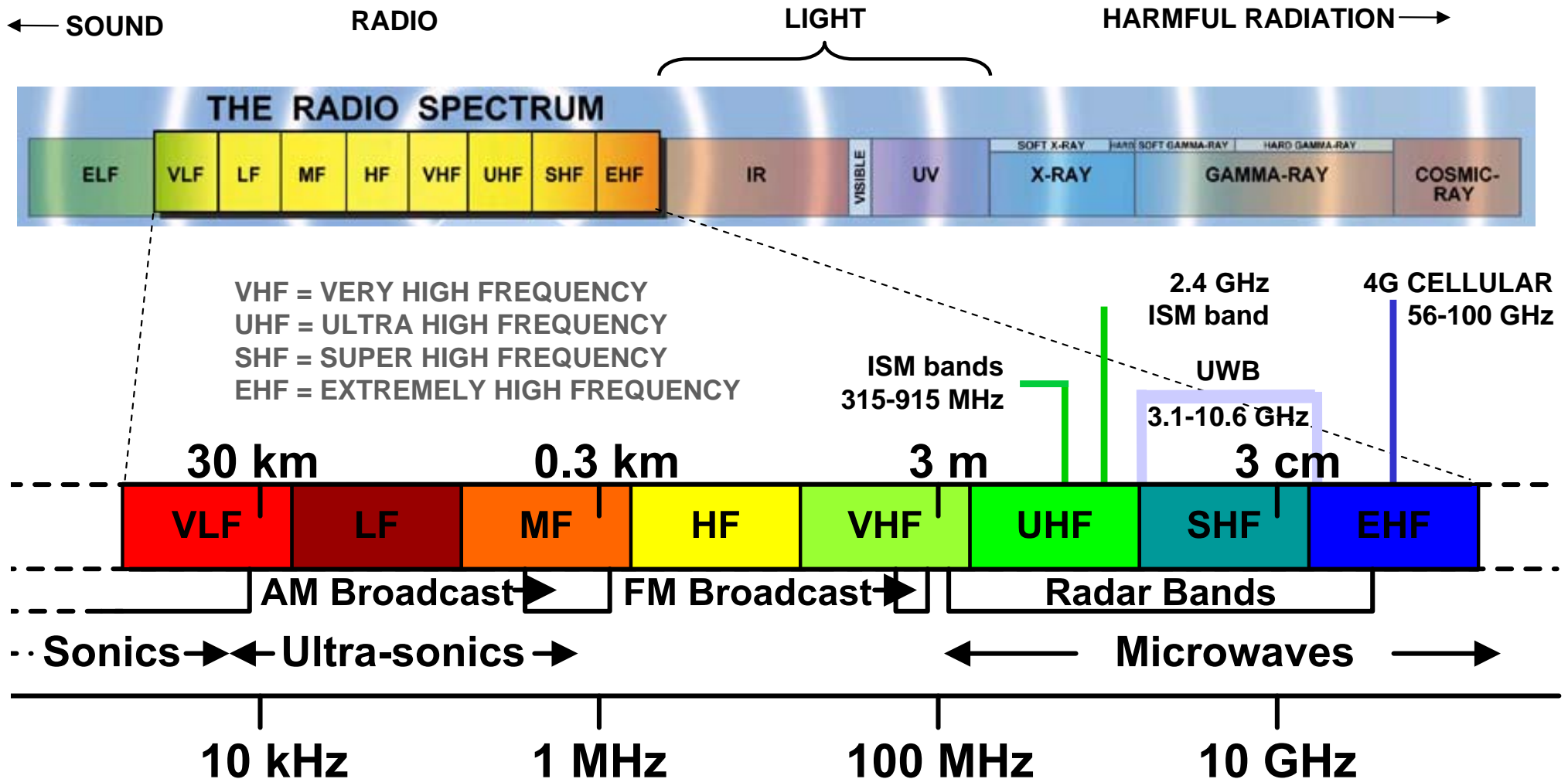 - Double the power = 3 dB increase
  - Half the power = 3 dB decrease

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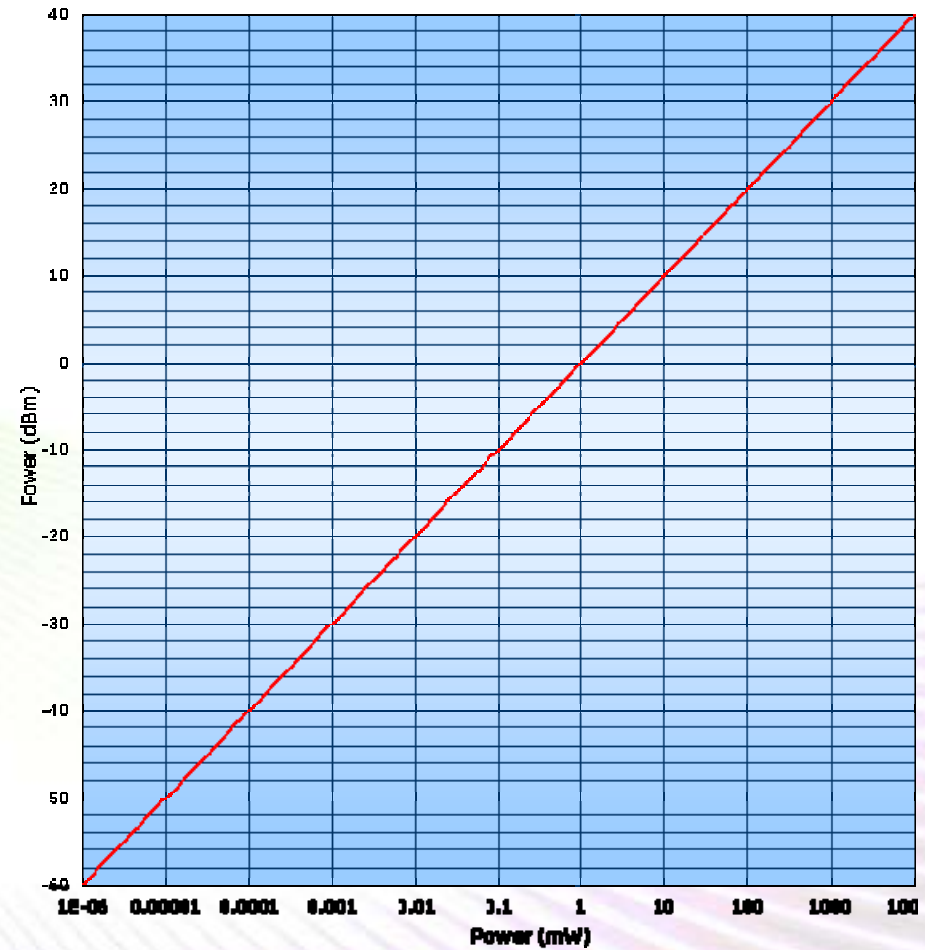
dBm to Watt

- ## About dBm and W

  - Voltage Ratio $aV = 20 \log (P2/P1)$ $[aV] = dB$

  - Power Ratio $aP = 10 \log (P2/P1)$ $[aP] = dB$

  - Voltage Level $V' = 20 \log (V/1\mu V)$ $[V'] = dB\mu V$

  - 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

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Electromagnetic Spectrum

← SOUND   RADIO   LIGHT   HARMFUL RADIATION →

THE RADIO SPECTRUM

| ELF | VLF | LF | MF | HF | VHF | UHF | SHF | EHF | IR | VISIBLE | UV | X-RAY (SOFT X-RAY / HARD) | GAMMA-RAY (SOFT GAMMA-RAY / HARD GAMMA-RAY) | COSMIC-RAY |

VHF = VERY HIGH FREQUENCY
UHF = ULTRA HIGH FREQUENCY
SHF = SUPER HIGH FREQUENCY
EHF = EXTREMELY HIGH FREQUENCY

2.4 GHz
ISM band

4G CELLULAR
56-100 GHz

ISM bands
315-915 MHz

UWB
3.1-10.6 GHz

| 30 km | 0.3 km | 3 m | | 3 cm | |
| VLF | LF | MF | HF | VHF | UHF | SHF | EHF |

AM Broadcast →   FM Broadcast →   Radar Bands

···Sonics→ ←Ultra-sonics→   ←Microwaves→

| 10 kHz | 1 MHz | 100 MHz | 10 GHz |

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

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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

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ISM/SRD License-Free Frequency Bands

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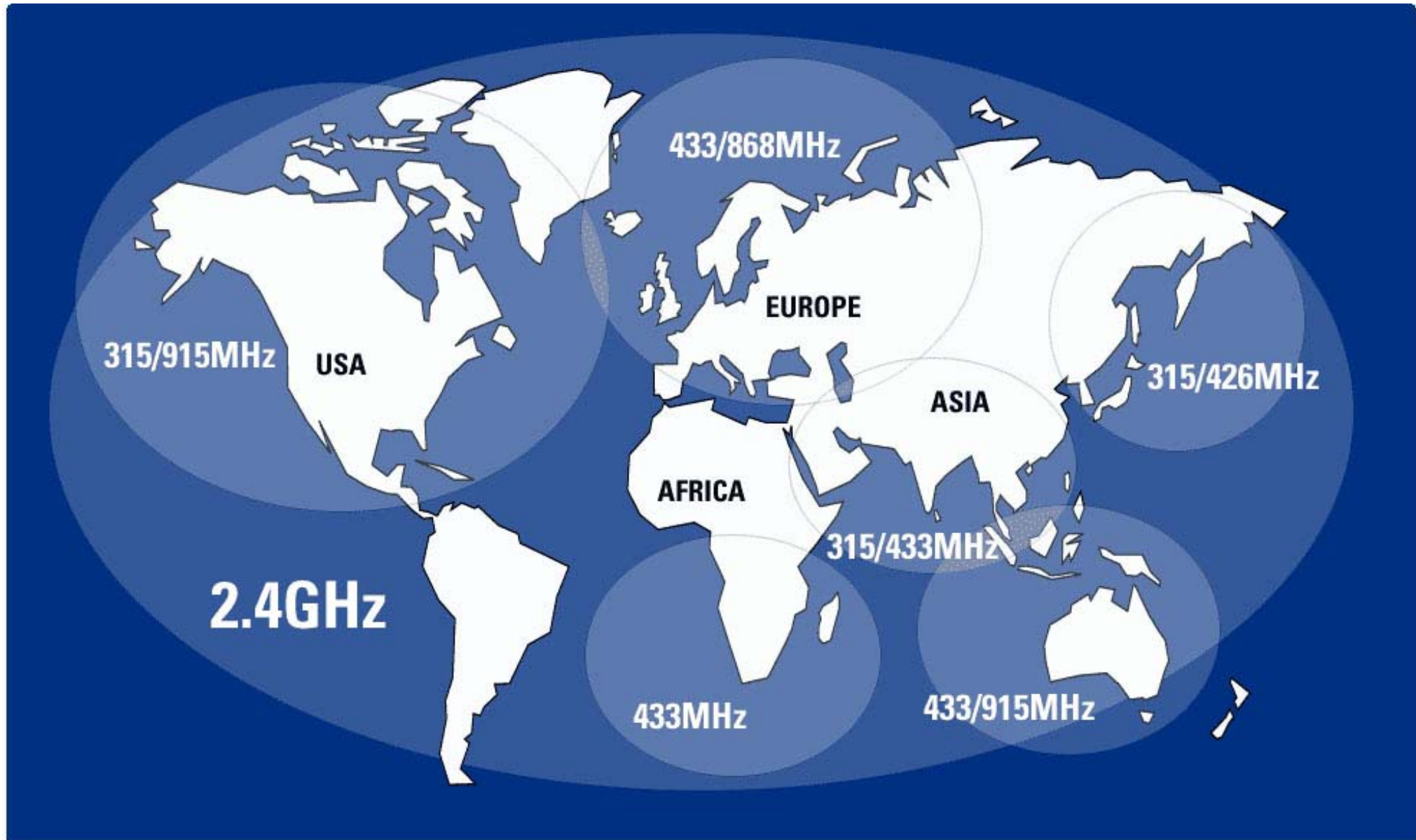
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RF Communication Systems

- **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

TX

TX

TX

TX

TX

TX

TRX

RX

RX
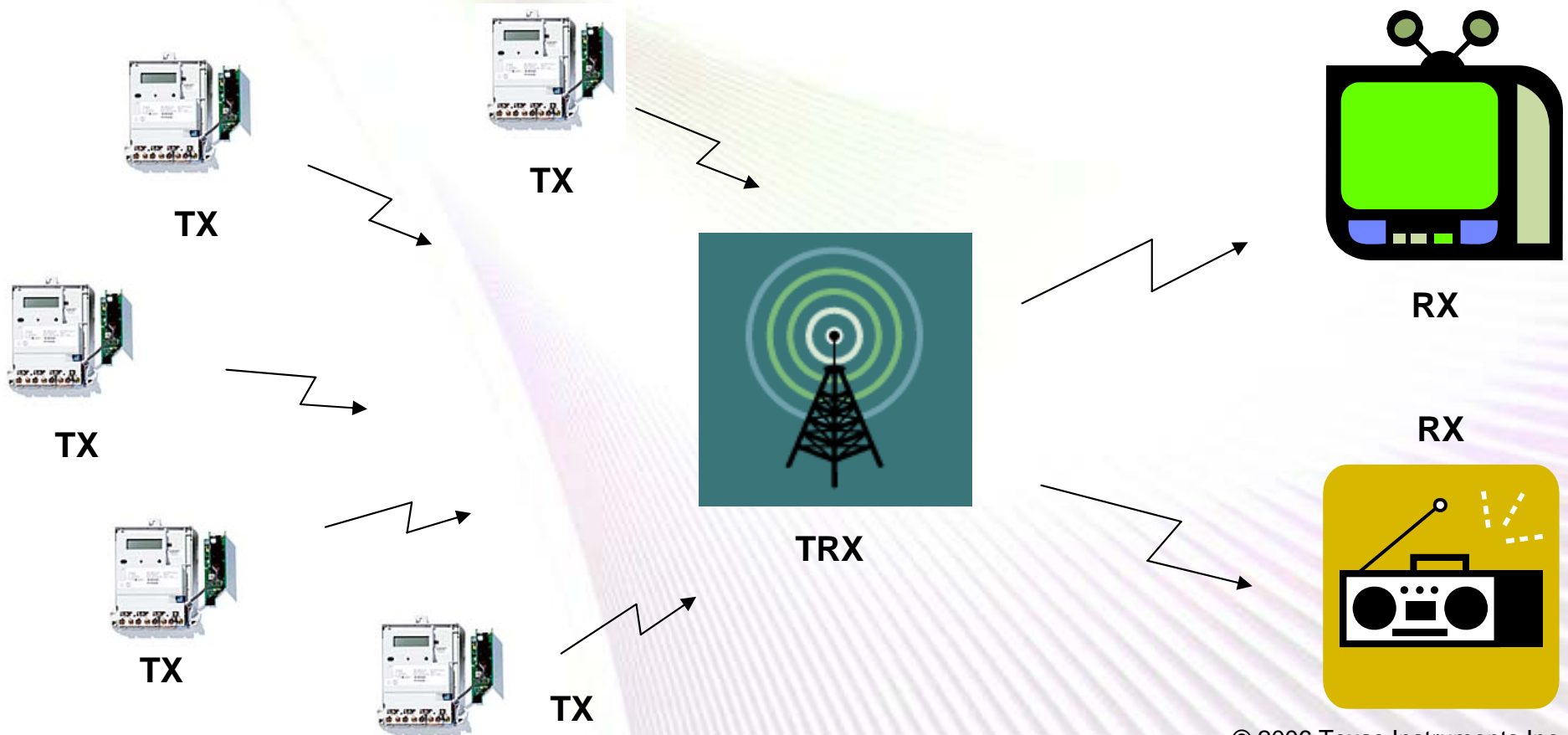
RF Communication Systems

- **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

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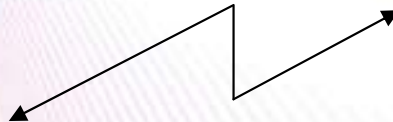
RF Communication Systems

- **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
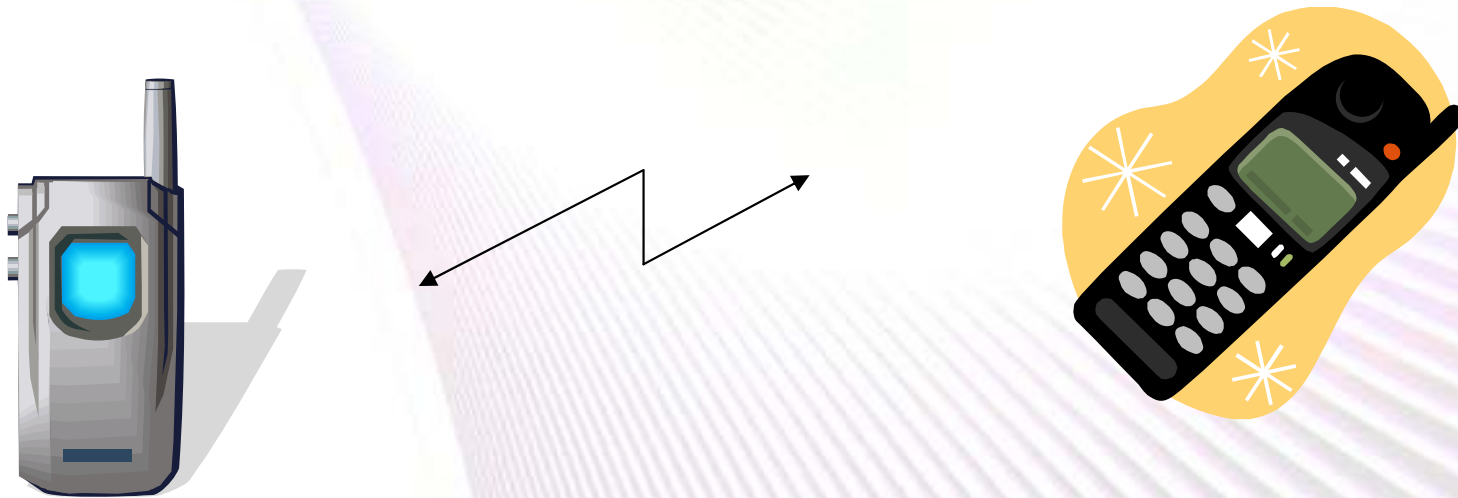
Agenda

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Wireless Communication Systems
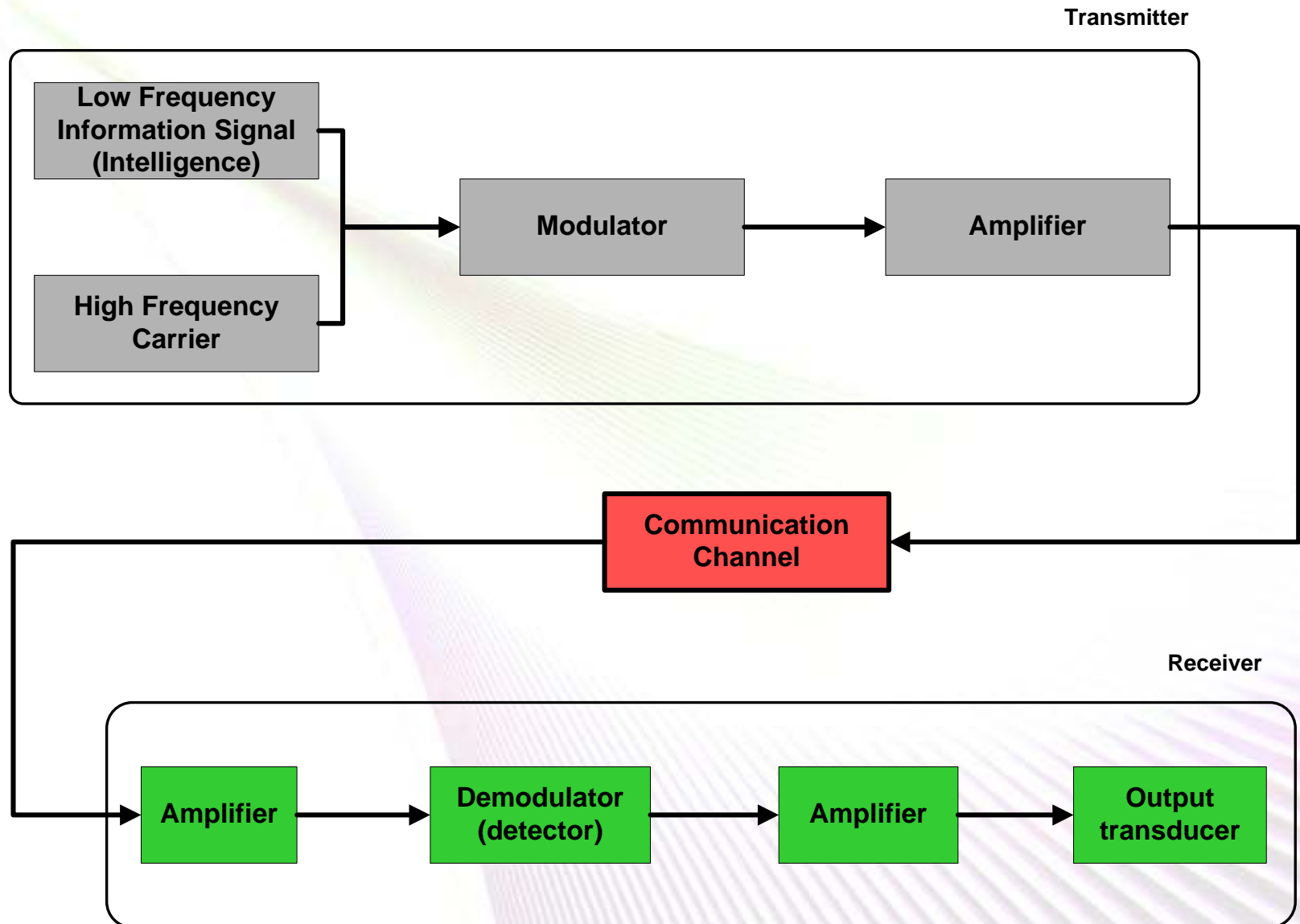
Transmitter

Low Frequency Information Signal (Intelligence)

High Frequency Carrier

Modulator

Amplifier

Communication Channel

Receiver

Amplifier

Demodulator (detector)

Amplifier

Output transducer

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Modulation and Demodulation

Radio Transmitter

Radio Receiver

Source: Lili Qiu

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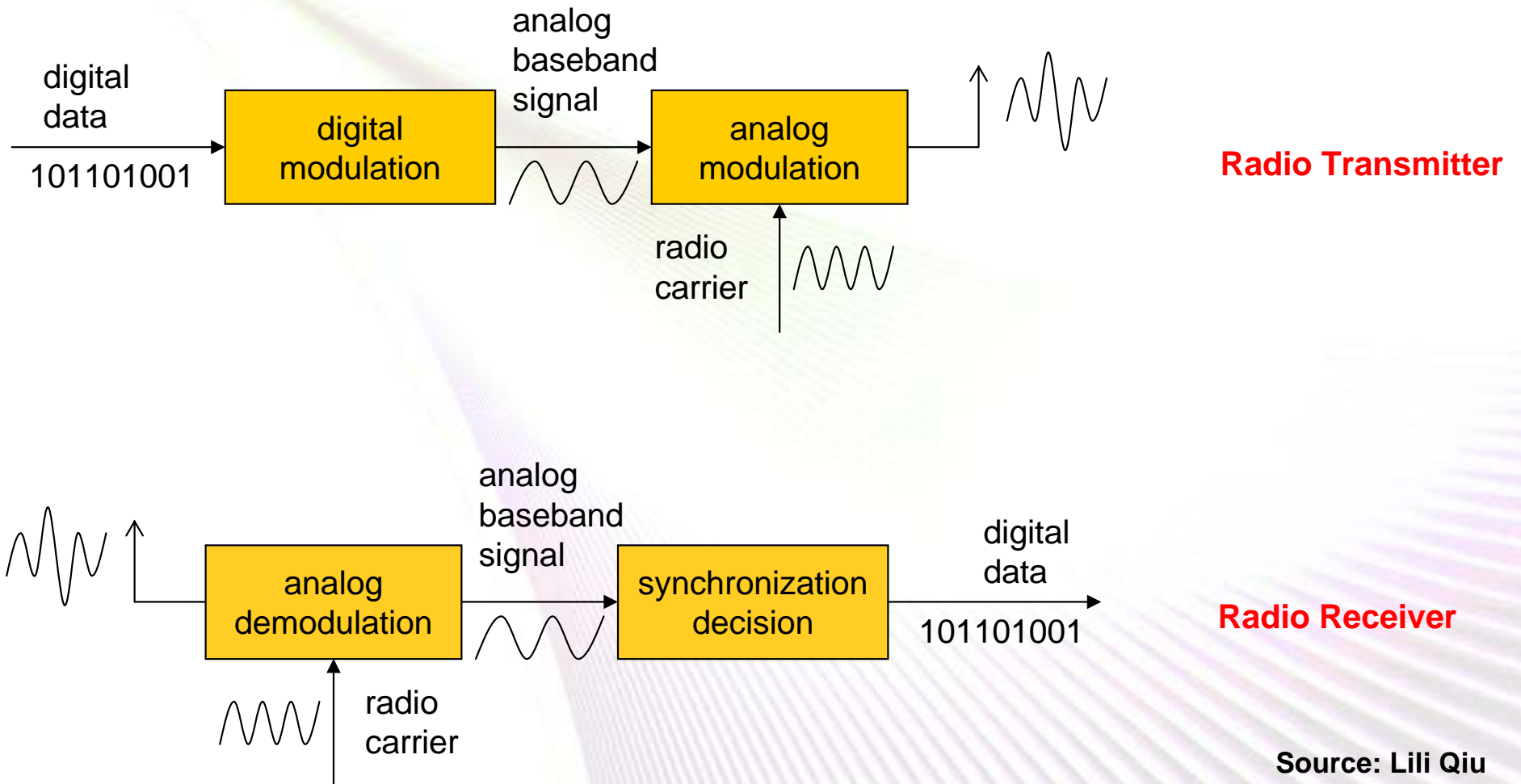
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Modulation Methods

- **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

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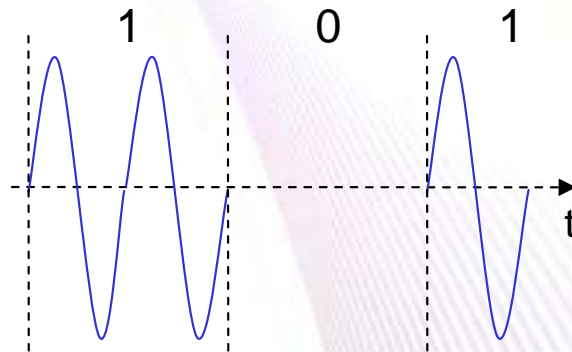
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Digital Modulation

- **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

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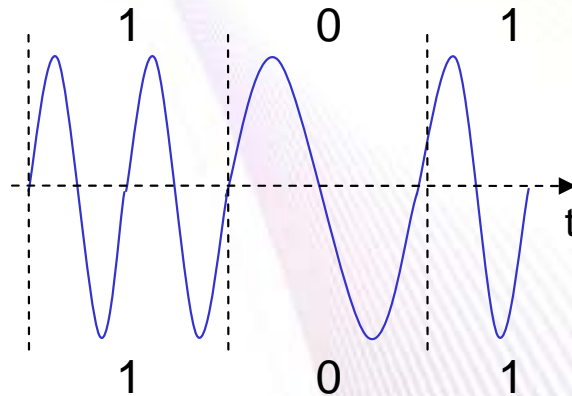
Digital Modulation

- **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
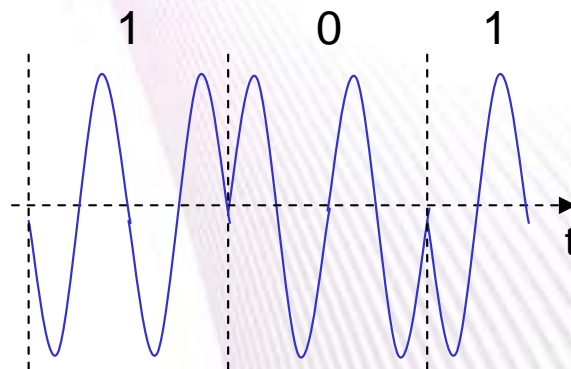
Source: Lili Qiu

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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

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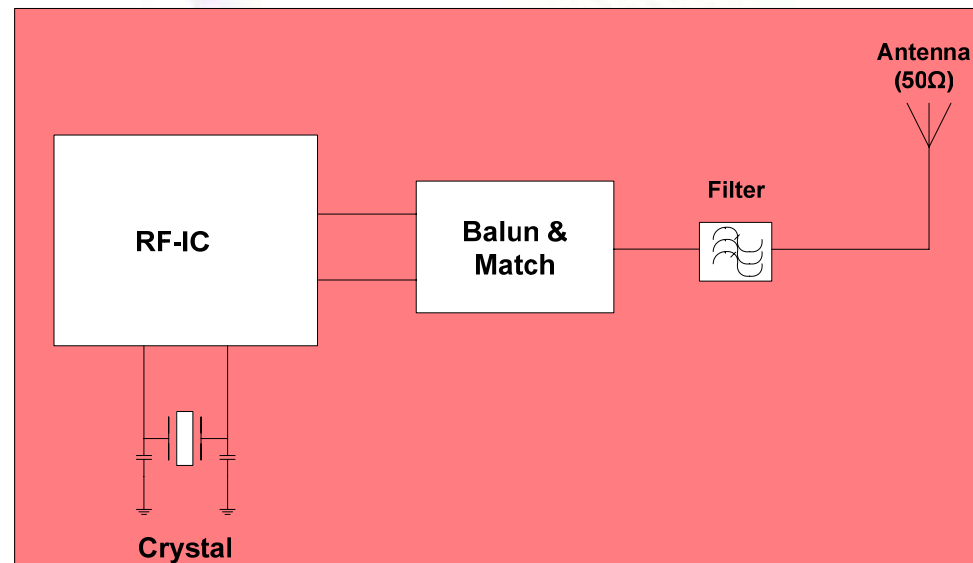
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Transmitter

- **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**

Frequency deviation

Frequency separation = 2 x df

Fc-df   fc   Fc+df   Frequency

DIO=low   DIO=high

FSK modulation

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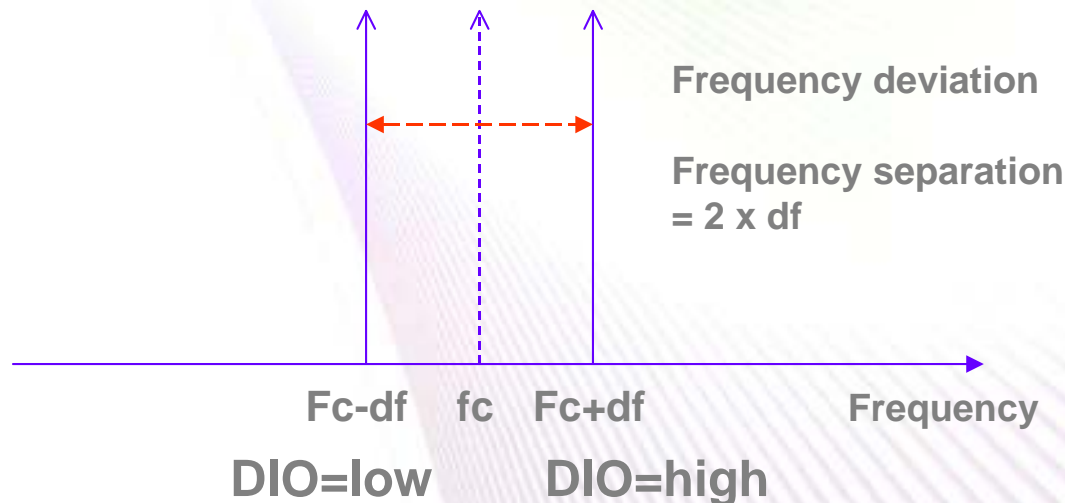
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Receiver Architecture

- **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

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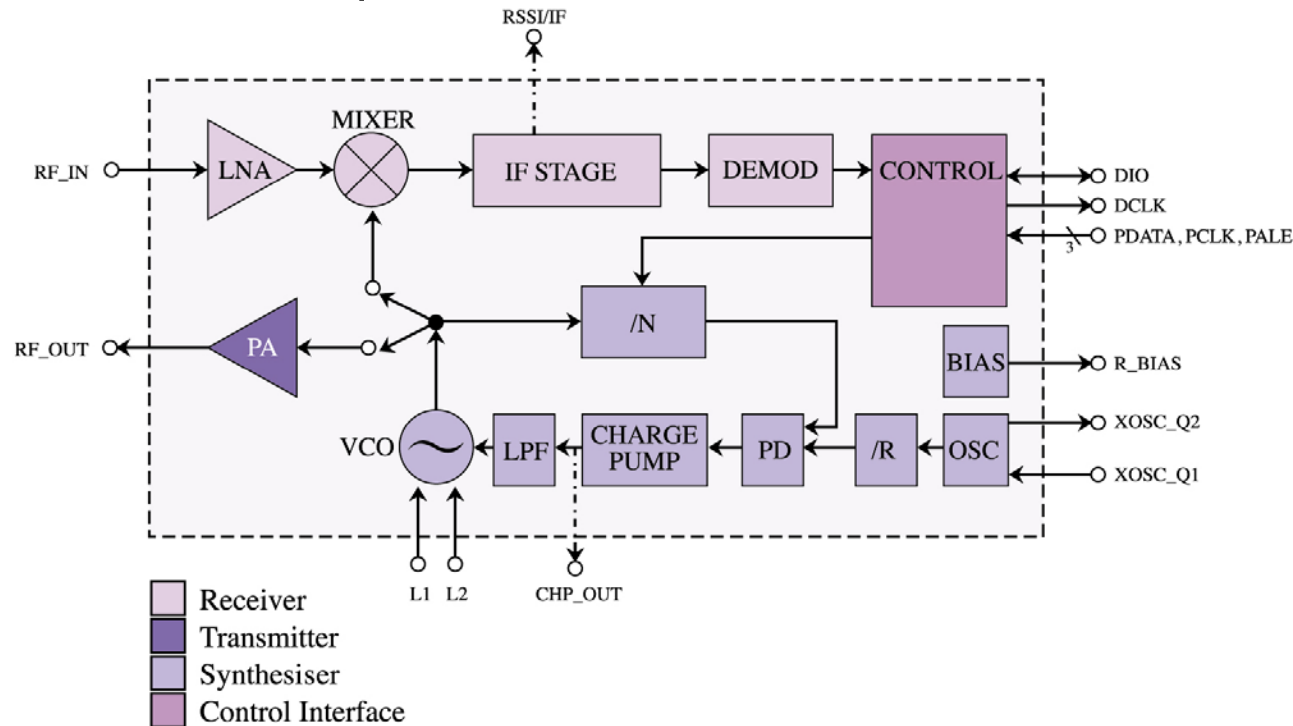
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Receiver Architecture

- ***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*

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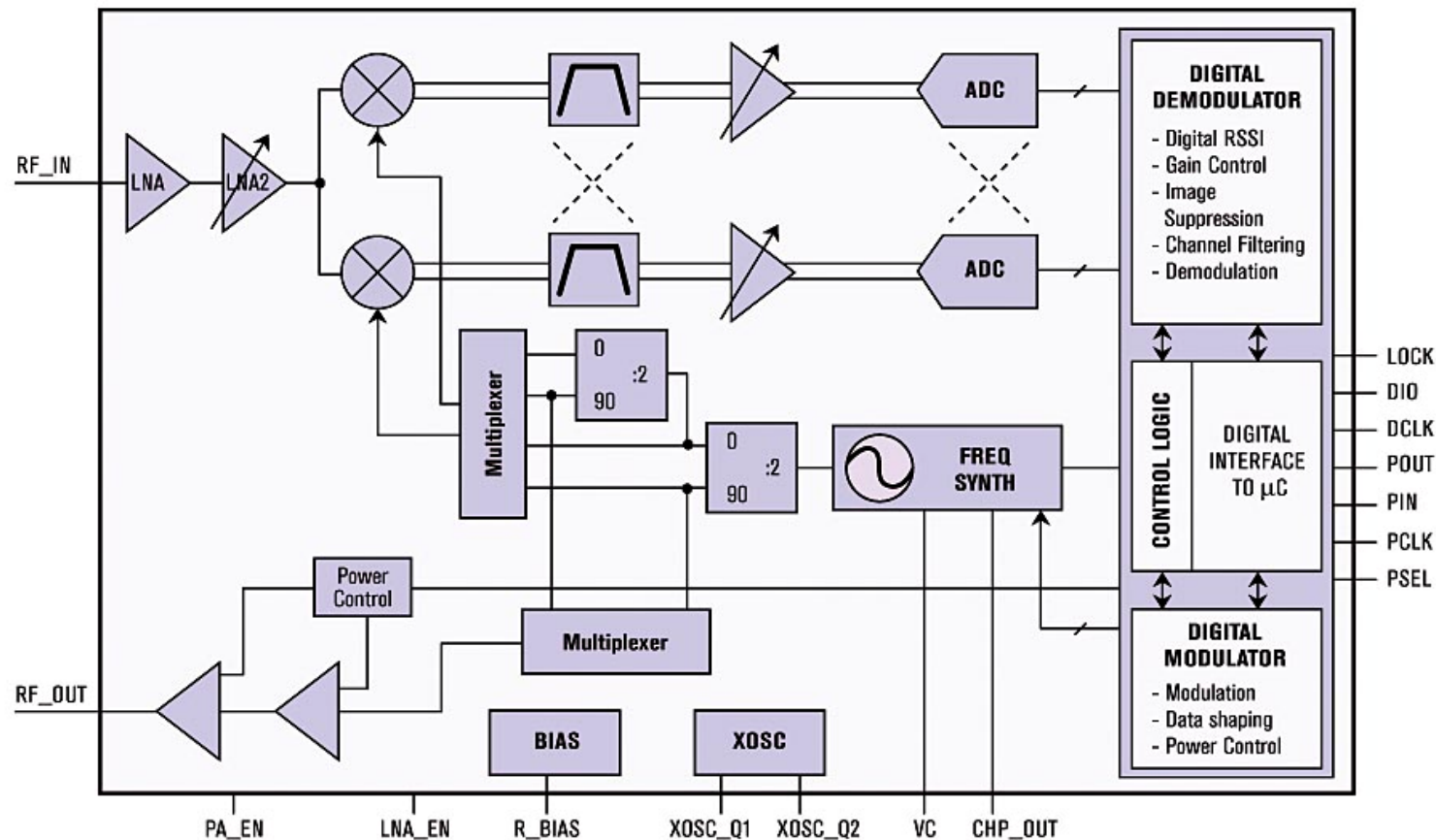
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Crystals

- **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

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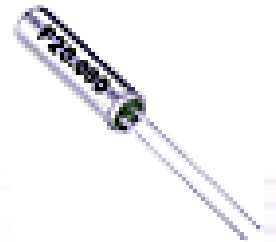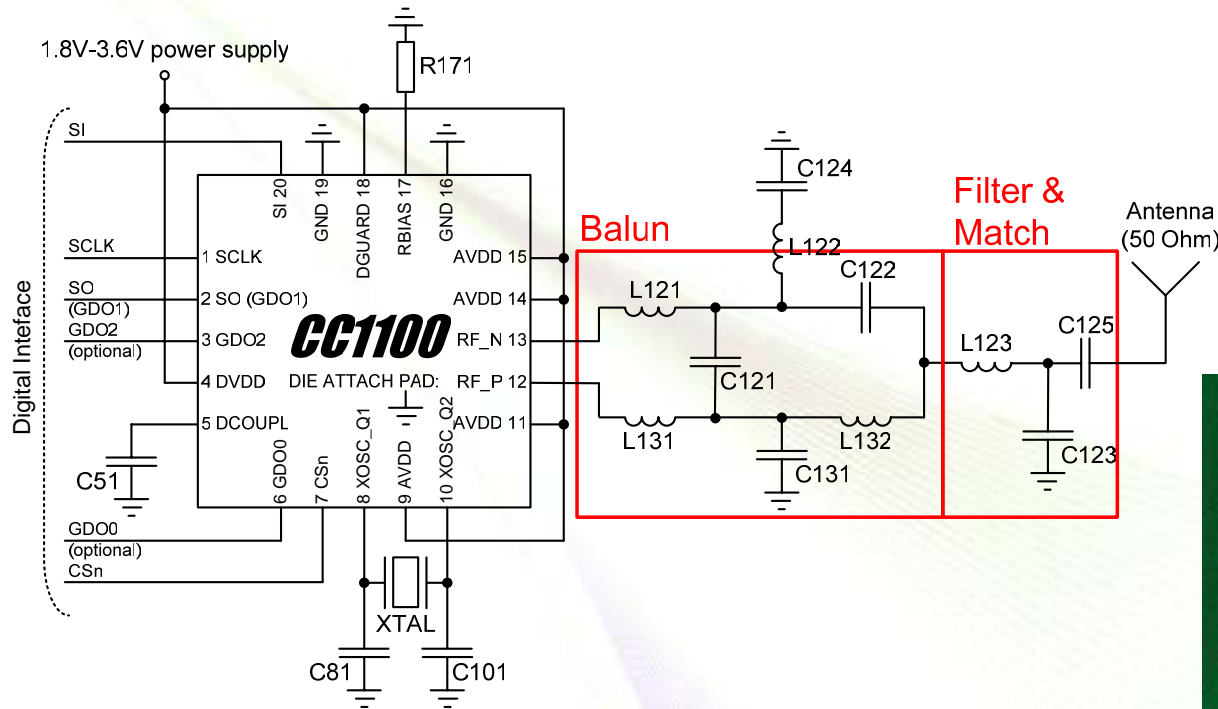
Balun & Matching

Differential signal out of the chip

Single ended signal

Balun and matching towards antenna
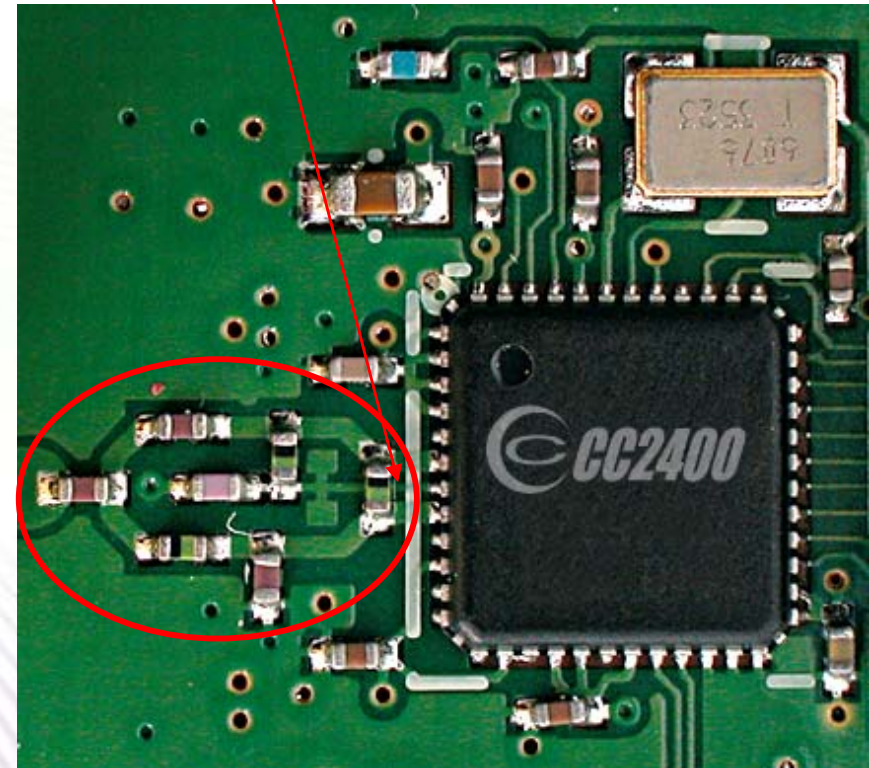
Antennas

Commonly used antennas:

- ## PCB antennas
  - Little extra cost (PCB)
  - Size demanding at low frequencies
  - Good performance possible
  - Complicated to make good designs
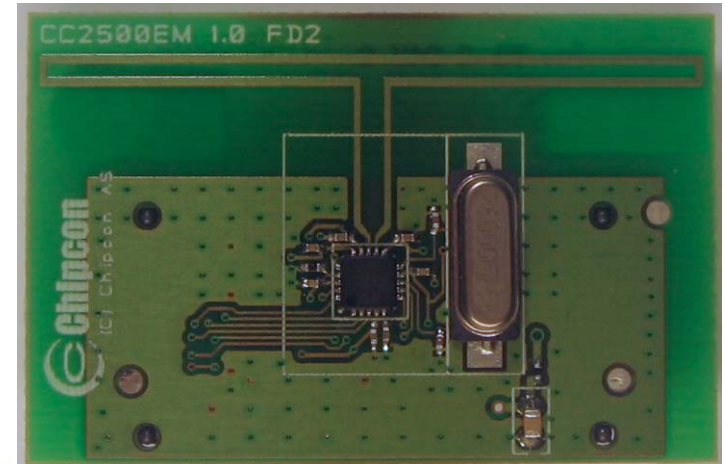
- ## Whip antennas
  - Expensive (unless piece of wire)
  - Good performance
  - Hard to fit in may applications

- ## Chip antennas
  - Expensive
  - OK performance

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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 !**

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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
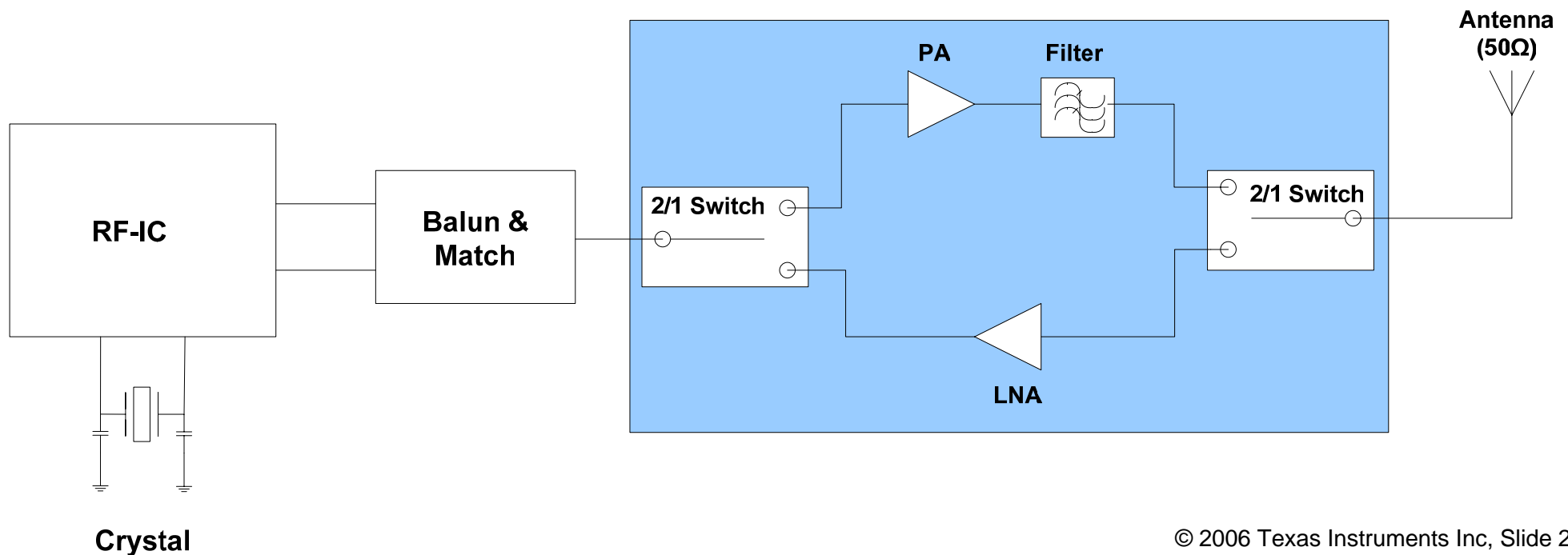
Adding an External PA

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**
- **Simpler control without external LNA**
  - No extra signal is needed from MCU to turn off LNA in low power

CC2420 — RF_P, RF_N, TXRX_SWITCH — BALUN — TX/RX Switch — PA (TX path) — LP filter — TX/RX Switch — ANT. RX path. Control logic and bias network.
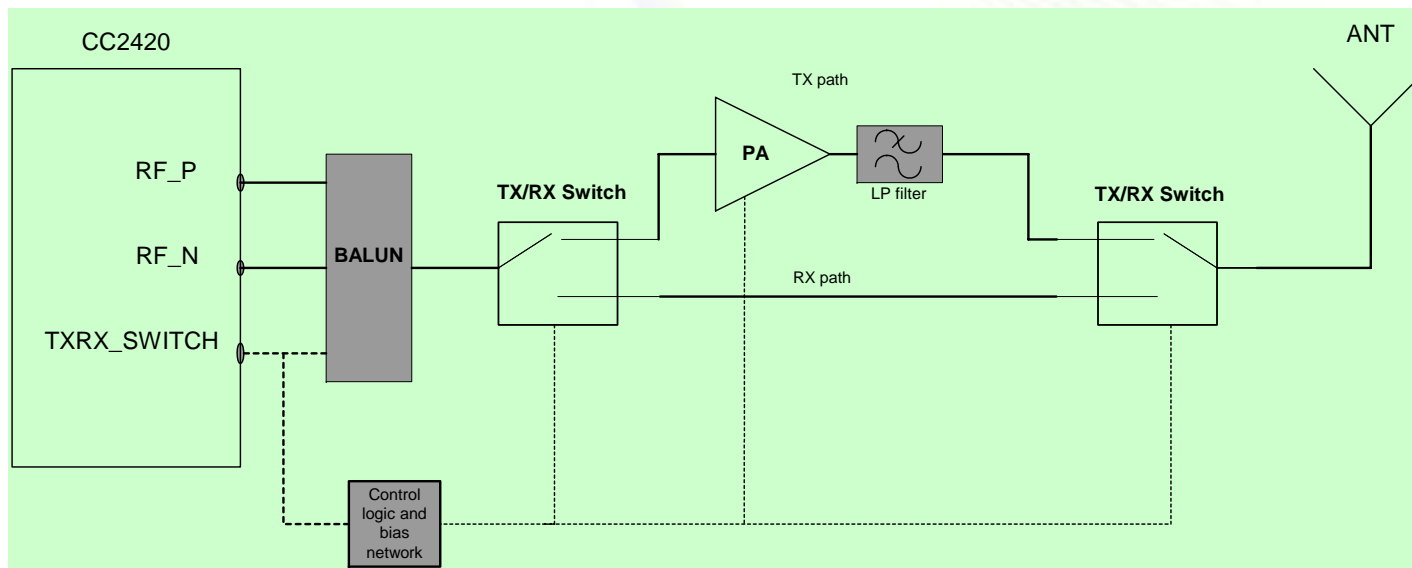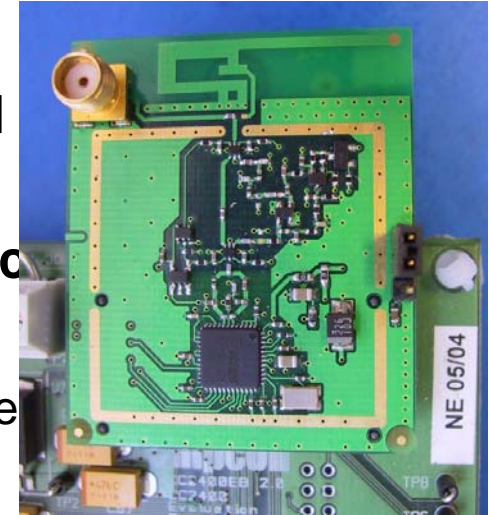
	CC2420EM	CC2420EM w/PA
TX current	17.4 mA	30.8 mA
RX current	19.7 mA	19.7 mA
Output power	0 dBm	9.5 dBm
Sensitivity	-94 dBm	-93.1 dBm
Line of Sight Range	230 meter	580 meter

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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

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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

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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

Ideal oscillator

Actual oscillator with phase noise

ω_c

ω_c
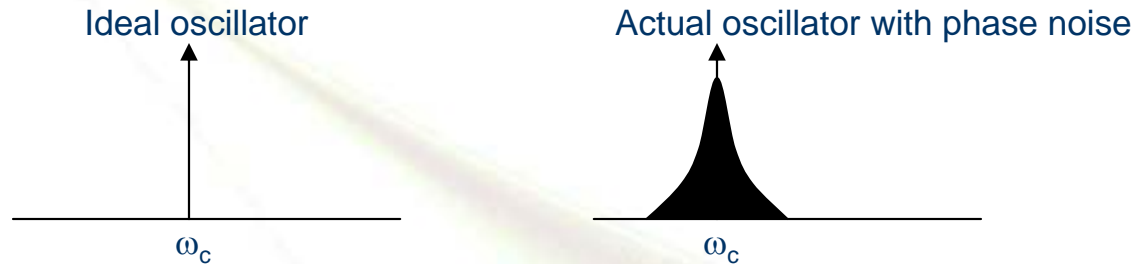
Down Conversion (receivers):

LO signal (no phase noise)

Interferer

Interferer

ω_o Wanted signal

ω_{IF}

Wanted signal

LO signal (with phase noise)

Interferer

Interferer

ω_o Wanted signal

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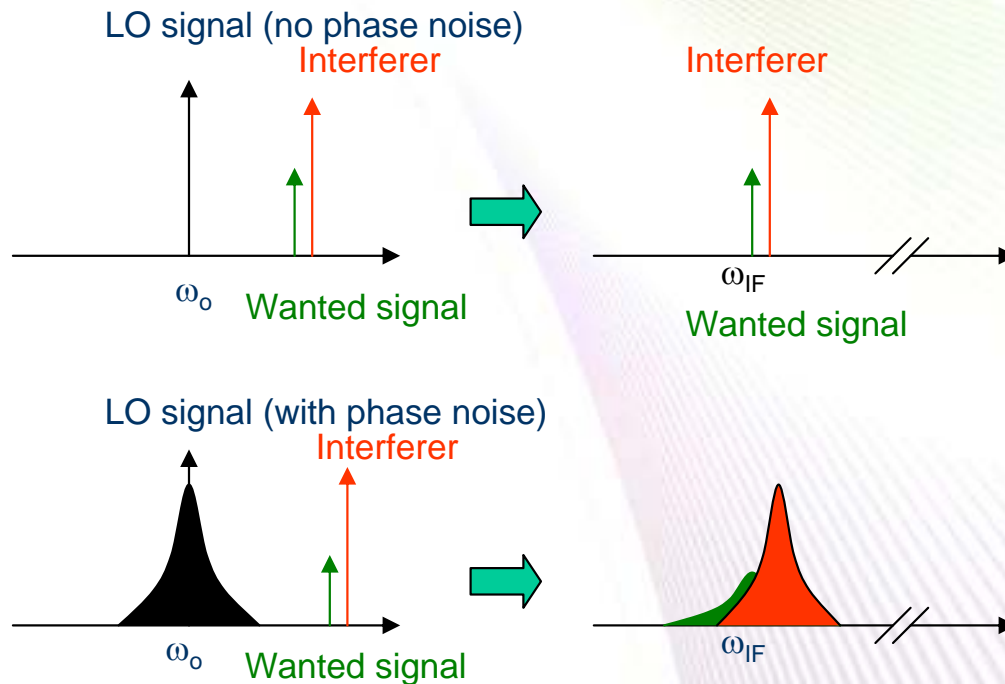
Down-converted bands consist of two overlapping spectra, with the wanted signal suffering from significant noise due to the tail of the interferer

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

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Phase Noise

Transmitters:

Nearby transmitter

Ideal oscillator
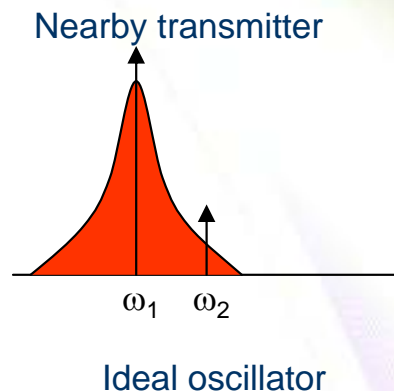
Difficult to detect weak signal at ω_2.

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

Bad   Good   **Frequency**
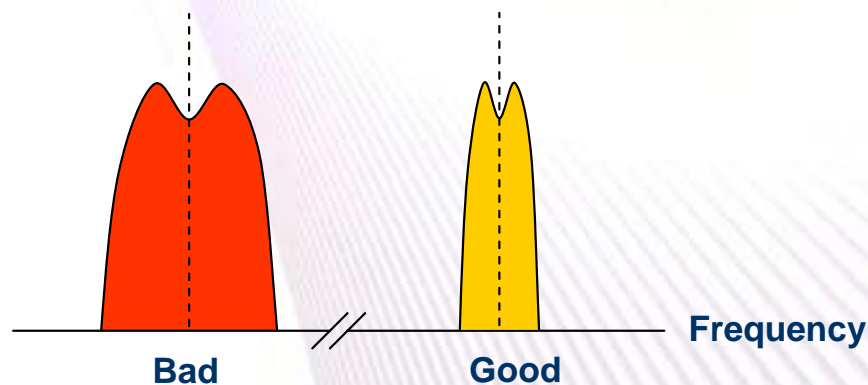
Narrowband Transmitter

- ## 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

Adjacent channel **Signal channel** **Adjacent channel**

BW   BW   BW

CC1020: ACP = -51 dBc

Frequency
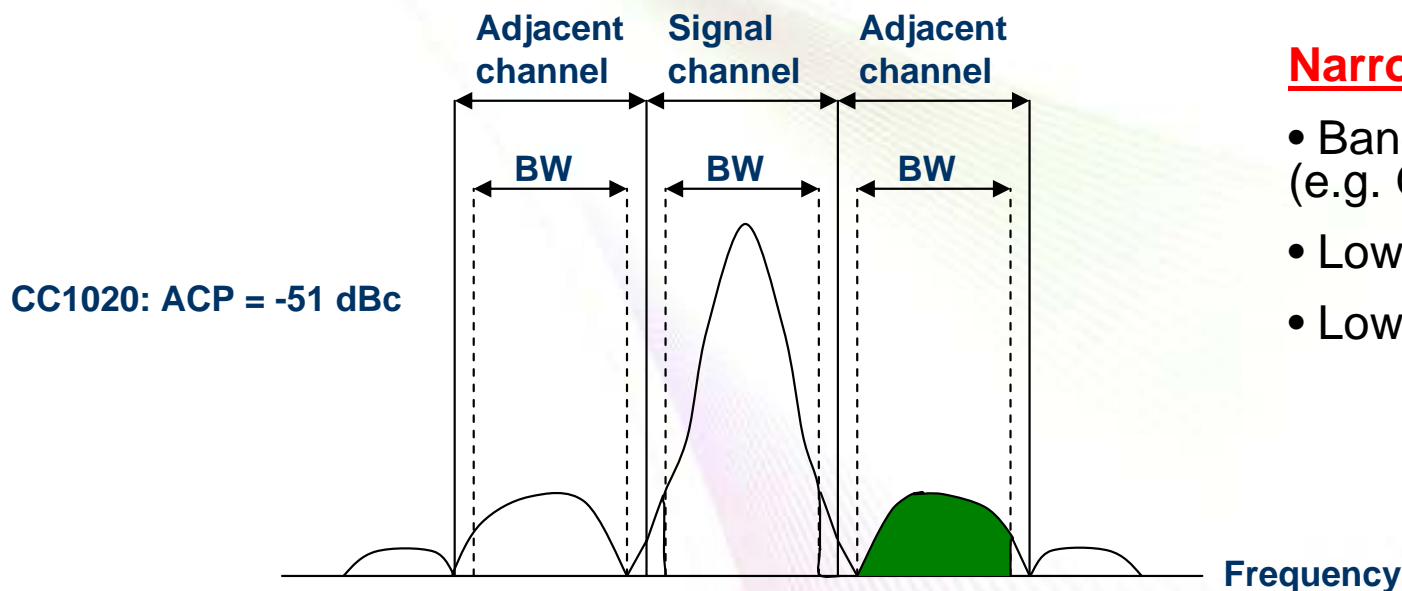
Narrowband characteristics:

- 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)

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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

Co-channel rejection in dB

Frequency

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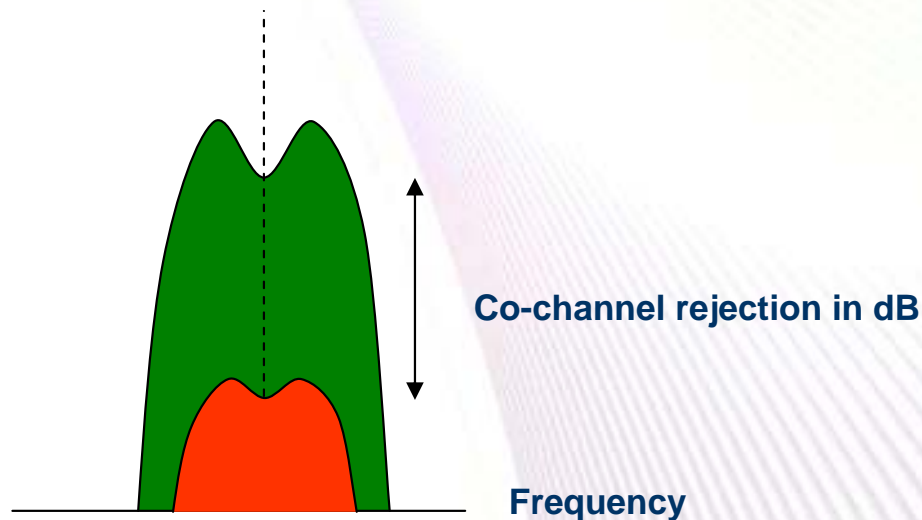
Receiver Selectivity

- ACR = Adjacent Channel Rejection or
- ACS = Adjacent Channel Selectivity
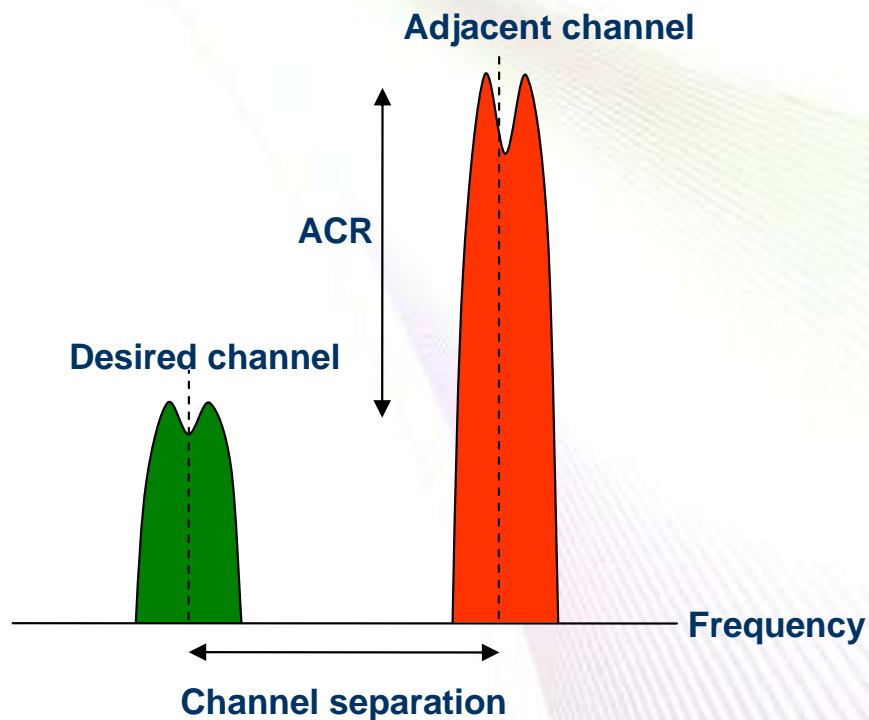
- **CC1020: 32dB @ 12.5 kHz**
- **Test method**
  - Wanted 3dB above sensitivity level
  - Interferer injected in the adjacent channel

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Receiver Selectivity

- **Selectivity, measured for channels "further out" (alternate channel selectivity)**

- **Same test method as ACR/ACS**
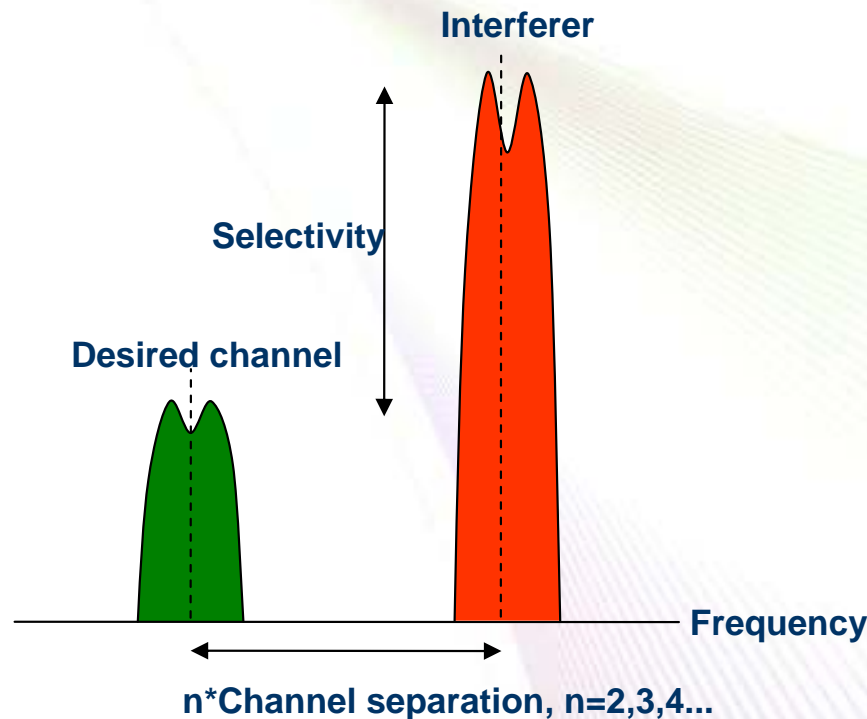
- **Low phase noise and narrow IF bandwith**
  ➡ good ACR/ACS

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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)**

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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**

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Image Rejection

- **Image Rejection**

IF-frequency

Image frequency   LO   Desired frequency
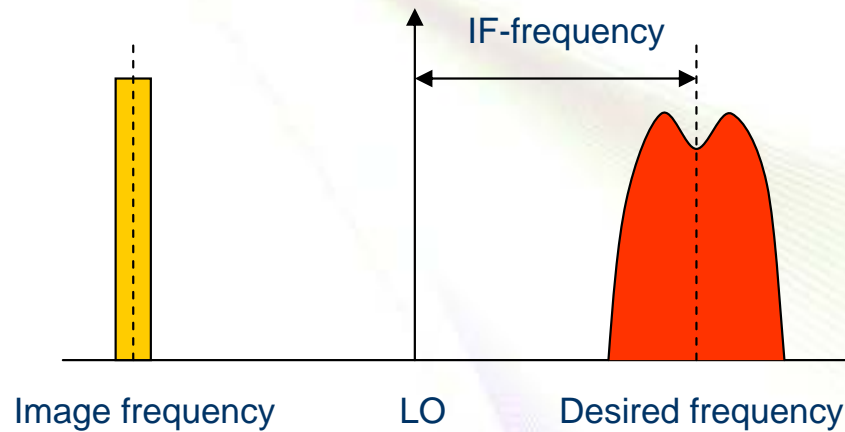
- *CC1000*
  - No image rejection

ω_{IF}

- *CC1020*
  - Image rejection

ω_{IF}

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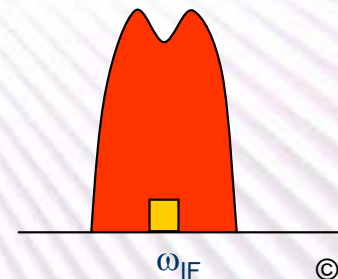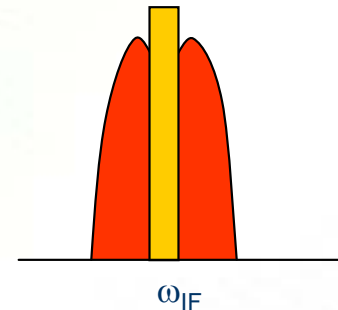
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Receiver Sensitivity

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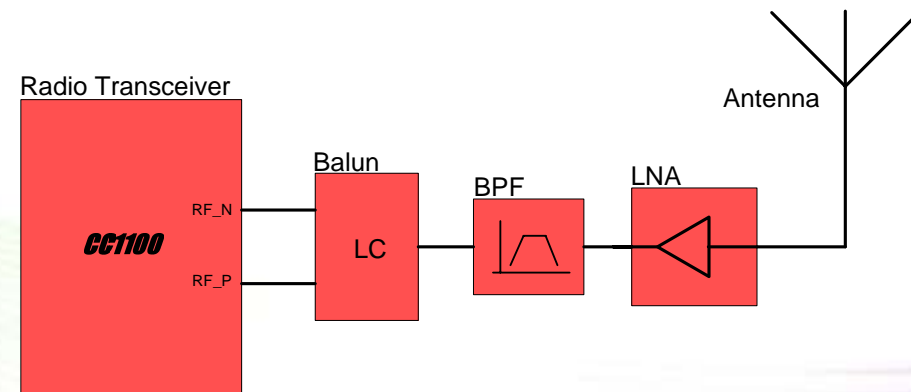
- **Lower noise bandwidth (narrowband)**
  - Blocking/linearity not changed
  - Good selectivity
  - Good frequency control needed

Radio Transceiver

Antenna

CC1100

RF_N

RF_P

Balun

LC

BPF

LNA

Radio Transceiver

Antenna

CC1020

RF_OUT

RF_IN

LPF

T/R Switch
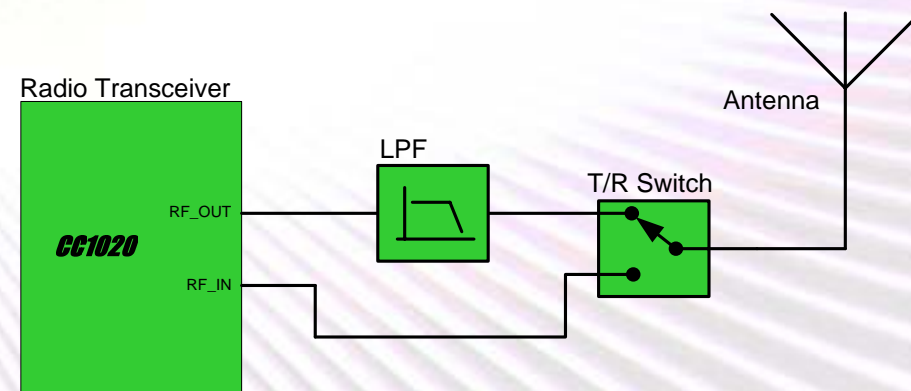
RF Measurement Equipment

- **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**

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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**

Power

802.11b/g   Microwave oven   Cordless   Frequency
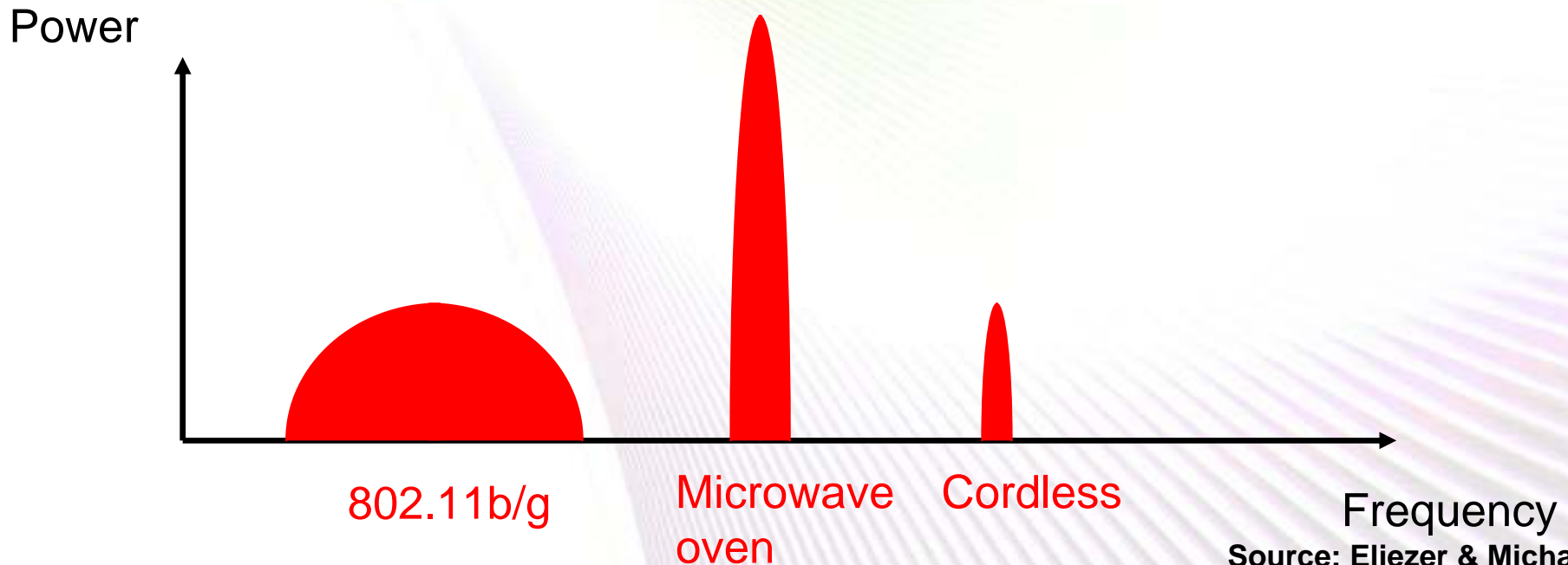
Source: Eliezer & Michael, TI

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TEXAS INSTRUMENTS

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)**

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General Model of a Spread Spectrum System

Input Data → **Channel Encoder** → **Modulator** → **Communication Channel** → **Demodulator** → **Channel Decoder** → Output Data

Spreading Code ↑ **Pseudorandom Noise** → Modulator

Spreading Code ↑ **Pseudorandom Noise** → Demodulator
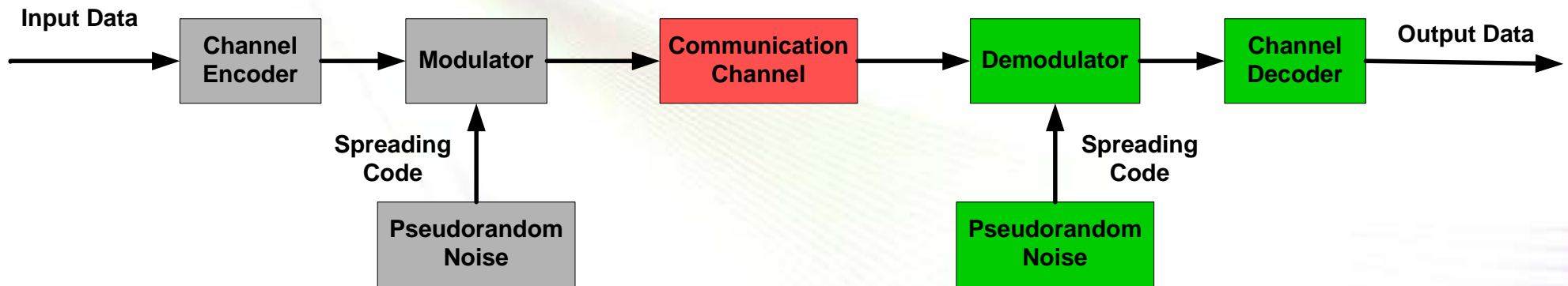
Direct Sequence Spread Spectrum

- **Each bit represented by multiple bits using spreading code**

- **Spreading code spreads signal across wider frequency band**

- **Good resistance against interferers**
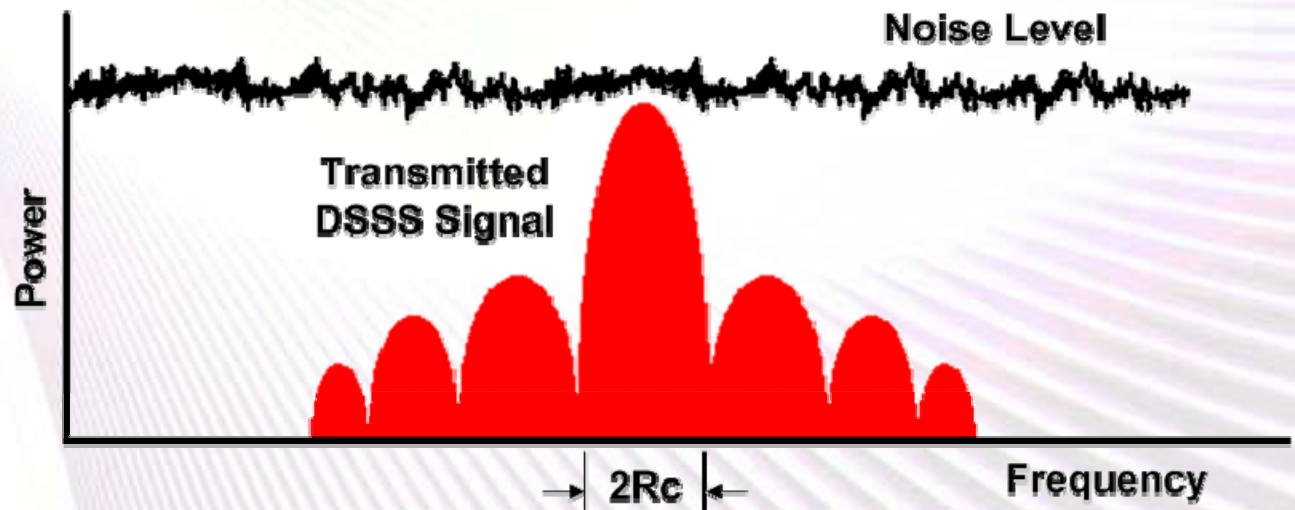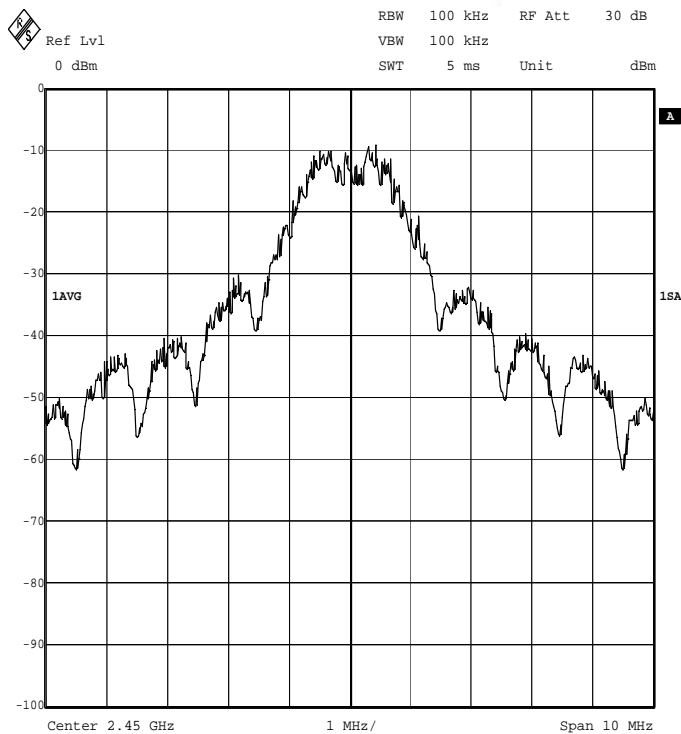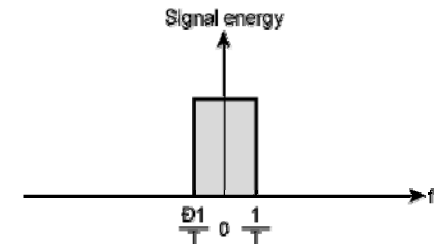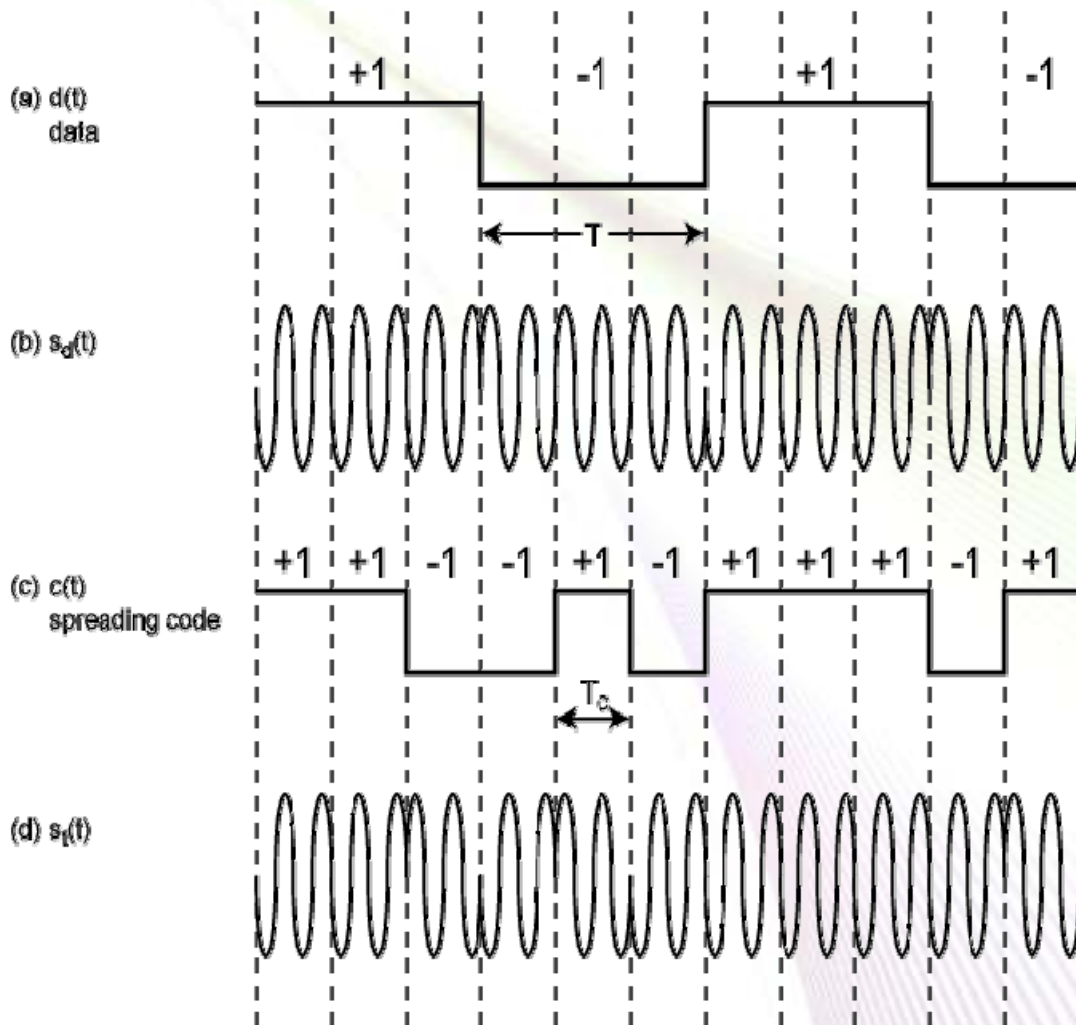
Ref Lvl	RBW	100 kHz	RF Att	30 dB
0 dBm	VBW	100 kHz	
	SWT	5 ms	Unit	dBm

Center 2.45 GHz   1 MHz/   Span 10 MHz

Date: 23.OCT.2003   21:34:19

Noise Level

Transmitted DSSS Signal

Power

2Rc

Frequency

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DSSS – BPSK Example
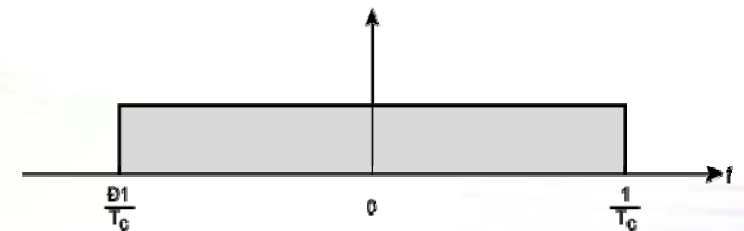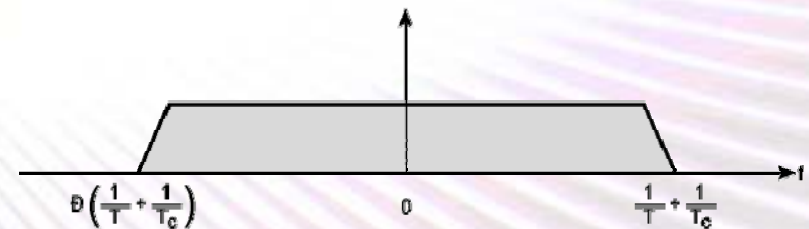
Source: William Stalling
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DSSS Spreading Mechanism

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	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		18
1		16
2		14
3		12
4		14
5		*24*
6		16
7		14
8		14
9		16
10		14
11		20
12		14
13		12
14		20
15		18

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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**

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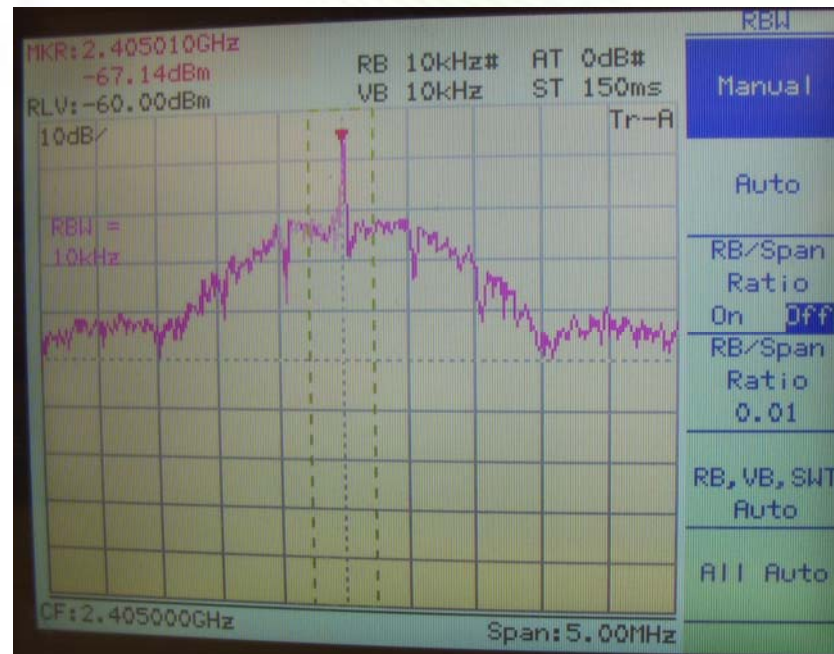
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Frequency Hopping Spread Spectrum (FHSS)

- **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**

Power

Frequency

Source: Eliezer & Michael, TI

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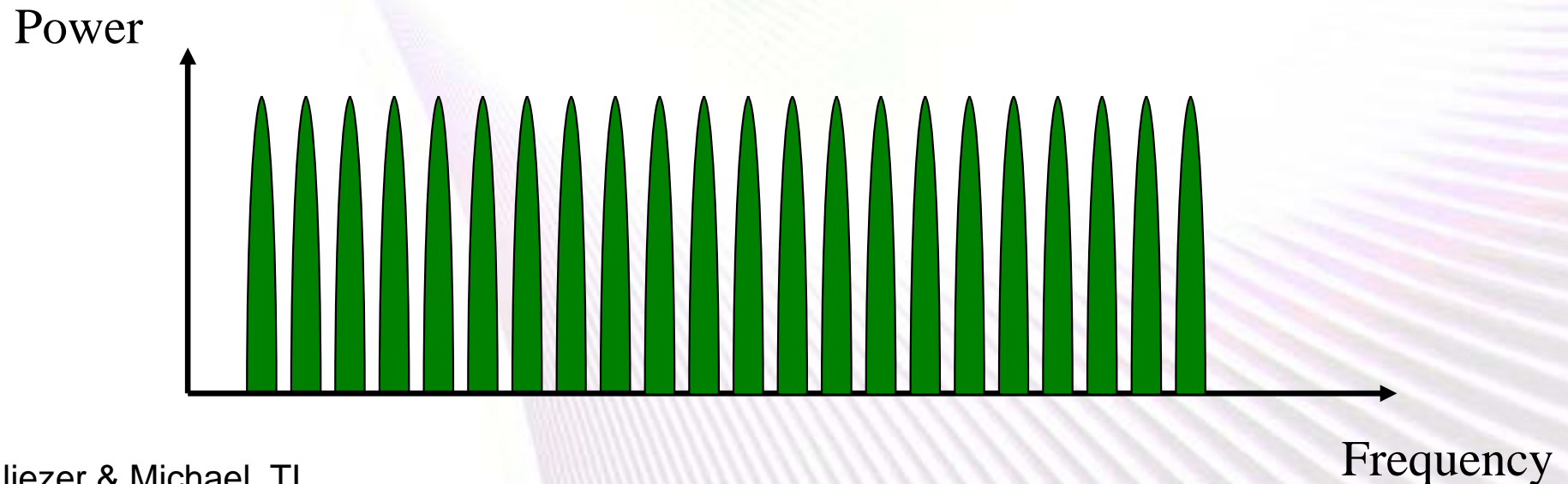
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2.4 GHz Devices – Static Frequency Hopping

- **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)**

Power

802.11b/g   Microwave oven   Cordless

Frequency

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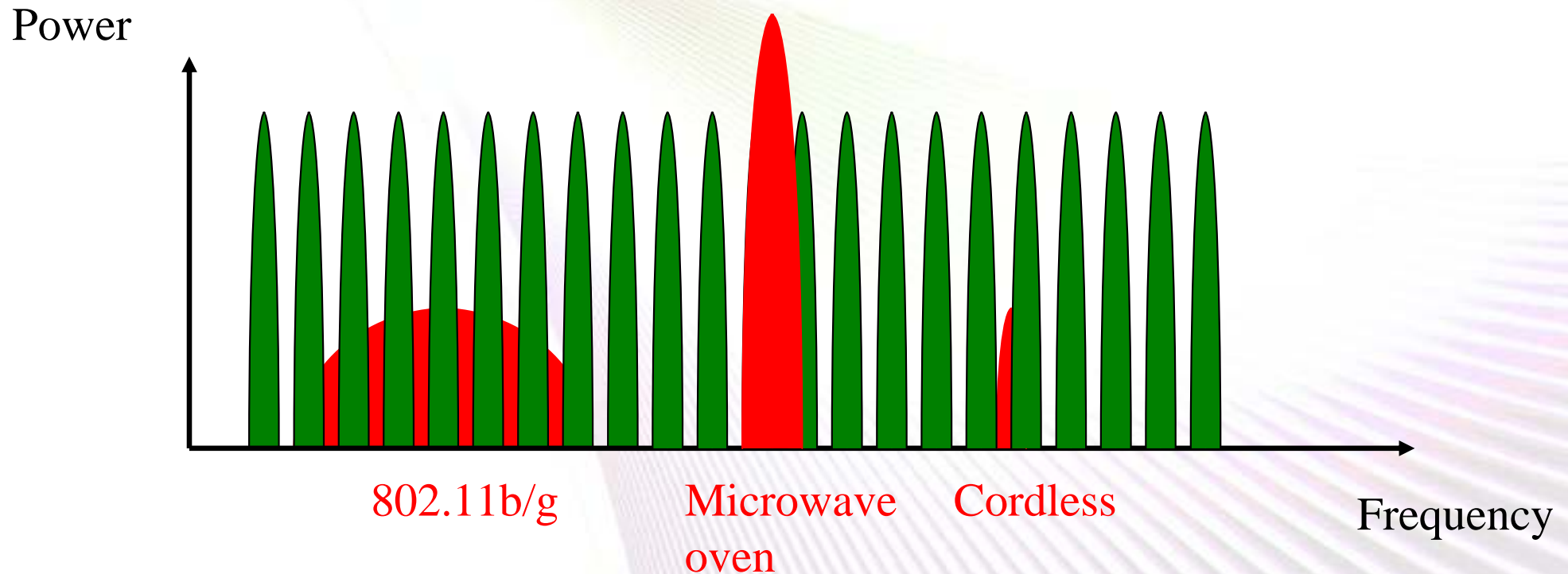
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2.4 GHz – Adaptive Frequency Hopping

- **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.**

Power

802.11b/g   microwave   cordless
                oven

Frequency

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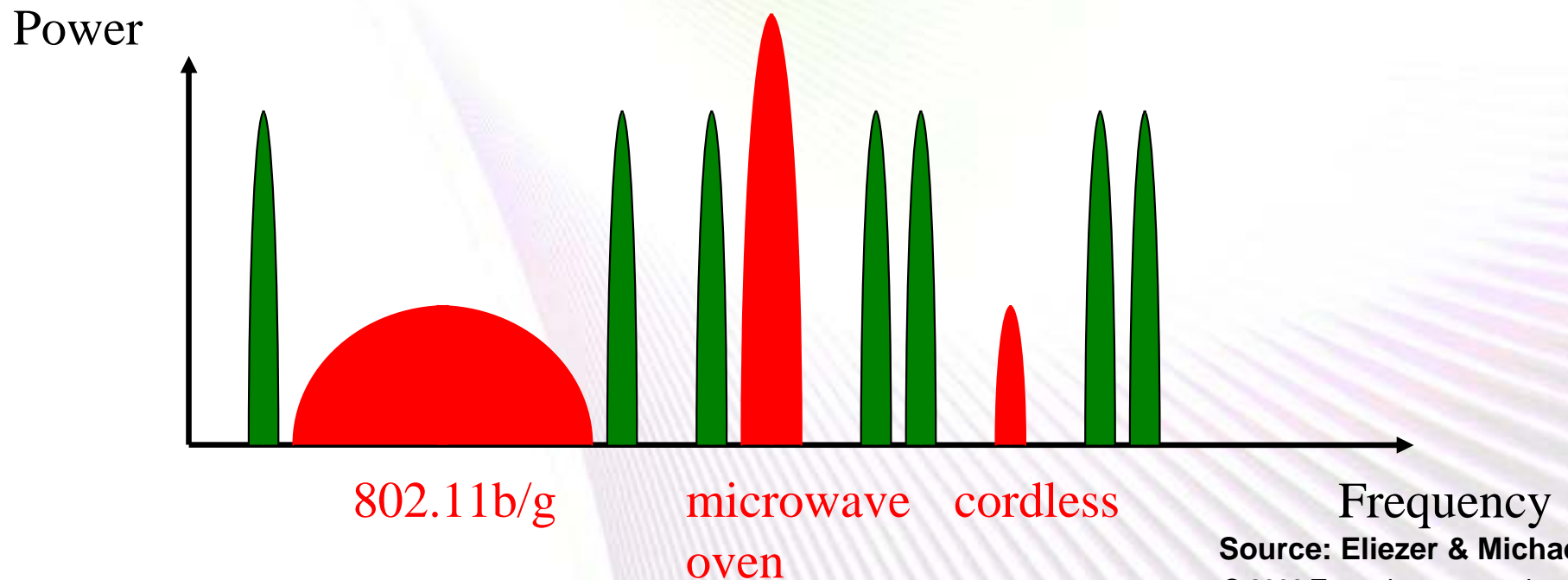
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Frequency Agility

- **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**
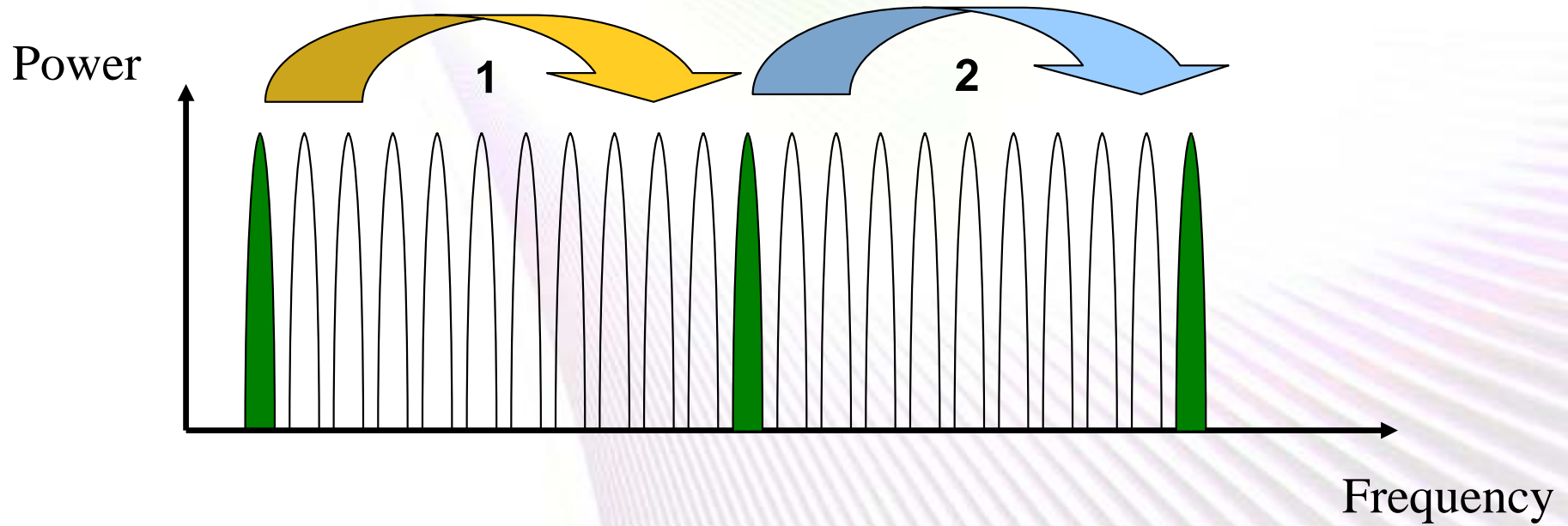
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Agenda

- Basics

- Basic Building Blocks of an RF System

- RF Parameters and RF Measurement Equipment

- Support / getting started

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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?

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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

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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

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Thank you for your attention!

Questions?

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IMPORTANT NOTICE