LPW100: An Introduction to Low Power Wireless Systems

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Abstract

This presentation serves as an overview of the parameters and considerations a designer would use to select a low-power wireless (LPW) solution. It also highlights the devices and tools from TI and how they fit in a typical LPW design.

Agenda

- RF Definitions
- Radio Modulation Schemes
- Radio Frequency Spectrum
- Stack Considerations
- Network Types
- Development Tools and EVMs

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Agenda

RF Definitions

RF Power Definitions

- **dBm** – power referred to 1 mW

  P_{dBm}=10log(P/1mW)

  0dBm = 1mW

  20 dBm = 100mW

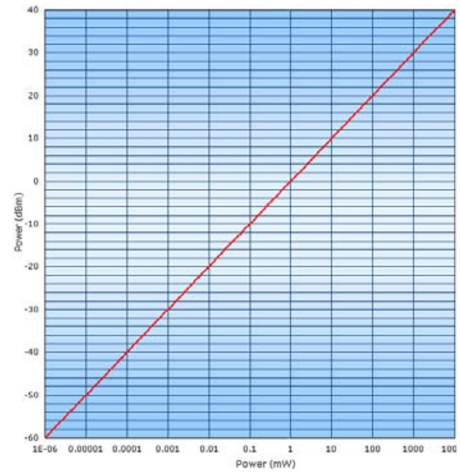
  30 dBm = 1W

  Example:

  -110dBm = 1E-11mW = 0.00001nW

  Power = V2/R:

  50 Ω load : -110dBm is 0.7uV



- Rule of thumb:

  6dB increase => twice the range

  3dB increase => roughly doubles the dbm power

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dBm vs W

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

About dBm and W

- Voltage Ratio, aV = 20 log (V2/V1), [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

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 $P' = 10 \log (P/1mW)$ $[P'] = dBm$
- Example: 25mW is the maximum allowed radiated (transmitted) power in the EU SRD band
  - $P' = 10 \log (25mW/1mW) = 10 * 1.39794$ dBm ~ 14 dBm

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dBm Typicals

For more information: http://en.wikipedia.org/wiki/DBm

dBm level	Power	Notes
80 dBm	100 kW	Typical transmission power of FM radio station with 30-40 miles range
60 dBm	1 kW	Typical combined radiated RF power of microwave oven elements
36 dBm	4 W	Typical maximum output power for a Citizens' band radio station (27 MHz) in many countries
30 dBm	1 W	Typical RF leakage from a microwave oven - Maximum output power for DCS 1800 MHz mobile phone
27 dBm	500 mW	Typical cellular phone transmission power
~~20 dBm~~	~~100 mW~~	~~Bluetooth Class 1 radio, 100 m range (maximum output power from~~ unlicensed FM transmitter). Typical wireless router transmission power.
18 dBm	70mW	Maximum output power of a Typical WLAN card
4 dBm	2.5 mW	Bluetooth Class 2 radio, 10 m range
0 dBm	1.0 mW	Bluetooth standard (Class 3) radio, 1 m range
−10 dBm	100 µW	Typical max received signal power (−10 to −30 dBm) of a wireless network
−70 dBm	100 pW	Typical range of Wireless received signal power over a network
−127.5 dBm	0.178 fW	Typical received signal power from a GPS satellite

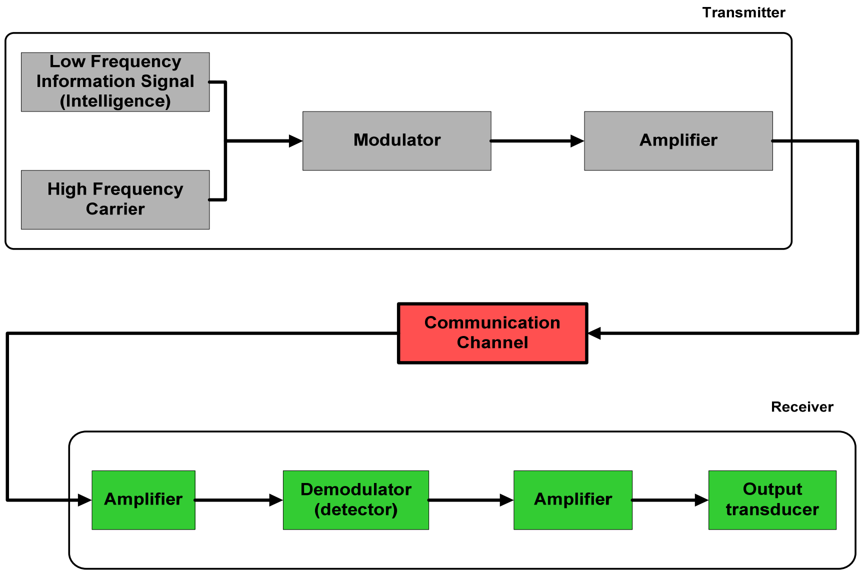
CC1100: -30dBm to 10dBm CC2520: -20dBm to 5dBm CC2591: 22dBm (max)

Radio Performance Definitions

- **Packet Error Rate (PER)**
  The percentage (%) of packets not received successfully
- **Sensitivity**
  Lowest input power with acceptable link quality (typically 1% PER)
- **Deviation/separation**
  Frequency offset between a logic ‘0’ and ‘1’ using FSK modulation
- **Blocking/selectivity**
  How well a chip works in an environment with interference.

Radio Modulation Schemes

Wireless Communication Systems



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 carrier 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**

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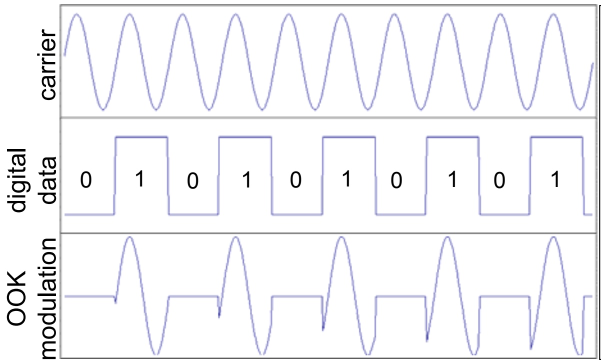
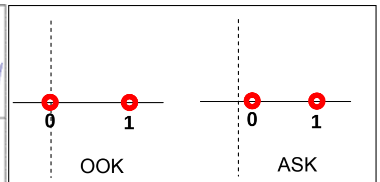
Digital Modulation – ASK

The modulation of digital signals is known as Shift Keying

Amplitude Shift Keying (ASK/OOK):

- **Pros: simple, duty cycling (FCC), lower transmit current**
- **Cons: susceptible to noise, wide spectrum noise**
  - **Rise and fall rates of the carrier's amplitude can be adjusted to reduce the spectrum noise at low to medium data rates. This is called Shaped OOK**
- **Common Use: Many legacy wireless systems**





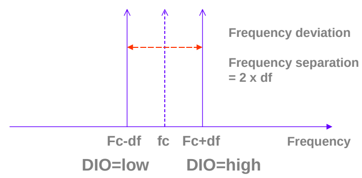
Signal Space Diagram

- **Each axis represents a 'symbol'**
- **OOK has two basis functions: sinusoid & no sinusoid**
- **OOK has two symbols: carrier & no carrier**
- **Distance between symbols predicts BER**

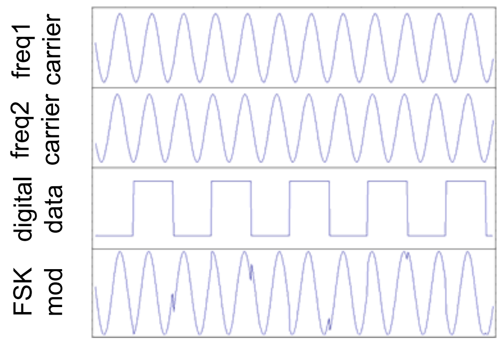
Digital Modulation - FSK

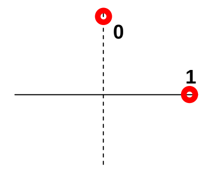
Frequency Shift Keying (FSK):

- Pros: Less susceptible to noise
- Cons: Theoretically requires larger bandwidth/bit than ASK
- Popular in modern systems
- Gaussian FSK (GFSK) has better spectral density than 2-FSK modulation, i.e. more bandwidth efficient



FSK modulation





Signal Space Diagram / Signal Constellation

- Each axis represents a 'symbol'
- Each basis function is 'orthogonal'
- Distance between symbols predicts BER

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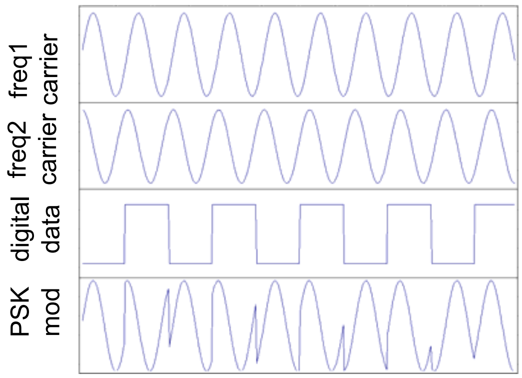
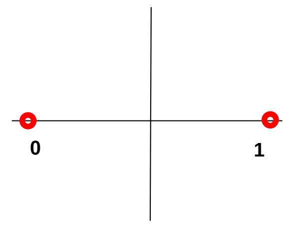
Digital Modulation - PSK

Phase Shift Keying (PSK):

- **Pros:**
  - **Less susceptible to noise**
  - **Bandwidth efficient**
- **Cons: Require synchronization in frequency and phase complicates receivers and transmitter**





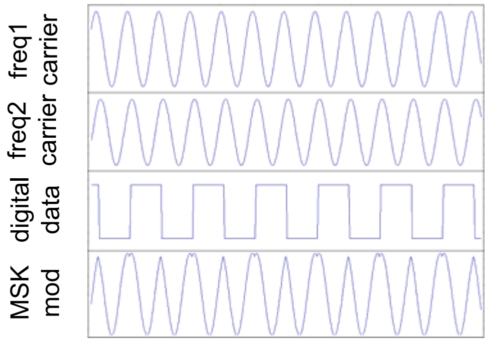
Signal Space Diagram / Signal Constellation

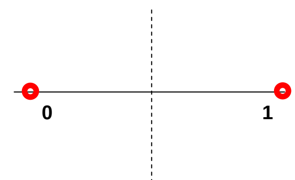
- **Each axis represents a 'symbol'**
- **Each basis function is 'orthogonal'**
- **Distance between symbols predicts BER**

Digital Modulation - MSK

Minimum Shift Keying (MSK):

- **Pros: Difference in Frequency is Half the bit rate**
  - **Very bandwidth efficient**
  - **Reduced Spectrum noise**
- **Cons: Require synchronization in frequency and phase ➔ complicates receivers and transmitter**





Signal Space Diagram / Signal Constellation

- **Each axis represents a 'symbol'**
- **Each basis function is 'orthogonal'**
- **Distance between symbols predicts BER**

Digital Modulation – QPSK/OQPSK

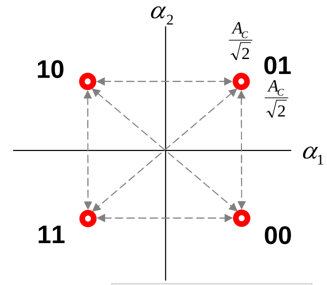
Quadrature Phase Shift Keying

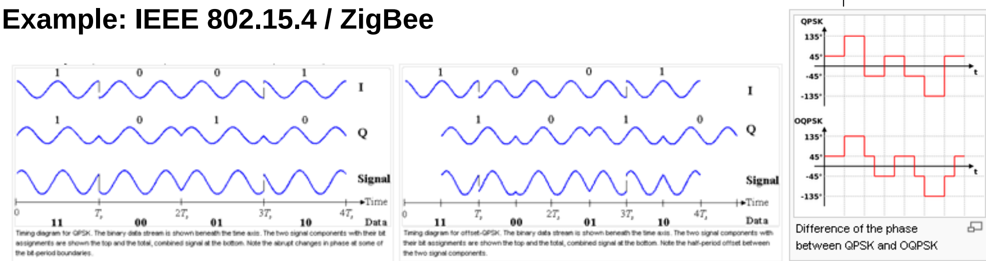
- **Pros: Symbol represents two bits of data**
- **Cons: Phase in the signal can jump as much as 180° causing out of band noise**

Offset Quadrature Phase Shift Keying

- **Pros: Offsetting the signal limits the phase jump to no more than 90°**

Example: IEEE 802.15.4 / ZigBee





http://en.wikipedia.org/wiki/Phase-shift_keying

Quadrature Phase Shift Keying

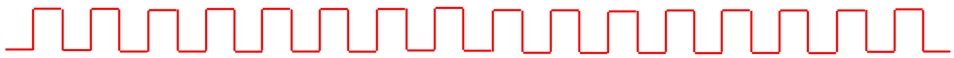
The modulated signal is shown below for a short segment of a random binary data-stream. The two carrier waves are a cosine wave and a sine wave, as indicated by the signal-space analysis above. Here, the odd-numbered bits have been assigned to the in-phase component and the even-numbered bits to the quadrature component (taking the first bit as number 1). The total signal is shown at the bottom.

Offest Quadrature Phase Shift Keying

Taking four values of the phase (two bits) at a time to construct a QPSK symbol can allow the phase of the signal to jump by as much as 180° at a time. When the signal is low-pass filtered (as is typical in a transmitter), these phase-shifts result in large amplitude fluctuations, an undesirable quality in communication systems. By offsetting the timing of the odd and even bits by one bit-period, or half a symbol-period, the in-phase and quadrature components will never change at the same time. In the constellation diagram shown on the left, it can be seen that this will limit the phase-shift to no more than 90° at a time. This yields much lower amplitude fluctuations than non-offset QPSK and is sometimes preferred in practice.

Preamble

The Preamble is a pattern of repeated 1's and 0's



4 bytes / 8 bytes

- **Which can be used by Receiver to pull Received Signal Strength Information (RSSI)**
  - **To trigger a Carrier Sense Flag**
  - **To qualify Sync Word to protect from false triggers**
- **An extended preamble can be sent by sending an STX with no data in the TX Buffer (or by not triggering the DMA in the SoCs)**
- **For data rates less than 500kb/s, a 4 byte Preamble is recommended, at 500kb/s, 8 bytes is recommended**

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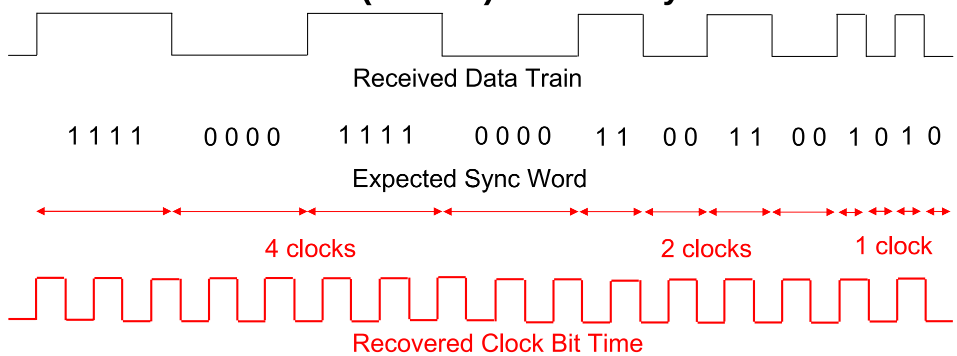
Clock and Data Recovery

- Data is asynchronous, no clock signal is transmitted.
- Clock is recovered (trained) with the Sync Word.



- **Sync Word is 2 Bytes Programmable & can be repeated**
  - **default 0xD391: 1101001110010001**
- **An 8 bit Sync Word can be accomplished by Extending the Preamble with the Sync MSB**

Radio Frequency Spectrum

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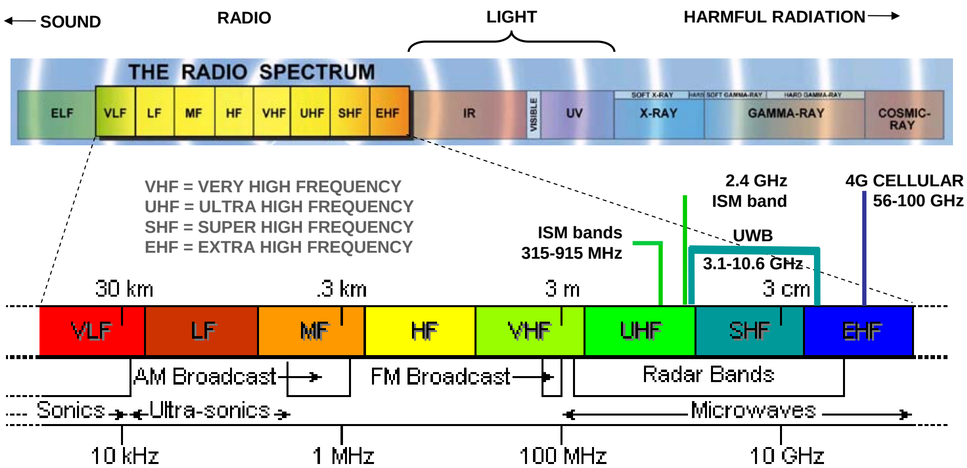
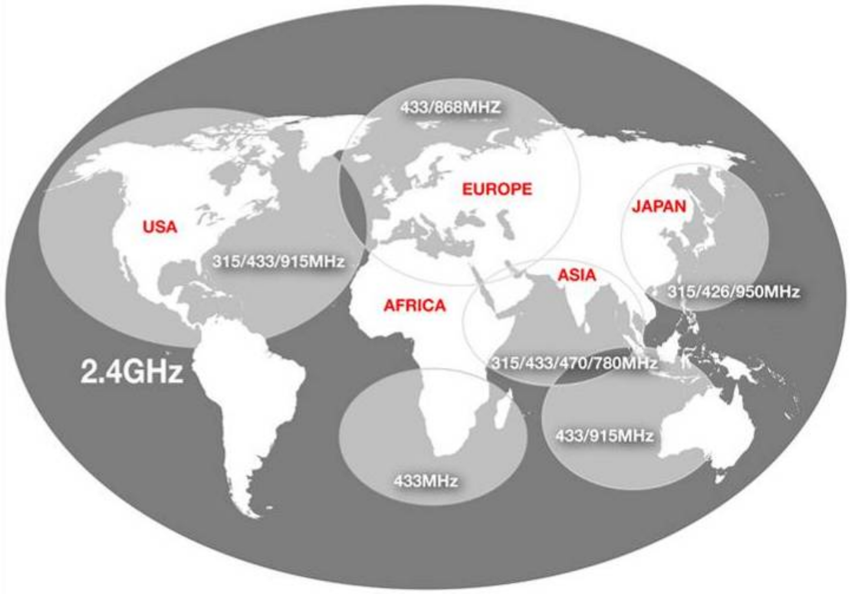
Electromagnetic Spectrum



Source: [JSC.MIL]()

Regulations ISM/SRD Bands



Regional Comparisons

United States
- 315/915MHz
- 2.4 GHz

Europe
- 433/868MHz
- 2.4 GHz

Japan
- 426MHz
- 2.4 GHz

Other National Requirements exist

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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The "World-Wide" 2.4 GHz ISM Band

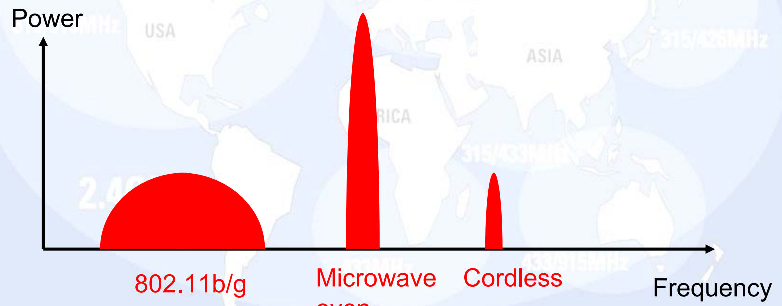
The 2400–2483.5 MHz band is available for license-free operation in most countries

- 2.4 GHz Pros
  - **Same solution for all markets without SW/HW alterations**
  - **Large bandwidth (83.5MHz) available, allows many separate channels and high datarates**
  - **100% duty cycle is possible**
  - **More compact antenna solution than below 1 GHz**

- 2.4 GHz Cons
  - **Shorter range than a sub 1 GHz solution (same output power)**
  - **Many possible interferers are present in the band**

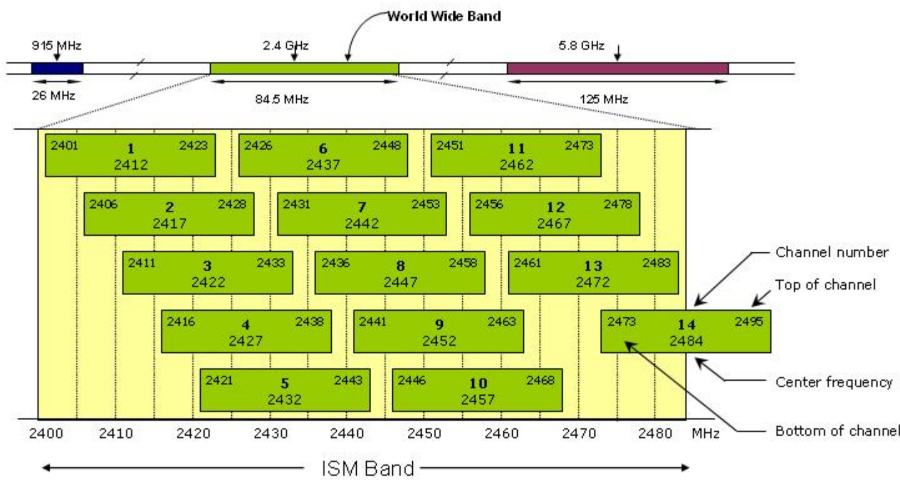
2.4 GHz ISM-band devices

- 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 occupy the 2.4 GHz frequency band



Source: Eliezer & Michael, TI

WiFi Channels in the 2.4GHz Space



Taken from: http://www.moonblinkwifi.com/2point4freq.cfm

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WiFi Channels in the 2.4GHz Space

802.11b WiFi Channels

Taken from: http://www.moonblinkwifi.com/2point4freq.cfm

In the United States and Canada there are 11 channels available for use in the 802.11b 2.4GHz WiFi Frequency range. This standard is defined by the IEEE.

Channel	Lower Frequency	Center Frequency	Upper Frequency
1	2.401	2.412	2.423
2	2.404	2.417	2.428
3	2.411	2.422	2.433
4	2.416	2.427	2.438
5	2.421	2.432	2.443
6	2.426	2.437	2.448
7	2.431	2.442	2.453
8	2.436	2.447	2.458
9	2.441	2.452	2.463
10 2.446	2.451	2.457	2.468
11	2.451	2.462	2.473

There are only 3 non-overlapping channels available in the 802.11b standard.

These are Channels 1,6, and 11.

For WiFi access points that are located near each other it is recommended that they each use one of the above non-overlapping channels to minimize the effects of interference.

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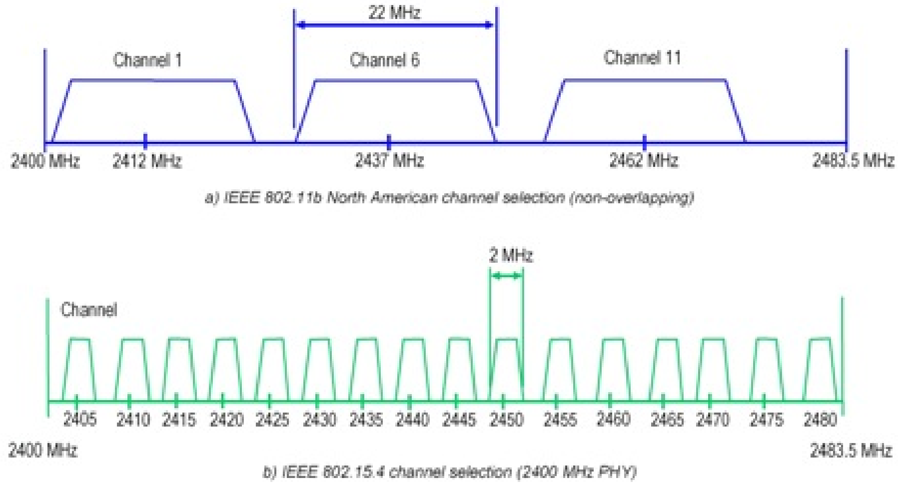
802.15.4 versus 802.15.4



Source: IEEE 802.15.4 specification

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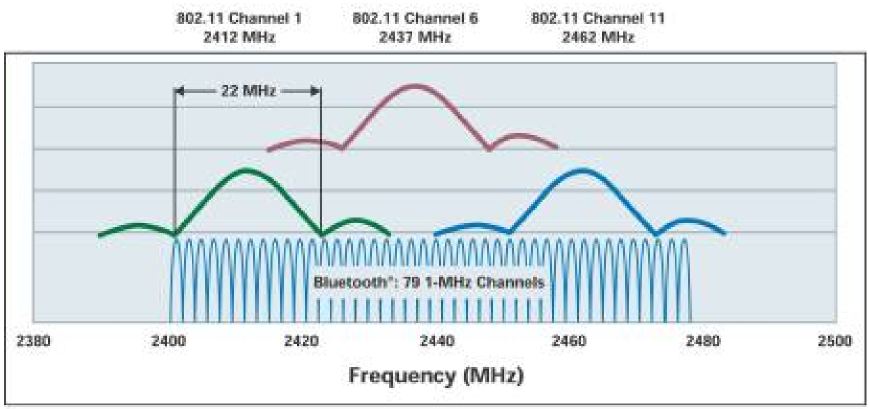
Bluetooth versus 802.11

The Coexistence Problem



- 802.11b/g and Bluetooth® occupy the same 2.4 GHz band
- 802.11b/g has a stationary 16 MHz width
- Bluetooth hops over the entire band typically 1600 hops/sec, occupying 1 MHz at a time
- Collisions in time and frequency cause Bluetooth and WLAN to drop packets

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Sub 1GHz ISM Bands

- **The ISM bands under 1 GHz are not world-wide**
- **Limitations vary a lot from region to region and getting a full overview is not an easy task**
  - Sub 1GHz Pros
    - **Better range than 2.4 GHz with the same output power and current consumption (assuming a good antenna – not easy for a limited space)**
  - Sub 1GHz Cons
    - **Since different bands are used in different markets it is necessary with custom solutions for each market**
    - **More limitations to output power, data rate, bandwidth etc. than the 2.4 GHz**
    - **Duty cycle restrictions in some regions**
    - **Interferers are present in most bands**

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Sub 1GHz ISM bands

- **902-928 MHz is the main frequency band**
  - The 260-470 MHz range is also available, but with more limitations
- **The 902-928 MHz band is covered by FCC CFR 47, part 15**
- **Sharing of the bandwidth is done in the same way as for 2.4 GHz**:
  - *Higher output power is allowed if you spread your transmitted power and don't occupy one channel all the time*FCC CFR 47 part 15.247 covers wideband modulation
  - Frequency Hopping Spread Spectrum (FHSS) with ≥50 channels are allowed up to 1 W, FHSS with 25-49 channels up to 0.25 W
  - Direct Sequence Spread Spectrum (DSSS) and other digital modulation formats with bandwidth above 500 kHz are allowed up to 1W
- **FCC CFR 47 part 15.249**
  - "Single channel systems" can only transmit with ~0.75 mW output power

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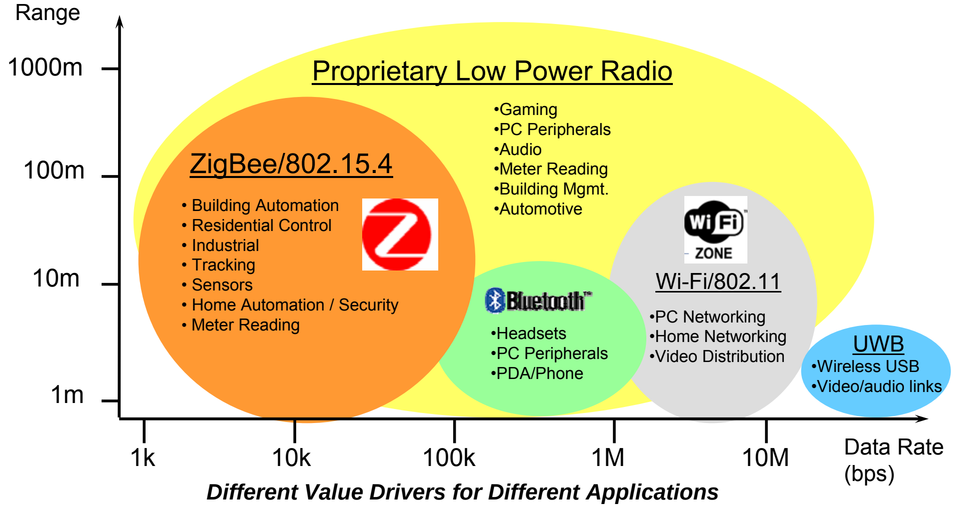
Available Wireless Standards

Short-Range Wireless Comparison



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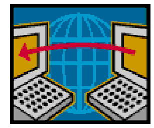
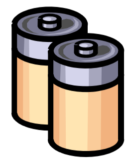
Typical Decision Parameters

Highest Data Rate
- WLAN/UWB (Video)
- Bluetooth (Audio)
- CC430/SimpliciTI (High Speed UART)
- Zigbee/802.15.4



Highest Battery Life
- CC430/SimpliciTI (Alkaline)
- Zigbee/802.15.4 (Alkaline/Li-Ion)
- Bluetooth (Li-Ion)
- WLAN/UWB (Line powered/Li-Ion)



Longest Range (Radio Only, not boosted)
- CC430/SimpliciTI (433MHz)
- Bluetooth Class 1
- WLAN
- Zigbee 802.15.4
- Bluetooth Class 2

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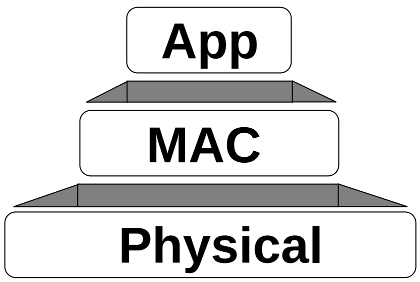
Stack Considerations



Software Stack Considerations

Layer \ Solution	Proprietary	SimpliciTI	IEEE 802.15.4	RF4CE	ZigBee
Application	Design Freedom	Design Freedom	Design Freedom	Design Freedom	Design Freedom
Higher Layer Protocol	Design Freedom	Design Freedom	Design Freedom	Remo TI	Z-Stack + Simple API
Lower Layer Protocol	Design Freedom	SimpliciTI	TI MAC	TI MAC	TI MAC
Physical Layer	all LPRF devices	CC111x, CC251x, CC243x, CC253x, CC430, MSP430+CC1101, CC2500 or CC2520	CC253x CC243x MSP430+CC2520	CC253x CC243x	CC253x CC243x CC2480
RF Frequency	2.4 GHz Sub 1 GHz	2.4 GHz Sub 1 GHz	2.4 GHz	2.4 GHz	2.4 GHz

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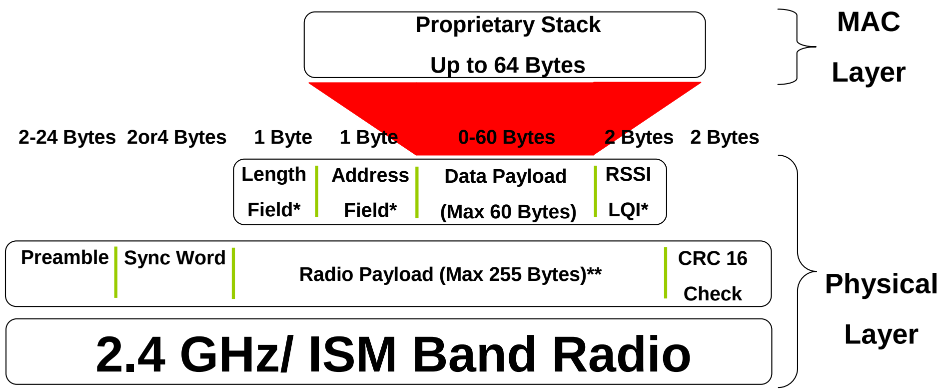
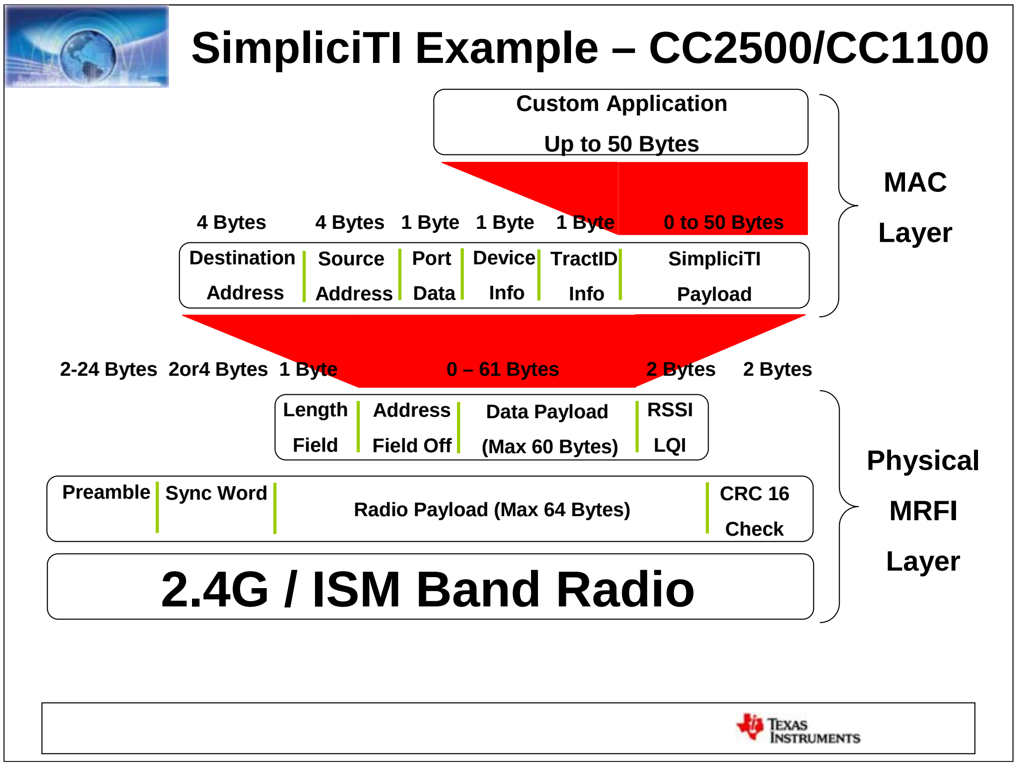
Proprietary Radio – CC2500/CC1100



* Optional Settings for the radio – activating these settings drops the useable payload

** Requires monitoring at refill of the 64Byte Tx Buffer



SimpliciTI Example – CC2500/CC1100
Custom Application
Up to 50 Bytes
MAC
Layer
4 Bytes
4 Bytes
1 Byte
1 Byte
1 Byte
0 to 50 Bytes
Destination Address
Source Address
Port Data
Device Info
TractID Info
SimpliciTI Payload
2-24 Bytes
2or4 Bytes
1 Byte
0 – 61 Bytes
2 Bytes
2 Bytes
Length Field
Address Field Off
Data Payload (Max 60 Bytes)
RSSI LQI
Preamble
Sync Word
Radio Payload (Max 64 Bytes)
CRC 16 Check
2.4G / ISM Band Radio
Physical
MRFI
Layer
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802.15.4 OSI Layers

	2 Bytes	1 Byte	0-20 Bytes	<= 104B	2 Bytes
ACK Frame	Frame Control	Sequence Number	Frame Check		
Data Frame	Frame Control	Sequence Number	Address Info	Data Payload	Frame Check
Command Frame	Frame Control	Sequence Number	Address Info	Command Payload	Frame Check
Beacon Frame	Frame Control	Sequence Number	Address Info	Beacon Payload	Frame Check

MAC Layer

Synchronization Header	Radio Specific Header	Radio Payload (Max 127 Bytes)

2.4GHz/Sub 1GHz Radio

Physical Layer

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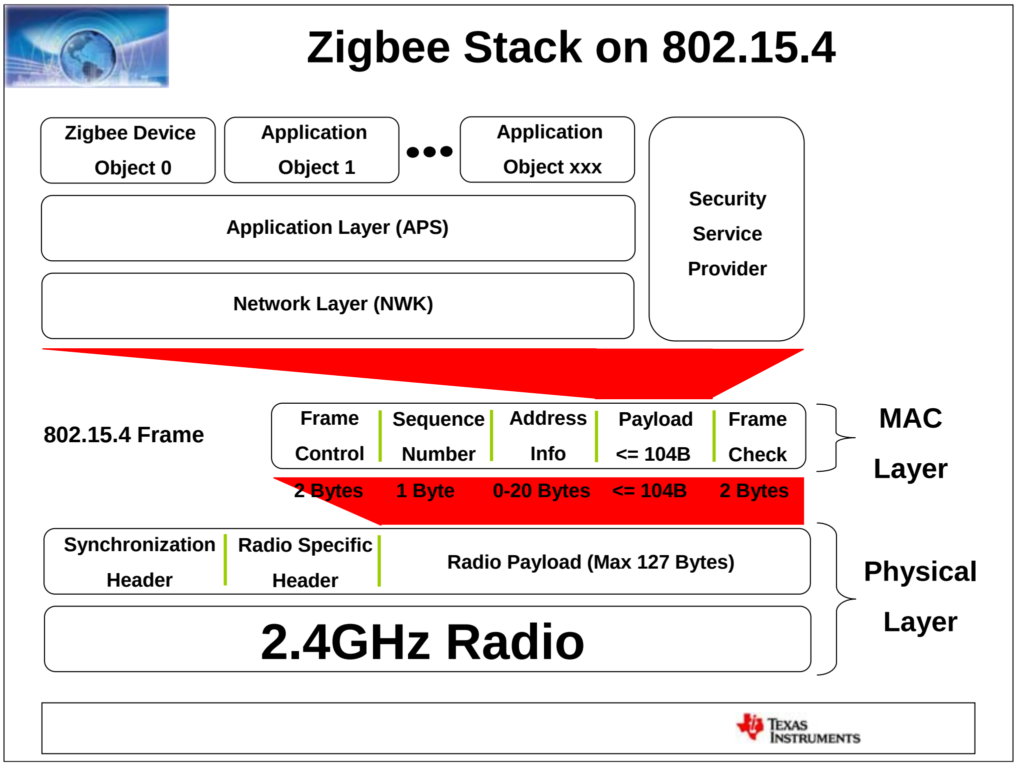
Zigbee Stack on 802.15.4
Zigbee Device Object 0
Application Object 1
Application Object xxx
Application Layer (APS)
Network Layer (NWK)
Security Service Provider
802.15.4 Frame
Frame Control
Sequence Number
Address Info
Payload <= 104B
Frame Check
2 Bytes
1 Byte
0-20 Bytes
<= 104B
2 Bytes
MAC Layer
Synchronization Header
Radio Specific Header
Radio Payload (Max 127 Bytes)
2.4GHz Radio
Physical Layer
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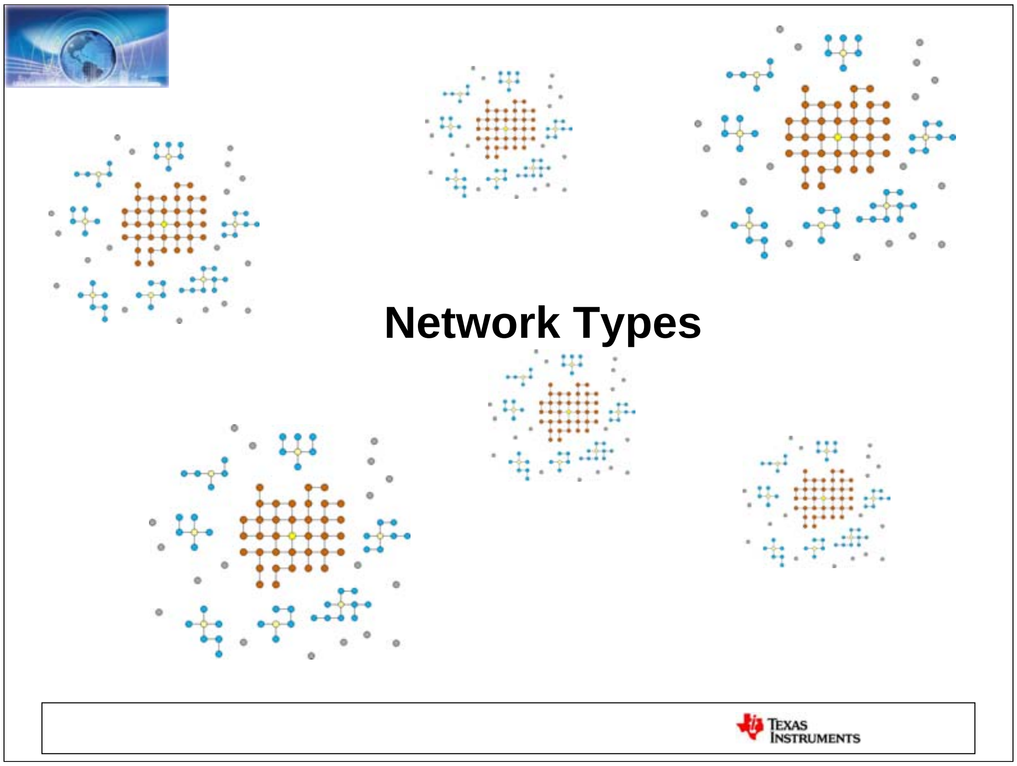
Network Types
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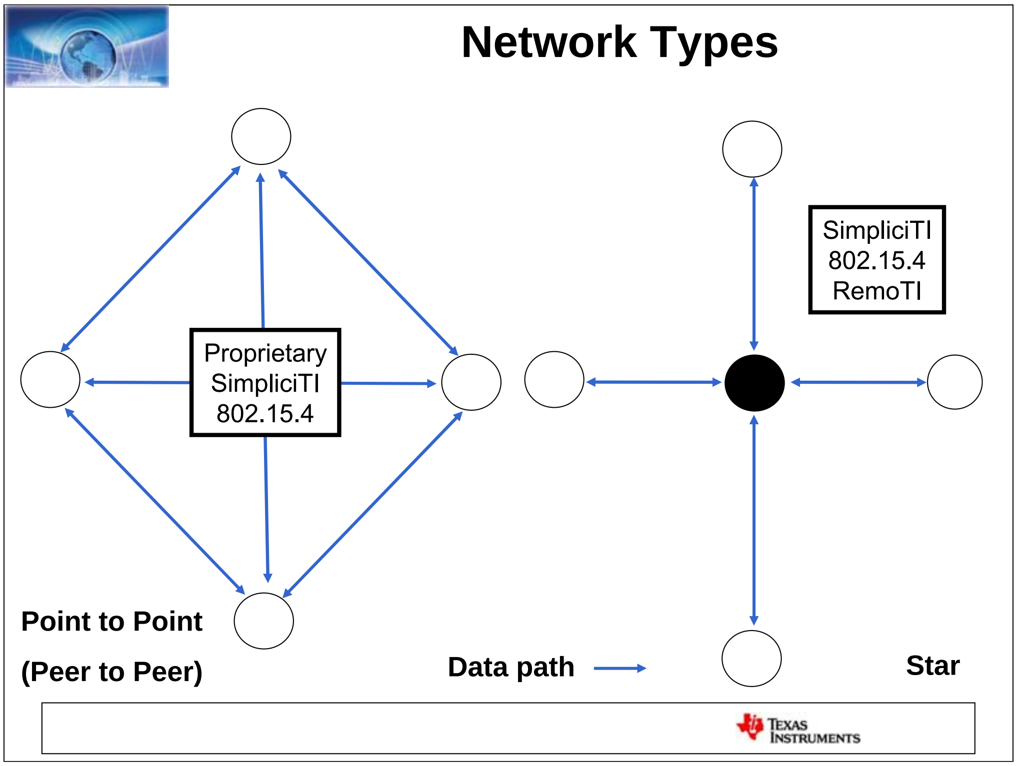
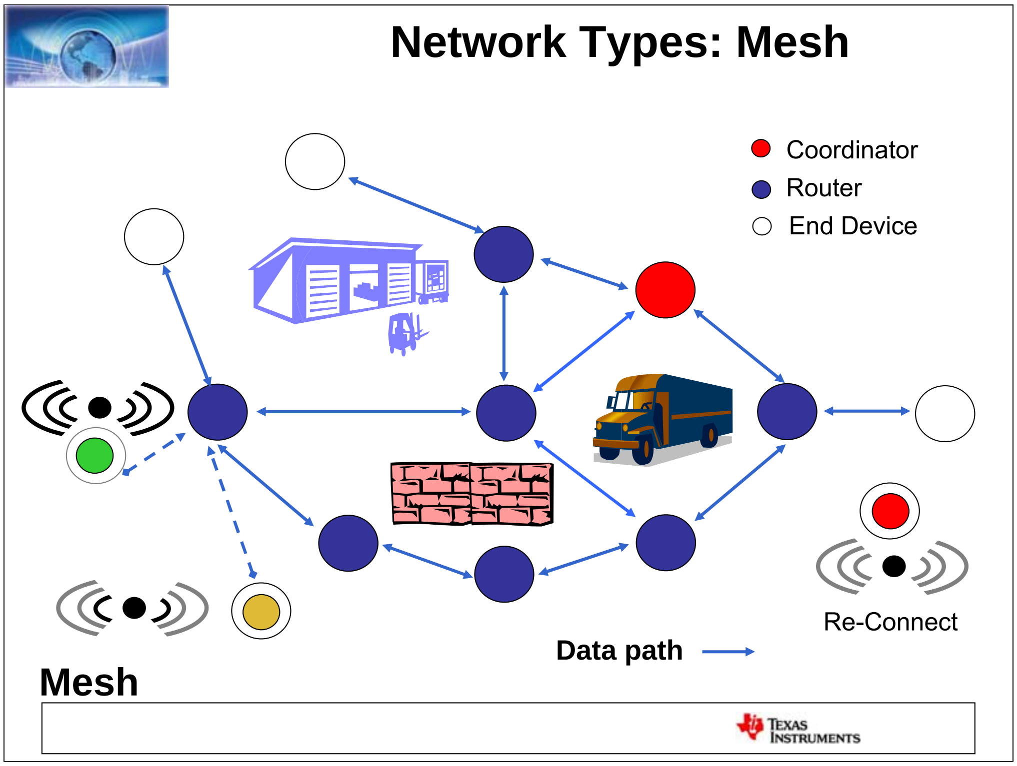

Network Types
Proprietary
SimpliciTI
802.15.4
SimpliciTI
802.15.4
RemoTI
Point to Point
(Peer to Peer)
Data path
Star
Texas Instruments


Network Types: Mesh
Coordinator
Router
End Device
Re-Connect
Data path
Mesh
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LPRF Tools

Software Stacks

- Z-Stack - ZigBee Protocol Stack from TI
  - One of the first ZigBee stacks to be certified for the ZigBee 2006 certification
  - Supports multiple platforms such as CC2480, CC2431 and CC2520+MSP430 platform
  - ZigBee 2007/PRO available on CC2530 and MSP430 platform
- TIMAC
  - A standardized wireless protocol for battery-powered and/or mains powered nodes
  - Suitable for applications with low data-rate requirements
  - Support for IEEE 802.15.4-2003/2006
- SimpliciTI Network Protocol – RF Made Easy
  - A simple low-power RF network protocol aimed at small RF networks
  - Typical for networks with battery operated devices that require long battery life, low data rate and low duty cycle
- RemoTI Remote control
  - Compliant with RF4CE V1.0
  - Built on mature 802.15.4 MAC and PHY technology
  - Easy to use SW, development kits and tools

All software solutions can be downloaded free from the TI web

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Development Kits

Example: CC1110-CC1111DK

The typical LPRF development kit contains

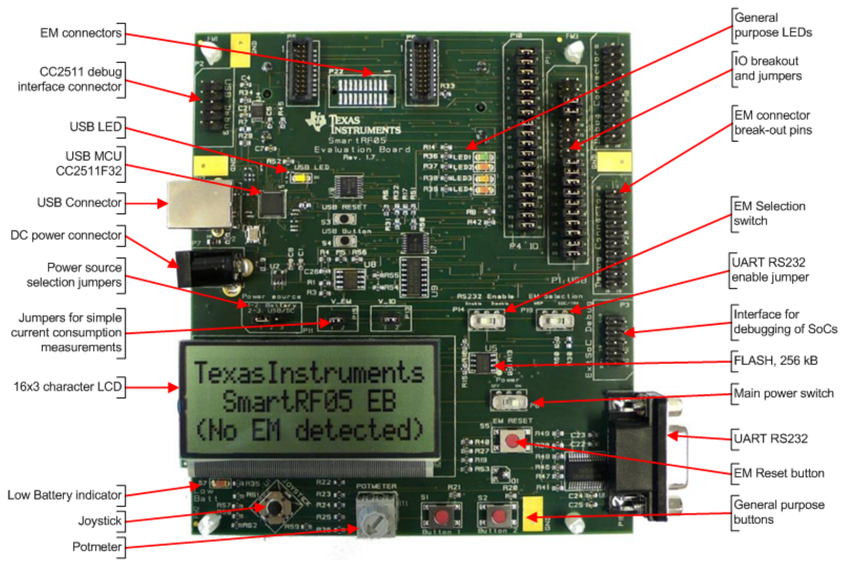
2x RF EMs
2x SmartRF Boards
2x Antennas
Div cables
Div documentation

Preprogrammed with a packet error rate (PER) test for practical range testing

When ordering DKs for under 1GHz, make sure you order the right frequency range:

- 433MHz
- 868-915MHz

SmartRF Evaluation Board



SmartRF Studio

- **SmartRF Studio is a PC application to be used together with TI's development kits for** *ALL* **CCxxxx RF-ICs.**

- **Converts user input to associated chip register values**
  - ***RF frequency***
  - ***Data rate***
  - ***Output power***

- **Allows remote control/configuration of the RF device when connected to the PC via a SmartRF Evaluation Board**

- **Supports quick and simple performance testing**
  - ***Simple RX/TX***
  - ***Packet RX/TX***
  - ***Packet Error Rate (PER)***

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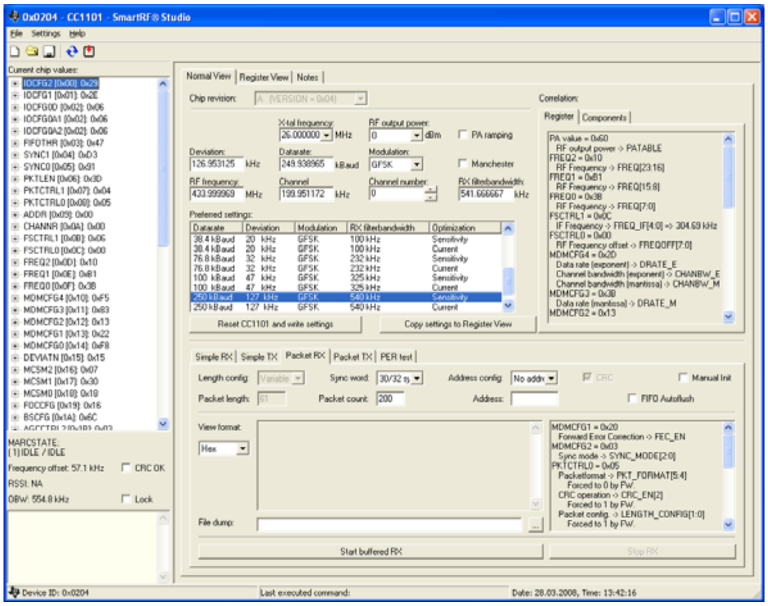
Download the tool here: www.ti.com/smartrfstudio

The tool is updated frequently – make sure you have the latest revision for the most up to date register settings and features.

SmartRF Studio



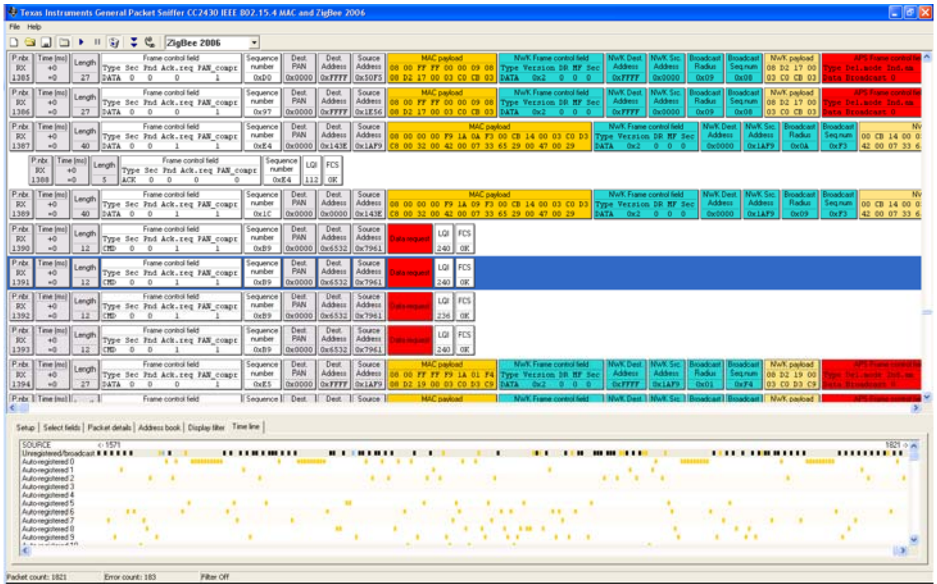
Packet Sniffer

- Captures and parses packets going over the air
- Useful debugging tool for any protocol/SW designer
- PC Tool available for FREE

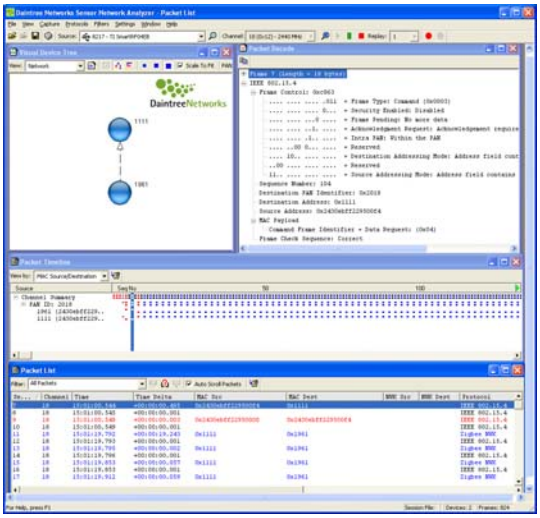
- Supported protocols
  - SimpliciTI
  - RemoTI (RF4CE)
  - ZigBee
  - Generic protocol

- Hardware required for packet sniffing
  - CC2430DB
  - SmartRF04EB + CC1110/CC2510/CC2430
  - SmartRF05EB + CC2520/CC2530

Packet Sniffer



Daintree Sensor Network Analyzer



- Professional Packet Sniffer
- Supports commissioning
- Easy-to-use network visualization
- Complete and customizable protocol analyzer
- Large-scale network analysis
- Performance measurement system

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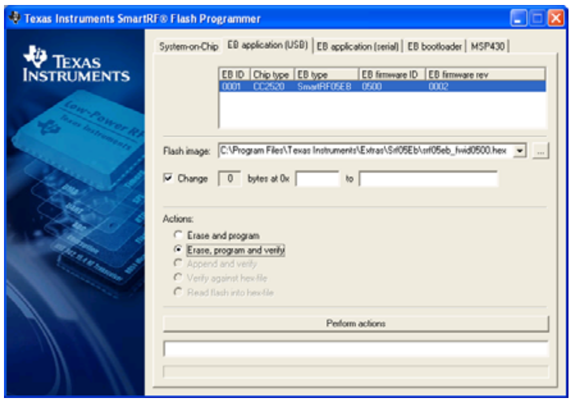
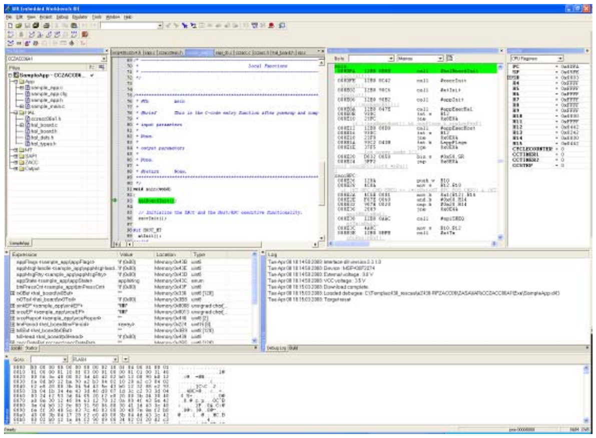
SmartRF Flash Programmer



- **Use this tool to program an application on a System-on-Chip CC1110, CC1111, CC2510, CC2511, CC2430, CC2431**
- **Program IEEE addresses on CC2430/CC2431**
- **Can also be used to program any MSP430 using either MSP-FET430UIF or eZ430 Emulator Dongle**
- **Firmware upgrades on the Evaluation Boards**

IAR Embedded Workbench



- IDE for software development and debugging
- Supports
  - All LPRF SoCs
  - All MSP430s
- 30 day full-feature evaluation version
  - Extended evaluation time when buying a SoC DK or ZDK
- Free code-size limited(4k) version

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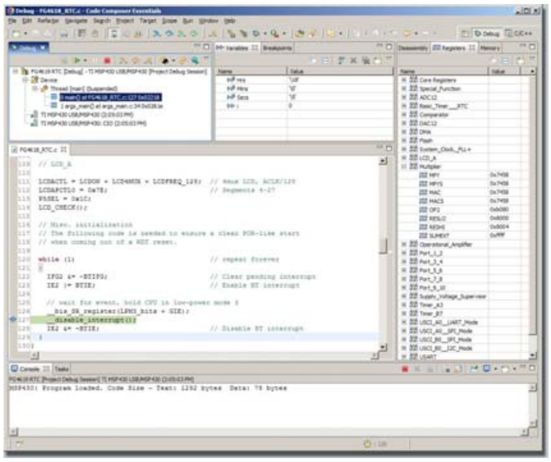
Code Composer Essentials



- **IDE for software development and debugging**
- **Supports**
  - **All MSP430s**
- **Free code-size limited (16k) version**

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Getting Started with TI LPRF

Questions?