RF Hardware System Design

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Abstract

- There are several aspects to consider when designing an RF system. This presentation discusses
  - Regulations
  - How to select correct IC for the application
  - HW design issues
  - PCB layout issues
  - HW testing
- There are also links to resources provided by TI to make it easier for customers to finalize their products.

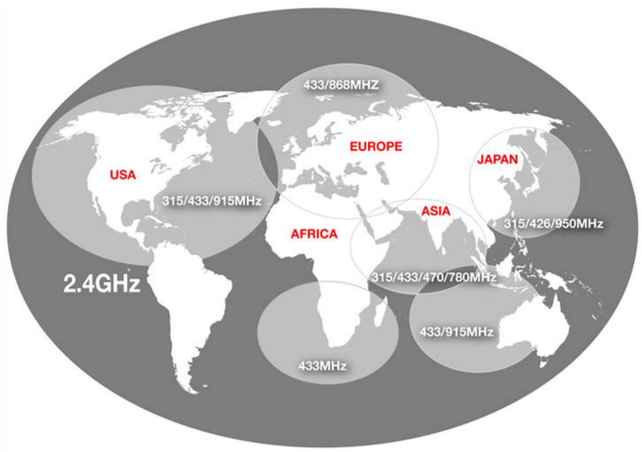
Planning and Evaluation Phase

- Regulations
- Selecting correct chip for the application

TEXAS INSTRUMENTS

Frequency Regulations

- End products must comply with national regulations



- Know the regulations before you start the development

The end product must comply with local regulatory requirements in all countries it is going to be sold. Several countries follow the same standard or have similar requirements.

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

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

SRD – Short Range Device

ISM – Industrial Science and Medical

Regional Differences

- Europe – ETSI
  - 433/868 MHz
  - 2.4 GHz
- USA – FCC
  - 315/402/915 MHz
  - 2.4 GHz
- Japan – ARIB
  - 315/426/950 MHz
  - 2.4 GHz
- China
  - 470 MHz
  - 2.4 GHz
- Other national requirements

European Telecommunications Standards Institute – ETSI responsible for frequency regulations in Europe. http://www.etsi.org/

Federal Communications Commission – FCC is responsible for frequency regulations in USA. http://www.fcc.gov/

Association of Radio Industries and Businesses – ARIB is responsible for frequency regulation in Japan. http://www.arib.or.jp/english/

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

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

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

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

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

Regulatory Requirements

- Before starting any development you need to look into and understand the regulatory requirements
  - Frequency bands
  - Output power
  - Spurious emission
  - Adjacent channel power
  - Occupied bandwidth
  - Sensitivity
  - Selectivity and blocking
  - Duty cycle
  - Listen Before Talk
  - Frequency hopping

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Spurious emission in US: The general limits for the emission of intentional or unintentional radiators are given in section 15.209. Above 960 MHz the limit is -41.2 dBm (500 uV/m at 3 m distance). When operating under section 15.249 the general limits apply. When operating under section 15.247 the spurious emission must only be 20 dB below the carrier UNLESS it falls within one of the restricted bands defined in section 15.205. As an example, when operating in the in the 902-928 MHz frequency range the 3^{rd}, 4^{th}, 5^{th}, and 6^{th} harmonic falls within restricted bands. In the restricted bands the general limits of -41.2 dBm apply.

A duty cycle correction factor can be used above 1000 MHz. For determining the duty cycle correction factor when the period is < or equal 100 ms, use the equation 20 log (on time/period). When the period is greater than 100 ms, use the worst case 100 ms (the 100 ms with the greatest on time). Per Section 15.35(b) the peak limit is 20 dB above the average limit of -41.2 dBm

Adjacent channel power is the part of the total power output of a transmitter which falls within a specified bandwidth centered on the nominal frequency of either of the adjacent channels.

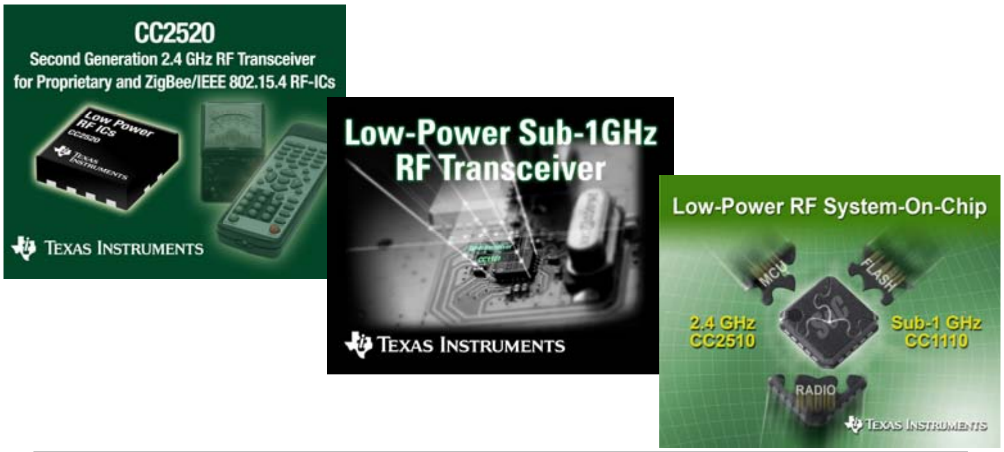
Selectivity and **blocking** is a measure of the capability of the receiver to operate satisfactorily in the presence of an unwanted signal. Selectivity is usually specified for adjacent and alternate channels and blocking for other frequency offsets.

Duty cycling and **LBT** is used in Europe to allow more users to ”share the air”. Some alternatives to duty cycling to allow more users are low output power (Japan and US) and frequency hopping . **Frequency hopping**: Check standard for mimimum number of channnels, BW and output power

The different standards have different requirements on how the different parameters shall be measured.

Which IC to Choose for My Application?

- There might not be an easy answer to this question as it depends on several parameters and application scenarios



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Go through questions in the next slide to find best chip for the application

What are Your Requirements?

- Operating frequency vs range and market
- Data rate vs range and active current consumption
- Regulatory requirements
  - E.g. Narrowband in Japan or Europe
  - E.g. 780 MHz in China
- Standard or proprietary solution
- Radio + MCU or SoC solution
- USB interface option
- Application scenarios
- Digital feature set
  - Features that put less burden on the MCU

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The operating frequency affects the propagation of an RF signal. Theoretically, for same output power, sensitivity, and antenna gain, reducing the frequency by a factor of 2 doubles the range. Thus, the choice of frequency has a big impact on the range of a RF system.

For some markets, e.g. RKE, range is important and regional differences in regulator requirements might lead to different HW versions of the product for different markets. E.g. 868 MHz in Europe, 915 MHz in US.

The operating frequency also depends on the market. A game pad for instance would typically use the global 2.4 GHz. Same is true for Guitar Hero. Long range is typically not required for these applications.

High data rate requires wider receiver filter bandwidth. A wider receiver filter accepts more noise into the receiver and reduces the sensitivity and hence the range of the system. Different devices do not necessarily support the same maximum data rate so it is important to choose a device that supports the desired data rate. High data rate means less time in RX/TX and hence lower active current consumption.

ZigBee® and IEEE 802.15.4 requires a specific modulation format. In order to comply with these standards it is important to choose a chip that supports this modulation format.

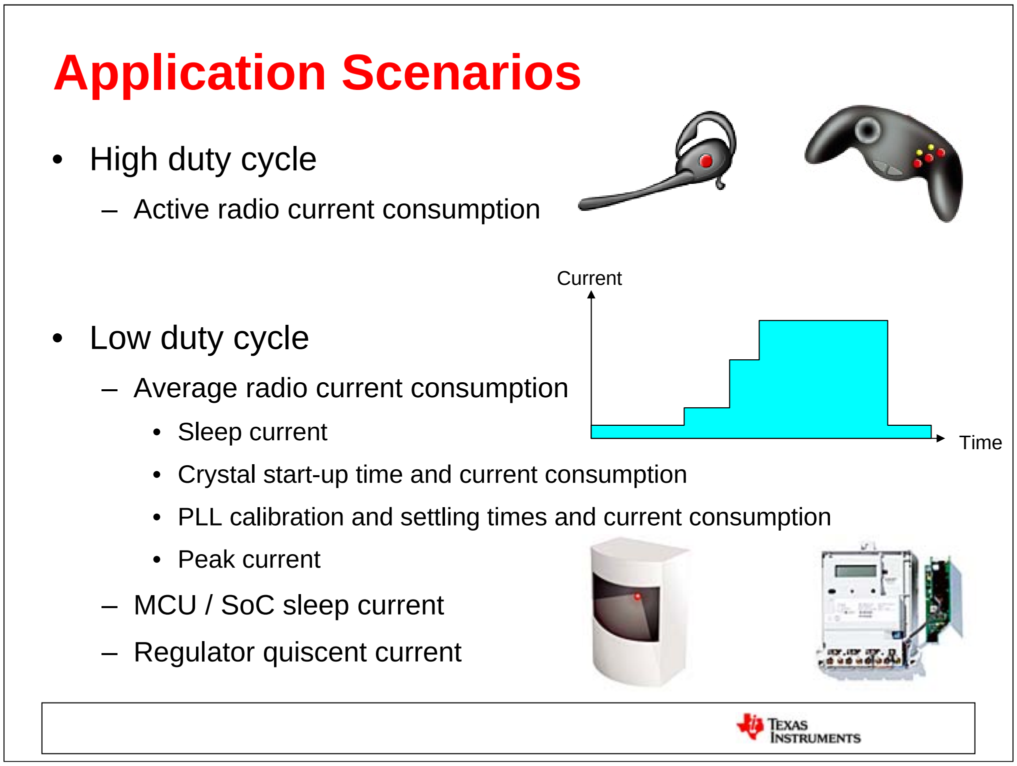
The choice between a System-on-Chip solution or a separate transceiver and micro controller will affect the cost and required board space.

SoC (e.g. CC2510, CC1110, CC2511, CC1111)

- Easy manufacturing
- No communication overhead because radio can send data directly from memory
- Low system cost if the application is a good fit with the MCU and peripherals of the SoC
- Small size

•2-chip solution (e.g. MSP430 + CC1101, CC2500)

- Flexibility: MCU can be tailored to system requirements
- Different MCU options can be used in the same system
- Ultra low power features of the MSP430 enables very low power consumption, especially in applications where MCU is used often without RF



High duty-cycle applications (medium/short battery lifetime/operating time) includes wireless game controllers, wireless audio etc.

If the radio is on most of the time, and the surrounding electronics does not add much to the total current budget, the radio active current consumption is the most important parameter.

Low duty-cycle applications (years of battery lifetime/operating time) includes sensors etc.

The system must be considered; MCU sleep current and regulator quiescent current are just as important as the radio current consumption. Critical that the radio on-time, crystal start-up time, and PLL calibration and settling times are as short as possible. Power down current of the radio is a major parameter.

Important points for minimum average current consumption:

•Low SLEEP current

•Fast crystal start-up time and low crystal current consumption

•Fast PLL calibration (and settling) and low current consumption

•Terminate RX if there are no signal at the antenna (Carrier Sense)

•Low RX peak current

•Minimum duty cycle

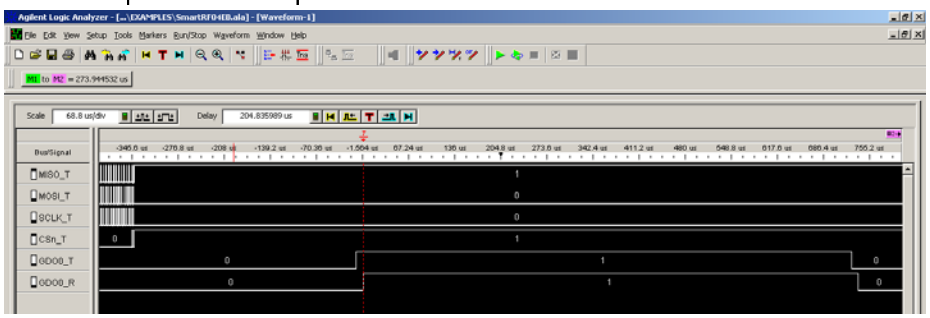
•Minimum MCU activity

Digital Features (1)

Feature: Interrupt to MCU when data sent/received
Benefit: MCU can do something else useful or be put to sleep

TX:
- Write data to TX FIFO
- Set into TX with one simple command
- Interrupt to MCU that packet is sent

RX:
- Strobe into RX with one simple command
- Interrupt to MCU that packet is received
- Read RX FIFO



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There will be minimum MCU activity if the MCU is only notified when data is received or transmitted and if the MCU can be put into RX/TX with a simple (1 byte) command.

<u>**Example:** CC2500/CC1100/CC1101</u>

•The GDO0_T signal goes high after the sync word is transmitted.

•The packet has been sent when the GDO0_T pin is de-asserted.

•The transmitter will be in the state determined by the programmed TX OFF-mode after GDO0_T is de-asserted.

•The GDO0_R signal goes high after the sync word is received.

•The packet has been received when the GDO0_R pin is de-asserted.

•The receiver will be in the state determined by the programmed RX OFF-mode after GDO0_R is de-asserted.

CC2500/CC1101 can be put into RX/TX with a simple (1 byte) command.

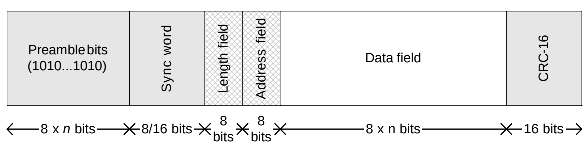
The MCU can be put into low power mode and wait for interrupt.

For details on CC2500/CC1101 GDO pin usage see DN505. http://www.ti.com/lit/swra121

Digital Features (2)

Feature: On-chip packet handling
Benefit: MCU can do something else useful or be put to sleep

- Preamble generation
- Sync word insertion/detection
- Address check
- Flexible packet length
- Automatic CRC



It is an advantage to have HW support for packet oriented radio protocols built into the radio. Packet handling features (automatic insertion of preamble and sync word, CRC insertion/check, interrupt when packet sent/received etc.) puts less burden on the MCU. Putting the MCU in low power mode until interrupt received reduces current consumption.

In transmit mode, the packet handler could add the following elements to the packet stored in the TX FIFO:

•A programmable number of preamble bytes.

•A synchronization Word.

•Compute and add a CRC checksum over the data field.

In receive mode, the packet handling support could de-construct the data packet:

•Preamble detection

•Sync word detection

•Address check?

•Compute and check CRC?

Digital Features (3)

Feature: a) Discarding false/error packets in RX and b) do a CRC check

Benefit: Minimize current consumption

a) Minimize time in RX processing false packets
- Check carrier sense
- Check for valid preamble
- Check for valid sync word
- Check length byte
- Check for valid address

b) Only notify MCU when a valid packet has been received
- Automatic CRC check
  - Packet discarded if CRC fails
  - Interrupt to MCU if CRC OK

If the received signal qualifiers are integrated in the radio, false/error check can be done without MCU intervention.

Put MCU into low power mode and wait for an interrupt that a valid packet has been received to minimize current consumption. Transceivers from TI have digital output pins, which generates an interrupt to the MCU if a packet has been received with OK CRC.

Selection Guide

PRODUCT COMPARISON GUIDE FOR 2.4 GHz

FEATURES/PRODUCT	CC2400	CC2420	CC2430	CC2431	CC2550	CC2500	CC2510
Product type	Transceiver	Transceiver	SoC	SoC	Transmitter	Transceiver	SoC
Programmable frequency, MHz	2400 – 2483	2400 – 2483.5	2400 – 2483	2400 – 2483	2400 – 2483	2400 – 2483	2400 – 2483
Frequency resolution	1 MHz	1 MHz	1 MHz	1 MHz	427 Hz	427 Hz	427 Hz
Operating supply voltage	1.6 – 2.0 V	2.1 – 3.6 V	2.0 – 3.6 V	2.0 – 3.6 V	1.8 – 3.6 V	1.8 – 3.6 V	2.0 – 3.6 V
Current consumption (RX) at 0 dBm (TX)	24.0 mA 19 mA	19.7 mA 17.4 mA	27 mA 24.7 mA	27 mA 24.7 mA	N/A 22.8 mA	12.8 mA 21.6 mA	22 mA 23 mA
Data rate (max)	1.0 Mbps	250 kbps	250 kbps	250 kbps	500 kbps	500 kbps	500 kbps
Receiver sensitivity	-101 dBm at 10 kbps and BER = 10-3 -85 dBm at 1Mbps and BER = 10-3	-94 dBm at PER < 1%	-94 dBm at PER < 1%	-94 dBm at PER < 1%	N/A	-89 dBm at 250 kbps BER =10-3 -99 dBm at 10 kbps	-88 at 250 kbps BER = 10-3 -98 dBm at 10 kbps
Programmable output power ranging from	-25 to 0 dBm	-25 to 0 dBm	-24 to 0 dBm	-24 to 0 dBm	-20 to 1 dBm	-20 to 1 dBm	-30 to 1 dBm
Multi channel systems/FHSS	Yes	Yes	Yes	Yes	Yes	Yes	Yes
RSSI output	Digital	Digital	Digital	Digital	N/A	Digital	Digital
Integrated bit synchronizer	Yes	Yes	Yes	Yes	N/A	Yes	Yes
Integrated packet handling	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Data buffering	32 bytes FIFO	128 bytes TX 128 bytes RX	128 bytes TX 128 bytes RX DMA	128 bytes TX 128 bytes RX DMA	64 bytes	64 bytes TX 64 bytes RX	128 bytes (TX) 128 bytes RX DMA
Internal RF switch/IF Filter	Yes	Yes	Yes	Yes	N/A	Yes	Yes
RF chip interface	Differential	Differential	Differential	Differential	Differential	Differential	Differential
Package type	QFN-48, 7x7 mm	QLP-48, 7x7 mm	QLP-48, 7x7 mm	QLP-48, 7x7 mm	QLP-16, 4x4 mm	QLP-20, 4x4 mm	QLP-36, 6x6 mm
Complies with EN 300 220, FCC CFR 47, part 15 and ARIB STD-T66	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Integrated microcontroller	-	-	Yes	Yes	-	-	Yes
Voltage regulator	-	2.1 – 3.6 V input voltage	2.0 – 3.6 V input voltage	2.0 – 3.6 V input voltage	1.8 – 3.6 V input voltage	1.8 – 3.6 V input voltage	2.0 – 3.6 V input voltage
IEEE 802.15.4 compliant	-	Yes	Yes	Yes	-	-	-
Hardware MAC encryption/ authentification	-	Yes	Yes	Yes	-	-	-
Program memory	-	-	32 kB/64 kB/ 128 kB Flash	128kB Flash	-	-	32 kB Flash
Data memory	-	-	4 kB + 4 kB SRAM	4 kB + 4 kB SRAM	-	-	4 kB SRAM

The Low-Power RF selection guide contains a separate comparison chart for 2.4 GHz and sub-1 GHz products. This makes it easy to compare the different products and choose the right part. The Low-Power RF selection guide can be downloaded from www.ti.com/lprf. On the same web page you will also find two online quick search tools that can be of help.

Available at: http://www.ti.com/lprf

Get a Development Kit!

- Evaluate the product
  - Understand the device operation
  - Range testing
  - RF performance
  - Digital features
- Develop a prototype
  - Use MCU and various peripherals on motherboard together with radio
  - Use your own MCU and connect to radio
- Run application examples available from the web
- Use SmartRF® Studio to find optimum register settings

Do not Hesitate to Ask for Help

- Ask for help at an early stage
  - Do not wait until you are into the development phase
  - Reduce time to market
  - Minimize development risk
  - Sometimes an RF specialists is required

- Contact your local FAE

- Customer Support
  http://www.ti.com/support
  Email, Product Information Centers: Americas, EMEA, Japan, Asia

- TI LP RF forum / E2E community
  http://www.ti.com/lprf-forum

Where to ask for help

E2E – Engineer to Engineer

FAQs, Design and Application Notes

- FAQs: https://community.ti.com/forums/51.aspx
- DN: https://community.ti.com/search/SearchResults.aspx?tag=DN&orTags=0
- AN: https://community.ti.com/search/SearchResults.aspx?tag=AN&orTags=0

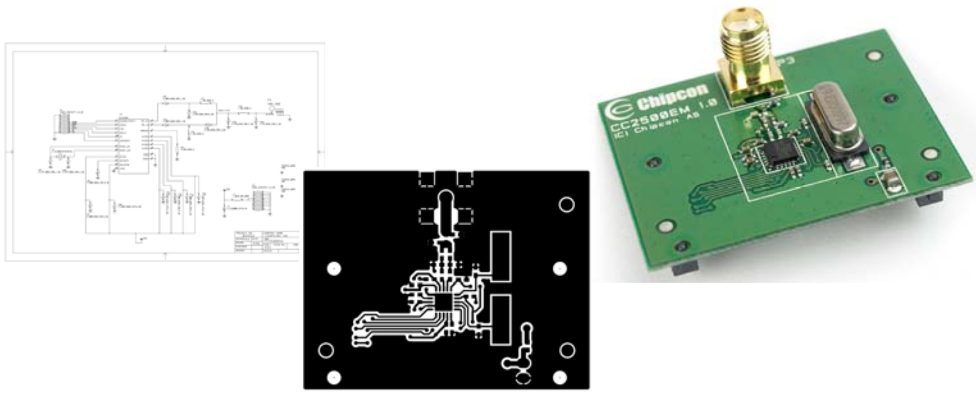
Where to find FAQs, Design- and Application Notes

Development Phase

- Decoupling capacitors
- Crystal
- Balun
- Range extension
- Powering LPRF products
- PCB layout

HW Development

- Copy the reference design
  - TI provides a reference design for all LPRF products
  - Important to make an exact copy of both layout and schematics



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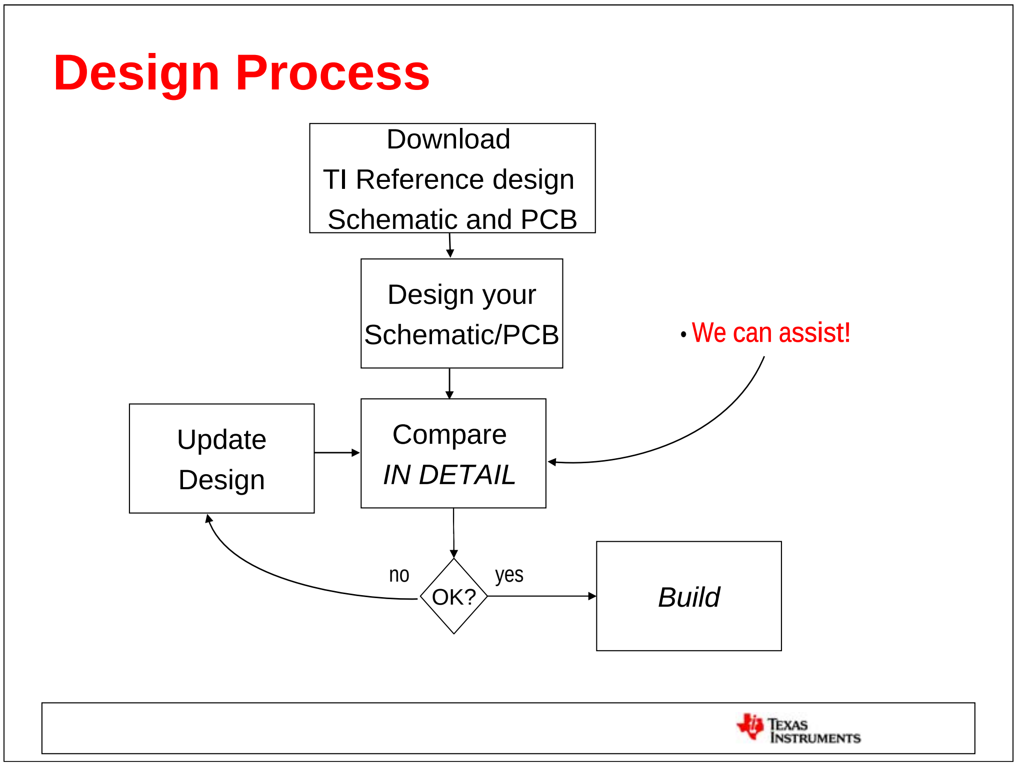
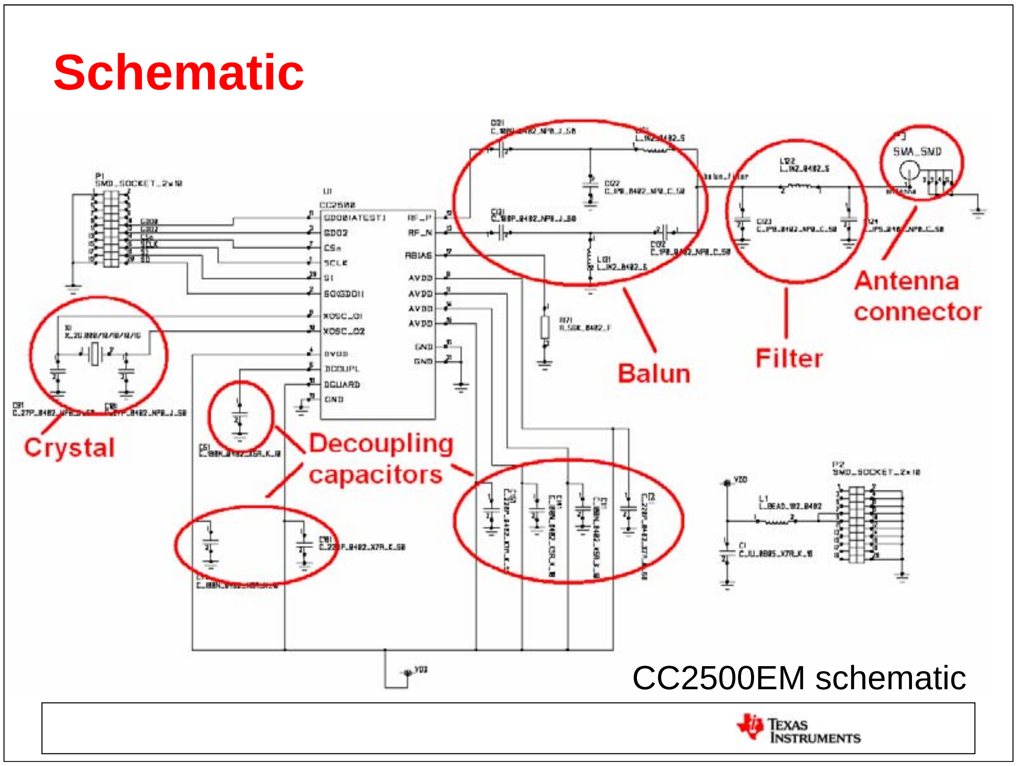
TI provides schematics and Gerber files. Use the exact same values and placement of decoupling capacitors, balun, matching, and filter components.



Design review is the best way to avoid unnecessary board spins.

Copy ***exactly*** the reference design. Use our Gerbers.

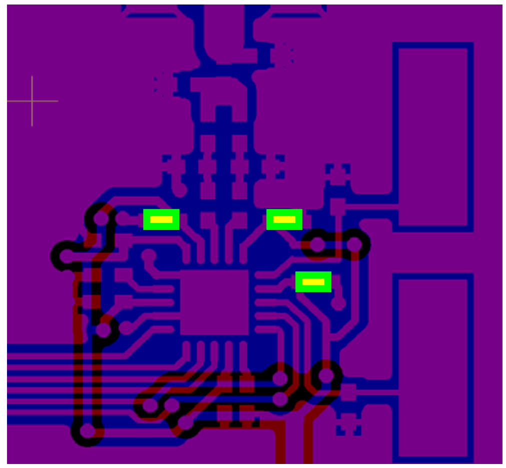


The schematics in the reference designs show the value of each decoupling capacitor and which pin they shall be placed adjacent to.

It is important to use the exact same values for the components in the balun, match, and filter which is placed between the antenna and the chip.

Decoupling Capacitors

- Proper decoupling important for
  - Optimum performance
  - Regulatory issues



TEXAS INSTRUMENTS

Poor decoupling could lead to:

•Increased phase noise

•Spurious outputs

•Violate adjacent channels in TX

•Decreased sensitivity and selectivity in RX

Notes on decoupling capacitors:

•Ensure decoupling capacitors are on same layer as active component for best results

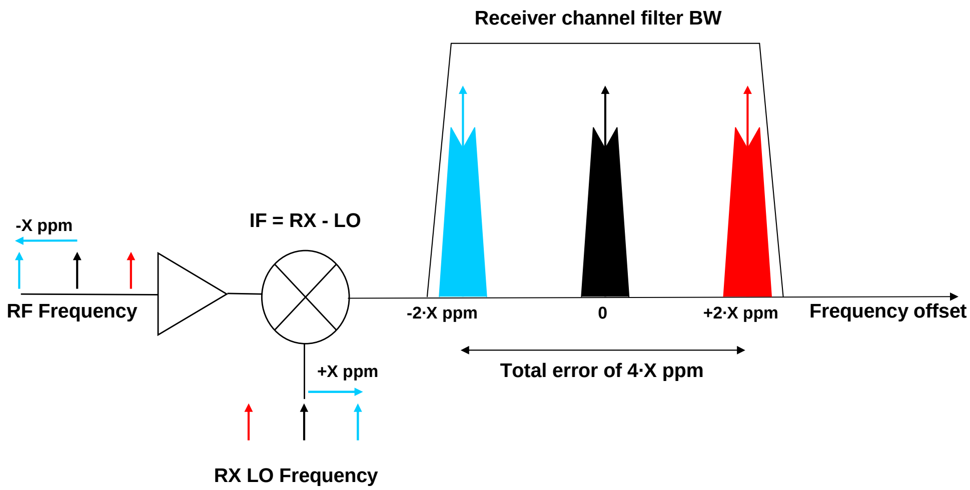
•Route power into the decoupling capacitor and then into the active component

•Each decoupling capacitor should have a separate via to ground

•The decoupling capacitor shall be placed close to the pin it is supposed decouple

Crystal Accuracy

- Compromise between RF performance and crystal cost



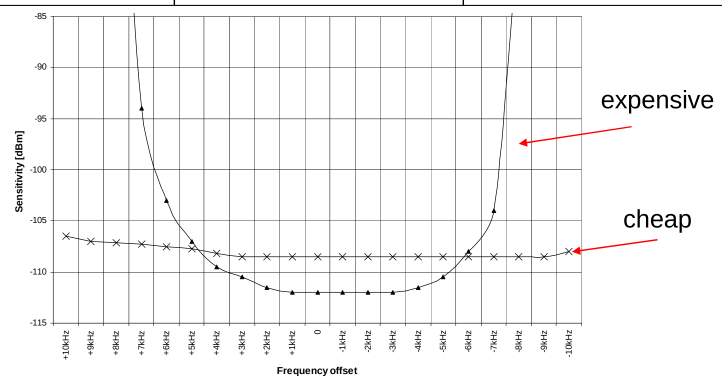
Wider RX filter bandwidth:
•Reduced sensitivity and close-in selectivity
•Temperature compensation might not be neccessary
•Allows cheaper (i.e. less accurate) crystal to be used

If the RX filter BW changes by a factor X, the theoretical sensitivity changes by 10log(X)

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

CC1020 Crystal Accuracy Example

Max frequency offset	~ ±5 kHz	~ ±20 kHz
Crystal accuracy	±5.7/2.8 ppm	±23/11.5 ppm
Sensitivity	-112/-111 dBm	-107/-107 dBm
Range	X meters	X/1.6 meters



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The numbers are for 433/868 MHz operation using CC1020. In the calculations it is assumed that the receiver and transmitter use the same type of crystal and drift in opposite directions. This is a worst case scenario.

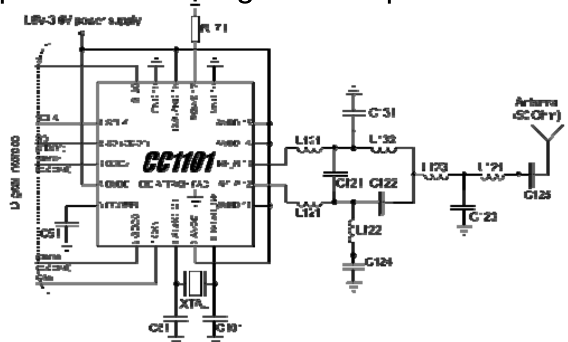
19.2 kHz and 51.4 kHz RX filter bandwidth were used in the sensitivity vs frequency offset measurements

Narrowband applications in Europe (EN 300 220): Maximum ±5.8/2.9 ppm frequency error at 433/868 MHz for 25 kHz channel spacing

Narrowband applications in Japan (ARIB STD T-67): Maximum ±4 ppm frequency error at 426 MHz for 12.5 kHz channel spacing

Balun

- **In TX:** Convert from differential to single ended signal and provide optimum matching for lowest possible current consumption and highest possible output power
- **In RX:** Convert from single to differential ended signal and provide optimum matching for best possible sensitivity



The word filterbalun is in this presentation used to describe all the components necessary to implement a balun, filter and to ensure proper impedance matching between the radio and the antenna. A balun is a network that transforms from a balanced to an unbalanced signal, hence the name balun.

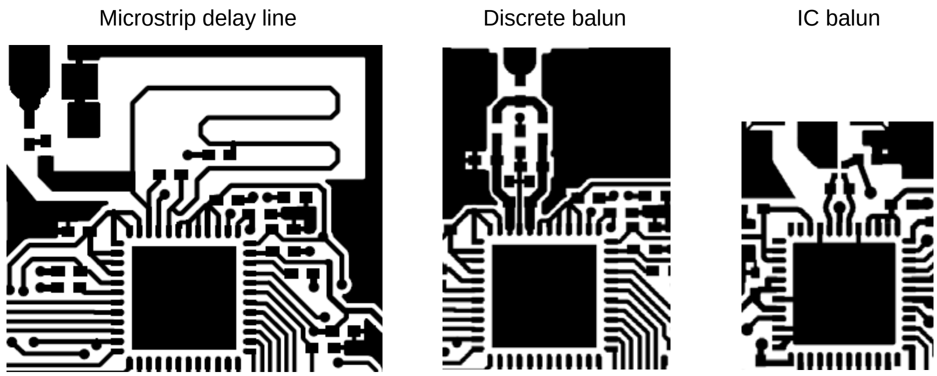
The balun has a ±90 degrees phase shift implemented by using a low pass filter and a high pass filter. The important part is to keep the balun as symmetrical as possible. Therefore the trace length from the single ended port to each of the RF–pins should be equal to achieve best amplitude and phase balance in the balun. An unbalance in the balun causes higher harmonic level, especially at the 2nd and 4th harmonic. Another effect of having an unsymmetrical balun is reduced output power at the single ended side of the balun. Both component values and component placement is important to achieve best possible symmetry in the balun.

Notes on CC11xx: An ideal output signal from the CC11xx products in TX mode is a square wave signal at the RF_P and RF_N pins and a sine wave at the antenna port. To achieve this, the filterbalun must reflect the harmonics back towards the RF_P and RF_N ports. The shape of the square wave pulse depends on the impedance at the different harmonics. Preferably the odd harmonics should be reflected back towards the chip with high real part of the impedance. The current consumption in TX depends on the shape of the signal at RF_P and RF_N. Lowest possible current consumption is achieved by having the odd harmonics (3rd and 5th) reflected back as described above. Unexpected high current consumption in a design may be caused by incorrect or missing reflection of harmonics. The simplest way of reflecting the harmonics towards the chip is to have a differential low pass filter between the CC11xx and the balun. Ideally the series inductors, L121 and L131, will reflect harmonics towards the chips with high real part of the impedance. The low pass filter will also lower the harmonics level into the balun and reducing the risk of having unwanted radiated power through the balun and the single ended filter.

See Design Note DN017 for more details: http://www.ti.com/lit/swra168

Different Balun Implementations

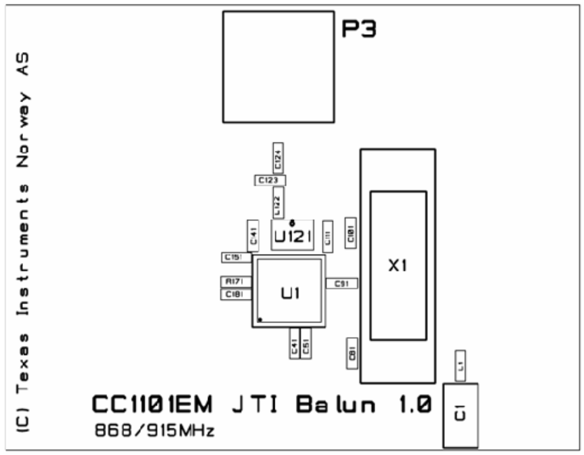
- Trade-off: PCB area versus cost



No routing under the balun!

JTI Balun for CC1101

- Same performance as discrete solution
- Component placement influences RF performance



Johanson Technology Balun for CC1101:

The component placement influences the RF performance. In the event that the reference design [http://www.ti.com/lit/zip/swrc112] can not be copied then it is important to position the inductor L122 so that the coupling effects to the Matched Balun Filter U121 are minimized as much as possible. Experiments with placing L122 in parallel to U121 showed that coupling was evident and the Matched Balun Filter performance was not optimum. Keep the inductor L122 at 90 degrees to the balun as shown in the figure or position it on the left side of U121 to avoid coupling to pin 6 of U121.

IC Balun Reference Designs

- CC2420 + Anaren, AN054
  - http://www.ti.com/lit/swra155
- CC2430 + Anaren, AN055
  - http://www.ti.com/lit/swra156
- CC11xx + Johanson, DN025
  - http://www.ti.com/lit/swra250

- *CC2500/CC251x* + *Anaren*
  - http://www.anaren.com/content/File/Ann_CC2500_Rev_B.pdf
- *CC2430* + *Johanson*

- The ones in *italic* are not yet published on TI web

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Anaren use 2 external components

Johanson might need additional LC LP filter. Depends on output power and duty cycle (FCC relaxation factor). See design note DN025 for details.

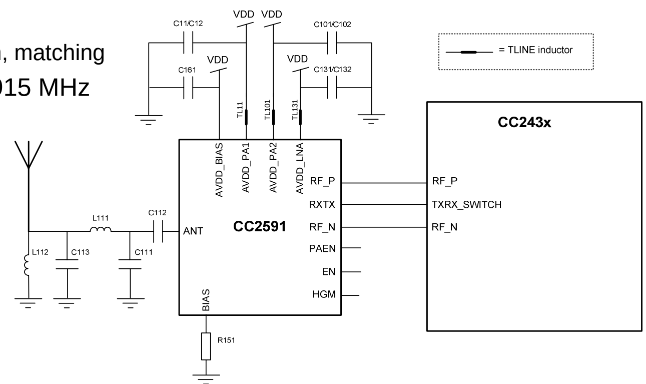
Matching

- Tune matching network to maximize output power while maintaining good spectrum properties
- Optimized for output power does not necessarily mean best sensitivity

We have seen that when customers do an optimization for output power, they can get more power, but they get it by putting out more energy in the band with a bunch of waveform distortion, so the spectrum looks more like the plot on the right instead of the desired spectrum. The EVM will be poor. The lesson here is to make sure that you are optimizing both output power and EVM – not just using a power meter to get maximum power.

Extending Range (1)

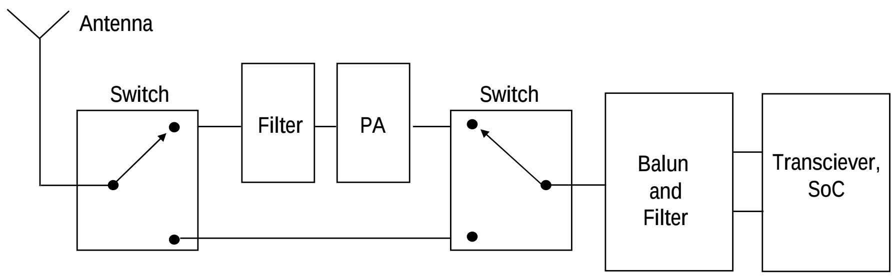
- Add external LPRF range extender
  - Seamless connection to LPRF transceivers and SoCs
  - CC2590/91 for 2.4 GHz operation
    - LNA, PA, balun, matching
  - CC1190 for 868/915 MHz operation
    - LNA and PA



CC2591 increases the link budget by providing a Power Amplifier (PA) for improved output power and a Low Noise Amplifier (LNA) with a low noise figure for improved receiver sensitivity. CC2591 further contains RF switches, RF matching and a balun for a seamless interface with e.g the CC2430. This allows for simple design of high performance wireless applications.

Extending Range (2)

- Add external PA to boost output power
  - Make sure harmonics are attenuated sufficiently
  - Star routing of power. Separate filtering of power (bead and capacitor or LDO)
- Large capacitor close to PA (charge reservior)



The transceiver/SoC generates harmonics and these are amplified by the external PA. The transceiver/SoC harmonics must therefore be attenuated before being fed to the external PA.

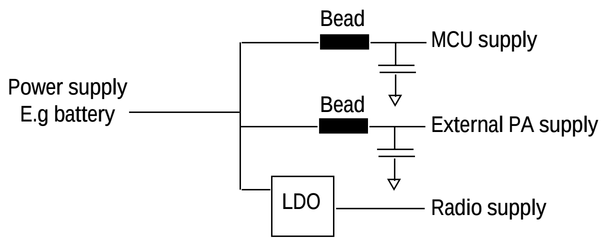
The external PA also generate harmonics. A filter must be included between the external PA and the T/R switch to get below regulatory requirements w.r.t spurious emission (harmonics). A passive LC filter can be used.

Include a large capacitor as close to external PA as possible. Basic idea is to reduce transportation of current spikes on the board and reduce voltage dip on the supply line when external PA is enabled.

Check the regulations for maximum allowed power.

Power Routing

- Separate supply lines going to MCU, radio, and range extender
  - Goal: Minimize noise from other parts interfering with radio performance
  - Star routing
  - Use L-C network or LDO
  - LDO will lower voltage drop on radio supply when external PA is switched on



Star routing is an efficient design method to minimize noise from other parts of the system interfering with radio performance.

Each power line shall be decoupled separately close to the MCU, external PA, and radio. It is also good design practice to include series beads on the different power supply lines.

Powering LPRF Products

- Batteries

- Linear Voltage Regulators (Efficiency ~ Vout/Vin, e.g 3.6 V supply and 1.8 V operating voltage ~ 50%)

- Switch Mode DC/DC Converters (Up to ~95% efficiency)
  – Buck
  – Boost
  – Buck-boost

TEXAS INSTRUMENTS

Linear Voltage Regulators

- Efficiency: $\eta = \dfrac{V_{out} \cdot \overline{I_{Load}}}{V_{in}\left(\overline{I_{Load}} + I_q\right)}$
  - e.g 3.6 V supply and 1.8 V operating voltage ~ 50%
- Low Drop-Out voltage regulators (LDOs)
- Good Power Supply Ripple Rejection (PSRR)

The major advantage of an LDO IC is its relatively “quiet” operation because it does not involve switching. In contrast, a dc/dc converter typically operates between 50 kHz and 1 MHz, which can produce EMI that affects analog or RF circuits.

Advantages:

•Few external components

•Inexpensive

•Small in size

•”Quiet” (no switching)

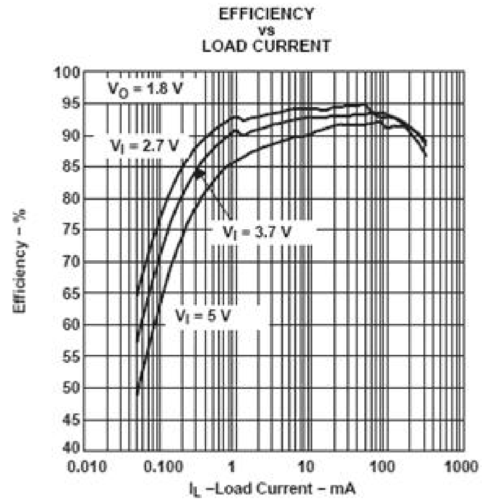
Disadvantages:

•Inefficient

•Power is lost as heat

DC/DC Converters

- Up to 95% efficiency
- Nearly independent of the input/output voltage ratio
- Switching continuously decreases the efficiency
- Light load mode



- DN019: Powering LPW products
  - http://www.ti.com/lit/swra173

Texas Instruments

Advantages:

•High efficiency

•Inexpensive (but more than LDO)

Disadvantages:

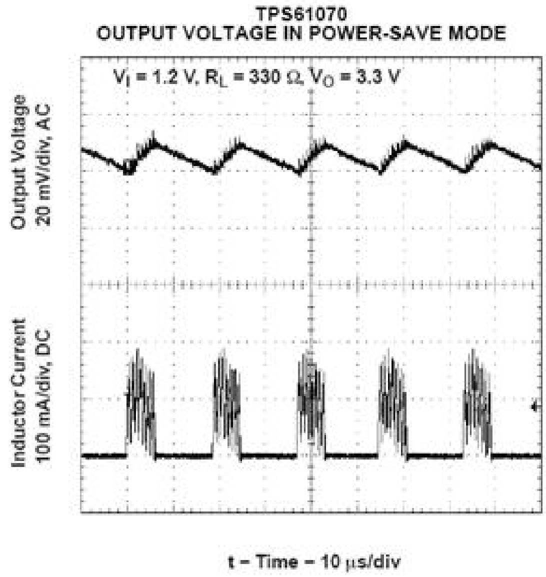
•Number of external components

•Board space compared to LDO

•Switching noise

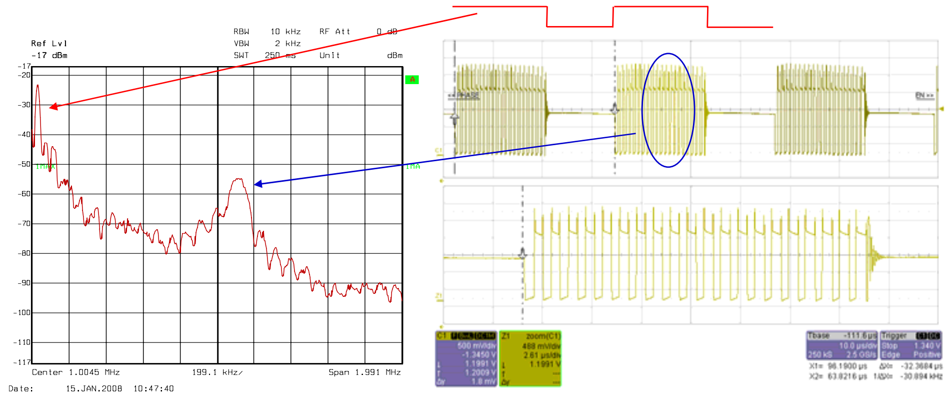
•PCB layout

Switching Noise



The regulator only switches when the output voltage is below a certain threshold

Switching Noise

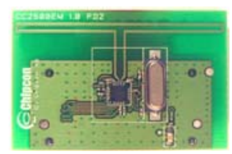


TPS61070 Noise Spectrum and Switching Frequency. I_{load} = 25 mA

Choice of Antenna

- Great impact on the total system performance
- Lower frequency requires larger antennas
- Cost and performance vs board size
- Several reference designs available from www.ti.com/lprf

- AN058: Antenna Selection Guide
  - http://www.ti.com/lit/swra161



Texas Instruments

Since a 6 dB increase in the link budget increases the range by a factor of 2, the antenna performance has a major impact on the total system performance. Generally, more space available makes it easier to implement an efficient antenna. If the available board space is limited, a chip antenna could be a good solution. Chip antennas could be a good choice to obtain compact solutions at frequencies below 1 GHz .

Designing a PCB antenna is a difficult task and requires EM simulation tools. Such simulation tools are very expensive and it is not straight forward to configure them to perform accurate simulation. It is therefore recommended to make a copy of one of the antenna reference design available from www.ti.com/lprf.

TI Antenna Reference Designs (1)

- **General Antennas**
  - AN058 Antenna Selection Guide (SWRA161)
  - AN003 SRD Antennas (SWRA088)
  - Application Report ISM-Band and Short Range Device Antennas (SWRA046)
- **2.4 GHz**
  - AN040 Folded Dipole for CC24xx (SWRA093)
  - AN043 PCB antenna for USB dongle (SWRA117)
  - Fractus Antenna App.note. (SWRA092)
  - DN001 Antenna measurement with network analyzer (SWRA096)
  - DN004 Folded Dipole Antenna for CC25xx (SWRA118)
  - DN0007 Inverted F Antenna for 2.4 GHz (SWRU120)
  - AN048 Chip Antenna (SWRA092)
  - DN026 CC2430 Quarter Wave Pinyon Antenna (IP) (SWRA251)
  - DN027 CC2430 Half Wave Pinyon Antenna (IP) (SWRA252)
  - DN028 CC2510 Quarter Wave Pinyon Antenna (IP) (SWRA253)
  - DN026 CC2510 Half Wave Pinyon Antenna (IP) (SWRA254)

TEXAS INSTRUMENTS

TI is constantly providing new application notes on antenna reference designs. Check the web for new publications.

With the IP antenna a royalty must be paid to the antenna company since the antenna design is protected by patents. An IP antenna can be viewed as a chip antenna with respect to cost.

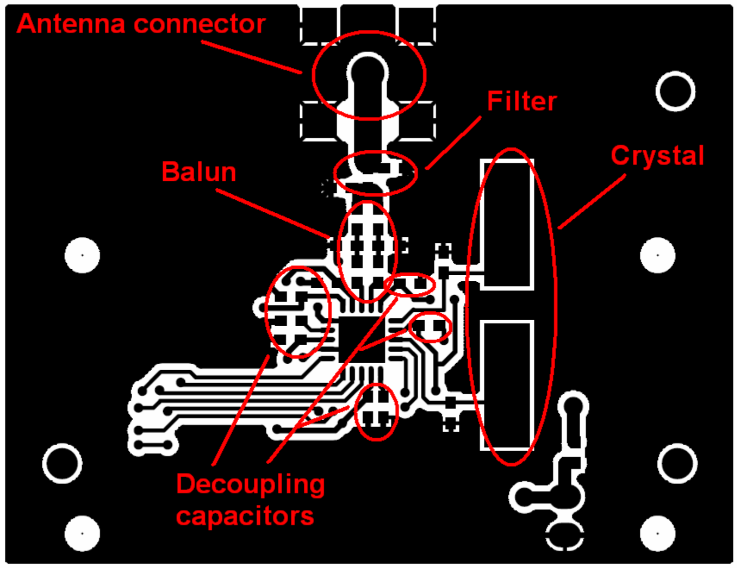
Application Note 58 – Antenna Selection Guide gives an overview of all TI antenna reference design with links to the documentation and layout. AN058 also contains general RF theory and guidelines on how to characterize antennas: AN058: http://www.ti.com/lit/swra161

TI Antenna Reference Designs (2)

- **868/915 MHz**
  - DN008 868 and 915 MHz PCB antenna (SWRU121)
  - DN016 915 MHz Antenna Design (SWRA160)
  - DN023 868/915 MHz PCB inverted-F antenna (SWRA228)
  - DN024 868/915 MHz Meandering Monopole PCB antenna (SWRA227)

TI is constantly providing new application notes on antenna reference designs. Check the web for new publications.

PCB Layout (1)



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To ensure proper performance it is important to implement the same layout of the balun, match, and filter as in the reference design. Changing the placement of these parts might require tuning on the component values to obtain the desired performance. Tuning requires advanced RF skills and the proper equipment.

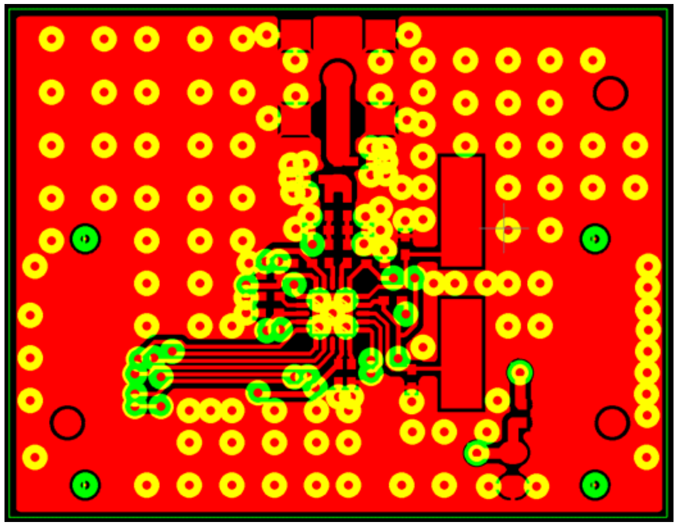
Star routing of the power lines are used to prevent noise from one line coupling in on to other power pins and cause reduced performance. No power or signal lines should be routed beneath the balun, match and filter.

We recommend that you always copy the balun part of the circuit exactly from our reference design because the amplifier has to match at both the fundamental and also at the harmonics of the fundamental. The RF experts that designed our EVMs have spent a lot of time and energy getting this exactly right, so please don't mess around with it!

The two shunt capacitors in the LC filter (next to the SMA antenna connector) are placed 180 degrees to each other to minimize crosstalk.

Decoupling capacitors are placed as close as possible to the pin they are supposed to decouple.

PCB Layout (2)

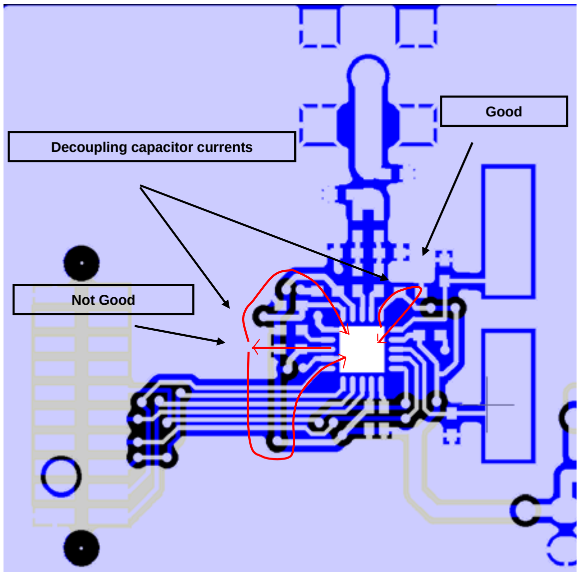


It is important to connect the ground plane on the different layer with several vias. This must be done to ensure that board doesn't have ground "fingers" or "islands" that can act as antennas and pick up noise.

It is important that the ground pad under the chip is connected to the ground plane below.

All decoupling capacitors should also have vias placed close to the *capacitor* ground pad to ensure a short path to the ground plane on the bottom (ground) layer and back to the *chip* ground pad.

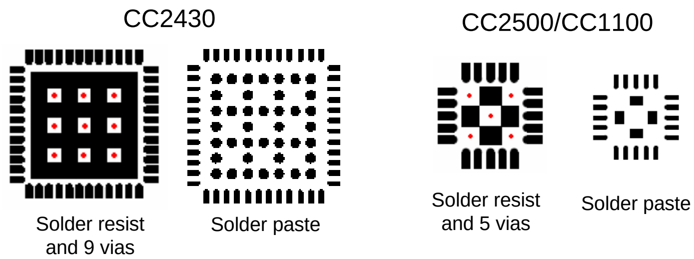
Current Return Path



- Minimize spurious emission
  - Solid ground plane from capacitor ground pad back to the chip

The lowest impedance return path is in a plane directly underneath the signal trace since this provides the lowest inductance path. A spurious emission problem could occur when there are discontinuities in the current return path. These discontinuities cause the return current to flow in larger loops, which increases the radiation from the board

Die Attached Pad Vias and Solder Paste



- Vias should be covered with solder mask to avoid migration of solder through the vias
- The solder paste coverage should not be 100% to avoid splattering and solder balling

Texas Instruments

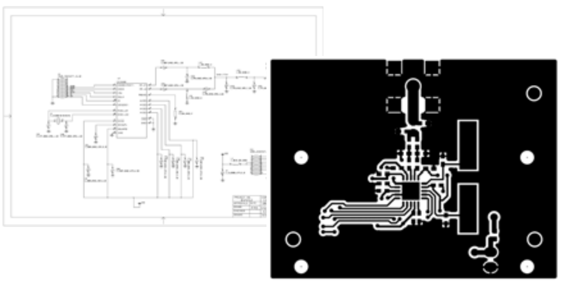
The area under the chip is used for grounding and shall be connected to the bottom ground plane with several vias for good thermal performance and minimum inductance to ground. In the reference designs available from the TI web site several vias are placed inside the exposed die attached pad. The number of vias used depends on the package size. These vias should be “tented” (covered with solder mask) on the component side of the PCB to avoid migration of solder through the vias during the solder reflow process. See drill file included in the reference design for information about number and placement of vias, recommended solder paste and solder resist.

The solder paste coverage should not be 100%. If it is, out gassing may occur during the reflow process, which may cause defects (splattering, solder balling). Using “tented” vias reduces the solder paste coverage below 100%.

See the relevant Gerber (layout) files for more details on solder paste coverage and the number of vias used.

HW Development Conclusion

- **Copy the reference design**
  - TI provides a reference design for all LPRF products
  - Important to make an exact copy of both layout and schematics



TI provides schematics and Gerber files. Use the exact same values and placement on decoupling capacitors, balun matching and filter components.

Test Phase

- Test equipment
- HW testing

Test Equipment

- "It is hard to do RF development without the proper test equipment"
- Required: Spectrum Analyzer, Signal Generator, and Oscilloscope

- Optional: Vector Network Analyzer, Power Meter, and Function Generator

Vector Network Analyzers

Component Characterisation – insertion loss

S-parameters - impedance matching

Spectrum Analyzers

Output Power, harmonics, spurious emission

Phase Noise

ACP (Adjacent Channel Power)

OBW (Occupied Bandwidth)

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

How and What to Test?

- Testing shall be divided up in separate parts, independent of each other
- Hardware, software, and antenna shall be tested separately

It is crucial to test separate parts of the RF system isolated or independently of each other. This way it is easier to verify that the different part or modules are working correctly and to discover potential problems. Testing smaller parts of the system during development reduces the risk of needing to debug a large and complex system to resolve problems when the design is nearly finished.

Narrow Down the Problem

- Check if the problem is SW or HW related
  - Test the SW with well-known working HW, evaluation modules
  - Test the HW with well-known working SW, SmartRF® Studio
- If it is hardware related:
  - Compare the design with our reference design
  - Check mounting of the chip and other components
  - Mount the radio on our EVM to check if the chip is damaged
- If it is software related:
  - Compare the code with our software examples and libraries
  - Test the functionality of each “module” to isolate the problem
  - Compare register settings with values in SmartRF® Studio

Texas Instruments

To test the SW with a well-known HW, the control lines from the MCU should be connected to an evaluation module. This could be done by soldering the wires directly to the EM module or plug the EM in SmartRF0xEB (x = 4,5) and use one of the test connectors to connect the signals. See the development kit user manual for information about what connectors to use.

To test the HW with a well-known SW, connect SmartRF0xEB (x = 4,5) to the radio on the prototype board and disable the MCU. With this setup SmartRF® Studio can be used to perform HW testing and no software bugs will affect the result.

Use SmartRF® Studio as:

-“Spectrum analyzer” (Simple RX)

-“Packet sniffer” (Packet RX)

-“Signal generator” (Packet TX)

Make Sure the Design has Some Test Pins

- Needed pins for transceivers/transmitters:
  - CSn, SCLK, SI, SO, VCC, GND, (GDOx)
- Needed pins for SoC:
  - DD, DC, Reset_n, VCC, GND

Texas Instruments

To be able to control a transceiver with SmartRF® Studio using SmartRF04EB (x = 4,5), CSn, SCLK, SI, SO, VCC and GND need to be connected to the module.

To be able to control a System-On-Chip with SmartRF® Studio using SmartRF0xEB (x = 4,5), data debug (DD), data clock (DC), Reset_n, VCC and GND need to be connected to the module. Notice that pin 9 on the debug connector can be used to supply power to the module. Pin 2 on the debug connector is connected to a voltage converter and if the module uses its own power supply this pin must be connect to VCC on the module to ensure correct voltage on the signaling between SmartRF0xEB (x = 4,5) and the prototype.

See Design Note DN011 for more details. http://www.ti.com/lit/swra149

HW Testing

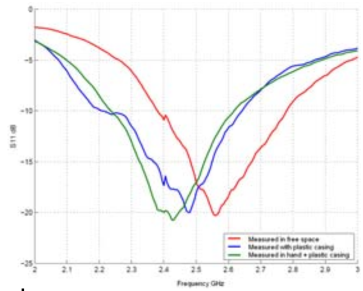
- Output power
  - Connect to an SMA antenna if possible, or else solder a semi rigid coax cable to the connection point of the antenna and disconnect the antenna
  - Transmit a carrier, deviation = 0
  - Measure with a spectrum analyzer or power meter
- Sensitivity
  - Connect to an SMA antenna if possible, or else solder a semi rigid coax cable to the connection point of the antenna and disconnect the antenna
  - Use an RF generator or development kit as transmitter
  - Monitor the received data on an oscilloscope or a dedicated BER/PER tester

Texas Instruments

When measuring output power and sensitivity it is recommended to disconnect the antenna and solder on a 50 ohm semi rigid coax cable at the antenna feed point (but disconnect antenna!).

If no RF equipment is available a development kit and attenuators can be used to generate the desired signal. See Design Note DN002 for more information about sensitivity measurements: http://www.ti.com/lit/swra097

Antenna Testing



- Reflection
  - Measured with a network analyzer.
  - Should be less than -10 dB or VSWR=2 across the desired frequency band.
- Radiation pattern
  - Should be measured in an anechoic chamber.
- Bandwidth
  - Use a test program that steps a carrier across the desired frequency band. Use max hold on spectrum analyzer to measure the variation in output power.

Objects in the vicinity of the antenna will affect the performance. Thus it is important to test the antenna in the actual environment were it is going to be used. E.g. an antenna for a remote control should be characterized with the actual plastic encapsulation since such plastic can move the optimum frequency with more than 50 MHz for a 2.4 GHz solution.

Access to anechoic chambers is expensive. A cheaper solution could be to do testing in an open field and use the development kit as a receiver. By reading the RSSI value from SmartRF® Studio and rotating the antenna it is possible to get an indication of how the radiation will vary around the antenna.

More than 90% of the available power will be delivered to the antenna if the reflection at the feed point is less than -10 dB. For more information about reflection measurements see Design Note DN001: http://www.ti.com/lit/swra096

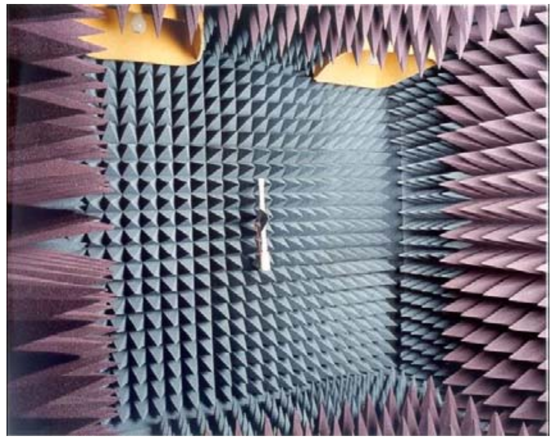
Radiated Tests are Required

- When testing for regulatory compliance radiated tests are required
- There might be a difference in radiated and conducted performance
  - Spurious emission might be *attenuated* by the finite antenna bandwidth
  - Spurious emission might be *radiated* from the PCB itself or components on the PCB resulting in increased spurious emission in radiated measurements

Texas Instruments

Compliance with Regulatory Limits

- All products needs to be compliant with the RF regulations in the country they are going to be sold
  - ETSI
  - FCC
  - ARIB
- Test house
  - Self Declaration
  - Approval
  - Approved Test House



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

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

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

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

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

Measurements must be performed at an accredited test house. The test house must write a report that confirms compliance with the different standards which the product has been tested against. In some cases, e.g. FCC, it is also required to fill in an application and apply for an approval. Compliance testing is an expensive task and making changes to our reference design increase the chance of failing the compliance test.

Questions?