From Wired To Wireless

Converting a Wired Design to Wireless Using Low Power Wireless Technologies

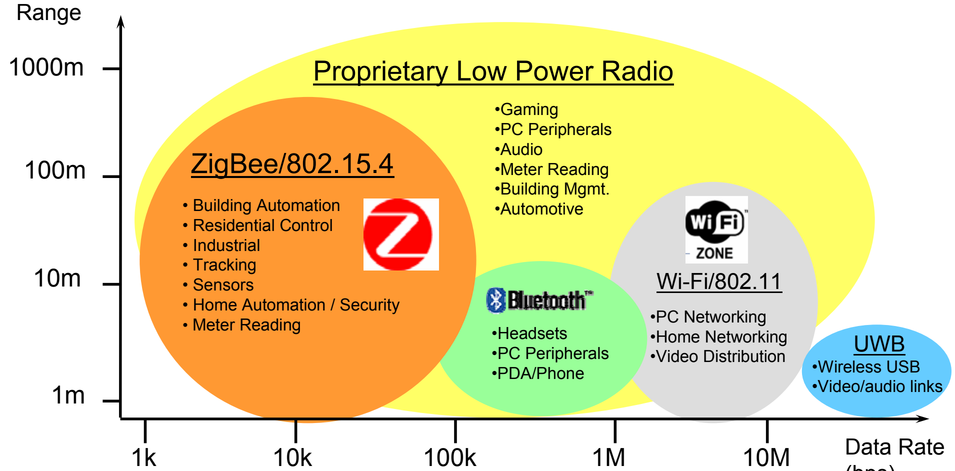
Agenda

- Hardware
  - Frequency band
  - Range
  - Coexistence
  - Low Power

- Software
  - What does TI offer
  - Proprietary or Standard
  - Quality of Service
  - Other decision factors

Hardware

Short Range Wireless



Different Value Drivers for Different Applications

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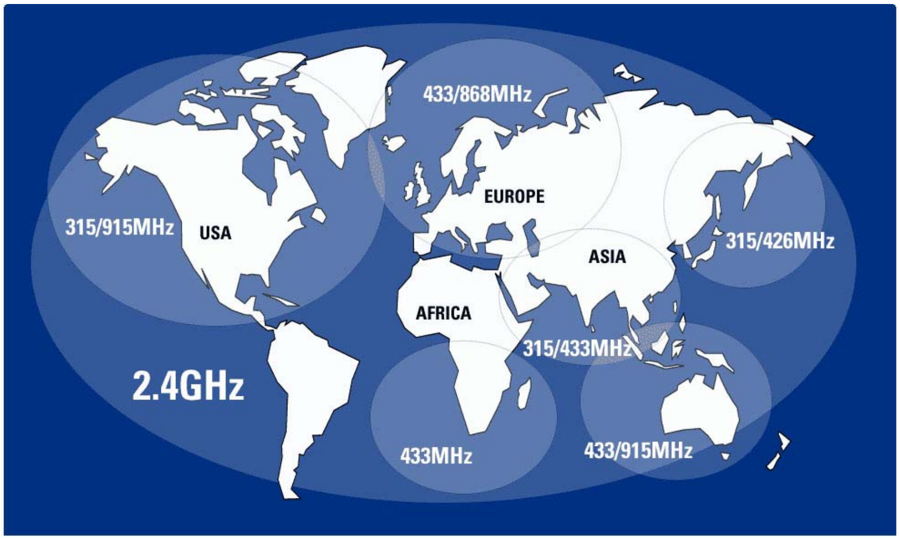
ISM/SRD Bands



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 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 (with the same current consumption)
    - Many possible interferers are present in the band

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Range Estimations using Friis Eq.

$$P_r = \frac{G_t G_r \lambda^2}{(4\pi R)^2} P_t \Rightarrow R = \sqrt{\left(\frac{G \cdot c}{4\pi f}\right)^2 \frac{P_t}{P_r}}$$

- Theoretical calculation of range, free space propagation
- Pr = Received power
  Pt = Transmitted power
  G = Antenna gain = e_r * D
  e_r = Antenna efficiency
  D = Antenna directivity
  λ = Wave length
  f = frequency
  c = Speed of light
- Rules of Thumb
  – 6 dB increase of output power or improve sensitivity by 6db the range is doubled.
  – Doubling the RF frequency reduces the range by a factor of 2

Range Estimations

$$R = \sqrt{\left(\frac{G \cdot c}{4\pi f}\right)^2 \frac{P_t}{P_r}} = \sqrt{\left(\frac{1 \cdot 3E8}{4 \cdot \pi \cdot 2.44\,E9}\right)^2 \frac{1E-3}{1.26\,E-12}} = 276\ m$$

- Theoretical calculation of range, CC2500
- Pr = -89 dBm = 1.26E-12 (Sensitivity at 250 kbps)
  Pt = 0 dBm = 1E-3
  G = 0 dB = 1 (Assuming same gain on both antennas)
  f = 2.44 GHz
  c = 3E8
- For more details about range, see DN018 Range Measurements in an Open Field Environment (swra169)

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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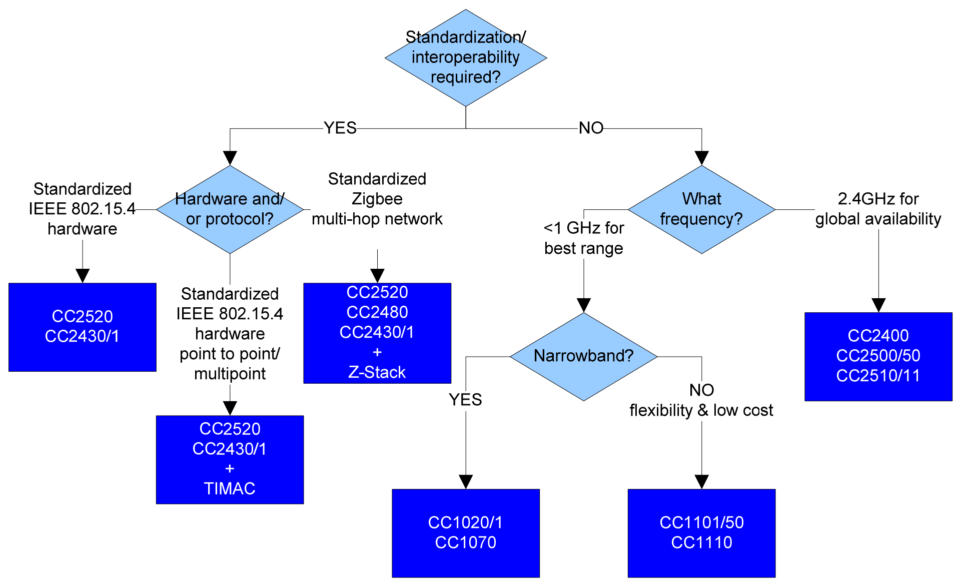
Low Power Wireless Decision Tree



Coexistence

- Radio must have good selectivity
  - Otherwise frequency hopping is not effective
  - Poor selectivity = higher chance of collisions
- High speed is not a substitute for selectivity
  - Many interferers are high duty cycle
  - Probability of collision is a product of duty cycle and selectivity
- Protocol also plays an important part
  - Frequency hopping or frequency agility effective at co-existing with stationary sources like WLAN
  - Adaptive frequency hopping or frequency agility works well with other AFH or FA systems as well

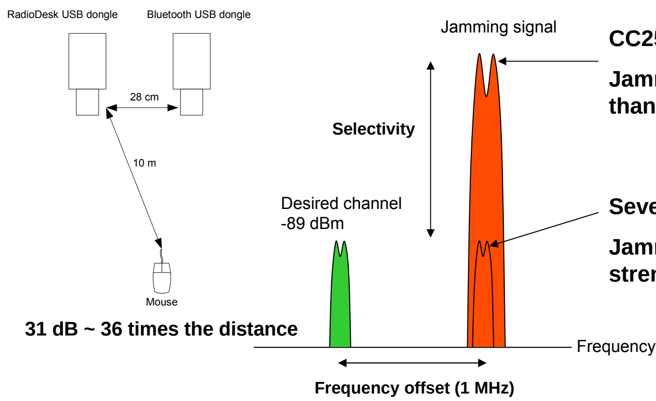
- COEXISTENCE = RELIABILITY

Selectivity

- Very important parameter for coexistence
- Describes how well interfering signals are rejected
- Near-far problem = a close interferer will present a much stronger signal than a far-away wanted signal
- A very strong signal will prevent communication all together (saturation), a weaker one will reduce the communication range
- For a receiver with very poor selectivity, frequency hopping will not help much, as even off-frequency interference is not attenuated sufficiently

Selectivity (2)

- How much stronger jammer can the chip tolerate without “losing” sensitivity – in dB



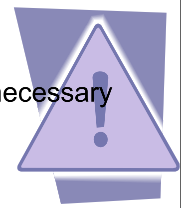
CC2500 performance: 31dB

Jammer is 1259 times stronger than the wanted signal

Several competitors: 0dB

Jammer has the same signal strength as the wanted signal

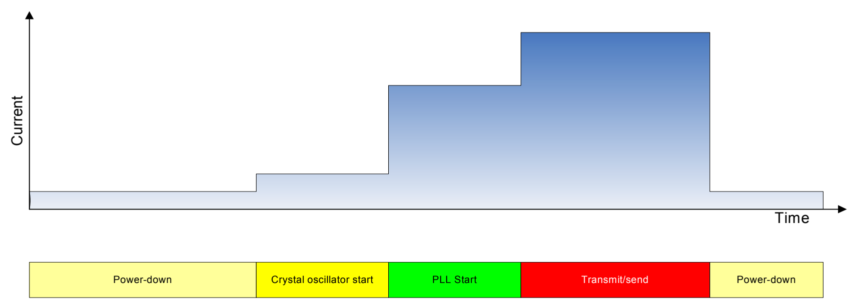
Low-power Essentials



- Attain the lowest possible duty cycle
- Send data only when needed, do not send more data than necessary
  - Use the highest data rate you can (trade-off vs. range)
  - Watch out for protocol-related overhead
  - Make sure to understand synchronization issues (receiver must remain on long enough to compensate for drift)
- Use the lowest possible voltage
- Most RF chips draw a constant current regardless of voltage, or have reduced current draw at lower voltages
  - Using a switch-mode regulator with low quiescent current to maximize battery lifetime

Low-power Essentials

- Current consumption in TX/RX and transmission time (data rate) does not show the full picture
- Fast crystal oscillator start-up time and calibration time reduce overall power consumption
- Calculate the average current to estimate battery lifetime
- Adaptive output power – don't send with full power if close by



For power consumption, high data rate does not help much for short packets. Far more important is quick start-up. CC1100/CC2500 has the quickest start-up time on the market, both for turning on the crystal oscillator and for waking up into RX and TX mode.

Different Scenarios (1)

- High duty-cycle applications (100s of hours operating time) – wireless game controllers, wireless audio etc.
  - Often limited by other circuitry than the radio
  - If radio is a major factor and is on most of the time, active current consumption is the most important parameter. In some cases, a high data rate can save power (if data throughput is the limiting factor)
  - Use of switch-mode regulators can have a major effect on the battery life time

Different Scenarios (2)

- Medium duty-cycle applications (months of operating time) – wireless keyboards and mice etc.
  - Synchronization between devices a major issue
  - Battery lifetime affected by many parameters
  - Switch-mode regulators can help battery life time

Different Scenarios (3)

- Low duty-cycle applications (years of operating time) – sensors etc.
  - Shelf life of the battery a major factor together with power-down current of the radio
  - Critical that the radio on time is as short as possible
  - The system must be considered; MCU sleep current and regulator quiescent current are just as important as the radio

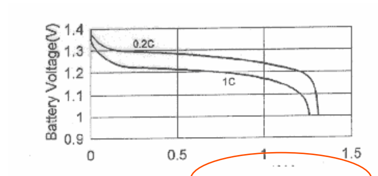
Xtal/Oscillator

- Clock drift between two units is unavoidable
- Increased drift means increased time in RX to ensure packet reception
- RX must be turned on early in case the other units clock is fast
  - Increases probability of receiving a false packet that requires additional RX time and processing
- RX timeout must be increased in case the other unit's clock is slow
  - Short RX timeout is preferable to limit RX time when no unit is transmitting
- Resync time from sleep mode is increased with clock drift
- Results of oscillator drift:
  - Increased RF on-time
  - Increased probability of receiving false packets
  - Decreased maximum sleep time Note: There is a trade-off versus crystal cost and crystal power consumption

TEXAS INSTRUMENTS

Switch Mode Voltage Regulators

- Switch mode voltage regulators have high efficiency (~90%)
- A good switch mode regulator has low quiescent current
- Output voltage is stable for a large range of input voltages
- Choice of the right regulator and the right battery allows maximum utilization of the battery capacity
- Make sure that the regulator accepts the full range of battery voltages from maximum (charge) to fully drained voltage
- Include battery monitoring circuitry to avoid harming batteries and thus maintain good performance over time
- Note: There is a trade-off versus system cost, complexity, board space and switching noise



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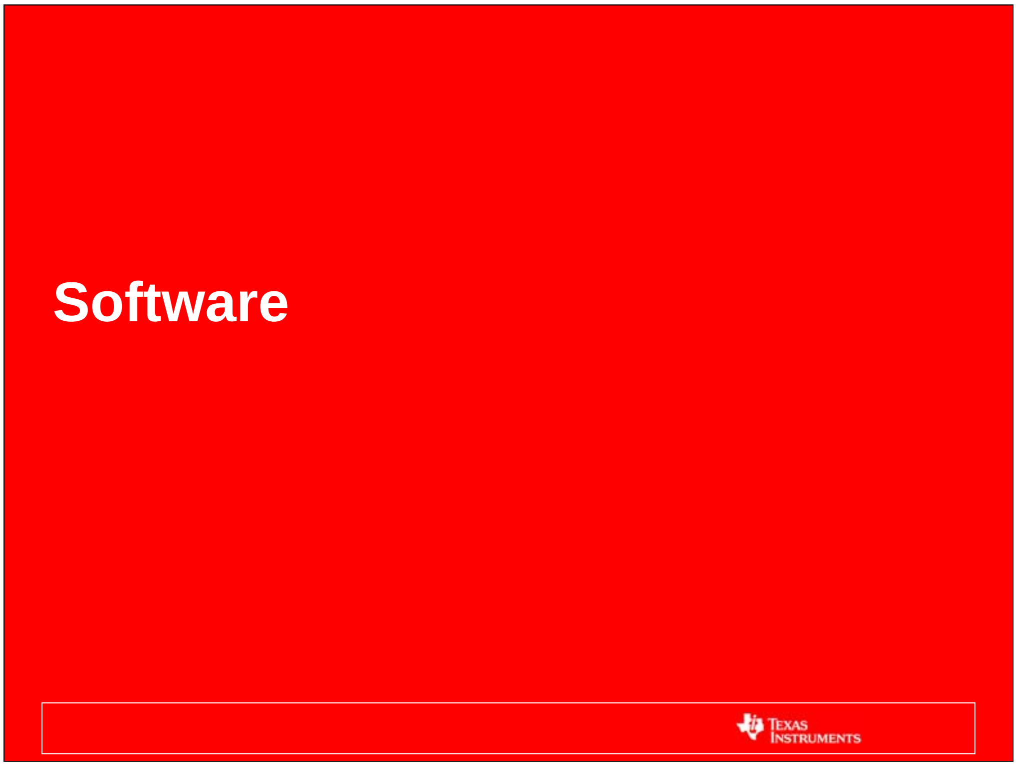
Operating Voltage

- Use the lowest possible operating voltage
- Most RF chips draw a constant current regardless of voltage, or even have reduced current draw at lower voltages
- Switch mode regulators draw less input current when output voltage is reduced
- RF performance is often increased when operating power and core power approaches each other
- Increased RF performance yields decreased system power consumption
  - Sensitivity limit decreases -> RX current draw decreases
  - Bit error rate / packet loss decreases -> Reduced retransmissions
  - Output power may be decreased while maintaining performance

TEXAS INSTRUMENTS



TI LPW offers several low power RF solutions by providing the required Hardware and Software.

As a result there is no need to promote one specific low power RF protocol as the solution for all applications to each and every customer.

However, it is important to make the customer chose the best fitting protocol for the targeted application in order to get optimal performance and meet expectations.

This part of the presentation looks at different aspects one should consider before deciding which of the low power RF protocols offered by TI LPW to use in a certain application.

Many competitors have only 1 or two RF protocols, hence, they do their best to convince the customer that their solution is the best for each application.

However, if you have a *hammer* it is not smart to see a *nail* in every application; especially not if you also have other *tools* in your pocket, because in case it is a *screw* it is better to have a *screw driver*.

The decision of which of the TI protocols fits best is not easy, hence, the following slides will give some idea of what decision criteria and which aspects to look at.

Content

- Low Power RF protocol overview
- Decision criteria - What to consider?
- Where to find the SW and additional information

TEXAS INSTRUMENTS

The presentation consists of 3 different parts:

1) The schematic overview over the different solutions to get a rough idea about the differences
2) The list of decision criteria one should think of before deciding which protocol to use in order to avoid sub-optimal solutions.
3) A link collection on where to find additional information about the different protocols.

Low Power RF protocol overview

- Which low power RF protocols does TI LPW offer?

Low Power RF protocol overview

Layer \ Solution	Proprietary	SimpliciTI	MAC 802.15.4	ZigBee
Application	Design freedom	Design freedom	Design freedom	Design freedom*
Higher Layer Protocol	Design freedom	Design freedom	Design freedom	ZigBee
Lower Layer Protocol	Design freedom	SimpliciTI	IEEE 802.15.4	IEEE 802.15.4
Physical Layer*	TI HW	TI HW	IEEE 802.15.4	IEEE 802.15.4

Increasing interoperability

* ZigBee defines application user profiles

This slide is a simplification and does not contain all details, because if it did, it would be far too complex. The main idea is to show that the different offerings have significant differences in which parts they offer and which part the user can/must design himself.

In the following some info is given on how to read the scheme followed by some additional comment.

The 1st column explains the 4 different layers:

-The physical layer; i.e. the HW/chip used.

-Where TI HW stands for all TI RF chips

-Where IEEE 802.15.4 in principle stands for all IEEE 802.15.4 compliant platforms, but in this case it mainly addresses TI's IEEE 802.15.4 HW (CC2420, CC2430/2431, CC2520, CC2480, …)

-The lower layer; i.e. the SW driving the radio

-In some cases known as HAL (TI-MAC and Z-Stack) or MRFI (SimpliciTI)

-The higher layer protocol; i.e. special network protocol functionality

-Here it is important to mention that SimpliciTI and TI-MAC might also offer some Higher Layer Protocol functionality but as they do not provide all it is not marked as such.

-In ZigBee these are given by the standard (NWK layer etc.)

-Application layer

-For all protocols the user can free to write the application; however, for ZigBee the standard offers so-called application user profiles that standardize the communication in order to garantue real 100% interoperability; hence, the footnote.

-General comments:

-Obviously the interoperability increases from the left to the right as more details are defined/standardized.

-The blocks are equally wide, however, the different protocols do not aim at the same "size"; the different solutions differ in feature set, code size, etc. (For more details about this the reader is referred to the last slide with the overview of links)

Decision criteria

- What to consider when choosing the right protocol for the target application?

Some users tend to look at the feature set of the protocols and then think the more the better or they do not see the differences between them as both might use the same wording but actually mean different things.

This section addresses some issues the user should consider in order to be confident that the right protocol is chosen.

Quality of Service

First of all one must determine which Quality of Service the application requires before looking into the detailed decision criteria

Quality of Service (QoS)

- Reliability
- Battery life time
- Latency
- Co-existence

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Quality of Service is a term in many other Wireless technologies (e.g. mobile phones)

When defining an application one often has already quite a clear picture of what kind of Quality of Service is expected:

-Reliability: Can one live with broken link, dead node, missed packets?

-Battery life time: How long should the battery powered devices last? Retransmissions increase power consumption. This parameter depends on how well HW and SW are set together to a low power system.

-Latency: How fast must a message travel between A and B; can there be retransmissions? Depending on the effective/resulting data rate several transmissions might be needed to get big messages across which increases latency.

-Co-existence: What about systems in the near proximity (neighborhood) of the application? Can it cope with parallel systems? Other radio technologies).

Decision criteria (Part 1 of 2)

- **Frequency**
- **Interoperability / standard**
- **Topology**
  - Mesh? Star? Point-to-point?
- **Time-to-market**
- **Available Expertise**
  - RF and SW protocol know-how
  - Using 3rd parties?

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(also see next slide)

This list is not complete but contains the decision criteria that are believed to be the most important to consider when looking at which protocol to use.

Of course one should first have a clear picture of which application one needs and which features the final product must provide.

Frequency: Obviously the Frequency determines which HW can be used, but it also has an influence on the protocol as TI-MAC and ZigBee target the 2.4GHz space. Frequency is also relevant with respect to targeted market due to RF regulations (2.4GHz only global frequency band)

Interoperability: This is important in case that the product should be capable to interact with products from other vendors. ZigBee is the only solution providing 100% interoperability. The TI-MAC can if the others are III 802.15.4 compliant and both parts have agreed on the Higher Layer and Application protocol. SimpliciTI can provide it as well if the parties agree on how to use the SimpliciTI protocol.

Topology:

Does one need only point to point, or is a mesh NWK preferred/needed? A mesh could provide more range without using a high radio range (less interference).

Time to market: Depending on the application it might often be easier to go with a protocol that offers the features needed (ZigBee, TI-MAC, SimpliciTI) then implementing them from scratch. However, it is important to check what is needed and what is offered. Also the learning curve with the protocol (due to its complexity) has an influence on the time to market.

Available expertise: Depending on the know how and experience available one might prefer a certain protocol. If one has none one could hire a 3rd party. It is important to have both RF and SW protocol expertise.

Decision criteria (Part 2 of

- **SW feature set**
  - Memory footprint and RAM usage
  - Effective data rate
  - Power consumption (number of messages needed etc.)
  - Extended features (e.g. over-the-air-download)
  - API complexity (easy to use?)
- **HW feature set**
  - RF performance
  - Power consumption
  - Available resources for application (peripherals, memory, interfaces, etc.)
  - Design effort

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(see also previous slide)

SW feature set: Does the protocol provide what is needed?

-Is there enough memory for the code and operation? (flash & RAM)

-Is the effective data rate that can be achieved for the targeted traffic model sufficient?

-Is the SW supporting the targeted power consumption?

    -Number of messages

    -Number of retransmissions etc.

-Are there any extended features that should be used; e.g. over the air download of new firmware? Location?

-Is the API of the SW easy to use? Is the SW in total easy to use and understand?

HW feature set: Does the hardware provide what is needed?

-Is the RF performance good enough? (Sensitivity, max TX power, Selectivity)

-How does the power consumption look like and is it easily controlled by the SW?

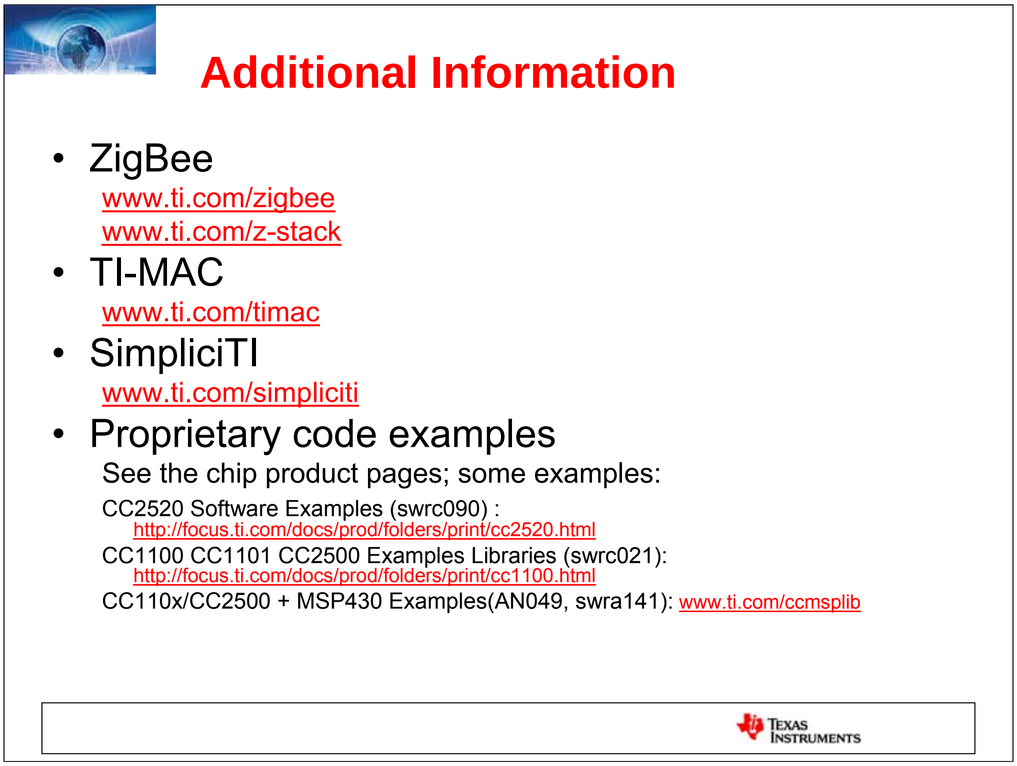
-Does the HW provide the peripherals needed (timers, interfaces, etc.)?

-Is it difficult to design the final layout? Are there reference designs?

Additional Information

- Where to find the SW and additional information?

This section guides the user to additional info



Links to the different protocols.

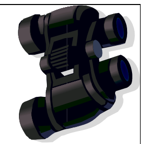
For the proprietary solution there is no single product, hence, no single product page. Instead the users can have a look at the available sample applications (e.g. PER test) and see how those can be used to write their own solutions. They can be found on the chip product page.

Thank you for your attention!

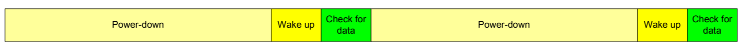
QUESTIONS?

Extras...

Protocol concept: Polling



- A polling receiver wakes up periodically and searches for data
- Basic technique in low-power design
- Timing depends on the behavior of the transmitter
- If the transmitter transmits periodically as well, the receiver on-time must be long enough to compensate for drift between the transmitter and the receiver. CC1100 and CC2500 include a wake-on-radio function where the radio performs polling without MCU intervention (based on internal RC oscillator)
- MSP430, CC2510, CC2511 and CC1110 SoCs support 32.768 kHz crystal for very accurate low-power polling



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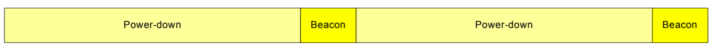
Protocol concept: Beaconing

- Refers to a technique where a beacon packet is transmitted periodically
- Used to maintain synchronization; receiver(s) can synchronize on the beacon packet
- Best suited to systems where one unit can be the master, and where this master has access to more power than the other units

- Example: The RadioDesk™ USB dongle transmits a beacon every frame (nominally every 4 ms)

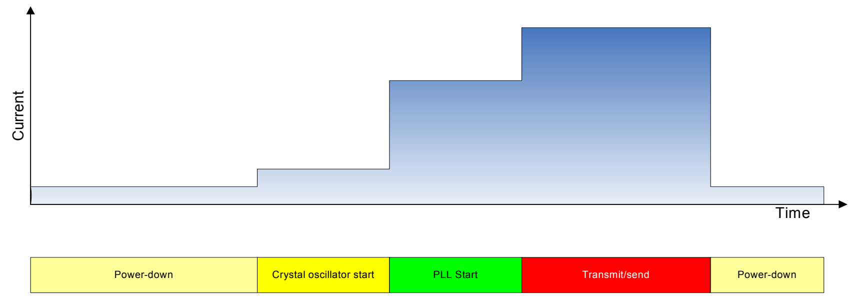


Low Power: Limit RF on time

- Use a high RF data rate
  - Finishes packet transmission faster, increases idle/sleep time
  - **Note:** High RF data rate compromise sensitivity and range
- Buffer data in MCU memory or RF-IC FIFO
  - If using the FIFO, use buffer read/write mode to minimize SPI operations. SPI communication consumes power.
- Transmit when full packet length data is held in buffer or/and at a specific time event
  - Directly after receiving data
  - Directly after receiving a beacon
  - On the timeout of a timer
  - Immediately when data is available if the receiving node can accept this
- For two way protocols, go as quickly as possible from transmit to receive or receive to transmit
  - Use ”off-modes” to switch directly between RX and TX
- Minimize RX window length
  - Window length can be adjusted adaptively. Default use short window, increase when packets are missed as a result of RX timeout.

Low Power: Waking up the radio

- Waking up a radio from sleep takes it through several immediate steps
- The current used in each step, and how long each step lasts, is important when figuring what the average current will be
- Looking at these figures is also very important when comparing different radios



Low Power: Sleep whenever possible

- If there is no data to transmit, be quiet or go to sleep
- If necessary: inform other network units of your intention to be quiet or go to sleep. Agree on silence time to allow other units to sleep as well. allows for minimum total system power consumption in networks with more than one unit with limited power
  - Adds overhead and possibly one extra transmission -> use with care
- Is it necessary to wake up on RF activity?
  - If yes, use the WOR feature If no, wake only on pin change interrupt or similar
- A number of system power modes may be implemented
  - Latency is traded against power consumption.
  - Long periods of inactivity justifies lower power and increased wake-up latency.
- In intermediate power modes, the radio may transmit and/or receive a beacon periodically just to maintain synchronization

Low Power: Sleep whenever possible

- When the RF link is idle, put the device to sleep
  - All Chipcon RF-IC's have one or more sleep modes
- Calculate acceptable wake-up time and consider the power consumption during wake-up and re-synchronization
- Find the best sleep period from:
  - Acceptable system latency
  - Power consumption during resynchronization at wake-up
  - Crystal drift
  - Available sleep timer period
- Consider system power consumption
  - Wake-on-radio lets the MCU sleep as much as possible
  - Power down all unused peripherals and or components
  - Minimize digital (inter-chip) communication

Low Power: Packet Length

- To minimize packet overhead, use long packets
- To maximize RF idle time between packets, use long packets
- Check/test the required preamble length
  - CC2500 @ 250 kbps: 4 bytes preamble recommended
  - CC2500 @ 500 kbps: 8 bytes preamble recommended
- To minimize packet loss, use short packets
- To minimize packet retransmission, use short packets
- To minimize latency, use short packets
- Choice of packet length is a trade off!
  - Probability of packet loss
  - Impact of packet loss (added processing, increased RF on-time)
  - Acceptable latency/Packet overhead
  - Acceptable buffer memory or maximum FIFO size

Low Power: Discard False Packets

- Packets from other systems will sometimes be received
- Noise will occasionally be interpreted as a packet
- A packet may be valid but not relevant to a specific receiver
- In these cases it is essential to use as little power as possible on the false packets:
  - Determine if the packet is OK and relevant to you as quickly as possible
  - If not, discard packet and stop receiving
  - Only restart receiving if a valid packet may still be received, else go to idle/sleep
  - In time slotted protocols there is no need to receive if it is known that false packet will collide with the timeslot for the valid packet
  - It is no use transmitting if the channel is already busy
  - Addressing and length field at the start of a packet
  - Automatic address and length filtering
  - Automatic CRC check and packet discarding
  - Clear Channel Assessment
  - RSSI

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Low Power: Adjust Output Power

- Do not transmit with more power than needed!
- CC2500 transmit mode current:
  - 0 dBm: 21.2 mA   -6dbm 15.1mA   -12dbm 11mA
- Use RSSI to adjust output power
  - Attenuation may be different for transmit and receive
  - Preferably use RSSI measured in receiving unit to adjust TX power in the other unit. => Power up/down command must be transmitted over the air.
- A simpler method is to use the units own received RSSI to adjust transmit power
  - OK when RF channel is symmetric. Less protocol overhead.
- Note: RX current increases when received signal is weak
  - 250kbps, current optimized at sensitivity limit: 16.6 mA
  - 30 dB above sensitivity limit: 13.3 mA

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Low Power: Summary

- Limit the RF on-time (TX and RX)
- Use sleep modes/power saving modes/wake-on-radio
- Only transmit or receive when necessary
- Do not transmit with more power than you need
- Use good crystals to minimize drift between devices
- Use a suitable switch mode voltage regulator
- Make sure you can utilize all of the battery capacity
- Run at the lowest possible voltage
- Minimize calibration time
- Minimize frequency hopping channel-table synch time
- Take care when choosing packet length
- Minimize packet overhead
- If power availability is unevenly distributed, design your protocol to take advantage of this
- Discard false packets/error packets as quickly as possible
- Minimize packet retransmission
- Use power-optimized RF register settings

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Frequency Hopping

- Hop tables for frequency hopping need to be synchronized at link set-up or pairing
- Use a small set of pre-defined frequencies before synchronization is obtained
- Design synchronization procedure to minimize synchronization time/RF on-time
  - Introduce a well known timing difference between the units, calculate the difference that results in the shortest sync time
  - If one unit has more power, let this unit stay in RX for a long time to listen for (power limited) units that want to synchronize
  - Use a single synchronization frequency if allowed by applicable RF regulations and if enduring interference is unlikely
- For long hopping tables, do not transmit table. Transmit a key that is used to generate table internally
- Minimize calibration when changing frequency
- Use adaptive frequency hopping to avoid interference
  - Interference causes retransmission and/or increased RX time and increased processing