Optimizing Power in Low-Power RF Designs

Agenda

- Low-Power RF Design Considerations
- CC1100 and CC2500 Features

Application Scenarios

- High duty cycle
  - Active radio current consumption

- Low duty cycle
  - MCU sleep current
  - Regulator quiscent current
  - Average radio current consumption

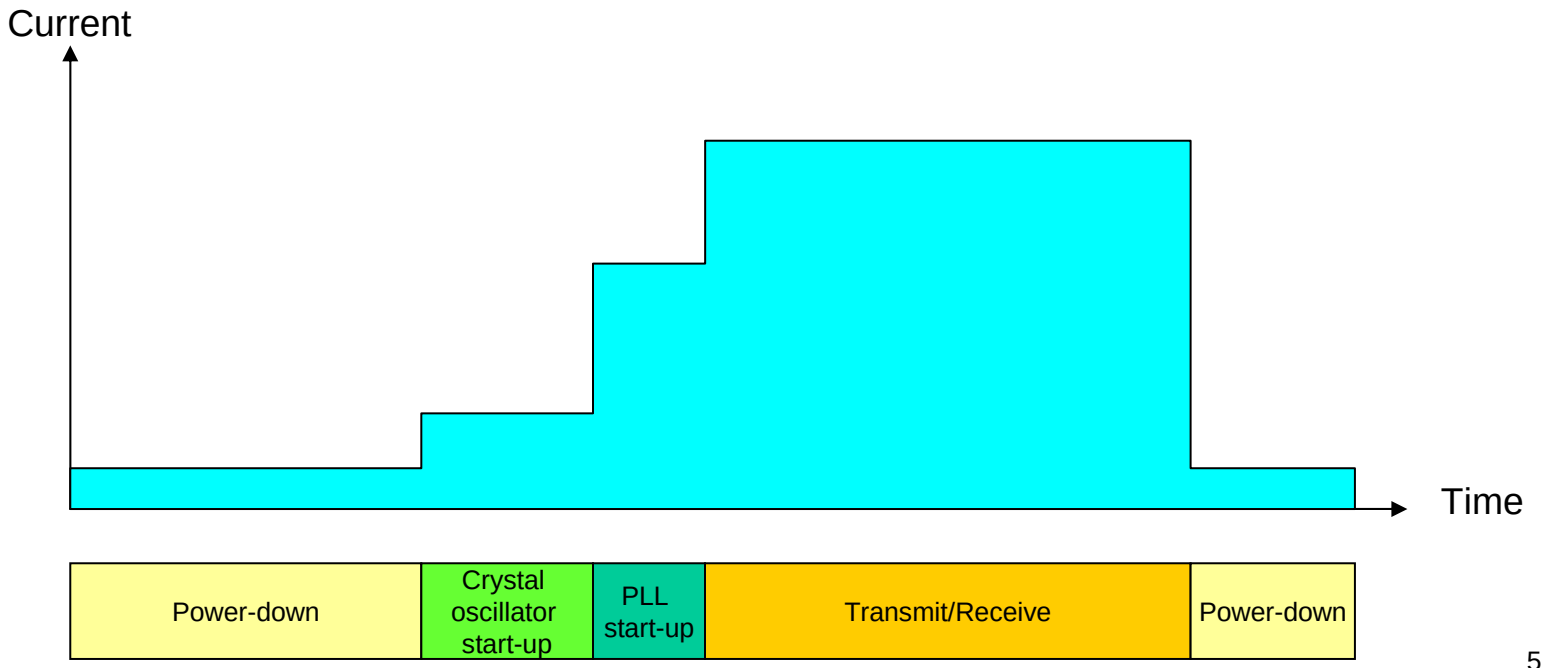
Low-Power Essentials

- Use 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

- Use the lowest possible voltage
  - RF chips have reduced current draw at lower voltages
  - Low voltage degrades RF performance
  - Above not a problem if on-chip regulator
- Use a switch-mode regulator with low quiescent current to maximize battery lifetime

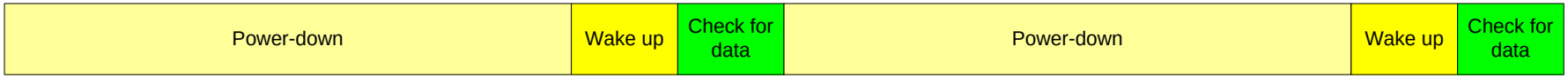
Waking up the Radio

- Waking up a radio from sleep takes it through several intermediate steps
- Calculate the average current to estimate battery lifetime

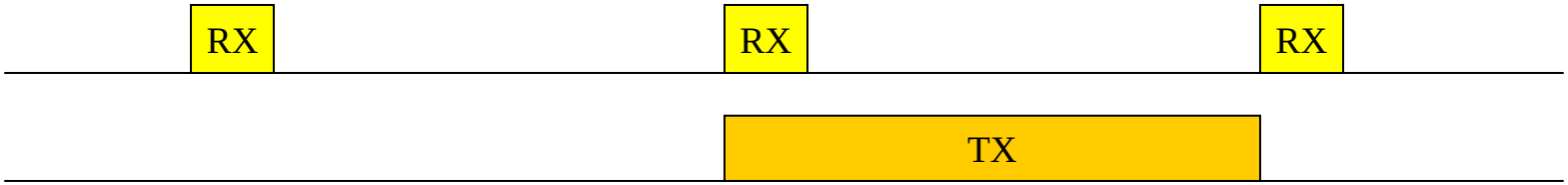


Polling Receiver

- Use a polling receiver if possible
  - Wakes up periodically and searches for data



  - Timing depends on behavior of the transmitter



RX-TX Switching

- For 2-way protocols, go as quickly as possible from transmit to receive mode or vice versa

Worst case:

Best case:

Adaptive Output Power Programming

- Do not transmit more power than needed!

- The output power can be lowered when operating at close range to reduce TX current consumption

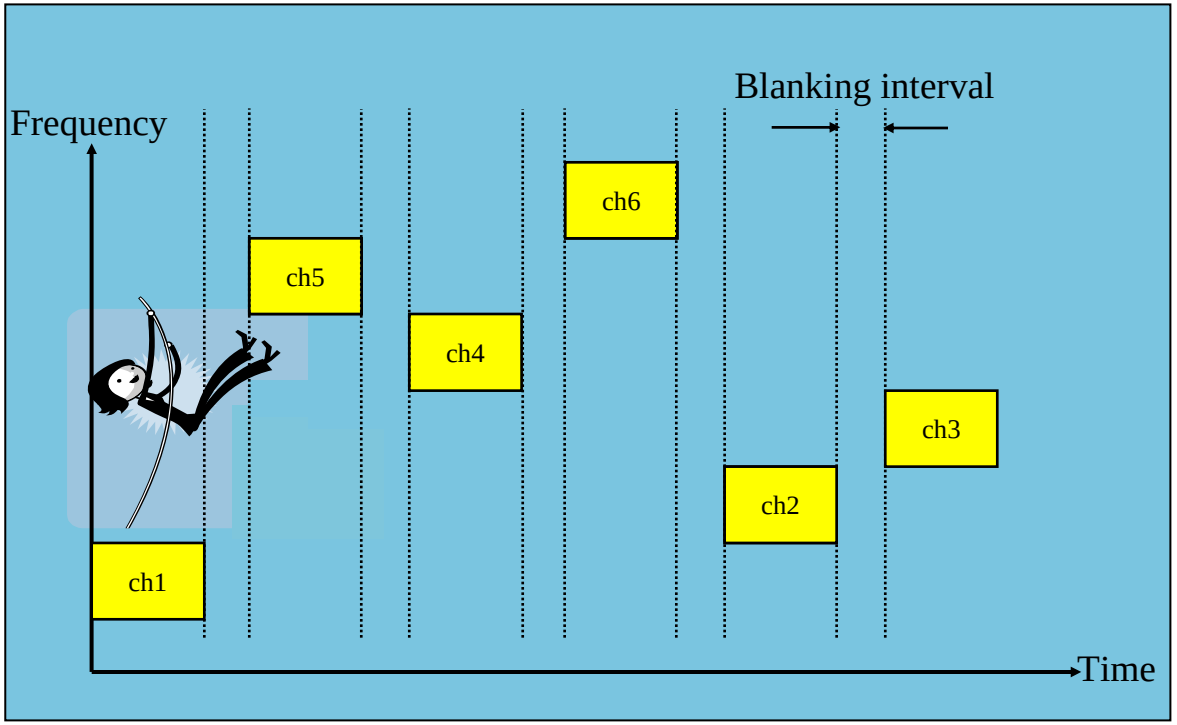
Discard False/Error Packets in RX

- 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

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

Frequency Hopping System

- Fast settling PLL important to minimize blanking interval
- Minimize synchronization time



Data Sheet and Register Settings

- Read the data sheet carefully
- Register settings
  - Optimized for sensitivity?
  - Optimized for current consumption?
- Example (non-TI transceiver):

Mode	Sensitivity [dBm]	RX current [mA]
1	-112.5	20.1
2	-105.8	19.0
3	-92.2	17.6

- On-chip packet handling features put less burden on MCU

Agenda

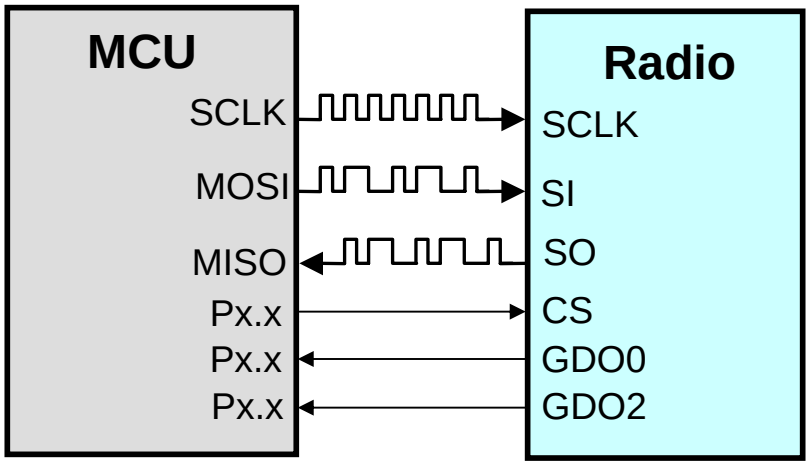
- Low Power RF Design Considerations
- CC1100 and CC2500 Features

CCC1100 and CC2500 Key Features

- **The Market's Lowest System Cost**
  - Very low price per chip
  - Very few external components required
  - Very small footprint (4 x 4 mm, 20/16 pin QFP package)
- **Low-Power Consumption**
- **High integration**
  - Powerful on-chip packet handling
  - Offloads the MCU and allows use of an inexpensive MCU
- **High Flexibility**
  - Programmable RF frequency, modulation format, data rate, packet format, output power, receiver bandwidth etc.
- **Excellent Radio Performance**
- **Can be used for multi channel operation**
  - Fast settling PLL
- **Supply Voltage Range:** 1.8 – 3.6 V
  - Operation down to 1.8 V allows for full utilization of batteries
- **Temperature Range:** -40 to +85˚C
- **Programmable data rate:** 1.2 – 500 kbps
- **Modulation formats:** FSK, GFSK, MSK, OOK/ASK

MCU Interface

- The radio is configured via a simple 4-wire SPI compatible interface



- 3 generic digital outputs (GDO) pins

SPI Access

- Address Header (Header byte)

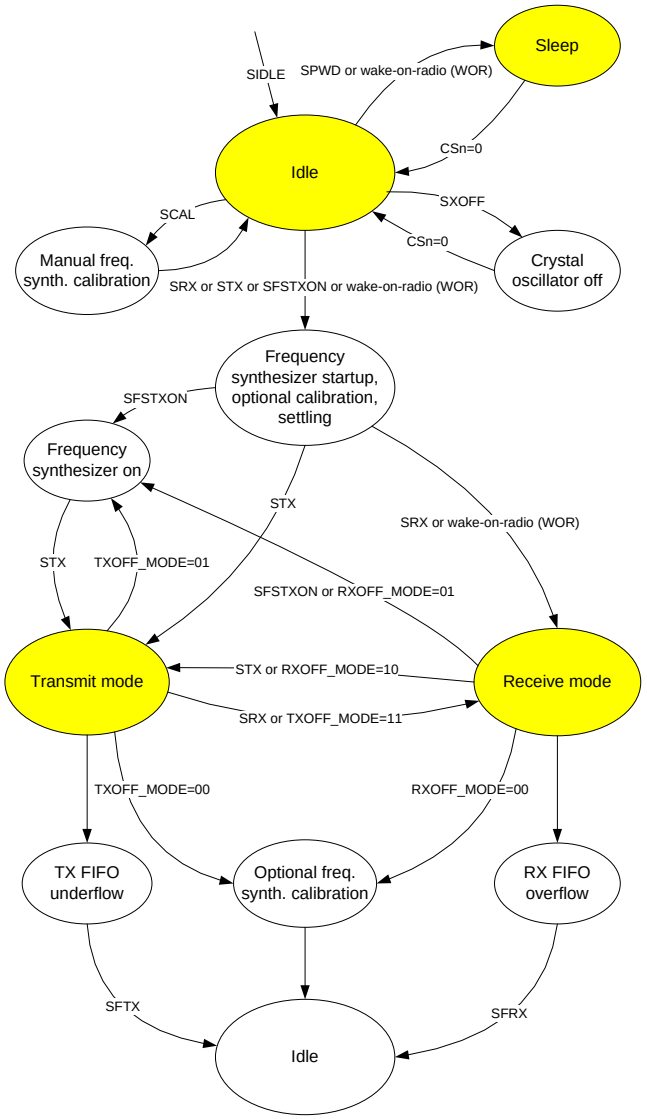
$\overline{R/W}$	B	A5	A4	A3	A2	A1	A0

- Single Access
- Burst Access
- Example:

34 registers. SPI speed of 8 MHz
Single access: 2·34·8/8 MHz = 64 us
Burst access: (8+34·8)/8 MHz = 35 us

Command Strobes

- Important Strobes
  - SRX, STX, SPWD
- Programmable OFF modes when RX/TX ends
- Automatic or manual VCO and PLL calibration



Chip Status Byte

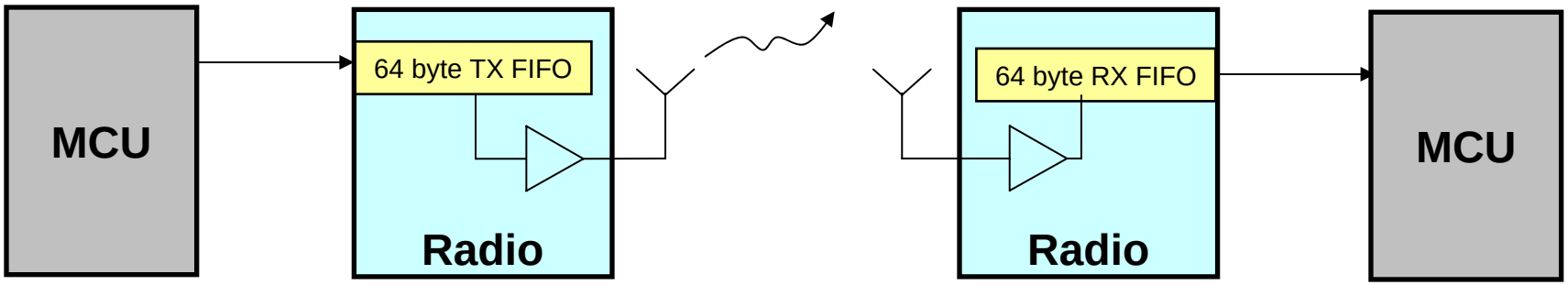
- Contains key status signals useful for the MCU

Bits	Name	Description
7	CHIP_RDYn	Stays high until power and crystal have stabilized. Should always be low when using the SPI interface.
6:4	STATE[2:0]	Indicates the current main state machine mode
3:0	FIFO_BYTES_AVAILABLE[3:0]	The number of bytes available in the RX FIFO or free bytes in the TX FIFO (depends on the read/write-bit). If FIFO_BYTES_AVAILABLE=15, there are 15 or more bytes in RX FIFO or 49 or less bytes in the TX FIFO.

Value	State	Description
000	IDLE	Idle state (Also reported for some transitional states instead of SETTLING or CALIBRATE)
001	RX	Receive mode
010	TX	Transmit mode
011	FSTXON	Frequency synthesizer is on, ready to start transmitting
100	CALIBRATE	Frequency synthesizer calibration is running
101	SETTLING	PLL is settling
110	RXFIFO_OVERFLOW	RX FIFO has overflowed. Read out any useful data, then flush the FIFO with SFRX
111	TXFIFO_UNDERFLOW	TX FIFO has underflowed. Acknowledge with SFTX

RX and TX FIFO

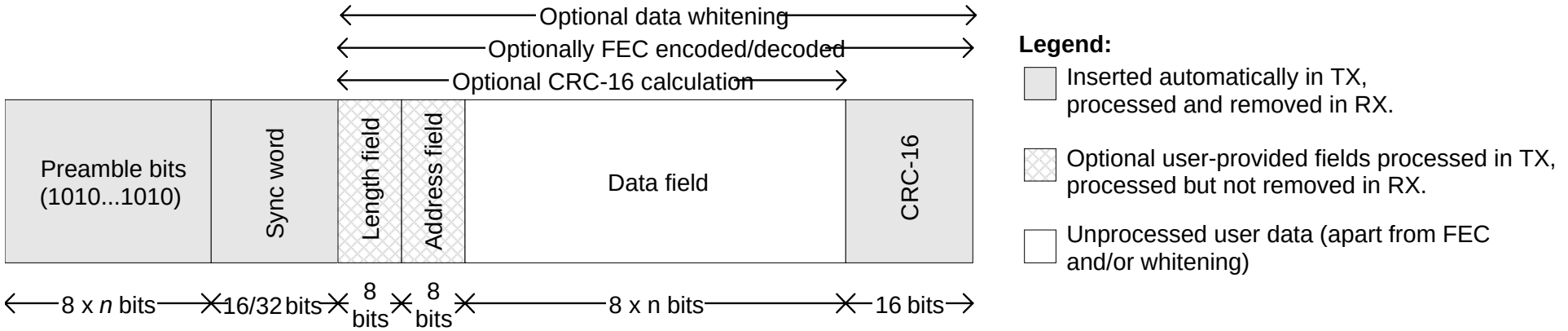
- Separate 64-byte RX and TX data FIFOs



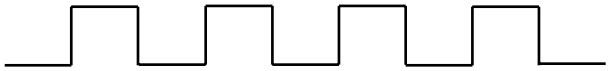
- Allow burst mode data transmission
- Burst mode data transmission with high over-the-air data rate reduces overall power consumption
- Burst mode data transmission with slow over-the-air data rate improves range

Packet Handling

- Full packet handling included
  - Preamble generation
  - Sync word insertion/detection
  - Address check
  - Flexible packet length (fixed, variable, or infinite)
  - Automatic CRC



Received Signal Qualifiers

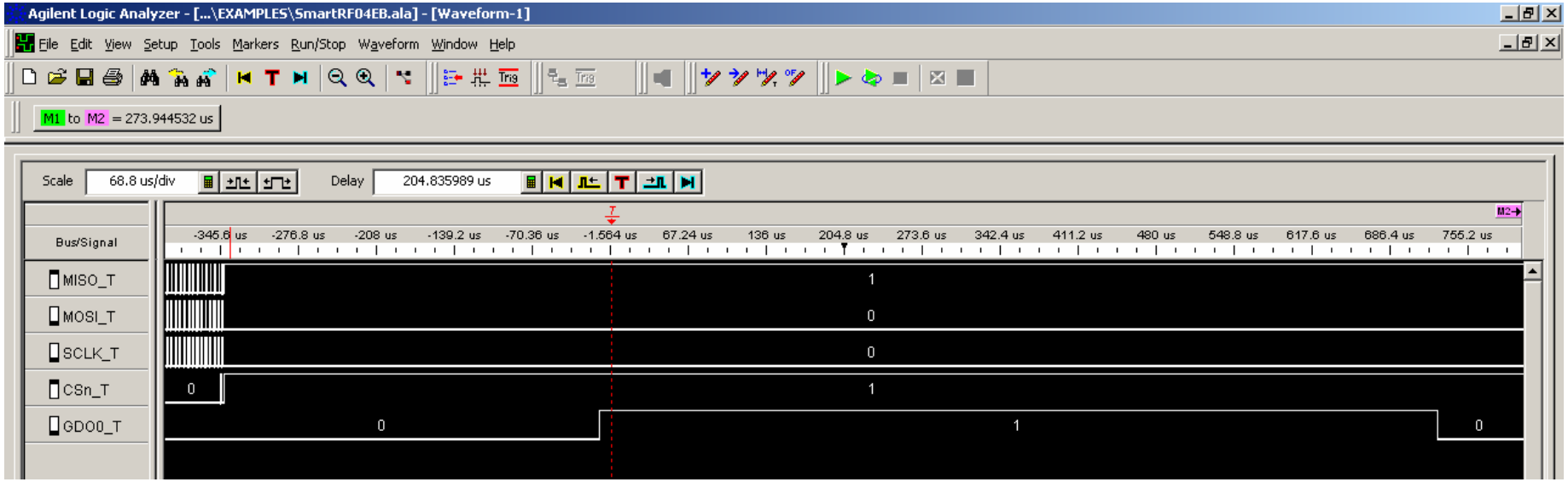
- When RX is activated the transceiver will start looking for a valid sync word
- Important to reduce likelihood of false sync word detection
  - Carrier Sense indicator 
  - Preamble Quality Threshold (PQT) 
  - Sync word qualifier

Packet Filtering in Receive Mode

- Packet length filtering
  - Maximum packet length is programmable. If received length byte has a larger value, packet is discarded and receive mode is restarted
- Address filtering
  - If received address matches a valid address, packet is received and written to RX FIFO
  - If no match, receive mode is restarted
- CRC filtering
  - If CRC check fails the entire RX FIFO will be flushed
  - Next state is programmable (IDLE, FSTXON, TX, stay in RX)

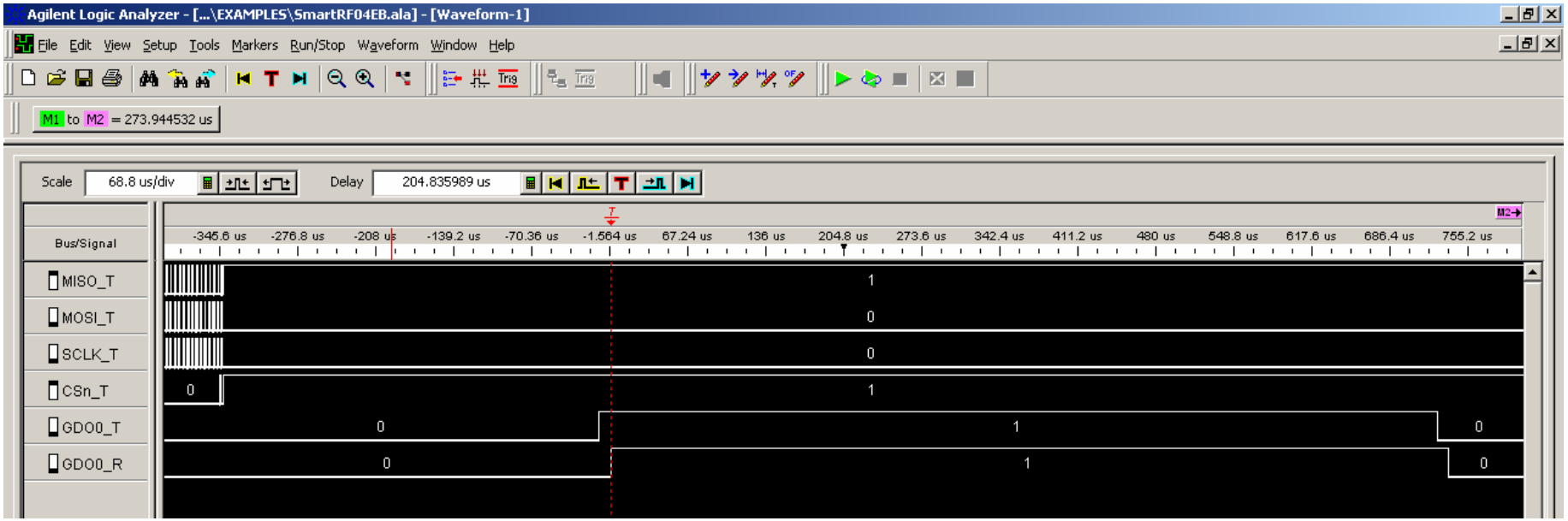
Simple Packet Transmission

- Write data to TX FIFO
- Command strobe STX
- Interrupt to MCU that packet is sent (use a GDOx signal for indication)



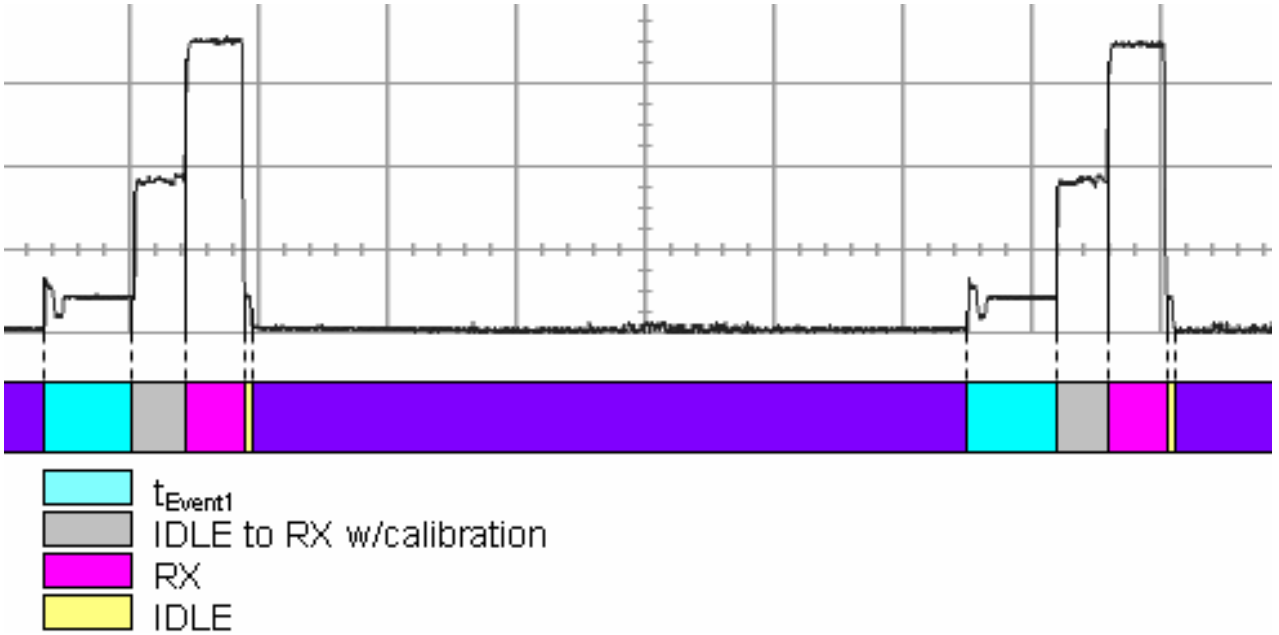
Simple Packet Reception

- Strobe SRX
- Interrupt to MCU that packet is received (use a GDOx signal for indication)
- Read RX FIFO



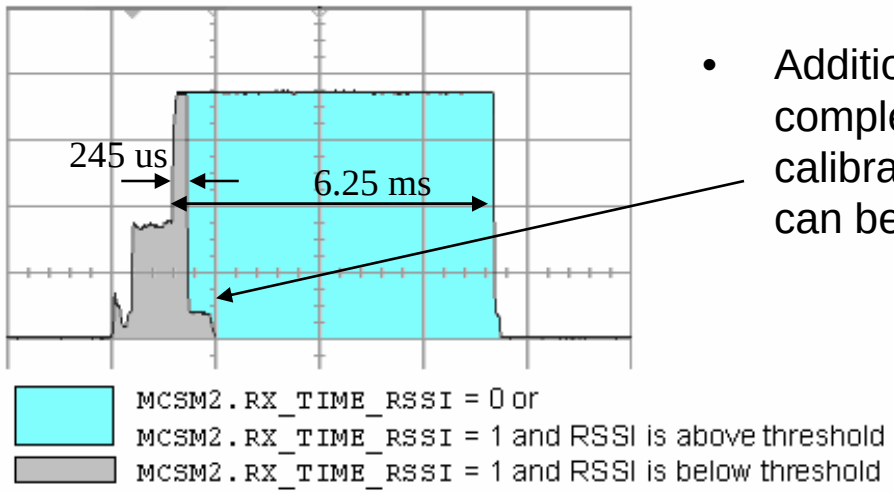
Wake-On Radio

- Wake-on-radio function allows very low average power consumption in a polling receiver (a few tens of μA)



- If data is received
  - Go to IDLE, RX (new sync search), TX or FSTXON

WOR Case Study (1)



- Additional time in IDLE to complete RC oscillator calibration. RC calibration can be disabled

- Assume 50 ms polling interval
- T_event1 is 346 us
- RX timeout programmed to 6.25 ms
- Current:
  - SLEEP: 0.9 uA - IDLE: 1.6 mA
  - SYNTH: 8.2 mA - RX: 16 mA

WOR Case Study (2)

1) RX timeout only (independent of RF signal)

or

2) Check for carrier sense and signal above threshold

- Average current with PLL calibration:
  - 0.346 ms·1.6 mA + 0.809 ms·8.2 mA + 6.25 ms·16 mA + 42.595 ms·0.0009 mA / 50 ms = 2.14 mA
- Average current without PLL calibration:
  - 0.346 ms·1.6 mA + 0.09 ms·8.2 mA + 6.25 ms·16 mA + 42.595 ms·0.0009 mA / 50 ms = 2.02 mA

WOR Case Study (3)

Check for carrier sense and signal below threshold

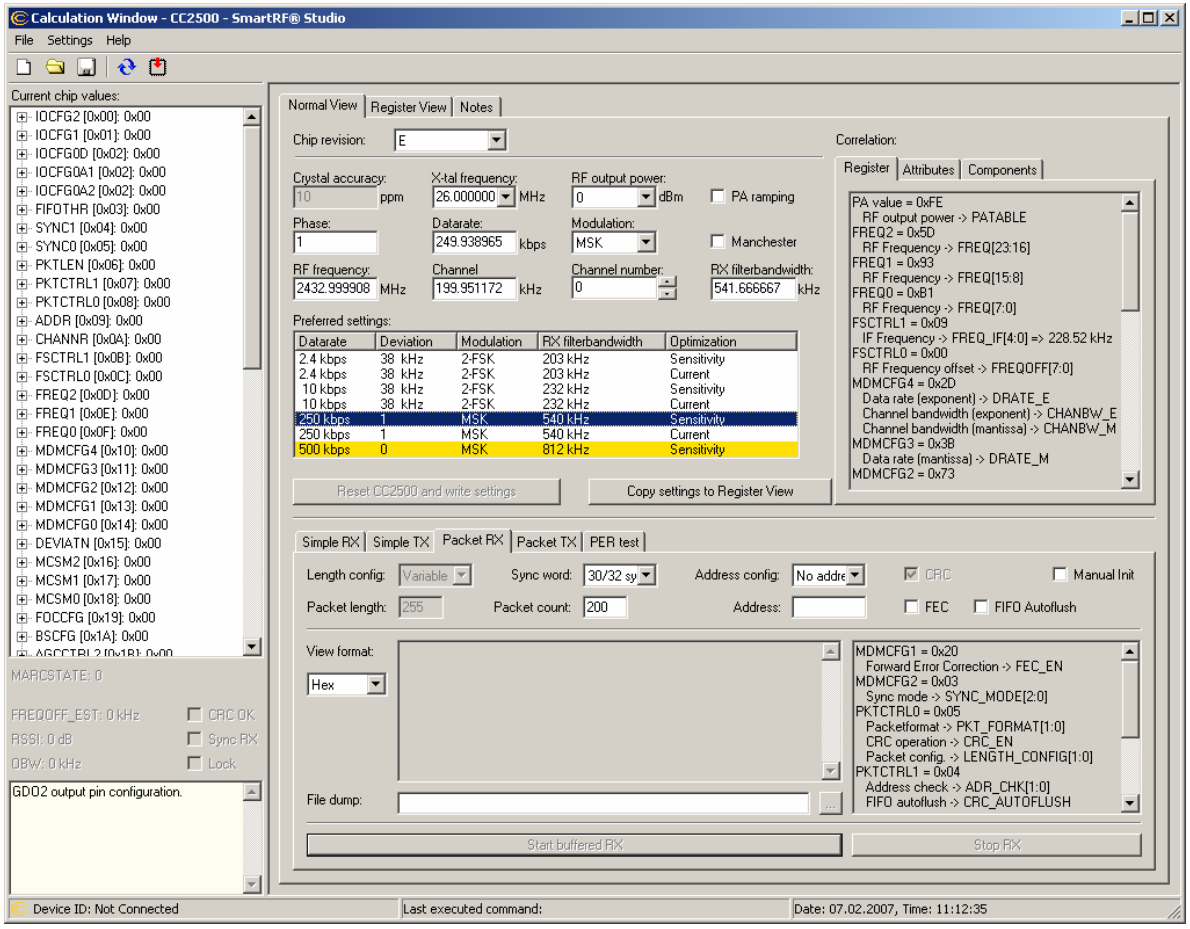
- Average current with PLL calibration:
  - 0.346 ms·1.6 mA + 0.809 ms·8.2 mA + 0.245 ms·16 mA + 0.580 ms·1.6 mA + 48.02 ms·0.0009 mA / 50 ms = 0.24 mA
- Average current without PLL calibration:
  - 0.346 ms·1.6 mA + 0.09 ms·8.2 mA + 0.245 ms·16 mA + 1.299 ms·1.6 mA + 48.739 ms·0.0009 mA / 50 ms = 0.14 mA
- Average current without PLL and RC calibration:
  - 0.346 ms·1.6 mA + 0.09 ms·8.2 mA + 0.245 ms·16 mA + 49.319 ms·0.0009 mA / 50 ms = 0.11 mA

PLL and VCO Calibration

- Calibration is needed to operate at the correct RF frequency
- Full calibration
  - Not a good solution for FHSS systems
- Relaxed calibration
- Calibration replaced by a look-up table
  - Used to minimize blanking interval in FHSS systems

Register Optimization

- Optimized for RX current or sensitivity. Your choice!



Demonstration - RadioDesk™ from TI

RadioDesk is a complete 2.4GHz wireless solution for makers of HID devices

(remote control, keyboard, mouse etc…)

RadioDesk main focus

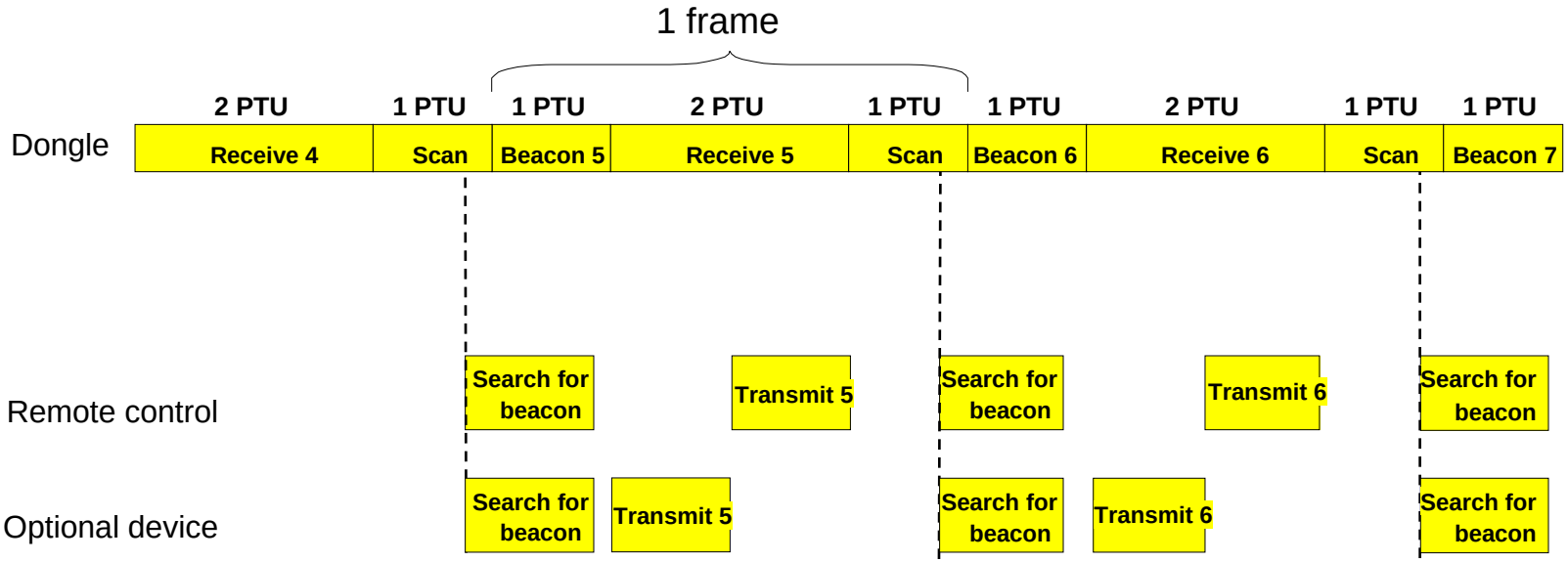
- **Robustness and coexistence with other 2.4 GHz systems (WLAN, Bluetooth, cordless phones, microwave ovens)**
  - Adaptive frequency hopping protocol
  - Radio provides excellent blocking and receiver selectivity
- **Long battery lifetime**
  - RadioDesk protocol designed for low-power utilizing excellent sleep modes
  - Radio has low peak current consumption and very quick start-up time (reducing on-time)
  - Current Consumption: 1mA active & 0.0003mA sleep
- **Low system cost**
  - Low cost parts: CC2510 SoC
- **Range**
  - Very good radio sensitivity

Hardware Solution

- **System-on-Chip solution for remote control, keyboard, mouse and dongle**
  - Remote control
    - CC2510: SoC with integrated CC2500 transceiver, MCU and flash
    - Up to 90 buttons without IO expander
  - USB dongle
    - CC2511: CC2510 SoC with full speed USB (12Mb/s)
    - Only uses the USB HID standard, no extra software needed on PC
  - Optional AES-128 encryption with no additional latency or current consumption

Software solution

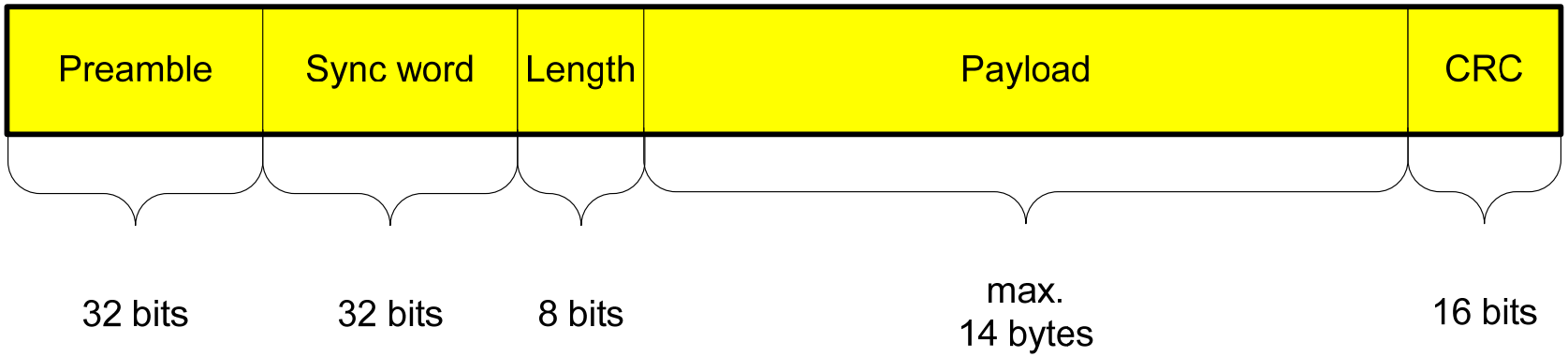
Time Division Multiple Access (TDMA) solution:



- The frame can be extended to allow more devices
- The RF frequency is changed for every frame
- Each PTU is 2ms

PTU: protocol time unit

RadioDesk protocol - packet



- **Max packet size 25 bytes (configurable)**

Thank you for your attention

Questions?

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