Project: IEEE P802.15 Working Group

Submission Title: [UWB Wakeup Signalling]

Date Submitted: [12th Nov 2021]

Source: [Michael Mc Laughlin, Ryan Bunch, Marcus Granger-Jones] Affiliation [Qorvo]
Address [ ]
E-Mail:[michael.mclaughlin (at) qorvo.com]

Re: [Proposed enhancements to 802.15.4 UWB]

Abstract: [Input to the technical requirements discussion for the 4ab project]

Purpose: []

Technical Guidance [1]

PAR Objective	Proposed Solution (how addressed)
Safeguards so that the high throughput data use cases will not cause significant disruption to low duty-cycle ranging use cases.	
Interference mitigation techniques to support higher density and higher traffic use cases	
Other coexistence improvement	
Backward compatibility with enhanced ranging capable devices (ERDEVs).	
Improved link budget and/or reduced air-time	Proposal dramatically improves wakeup receiver link budget
Additional channels and operating frequencies	
Improvements to accuracy / precision / reliability and interoperability for high-integrity ranging;	
Reduce complexity and power consumption;	Proposal dramatically improves UWB wakeup receiver power consumption
Hybrid operation with narrowband signaling to assist UWB;	Reduces the requirement for narrowband signaling
Enhanced native discovery and connection setup mechanisms;	Allows a UWB transmitter to address individual devices and to wake them up.
Sensing capabilities to support presence detection and environment mapping;	
Low-power low-latency streaming	
higher data-rate streaming allowing at least 50 Mbit/s of throughput.	
Support for peer-to-peer, peer-to-multi-peer, and station-to-infrastructure protocols;	proposes a station-to-infrastructure protocol
Infrastructure synchronization mechanisms.	Improves infrastructure synchronization

UWB Wakeup Signalling

A wakeup signal and detector using Ultra Wideband

UWB and a companion Narrowband radio

- There are 3 main reasons that a narrowband radio is often paired with UWB

1. Range for data transfer of narrowband vs UWB
   Actually UWB has 2 x range of a typical narrowband radio. See backup slides
2. Comms with a smartphone
   This is not usually an issue and will shortly be much less of an issue. See backup slides
3. UWB wakeup radio is not thought to be practical
   - Receiver too power hungry
   - Link margin for WuRx is thought to be MUCH lower than for UWB data

These reasons are used to justify adding a second distinct radio with it’s associated extra cost, extra RF receive and transmit strips and extra separate antennas

UWB Wakeup Radio

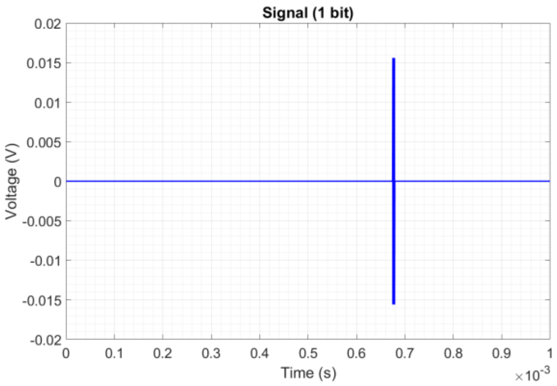
- Challenges for UWB wake-up radio vs NB
  - Ultra Wideband has very limited mean Tx power
    - -14dBm vs typically +5dBm for Bluetooth/Zigbee
  - 500MHz Bandwidth means thermal noise power is -87dBm
    - Bluetooth and Zigbee use 1 or 2MHz bandwidth => -114/-111dBm noise power

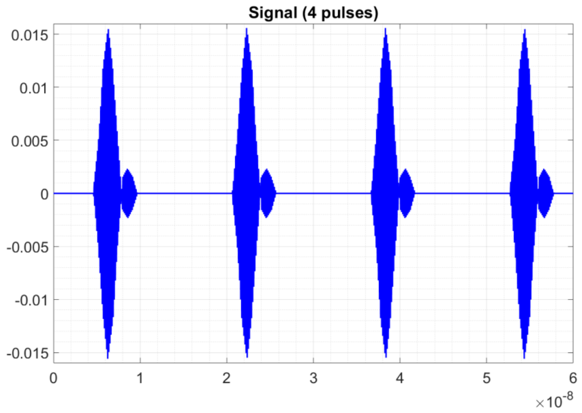
- Note that even for NB Wake Up Radios, it is a tough challenge to get enough sensitivity to match the data sensitivity without using a lot of current

- Here we present an architecture for a UWB wakeup radio
  - **with a better link margin than 6.8Mbps UWB**
  - **at a power consumption that lasts 4 years on a coin cell battery**

Proposed UWB Wakeup Signal

- Transmitter sends 4µs of, 4z like, STS sequence every 1ms. One pulse every 16ns.
  - Applies gain of 24dB, i.e. signal is boosted so that average power in 1ms is -14.3dBm
  - Pseudo-random pulse polarity with good auto-correlation properties
  - 4µs is 250 pulses = 37nJ energy => 148pJ / pulse
- Use OOK type modulation, i.e. burst for ‘one’, no burst for ‘zero’
- Receiver only listens to small proportion of 1ms “slots” e.g. 1 slot in 20 in order to save power
- Transmitter precedes it’s wake-up code with enough ‘ones’ so that receiver will be guaranteed to be listening for at least one of those ‘ones’

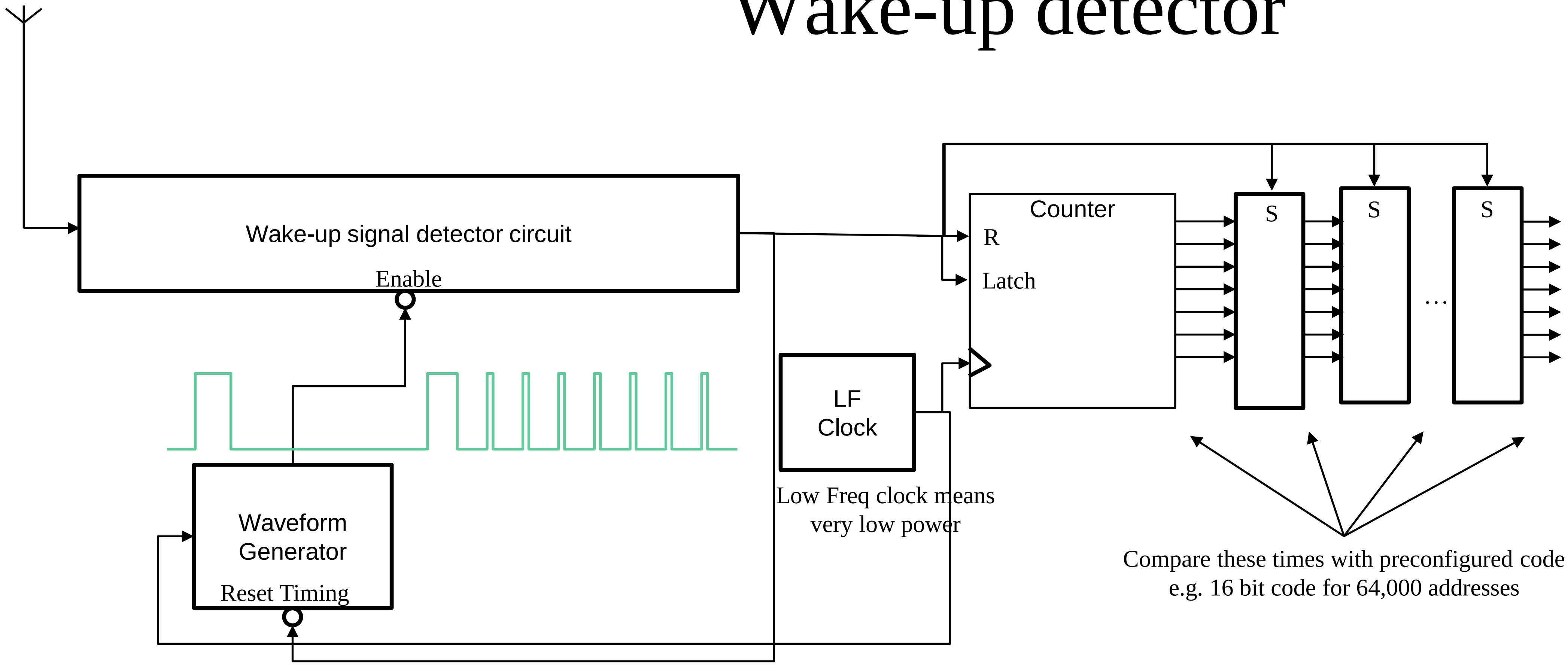




Transmitter Energy Consumption

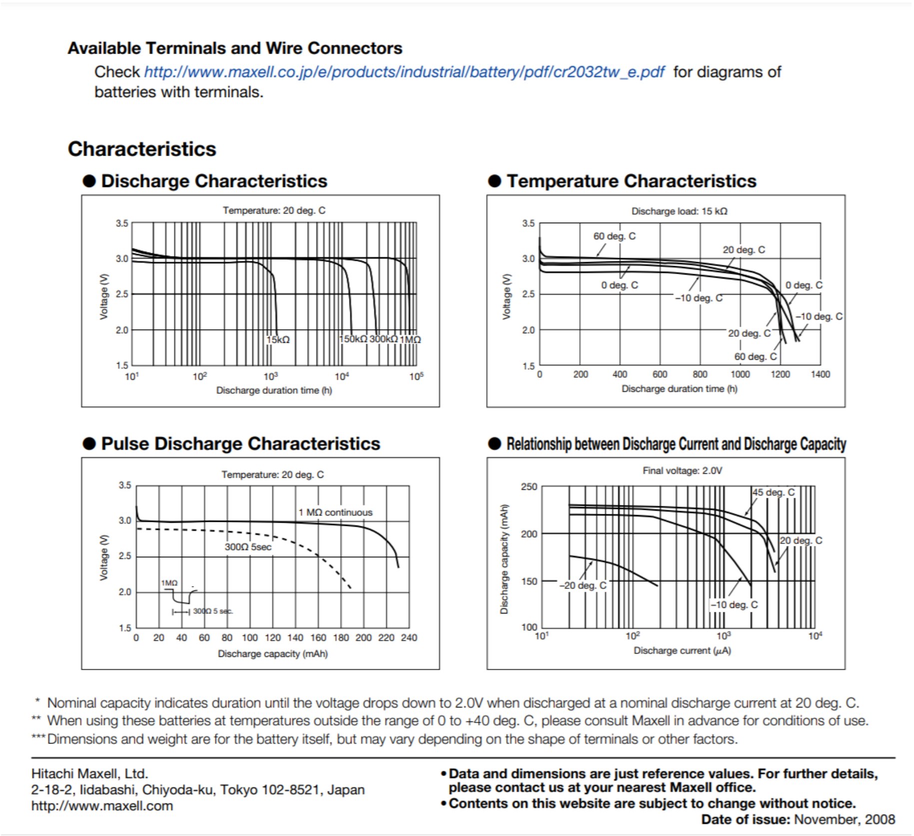
- 24dB of gain means the burst is sent at +10dBm albeit for only 4µs
- This is challenging for low voltage CMOS, so it’s likely that the transmitter will need an external power amplifier
  - Wake-up transmitters are not nearly as cost sensitive as, say, location tags.
- Despite this, the transmitter power consumption is low; Each 1ms bit still only uses 37nJ
- The transmitter duty cycle is 250:1 => Even a 1 Watt transmitter would only use 4mW on average

Wake-up detector



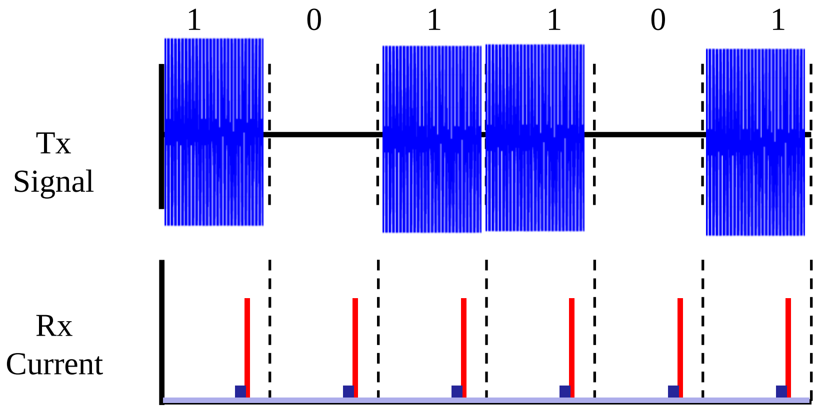
How much current can WuRx draw?

CR2032 Capacity	**225**	**mAh**	
Average Vbat	2.9	V	
Energy	2349	Joules	
Vdd	1.2	V	
Lifetime	4	years	
DCDC Efficiency	65%		
Average Cont Current	**10.09**	**µA**	

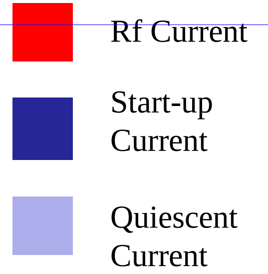


Detector Circuit along lines of Dissanyake paper[1]

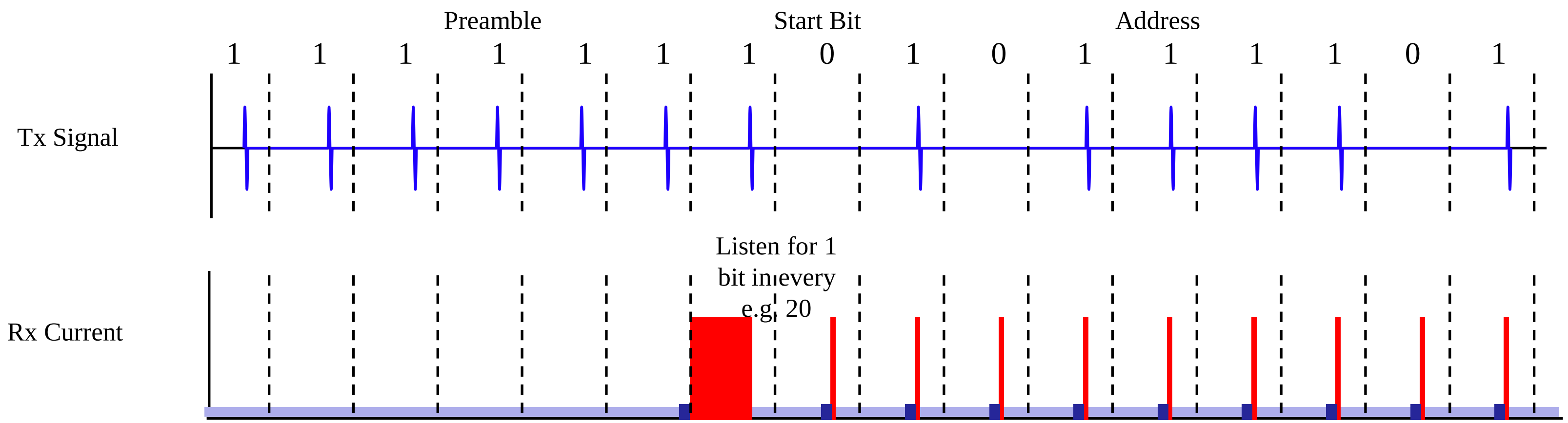
- Draws inspiration from Dissanyake paper[1]
  - https://ieeexplore.ieee.org/document/8777956
- In [1] Tx transmits for whole bit duration
- We only transmit for e.g. 0.4% per bit
- At first, receiver needs to be on for whole bit, because burst position is unknown
- Transmitter send a preamble of repeated 1s, .e.g repeats first “1” 20 times
- Once first burst is detected, position of next burst is known



Original Scheme



[1] A -108dBm Sensitivity, -28dB SIR, 130nW to 41µW, Digitally Reconfigurable Bit-Level Duty-Cycled Wakeup and Data Receiver
Anjana Dissanayake et al., 2020 IEEE Custom Integrated Circuits Conference (CICC)



Wake-up Receiver (WuRx)

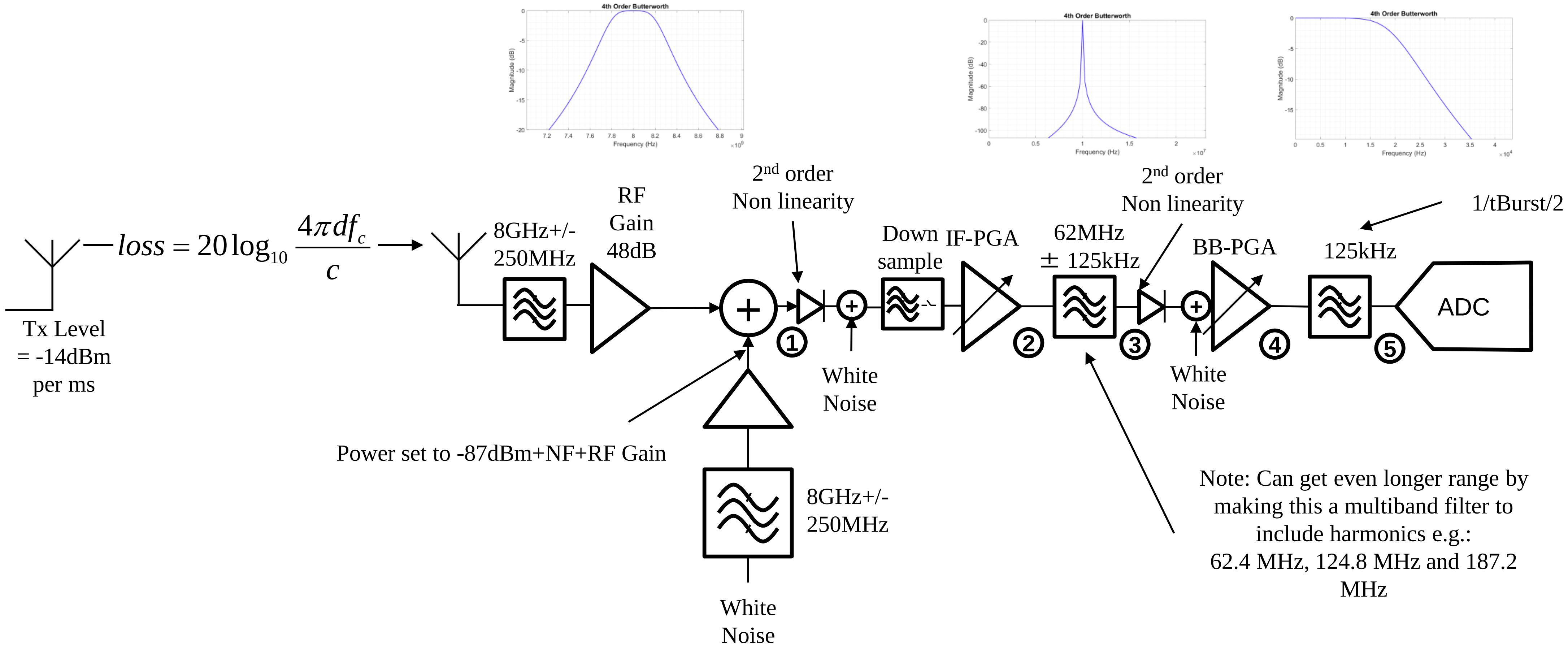
- Receiver listens for 1ms in every, say, 20ms
- If UWB signal detected, it records the position in the 1ms that this occurred and passes this along to a waveform generator
- The waveform generator enables the detector circuitry every ms for, e.g., 4µs + a startup time and uncertainty time around the expected position of the burst e.g. 5µs or 10µs
- The digital receiver records the time between burst detections
  - This tells it how many zeros are between ones

Burst level duty cycling

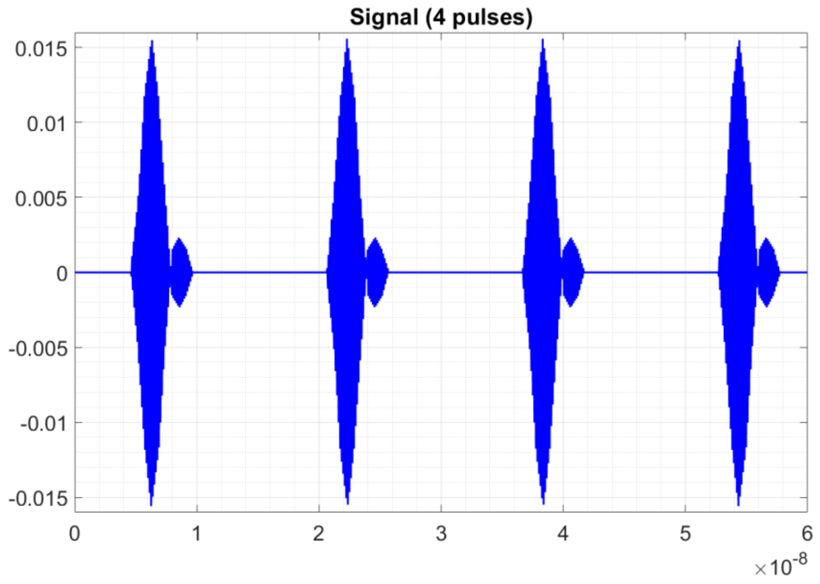
- Detector Circuit takes, say, 200µA, while RF is on
- RF stage has 48dB voltage gain prior to 1st detector
- If we use 20:1 duty cycle => 10µA average
  - Note power budget: ~10µA
- To ensure wake-up signal seen, transmitter sends 20 ones before the wakeup address
- Latency for 16 bit address is 20ms+17ms=37ms

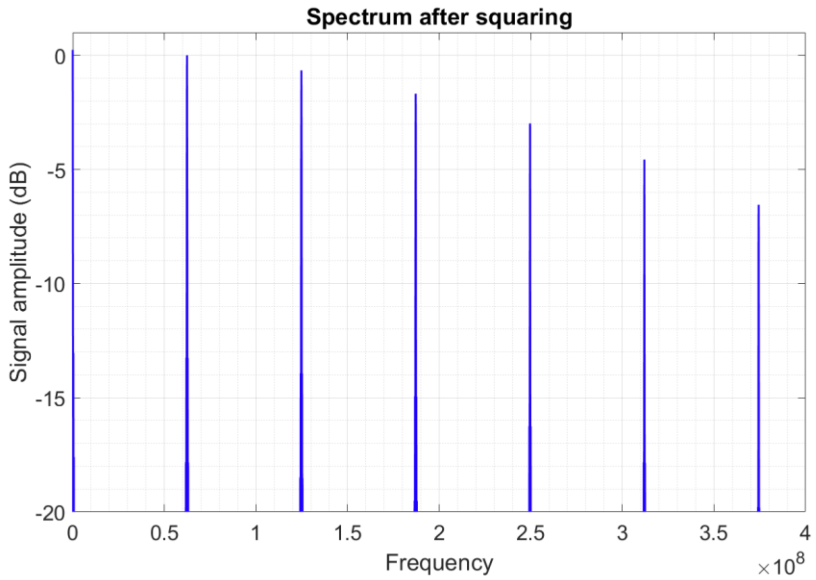
*https://ieeexplore.ieee.org/document/8777956

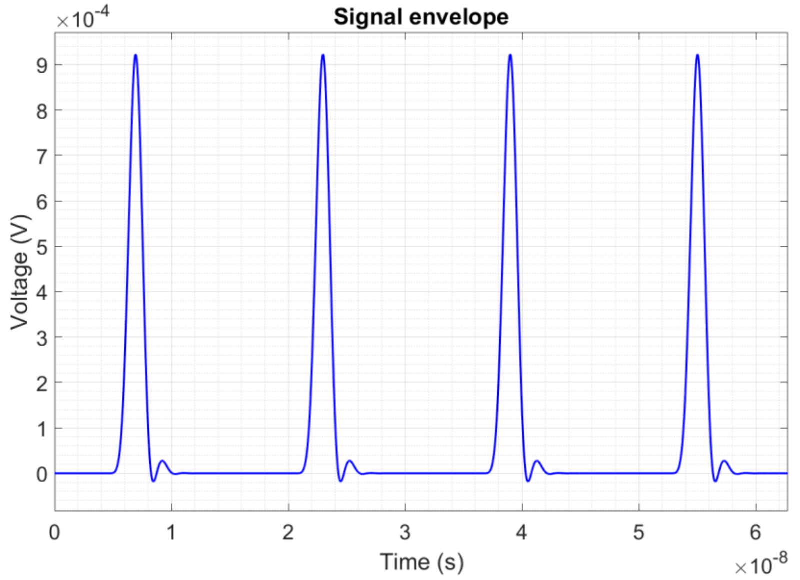
Matlab Simulation model



- Pulses are narrow compared to pulse separation
- Envelope is rich in harmonics
- It increases range if that extra power is gathered in

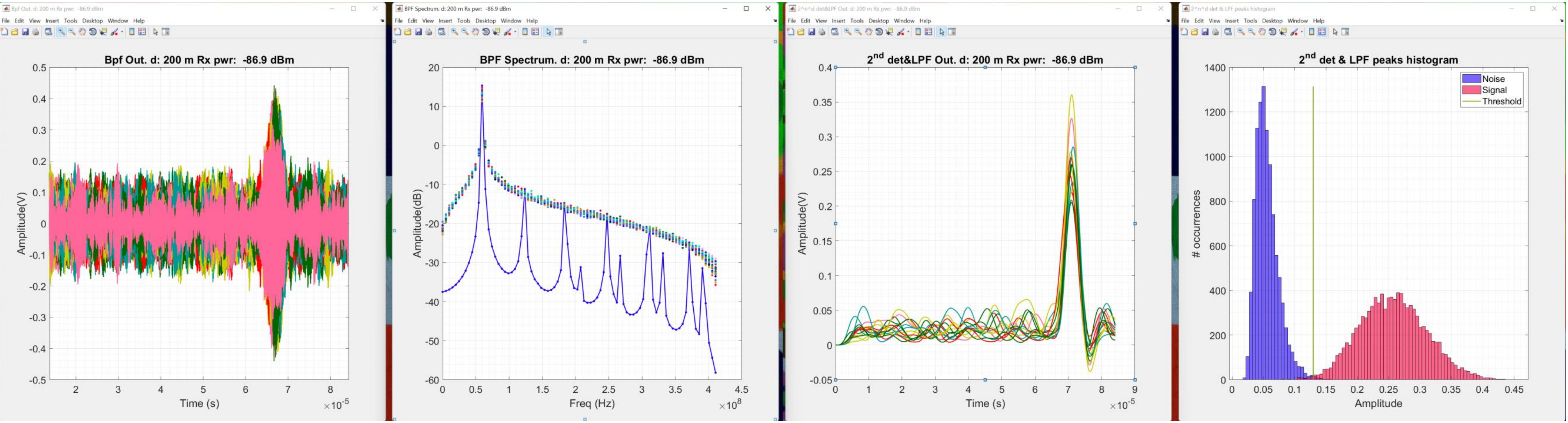






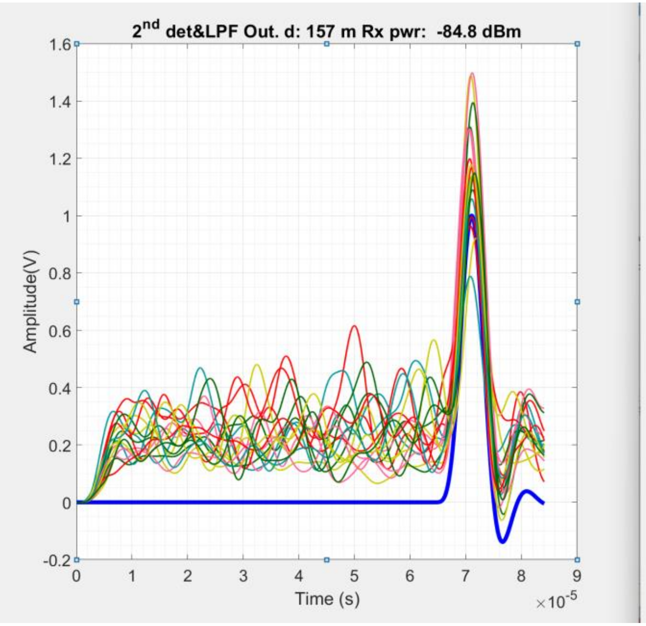
200m: no detector self noise. Single band BPF

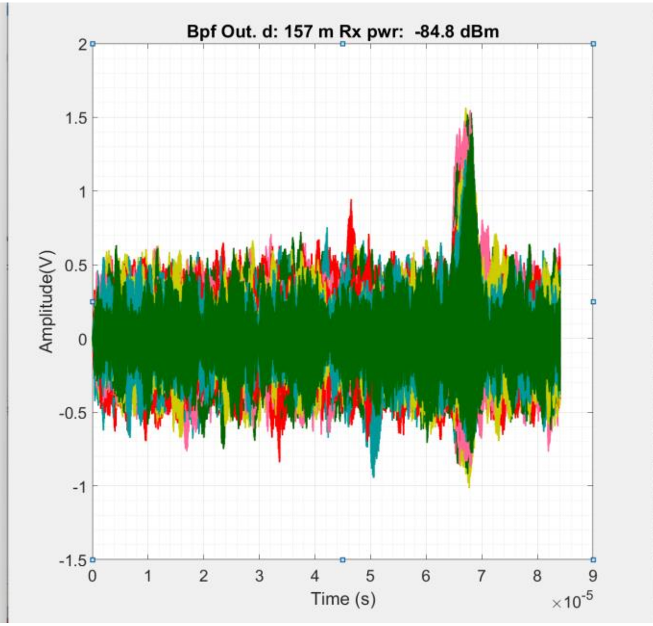
- 2nd Det Noise: = 0.056 ± 0.019 , Signal: = 0.26 ± 0.053. False Positives: 43/10000 Missed: 54/10000
- Approximately 1% BER

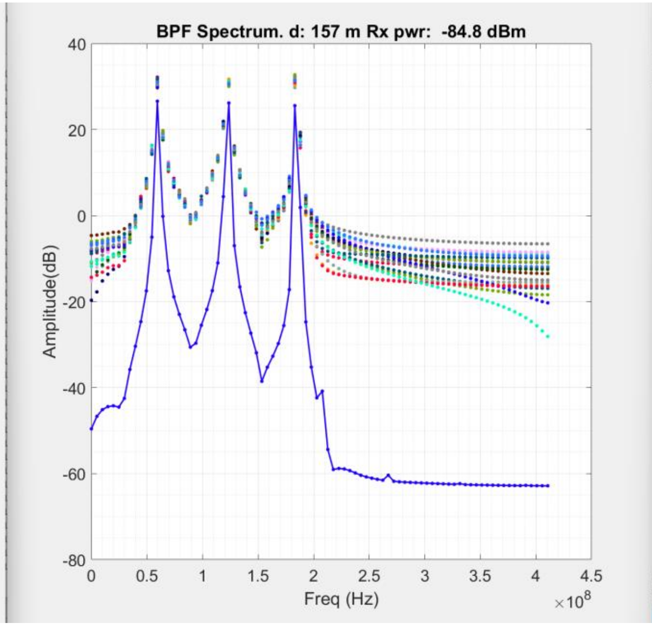


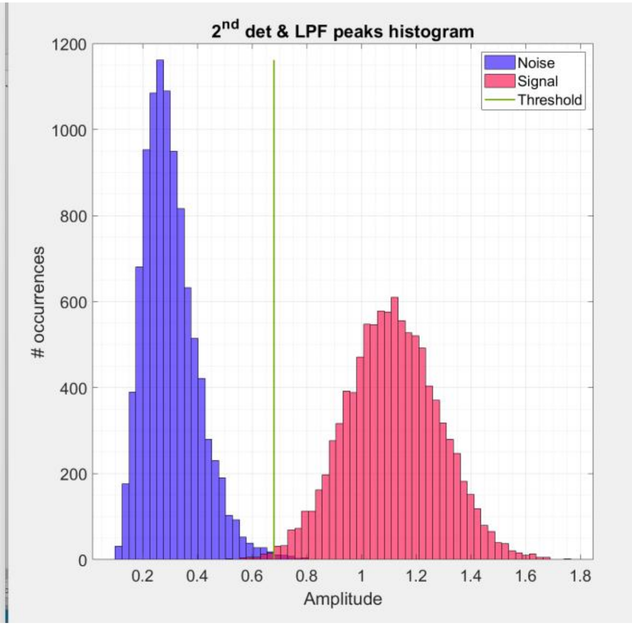
157m: Non-ideal sq. law detect and multiband BPF

2nd Det LPF. False Positives: 39/10000 Missed: 46/10000 Noise: = 0.3 ± 0.1 , Signal: = 1.1 ± 0.17
BER <1%



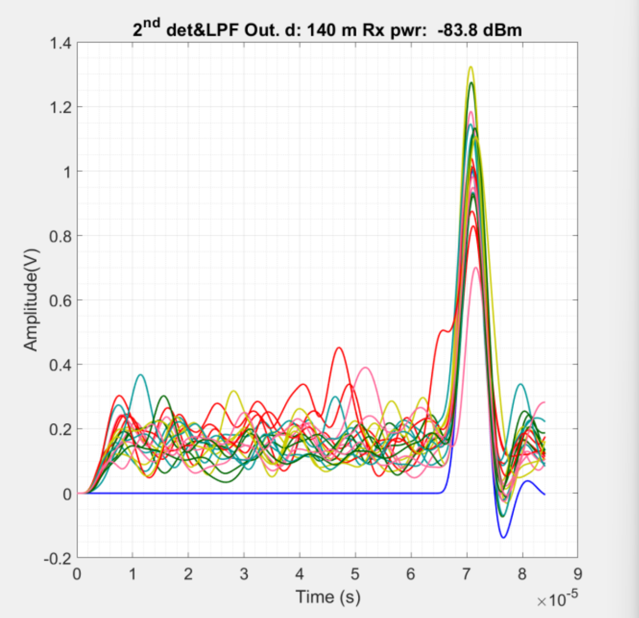


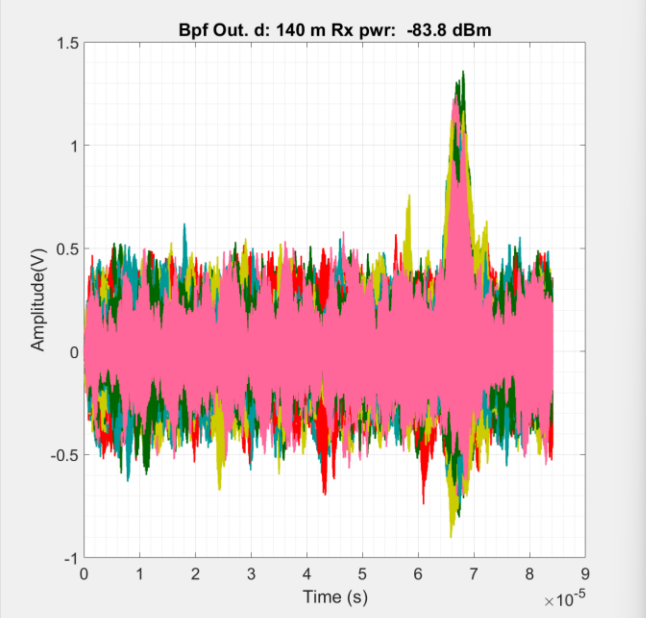


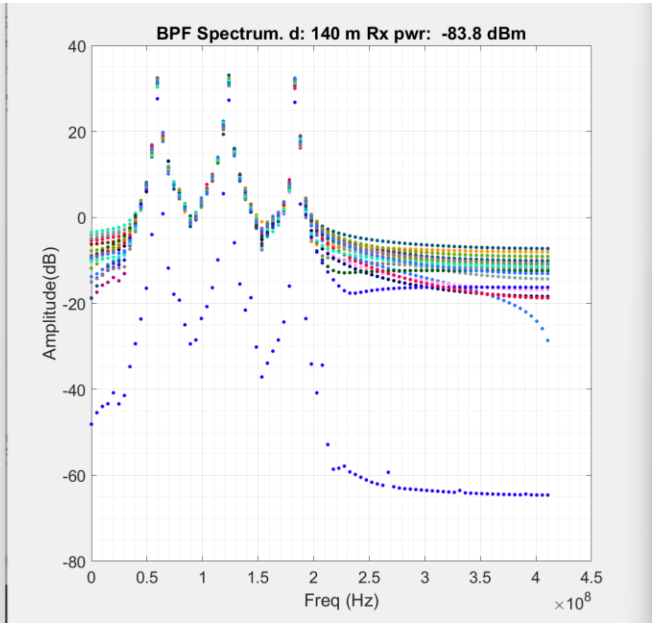


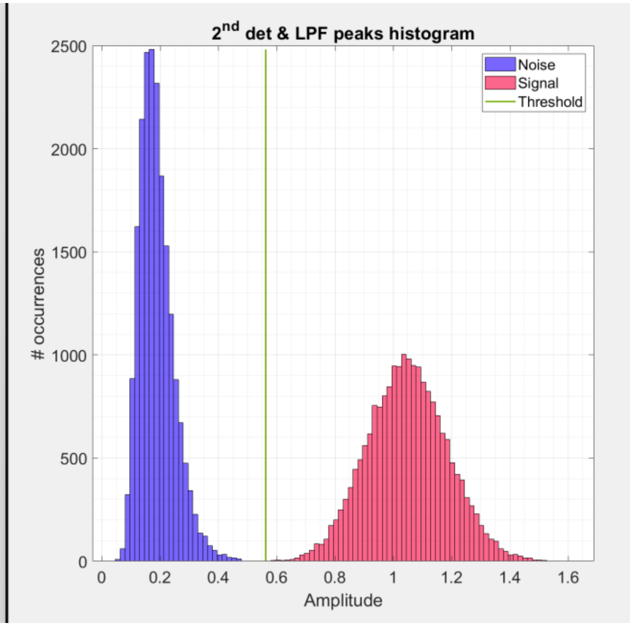
140m: Non-ideal sq. law detect and multiband BPF

2nd Det LPF. False Positives: 0/20000 Missed: 2/20000 Noise: = 0.19 ± 0.06 , Signal: = 1 ± 0.14
BER =0.01%

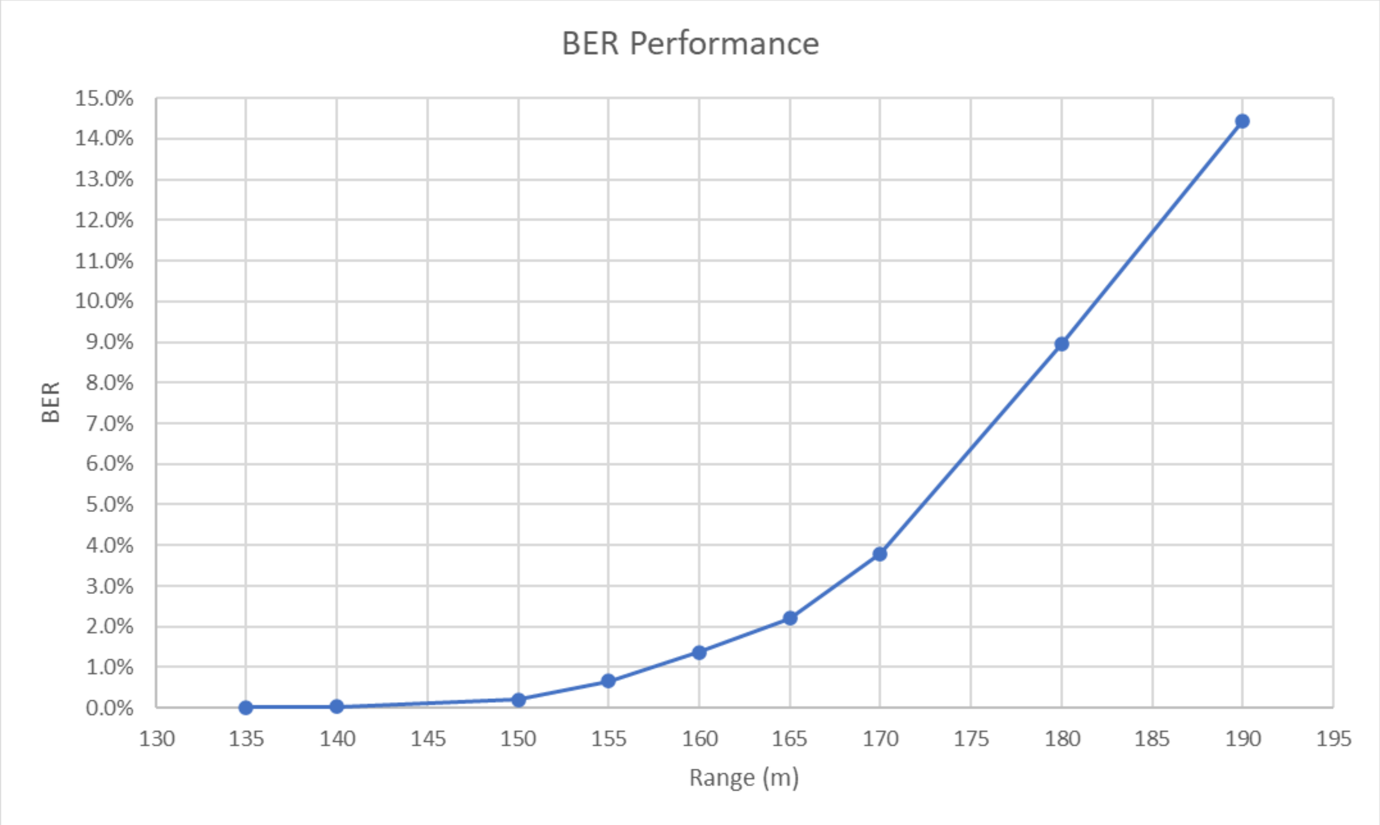






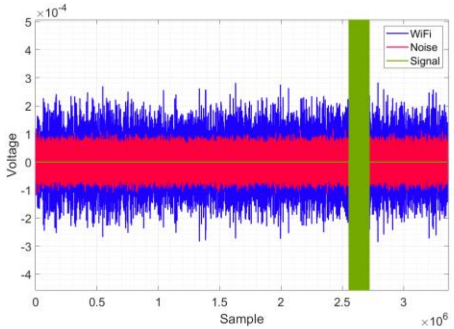


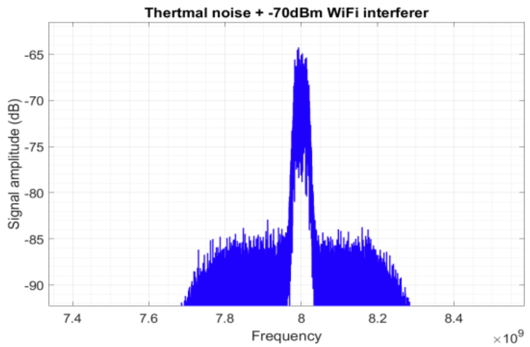
BER vs distance. Non ideal detector.

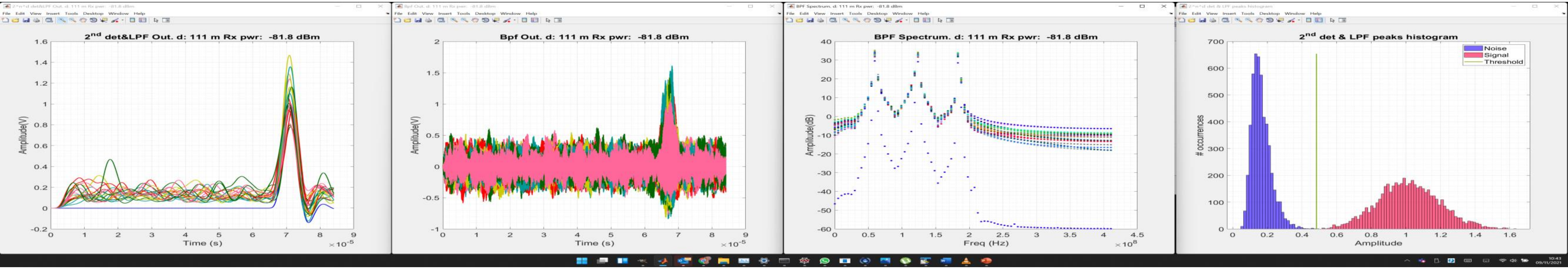


In-band interferer. 40MHz BW WiFi at 8GHz

Increased receive power by 3dB from sensitivity point (from -84.8 to -81.8) and added -70dBm 40MHz BW WiFi signal.
Error rate was 5 errors in 5000 bits = 1% False Positives: 2/5000 Missed: 3/5000 Noise: =   0.16 ±   0.057 , Signal: =   1 ±   0.18
SI Rejection Ratio = 14.8dB => better than 802.15.4z BPRF data mode at 6.8Mbps (~10dB)
If we just looked for in-band energy, the interferer would look like thermal noise and would have much lower immunity







Analog 22nm circuit performance

- We have a implemented 22nm CMOS layout simulation backing up the Matlab sims
- Gives the following results
  - Range: >150m for 1% BER
  - Range: 140m for 0.1% BER
  - Area: very small
  - Power consumption: 230µA RF + 100µA Digital (330µA => 33:1 duty cycle)
  - => 49ms latency for a 16 bit address

- We expect to improve the range and power consumption with further work

Key takeaways:

- An STS type sequence at 62.4MHz PRF using a code with good auto-correlation to decide the pulse polarity and make it "white"
  - has approximately the same mean power as peak power in a 50MHz bandwidth
- This property allows a 4µs burst to be sent with 24dB extra power boost
- Increases the range by a factor of 16 to 150m (LOS)
  - (Actually better than 16 'cos non-coherent detector)
- The short burst allows power duty cycling up to a factor of 250:1
  - 4µs in every 1ms
- => power consumption can be reduced by up to a factor of 250 (depending on implementation)
  - So 10µA becomes somewhere between 200µA and 2.5mA
  - Increased duty cycling gives lower power but also longer latency which rules out some applications
    - Good circuit design i.e. lower power, gives better latency
- Instead of usual practice of looking for DC after square law detector we:
  - look for a 62.4MHz tone signifying the presence of an envelope of pulses at 62.4MHz+/-125kHz
    - Much less prone to interference (Interferer needs a 62.4MHz envelope)
    - less prone to DC offset effects
    - and less prone to 1/f noise i.e. flicker noise
- Use a multiband BPF gathers multiple harmonics to improve range

Summary

- We have presented a Wake-up radio that uses the UWB channel and achieves the better range and interference rejection than UWB 4z data mode and lasts 4 years on a coin cell battery

- Lots of new applications that wouldn't have been possible before will be dreamt in the future if we adopt this.

- This further reduces the need for a companion Narrowband Radio
  - Note: Narrowband radio DOES still have applications where it will enhance the performance
    - e.g. Although not typically implemented, NB has the option to transmit at +15dBm
    - This takes a lot of transmitter power consumption (of the order of 802.11), but there are applications where this is not a big drawback

Backup Slides

1. Range: UWB vs NB (for data transfer)

There is a misconception that UWB is lower range than Narrowband (NB)

As discussed by Name Surname (Doc 15-21-0394) the range for UWB can be much greater than for NB

The main factors which determine the range difference are:

- UWB nominal Tx power is typically 19dB lower than NB (-14dBm vs +5dBm)
- Relative noise figure (We have assumed equal. NB is typically worse)
- Coding gain (UWB has typically 5dB more than 15.4/BT)
- Tx Power Gain for very short packets (10dB for UWB vs 0dB for NB)
- Relative bitrate (3dB loss for every doubling of bitrate)
- Fading loss (0dB for UWB vs 20dB for NB)
    - More generous than 15-21-0394's 30dB
    - Multipath actually helps UWB

By my calculations, a UWB radio at 3.4Mbps and 8GHz centre frequency will have up to *double* the LOS range of a narrow band radio.

UWB ☑ NB ☒

Note: Red text are user configurations. Black text is calculated.

Parameter	802.15.4z BPRF	802.15.4 5.9GHz	BT4.0 LE 2.4GHz	802.15.4ab (No STS)
Throughput	*6800 kb/s*	*250 kb/s*	*1000 kb/s*	*3400 kb/s*
Bandwidth	*500 MHz*	*2 MHz*	*1 MHz*	*500 MHz*
Data rate PRF	*64 MHz*	*na*	*na*	*256 MHz*
Spectral Density (dBm/MHz)	*-41.3*	*na*	*na*	*-41.3*
Packet Length (octets)	*12*	*12*	*12*	*12*
Max Gating Gain	*9.0 dB*	*0.0 dB*	*0.0 dB*	*10.0 dB*
Rx Noise Figure (RF Strip + Balun + Ext + Antenna)	*6.0 dB*	*6.0 dB*	*6.0 dB*	*6.0 dB*
Algorithmic Loss (CMF, Timing, Carrier, Phase Noise)	*0.0 dB*	*0 dB*	*0 dB*	*0 dB*
Tx backoff: Tx spectrum not flat, Power level not ideal	*1.0 dB*	*1 dB*	*1 dB*	*1 dB*
Minimum E_b/N_0 (1% PER)	*3.5 dB*	*8.5 dB*	*8.5 dB*	*3.5 dB*
Fading Loss	*0.0 dB*	*20 dB*	*20 dB*	*0 dB*
Average Tx power, P_T *(Taking backoff & gating gain into account)*	-6.3 dBm	5.0 dBm	5.0 dBm	-6.4 dBm
Backoff for mean 1ms power limit	***0.0 dB***	***na***	***na***	***1.1 dB***
Pulses per bit	8	na	na	64
Tx antenna gain, G_R	*0 dBi*	*0 dBi*	*0 dBi*	*0 dBi*
Rx antenna gain, G_R	*0 dBi*	*0 dBi*	*0 dBi*	*0 dBi*
Data PRF gain vs 4z BPRF	0.0 dBm	na	na	6.0 dBm
Geometric center frequency $\sqrt{f_{min}.f_{max}}$	7983 MHz	5900 MHz	2450 MHz	7983 MHz
Path loss at 1 meter. $L_1 = 20log_{10}(4\pi f_c/c)$	50.5 dB	47.9 dB	40.2 dB	50.5 dB
Additional Path loss at d m $L_2 = 10log_{10}(d^2)$	38.5 dB	42.7 dB	44.3 dB	48.3 dB
Rx Power at 1 metre	-57 dBm	-42.9 dBm	-35.2 dBm	-56.9 dBm
Rx Antenna Power P_R *at Max Distance*	-95 dBm	-86 dBm	-80 dBm	-105 dBm
Rx Noise Power into ADC	-81.0 dBm	-105.0 dBm	-108.0 dBm	-81.0 dBm
Antenna noise power per bit	-105.7 dBm	-120.0 dBm	-114.0 dBm	-108.7 dBm
ADC in noise power per bit, P_N	-100 dBm	-114 dBm	-108 dBm	-103 dBm
Min. Rx Sensitivity Level (Excluding fading)	-95 dBm	-106 dBm	-100 dBm	-105 dBm
LOS Distance	**84 m**	**136 m**	**164 m**	**260 m**
Indoor NLOS Distance	22 m	27 m	29 m	35 m

2. Comms with a smartphone

- Many, if not most, UWB applications don’t involve a smartphone
- All smartphones have Bluetooth but most don’t have UWB
- This is changing. All new high-end smartphones have UWB
  - This will filter down to all smartphones fairly soon
- This is no longer a valid argument for a narrowband companion radio especially in many applications

UWB ☑ NB ☒