

Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: [Elements of an IR-UWB PHY for Body Area Networks]

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Abstract: [Elements of an IR-UWB PHY suited for BAN are outlined and the resulting expected performance of a system adopting such elements are highlighted]

Purpose: [Trigger discussions amongst groups and companies willing to propose an UWB PHY; and initiate consolidation of different UWB PHY proposals in view of hearing of formal answers to the call for proposals]

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Presentation outline

- Introduction
 - Advantages and Drawbacks of IR-UWB in BAN context
 - Existing UWB-IR systems

- Elements of an IR-UWB PHY for BAN
 - Burst concatenation & Data encoding
 - Coping with ISI
 - Proposed system overview

- Performance analysis
 - Receiver types
 - Link budgets
 - Power consumption

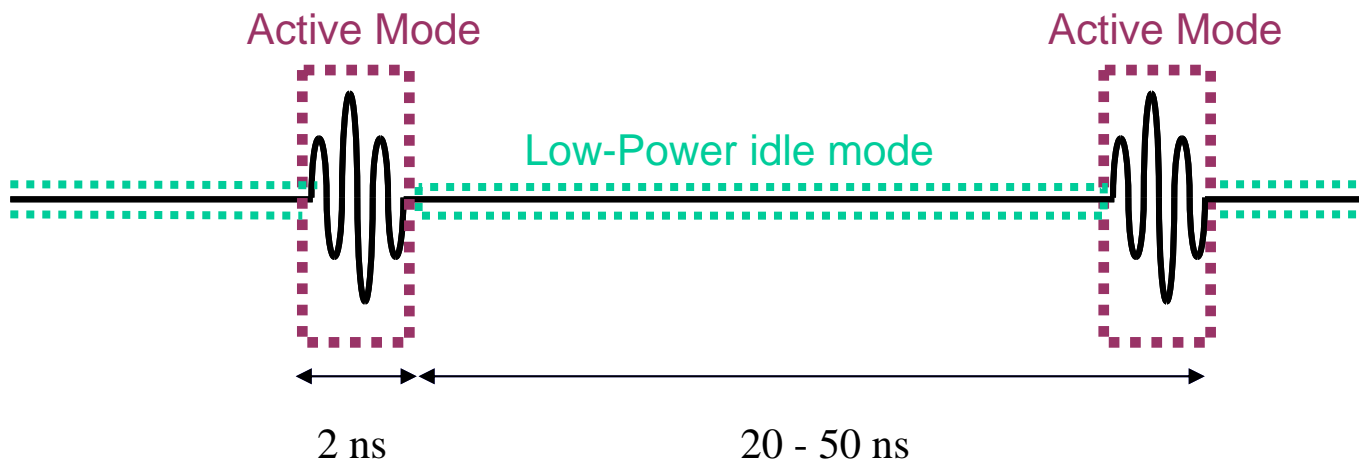
- Conclusions

Intro: Advantages of IR-UWB in WBAN

- Flexible data rates
 - Constant PRF, changing # pulses per bit
 - data rate vs. range tradeoff
- Multi User Capabilities
 - Scarce nature of air interface -> few collisions
 - Spreading gain of many pulses per bit
 - Uncoordinated operation possible with smooth performance impact
 - High node density
- Reduced Interference – Low Radiated Power (-41.3 dBm/MHz)
 - To medical instruments
 - To existing CE devices and services
 - Limited RF energy transfer to human body
- Interference robustness
 - Plenty of spectrum to chose from (3-10 GHz)
 - Few services currently operating at such frequencies

Intro: Advantages of IR-UWB in WBAN

- Ultra Low Power Consumption
 - Rely on low duty cycle of IR-UWB signal (typically <10%)
 - Switch off Radio between Pulses at both Tx and Rx
 - Low Complexity Tx/Rx schemes



Intro: Challenges for IR-UWB in WBAN

- High attenuation @ considered frequencies
 - Shadowing effect of the body
 - Limited range especially at higher data rates
 - No communication through the body
 - Implants are not an option
 - Body shadowing at higher data rates?
 - Challenge is also an opportunity: higher spatial reuse possible
 - Allows higher node density

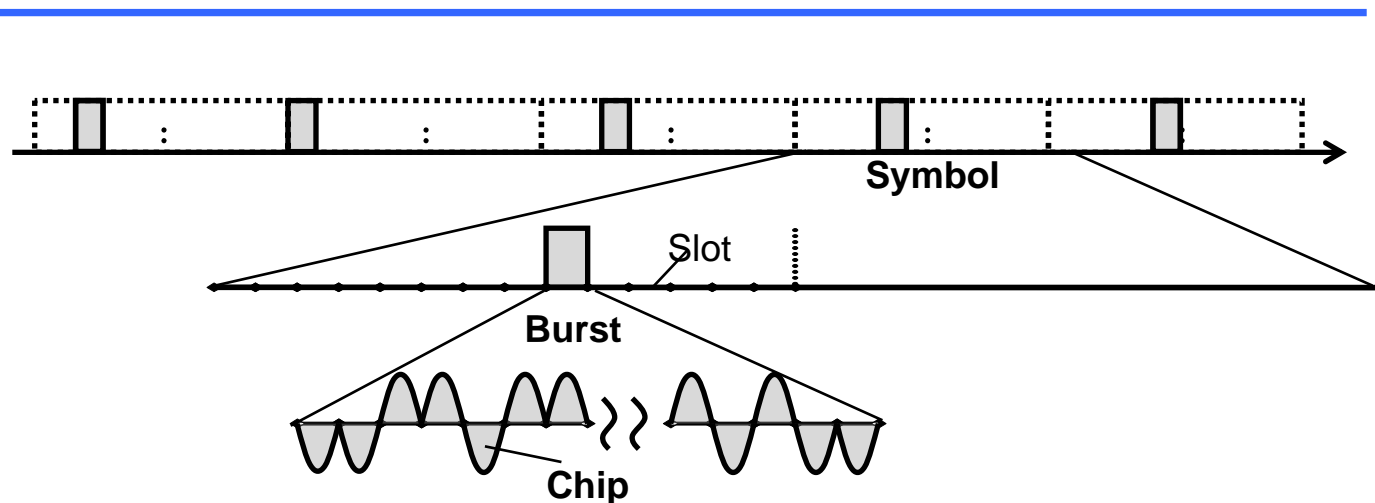
- Accurate timing references usually required
 - Information in very short pulses, timing needs to be known accurately
 - Need to maintain timing information over silent portions between pulses

Existing IR-UWB systems: Isolated Pulses & IEEE 802.15.4a

UWB IP

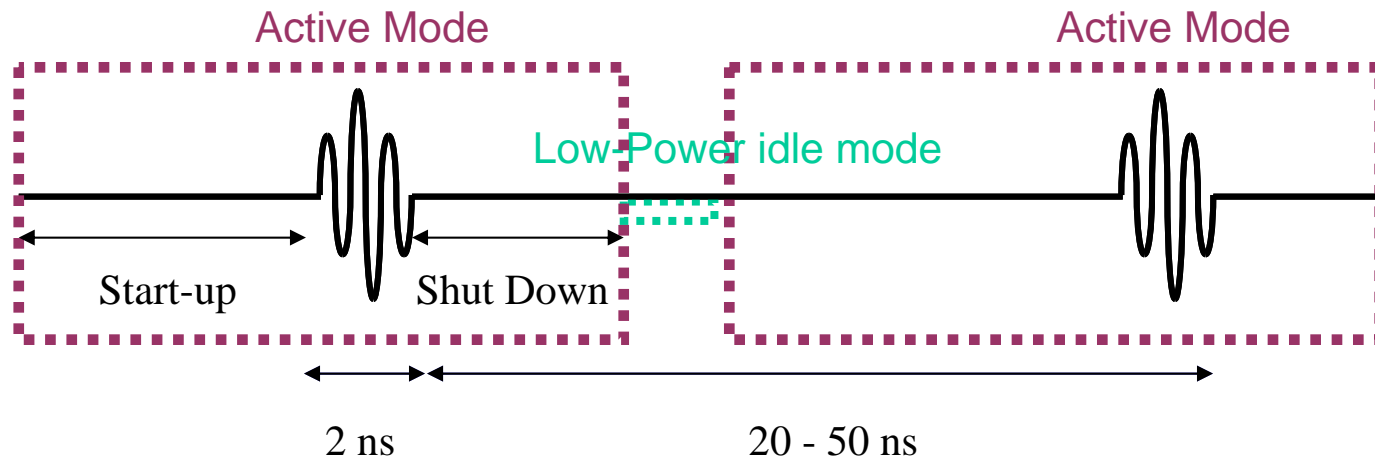


UWB 4a



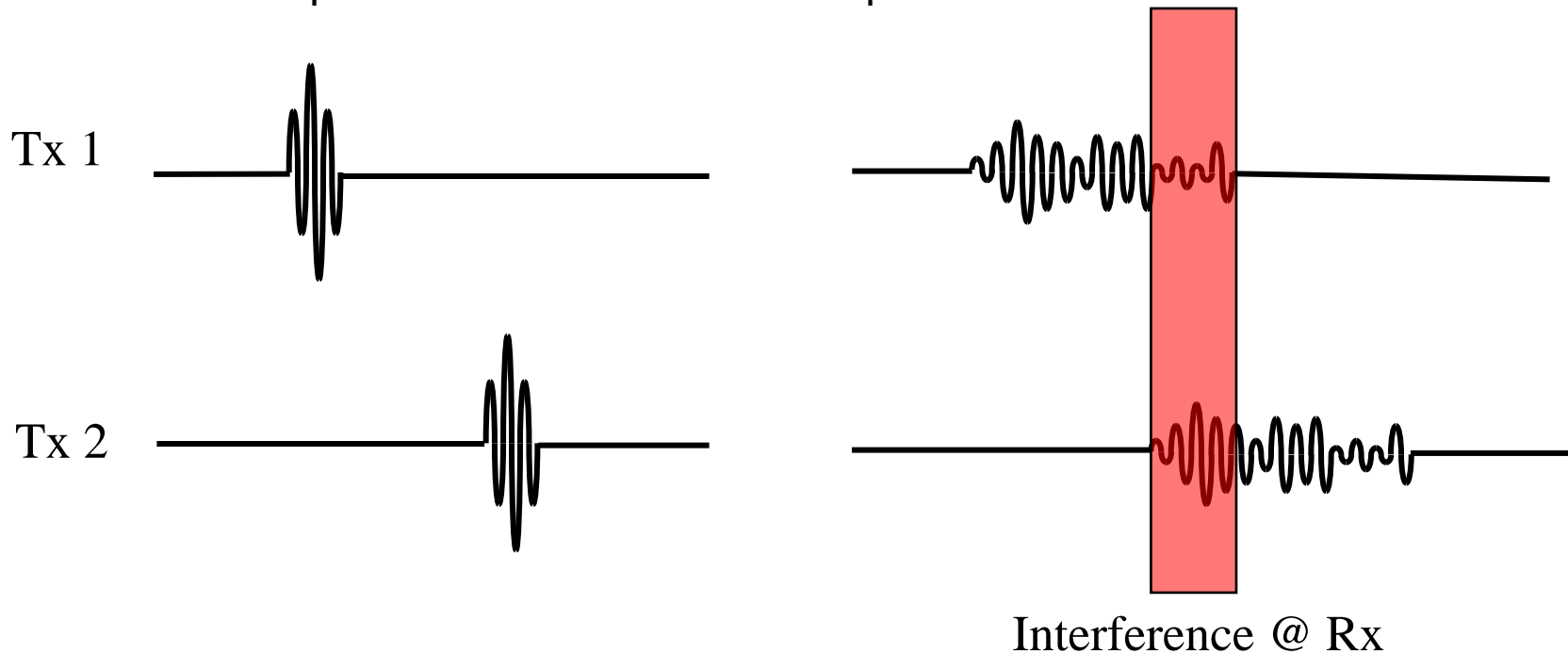
Pros and Cons of Isolated Pulses UWB

- Information encoding:
 - PPM, BPSK, OOK & combinations thereof
- Advantages
 - One pulse processed at a time
- Drawbacks
 - Power consumption increase by start-up and shut-down overheads



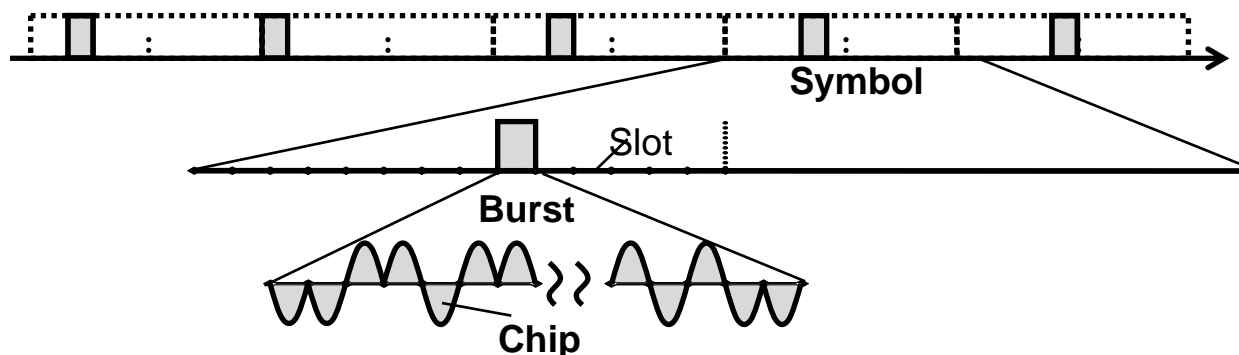
Pros and Cons of Isolated Pulses UWB

- Drawbacks
 - Channel Delay Spread
 - Impact on multi-User interference: Pulses from several users well separated in time @ Tx overlap @ Rx



IEEE 802.15.4a – Key aspects

- Mean PRF “fixed” (3.9 MHz, 15.6 MHz or 62.4 MHz)
- Isolated Pulses in Timing Acquisition Preamble
- Spectrum Divided in Channels of 500 MHz – Broader channels overlap
- Data encoded in both Phase and Position (PPM + BPSK)
- Various data rates supported (0.11 – 27 Mbps)
 - Change Symbol Duration and # Pulses per bit to change data rate
 - Isolated Pulses at highest supported data rates



Pros & Cons of 15.4a @ Low data rates

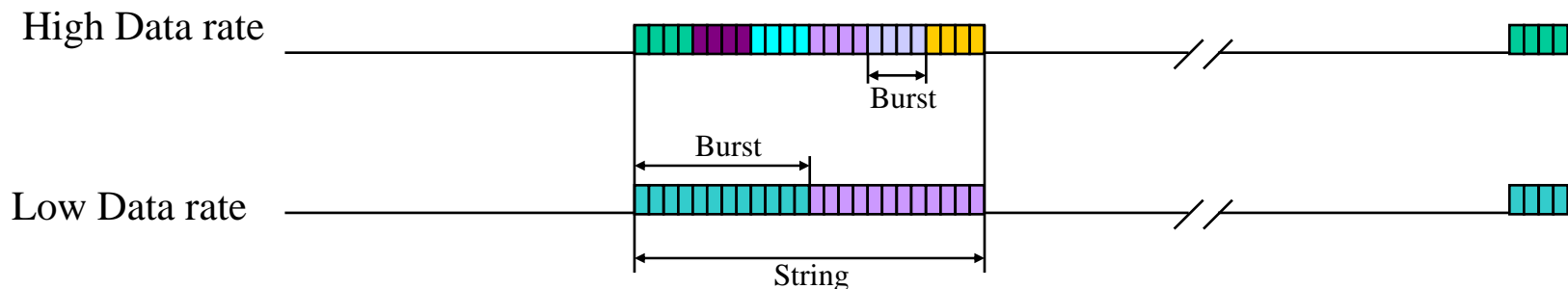
- Low data rate properties
 - Very long bursts of adjacent pulses (up to 512)
 - Very long silent portions between bursts (up to 10 microseconds)
- Key advantages
 - Power Consumption: Low startup overhead makes duty cycling efficient
 - Multi User Interference:
 - low probability of collision between bursts
 - Large spreading gains allow to survive such collisions
 - ALOHA is foreseen as an option in MAC
- Drawback:
 - Required timing reference accuracy:
 - Information encoded in absolute phase of the burst
 - Avoiding phase ambiguity @ start of a burst
 - Maintain accurate enough timing reference between bursts is a challenge
 - Ex: 45 degrees @ 10 GHz = 0.0125 ns accuracy.
 - Maintain this over 10 microsec requires about 1ppm timing ref accuracy

Pros & Cons of 15.4a @ High data rates

- High data rate properties
 - Very short bursts of adjacent pulses – isolated pulses eventually
 - Short silent portions between bursts (down to 16 ns)
- Key drawbacks
 - Power Consumption: startup overhead makes duty cycling inefficient
 - Multi User Interference
- Advantage:
 - Required timing reference accuracy is less
 - Absolute phase information easier to exploit

Elements of an IR-UWB PHY for BAN

- Key target
 - Maintain efficient duty cycle at higher data rates
 - Eliminate accurate timing reference requirements
 - Maintain Multi-User Access capabilities
- Key concept
 - Freely inspired by 15.4a
 - Concatenate several *bursts* into relatively long *strings*
 - Fixed symbol duration, fixed string duration: burst length & number of bursts per string adapted in function of data rate



Elements of an IR-UWB PHY for BAN

- Data Encoding
 - PPM is no longer an option
 - OOK & Phase information remain possible
- OOK
 - Each bit is spread into a burst with a BPSK spreading code
 - Presence or absence of the burst to notify '0' or '1'
 - No absolute phase information required
- D-BPSK:
 - Start string with a fixed reference burst (BPSK spreading code)
 - First bit encoded as phase difference between first reference burst and second burst
 - Phase reference re-established @ Rx by reference burst
 - No need of RF phase-accurate timing reference throughout silent period
 - Phase-accurate reference only needed from one burst to the next

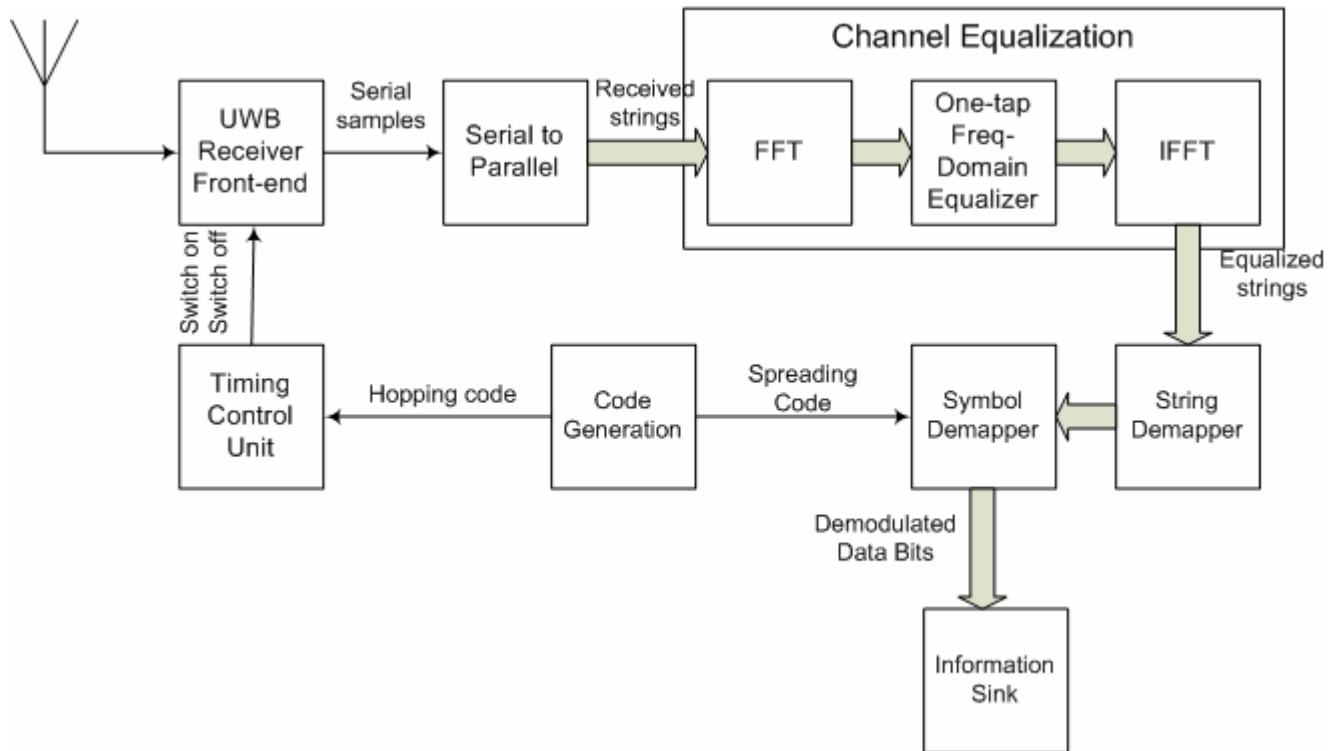
Elements of an IR-UWB PHY for BAN

- Inter-Symbol Interference
 - No silent interval between bursts + multipath channel
 - Interference between consecutive bursts
 - Problem especially acute at higher data rates
- Low data rates & ISI
 - Impact limited to a portion of a burst
 - Rake receivers should allow to cope
 - Possibly multiple fingers

Elements of an IR-UWB PHY for BAN

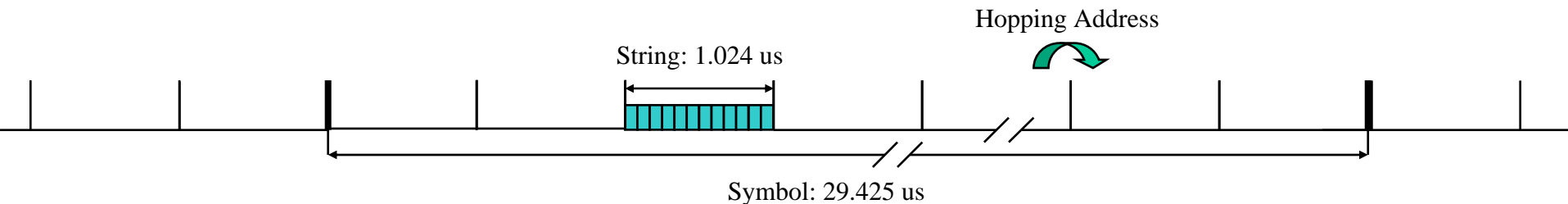
- High data rates & ISI
 - Interference from several bursts
 - Low spreading gain
 - Equalization probably required
- Frequency domain equalization
 - Zeros surrounding string act like a cyclic prefix
 - Channel matrix becomes circulant
 - Low complexity equalizers relying on FFT / IFFT become possible

Frequency Domain Equalization Receiver



Key aspects of a possible UWB PHY proposal for BAN

- Pulse shapes inspired by 15.4a
 - 500 MHz channels
 - Pulse shape ‘close to’ root raised cosine
 - Pulse amplitude 316 mV (max in 90nm CMOS @ 1V)
 - 17.4 MHz fills the FCC mask with that amplitude
- Stings, bursts & data rates
 - String length set to 512
 - Burst length from 1 to 512 Pulses
 - OOK for low data rates, DBPSK for higher data rates
 - Resulting data rates from 0.07 to 17.4 Mbps
 - 0.07 Mbps, 0.14 Mbps, 0.27 Mbps, 0.54 Mbps, 1.09 Mbps, 2.17 Mbps, 4.35 Mbps, 8.7 Mbps, 17.4 Mbps (& 34.8 Mbps for OOK)



Performance Analysis

- Different receivers considered
 - Energy-Based receiver
 - Rake Receiver (1 & 3 fingers)
 - Frequency Domain Equalization

- Different Channels Considered
 - AWGN (reference)
 - Channel model 3 (on-body to on-body)
 - Channel Model 4 (on-body to off-body)

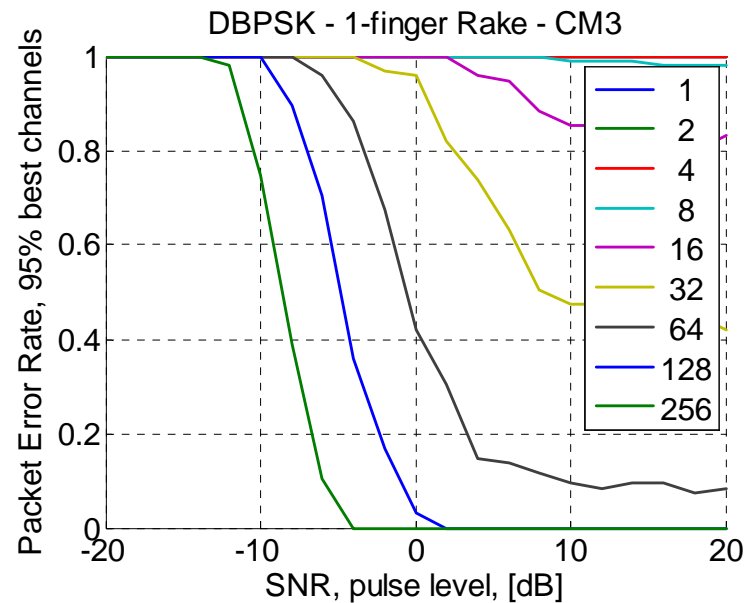
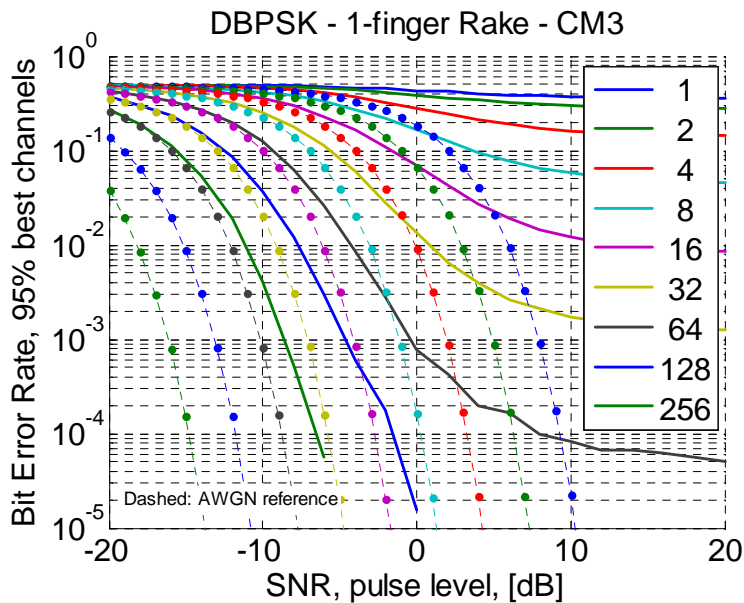
- Different Modulation Schemes considered
 - OOK
 - DBPSK

- No FEC coding considered!

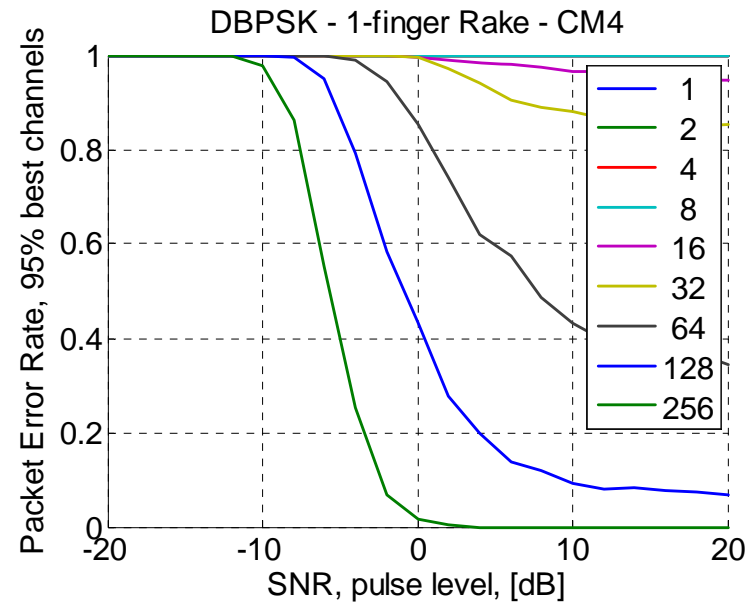
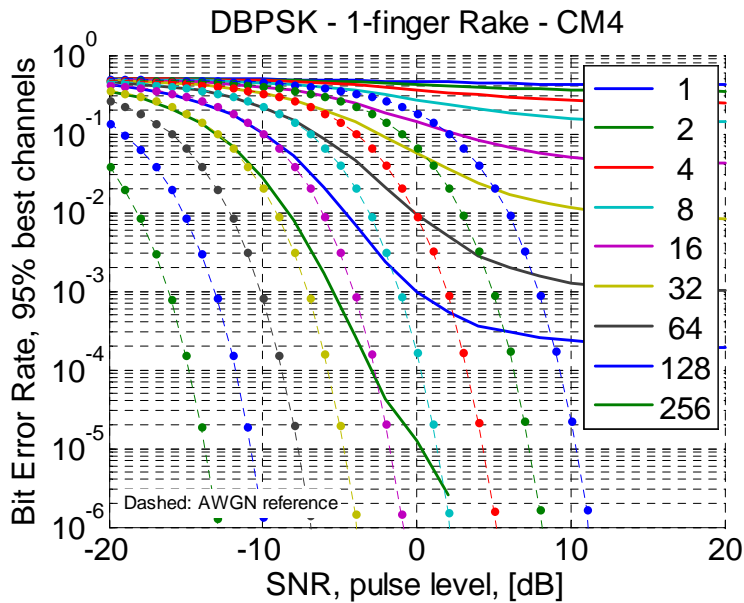
DBPSK – 1-finger rake

- Synchronised to strongest channel tap
- CM3: on-body to on-body
- CM4: on-body to off-body

DBPSK – 1 finger – CM3



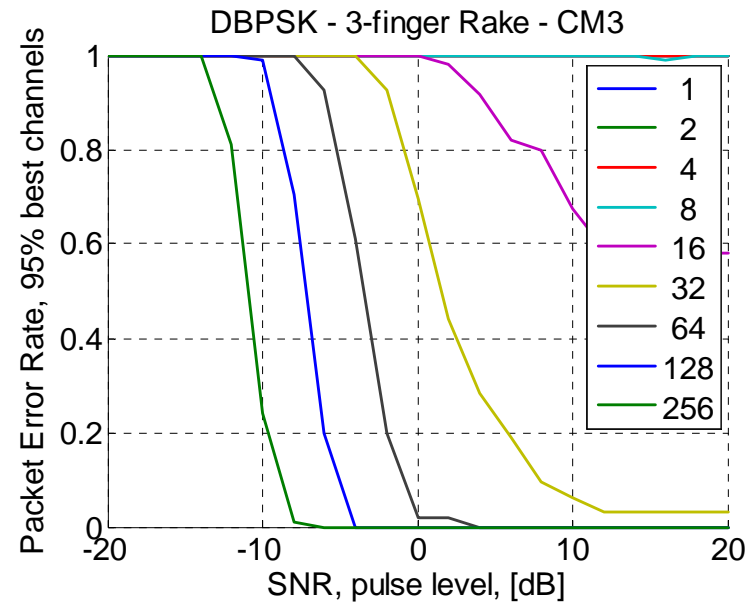
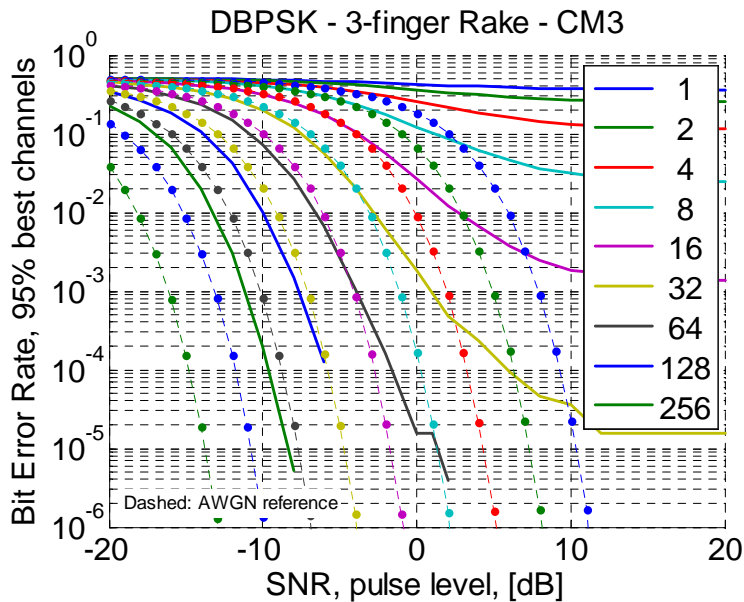
DBPSK – 1 finger – CM4



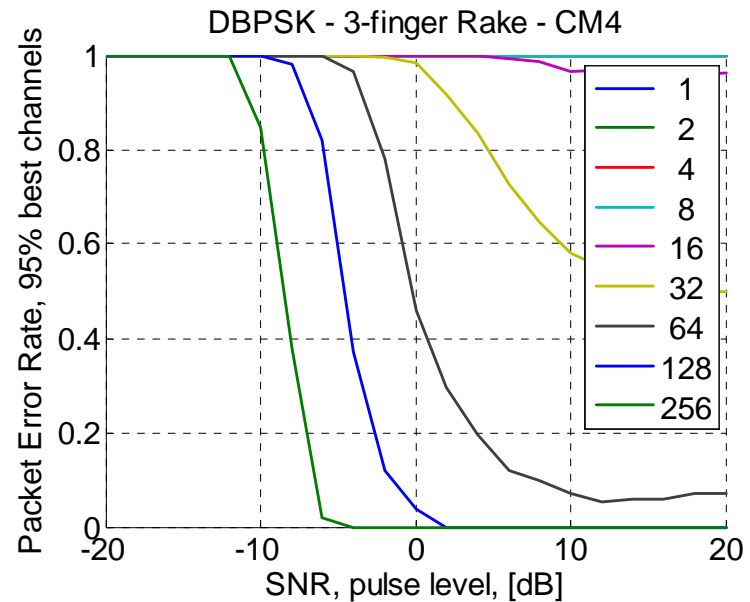
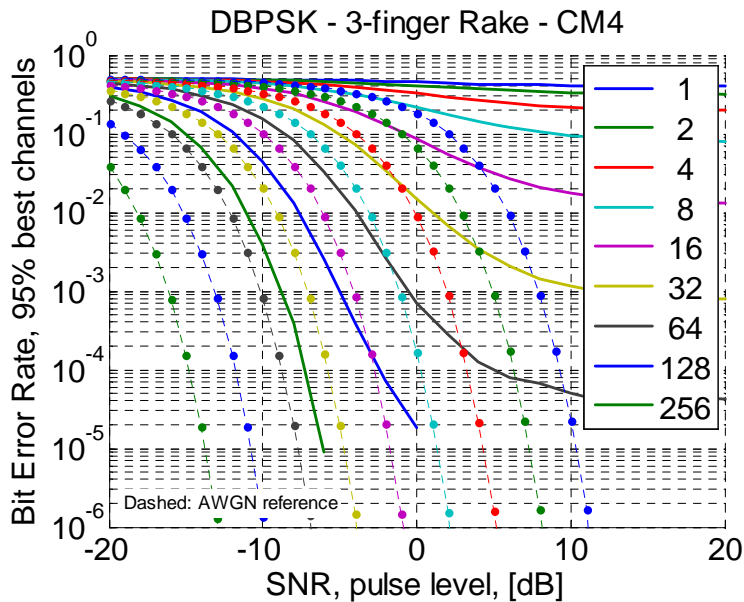
DBPSK – 3 finger rake

- Selective 3 finger rake,
using 3 most powerful channel taps
- Equal gain combining

DBPSK – 3 finger – CM3



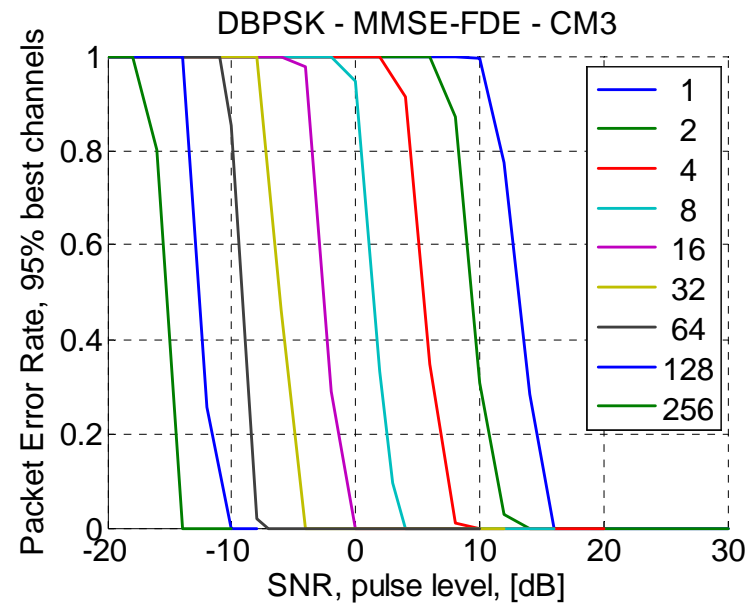
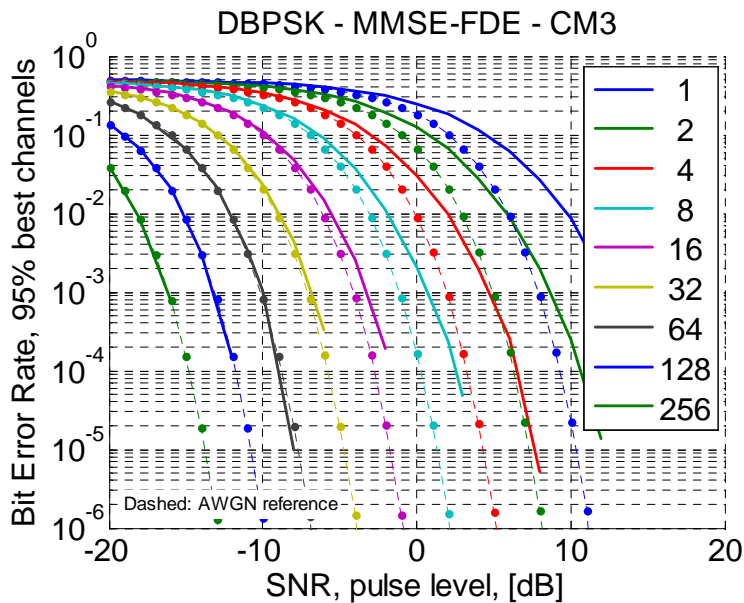
DBPSK – 3-finger – CM4



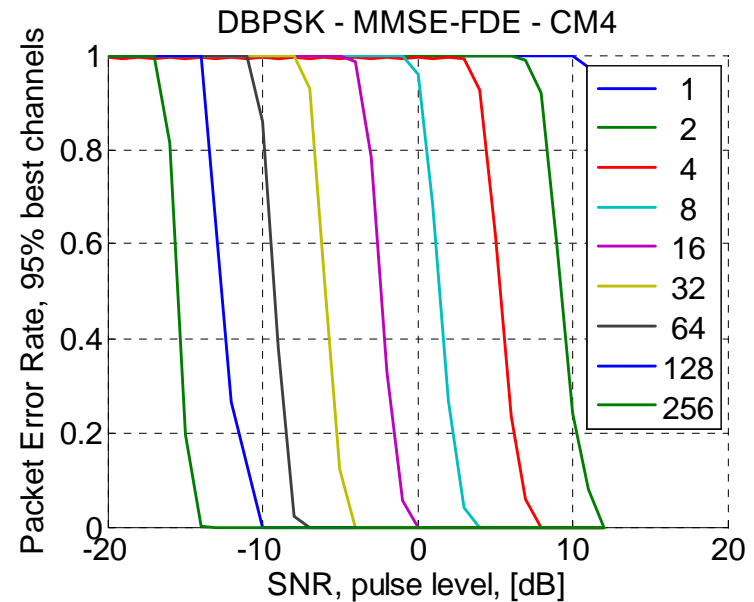
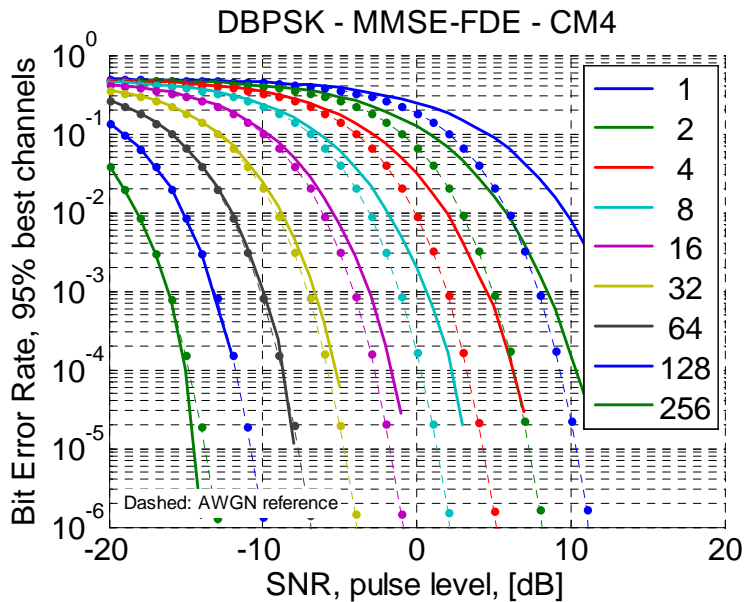
DBPSK – MMSE-FDE

- Frequency domain equaliser
- MMSE coefficients based on perfect channel knowledge

DBPSK – MMSE-FDE – CM3



DBPSK – MMSE-FDE – CM4



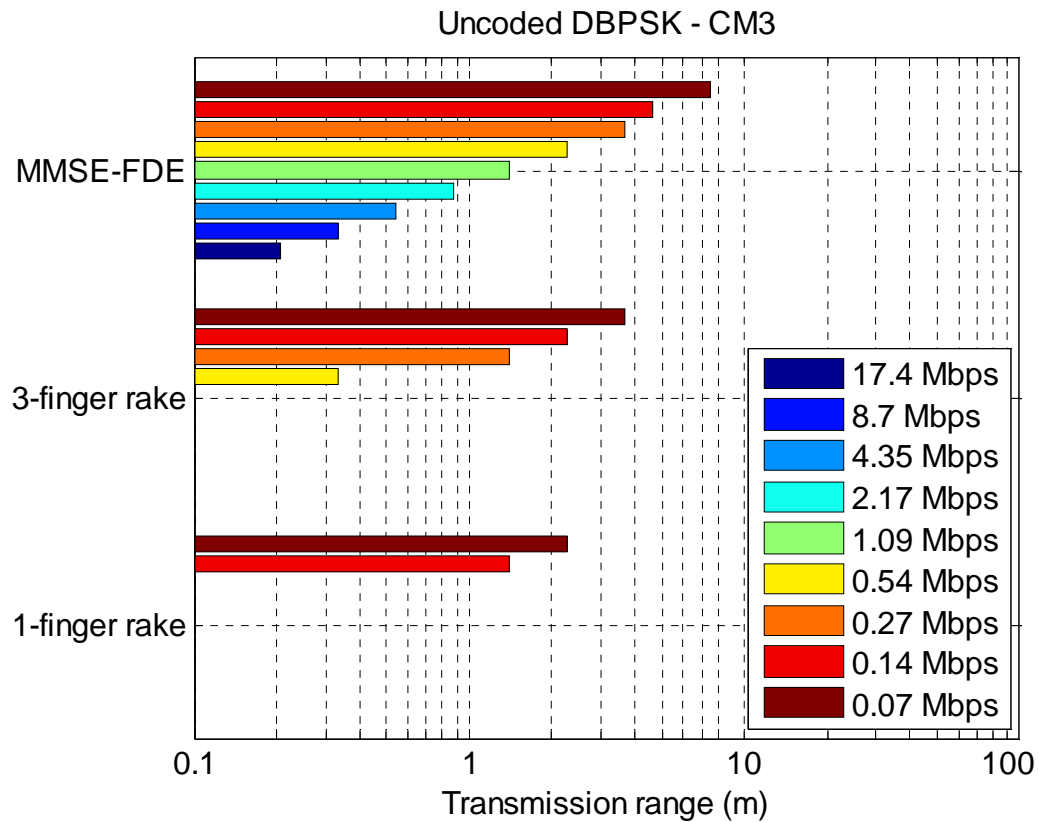
Conservative link budget assumptions

Transmitter	Transmit power	0 dBm	V _{peak} = 316 mV, 50 Ohm load
Channel	Antenna Gain	0 dB	
	Path loss		CM3/CM4 models
	Fading margin	9 dB	
Receiver	Thermal noise	-86 dBm	500 MHz, 30°C
	Noise figure	12 dB	
	Implementation loss	2 dB	

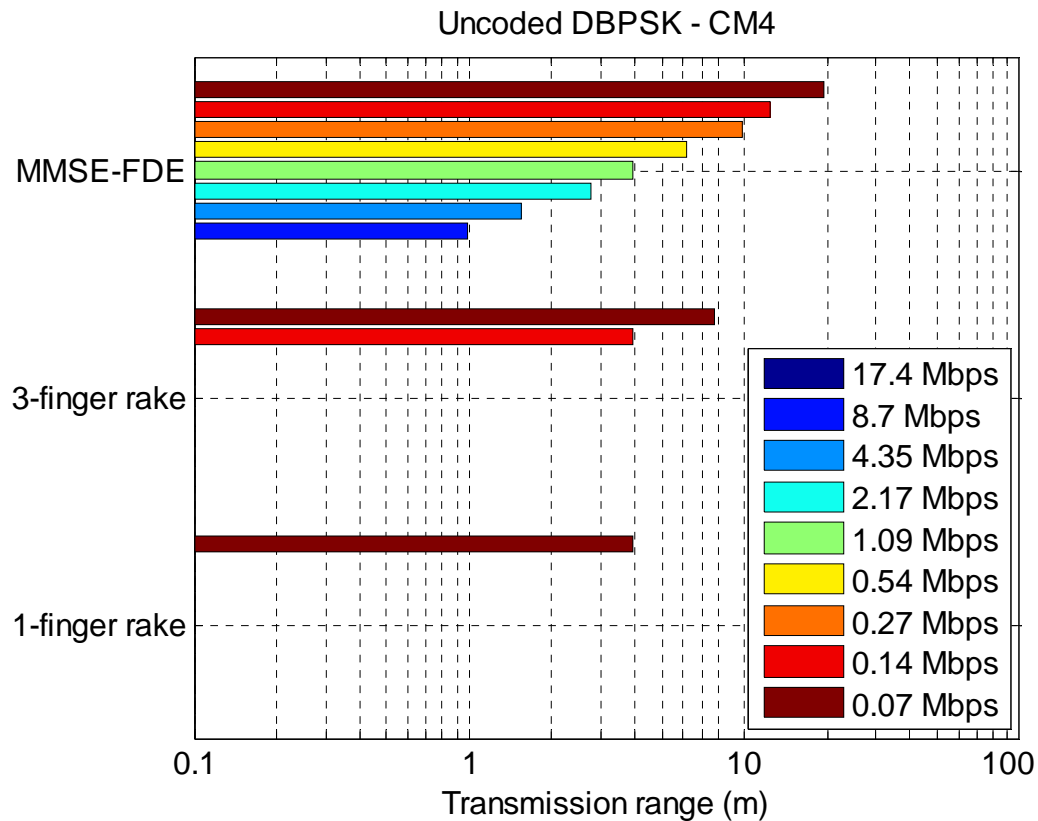
Path loss

- According to channel model document 08-0780-06-0006
- CM3:
$$PL [dB] = 19.2 * \log_{10}(d [mm]) + 3.38$$
- CM4:
 - Free space path loss
 - Centre frequency: 6 GHz

DBPSK – Uncoded Range – CM3



DBPSK – Uncoded Range – CM4



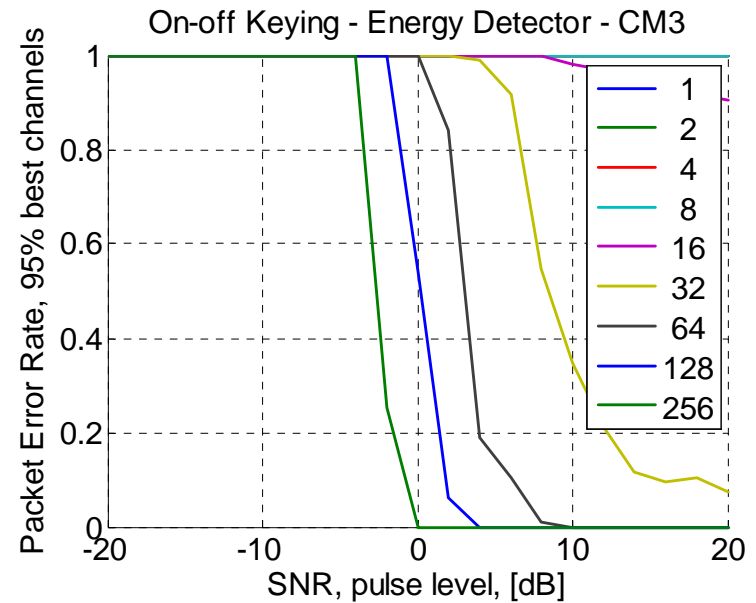
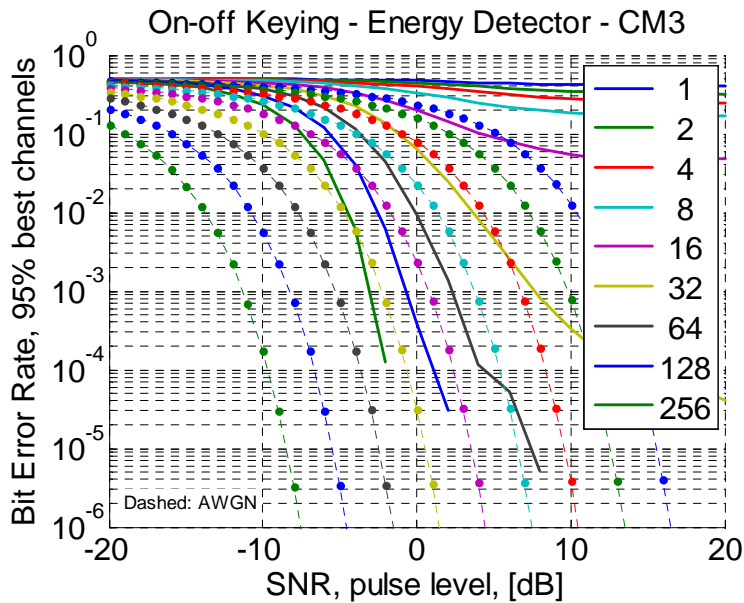
DBPSK - Comments

- Forward error correction not included yet:
 - Will eliminate/lower error floor for rake receivers;
 - Will extend range for all receivers

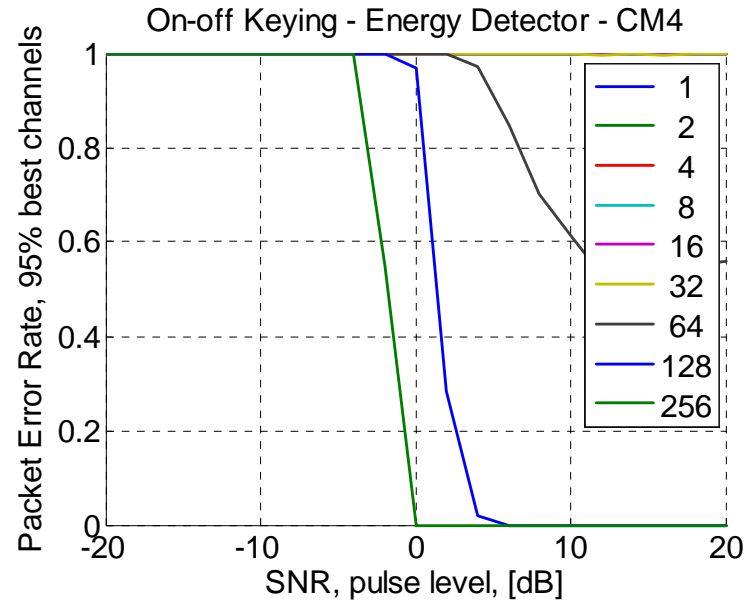
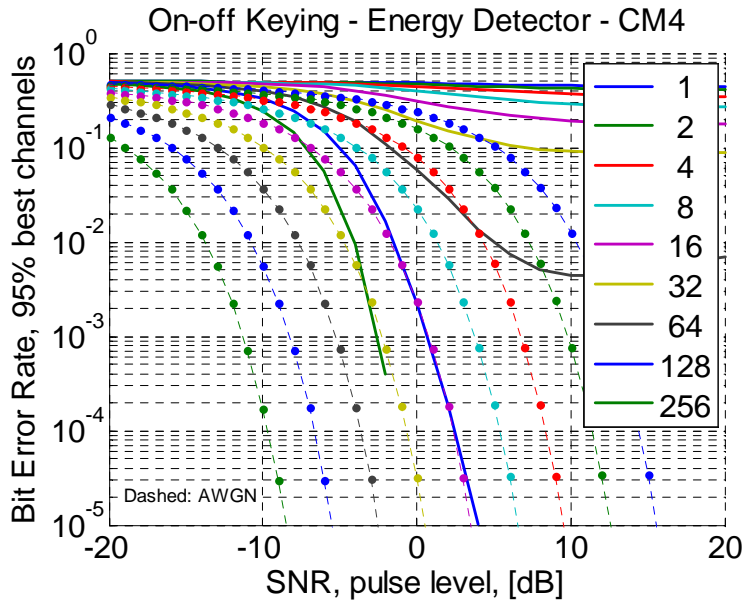
OOK – Energy Detector

- Energy detector chosen as simplest possible OOK receiver
- Threshold set at average signal power observed through the burst

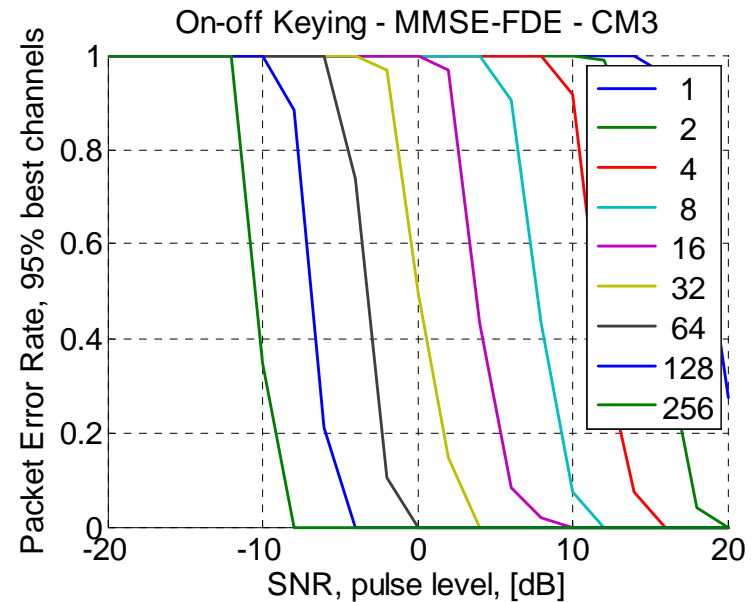
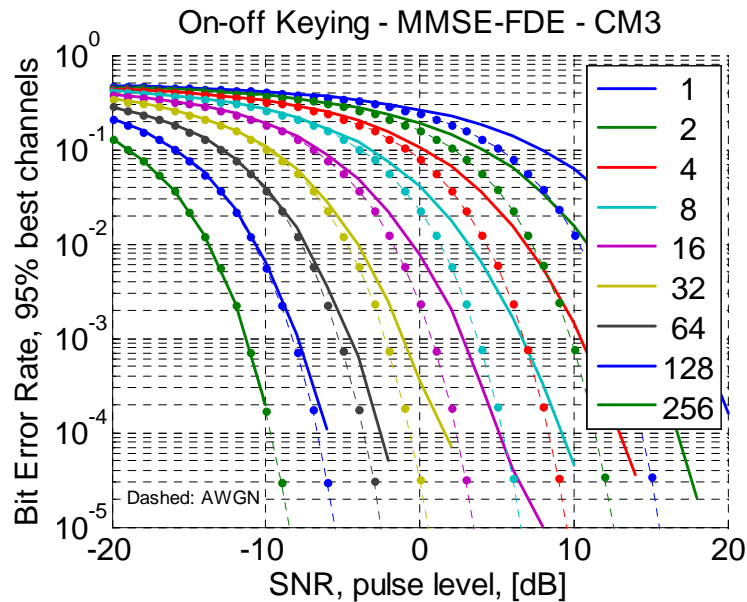
OOK – Energy detector – CM3



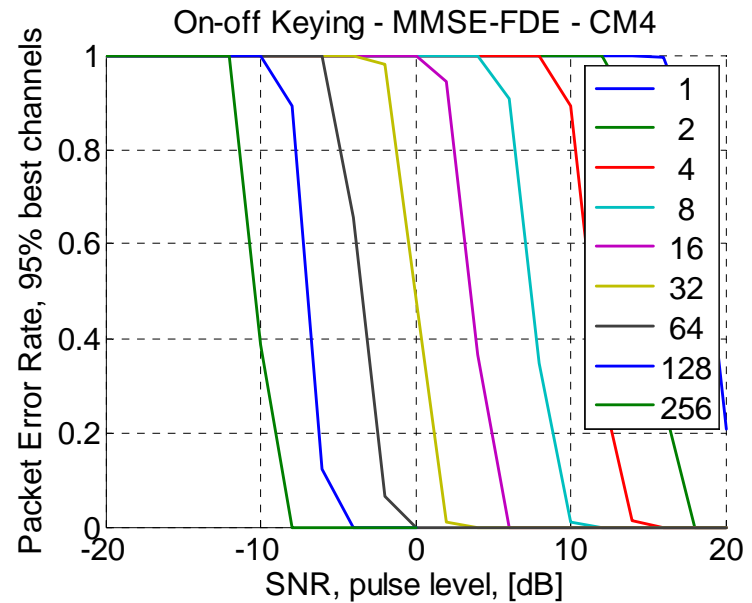
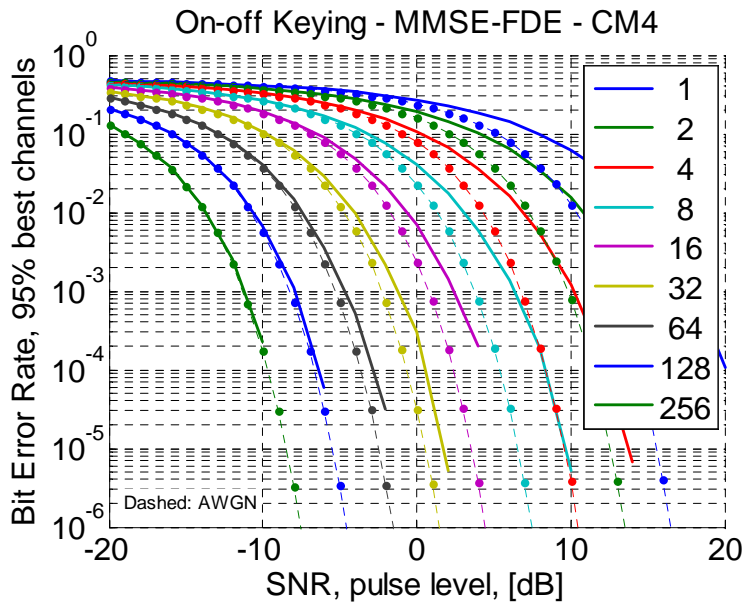
OOK – Energy Detector – CM4



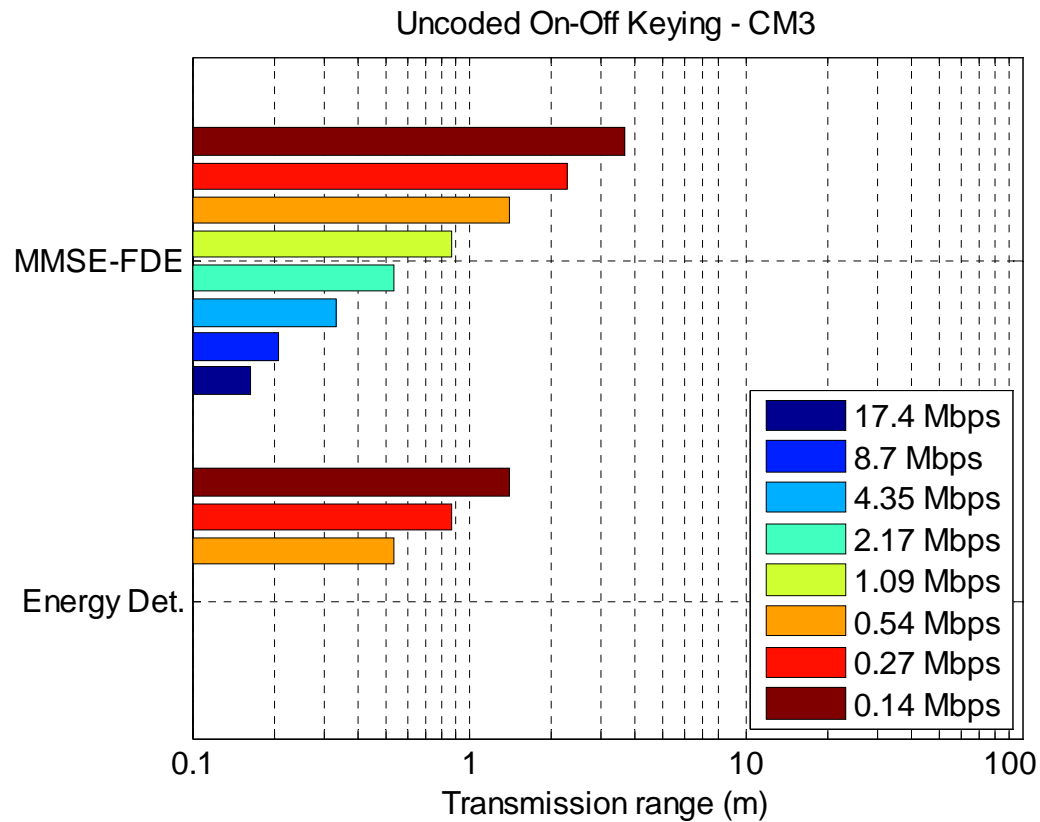
OOK – MMSE-FDE – CM3



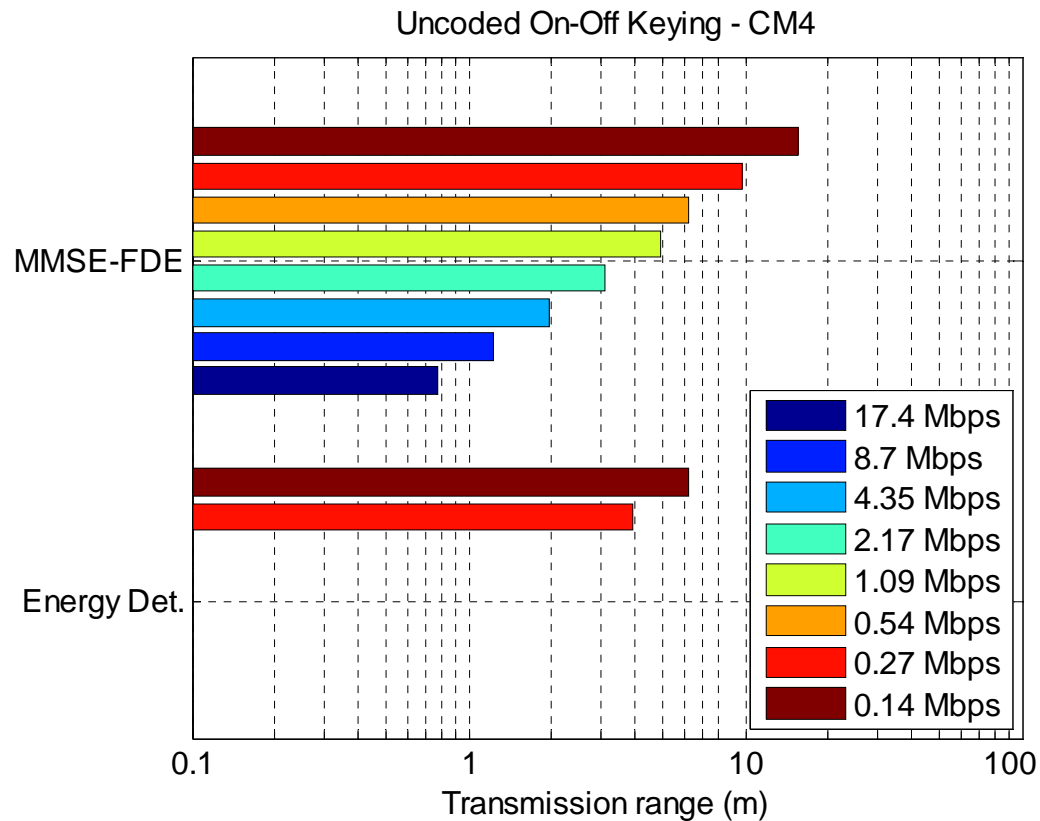
OOK – MMSE-DFE – CM4



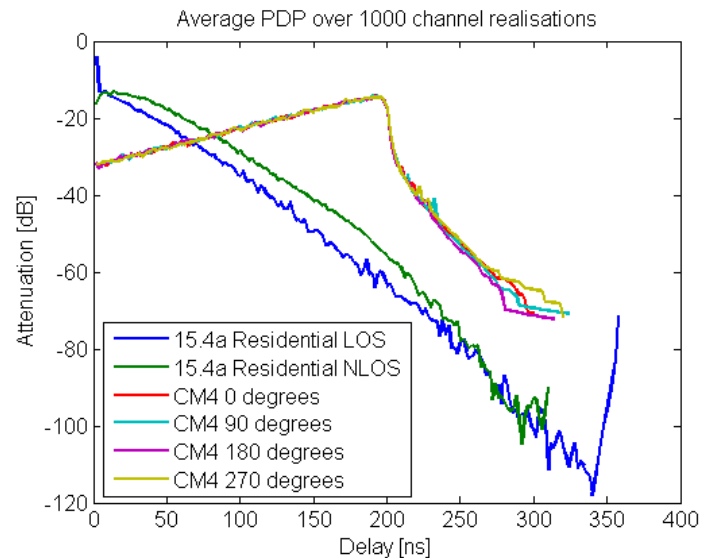
OOK – Uncoded Range – CM3



OOK – Uncoded Range – CM4



Channel Model issue: CM4 vs 15.4a

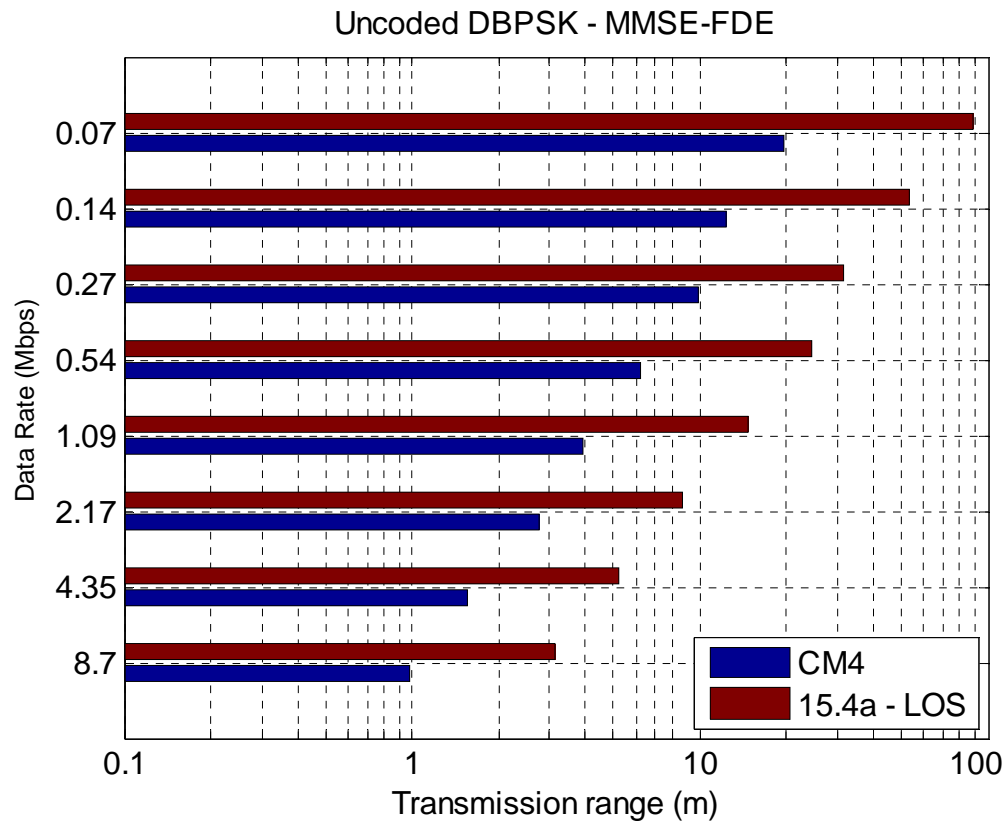


- Scattering environment too rich in CM4
- Delay spread over-estimated
 - Harms performance of OOK air interface
 - Harms performance of simpler receivers
- Impact of body shadowing not evident

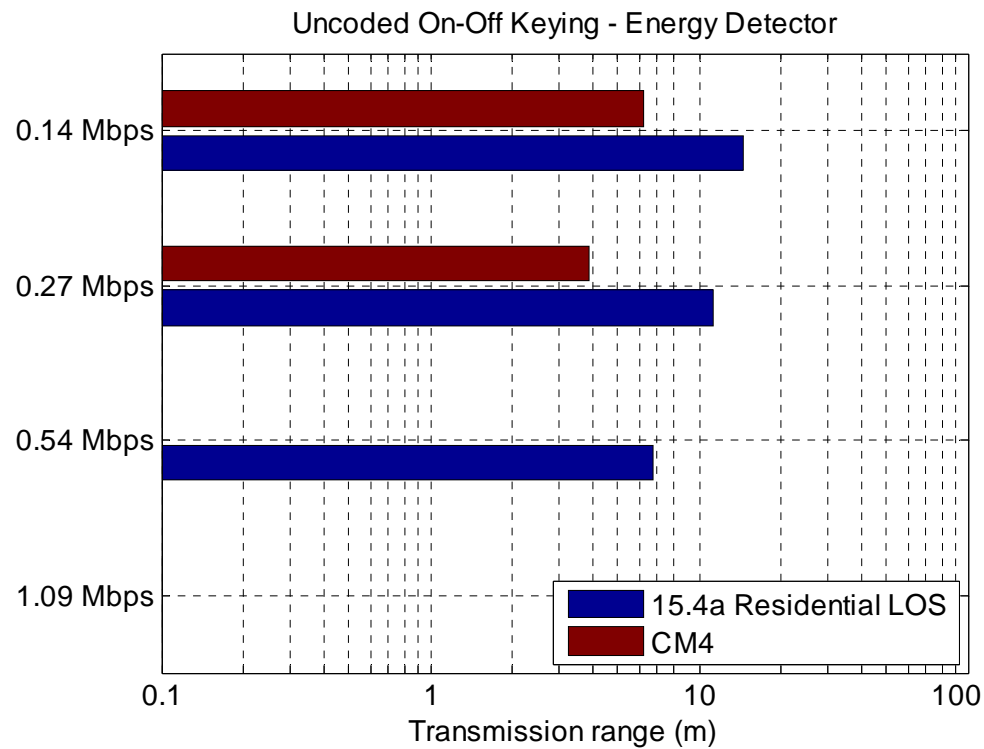
Extra: DBPSK – 15.4a Residential

- DBPSK, MMSE FDE in 15.4a UWB residential channels
- OOK, energy detector in 15.4a UWB residential channels
- Link budget as before, path loss exponent from 15.4a models:
 - LOS: $n = 1.79$

Extra: DBPSK, 15.4a Residential LOS

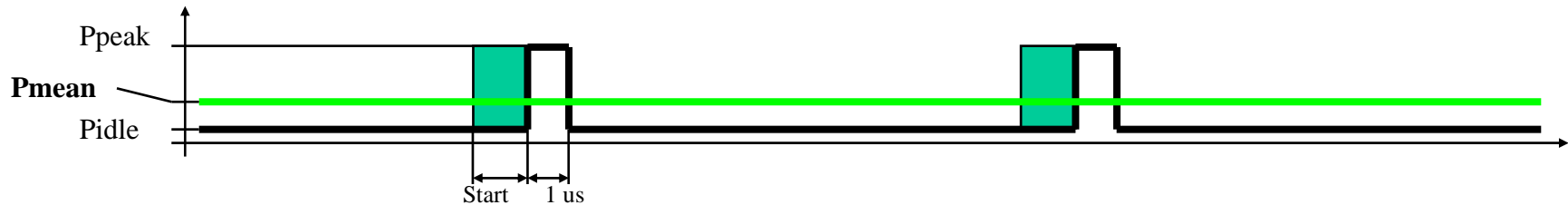


Extra: OOK - 15.4a Residential



Expected Power Consumption Figures

- Power consumption pattern



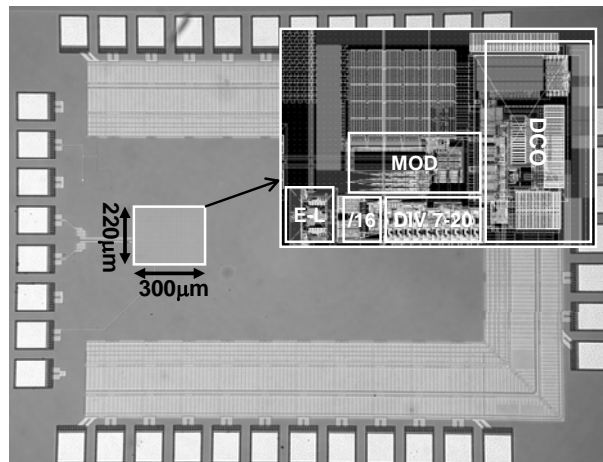
- Limiting peak current drawn from Battery
 - Use Capacitor to store energy from battery between strings
 - Draw current from capacitor to power-up during strings
 - Dimensioning Capacitor:
 - 0.1 V voltage drop for 50 mA supply over that duration of the string
 - 500 nF is sufficient, SMD component – Scales with string duration
 - Battery ‘sees’ only P_{mean}

Expected Power Consumption Figures (Conservative figures)

- Analog: Consider comparable figures for Tx & Rx:
 - P peak = 50 mW
 - P idle = 0.1 mW
 - Start time = 1 us
 - **Mean Analog Power < 3.5 mW**
- Digital: FFT is dominant
 - Duty cycling is applied to digital as well
 - FFT Power: 40 mW (512 Points FFT@ 200 MHz, 200 cycles/transform, C90, 8 bits)
 - On-time ~ 1 us per string
 - Mean power for FFT ~ 1.5 mW
 - **Complete Duty Cycled power for Digital should be < 5mW**
- Total Power Budget (Digital + Analog) @ full speed transmission:
 - **8.5 mW** for coherent receiver with FD Equalization
 - **4 mW** for energy-based Rx
 - **4 mW** for Tx

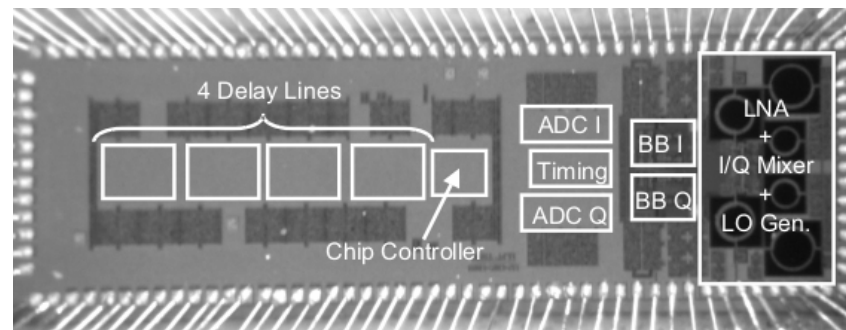
Evidence of practical feasibility

- ICs in our labs - Published Material
- Full Transmitter in C90 CMOS
 - Fully Duty Cycled
 - 1 mW Power consumption (P mean)
- ISSCC 2007



Evidence of practical feasibility

- 180 nm CMOS UWB Receiver successfully demodulates UWB signal @ Low Power
 - 3.1 – 5 GHz (UWB lower band)
 - 30 mW Power Consumption
 - No Signal Duty Cycling
- ISSCC 2006



Conclusions

- Group Pulses & Bursts into strings to increase Duty Cycling Efficiency
- Use OOK @ low data rates to let simple receivers operate
- Use DBPSK @ higher data rates to avoid costly timing reference
- Use FD-Equalizer at high data rates to avoid ISI-Induced performance issues

Conclusions

- Open to cooperation & mergers
 - Compatible with all pulse-based architectures
 - Possibility of having different encoding in the bursts (e.g CSS?)
 - Coding
 - Security
 - MAC
 - Common HW performance references for all UWB PHYs to evaluate performance