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]

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

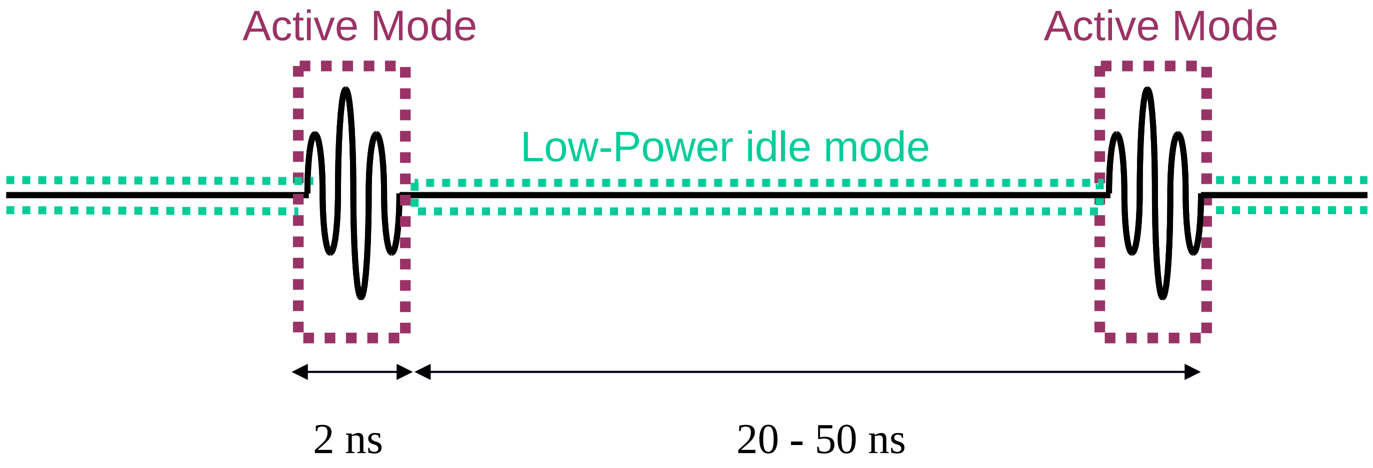
- Multi User Capabilities
  - Scarce nature of air interface -> few collisions
  - Spreading gain of many pulses per bit
  - Uncoordinated operation possible with smooth performance impact
  - High node density

- 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



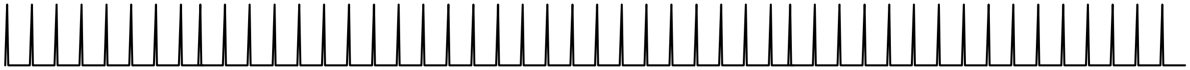
Intro: Challenges for IR-UWB in WBAN

- 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

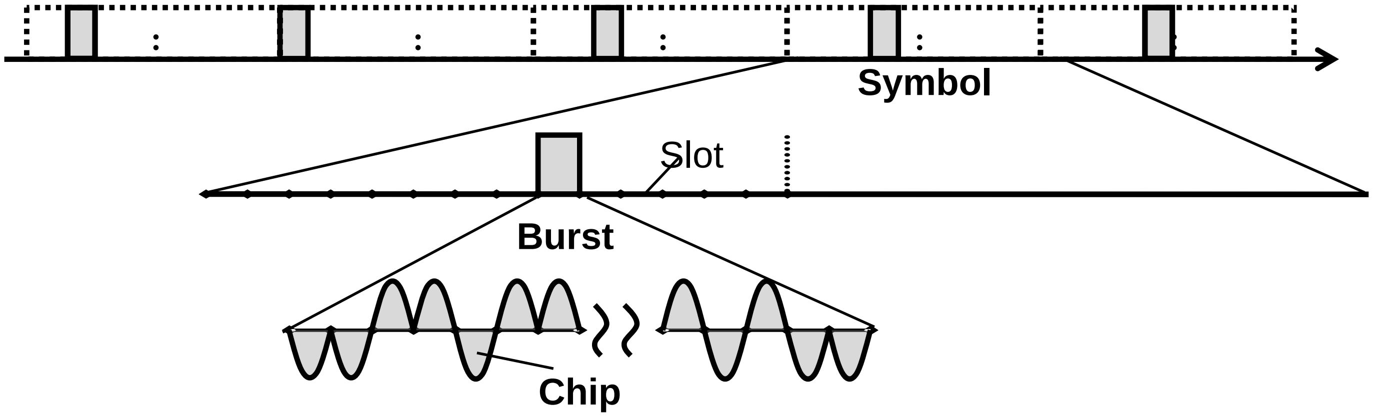
- Accurate timing references usually required
  - Information in very short pulses, timing needs to be known accurately
  - Need to maintain timing information over silent portions between pulses

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

UWB IP

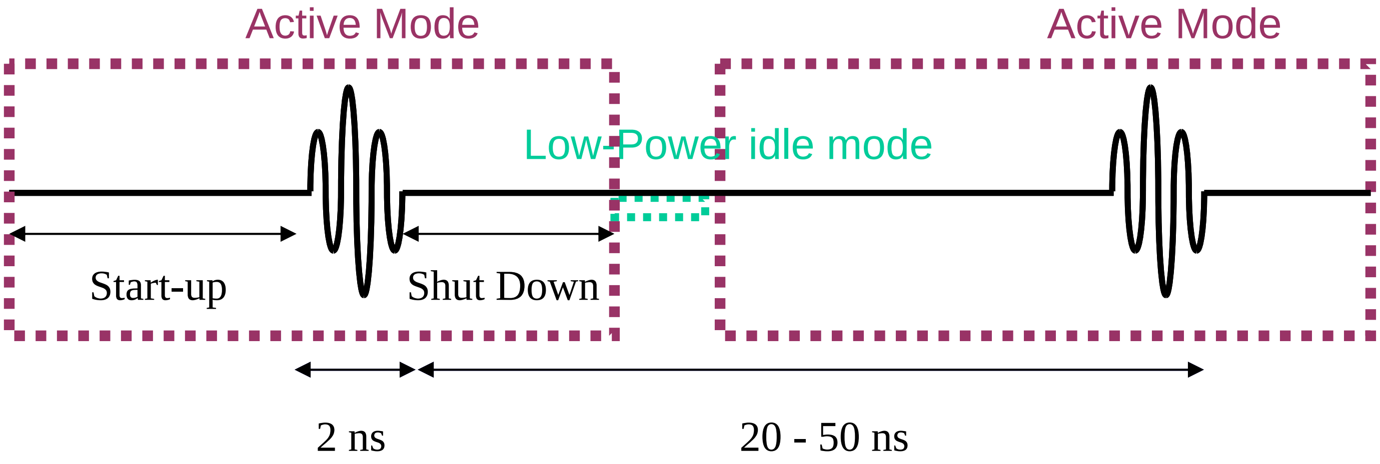


UWB 4a



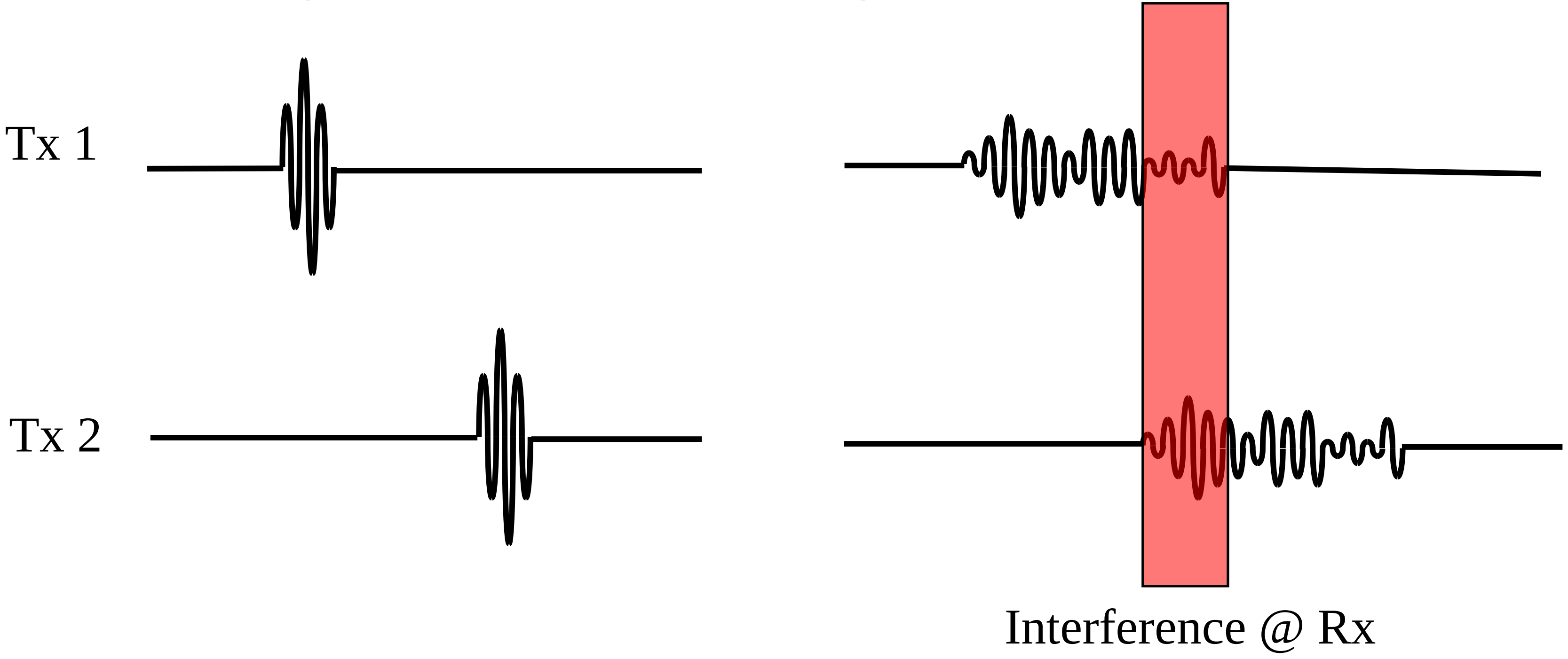
Pros and Cons of Isolated Pulses UWB

- 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



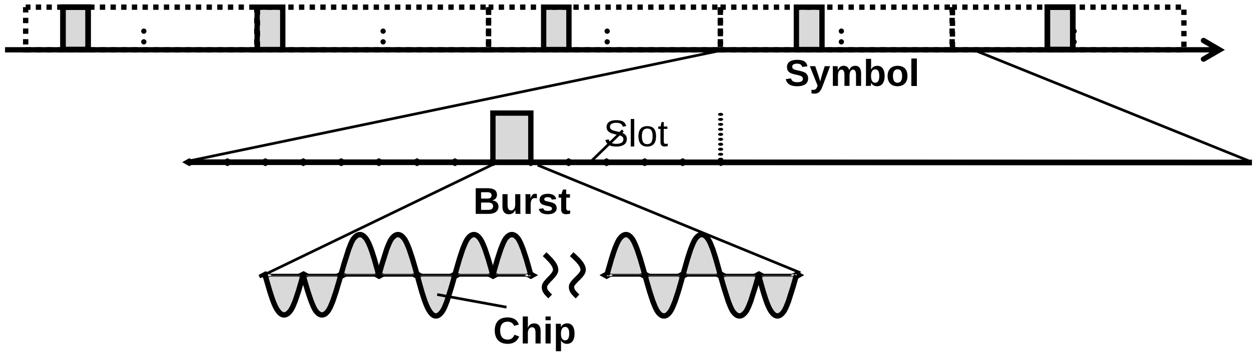
Pros and Cons of Isolated Pulses UWB

- 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

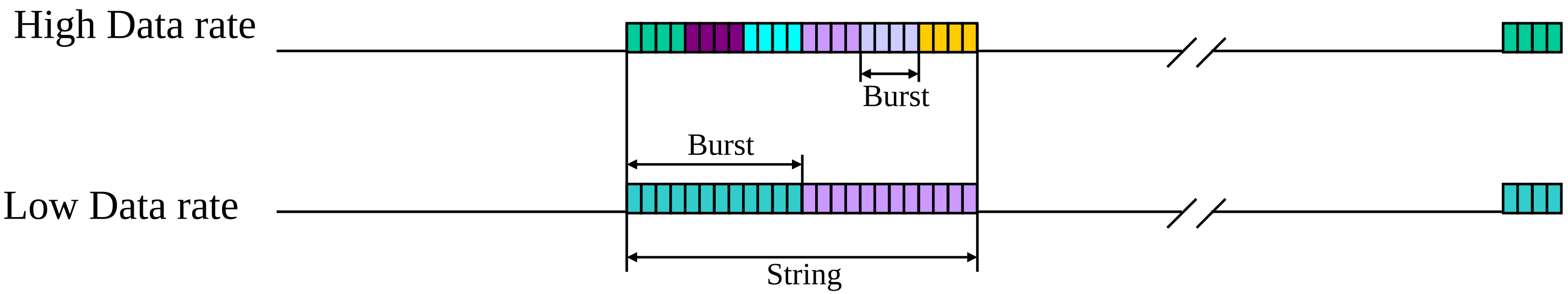
Pros & Cons of 15.4a @ High data rates

- 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

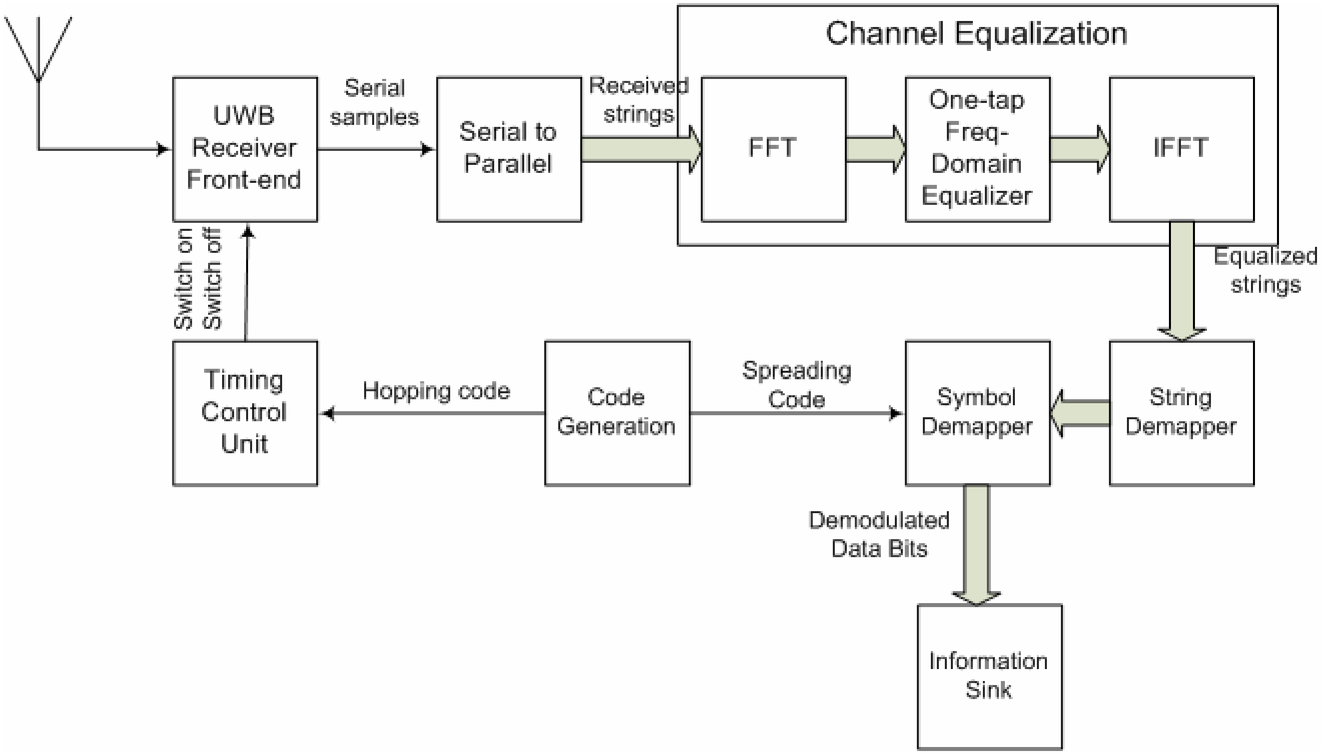
- Low data rates & ISI
  - Impact limited to a portion of a burst
  - Rake receivers should allow to cope
  - Possibly multiple fingers

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

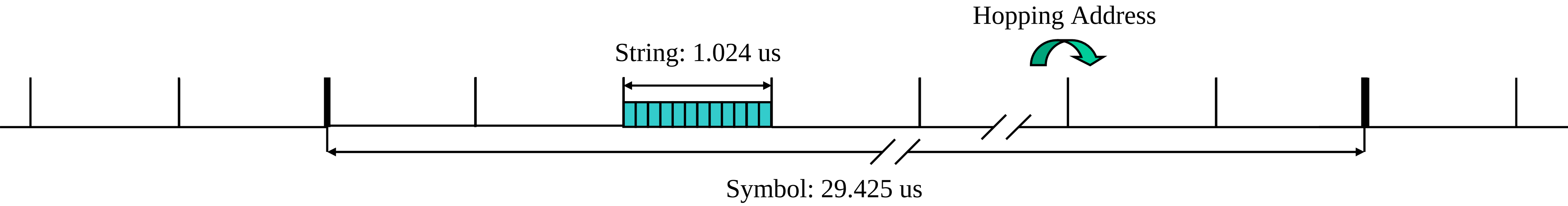
Frequency Domain Equalization Receiver



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)

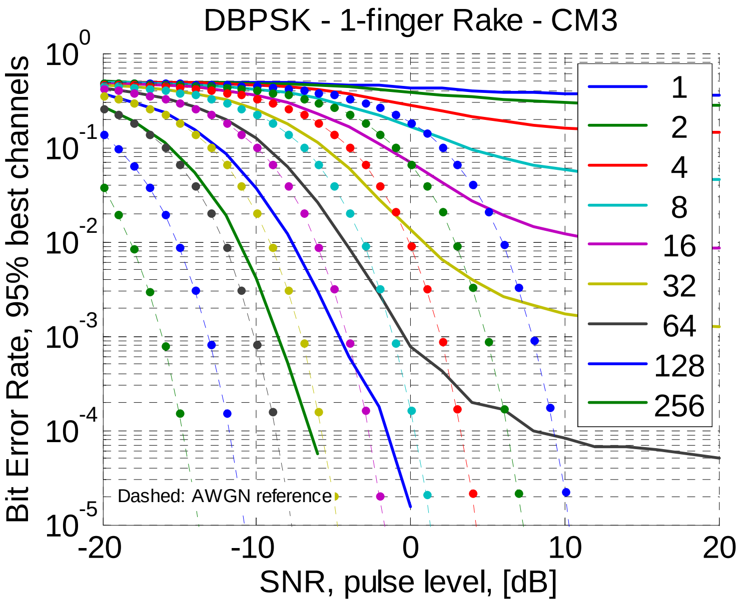
- Different Modulation Schemes considered
  - OOK
  - DBPSK

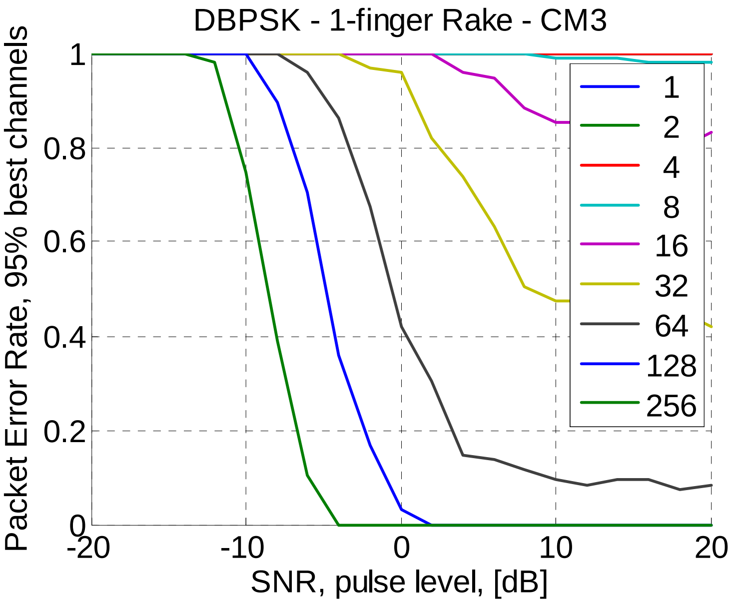
- No FEC coding considered!

DBPSK – 1-finger rake

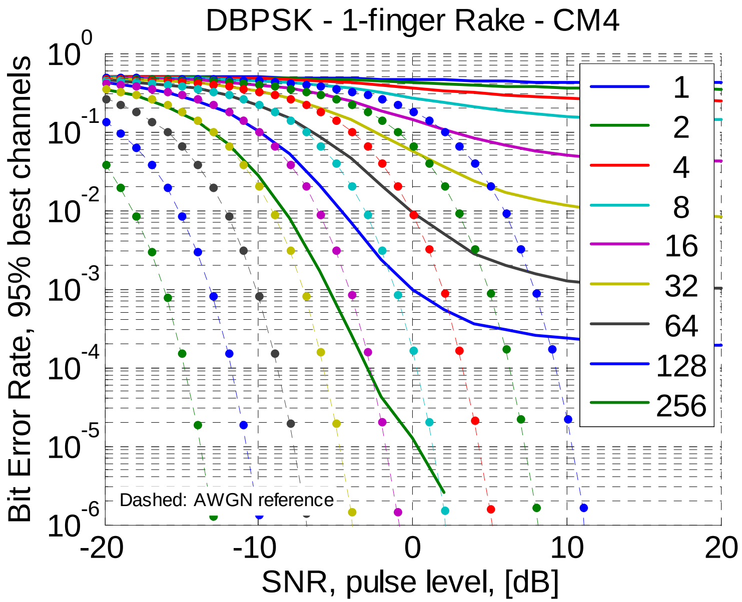
- Synchronised to strongest channel tap
- CM3: on-body to on-body
- CM4: on-body to off-body

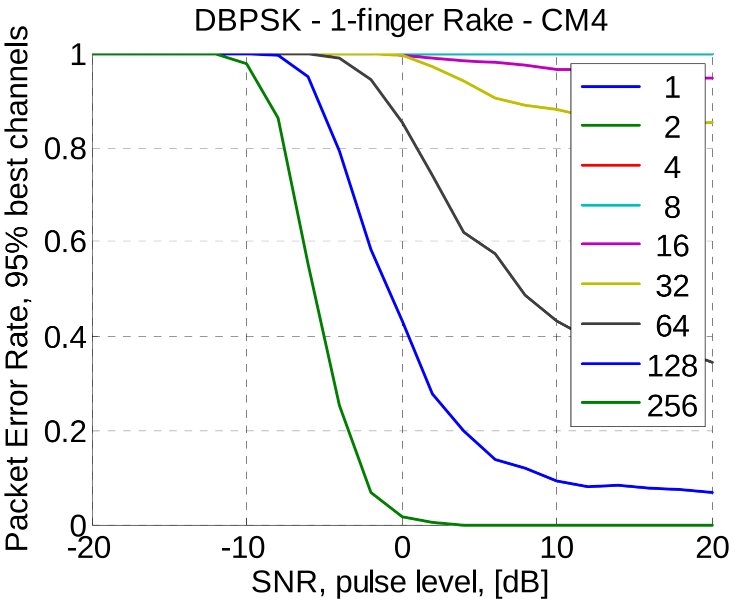
DBPSK – 1 finger – CM3





DBPSK – 1 finger – CM4

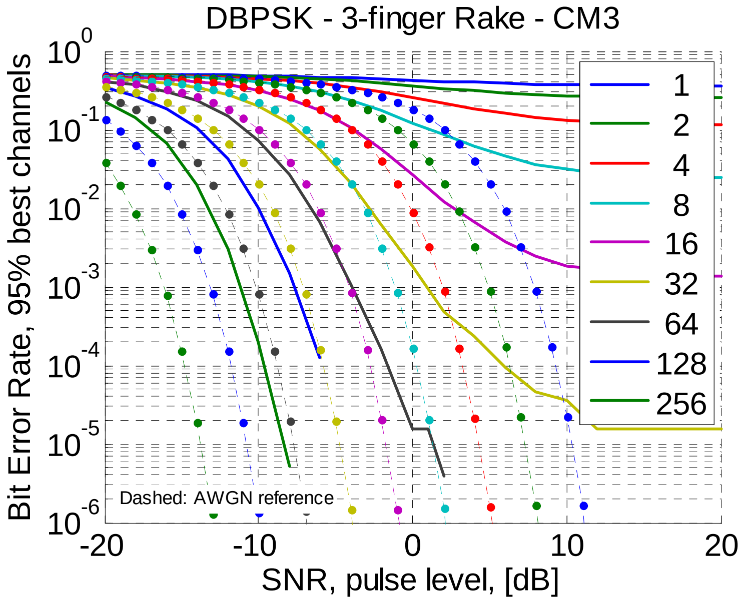


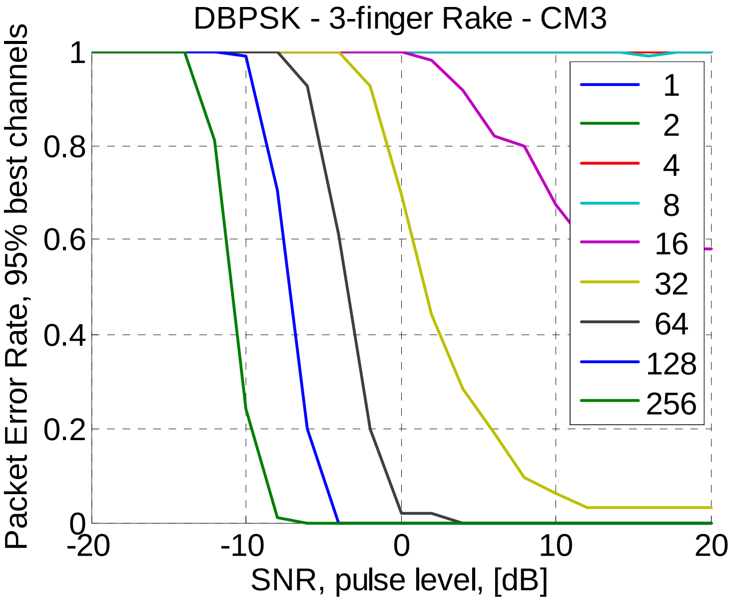


DBPSK – 3 finger rake

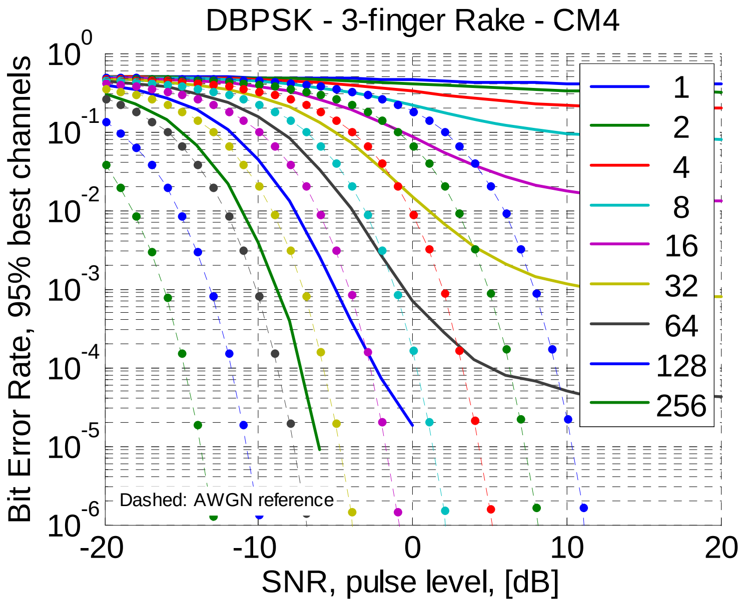
- Selective 3 finger rake,
  using 3 most powerful channel taps
- Equal gain combining

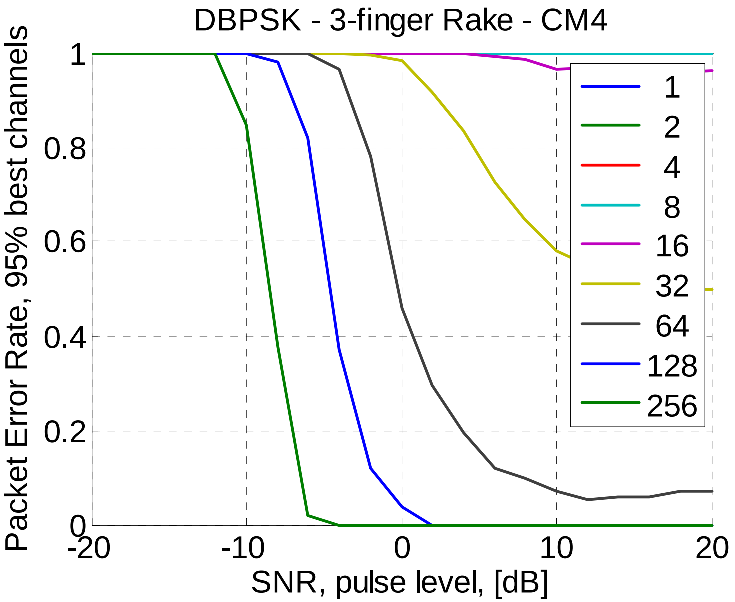
DBPSK – 3 finger – CM3





DBPSK – 3-finger – CM4

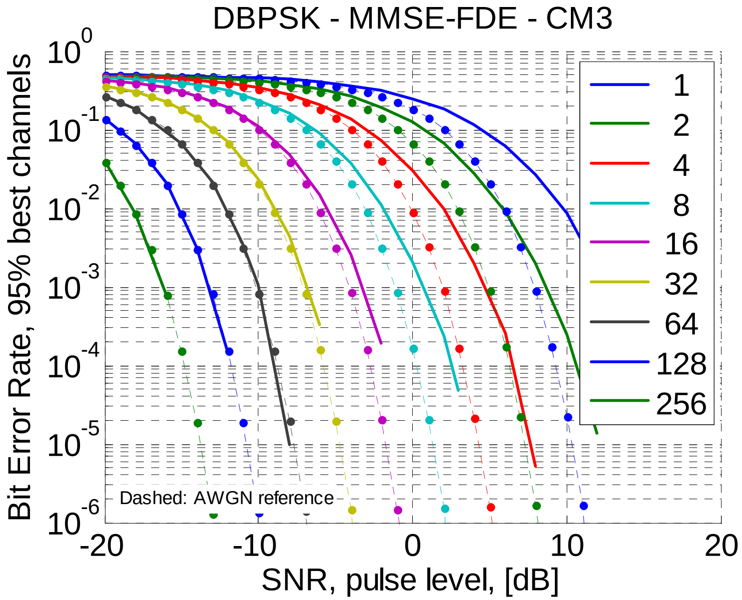


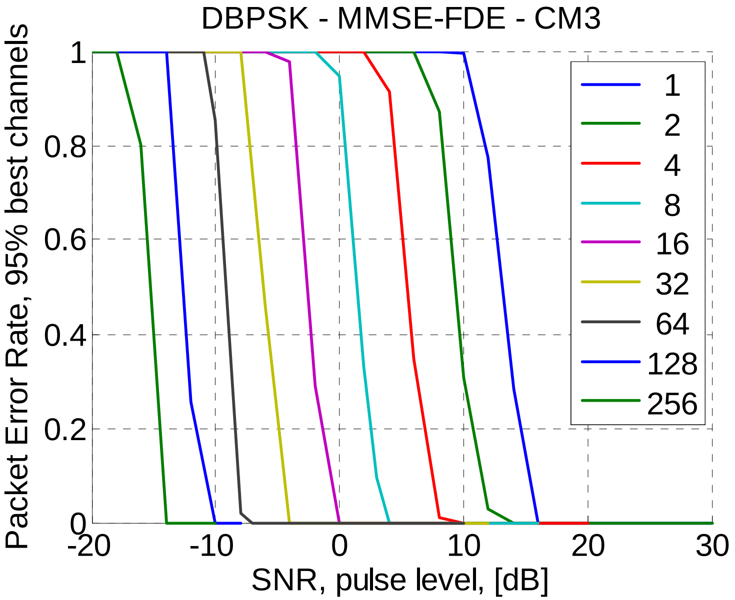


DBPSK – MMSE-FDE

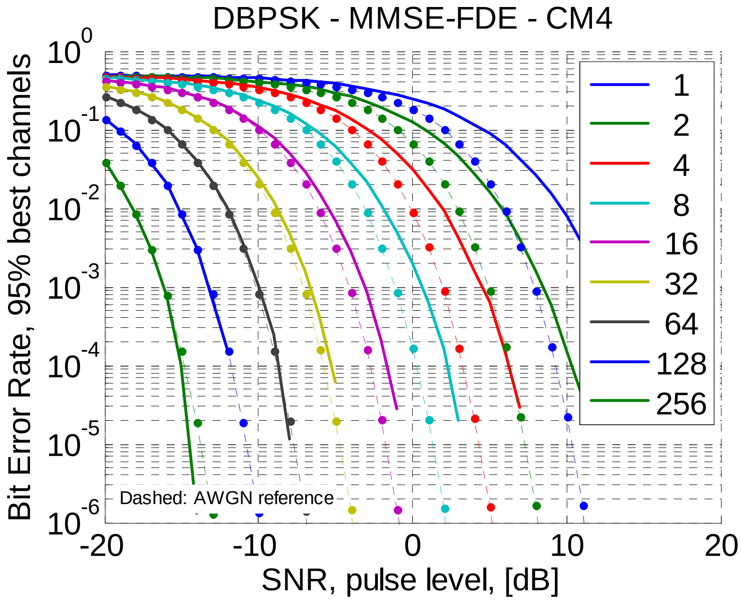
- Frequency domain equaliser
- MMSE coefficients based on perfect channel knowledge

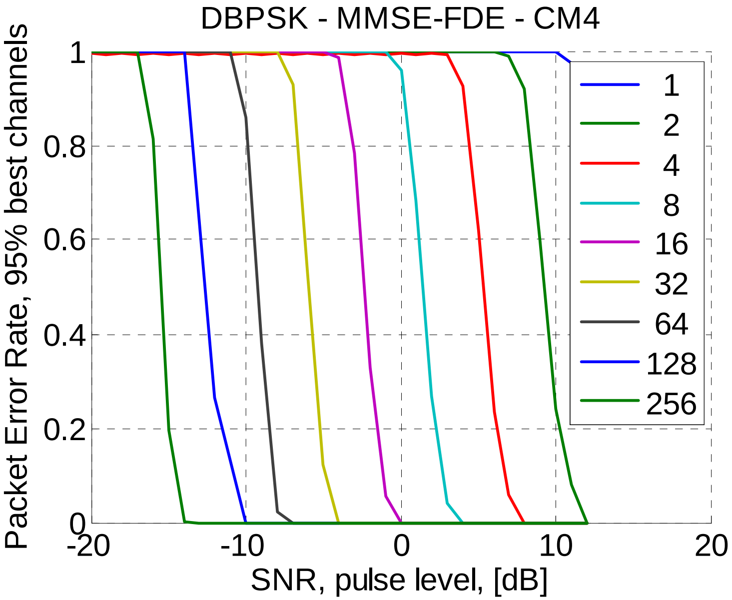
DBPSK – MMSE-FDE – CM3


DBPSK - MMSE-FDE - CM3


DBPSK - MMSE-FDE - CM3

DBPSK – MMSE-FDE – CM4





Conservative link budget assumptions

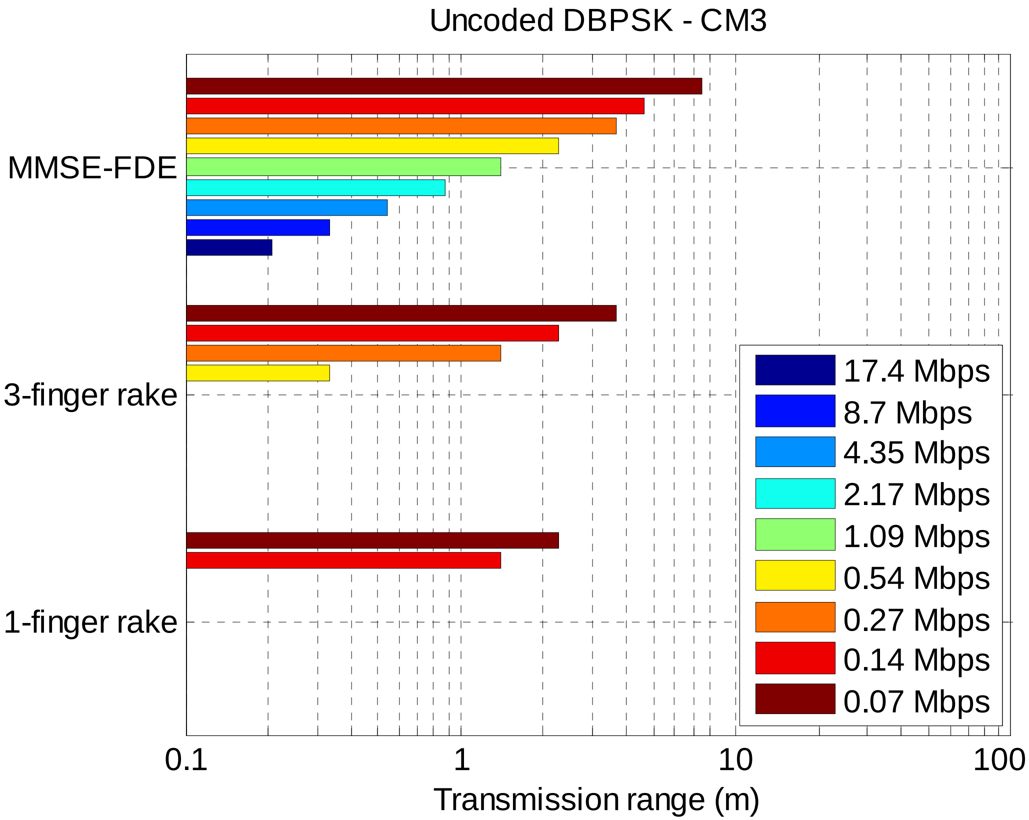
Transmitter	Transmit power	0 dBm	Vpeak = 316 mV, 50 Ohm load
Channel	Antenna Gain	0 dB	
	Path loss		CM3/CM4 models
	Fading margin	9 dB	
Receiver	Thermal noise	-86 dBm	500 MHz, 30^{o}C
	Noise figure	12 dB	
	Implementation loss	2 dB	

Path loss

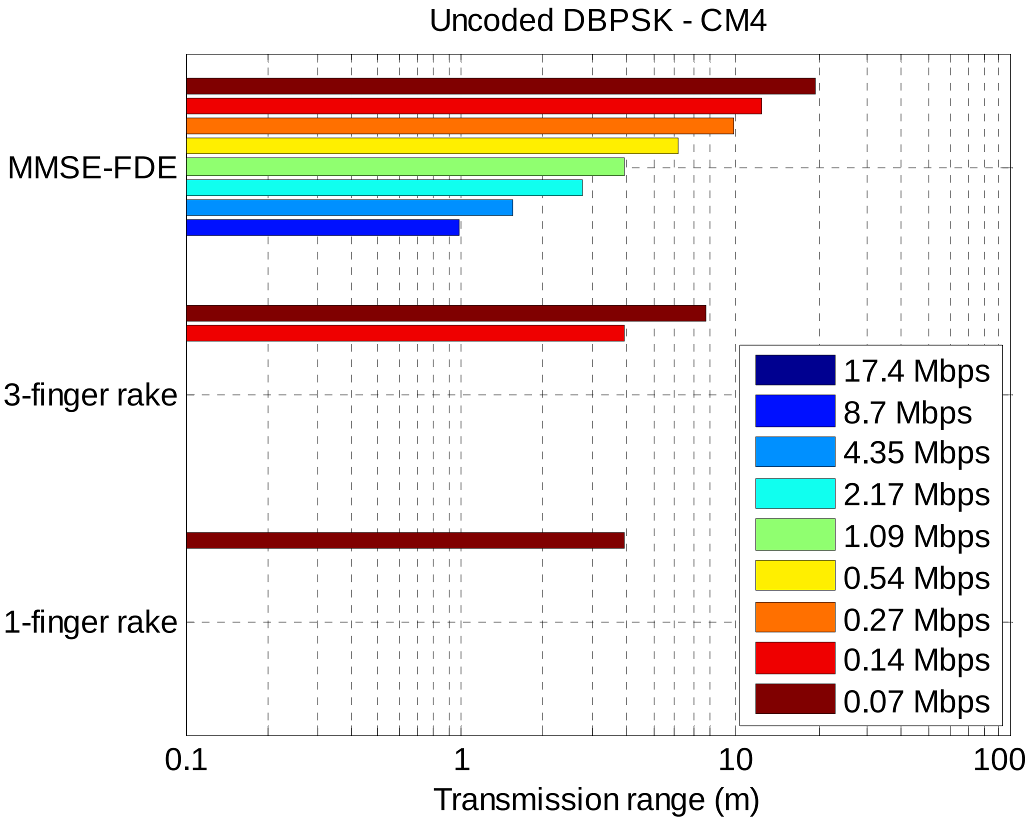
- According to channel model document 08-0780-06-0006
- CM3:

  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



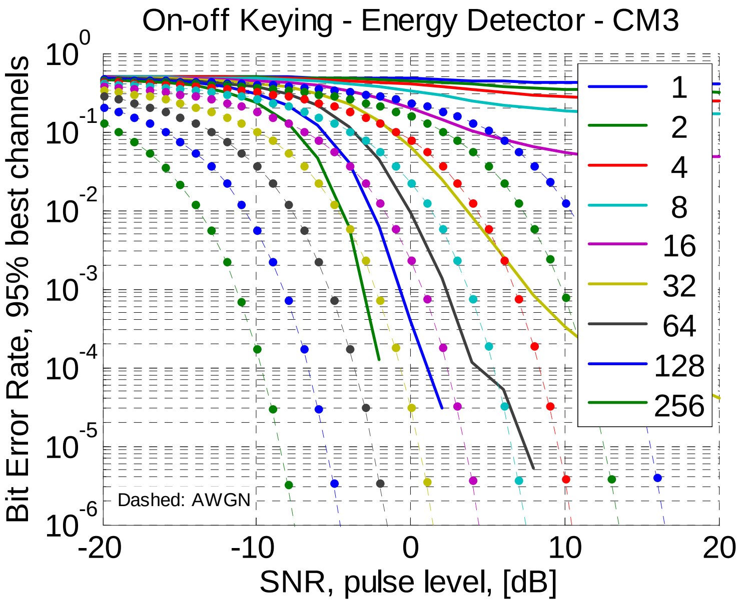
DBPSK - Comments

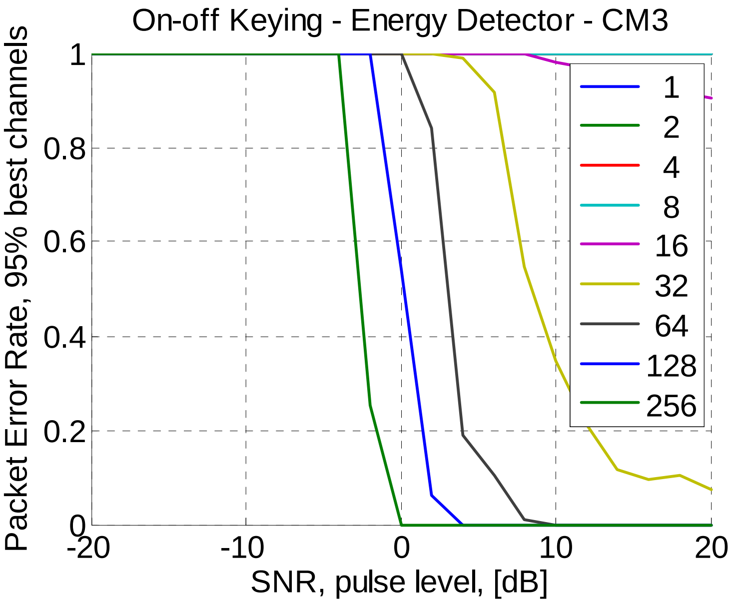
- Forward error correction not included yet:
  - Will eliminate/lower error floor for rake receivers;
  - Will extend range for all receivers

OOK – Energy Detector

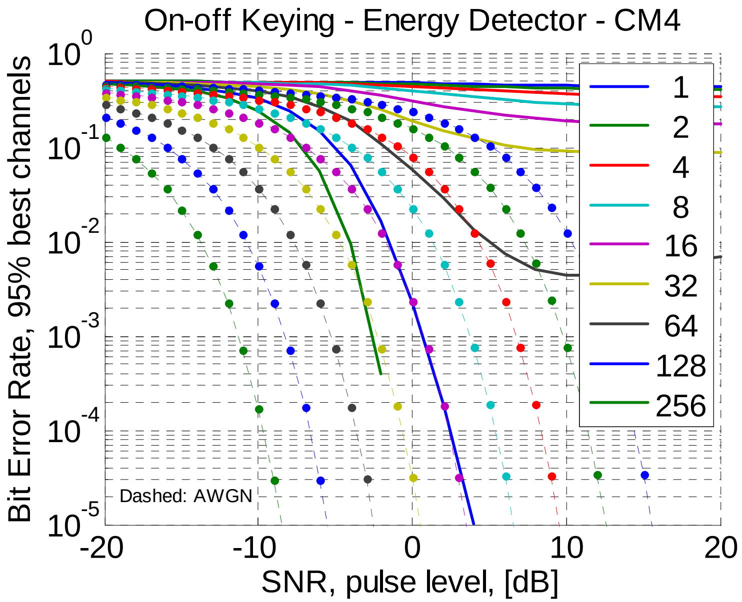
- Energy detector chosen as simplest possible OOK receiver
- Threshold set at average signal power observed through the burst

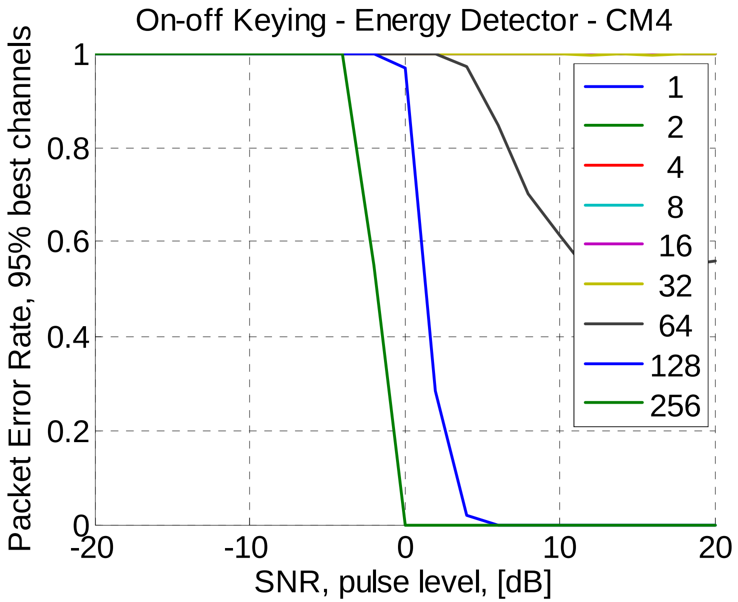
OOK – Energy detector – CM3



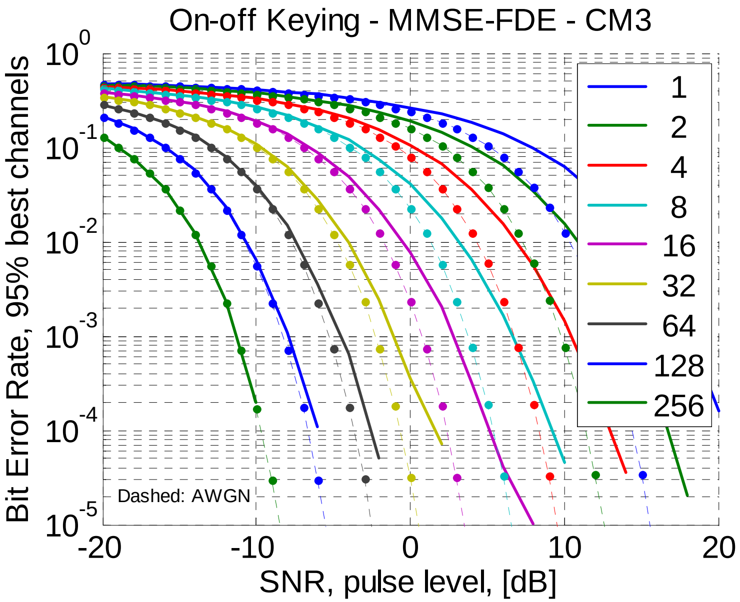


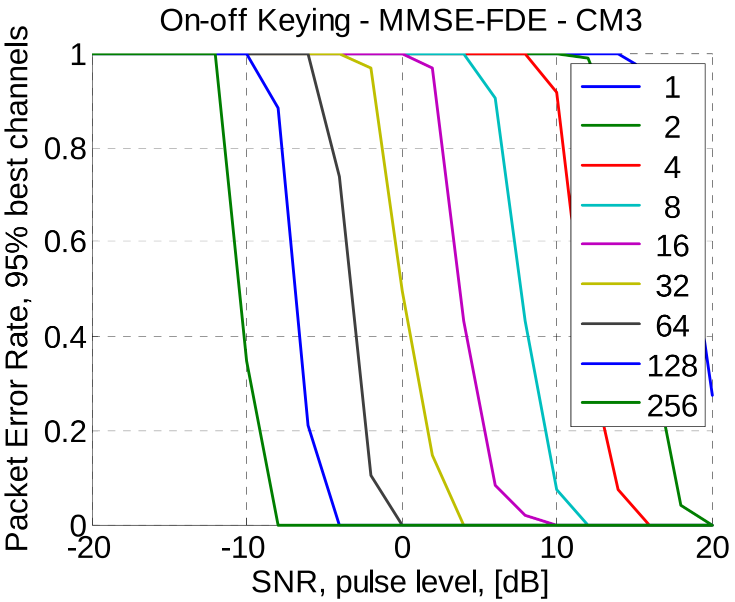
OOK – Energy Detector – CM4



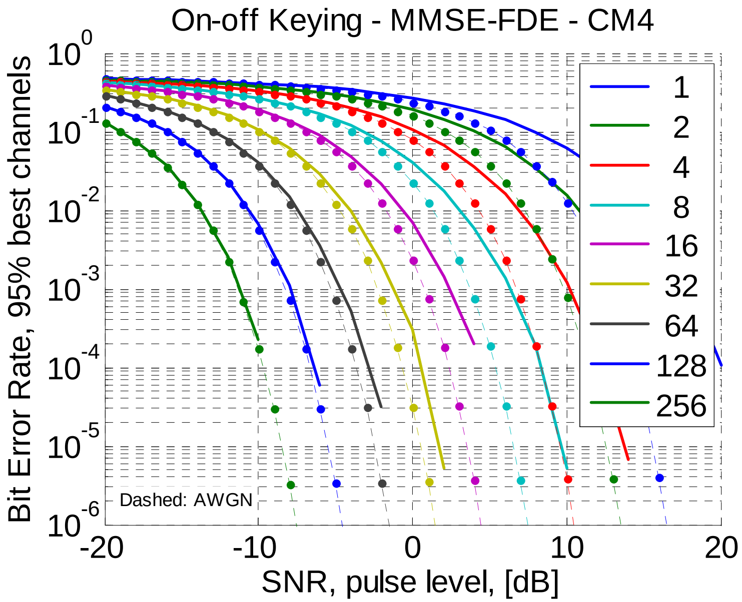


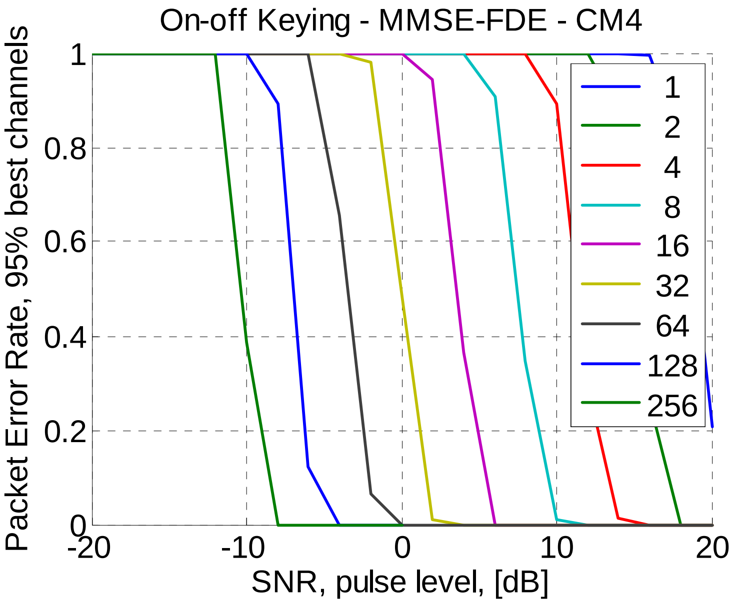
OOK – MMSE-FDE – CM3



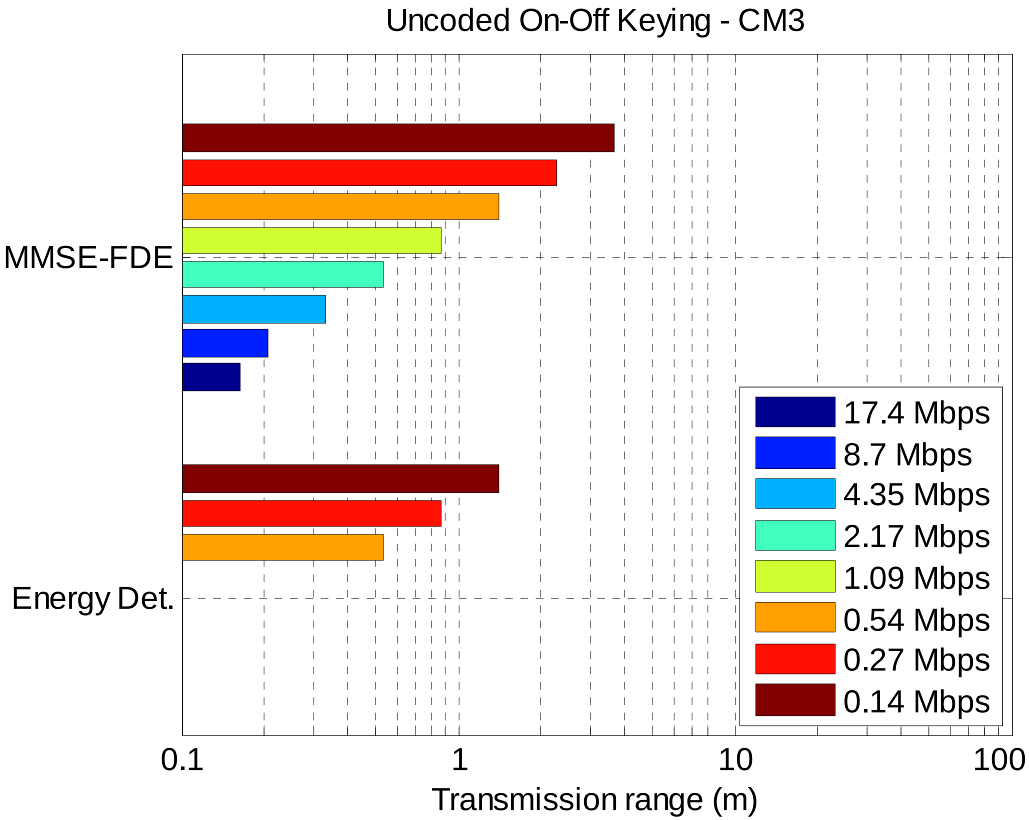


OOK – MMSE-DFE – CM4

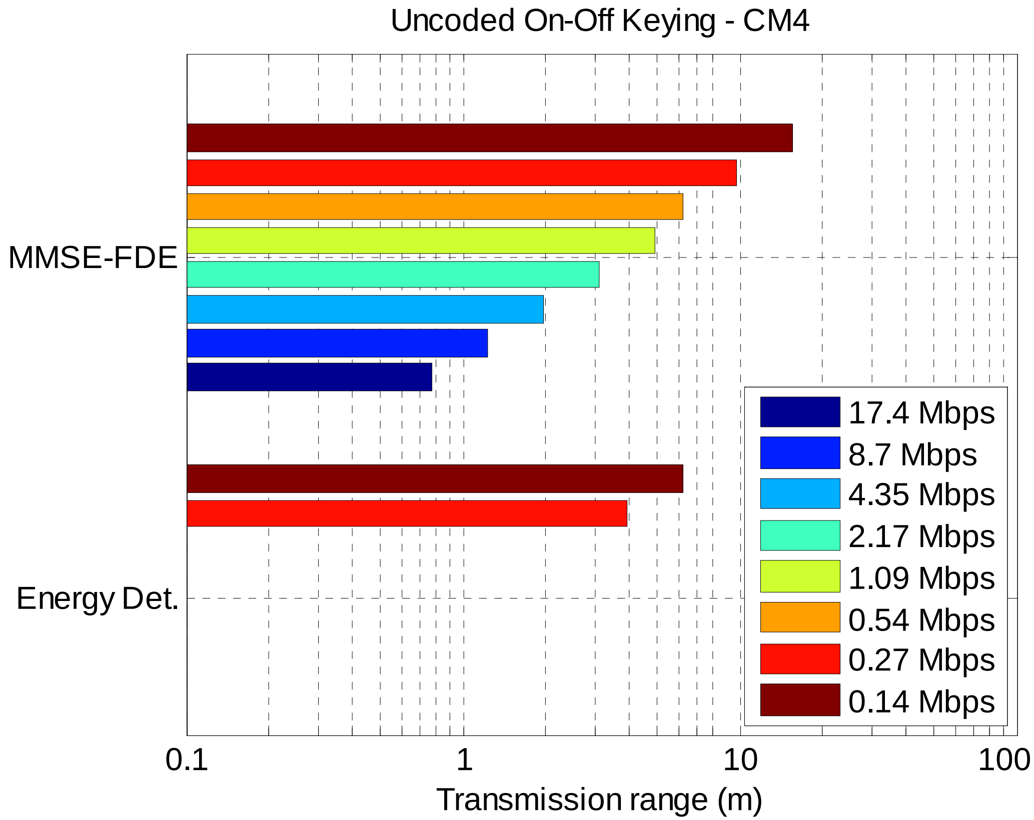




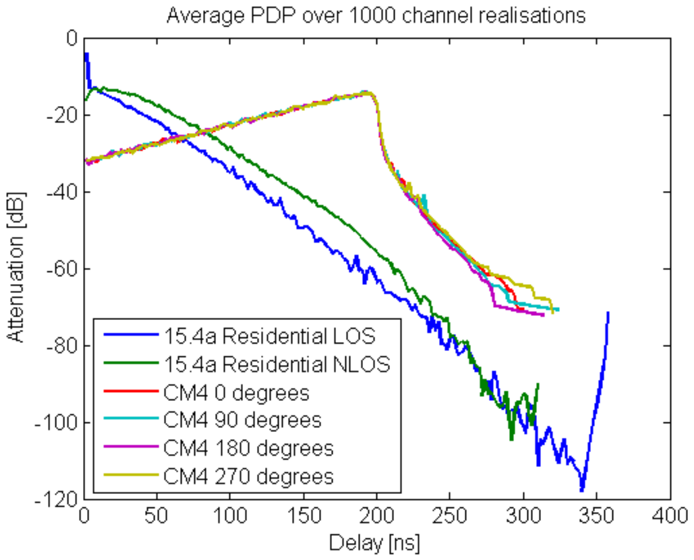
OOK – Uncoded Range – CM3



OOK – Uncoded Range – CM4



Channel Model issue: CM4 vs 15.4a

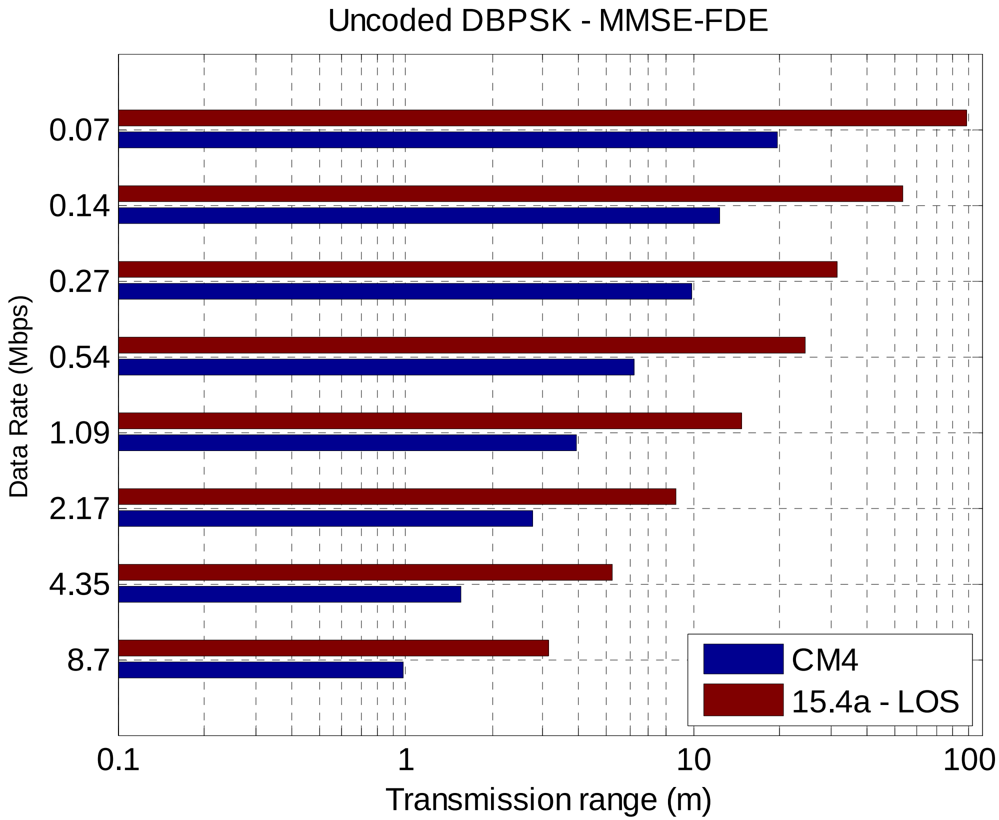


- Scattering environment too rich in CM4
- Delay spread over-estimated
  - Harms performance of OOK air interface
  - Harms performance of simpler receivers
- Impact of body shadowing not evident

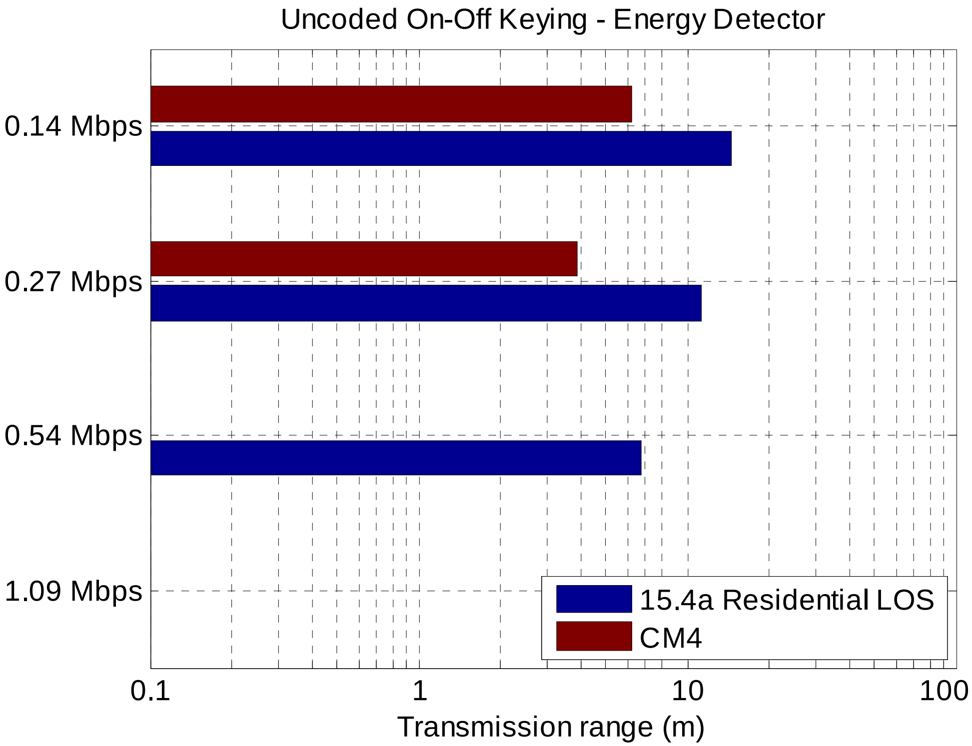
Extra: DBPSK – 15.4a Residential

- 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

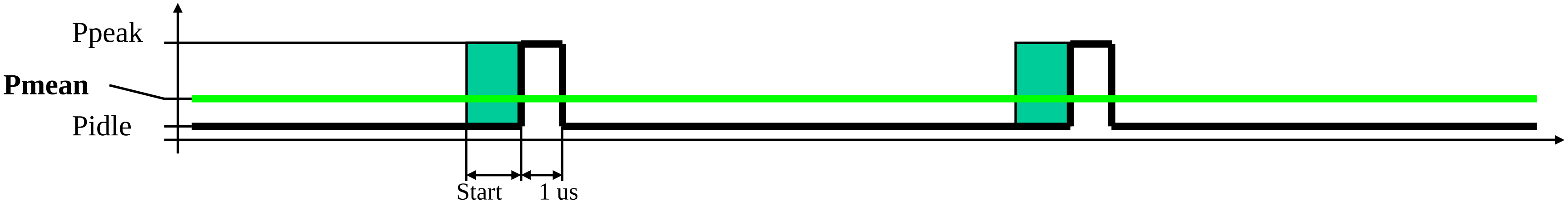


Extra: OOK - 15.4a Residential



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 Pmean

Expected Power Consumption Figures (Conservative figures)

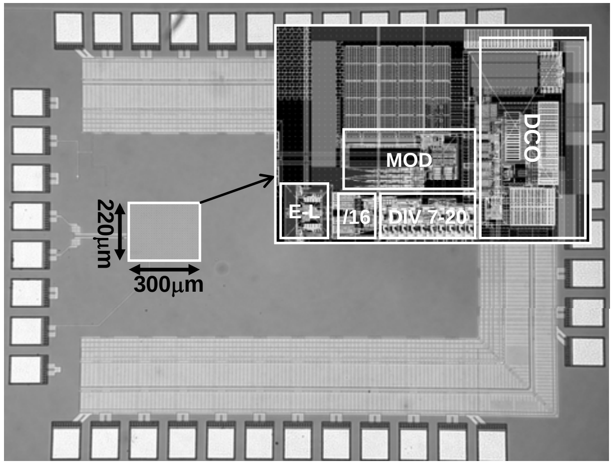
- Analog: Consider comparable figures for Tx & Rx:
  - P peak = 50 mW
  - P idle = 0.1 mW
  - Start time = 1 us
  - **Mean Analog Power < 3.5 mW**

- 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

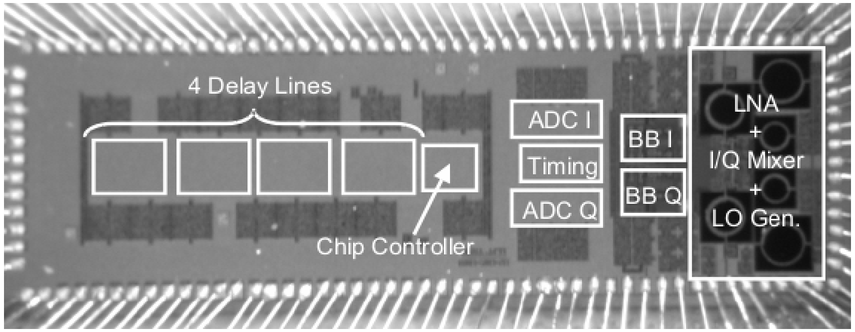
Evidence of practical feasibility

- 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