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

Submission Title: **Multi-User Support in UWB Communication Systems Designs**

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Source: Matt Welborn, **Company:** XtremeSpectrum, Inc
Address: 8133 Leesburg Pike, Vienna VA, 22182
Voice: 703-269-3000, FAX: 703-249-0249, **E-Mail:** mwelborn@xtremespectrum.com

Re: 802.15.3a Proposal Evaluation

Abstract: This joint contribution is offered in support of all monopulse candidate Alt PHY Proposals.

Purpose: The purpose of this document is to provide a joint contribution on multi-overlapping piconet performance issues to Task Group 3a.

Outline

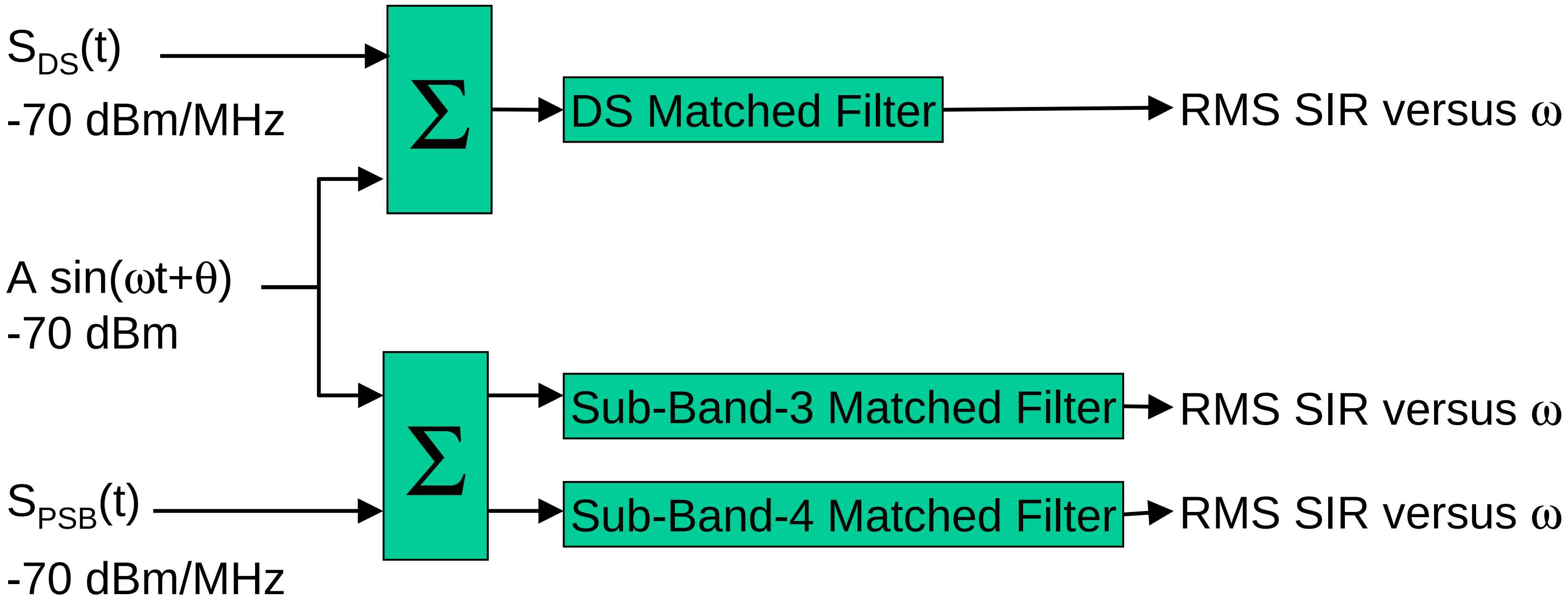
- Highlights of Spectrum Usage – NBI
  - See 03/211r2
- Fundamentals addressing multiple overlapping piconets

Narrowband Interference (NBI) Three Regimes

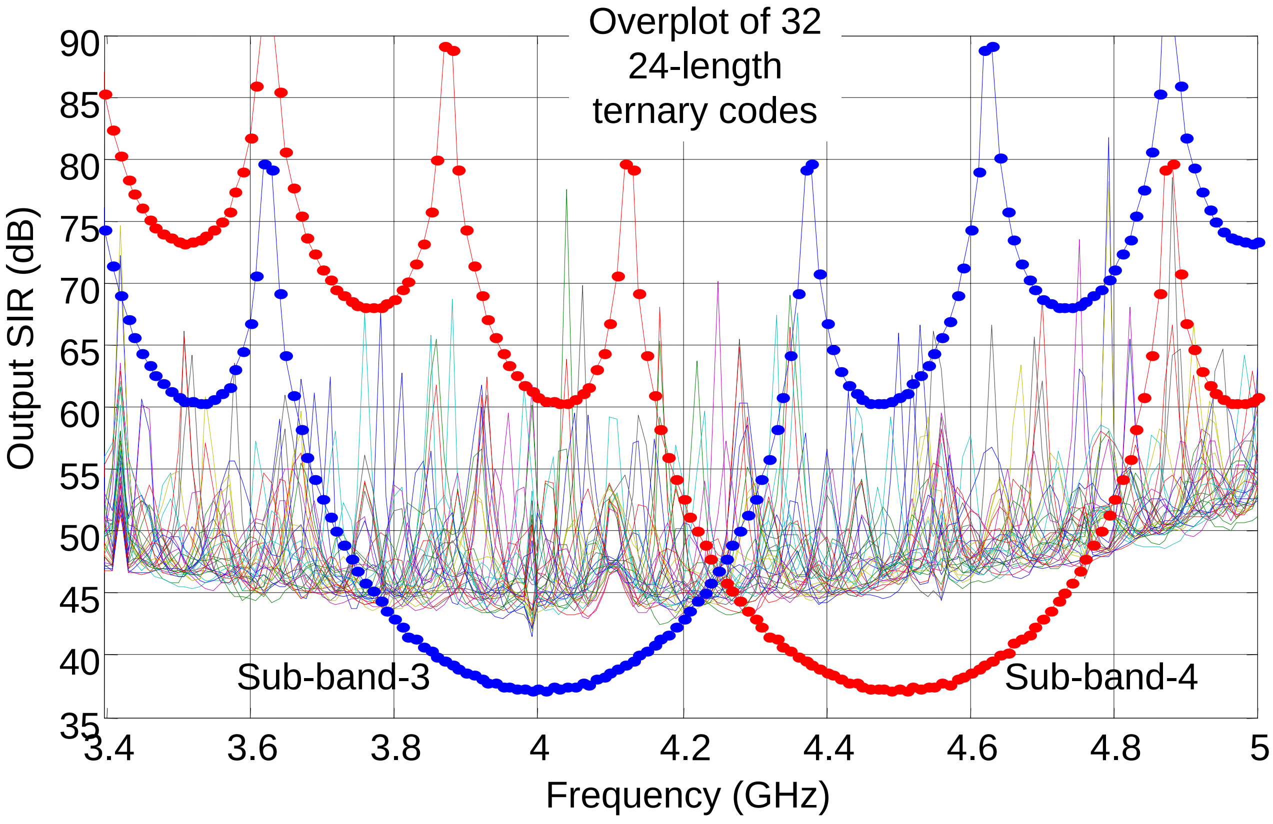
- Has to do with receiver
- Severe
  - Unprotected front-end saturates
  - Issue for all UWB systems
- Moderate
  - SIR margins exceeded design margin but front-end does not saturate
- Mild
  - Signal to Interference (SIR) is within the design margin of the system

Mild & Moderate Interference

- Signal to Interference (SIR) does not overload the front-end
- Pulsed subband system stops using the band
  - Diminishes data rate
  - Diminishes multi-user performance
- DSSS-UWB
  - Code processing gain allows greater RFI margin.
  - DSP can provide 10 dB additional gain
    - Well known algorithms can be applied – much work in UWB SAR and CDMA
    - Well known algorithms can demonstrate in excess of 10 dB
- Significant performance advantage for DSSS-UWB

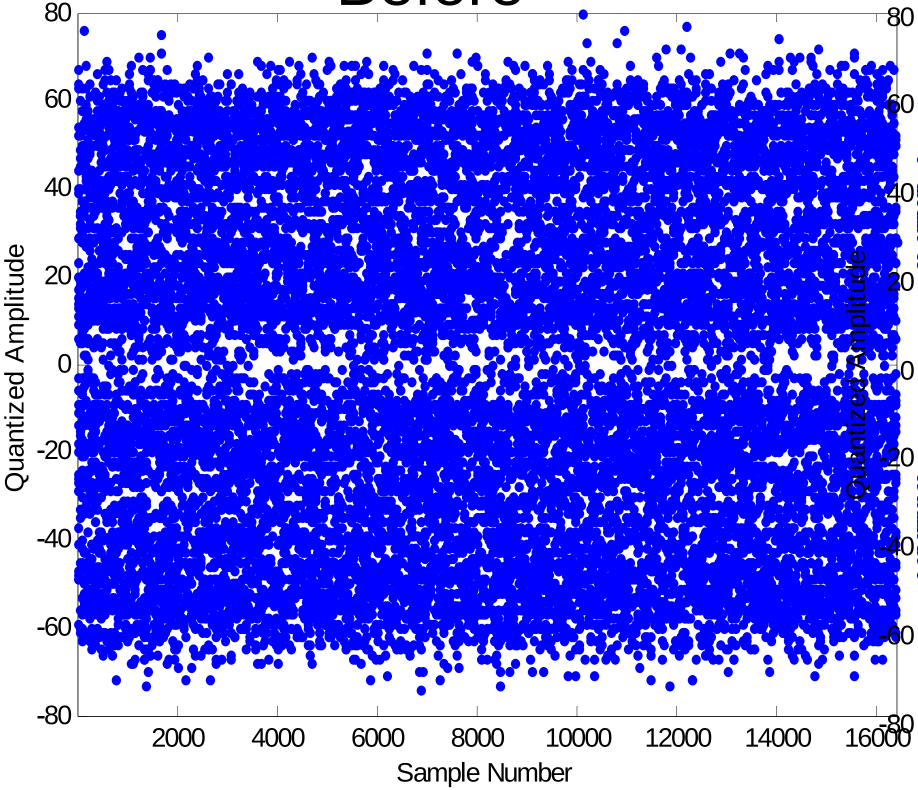

$S_{DS}(t)$
-70 dBm/MHz
A sin(ωt+θ)
-70 dBm
$S_{PSB}(t)$
-70 dBm/MHz
Σ
Σ
DS Matched Filter
Sub-Band-3 Matched Filter
Sub-Band-4 Matched Filter
RMS SIR versus ω
RMS SIR versus ω
RMS SIR versus ω

CDMA Processing Gain Margin Versus Pulsed Sub-band For Mild Interference

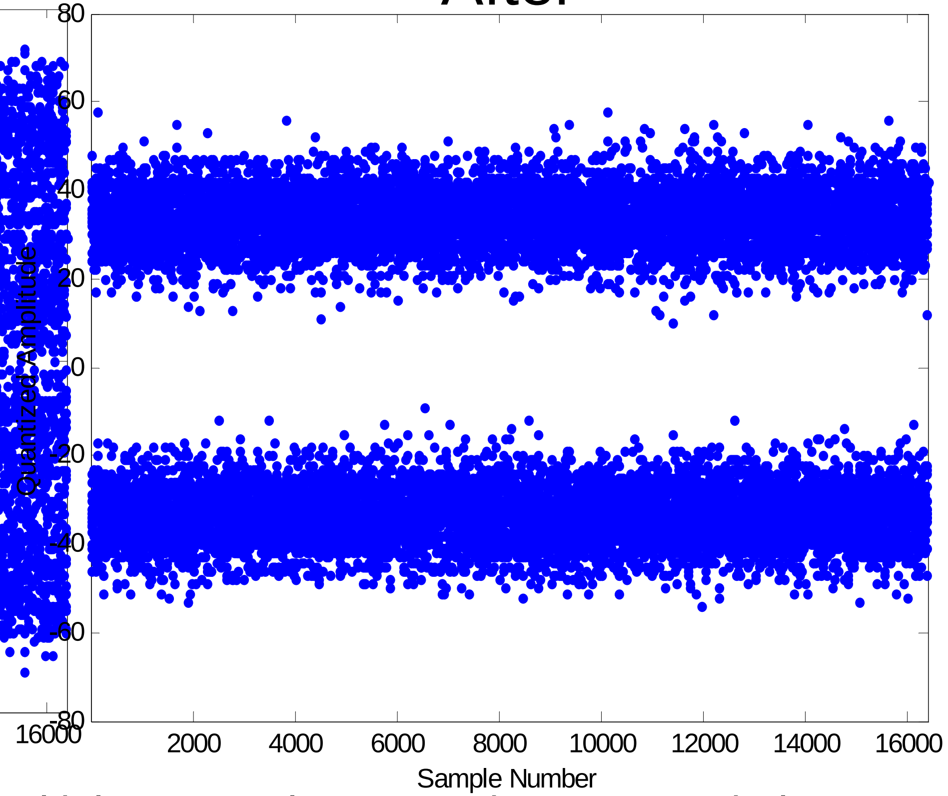


Example of NBI Extraction
Ideal data is at 15 dB SNR

SIR = 5 dB
Before



SNR = 15 dB
After



- Complexity of this algorithm is 4 multiply-accumulate operations per symbol
  - Many other algorithms possible
- DSSS advantage in NBI is a surprise result to some researchers!

Summary Narrowband Interference (NBI) Three Regimes

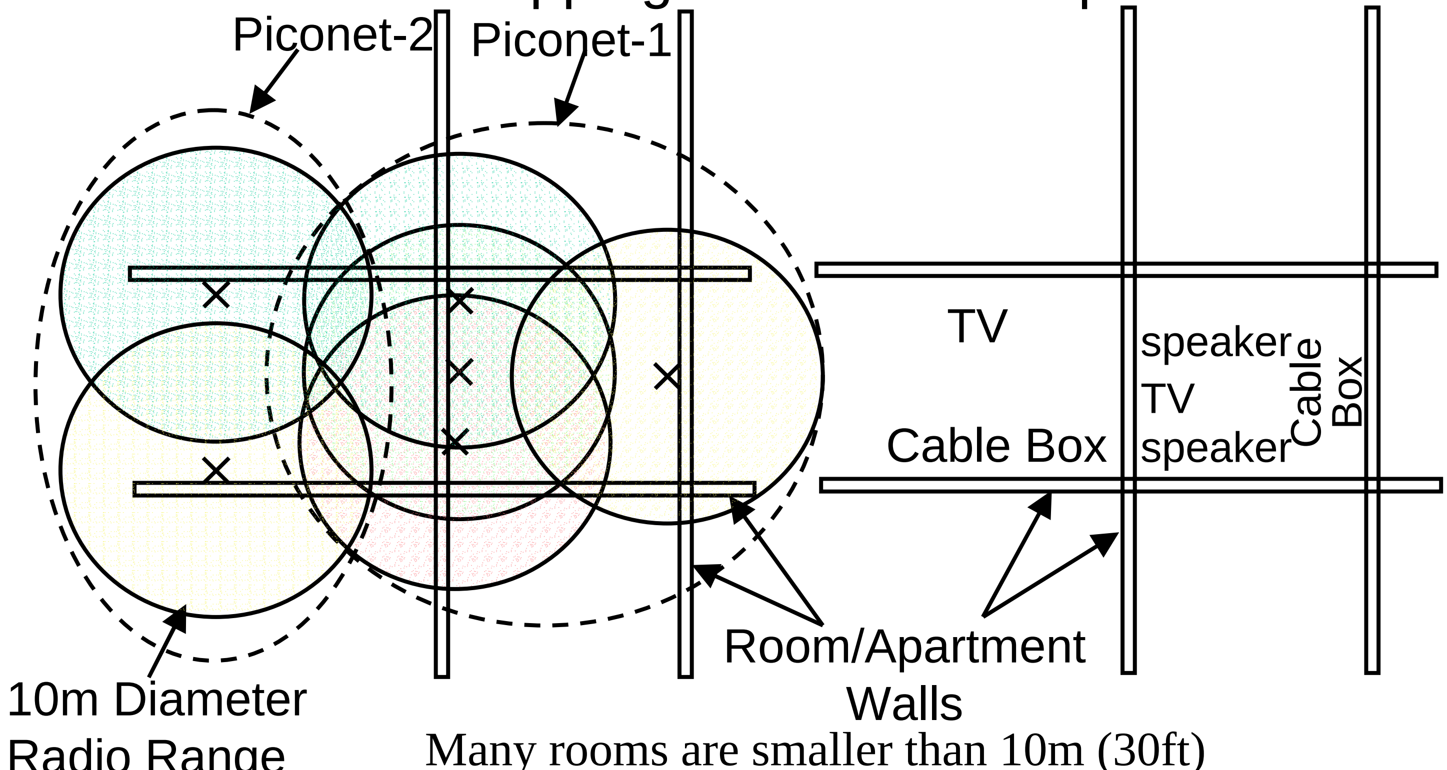
- Mild
  - Signal to Interference (SIR) is within the design margin of the system
  - The extra coding gain gives DSSS-UWB an advantage in more margin
- Moderate
  - SIR margins exceeded design margin but front-end does not saturate
  - DSP gives DSSS-UWB has an additional advantage of ~10dB over mild interference
    - This is a surprise result to some researchers!
- Severe
  - Unprotected front-end saturates -- Issue for all UWB systems
  - DSSS-UWB has slight advantage due to bandwidth ratio between notch filter and UWB waveform.

Multi-User Support in UWB Communication Systems Designs

- Purpose is to address the fundamentals that drive the “multi-user” (i.e. full-rate uncoordinated overlapping piconets) capabilities
- Consider predominant TG3A approaches
  - OFDM approaches
    - TI, Univ-Minnesota
  - “Multi-Band” or Pulsed sub-band centric approaches
    - Wisair, Intel, Time Domain, GA, Philips Labs, Samsung Labs
  - Monopulse-UWB (wide coherent contiguous bands) centric approaches
    - Single and few-band DSSS-CDMA with code-space or pulse-position M-BOK
    - Motorola, Sony, ST Micro, XtremeSpectrum, ParthusCeva, Mitsubishi

Overlapping Piconets - Key Requirement Spelled Out In PAR 2 Piconets In Adjacent Apartments Illustrates Problem

- As data-rates go up, ranges go down but radiated energy does not – i.e. high speed nets will interfere with distant low-speed nets
- Ultimately, quality of service (QoS) delivered will be driven by the isolation between overlapping uncoordinated piconets.



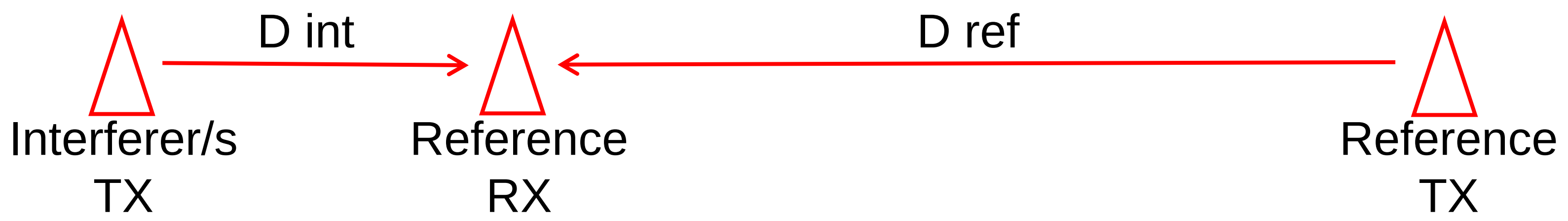
Many rooms are smaller than 10m (30ft)

Multi-user Performance Comparison
Two Critical Questions

- The most important questions for the multi-user mechanism are
  - What is the multi-user capability in a multipath channel
    - Critical because we are almost never in the clear!
  - How much does this capability degrade when NBI mitigation measures are applied
  - What is the multi-user capability for extreme near-far
    - This is the case when the interfering user is very close
      - As little as 6” apart on opposite sides of a wall of an apartment

MUI Testing Metrics Remain An Issue

- Multi-user testing, as described in IEEE document 03/031r9 - 5.3
- Metric is how far away must be the interfering transmitter/s be from a reference receiver and still achieve <8% PER
- Test is NOT fully defined, thus everyone's curves were based on different assumptions
  - Some used 10m for Dref,
  - others used 5m
  - others used whatever Dref gave them 6 dB margin on the 8% PER
  - ALSO – multipath channels were normalized differently
- Nonetheless, even though every dB is not accounted for, the trends reflect expectations based on the fundamentals

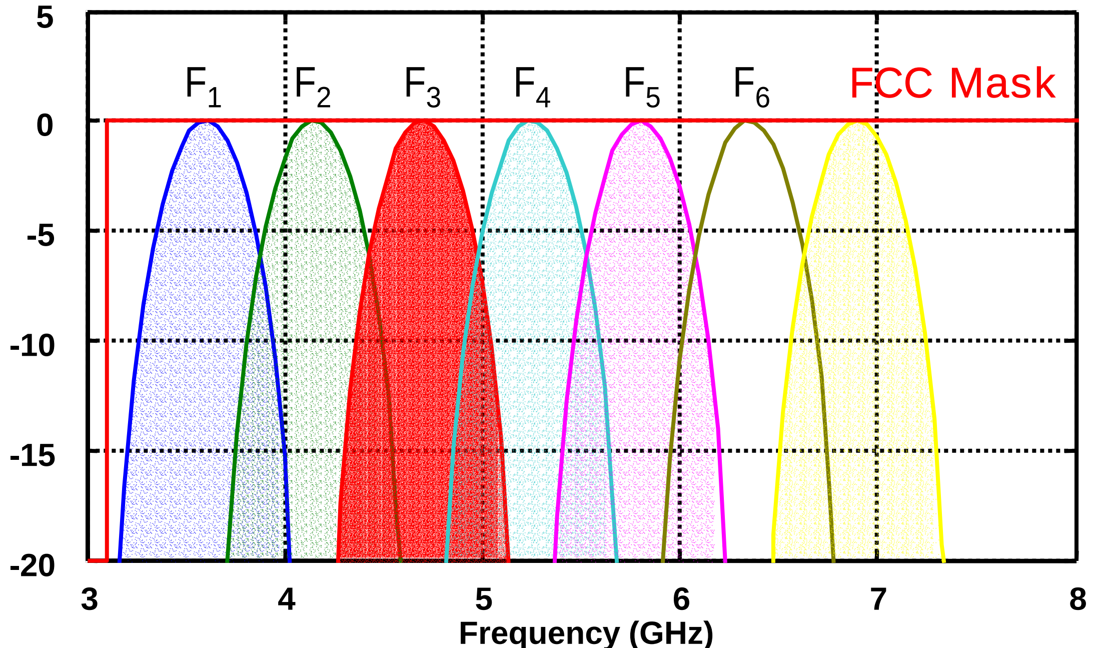


What Are Fundamental "Qualitative" Ideas That Drive

- Requirement is to simultaneously support
  - 4 full-rate uncoordinated overlapping piconets (one desired, three interfering)
  - Above in high multipath (e.g. CM-1,2,3,4)
  - Both the above Plus with NBI

- Outline of talk is to look at
  - Fundamentals of approaches
  - What the channel looks like
  - What performance we should expect given the channels
  - The matching of reported results from various proposals with expectations from looking at the fundamentals.

Introduction Pulsed Multiband



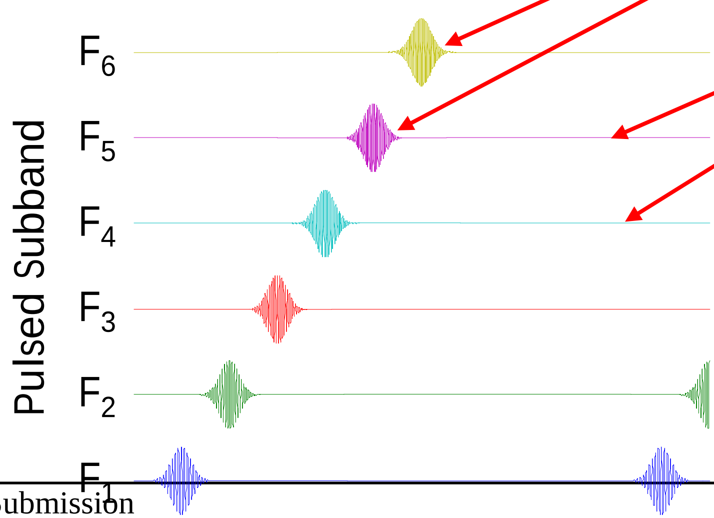
- Send pulses in sub-bands spaced out over the whole bandwidth
- Ideas include variations with and without CDMA on top
  - But codes in any band are very short
- 500 MHz to 700 MHz band plan – meets FCC 500 MHz criteria
- BPSK/QPSK each band
- Fast frequency hopping between bands

Most Important Pulsed Multiband Concepts

- Multipath concept
  - Pulsing on briefly (3-12 nsec) per band
  - Waiting for the channel response to taper off (25-80 nsec)
- Multi-user concept
  - Idea is other users can use the band when you are not
  - Mechanism is coded fast frequency hopping (FFH)
- Narrowband interference (NBI) concept
  - Don’t use (turn off) bands that have NBI
- Regulatory flexibility
  - Turn off bands that don’t fit host country

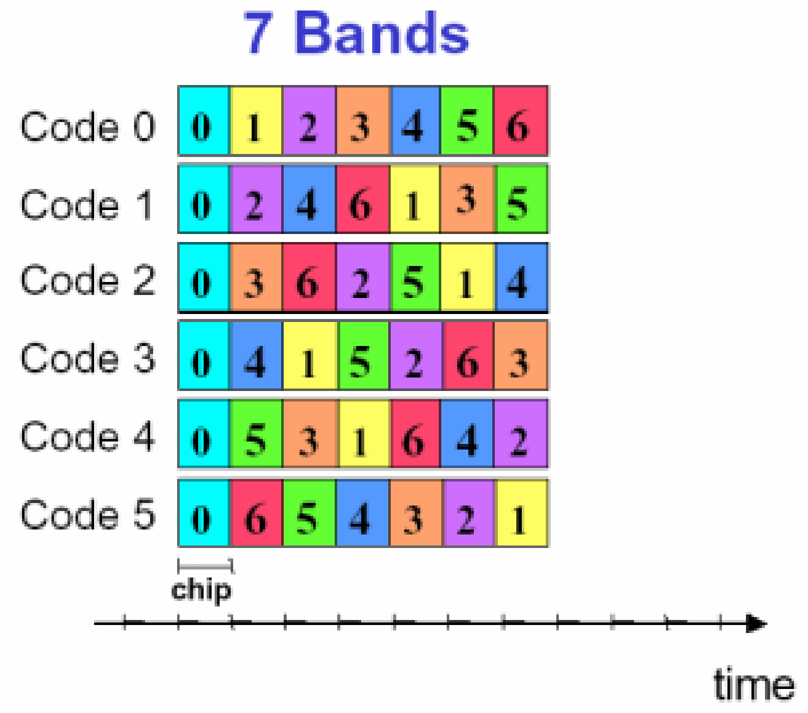
Some ideas depend on each frequency having same delay-time through channel so that hopping sequence is preserved

Idea depends on the channel having significant dead-time where other users may fit into the channel without multipath interference



Pulsed Multi-band Time Frequency Codes

- Length 7 time-frequency codes
- Six codes in family
- Every overlapping piconet adds a collision
  - Before multipath
  - Error absorbed by FEC

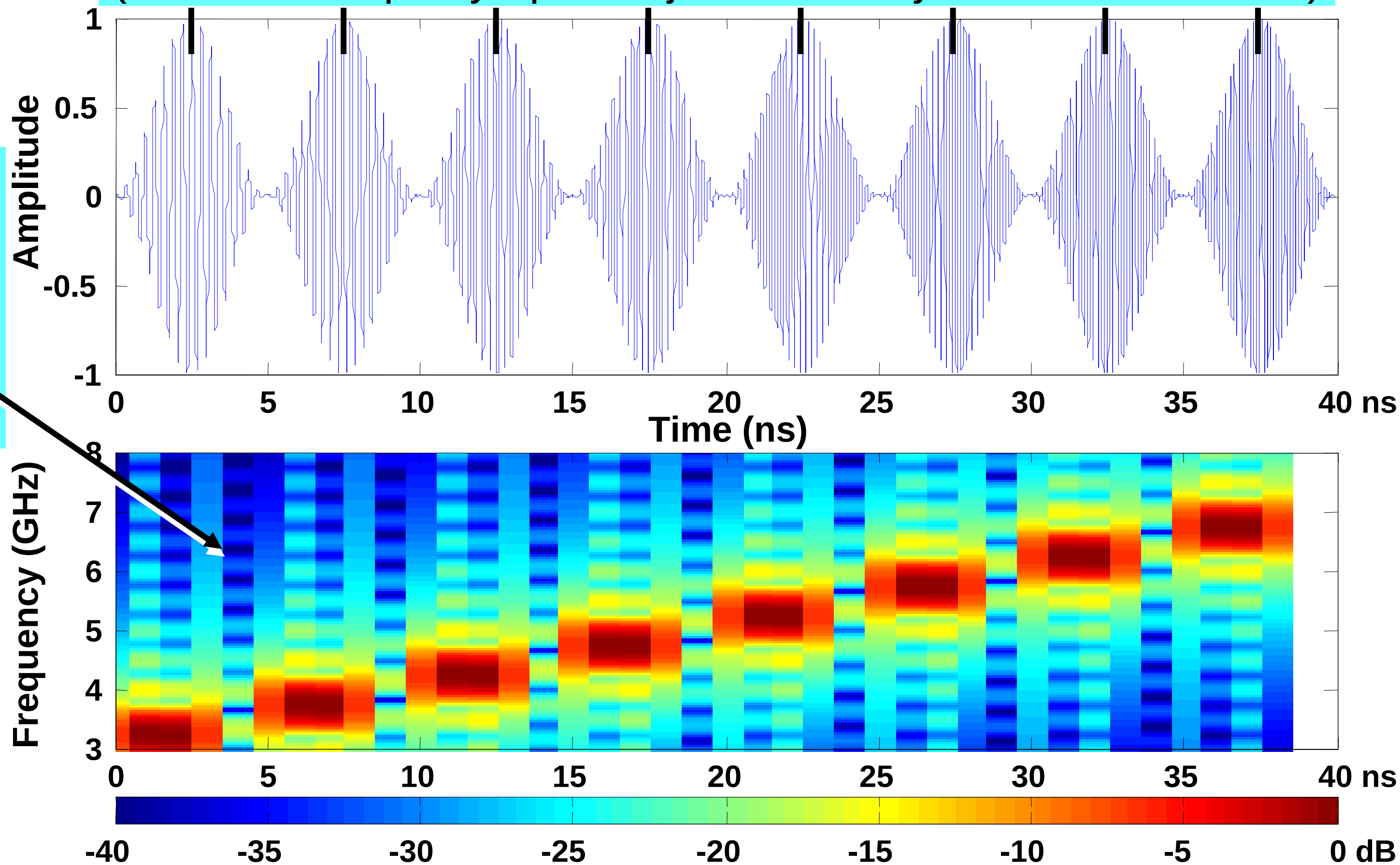


Pulsed Multiband Time-Frequency Analysis

- FFH works when the channel is clear—no multipath

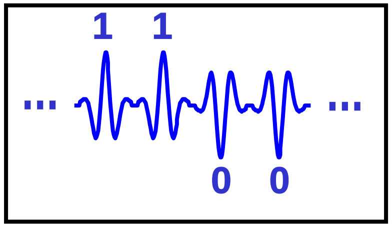
Idea is for pulses from every frequency band to be delayed in the channel by the same amount
(i.e. arrive equally spaced just like they were transmitted)

Idea is for other networks to fit into "off" times in each frequency band

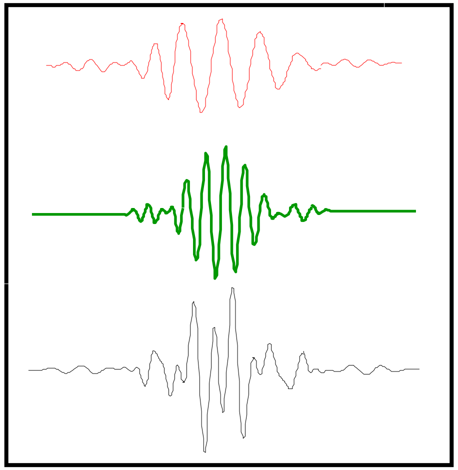


Introduction Direct Sequence UWB

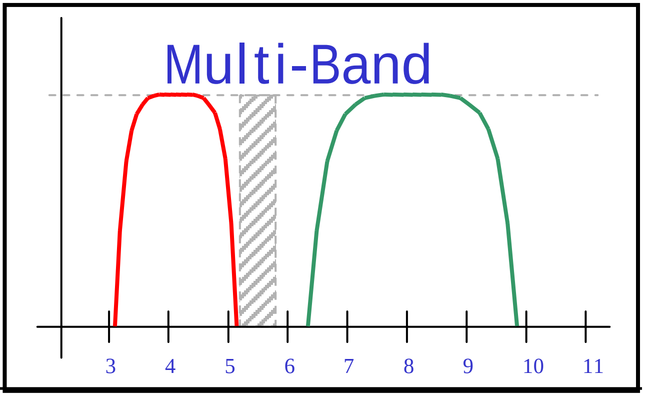
- High chip rate Direct Sequence Spread Spectrum
- High chip rate, longest code per unit time, lowest chip energy
  - **Maximum coding of transmitted energy**
- BPSK/QPSK modulation of chips



- Code Division Multiple Access CDMA
  - Long codes give large code sets with good performance
  - Give spectral nulls for both Xmit and Rec

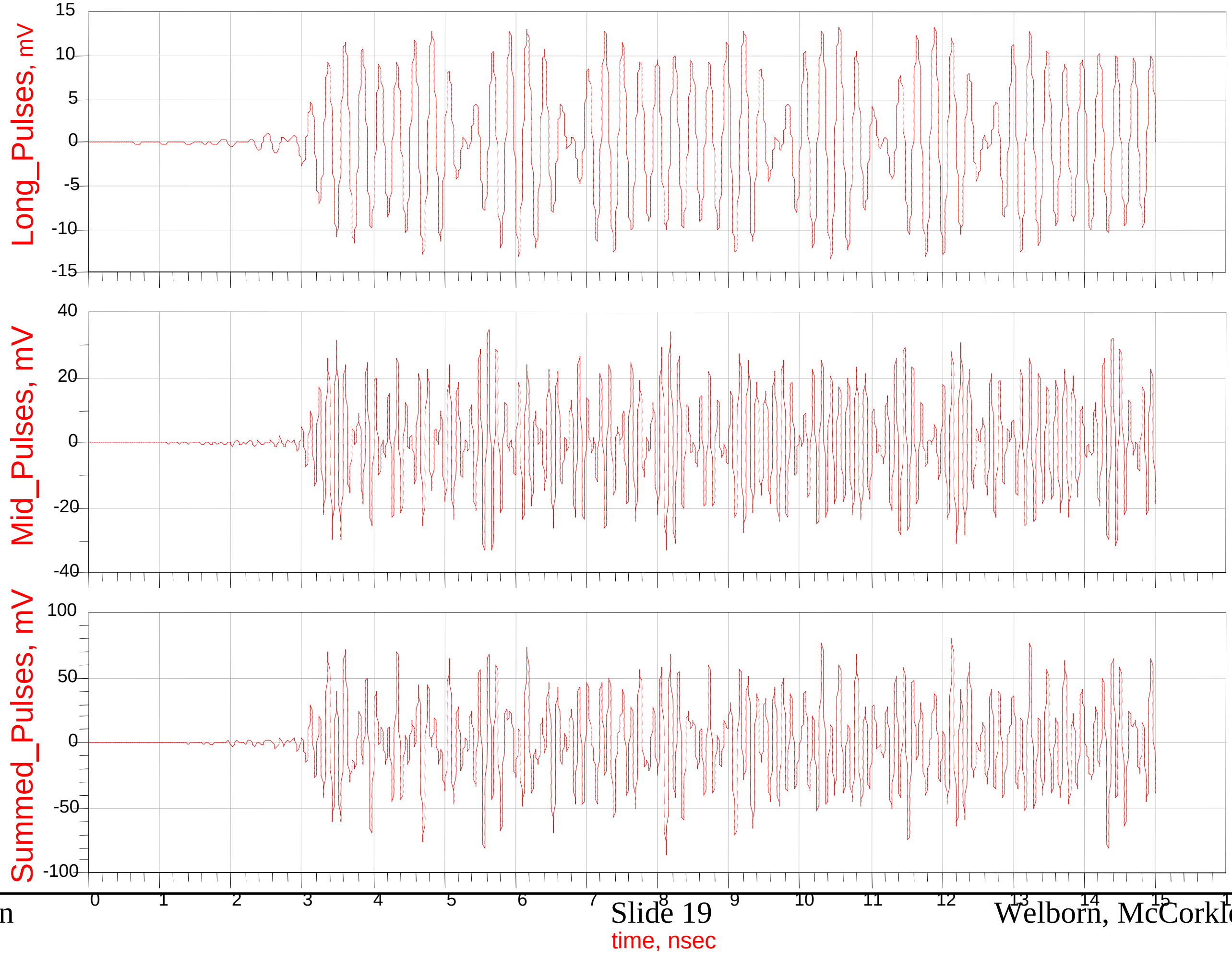


- Chip waveforms are programmable/soft selectable
  - Gives flexible spectrum use
  - Center frequencies & BW are selectable
  - Can easily add bands in the future
  - Some proposals have wide gap between bands gives >60 dB isolation for true FDM capacity



DS-UWB Signal In the Air Channel -- How Can This Work?

- Appears to fill the entire channel
  - How can another user share this channel—even without multipath?



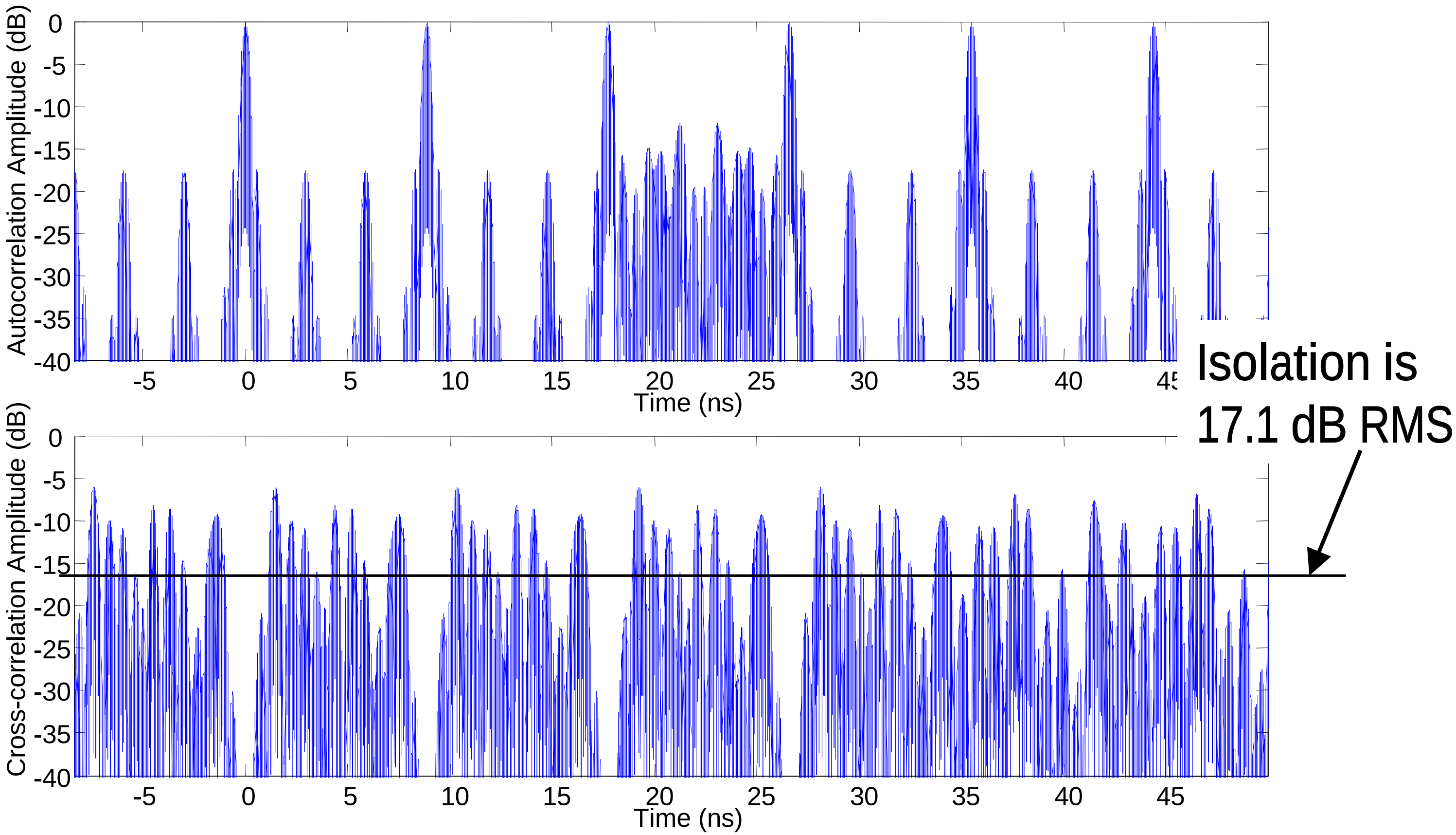
Answer is Coding

- Autocorrelation delivers single pulse performance
  - Solves multipath (with help from equalizer)
- Cross-correlation between user codes delivers multi-user performance
- Autocorrelation & cross-correlation both withstand multipath
  - Therefore single user performance is delivered for multi-user case
  - 24-chip ternary codes provide 14 dB RMS isolation in multipath
  - 32-chip ternary codes provide 15 dB RMS isolation in multipath
- This performance is simultaneous with NBI notches in codes

Coding Delivers Single-user & Multi-user performance

C1 correlated with C1 (user 1) Data Stream

Cross correlation between C1 & C2 Interfering Stream



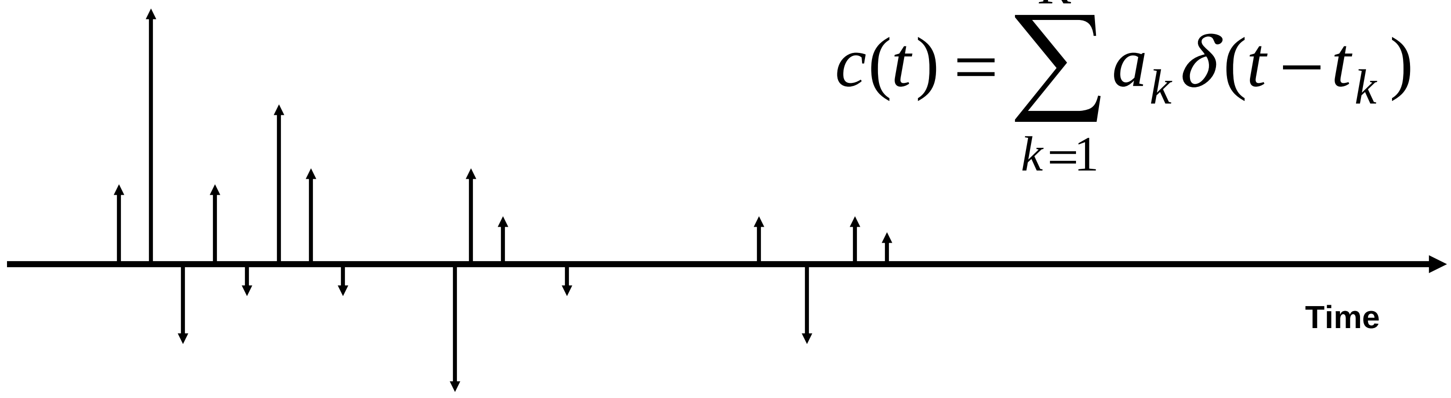
- Piconets are intentionally not synchronized. Codes are sliding past each other
  - Only the RMS cross-correlation matters

UWB Channel Model

- Real RF environments have multipath
  - Signals reflect from walls, floors, ceilings, furniture, people …
- To allow 'apples to apples' comparisons, IEEE 802.15.3a has developed a consistent channel model
  - Called the Saleh-Valenzuela (SV) model
- Four classes of channels defined by 802.15.3a
  - CM1: 0 to 4 meters, Line-of-sight (LOS)
  - CM2: 0 to 4 meters, Non-LOS (NLOS)
  - CM3: 4 to 10 meters, NLOS
  - CM4: Extreme NLOS (i.e. between apartments)
- There are 100 pre-computed realizations for each of the classes

The SV UWB Channel Model

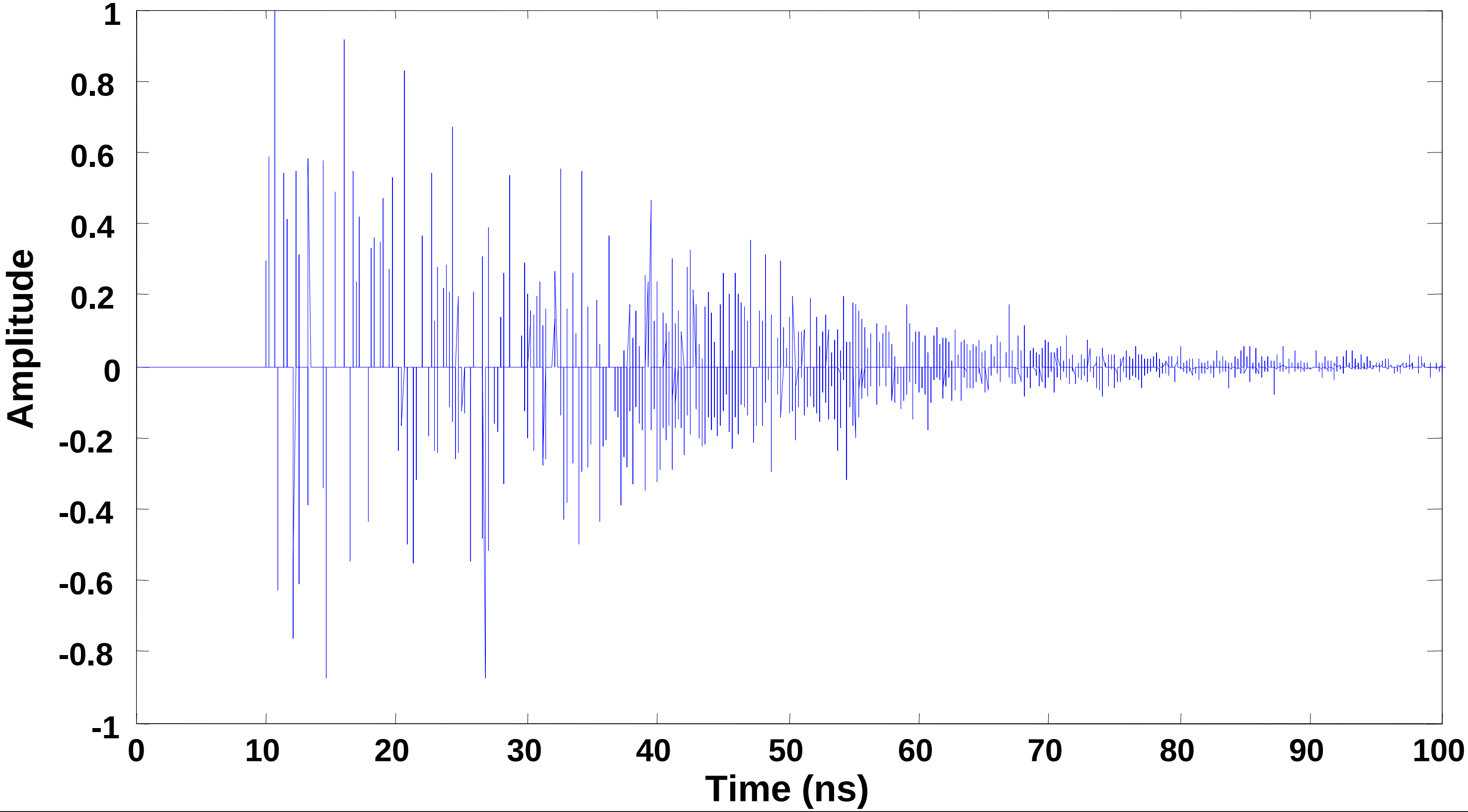
$$c(t) = \sum_{k=1}^{K} a_k \delta(t - t_k)$$



- The SV channel model is an infinite bandwidth statistical impulse train model representing the multipath
  – Impulses are multipath components with amplitudes, arrival times and polarities chosen according to parameterized model
  – Arrival times are non-uniformly spaced (i.e. “continuous” time)

Instance of CM-3 Channel

- Non-line of sight for 4 to 10 meter transceiver spacing
  - Real world would be a user in an adjacent room
- Delay spread is beyond 60 nsec



Application of SV

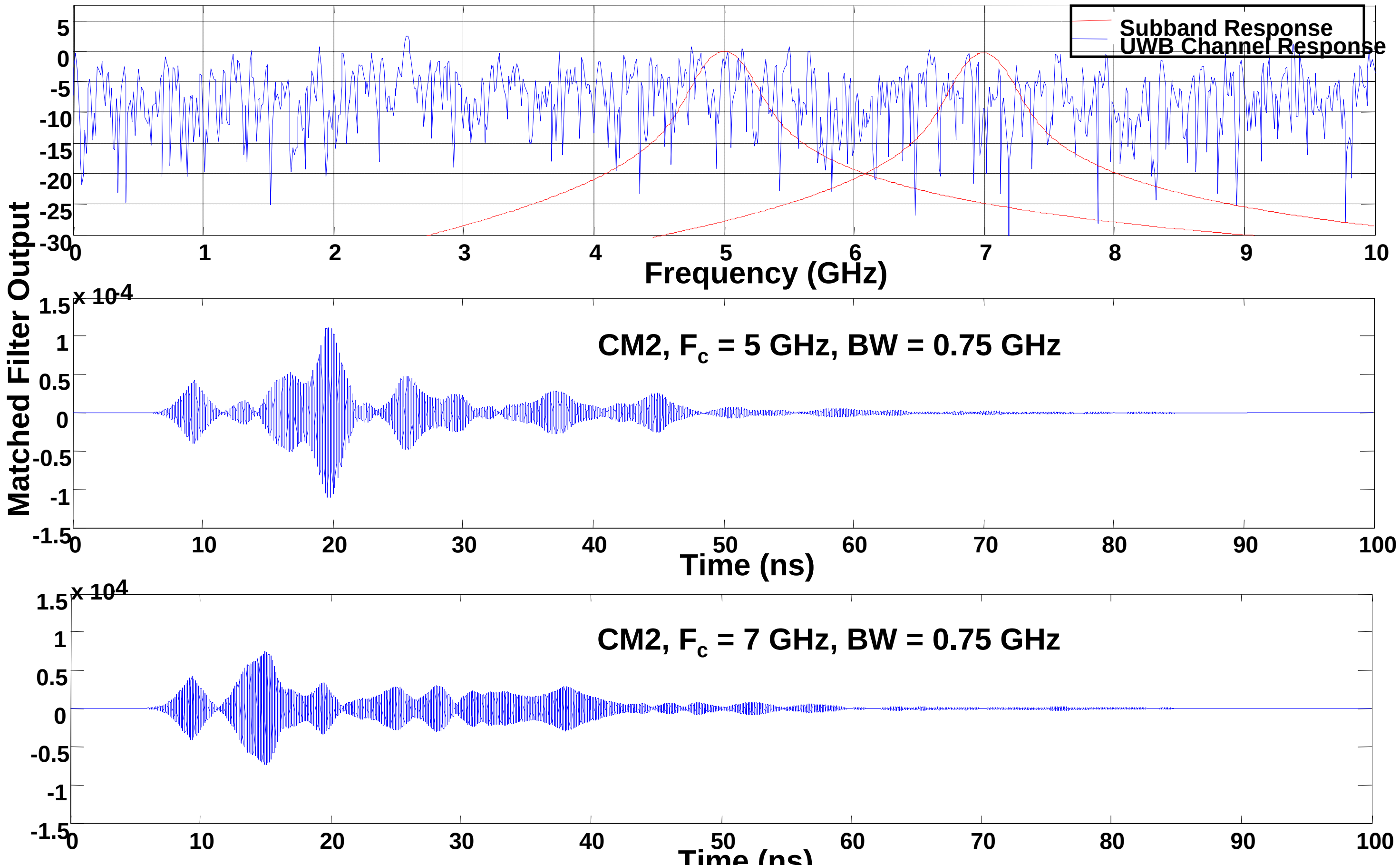
- The slides that follow apply CM2, CM3 & CM4 to both UWB technologies
  - Shows that Pulsed Multiband fails to provide multi-user isolation
    - Also shows hop timing is not preserved
  - Shows that DS-UWB CDMA delivers multi-user isolation

- Use of channel models CM2, CM3 & CM4 is appropriate
  - Typically interfering users are non-line of sight or obstructed
    - Other users at a tradeshow, hotel, airport etc.
    - An adjacent office or cube
    - A next door neighbor

- Methodology
  - Instantiate a realization of the infinite bandwidth channel model (CM_i)
  - Convolve with the transmitted waveform (i.e. Filter to the desired band/s)
    - Two cases shown here, 750MHz subbands at 5 GHz and 7 GHz
  - Run the receiver (convolve again)

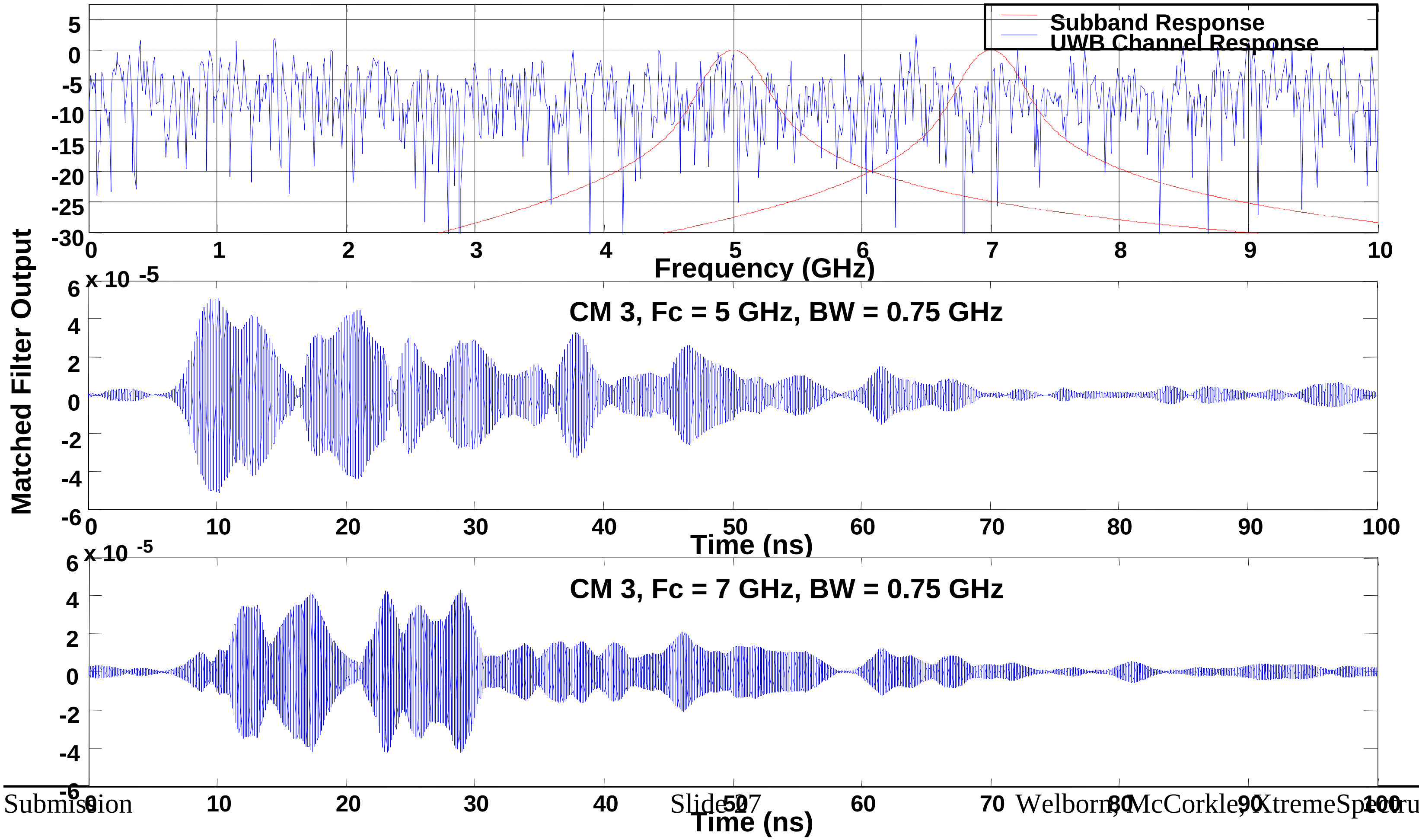
Channel Model CM-2 Applied to Pulsed Sub-band

- A single user fills the entire subband
  - No opportunity for another user to hop into “quiet” time
    - Not enough coding to separate users
- Hopping sequence is not preserved – delay in each band is different



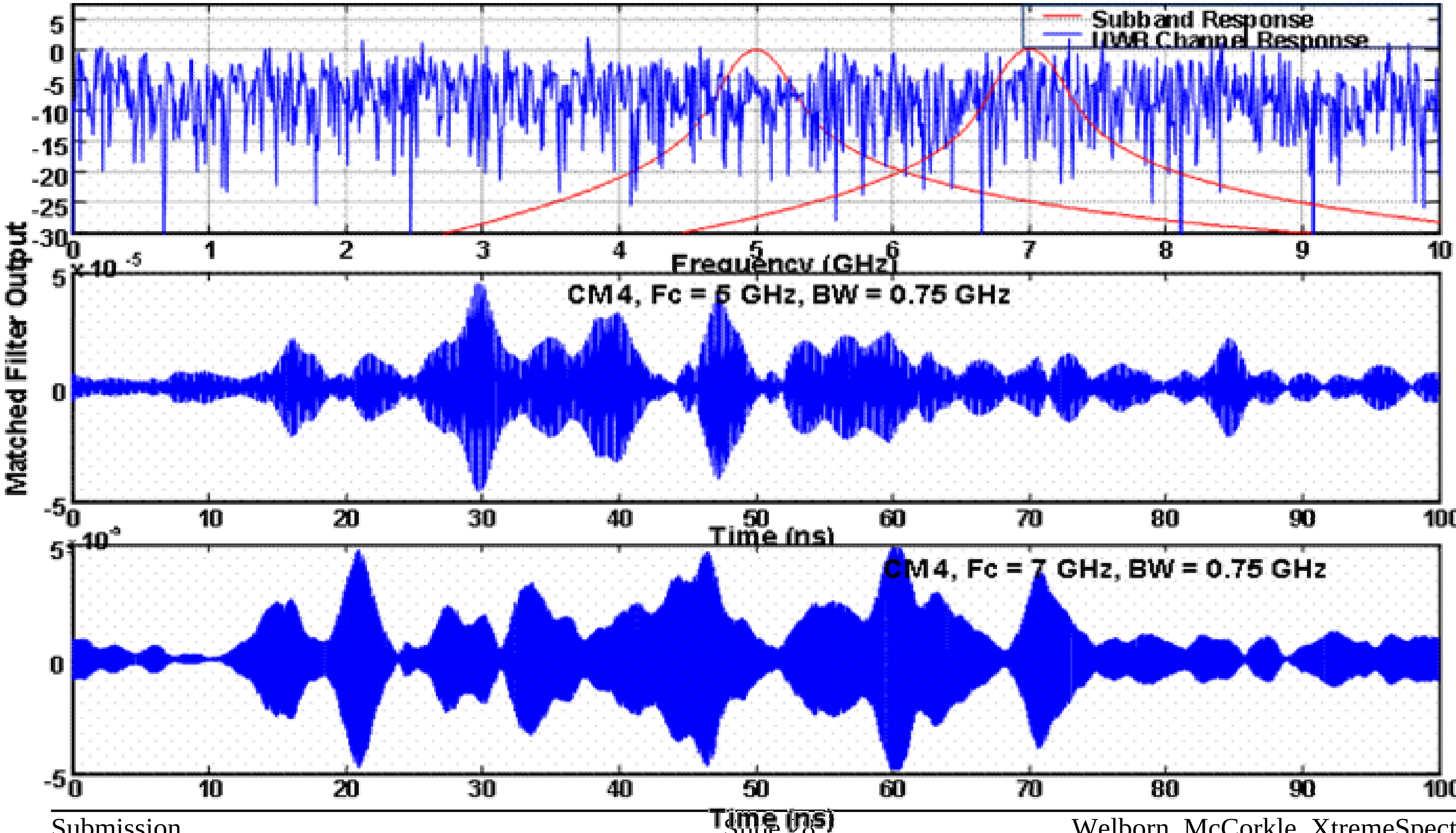
Channel Model CM-3 Applied to Pulsed Sub-band

- A single user fills the entire subband
  - No space for another user to hop - Not enough coding to separate users
  - Hopping sequence is not preserved – delay in each band is different



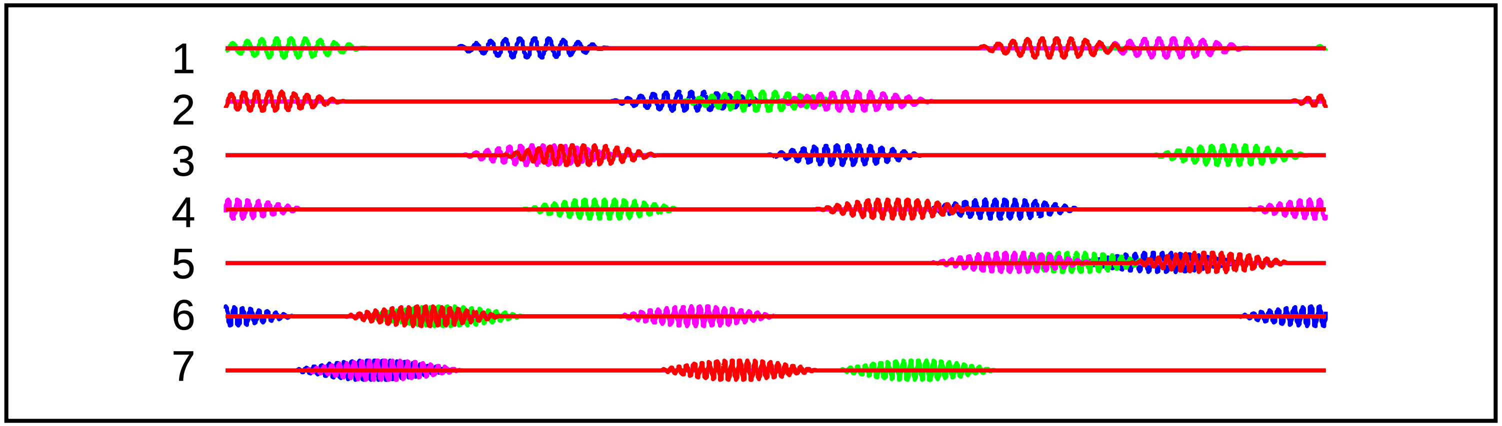
Channel Model CM-4 Applied to Pulsed Sub-band

- A single user fills the entire subband
  - No opportunity for another user to hop - Not enough coding to separate users
  - Hopping sequence is not preserved – delay in each band is different

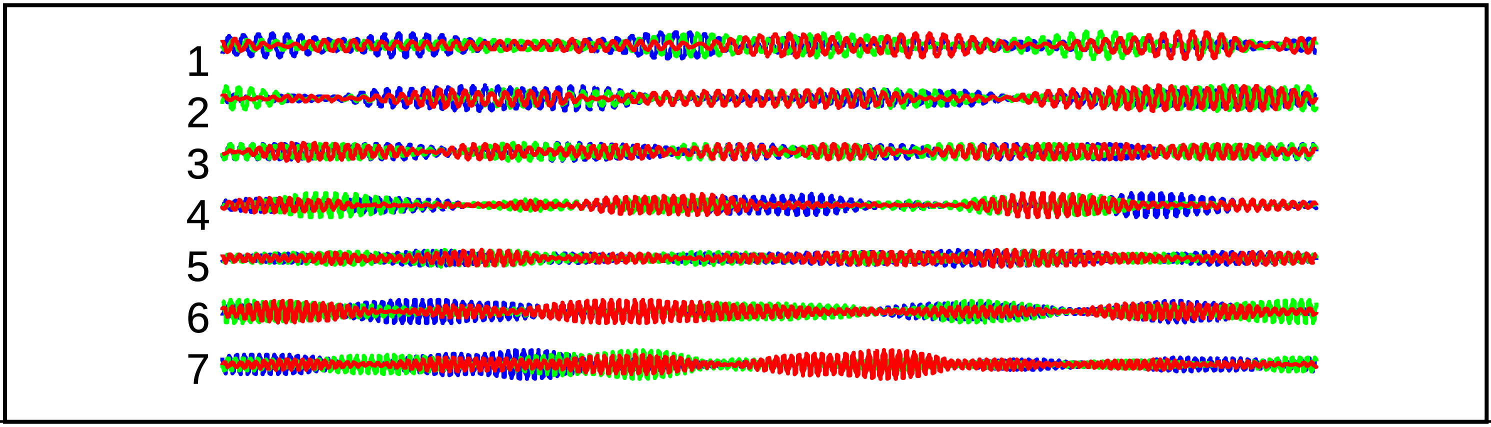


Time-Frequency Codes

- Three users with no multipath
  - 3 Collisions are already taking place—FEC must overcome

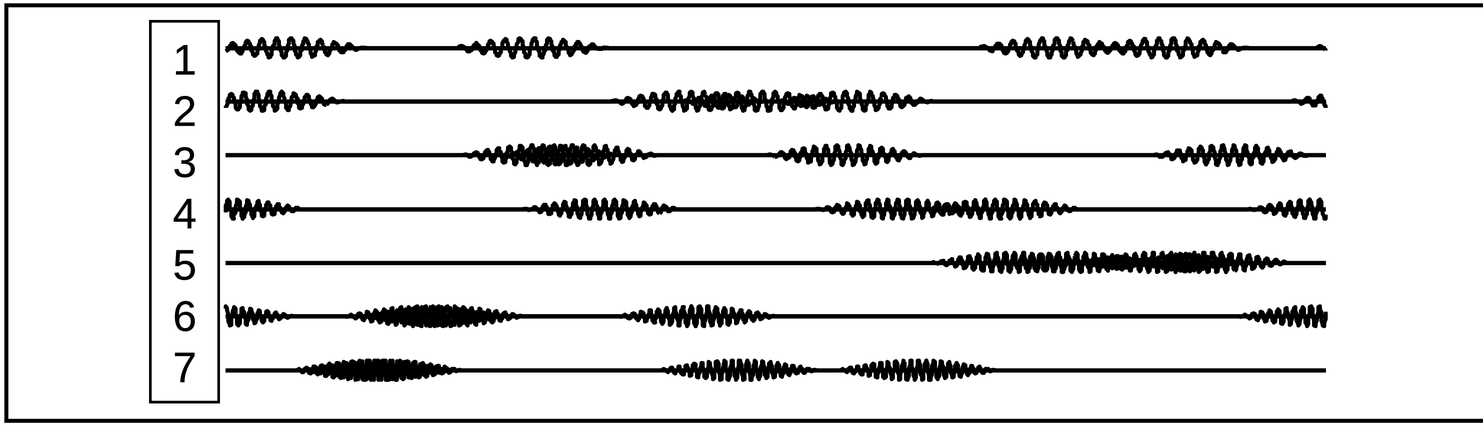


- Three users in multipath—overwhelmed by collisions
  Color used here to identify users – No “color” with pulsed-sub-bands



Time-Frequency Codes

- Three users with no multipath
  - 3 Collisions are already taking place—FEC must overcome



- Three users in multipath—overwhelmed by collisions
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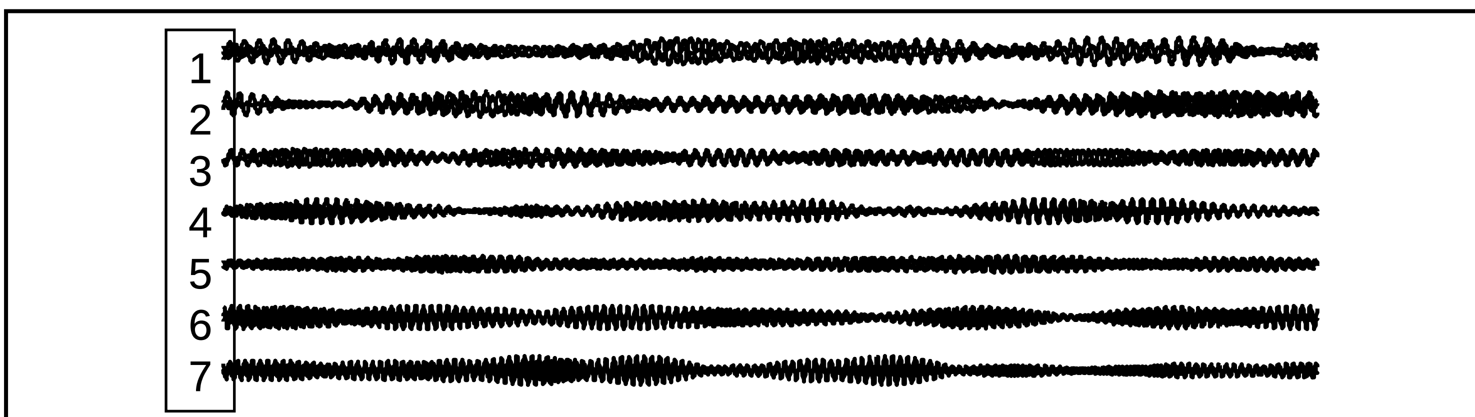
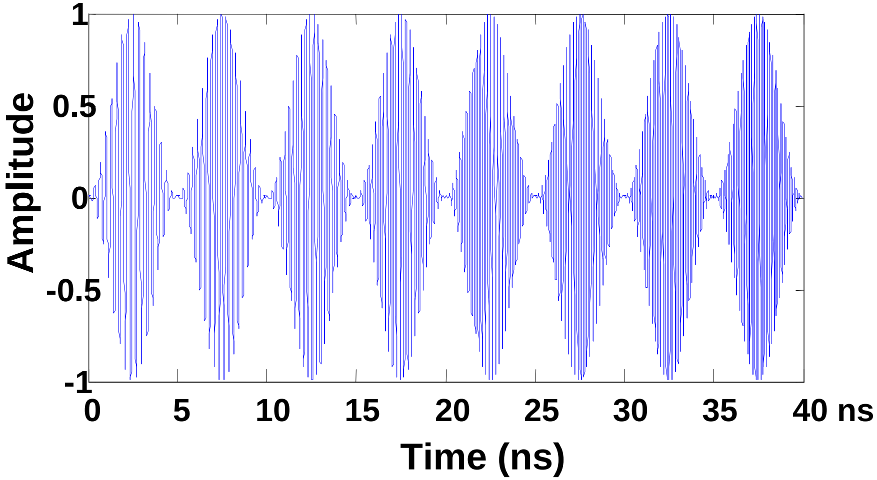
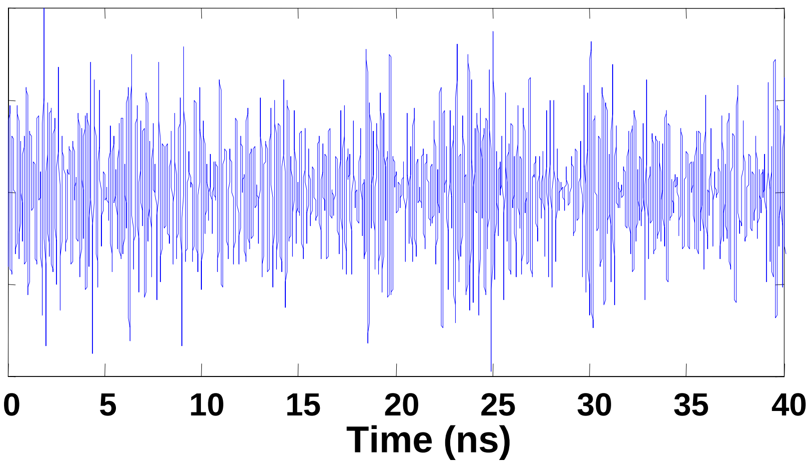


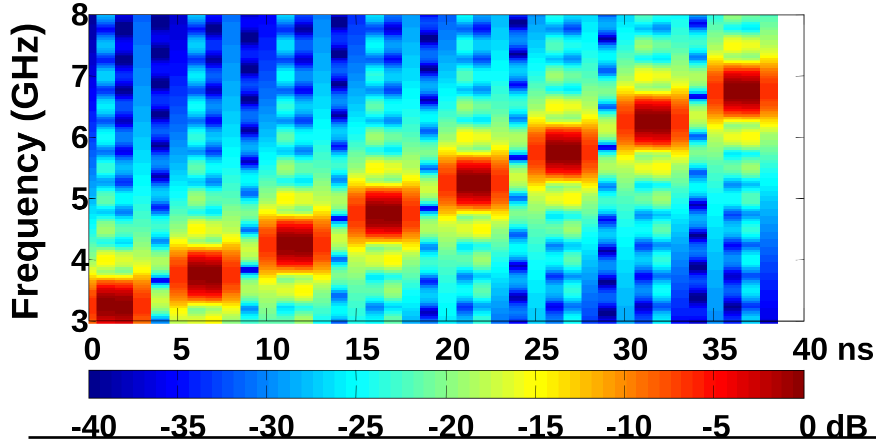
Pulsed Multiband Provides Little Multiuser Isolation And Is Overwhelmed When Combined With Multipath Channels

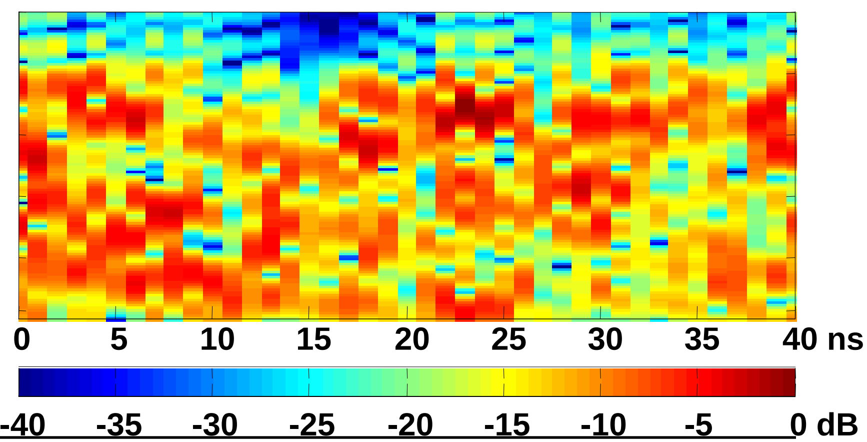
- Pulsed subbband with no multipath
- Subbands appear clear

- In CM-3 multiuser performance is poor
  - Subbands are full—no room for 2nd user
  - No coding isolation to separate them





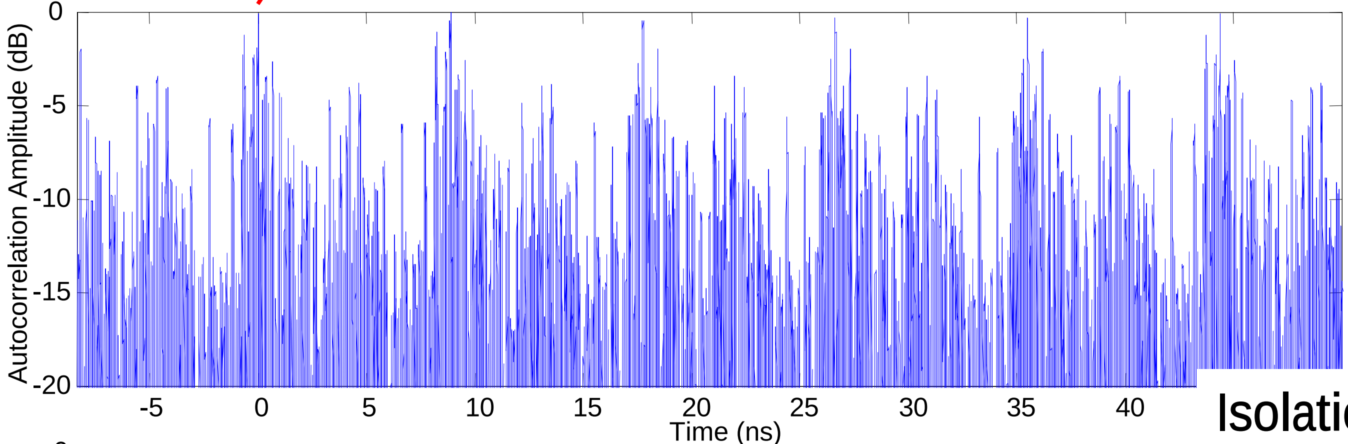




DSSS-CDMA UWB In the Exact Same CM-3 Channel

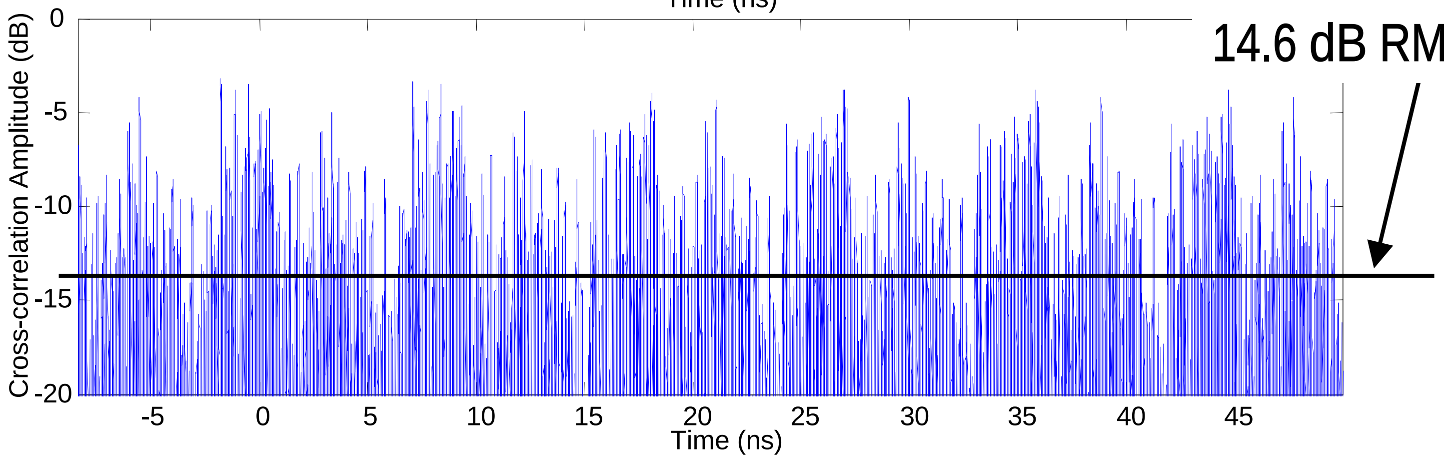
Autocorrelation property is preserved

C1 correlated with C1 (user 1) Data Stream



Isolation is 14.6 dB RMS

Cross correlation between C1 & C2 Interfering Stream



Isolation is 14.6 dB RMS – Only 2.5 dB off of clear channel

Demonstrable Robust Multi-User Performance in Multipath

Preliminary Results in the Various Proposals Are Consistent with Fundamentals

- OFDM
  - Never used for overlapping piconets – e.g. 802.11a uses FDM
  - Poorest performance – but consistent numbers in all multipath.
- Pulsed sub-band
  - Hopping sequence gives better performance than OFDM in easy cases, BUT…
  - FEC quickly overwhelmed with multipath and more users
    - 3 collisions experienced from 3 interfering piconets without multipath – more missing with multipath
    - Other bands can be missing from NBI mitigation taking away available sub-bands
- DSSS
  - Fundamental design is to address overlapping users
  - Best performance due to maximal coding of energy for each user

Simultaneously Operating Piconets with OFDM
From page 35 03141r3P802-15_TG3a-**TI**-CFP-Presentation.ppt

- Assumptions:
  - As specified in 03/031r9, dref = 10.0 meters for all tests.

- Single piconet (N= 1) interferer separation distance as a function of the reference and interfering multipath channel environments:

Test Link \ Interferer Link	CM1	CM2	CM3	CM4
CM1 (d_{int}/d_{ref})	10.5 m (1.05)	9.5 m (0.95)	10.9 m (1.09)	10.4 m (1.04)
CM2 (d_{int}/d_{ref})	9.8 m (0.98)	8.9 m (0.89)	10.3 m (1.03)	9.7 m (0.97)
CM3 (d_{int}/d_{ref})	9.8 m (0.98)	9.1 m (0.91)	10.3 m (1.03)	9.8 m (0.98)

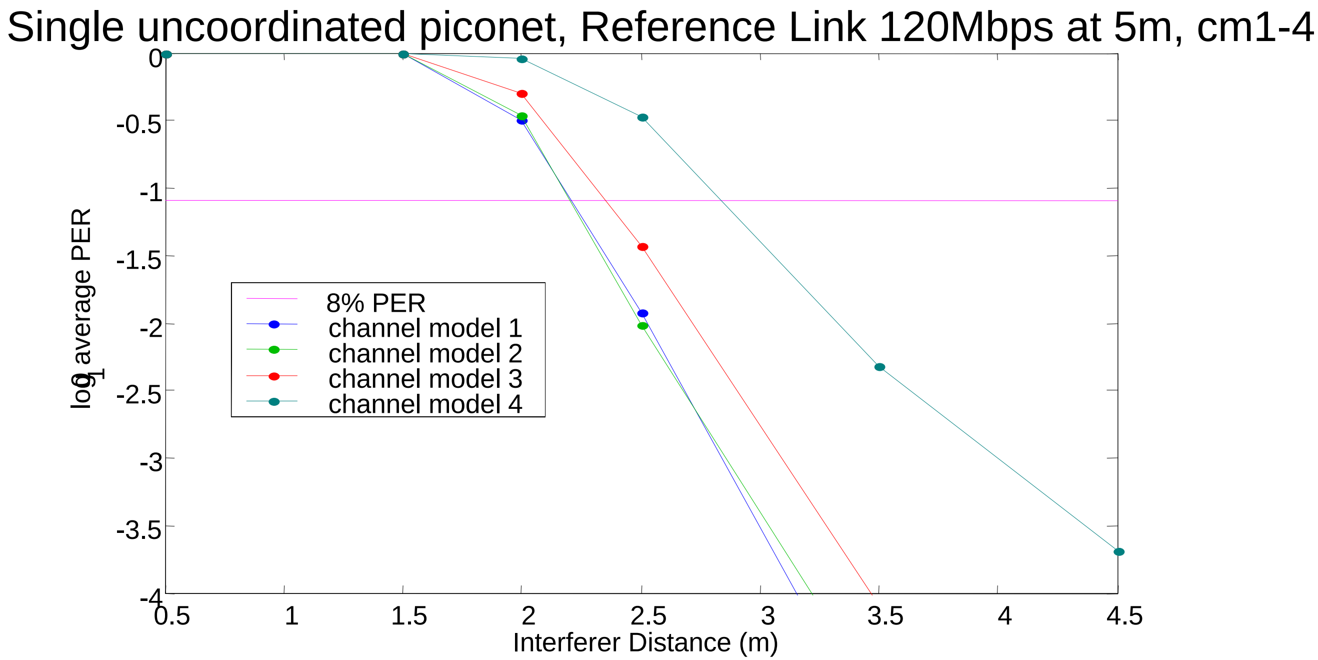
  - Results for N = 2 and N = 3 interferers as well as FDMA can be found in 03/142r2.

Simultaneously Operating Piconets With Pulsed Sub-Band From Page 59 of 03151r3P802-15_TG3a-**Wisair**-CFP-Presentation.ppt

- Reference distance has 6 dB margin relative to a single piconet scenario

Reference CM	d_{int} / d_{ref} 1 interferer	d_{int} / d_{ref} 2 interferers	d_{int} / d_{ref} 3 interferers
CM1	0.58	0.65	0.78
CM2	0.68	0.79	1.00
CM3	0.92	1.01	1.19
CM4	1.12	1.44	1.63

Simultaneously Operating Piconets With DSSS From Page 30 of 03123r3P802-15_TG3a-**ParthusCeva**-CFP-Presentation.ppt



Test Link \ Interferer Link	CM1	CM2	CM3	CM4
CM1-4 (Averaged)	0.44	0.44	0.48	0.68

SUMMARY

TREND SHOWS NO SURPRISES