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

Submission Title: [Time Domain's Proposal for UWB Multi-band Alternate Physical Layer for 802.15.3a]
Date Submitted: [3 March, 2003]
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Re: [802.15.3a Call for Proposals]

Abstract: [This presentation summarizes Time Domain's UWB Multi-band proposal for the 802.15.3a Alternate PHY standard.]

Purpose: [The presentation responds to the Call for Proposals issued by TG 802.15.3a, in consideration for the 802.15.3 Alternate PHY standard.]

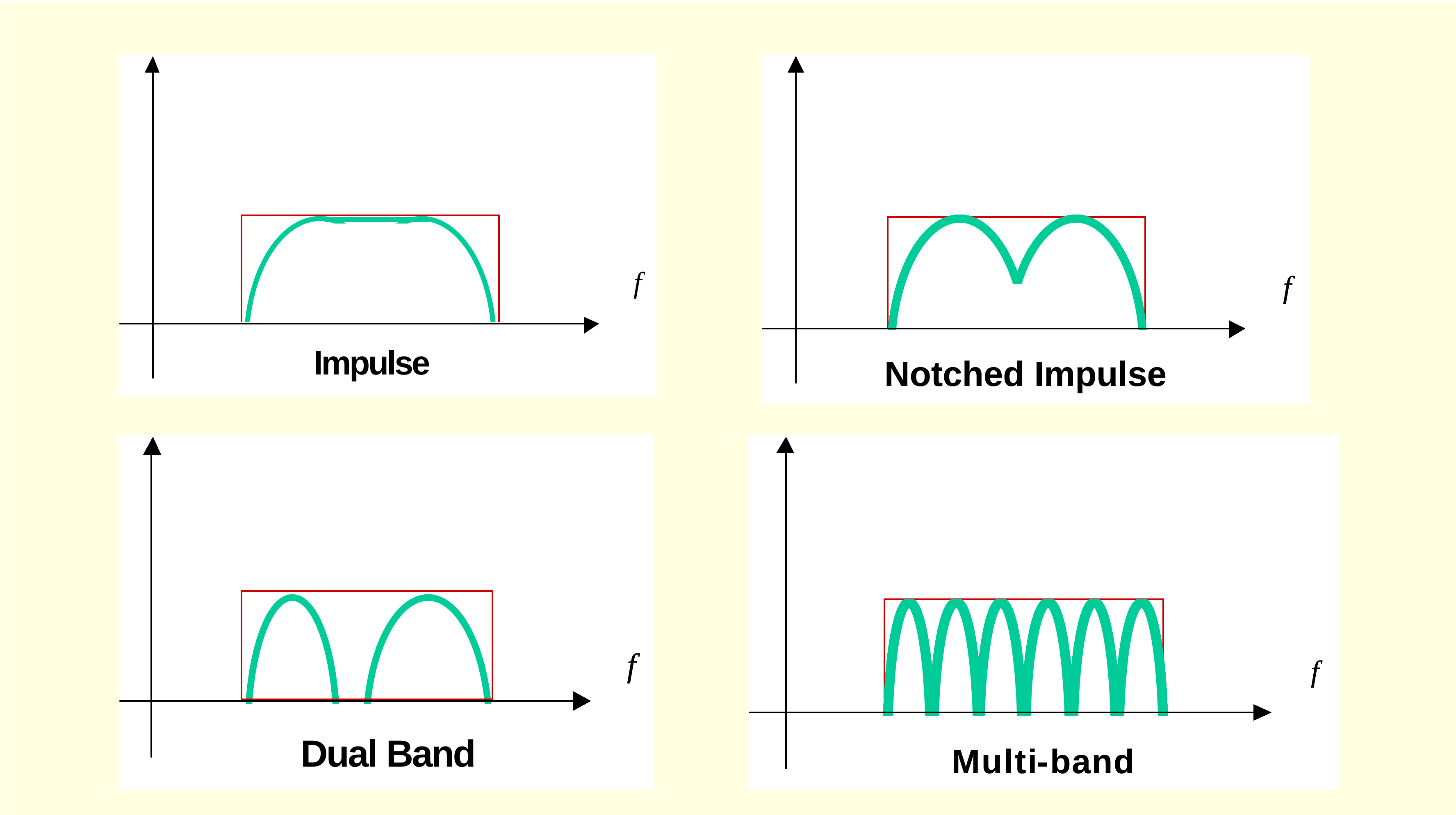
Time Domain Corporation

Proposal for UWB Multi-band Alternate Physical Layer for TG 802.15.3a

Key Selection Criteria Performance Metrics for WPAN Alt PHY

- Cost
- Power consumption
- High data rates
- Channelization
- Performance in multipath
- Interference rejection
- Coexistence

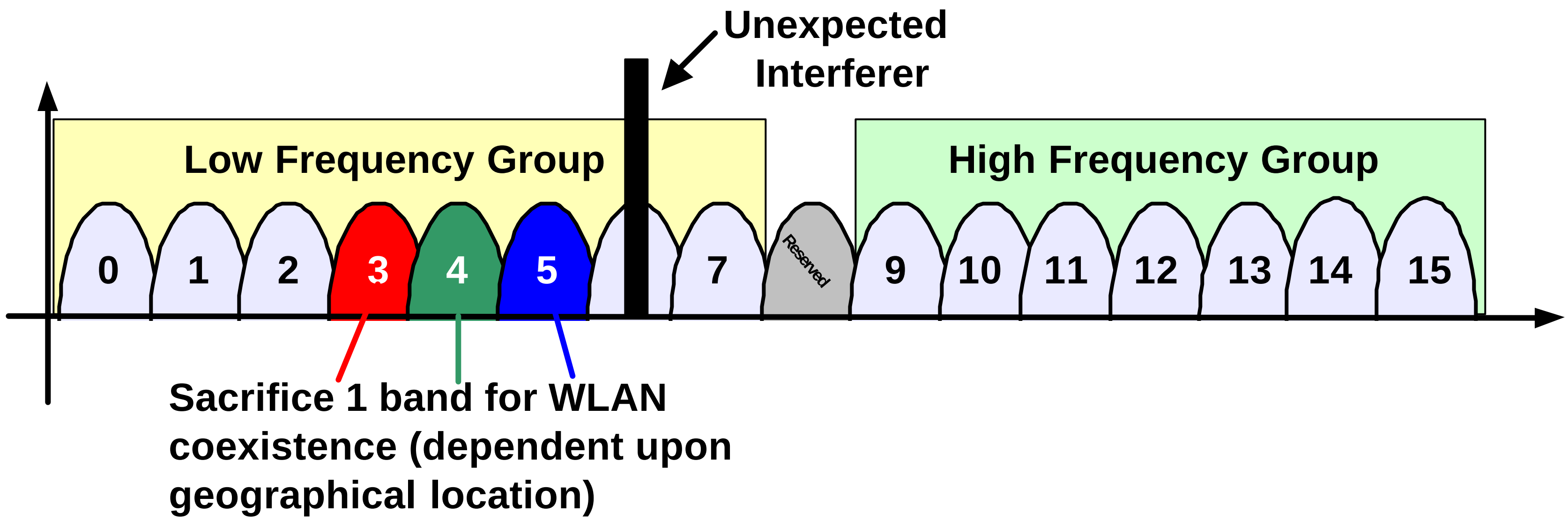
Overview of UWB Solution Space



Time Domain's Multi-band Solution

- Flexible spectrum use
- Time-frequency (TF) codes for multiple access (TFMA)
- Simple modulation schemes
- Standard Forward Error Correction (FEC)
- Graceful scalability with backward compatibility
- Strategies for increased multiple access capability in harsh environments

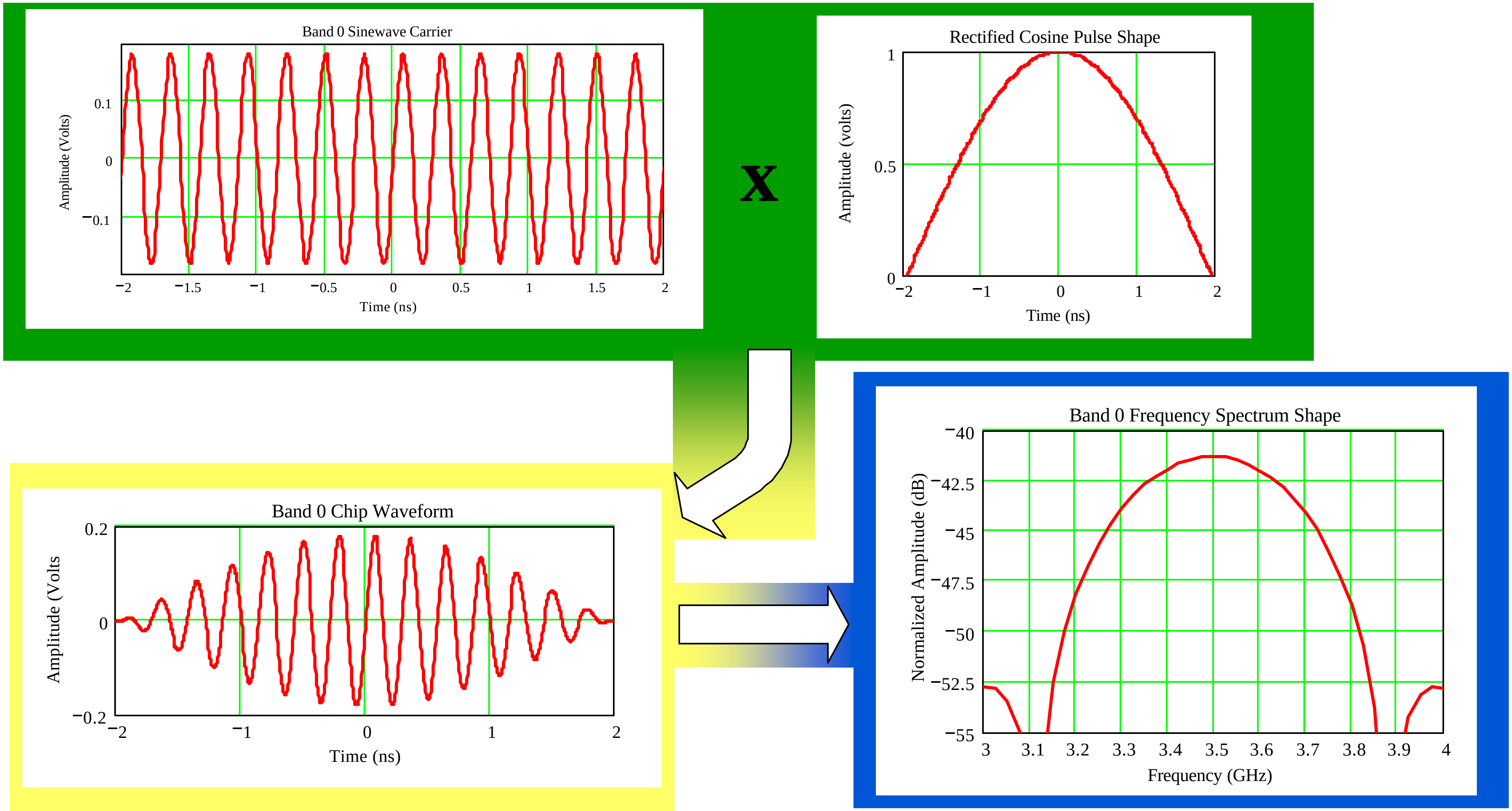
Flexible Spectrum Use



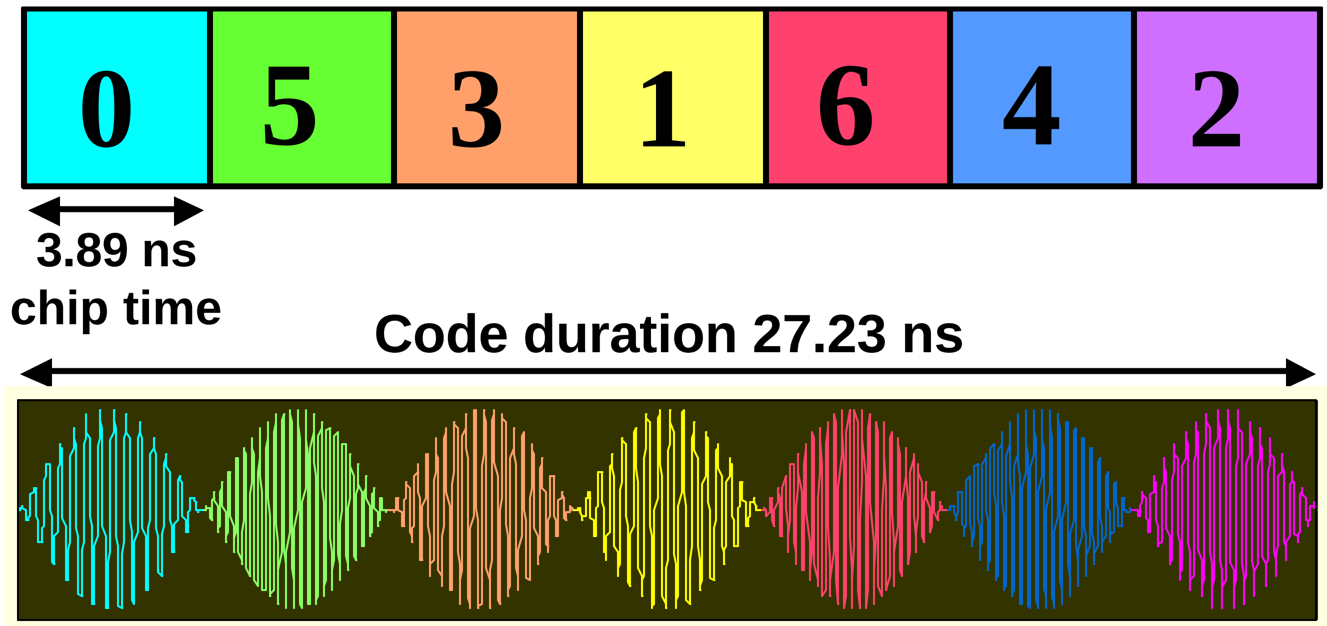
- ~520 MHz bands to best utilize spectrum
- 437 MHz band separation
- Adjacent band isolation: ~ 12 dB
  - Second band over is ~ 21 dB down
- Center frequencies chosen for ease of implementation

Signal Design Using 7 Bands

- 3.9 ns chip time
- Rectified cosine envelope

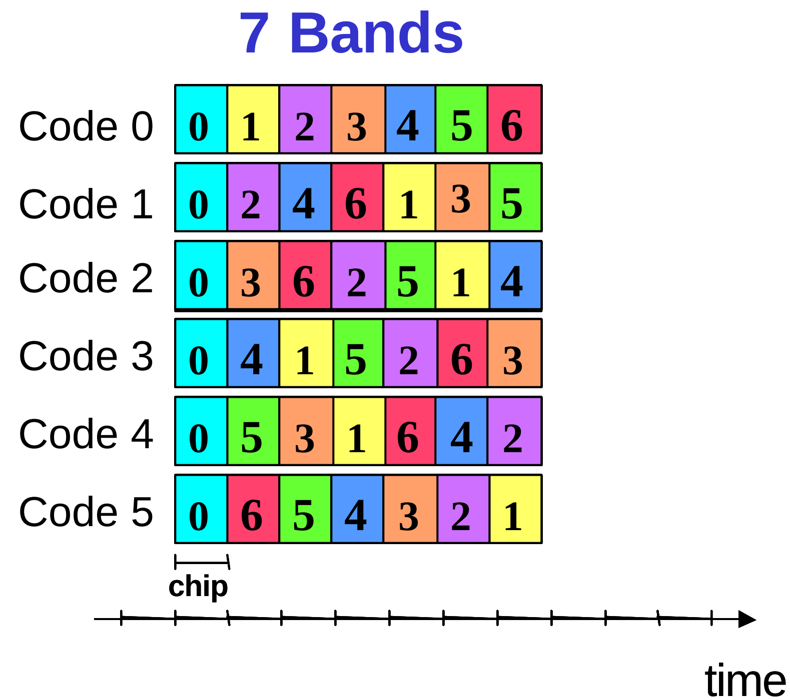


Length 7 Time-Frequency Code



- Time-Frequency Multiple Access (TFMA) radio
- One frequency on the air at a time
  - Enables simplicity in receiver architecture
  - Provides low power solution

Time-Frequency Code Design



- Length 7 time-frequency codes
- Linear congruential design
- 6 codes in family
- At most one collision between any two length 7 codes (provides 17 dB code isolation)
- Length 7 time-frequency codes provide good multipath resistance (approx 27 ns environment ring down)
- Yields 6 unique piconets

Data Modulation

- Use low order modulation for simplicity and reasonable dynamic range requirements
  - BPSK
  - QPSK
- Apply modulation on a per-chip basis
- Length 7 code (using all frequencies) yields raw data rates
  - 257 Mb/s for BPSK
  - 514 Mb/s for QPSK

Forward Error Correction (FEC)

- Convolutional encoder
  - ½ rate
  - ¾ rate
- Constraint length 7
- Industry standard generating polynomials
- Spreads each bit across spectrum
- Multi-band method with per-band modulation enables weighting of each frequency band in soft decision

Modulation Schemes

- 8 modulation combinations defined
  - Fits within existing 3-bit PHY Header field

	Modulation Scheme				Payload Bit Rate (Mb/s)		
Index	BPSK	QPSK	FEC	Frequency Integration	4 Bands	7 Bands	14 Bands
0*	✓		None	✓	37	37	37
3	✓		½ Rate		73	128	257
5		✓	½ Rate		147	257	514
7		✓	None		294	514	1028

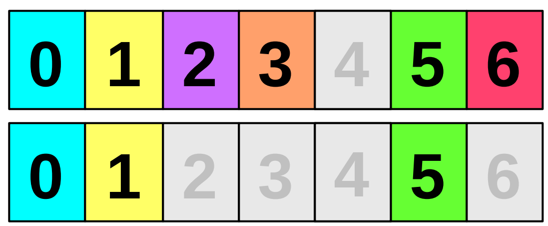
***Mode 0 is base rate: used for all header /beacon / CAP signaling**

Flexibility of Multi-band: Dynamic Band Management

- Monitor and report per-band performance
- Detect spectral problems, if any
- Four categories
  - Narrowband interferer
  - Channel fading
  - Nearby interfering piconet (near/far)
  - Multiple near-proximity piconets in extreme multipath

Solution for Narrowband Interference & Channel Fading

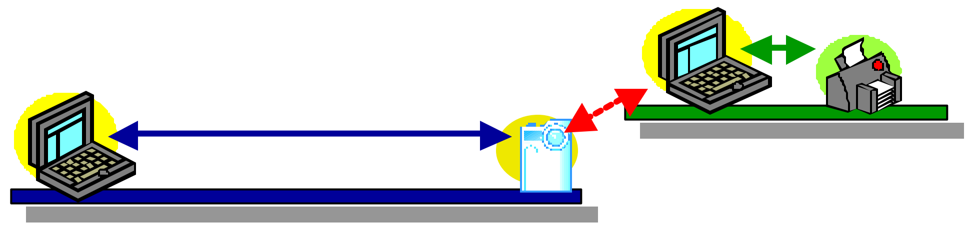
- Coordinate between DEVs within piconet to drop affected bands



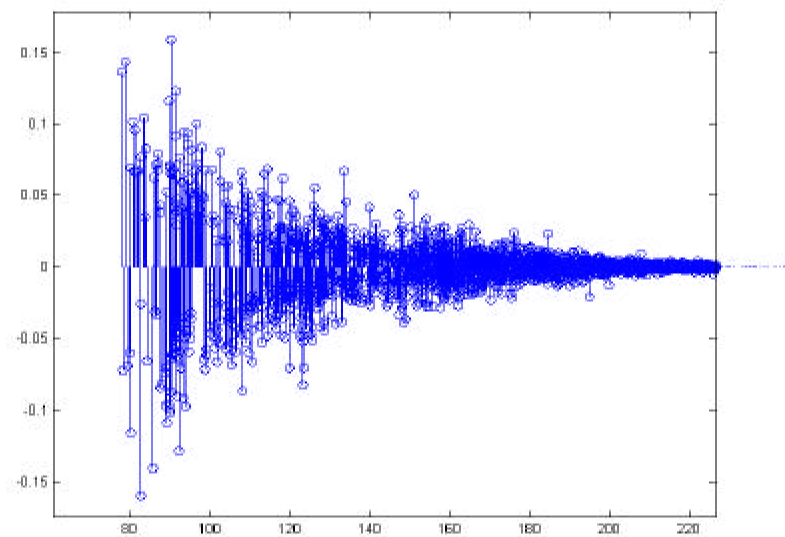
Example: Band 4 dropped

Solution for Nearby Interfering Piconet & Multiple Piconets in Extreme Multipath

- TF codes provide 17dB code isolation between channels in freespace
- In extreme situations, additional isolation required
- Activate FDMA (frequency division multiple access) strategy
- Continue using same TF codes
- Return to TFMA when conditions permit

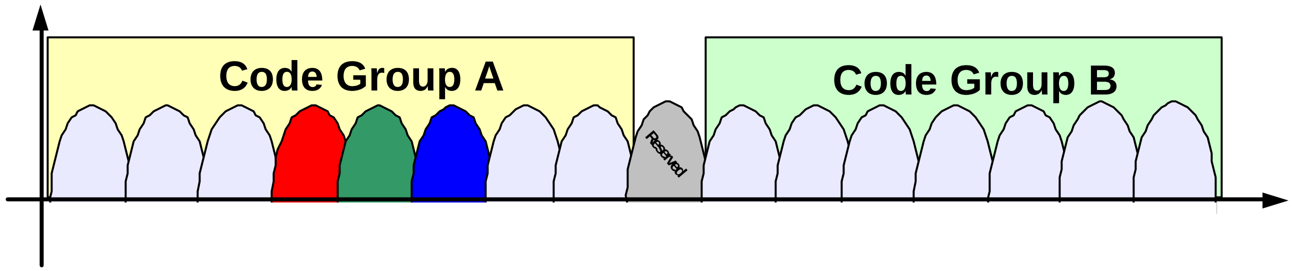


Near-Far Conditions



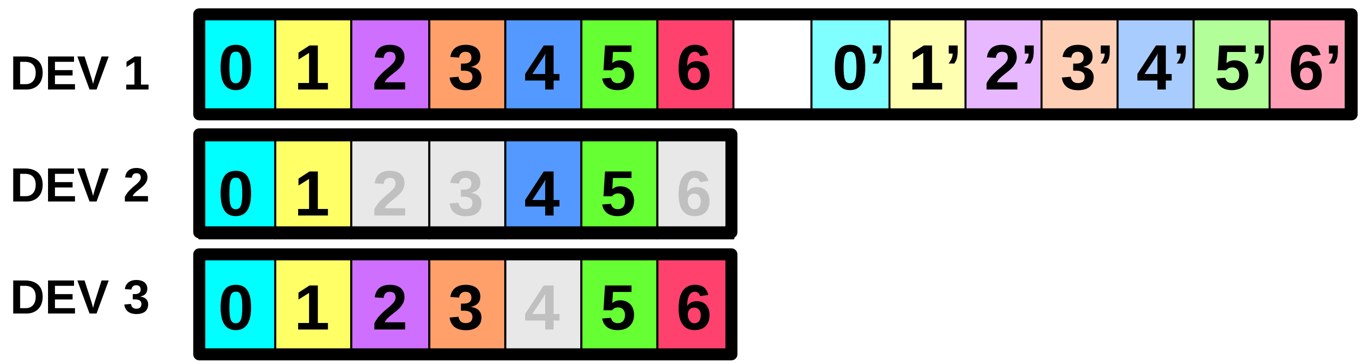
CM4 CIR Plot (Example)

Scalability: Very High Data Rates



- Codes are re-used in upper frequency group
- Enables 14-band DEVs allowing > 1 GHz raw data rate
- Requires transmission and reception of two bands simultaneously

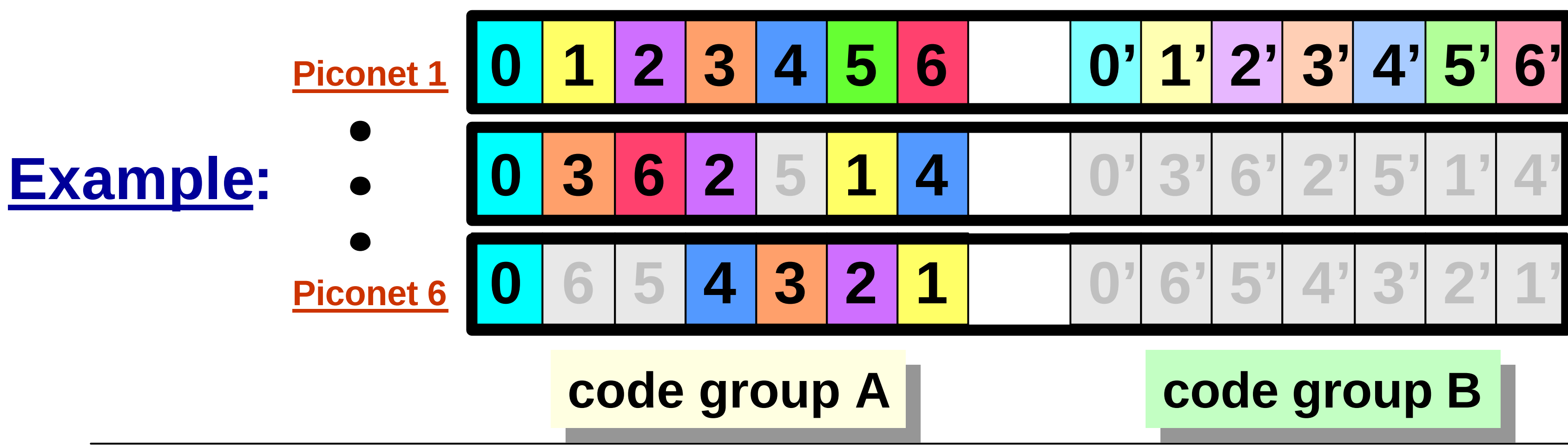
Scalability & Flexibility:
Within a Piconet



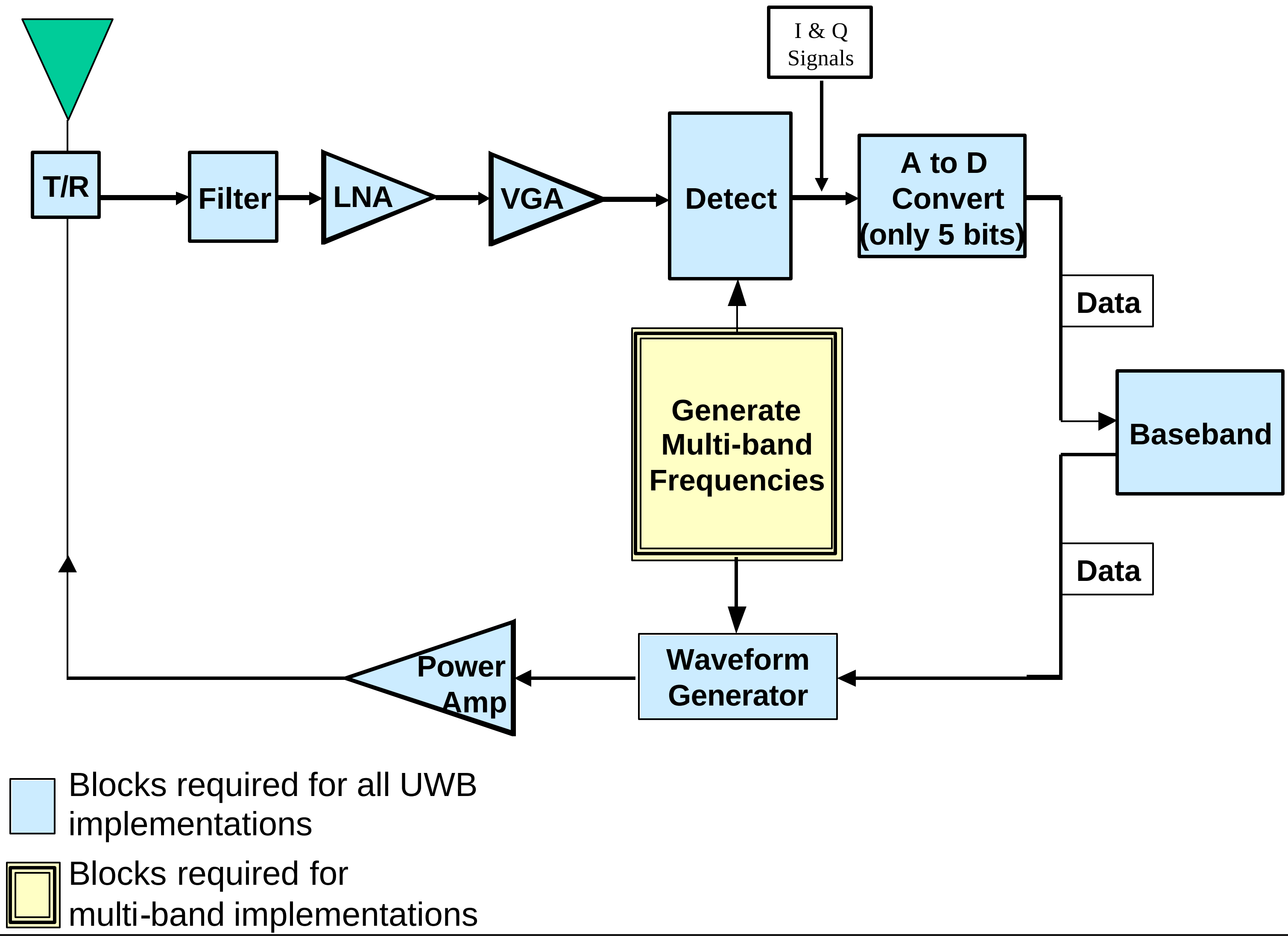
- Signaling design enables DEVs of different capability within a piconet to communicate
- Band assessment, negotiation easily enabled via minimal MAC supplements
- Enables products of varying capabilities to be tailored for different applications

Scalability:
Uncoordinated Piconets

- Code collision property holds for 14 bands
  - 1 collision in 7; 2 in 14
- Each piconet is independently configured
- Reconfiguring a given piconet does not adversely affect the other piconets



Example Implementation



Supporting Text Key Points Not Covered in Presentation

- Acquisition performance and timeline
- MAC enhancements
- Power consumption
- Packet definition
- More extensive analysis & simulation results

Summary Performance Results from Selection Criteria

- Link budget
- System Performance
- Simultaneous Operating Piconets
- Coexistence
- Interference Susceptibility
- Power Consumption
- Regulatory Impact

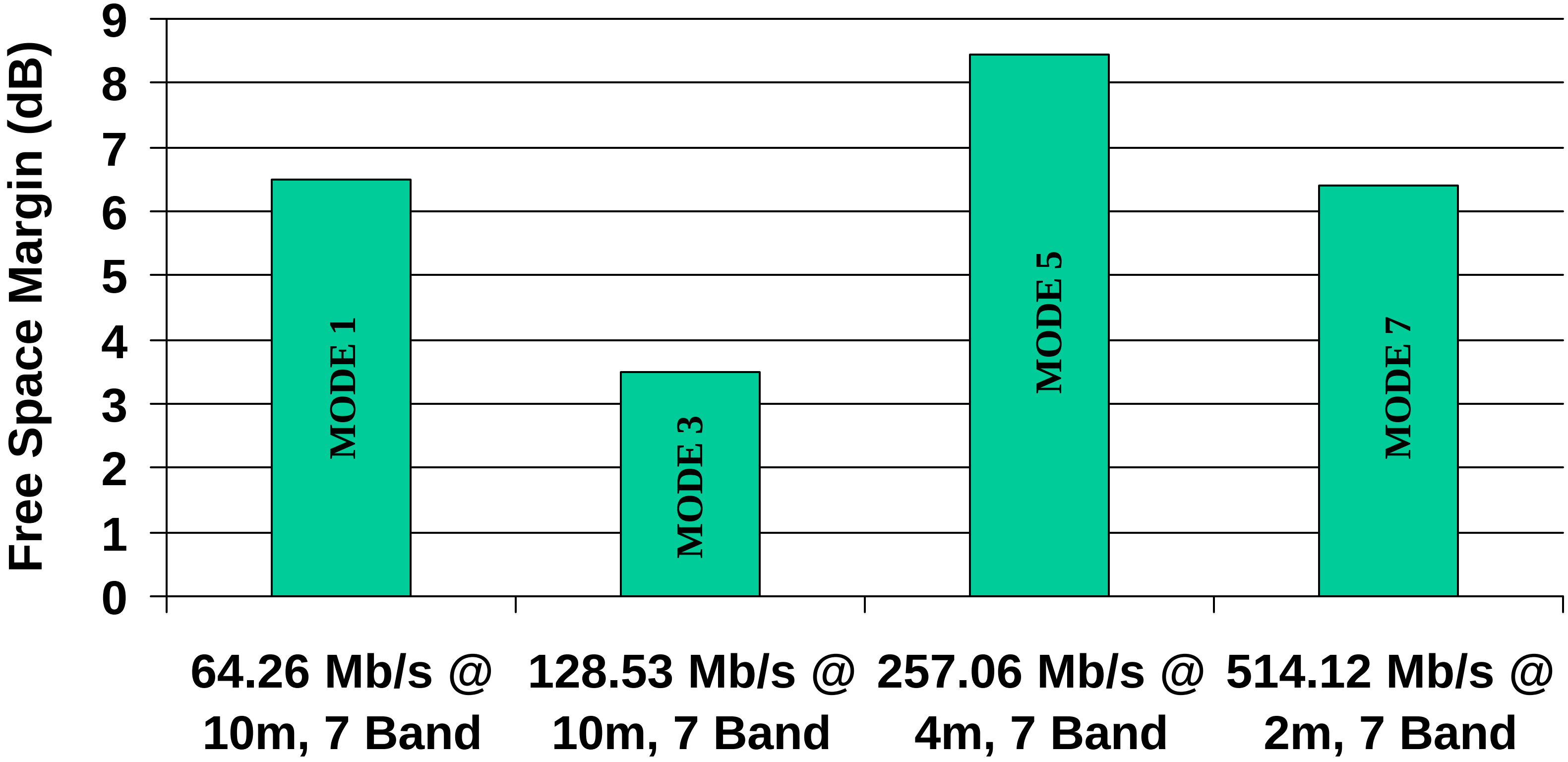
Link Budget

- Determine free space AWGN link budget margin for Multi-band radio
- Noise figure estimated at 7 dB
- Implementation loss estimated at 5 dB
- Receiver sensitivity is dependent on modulation type
- Data rates as high as 294 Mb/s for 4 band radio, 514 Mb/s for 7 band radio, and 1 Gb/s for 14 band radio

Link Budget Margin
7 Bands

Index	Modulation Scheme	Number of Bands	Payload Bit Rate	Link Budget Margin
0	BPSK, No FEC, no time integration, integrate all frequency bands	7	36.72	6.01 dB @ 10 m
1	BPSK, ½ rate FEC, time integration = 2, no frequency integration	7	64.26	6.50 dB @ 10 m
2	QPSK, ¾ rate FEC, no time integration, integrate all frequency bands	7	55.08	7.85 dB @ 10 m
3	BPSK, ½ rate FEC, no time integration, no frequency integration	7	128.53	3.50 dB @ 10 m
4	BPSK, ¾ rate FEC, no time integration, no frequency integration	7	192.79	8.20 dB @ 4 m
5	QPSK, ½ rate FEC, no time integration, no frequency integration	7	257.06	8.44 dB @ 4 m
6	QPSK, ¾ rate FEC, no time integration, no frequency integration	7	385.60	5.19 dB @ 4 m
7	QPSK, no FEC, no time integration, no frequency integration	7	514.12	6.41 dB @ 2 m

Link Budget Margin
7-Band Radio



Simulator Description

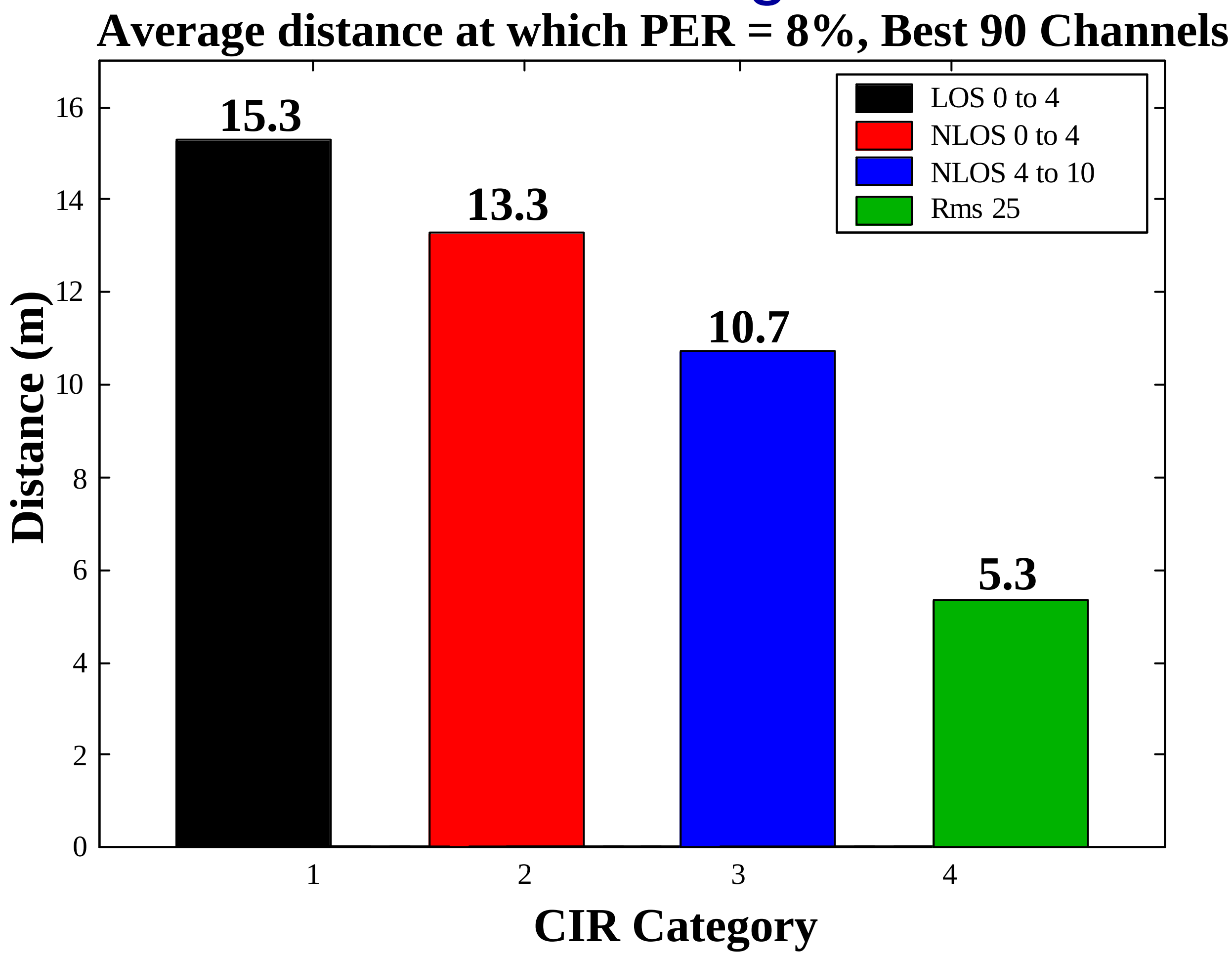
- **Operates primarily in the time domain**
- **Signals sampled at 100GHz**
- **Packet-oriented, i.e. for each packet**:
  - Adjusts gain
  - Thresholds preamble to acquire, characterizes received signal for demodulation
  - Demodulates and check-sums Header and Payload
  - Decodes using Viterbi algorithm
- **Describes an implementation model, not an ideal mathematical model**:
  - **7 dB Noise Figure**
  - **ADC Quantization (5 bits)**
  - **Real-time AGC algorithm**
  - **Signal compression**
  - **Realistic receive templates**
  - **Non-ideal channel estimation**
  - **Limited data-path precision**
  - **Phase errors**

System Performance

- Objective is to measure single-link performance in multipath
- Results simulated for all 400 CIRs in CMs 1-4
  - 10 distances simulated per CIR (from 24 m to 1 m)
  - 200 packets/run
  - 1024 octet payload
  - Results represent simulation of over 10 Gbits data
- Results presented for
  - 128 Mb/s and 257 Mb/s operation
  - No RAKE and two-finger RAKE

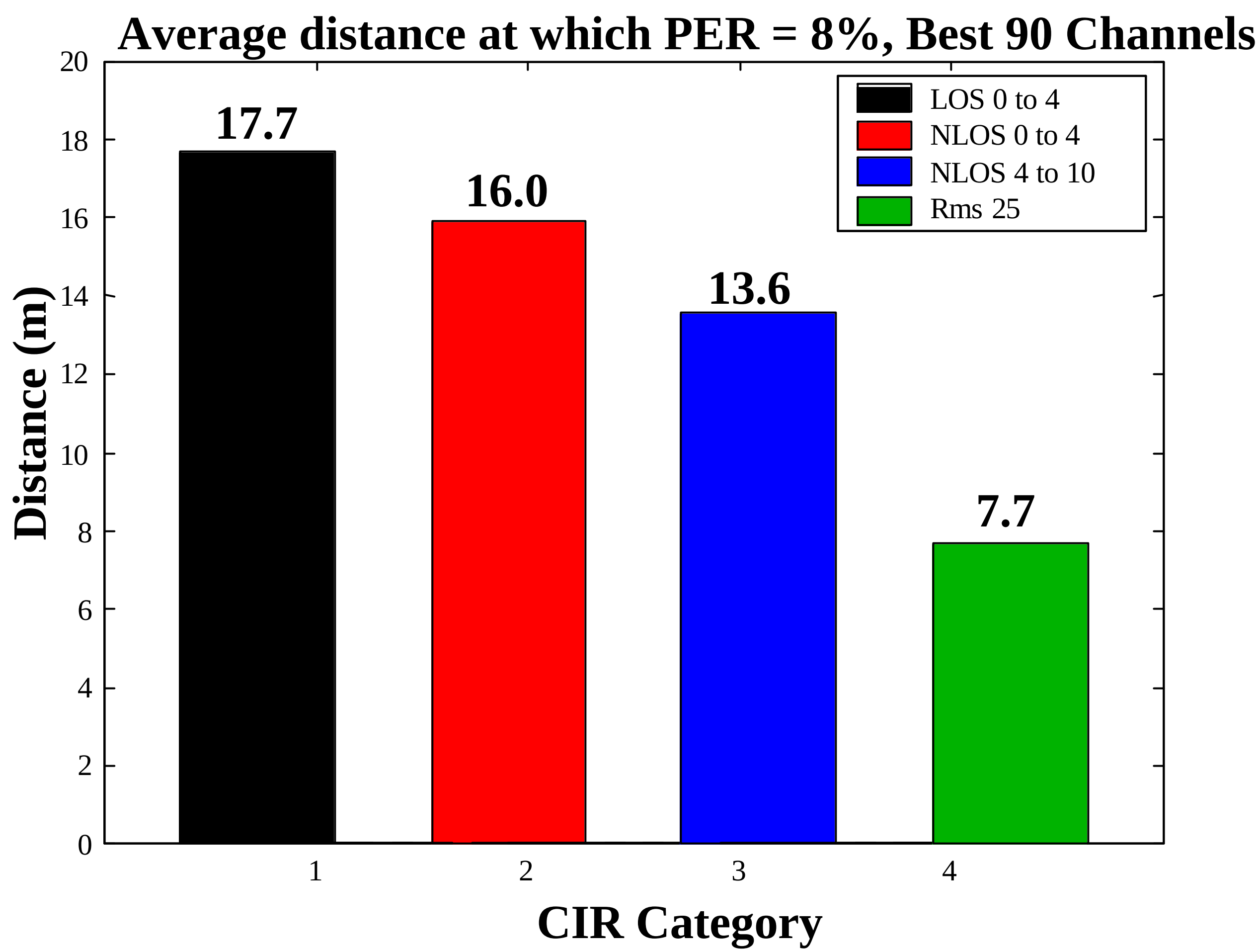
System Performance
128.4Mb/s - One Rake Finger

- 7 bands (skips UNII band)
- 100 CIR's from each of CM1 – CM4
- 200 packets
- 7dB Noise Figure
- Path-loss exponent of 2.0 in all cases
- BPSK, ½-rate FEC
- No rake



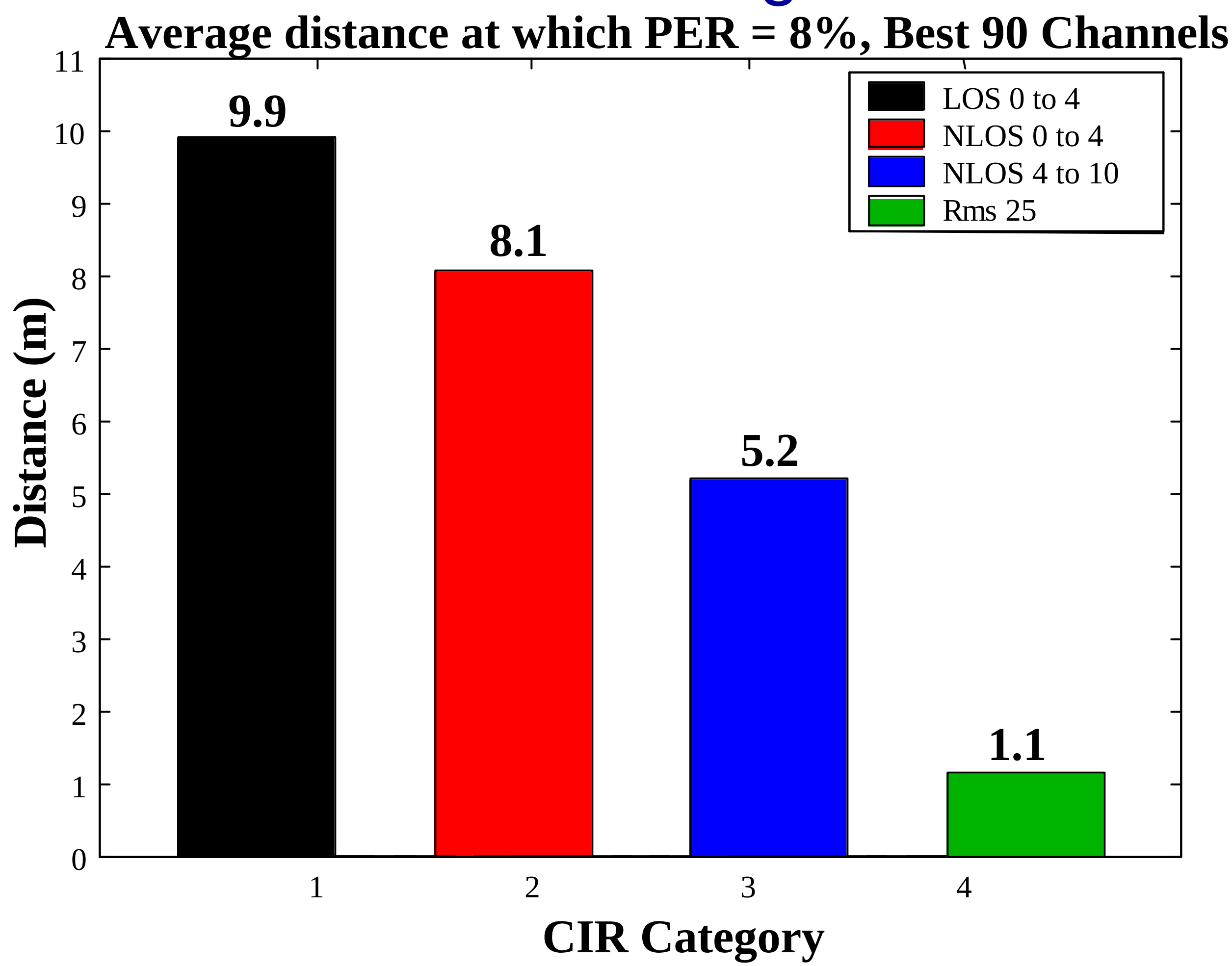
System Performance
128.4Mb/s – Two Rake Fingers

- 7 bands (skips UNII band)
- 100 CIR's from each of CM1 – CM4
- 200 packets
- 7dB Noise Figure
- Path-loss exponent of 2.0 in all cases
- BPSK, ½-rate FEC
- 2 Rake teeth



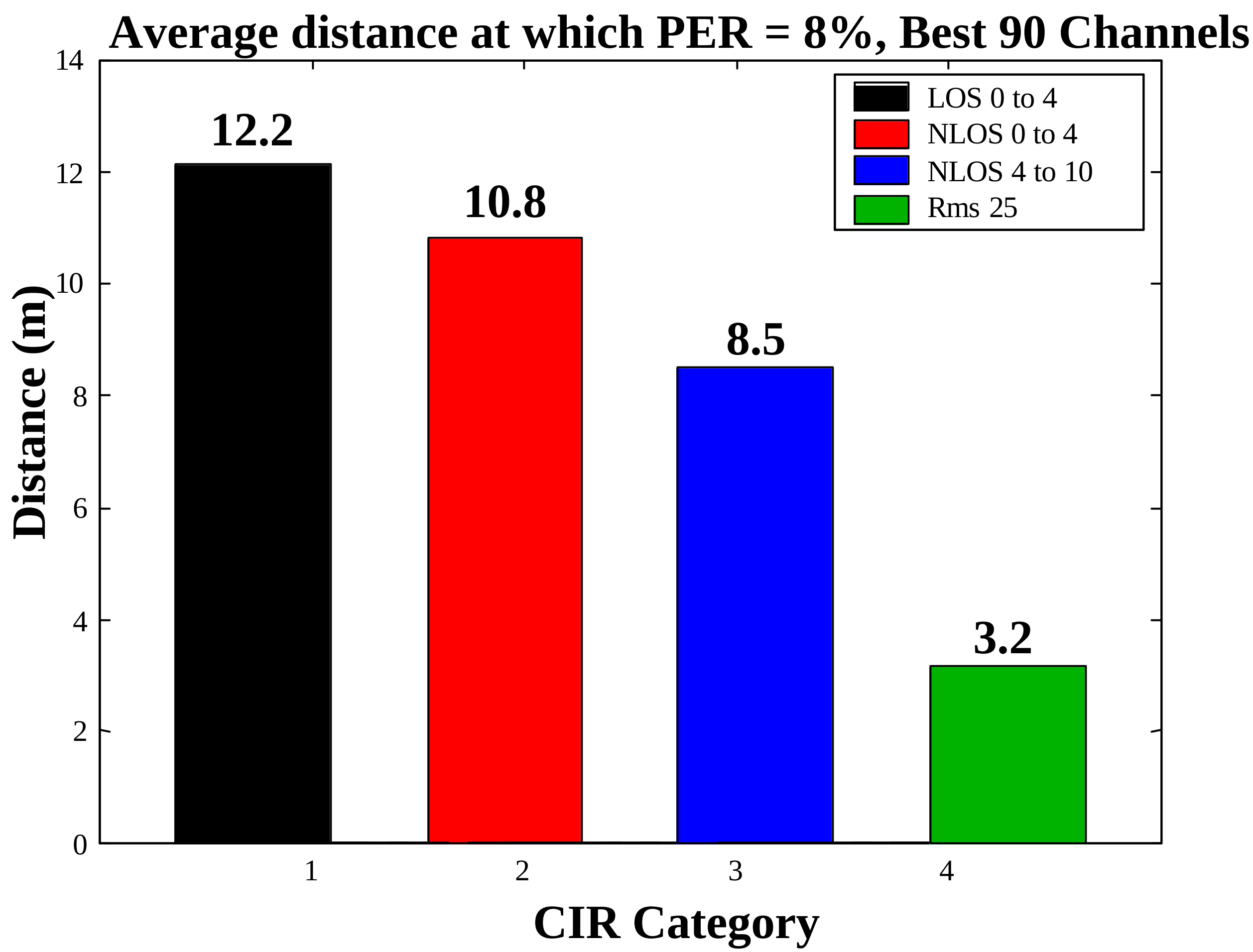
System Performance
256.7Mb/s – One Rake Finger

- 7 bands (skips UNII band)
- 100 CIR's from each of CM1 – CM4
- 200 packets
- 7dB Noise Figure
- Path-loss exponent of 2.0 in all cases
- QPSK, ½-rate FEC
- No rake



System Performance
256.7Mb/s – Two Rake Fingers

- 7 bands (skips UNII band)
- 100 CIR's from each of CM1 – CM4
- 200 packets
- 7dB Noise Figure
- Path-loss exponent of 2.0 in all cases
- QPSK, ½-rate FEC
- 2 Rake teeth



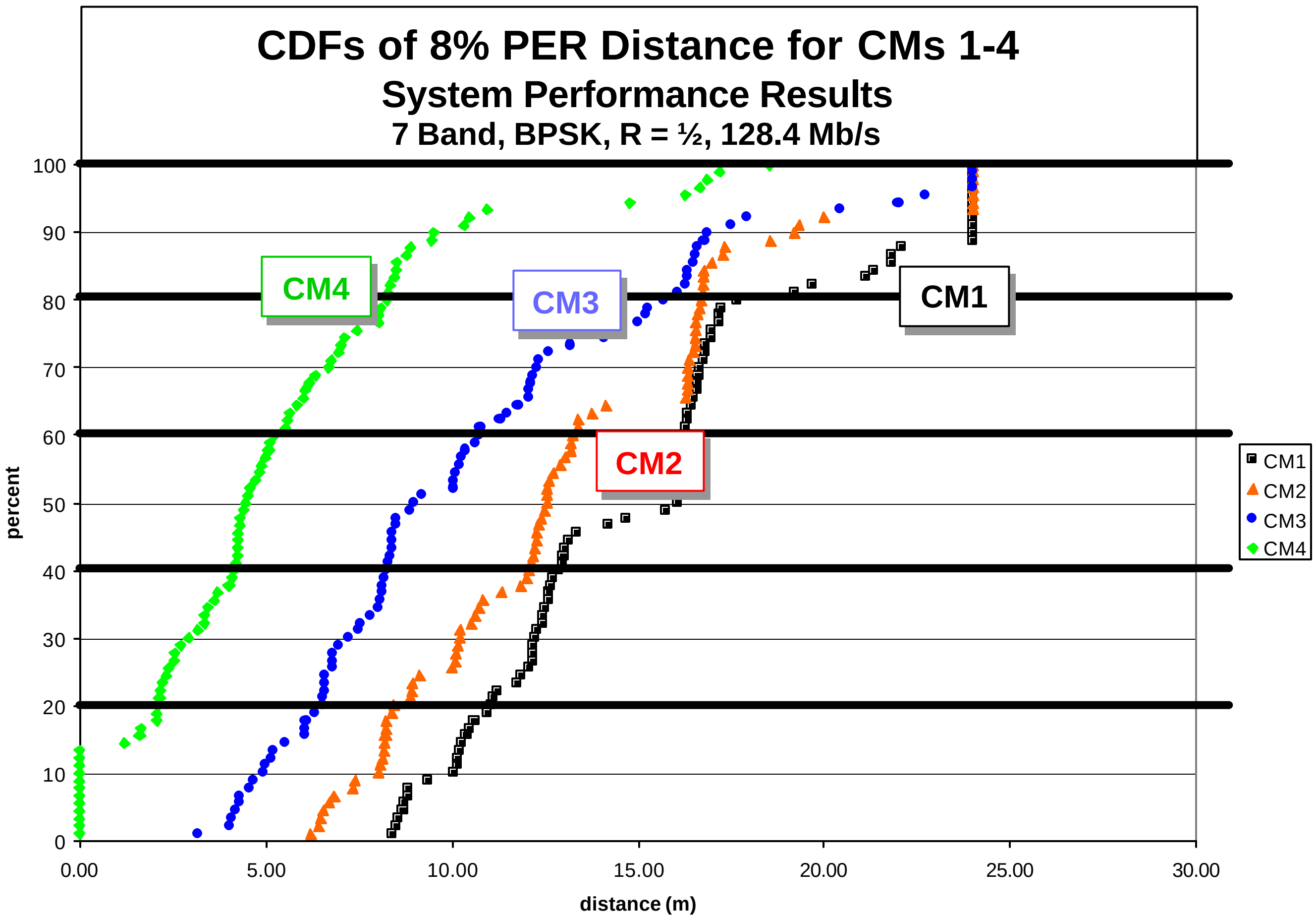
Simultaneously Operating Piconets

- **Objective is to evaluate uncoordinated piconet channelization in multipath**
- **N = 1 interferer case examined here**
- **Five different sets of CIRs for the reference link are being used:**
  - Freespace
  - To make simulation times feasible, representative channels from CMs 1-4 were chosen based on the quintiles of System Performance results:
    - **CM1 representatives**
      - CIRs 3, 59, 83, 81, and 40
    - **CM2 representatives**
      - CIRs 8, 56, 42, 31, and 58
    - **CM3 representatives**
      - CIRs 26, 39, 11, 60, and 62
    - **CM4 representatives**
      - CIRs 64, 79, 18, 52, 57

- **These representative channels were used as the reference links for the SOP simulations**
- **The quality of the reference link will impact SOP performance. This procedure allows us to quantify the effect.**

Choosing the Reference Channels

- Choice based on System Performance Results
- Link distance at which 8% PER was attained is recorded for each CIR in each CM.
- CDF of the 8% PER distance constructed
- Representative channels from each CM are the quintiles of the corresponding CDF

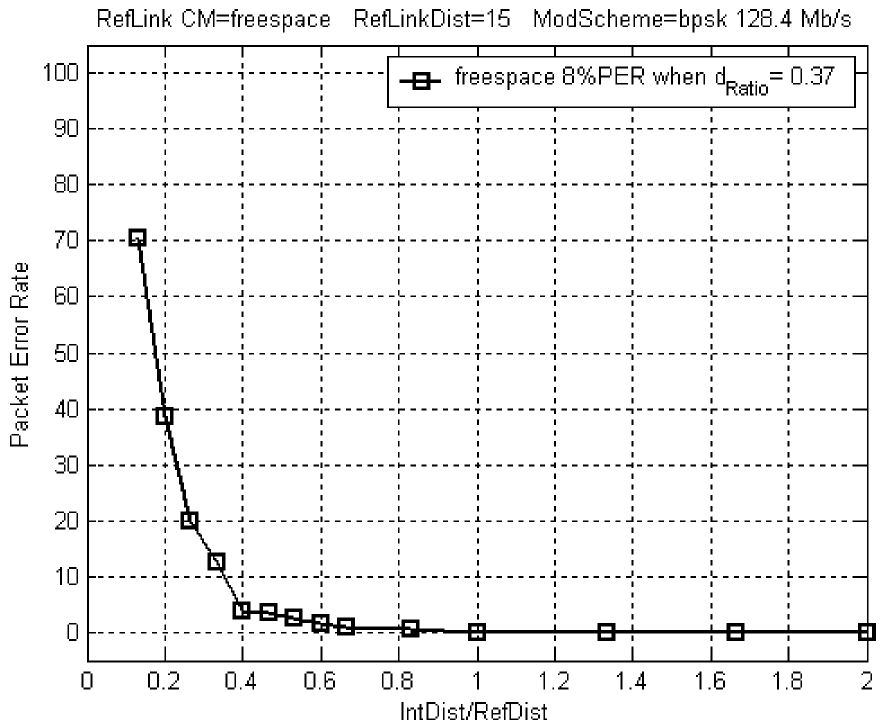


Simultaneously Operating Piconets

- **Freespace reference link simulated against all 300 CIRs from CMs 1-3 as the interfering links.**
- **All other representative reference links were simulated against 60 interfering links from channel models 1-4.**
  - 15 links from each of channel models 1-4.
- **Reference link distance is set at half the 8% PER distance (providing notionally a 6 dB margin).**
- **Interfering link is walked in.**
- **PER is recorded as a function of the ratio of the interfering link distance to the reference link distance.**

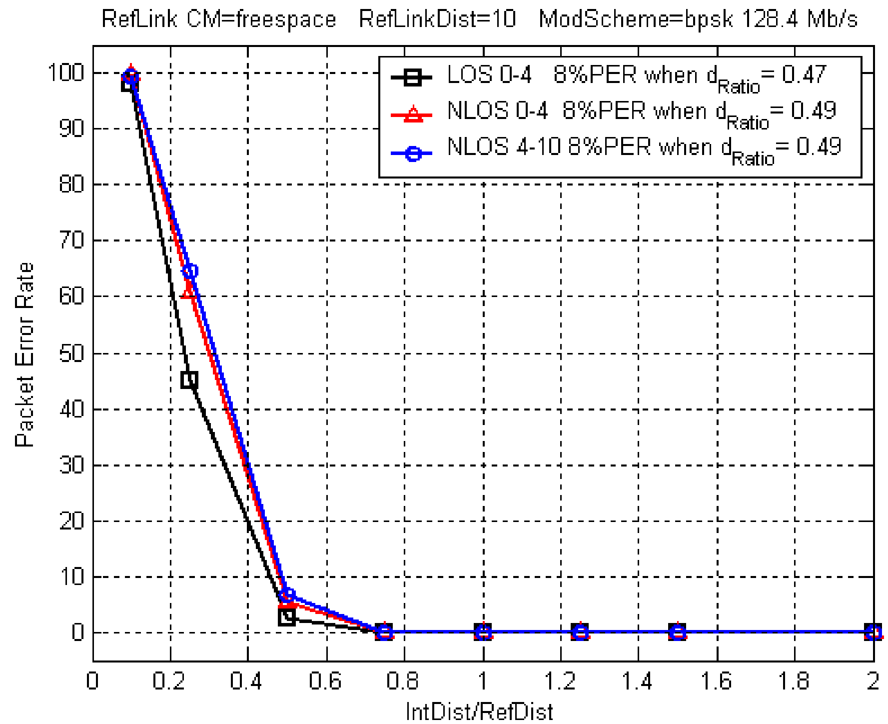
Simultaneously Operating Piconets
N = 1 interferer

Num. Bands	**7**
Modulation	**BPSK, ½-rate FEC**
Data Rate	**128.5 Mb/s**
Reference Link	**freespace**
Interfering Links	**freespace**



Simultaneously Operating Piconets
N = 1 interferer

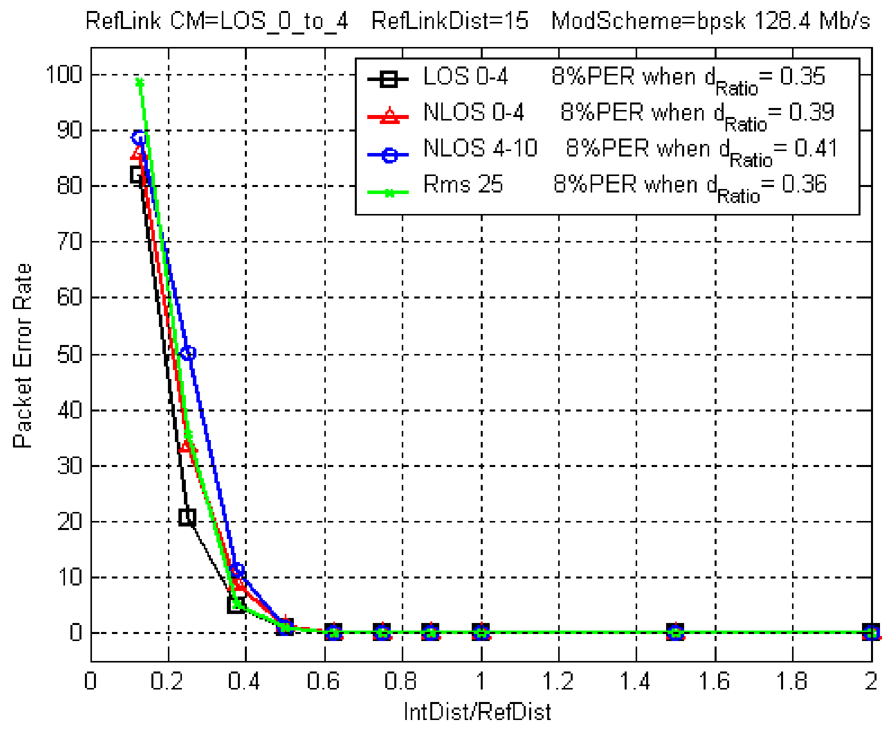
Num. Bands	**7**
Modulation	**BPSK, ½-rate FEC**
Data Rate	**128.5 Mb/s**
Reference Link	**Freespace, 10 m**
Interfering Links	**All CIRs in CMs 1-3**



Average performance in CMs 1-3

Simultaneously Operating Piconets
N = 1 interferer

Num. Bands	**7**
Modulation	**BPSK, ½-rate FEC**
Data Rate	**128.5 Mb/s**
Reference Link	**CM1, CIR 3**
Interfering Links	**CMs 1-4, CIRs 11-25**

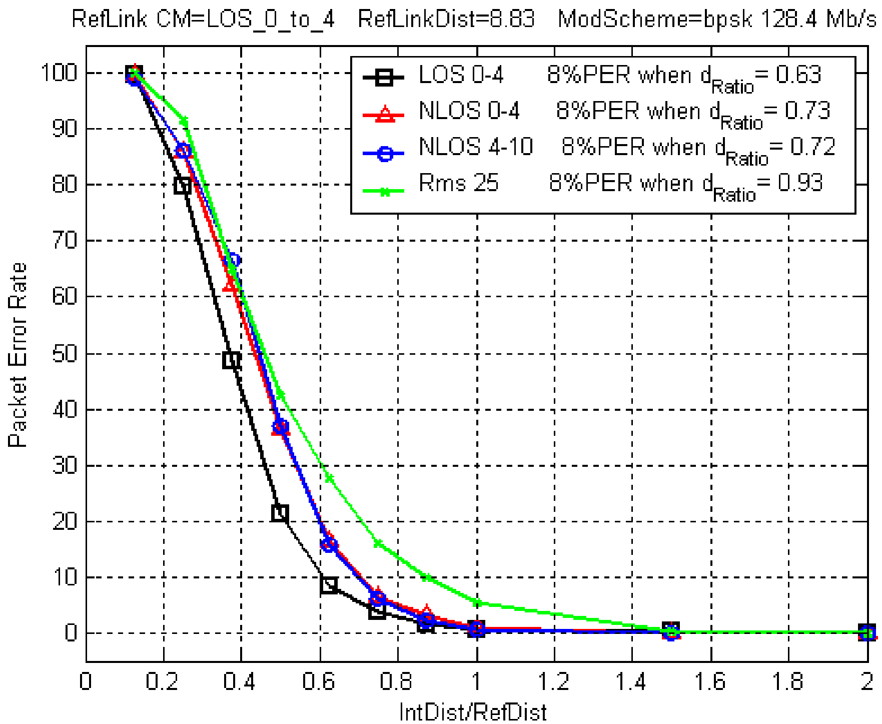


100th percentile System Performance CIR

Average performance in CMs 1-4, CIRs 11-25

Simultaneously Operating Piconets
N = 1 interferer

Num. Bands	**7**
Modulation	**BPSK, ½-rate FEC**
Data Rate	**128.5 Mb/s**
Reference Link	**CM1, CIR 59**
Interfering Links	**CMs 1-4, CIRs 1-15**

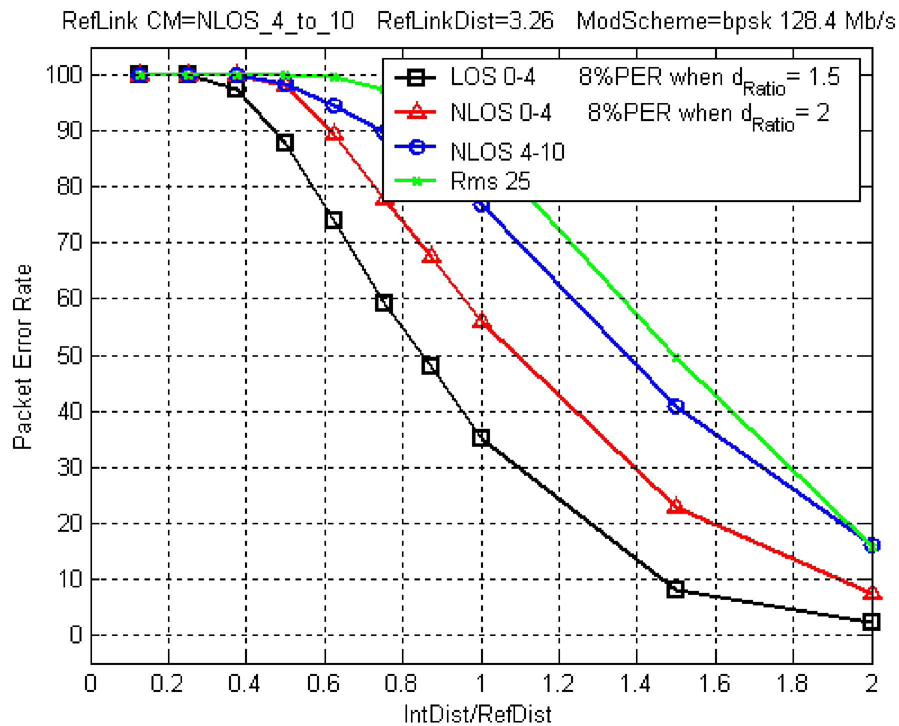


80th percentile System Performance CIR

Average performance in CMs 1-4, CIRs 1-15

Simultaneously Operating Piconets
N = 1 interferer

Num. Bands	**7**
Modulation	**BPSK, ½-rate FEC**
Data Rate	**128.5 Mb/s**
Reference Link	**CM3, CIR 62**
Interfering Links	**CMs 1-4, CIRs 81-95**



20th percentile System Performance CIR

Average performance in CMs 1-4, CIRs 81-95

Interpretation of SOP results

- Quality of reference link has more impact on SOP performance than nature of interfering channel:

Average 8% PER Distance Ratios from Simultaneously Operating Piconet Test

Ref. link / Sys. Perf. Rank	Reference link from …		
	CM1	CM2	CM3
100th percentile	0.38	0.64	0.60
60th percentile	1.4	1.15	1.63
20th percentile	1.65	1.55	----

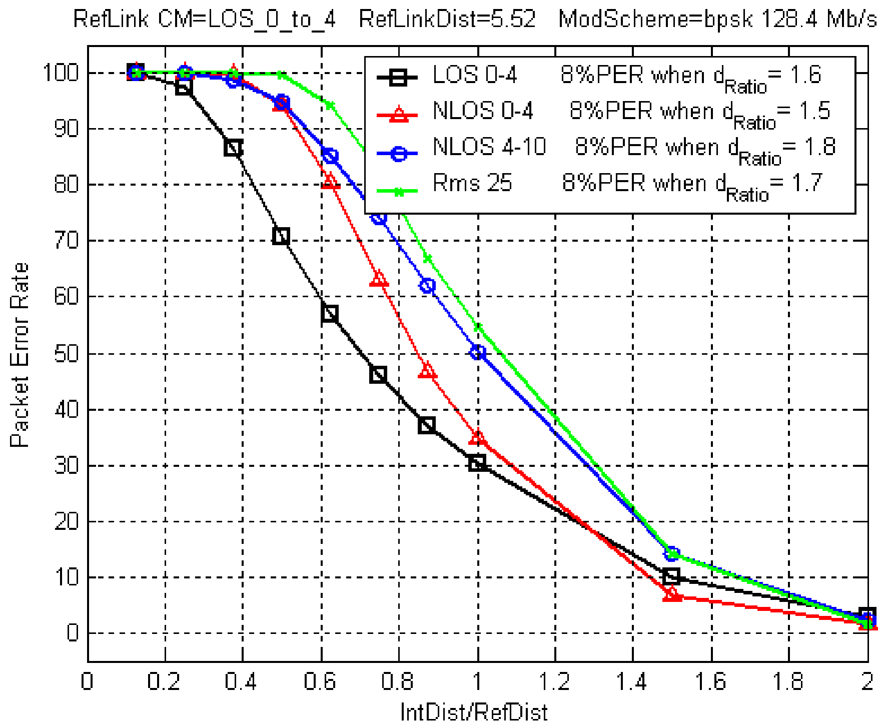
Strategies for Enhanced Channelization in Harsh Environments

- For significant fading on bands, drop the faded bands
- For very severe multipath and/or near-far scenarios, use FDMA

➔Both strategies yield dramatic improvement in SOP performance

Performance **before** dropping weak bands…

Num. Bands	**7**
Modulation	**BPSK, ½-rate FEC**
Data Rate	**128.5 Mb/s**
Reference Link	**CM1, CIR 40**
Interfering Links	**CMs 1-4, CIRs 81-95**

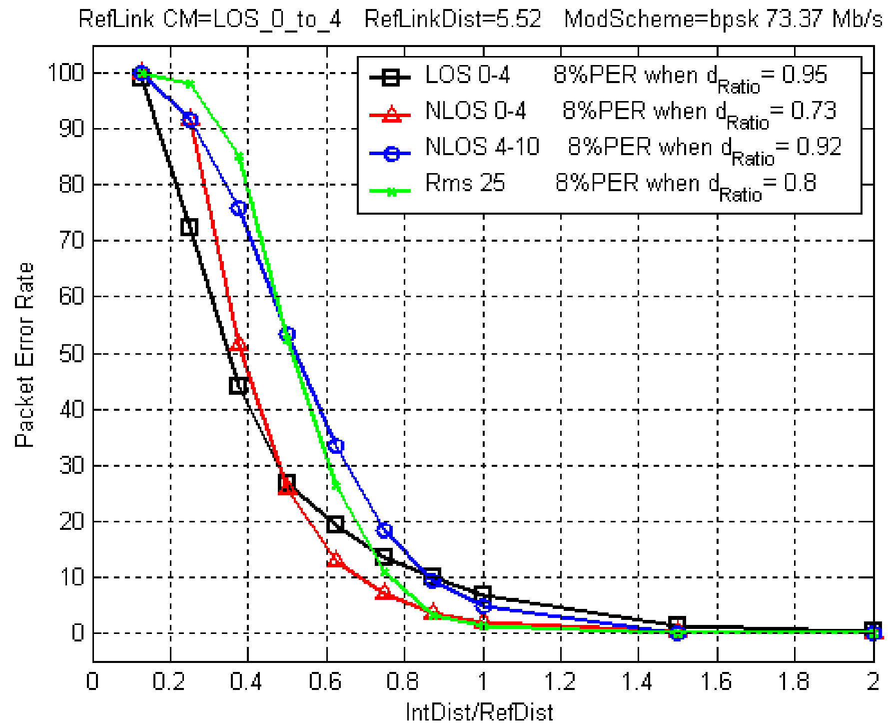


20th percentile System Performance CIR

Average performance in CMs 1-4, CIRs 81-95

Performance **after** dropping weak bands…

Num. Bands	**4 (0, 2, 6, 7)**
Modulation	**BPSK, ½-rate FEC**
Data Rate	**73.4 Mb/s**
Reference Link	**CM1, CIR 40**
Interfering Links	**CMs 1-4, CIRs 81-95 (interferer still transmitting on all bands)**



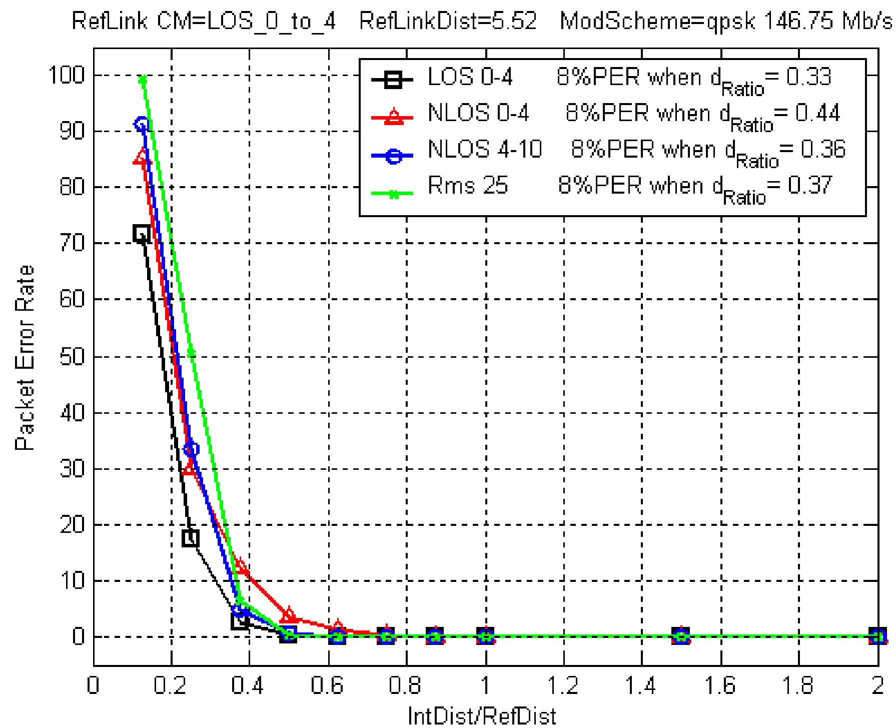
20th percentile System Performance CIR

- SOP performance now comparable to 80th percentile CIR

Average performance in CMs 1-4, CIRs 81-95

Performance **after** FDMA…

Num. Bands	**4 (0, 2, 6, 7)**
Modulation	**BPSK, ½-rate FEC**
Data Rate	**146.75 Mb/s**
Reference Link	**CM1, CIR 40**
Interfering Links	**CMs 1-4, CIRs 81-95 (interferer transmitting on bands 1, 3, 5)**



20th percentile System Performance CIR

- SOP performance now comparable to 100th percentile CIR

Average performance in CMs 1-4, CIRs 81-95

Simultaneous Operating Piconet Simulation Results Summary

- Time-frequency codes as implemented provide 8-10 dB of isolation between piconets in freespace.
- Multipath will decrease piconet isolation.
- Piconet isolation is enhanced by dropping severely faded bands in a multipath environment.
- FDMA techniques are employed in near/far and severe multipath scenarios.

Coexistence

- Determined 802.15.3a impact to 802.11a, 802.11b, 802.15.1, 802.15.3, and 802.15.4
- Receiver impact based on AWGN analysis
- Minimize impact to selected wireless standards by modifying the FCC indoor/handheld emission mask
- Banded approach naturally reduces emissions in the selected bands thereby reducing the additional filtering needs in the 802.15.3a radio implementation

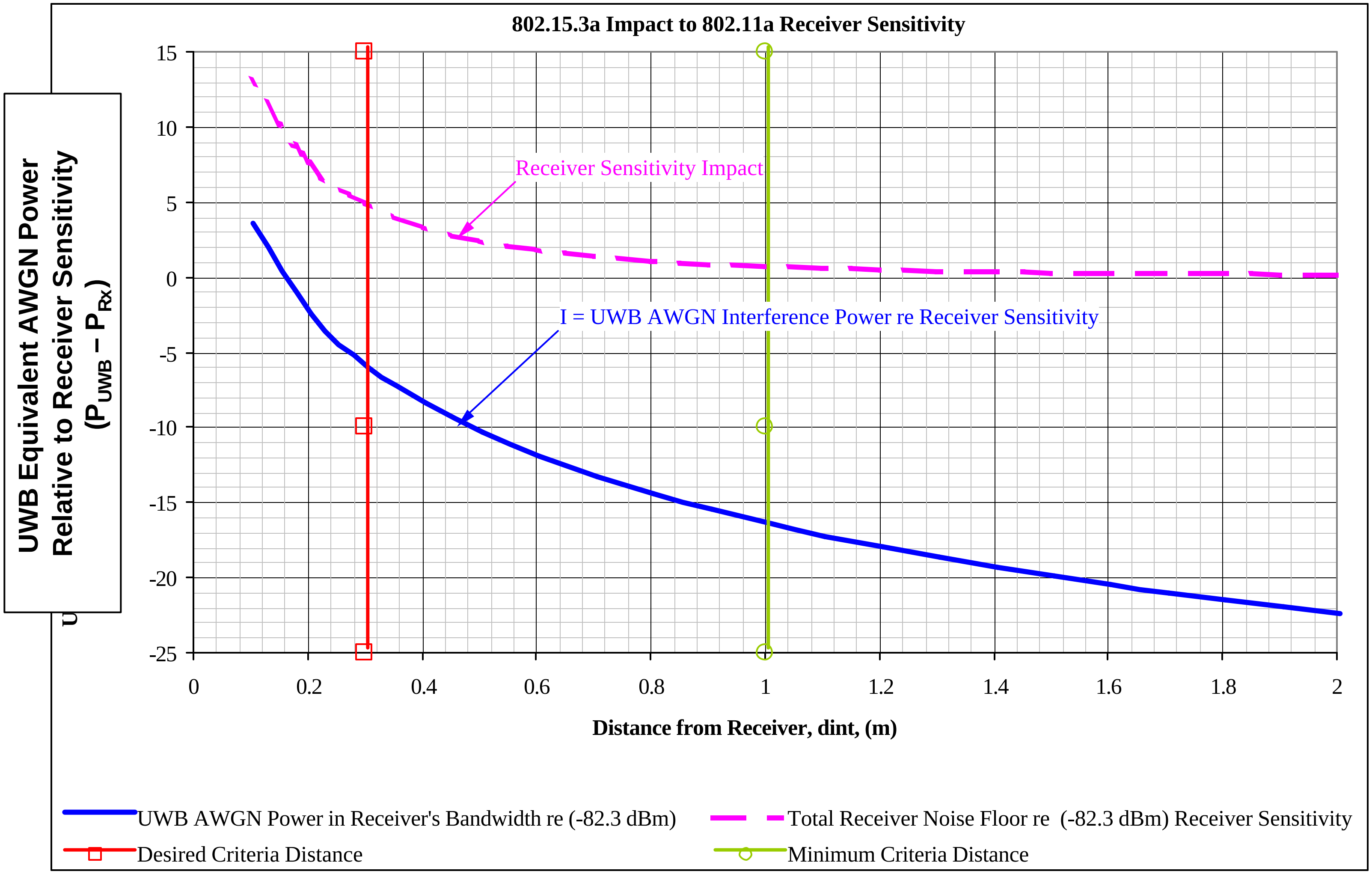
Coexistence Calculations

Wireless Service	**802.11b**	**802.15.1**	**802.15.3**	**802.15.4**	**802.11a**
Frequency of Operation (GHz)	2.4 - 2.484	2.4 - 2.484	2.4 - 2.484	2.4 - 2.484	5.15 - 5.35
Mod Type	DSSS CCK	GFSK	DQPSK	OQSPK	BPSK
Wireless Receive Antenna Gain (dBi)	0	0	0	0	0
Wireless Service Rec. NF (dB)	10	23	12	15	10
Wireless Service NBW (MHz)	22	1	12	2.5	16.6
$KT_{@25°C}$(dBm/MHz)	-174	-174	-174	-174	-174
Wireless Service Rec. Noise Floor (dBm)	-90.58	-91.00	-91.21	-95.02	-91.80
Data Rate (Mb/s)	11	1	22	0.25	6
Wireless Service Implementation Loss (dB)	4	3	4	5	5
Wireless Service Coding gain (dB)	0	0	0	5	5.1
Wireless Service BER	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05
Wireless Service Eb/No $_{@BER}$(dB)	10.6	18.0	12.0	10.0	9.6
Wireless Service Rec. Sensitivity (dBm) no UWB	**-75.98**	**-70.00**	**-75.21**	**-85.02**	**-82.30**
UWB EIRP (dBm/MHz) Minimum Criteria Mask (*1)	-61.3	-61.3	-61.3	-61.3	-53.8
UWB EIRP (dBm/MHz) Desired Criteria Mask (*1)	-65.9	-65.9	-65.9	-65.9	-64.3
FCC Handheld UWB EIRP Limit (dBm/MHz)	-61.3	-61.3	-61.3	-61.3	-41.3
Wireless Service Rec. Sensitivity (dBm) with Minumum Criteria UWB	**-71.44**	**-69.62**	**-71.86**	**-83.03**	**-77.35**
Wireless Service Rec. Sensitivity (dBm) with Desired Criteria UWB	**-66.89**	**-68.68**	**-67.82**	**-79.91**	**-77.38**

Notes:

*1) The EIRP density values are the smallest values of a comparison between the FCC handheld limit and the individual wireless service coexistence calculations.

Coexistence with IEEE 802.11a



Interference Susceptibility Analysis

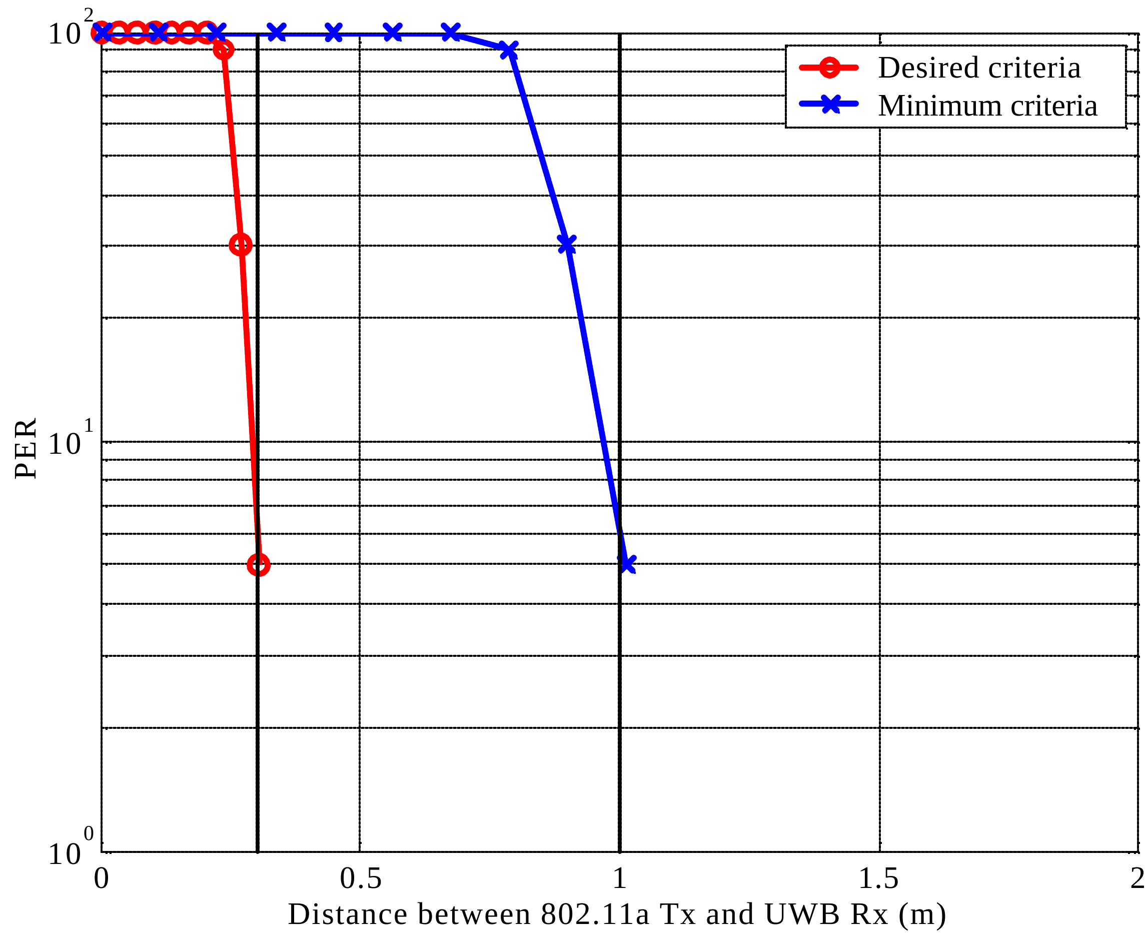
- IEEE 802.11 a, IEEE 802.11 b, IEEE 802.15.4, Bluetooth and Microwave oven
  - Interference models were incorporated into the simulator and analog front-end attenuation factors were determined for each interferer
  - The simulations were carried out using a receiver template with a rectangular envelope
  - Signal linearity with very wide dynamic range was assumed
  - Simulation results using an analog front-end filter and with mixer limitations will be presented in May

- Generic In-Band Tone and Modulated Interferers
  - Interference models were incorporated into the simulator and the received power of the interferer was varied for different center frequencies
  - There was a good correspondence between the receiver template frequency response at the center frequency of the interferer and the observed performance
  - The analysis was done assuming the sub-band overlapping with the interferer will not be used
  - The effect of not dropping the overlapping sub-band was also analyzed

Interference Susceptibility due to IEEE 802.11a Interferer

Attenuation requirements for the Analog Front-End

- 25 dB for Minimum criteria
- 35.4 dB for Desired criteria



Power consumption

Power Mode	Activity	Power Consumption
Idle	On state awaiting Tx and Rx commands	100 mW
Tx/Rx Prep	Preparing for Tx or Rx, programming registers	80 mW
Active Rx	Receiving @ 128.5 Mbit/sec	275 mW
Active RX	Receiving @ 257 Mbit/sec	325 mW
Active Tx	Transmitting (any data rate)	190mW
CCA	Clear channel assessment	225 mW
Power save	Power save mode	20 mW

Regulatory impact

- Banded radio flexibility can accommodate regulatory requirements of virtually any geopolitical region
- Radio will conform to all regions adopting US UWB regulations.
- Radio will meet projected regulatory requirements of Europe and Japan.

Conclusions

- Time Domain's Proposal
  - Is FCC compliant
  - Achieves data rate and range requirements
  - Enables low cost, low power solution
  - Exceeds channelization (6 channels)
  - Supplies robustness mechanisms for harsh environments
  - Provides flexibility in spectrum use
  - Defines growth path via number of bands
  - Requires minimal MAC supplements

Our multi-band approach enables a world-wide UWB WPAN standard that is scalable, flexible, and durable.

802.15.3a Early Merge Work

Time Domain will be cooperating with:

Intel	Wisair
Discrete Time	Philips
General Atomics	FOCUS Enhancements

Objectives:

- **“Best” technical solution**
- **ONE solution**
- **Excellent business terms**
- **Fast time to market**

We encourage participation by any party who can help us reach these goals.