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

Submission Title: Time Domain Supporting Text for 802.15.3 Alternate Physical Layer Proposal
Date Submitted: 3 March 2003
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Re: IEEE P802.15 Alternate PHY Call For Proposals (802.15.3-02/372r8, January 17, 2003)

Abstract: This document provides details supporting material for Time Domain's proposed alternate PHY for 802.15.3.

Purpose: This document further defines and clarifies IEEE P802.15-03/143.

TIME DOMAIN

Proposal for Alternate Physical Layer for 802.15.3

Contents

- Executive Summary
- Introduction
- PHY Proposal
- Scalability and Flexibility
- MAC Enhancements
- Performance
- Implementation Considerations
- Requirements Verification
- Conclusion

- **Executive Summary**
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Executive Summary

- Time Domain's UWB Multi-band approach is a viable solution for the high data rate PAN application
  - Flexible and adaptable to various regulatory and RF environments
  - Scalable to >1 Gb/s as silicon technology matures
- Supports or exceeds key technical requirements
  - Smooth a growth path to very high data rates
  - Provides 6 uncoordinated piconet channels
  - Minimal impact to 802.15 MAC
  - Low-cost implementation
  - Low power consumption

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Key Solution Requirements

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

Overview of Proposed Solution

- UWB Solution
- Multi-banded UWB
- Time Frequency Multiple Access (TFMA) Codes
- BPSK and QPSK Modulation
- Convolutional Encoding for FEC

Key Features of Proposed 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

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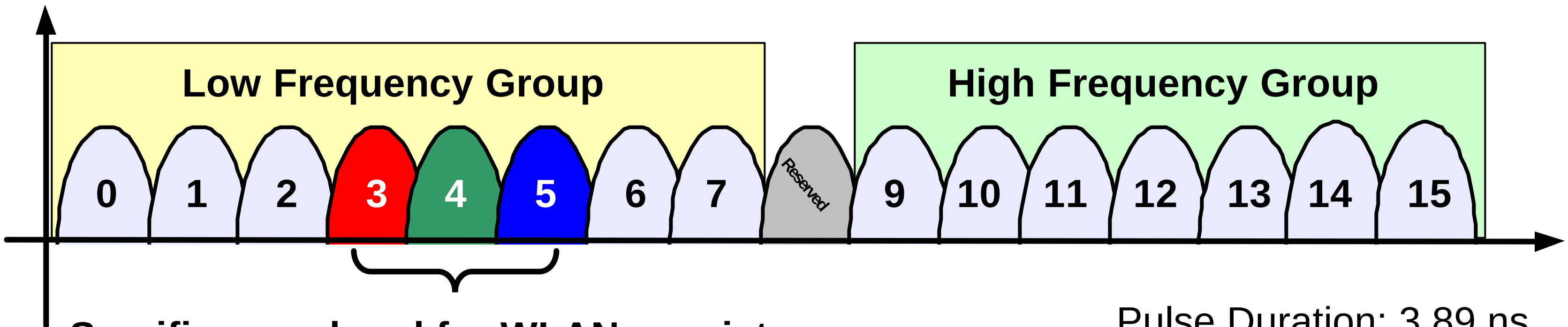
Multi-Band Approach

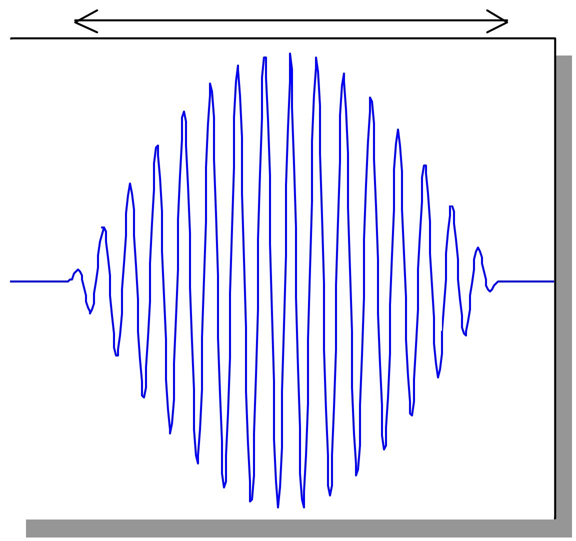
- Available spectrum divided into ~500-MHz UWB bands
  - Frequency agility for interference mitigation
  - Regulatory flexibility
  - Adds another dimension for coding
  - TFMA (Time-Frequency Multiple Access) for uncoordinated piconet channelization
  - Basic BPSK/QPSK modulation in each band
  - Convolutional encoding for FEC

Flexible Spectrum Use



Sacrifice one band for WLAN coexistence (dependent upon geographical location)

Pulse Duration: 3.89 ns



- Rectified cosine envelope
- ~520 MHz bands to best utilize spectrum
- 437 MHz band separation
- 257.0 MHz chip rate
  - 3.89 ns chip duration
- Adjacent band isolation: ~ 12 dB
  - Second band over is ~ 21 dB down
- Center frequencies chosen for ease of implementation

Band-Plan and Scalability

Low frequency group

Band number		
0	Low Frequency	3.236 GHz
	Center Frequency	3.496 GHz
	High Frequency	3.756 GHz
1	Low Frequency	3.673 GHz
	Center Frequency	3.933 GHz
	High Frequency	4.193 GHz
2	Low Frequency	4.110 GHz
	Center Frequency	4.370 GHz
	High Frequency	4.630 GHz
3	Low Frequency	4.547 GHz
	Center Frequency	4.807 GHz
	High Frequency	5.067 GHz
4	Low Frequency	4.984 GHz
	Center Frequency	5.244 GHz
	High Frequency	5.504 GHz
5	Low Frequency	5.421 GHz
	Center Frequency	5.681 GHz
	High Frequency	5.941 GHz
6	Low Frequency	5.858 GHz
	Center Frequency	6.118 GHz
	High Frequency	6.378 GHz
7	Low Frequency	6.295 GHz
	Center Frequency	6.555 GHz
	High Frequency	6.815 GHz

Sacrifice 1 band for WLAN coexistence (dependent upon geographical location) (bands 3, 4, 5)

8	Low Frequency	6.732 GHz
	Center Frequency	6.992 GHz
	High Frequency	7.252 GHz

This band is dedicated (reserved) for single band service.

High frequency "growth" group

Band number		
9	Low Frequency	7.169 GHz
	Center Frequency	7.429 GHz
	High Frequency	7.689 GHz
10	Low Frequency	7.606 GHz
	Center Frequency	7.866 GHz
	High Frequency	8.126 GHz
11	Low Frequency	8.043 GHz
	Center Frequency	8.303 GHz
	High Frequency	8.563 GHz
12	Low Frequency	8.480 GHz
	Center Frequency	8.740 GHz
	High Frequency	9.000 GHz
13	Low Frequency	8.917 GHz
	Center Frequency	9.177 GHz
	High Frequency	9.437 GHz
14	Low Frequency	9.354 GHz
	Center Frequency	9.614 GHz
	High Frequency	9.874 GHz
15	Low Frequency	9.791 GHz
	Center Frequency	10.051 GHz
	High Frequency	10.311 GHz

Piconet Coding: Overview

- **Based on time-frequency sequences (TFMA)**
- **Supports uncoordinated simultaneous piconet operation**
  - **Supports 6 distinct piconets at all data rates**
  - **Each piconet can use anywhere from 4 to 14 sub-bands**
  - **Interference between nearby piconets minimized via code design (1-collision property)**
- **Piconets can independently optimize their band selection (important for interference mitigation and channelization)**
  - **No coordination between piconets required**
- **Smooth growth path as more frequency bands are added**

Multiple Access with Uncoordinated Piconets

- **Code collisions between piconets minimized (1-in-7 collision property)**
- **Each piconet and DEV pair within a piconet can independently configure:**
  - How many bands to use
  - Which bands to use
- **Reconfiguring a given piconet does not adversely affect the other piconets**
- **No coordination between piconets needed**

Note: piconet assignments shown are not the only ones possible

Example:

	code group A								code group B						
Piconet 1	0	1	2	3	4	5	6		0’	1’	2’	3’	4’	5’	6’
Piconet 2	0	2	4	6	1	3	5		0’	2’	4’	6’	1’	3’	5’
Piconet 3	0	3	6	2	5	1	4		0’	3’	6’	2’	5’	1’	4’
Piconet 4	0	4	1	5	2	6	3		0’	4’	1’	5’	2’	6’	3’
Piconet 5	0	5	3	1	6	4	2		0’	5’	3’	1’	6’	4’	2’
Piconet 6	0	6	5	4	3	2	1		0’	6’	5’	4’	3’	2’	1’

Modulation and Error Correction

- BPSK, QPSK
- Convolutional encoding for FEC
  - Rates R = ½, ¾, 1
- Multi-band with simple BPSK/QPSK modulation enables straightforward weighting of individual bands in FEC soft decision
- Frequency integration
  - Each bit encoded on all bands within a time-frequency sequence wrap
- Time integration
  - Integrate multiple time-frequency sequence wraps

Payload Bit Rate

		Payload Bit Rate (Mb/s)		
Modulation Index	**Modulation Scheme**	**4-Bands**	**7-Bands**	**14-Bands**
0	BPSK, No FEC, Frequency integrate	36.7	36.7	36.7
1	BPSK, 1/2-Rate FEC, Time integrate x 2	36.7	64.3	128.5
2	QPSK, 3/4-Rate FEC, Frequency integrate	55.1	55.1	55.1
3	BPSK, 1/2-Rate FEC	73.4	128.5	257.1
4	BPSK, 3/4-Rate FEC	110.2	192.8	385.6
5	QPSK, 1/2-Rate FEC	146.9	257.1	514.1
6	QPSK, 3/4-Rate FEC	220.3	385.6	771.2
7	QPSK, No FEC	293.8	514.1	1028.2

- **Modulation Index 0 is the base-rate modulation**
  - **Used for all header/beacon/CAP signaling**

Frame Overview

- Same bands used for entire frame
  - Base-rate modulation for beacons and headers
  - Selectable payload bit rate
- No structural changes to existing 15.3 frame definition
  - Same MAC Header and HCS definitions
  - PHY Header data rate field mapped to modulation index
- Increased efficiency over 2.4-GHz PHY frame
  - Higher base-rate
  - Shorter preamble
  - Reduced IFS durations

Frame Preambles

Propose two preambles

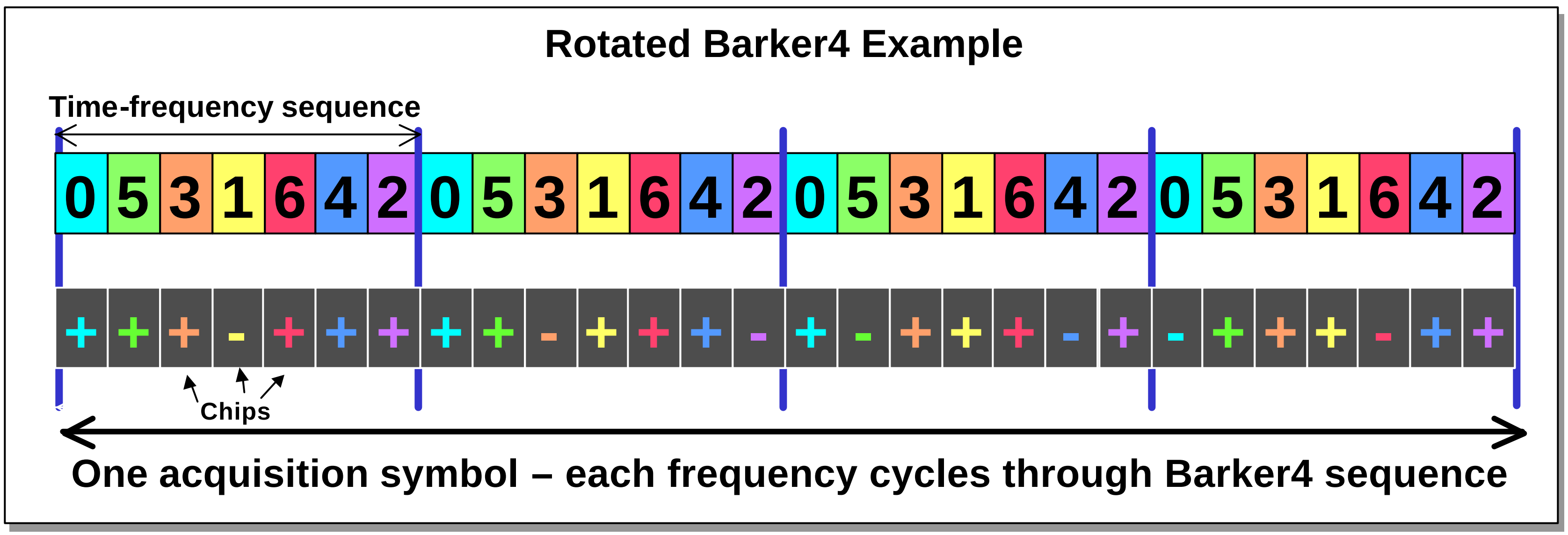
- Modulation indices 0 through 4 use an "Initial Preamble"
  - Supports the modulations longer-range performance
  - Modest effect on data throughput

- Modulation indices 5, 6, & 7 use a "Continuous Preamble"
  - Shorter preamble consistent with modulation range performance
  - More efficient with higher data rate modes

Preamble coordination (which preamble is being used) handled entirely within the PHY

Acquisition Coding

- Both preamble implement rotated Barker coding on top of TFMA coding to increase piconet isolation during acquisition
  - Initial Preamble uses Barker7 sequence
  - Continuous Preamble uses a Barker4 sequence
- Barker coding applied on a per-band basis
  - Provides enhanced piconet isolation during acquisition
  - Provides enhanced resistance to multipath during acquisition



Preamble Definition

Initial Preamble (Barker7 sequence):

- 44 repetitions of the Barker7 pattern: 8.4 µs
- A single inverted Barker7: 0.2 µs
- 8.6-µs total duration

Example Timeline (Actual allocation is implementer's choice)

Gain Init.	Threshold Timeout	Coarse Optimize	Fine Optimize	Phase Determination	Delimiter Detect
1.1 µs	2.7 µs	2.7 µs	1.5 µs	0.4 µs	0.2 µs

Continuous Preamble (Barker4):

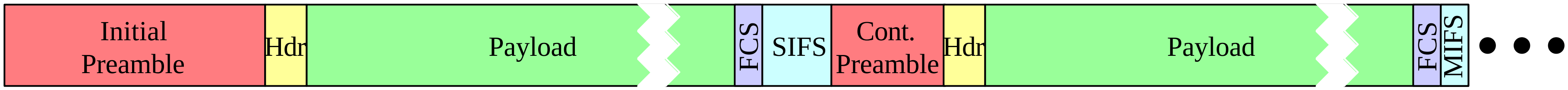
- 44 repetitions of the Barker4 pattern: 4.8 µs
- A single inverted Barker4: 0.1 µs
- 4.9-µs total duration

Example Timeline (Actual allocation is implementer's choice)

Gain Init.	Threshold Timeout	Coarse Optimize	Fine Optimize	Phase Determination	Delimiter Detect
0.7 µs	1.5 µs	1.5 µs	0.9 µs	0.2 µs	0.1 µs

Preamble Coordination

- Dual-preambles easily implemented
  - Handled entirely in the PHY
    - First frame preamble always the Initial Preamble
    - Rx PHY decodes modulation index from PHY header
    - Low-index modulations (0 to 4) continue to use Initial Preamble for all subsequent sequential frames
    - High-index modulations (5 to 7) use Continuous Preamble for subsequent sequential frames



Frame (Packet) Overhead

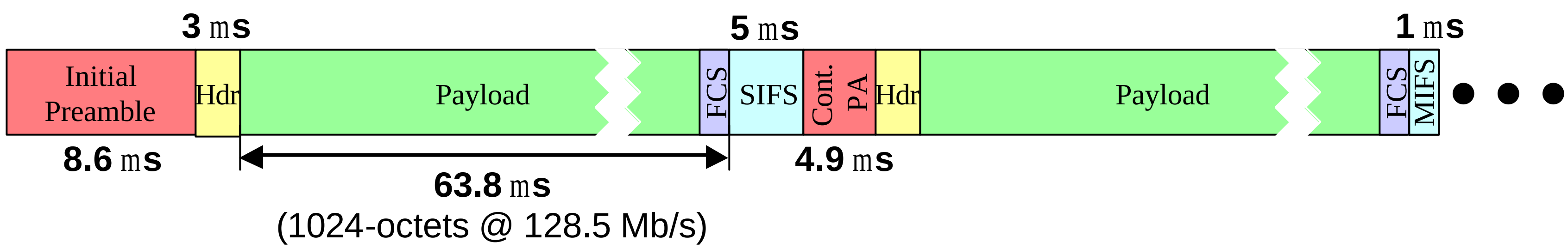
Frame Component	Size (octets)	Bit Rate (Mb/s)	Duration (μs)
Initial Preamble	-	-	8.60
Continuous Preamble	-	-	4.90
PHY Header	2	36.7	0.44
HCS	2	36.7	0.44
MAC Header	10	36.7	2.18
MIFS	-	-	1.00
SIFS	-	-	5.00
RIFS	-	-	18.60
BIFS	-	-	13.60
Frame Body	1024	128.5	63.75
Frame Body	1024	257.1	31.86

Calculations

- For information components
  - Duration = 8*Size/Bit Rate
- RIFS = 2*SIFS + Initial Preamble
- BIFS = SIFS + Initial Preamble

Typical Frame Durations

- 1024-octet frame body @ 128.5 Mb/s
- Total frame duration
  - 80.4 µs with SIFS and Initial Preamble
  - 72.7 µs with MIFS and Continuous Preamble

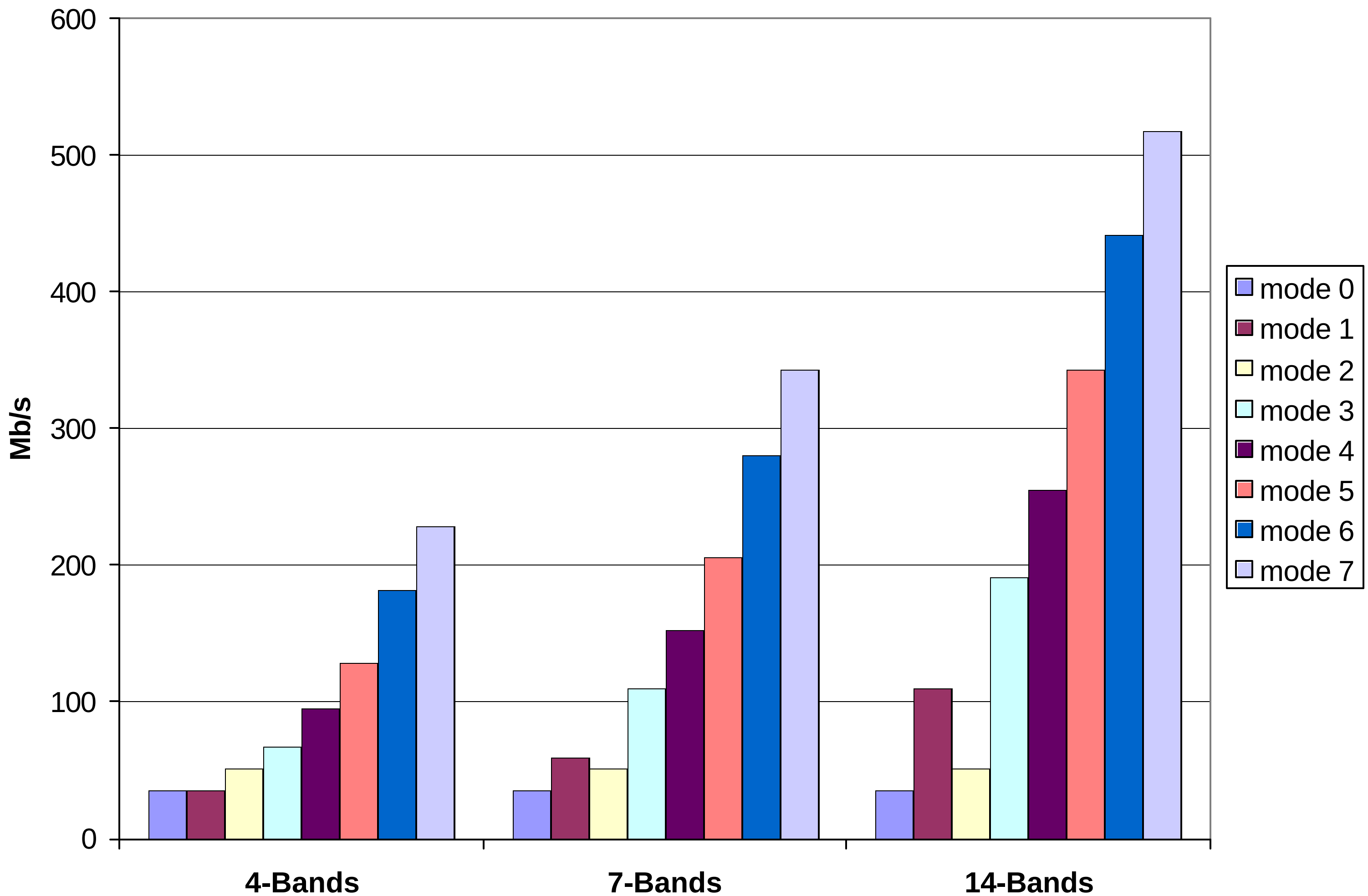


PHY-SAP Throughput

		Multi-Frame PHY-SAP Throughput (Mb/s)			Single-Frame PHY-SAP Throughput (Mb/s)		
Modulation Index	Modulation Scheme	4-Bands	7-Bands	14-Bands	4-Bands	7-Bands	14-Bands
0	BPSK, No FEC, Frequency integrate	34.9	34.9	34.9	34.4	34.4	34.4
1	BPSK, 1/2-Rate FEC, Time integrate x 2	34.9	59.0	109.5	34.4	57.7	105.0
2	QPSK, 3/4-Rate FEC, Frequency integrate	51.2	51.2	51.2	50.1	50.1	50.1
3	BPSK, 1/2-Rate FEC	66.7	109.5	191.2	65.0	105.0	177.9
4	BPSK, 3/4-Rate FEC	95.8	153.1	254.6	92.4	144.4	231.5
5	QPSK, 1/2-Rate FEC	128.3	205.5	343.1	117.0	177.9	272.5
6	QPSK, 3/4-Rate FEC	181.2	280.5	441.8	159.4	231.5	331.3
7	QPSK, No FEC	228.5	343.1	516.4	194.9	272.5	371.5

Modulation Index 0 is the base-rate modulation
Modulation Indices 5, 6, and 7 benefit from the use of the Continuous Preamble

Multi-Frame PHY-SAP Throughput vs. Band Utilization

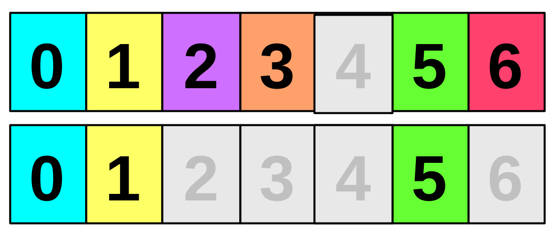


Flexibility of Multi-band: Dynamic Band Management

- 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

NB Interference Mitigation

- Bands are scanned periodically to detect NB interference
- When NB interference is detected, DEVs stop using affected bands in their data streams



Example: Band 4 dropped

FDMA for Enhanced Channelization

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

FDMA Algorithm

- DME algorithms determine when and how FDMA is implemented
  - Uses band assessment results to determine when FDMA is beneficial
  - Selects appropriate FDMA parameters (band subset allocation, etc.)
  - Initiates process of FDMA coordination (or responds to FDMA coordination requests)
  - Sets PHY for FDMA operation

Reserved Band

- A band is available for future services (e.g. low data rate).
- This allows deployment of very inexpensive single band implementations without degrading the throughput of piconets using multiple band radios.

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Multi-band Approach: Flexibility

- Individual DEV pairs are able to adapt to interference without coordination with other DEVs
- Adaptation strategy: don’t use sub-bands with poor signal quality
- Easy to adapt to different regulatory environments as well

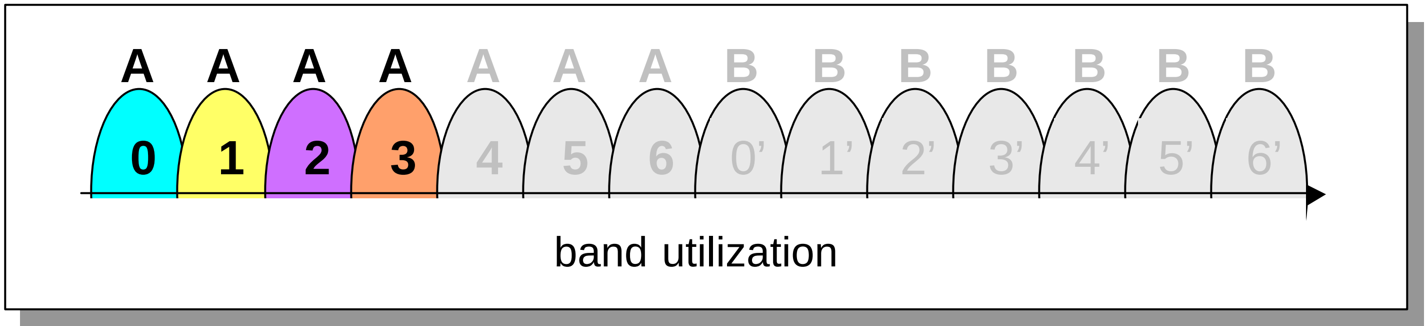
Regulatory Flexibility

- Conforming to different regulatory climates is as simple as deciding which bands to turn on and which to leave off.
- Waveform designed to conform to both indoor and hand-held FCC masks.
  - Modest side-band filtering required
- Single radio design with adaptive algorithms can automatically sense efficient use of spectrum in high use electromagnetic environments.

Scalability: MAC Enhancements and Band-Plan

- The simple MAC enhancements defined for the Multi-band approach support scaling to the full proposed capability of 14 bands
  - As higher RF frequencies become feasible, they are folded in naturally
  - Standard provides compatibility between higher-capability devices (using more bands) and lower-capability devices (using fewer bands)

Scalability: Piconet Coding
4-Band Design



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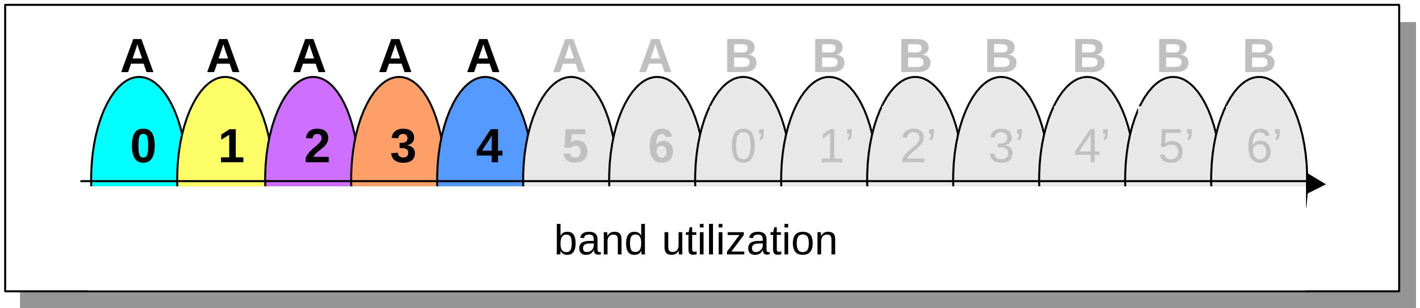
0	3	6	2	5	1	4
0	4	1	5	2	6	3
0	5	3	1	6	4	2
0	6	5	4	3	2	1

code group A

0’	1’	2’	3’	4’	5’	6’
0’	2’	4’	6’	1’	3’	5’
0’	3’	6’	2’	5’	1’	4’
0’	4’	1’	5’	2’	6’	3’
0’	5’	3’	1’	6’	4’	2’
0’	6’	5’	4’	3’	2’	1’

code group B

Scalability: Piconet Coding
5-Band Design



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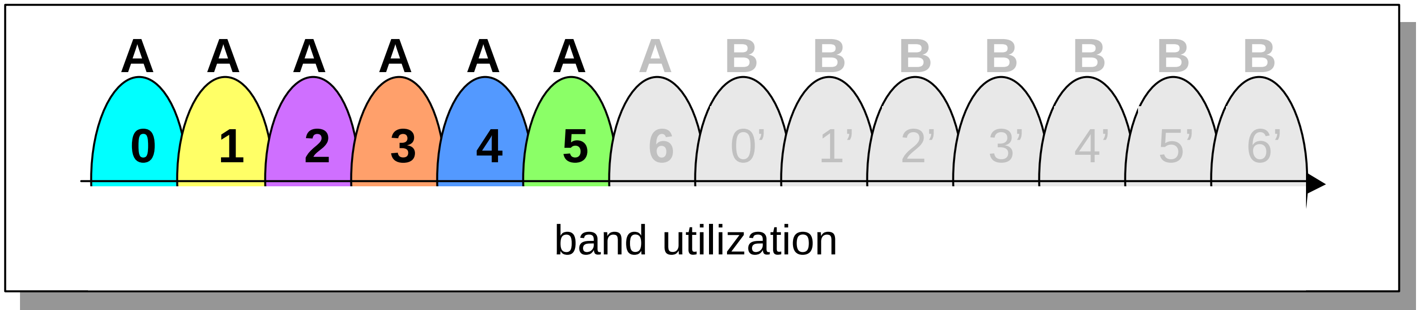
0	3	6	2	5	1	4
0	4	1	5	2	6	3
0	5	3	1	6	4	2
0	6	5	4	3	2	1

code group A

0'	1'	2'	3'	4'	5'	6'
0'	2'	4'	6'	1'	3'	5'
0'	3'	6'	2'	5'	1'	4'
0'	4'	1'	5'	2'	6'	3'
0'	5'	3'	1'	6'	4'	2'
0'	6'	5'	4'	3'	2'	1'

code group B

Scalability: Piconet Coding
6-Band Design



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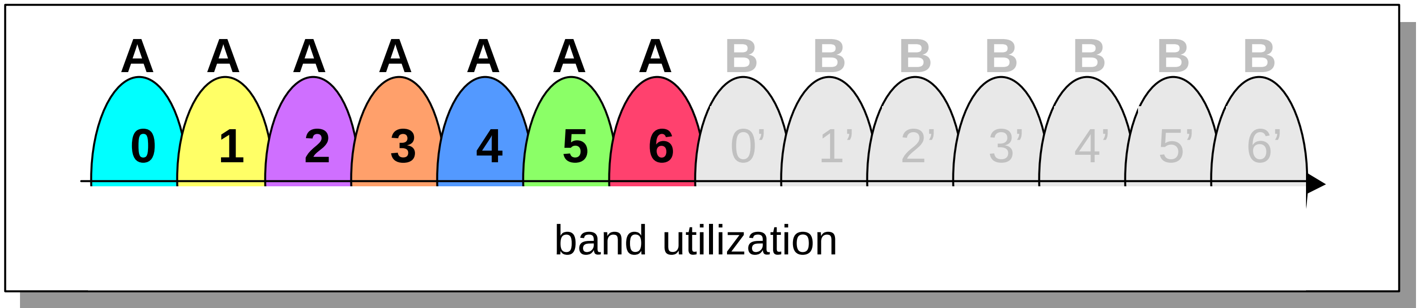
0	4	1	5	2	6	3
0	5	3	1	6	4	2
0	6	5	4	3	2	1

code group A

0’	1’	2’	3’	4’	5’	6’
0’	2’	4’	6’	1’	3’	5’
0’	3’	6’	2’	5’	1’	4’
0’	4’	1’	5’	2’	6’	3’
0’	5’	3’	1’	6’	4’	2’
0’	6’	5’	4’	3’	2’	1’

code group B

Scalability: Piconet Coding
7-Band Design



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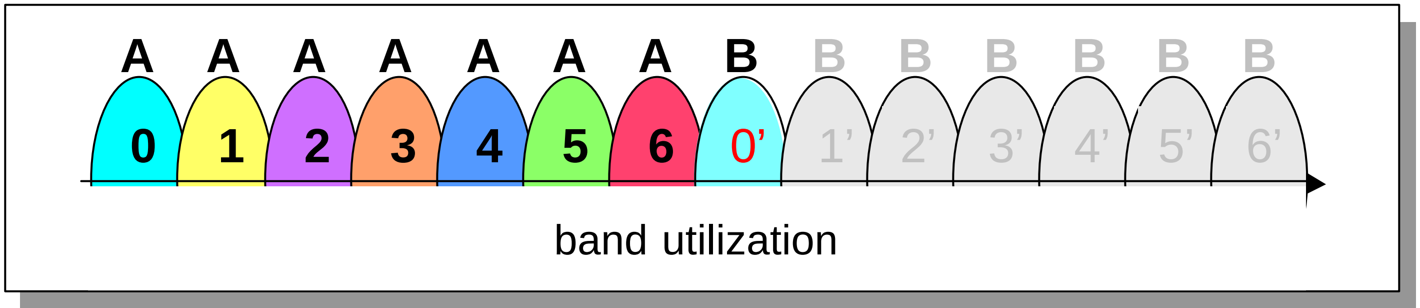
0	4	1	5	2	6	3
0	5	3	1	6	4	2
0	6	5	4	3	2	1

code group A

0’	1’	2’	3’	4’	5’	6’
0’	2’	4’	6’	1’	3’	5’
0’	3’	6’	2’	5’	1’	4’
0’	4’	1’	5’	2’	6’	3’
0’	5’	3’	1’	6’	4’	2’
0’	6’	5’	4’	3’	2’	1’

code group B

Scalability: Piconet Coding
8-Band Design



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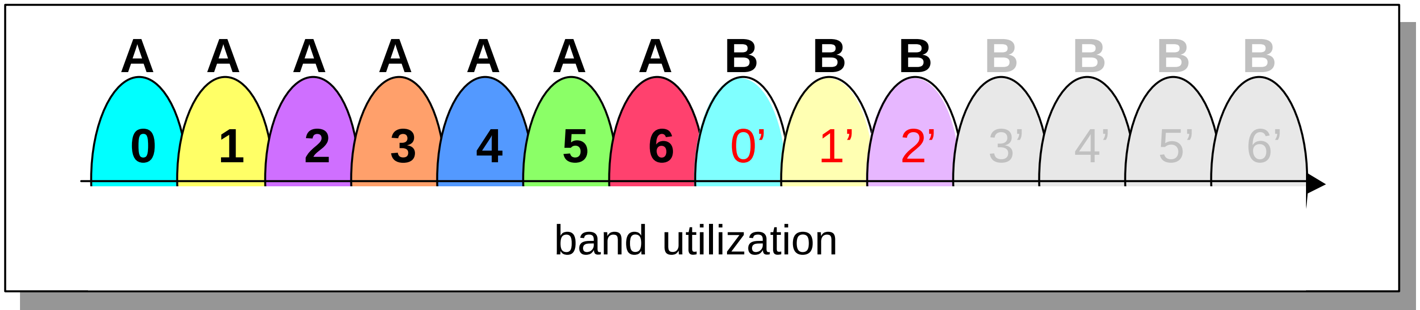
0	4	1	5	2	6	3
0	5	3	1	6	4	2
0	6	5	4	3	2	1

code group A

0’	1’	2’	3’	4’	5’	6’
0’	2’	4’	6’	1’	3’	5’
0’	3’	6’	2’	5’	1’	4’
0’	4’	1’	5’	2’	6’	3’
0’	5’	3’	1’	6’	4’	2’
0’	6’	5’	4’	3’	2’	1’

code group B

Scalability: Piconet Coding
10-Band Design



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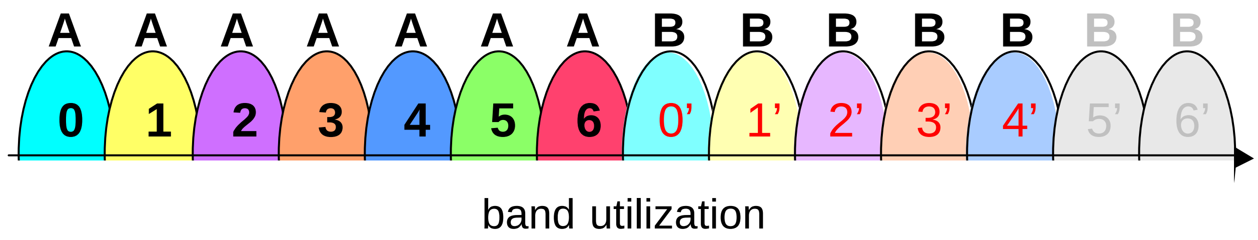
0	4	1	5	2	6	3
0	5	3	1	6	4	2
0	6	5	4	3	2	1

code group A

0'	1'	2'	3'	4'	5'	6'
0'	2'	4'	6'	1'	3'	5'
0'	3'	6'	2'	5'	1'	4'
0'	4'	1'	5'	2'	6'	3'
0'	5'	3'	1'	6'	4'	2'
0'	6'	5'	4'	3'	2'	1'

code group B

Scalability: Piconet Coding
12-Band Design



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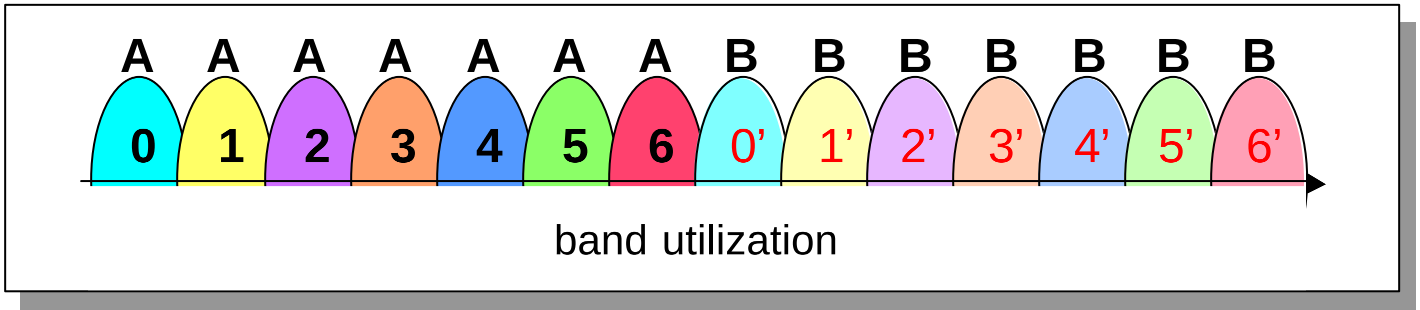
0	4	1	5	2	6	3
0	5	3	1	6	4	2
0	6	5	4	3	2	1

code group A

0’	1’	2’	3’	4’	5’	6’
0’	2’	4’	6’	1’	3’	5’
0’	3’	6’	2’	5’	1’	4’
0’	4’	1’	5’	2’	6’	3’
0’	5’	3’	1’	6’	4’	2’
0’	6’	5’	4’	3’	2’	1’

code group B

Scalability: Piconet Coding
14-Band Design



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0	3	6	2	5	1	4
0	4	1	5	2	6	3
0	5	3	1	6	4	2
0	6	5	4	3	2	1

0’	1’	2’	3’	4’	5’	6’
0’	2’	4’	6’	1’	3’	5’
0’	3’	6’	2’	5’	1’	4’
0’	4’	1’	5’	2’	6’	3’
0’	5’	3’	1’	6’	4’	2’
0’	6’	5’	4’	3’	2’	1’

code group A **code group B**

Scalability: Modulation

4 Band Operation

Maximum PHY-SAP Throughput: 228.5 Mb/s
Maximum Payload Bit Rate: 293.8 Mb/s

7 Band Operation

Maximum PHY-SAP Throughput: 343.1 Mb/s
Maximum Payload Bit Rate: 514.1 Mb/s

14 Band Operation

Maximum PHY-SAP Throughput: 516.4 Mb/s
Maximum Payload Bit Rate: 1028.2 Mb/s

Scalability: Power

- Implementation of radios using more than 7 bands involves a second frequency synthesizer and receiver chain. This will consume more power in the radio front end.
- The higher data rates associated with using more than 7 bands will consume more power in the FEC as well as the MAC.

Scalability: Complexity

- Implementing radios using more than 7 bands involves a design “cut and paste” operation.
- Multiple instances of architectural elements consume power and silicon area but do not increase complexity.

- Executive Summary
- Introduction
- PHY Proposal
- Scalability and Flexibility
- **MAC Enhancements**
- Performance
- Implementation Considerations
- Requirements Verification
- Conclusion

Multi-band Alt-PHY PIB Characteristics

- .3 Channels Becomes .3a Codes
  - 6 codes instead of 5 channels

    PHYPIB_NumChannelsSupported = PHYPIB_NumCodesSupported

    PHYPIB_CurrentChannel = PHYPIB_CurrentCode

    PHYPIB_CCAThreshold = PHYPIB_CCAThreshold
- .3 Data Rate Becomes .3a Modulation Scheme

    PHYPIB_DataRateVector = PHYPIB_ModulationVector
- New .3a Characteristic Called Bands
  - Assessed and selected similar to Channels, now Codes
  - Determines throughput along with selected Modulation Scheme

    PHYPIB_BandsSupported

    PHYPIB_CurrentBands

    PHYPIB_CBAThreshold

Supplemental PHY-SAP Primitives

- PHY Clear Code Assessment
- PHY Clear Band Assessment

MAC Supplements to Support Bands

- Extensions to .3 Information Elements
  - 7.4.4 Dev Association
  - 7.4.12 Dev Capabilities
- New Information Elements
  - 7.4.X Bands Allowed
  - 7.4.X Band Report
- Extensions to Support Piconet Parameter Change
  - 7.4.6 Piconet Parameter Change Information Element
  - MLME-PICONET-PARM-CHANGE Primitive

MAC Supplements to Support Bands (cont)

- New MLME Primitives
  - MLME-BAND-ASSESSMENT
  - MLME-REMOTE-BAND-ASSESSMENT
  - MLME-BAND-COORDINATION
  - MLME-BAND-ALLOCATION
  - MLME-BAND-REPORT
  - MLME-LINK-STATUS
- New MAC Command Frames
  - Band Coordination
  - Band Allocation
  - Remote Band Assessment
  - Link Status

Features Enabled by MAC Supplements

- Band selection based on
  - DEV capabilities
  - Network interference
  - Coexistence
  - Desired throughput and link performance
  - Optional spectrum sharing

Location Awareness

- Provision is made in the MAC to allow special packets supporting location awareness.
- Ranging packets would typically involve immediate acknowledgment protocols with “turnaround” time information included in the acknowledgment.
- Vendors would be free to implement ranging using these special packets and not impact communications activity within the piconet.

Required Changes to Existing MAC

- No changes to the existing 802.15.3 MAC are required
- The Alt-PHY can exist within the reserved fields of the existing protocol.

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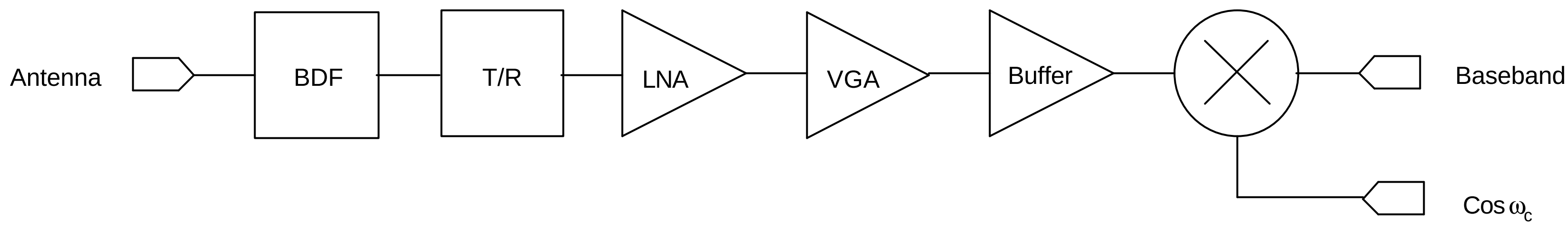
Performance Results

- Results shown for
  - Link Budget
  - System Performance
  - Simultaneously Operating Piconets
  - Signal Acquisition
  - Coexistence
  - Interference Susceptibility

Link Budget

- Determine free space AWGN link budget margin for Multi-Band Radio
- Receiver sensitivity is dependent on modulation type
- Data rates as high as 293.78 Mb/s for 4 band radio, 514.12 Mb/s for 7 band radio, and 1 Gb/s for 14 band radio

Receiver Noise Figure



Stage	BDF	T/R	LNA	VGA	Buffer	Mixer
Gain (dB)	-0.5	-2.0	20.0	15.0	0.0	6.0
Gain (Numeric)	0.9	0.6	100.0	31.6	1.0	4.0
NF* (dB)	**0.5**	**2.0**	**4.0**	**15.0**	**15.0**	**15.0**
Noise Factor	1.1	1.6	2.5	31.6	31.6	31.6
Cumulative Noise Figure, to Stage Input	**7.0**	**6.5**	**4.5**	**15.3**	**17.9**	**15.0**
Cumulative Noise Factor, to Stage Input	5.0	4.5	2.8	33.6	62.2	31.6

*Broadband Noise figure

Receiver Sensitivity

NF, receiver noise figure (dB)	7.00
T_0, temperature (K)	290.00
K, Boltzmanns constant	1.38E-23
Receiver AWGN niose floor density (dBm/Hz)	-1.67E+02
Receiver noise bandwidth (MHz)	4.14E+08
Total noise power in receiver bandwidth (dBm)	-80.81142
Target BER	1.00E-05
E_b/N_0 @ Target BER (dB)	9.60
Implementation loss (dB)	5.00
Minimum peak signal = "Rx sensitivity" (dBm)	**-66.21**

Implementation losses (estimated)

Waveform efficiency (dB)	3
Phase alignment error (dB)	1
Jitter (dB)	1
Total implementation losses (dB)	**5**

Receiver Sensitivity Depends on Modulation Types

Modulation Description	# of Bands	System Data Rate (Mb/s)	Overall Receiver Sensitivity (dBm)	1m Margin (dB)
BPSK, 1/2 FEC, x2 Time Integration, No Frequency Integration	4	36.72	-86.82	28.97
QPSK, 3/4 FEC, No time integration, Freq. Integration all Bands	4	55.08	-81.02	26.60
BPSK, 1/2 FEC, No time integration, No Frequency Integration	4	73.45	-80.81	25.97
BPSK, No FEC, No Time Integration, Freq Integration all Bands	4	36.72	-77.93	24.76
QPSK, 1/2 FEC, No time integration, No Frequency Integration	4	146.89	-77.80	22.96
BPSK, 3/4 FEC, No time integration, No Frequency Integration	4	110.17	-75.80	21.47
QPSK, 3/4 FEC, No time integration, No Frequency Integration	4	220.34	-72.79	19.71
QPSK, No FEC, No Time Integration, No Frequency Integration	4	293.78	-66.69	14.90
QPSK, 3/4 FEC, No time integration, Freq. Integration all Bands	7	55.08	-82.20	27.85
BPSK, 1/2 Fec, x2 Time Integration, No Frequency Integration	7	64.26	-83.13	26.50
BPSK, No FEC, No Time Integration, Freq Integration all Bands	7	36.72	-79.11	26.01
BPSK, 1/2 FEC, No time integration, No Frequency Integration	7	128.53	-77.12	23.50
QPSK, 1/2 FEC, No time integration, No Frequency Integration	7	257.06	-74.11	20.49
BPSK, 3/4 FEC, No time integration, No Frequency Integration	7	192.79	-72.11	20.25
QPSK, 3/4 FEC, No time integration, No Frequency Integration	7	385.60	-69.09	17.24
QPSK, No FEC, No Time Integration, No Frequency Integration	7	514.12	-63.00	12.43
QPSK, 3/4 FEC, No time integration, Freq. Integration all Bands	14	55.08	-84.10	28.97
BPSK, No FEC, No Time Integration, Freq Integration all Bands	14	36.72	-81.01	27.13
BPSK, 1/2 FEC, x2 Time Integration, No Frequency Integration	14	128.53	-78.52	23.01
BPSK, 1/2 FEC, No time integration, No Frequency Integration	14	257.06	-72.51	20.01
QPSK, 1/2 FEC, No time integration, No Frequency Integration	14	514.12	-69.50	17.00
BPSK, 3/4 FEC, No time integration, No Frequency Integration	14	385.59	-67.50	16.76
QPSK, 3/4 FEC, No time integration, No Frequency Integration	14	771.18	-64.49	13.75
QPSK, No FEC, No Time Integration, No Frequency Integration	14	1028.24	-58.39	8.94

Link Budget Margin

4 Bands

Index	Modulation Scheme	Number of Bands	Payload Bit Rate	Link Budget Margin
0	BPSK, No FEC, no time integration, integrate all frequency bands	4	36.72	4.76 dB @ 10 m
1	BPSK, ½ rate FEC, time integration = 2, no frequency integration	4	36.72	8.97 dB @ 10 m
2	QPSK, ¾ rate FEC, no time integration, integrate all frequency bands	4	55.08	6.60 dB @ 10 m
3	BPSK, ½ rate FEC, no time integration, no frequency integration	4	73.45	5.97 dB @ 10 m
4	BPSK, ¾ rate FEC, no time integration, no frequency integration	4	110.17	1.47 dB @ 10 m
5	QPSK, ½ rate FEC, no time integration, no frequency integration	4	146.89	2.96 dB @ 10 m
6	QPSK, ¾ rate FEC, no time integration, no frequency integration	4	220.34	7.67 dB @ 4 m
7	QPSK, no FEC, no time integration, no frequency integration	4	293.78	2.86 dB @ 4 m

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

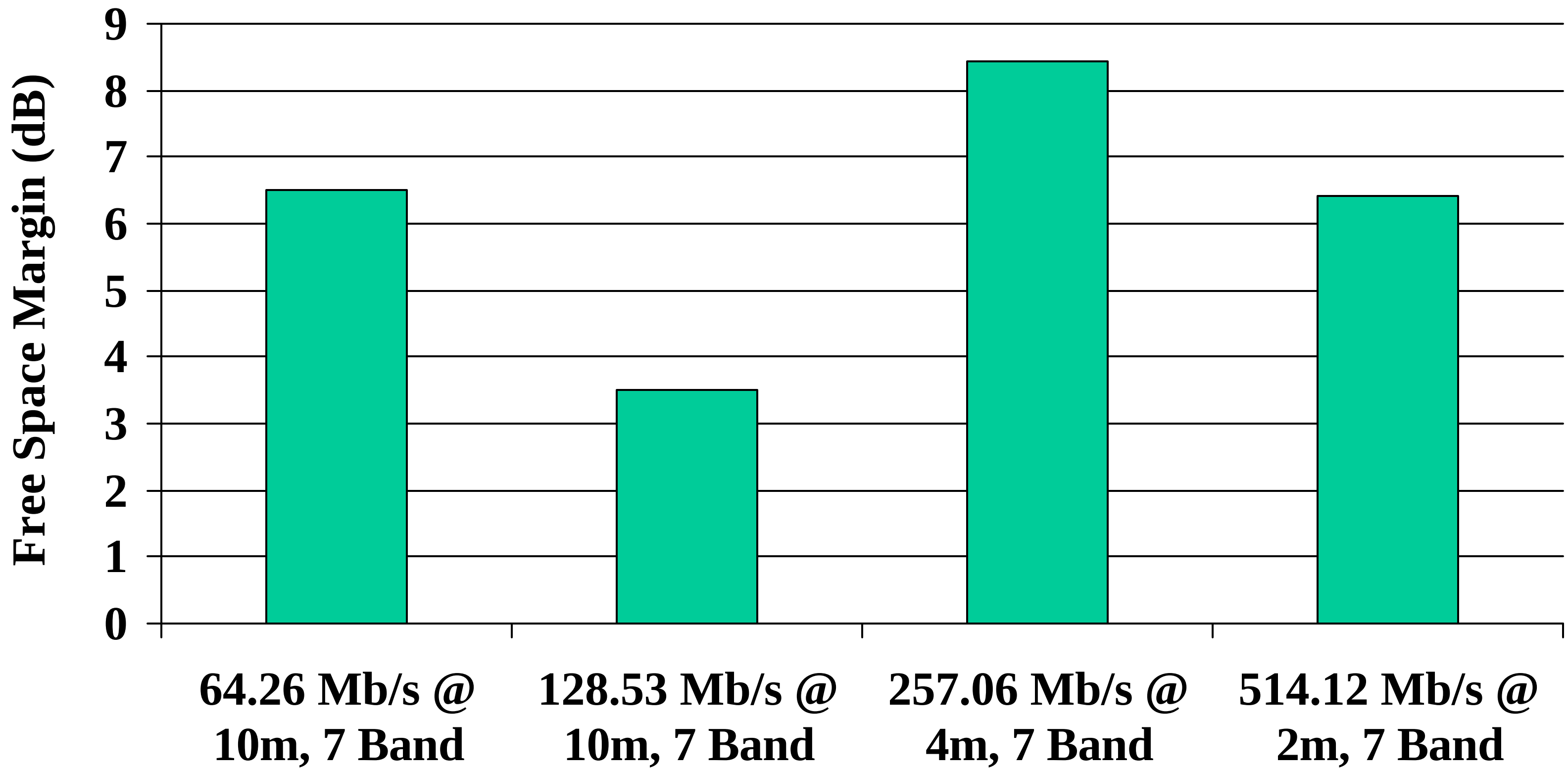
Link Budget Margin

14 Bands

Index	Modulation Scheme	Number of Bands	Payload Bit Rate	Link Budget Margin
0	BPSK, No FEC, no time integration, integrate all frequency bands	14	36.72	7.13 dB @ 10 m
5	QPSK, ½ rate FEC, no time integration, no frequency integration	14	514.12	4.95 dB @ 4 m
6	QPSK, ¾ rate FEC, no time integration, no frequency integration	14	771.18	1.70 dB @ 4 m
7	QPSK, no FEC, no time integration, no frequency integration	14	1028.24	2.92 dB @ 2 m

Link Budget Margin

7-Band Radio



Simulation Results

- Results shown for
  - System Performance
  - Signal Acquisition
  - Simultaneously Operating Piconets
  - Coexistence
  - Interference Susceptibility

Simulator

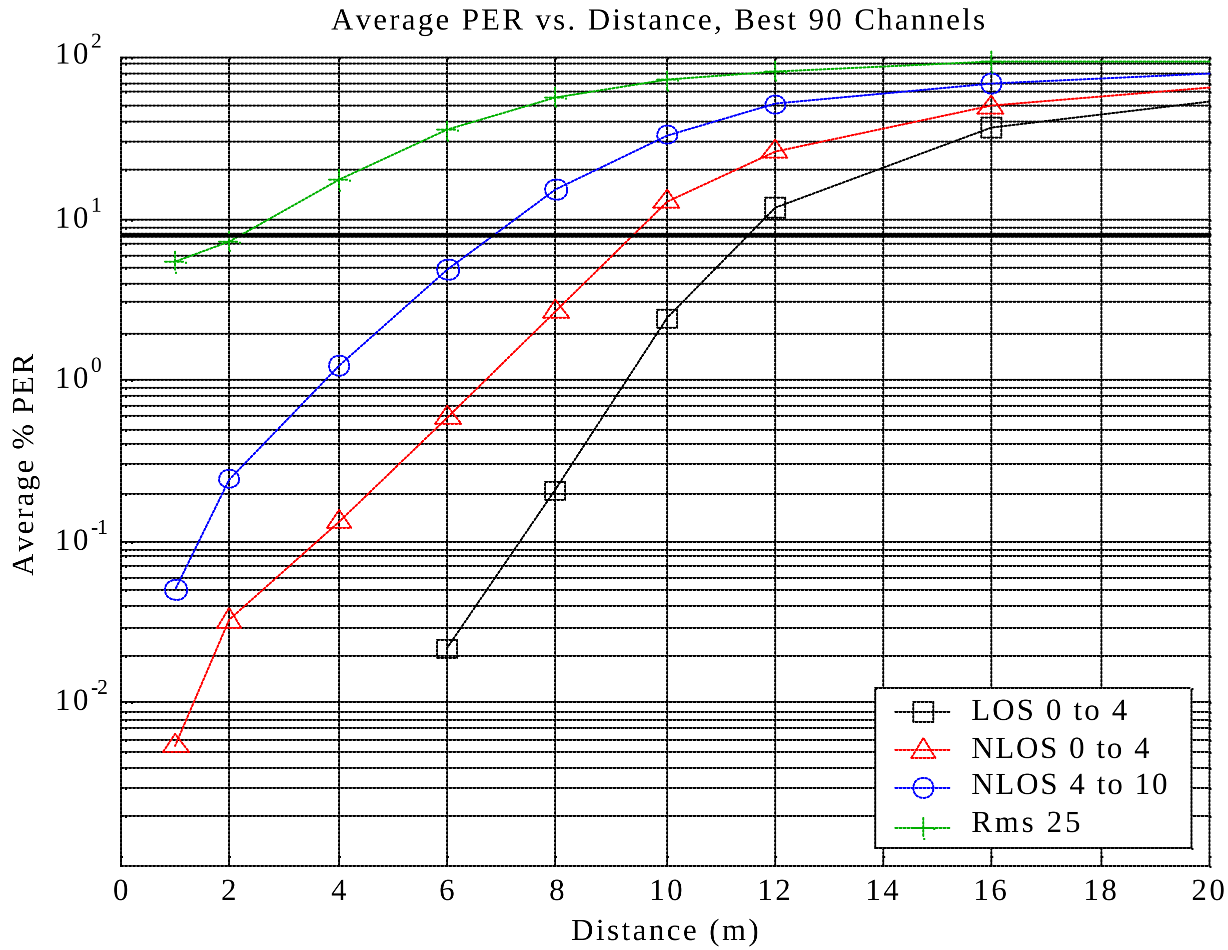
- **Operates primarily in the time domain**
- **Signals sampled at 100GHz**
- **Packet-oriented, i.e. for each packet**:
  - Adjusts gain
  - Thresholds preamble to acquire, characterizes received signal for demodulation
  - Demodulates and check-sums Header and Payload
  - Decodes using Viterbi algorithm
- **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

- Goal 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^{10} bits
- Results presented for 128 Mb/s and 257 Mb/s operation
  - Barker4 preamble currently being used for all cases.
  - No RAKE and 2-finger RAKE evaluated

System Performance – 128.4Mb/s

- 7 bands (skips UNII band)
- 100 CIRs 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



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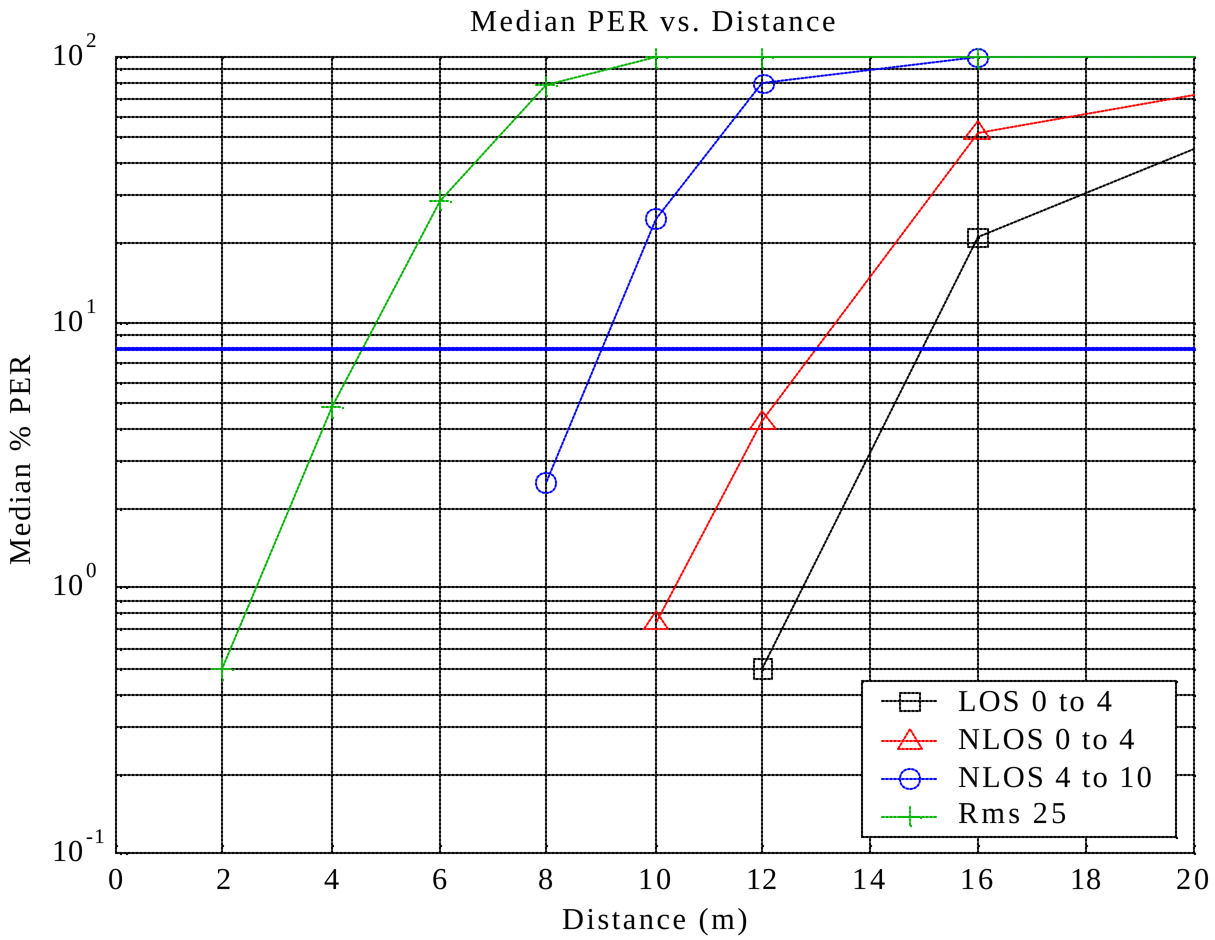

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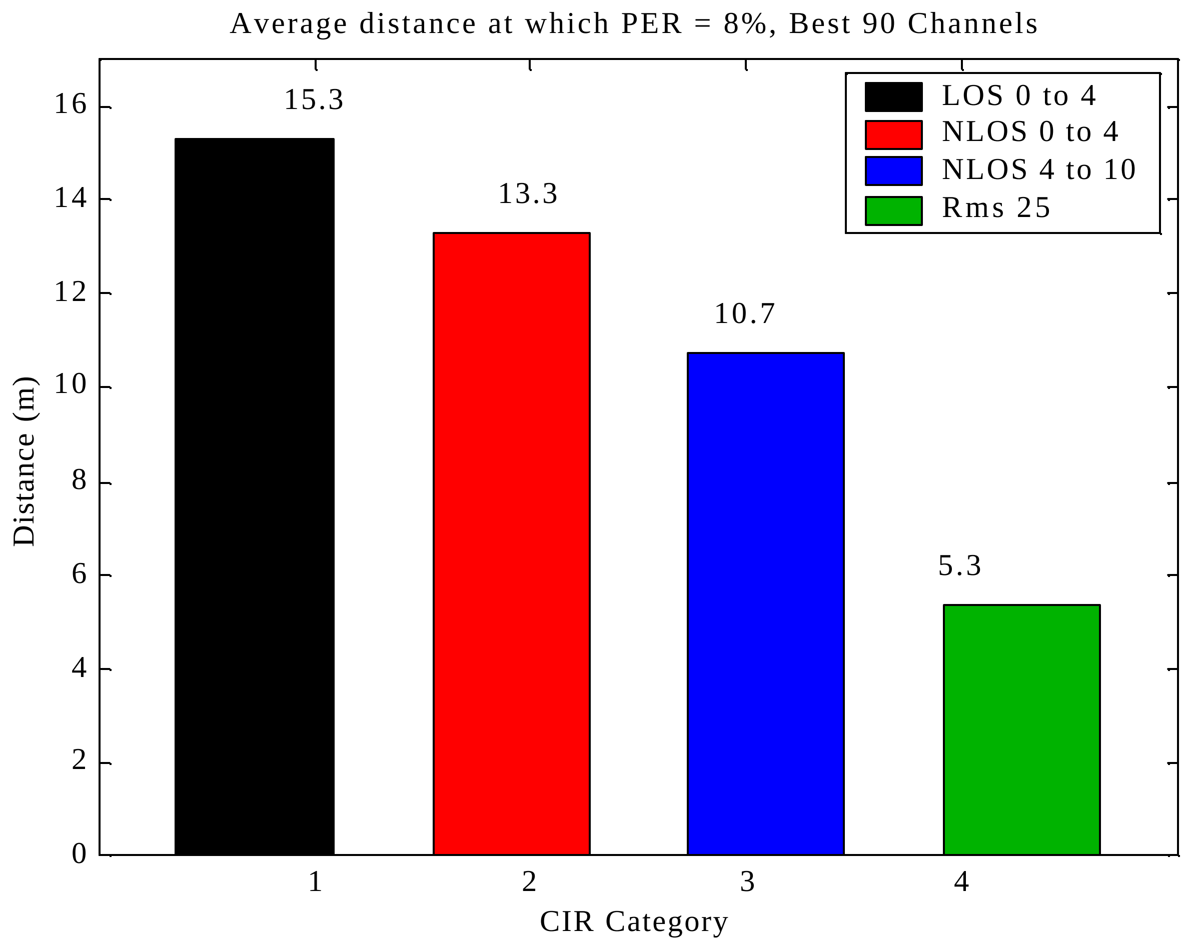

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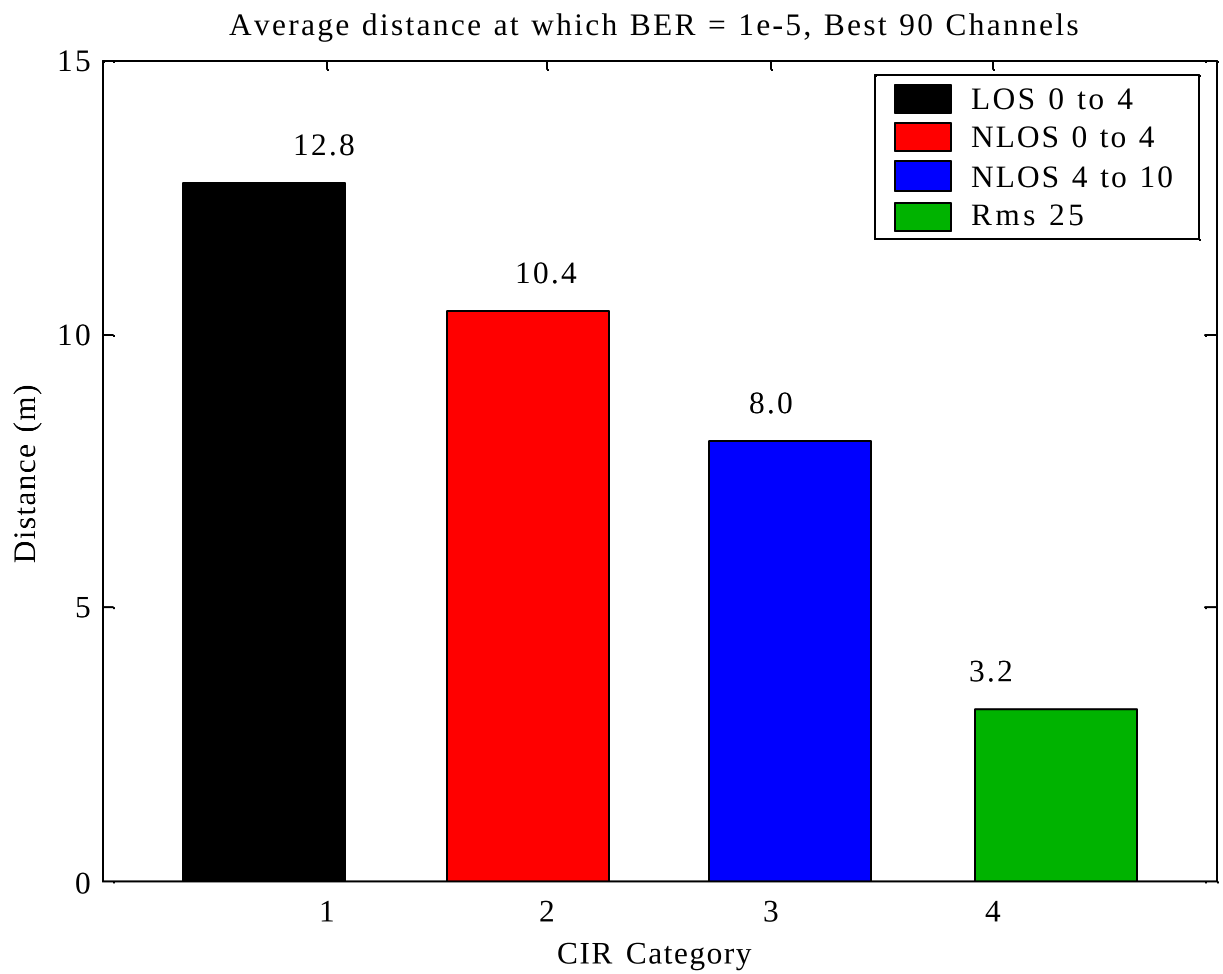

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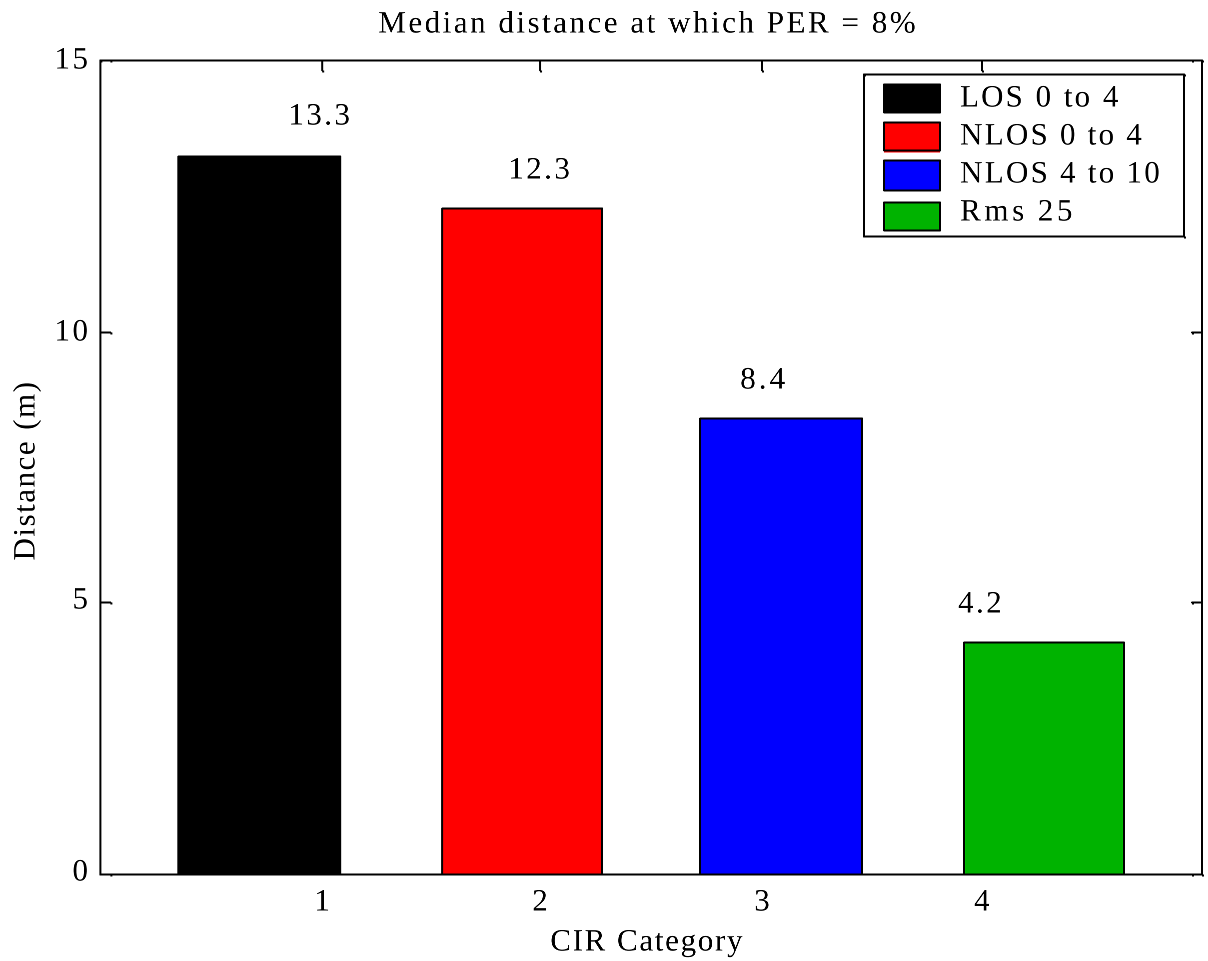

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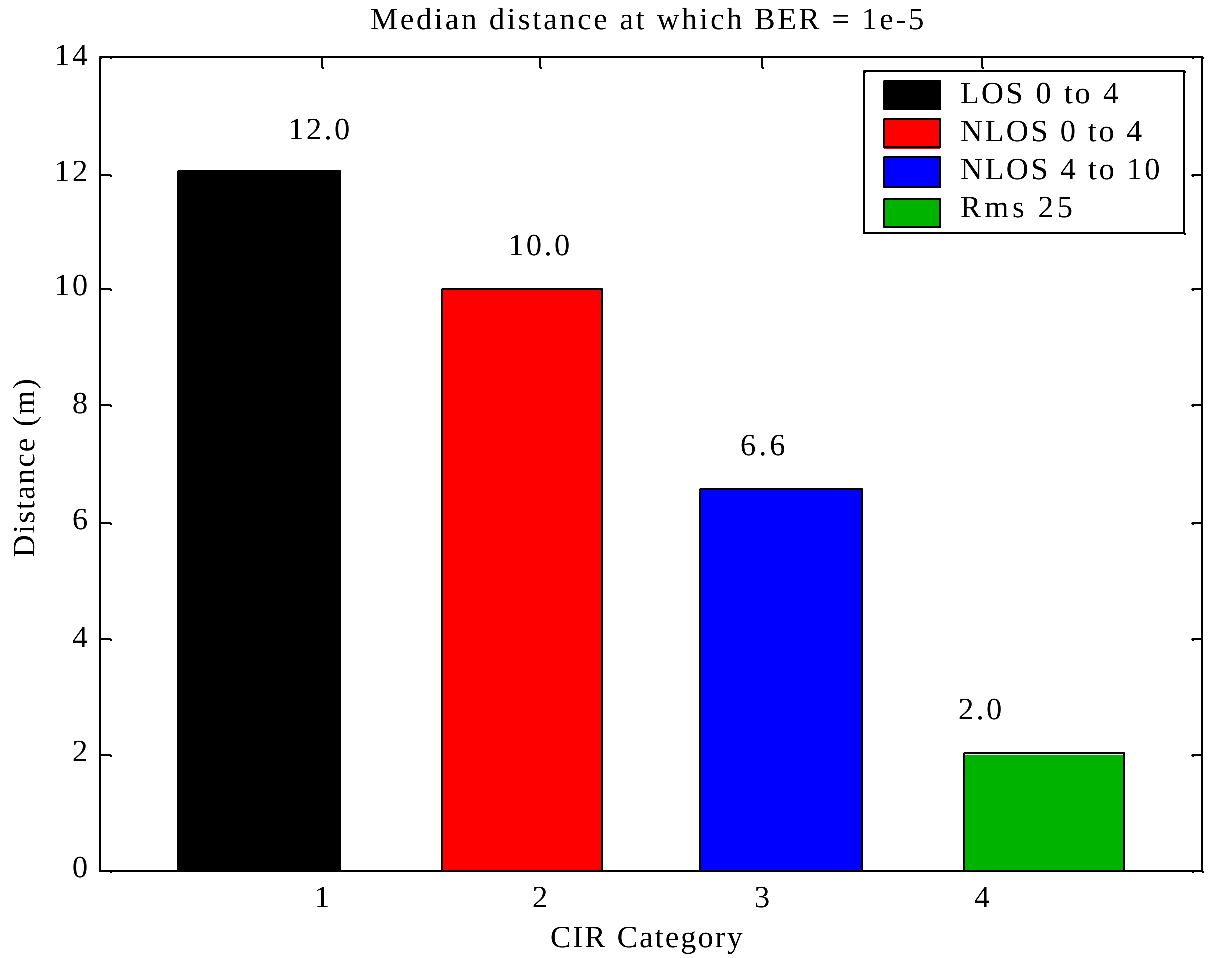

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- 7 bands (skips UNII band)
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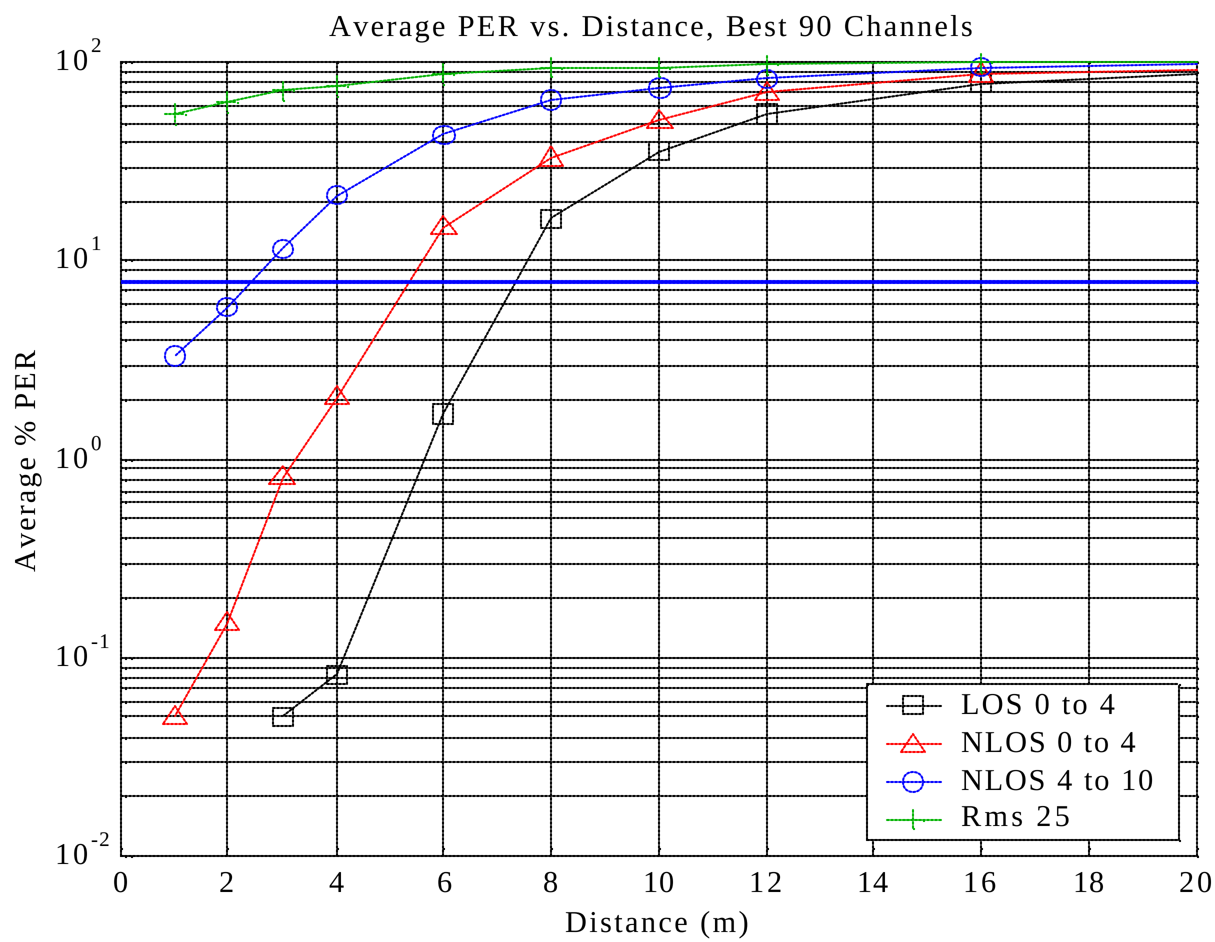

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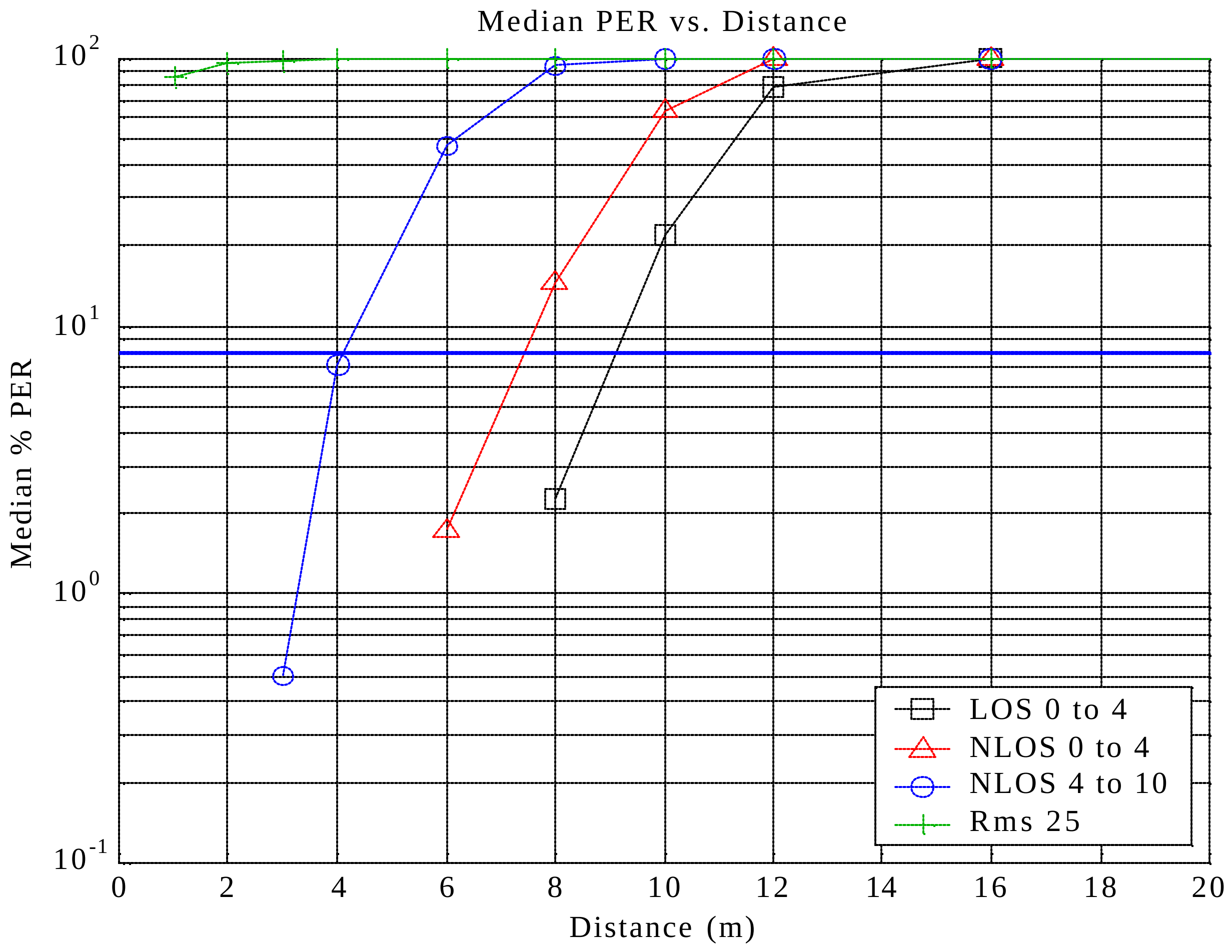

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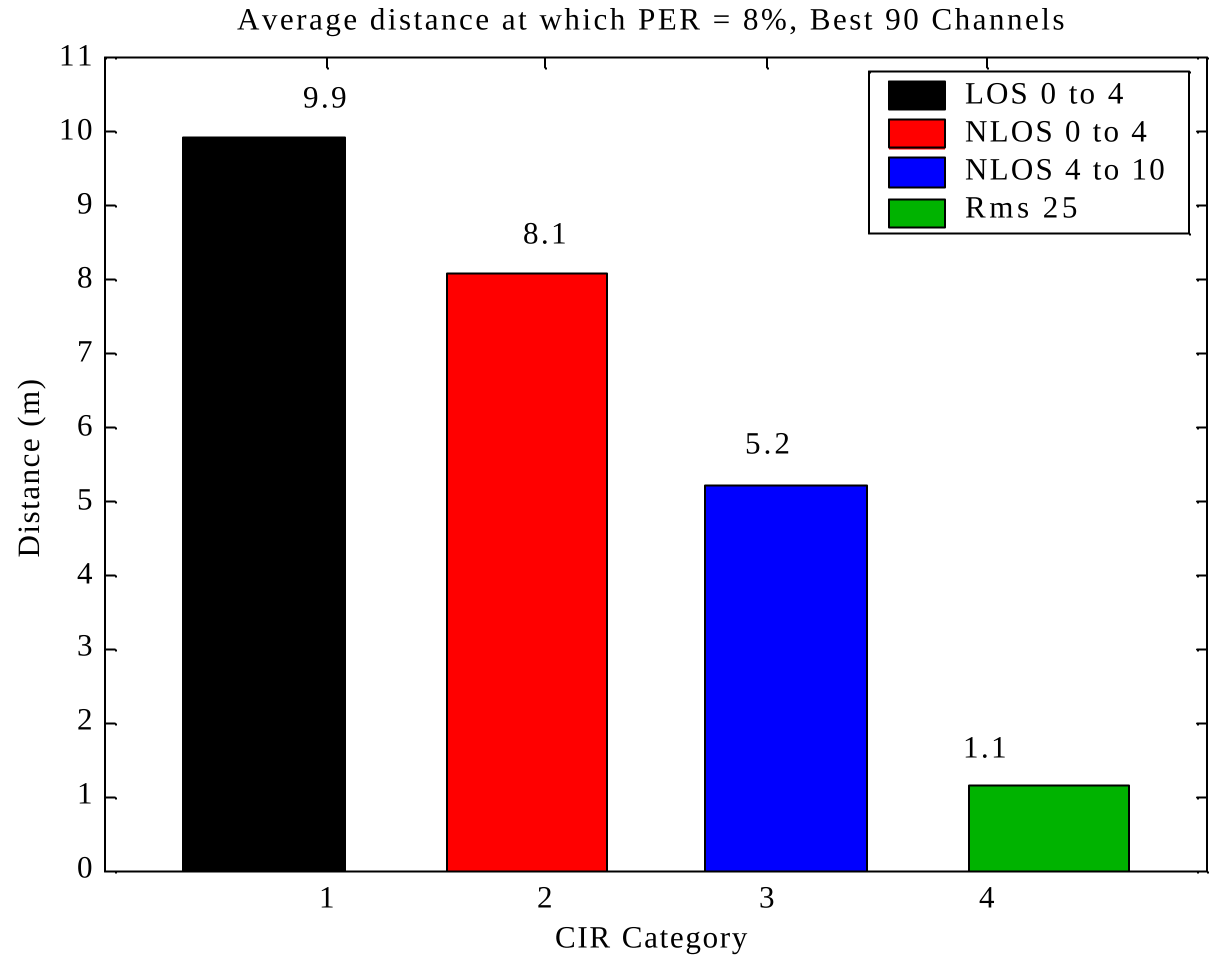

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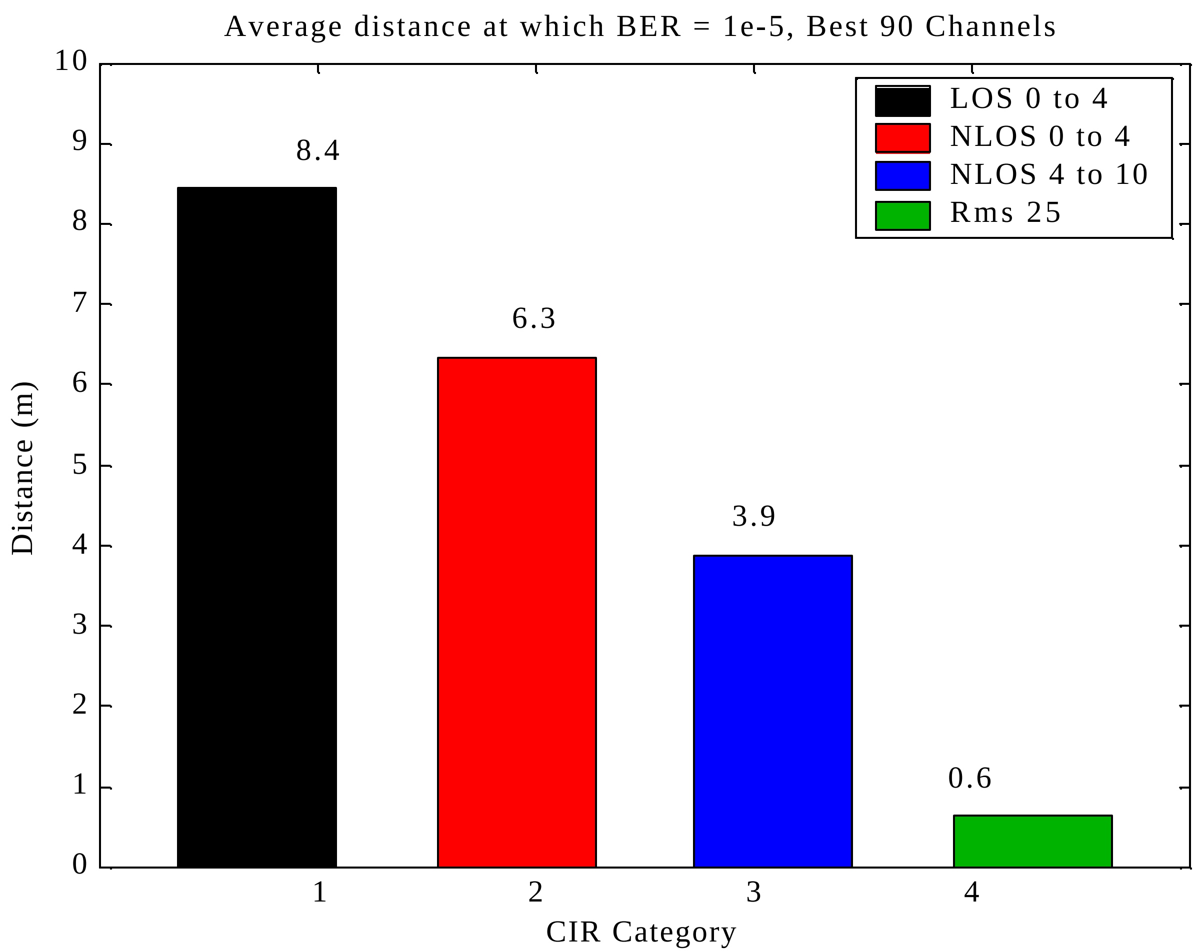

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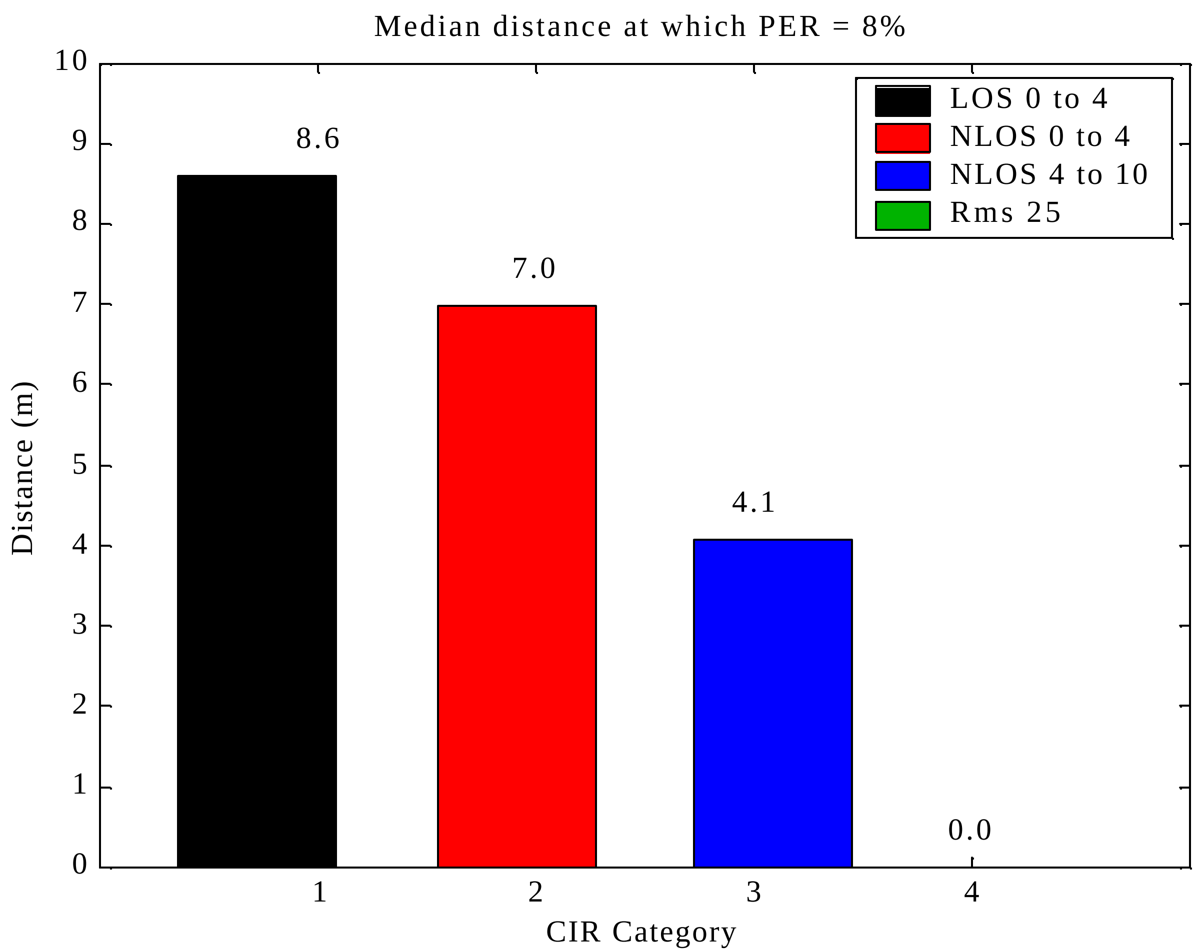

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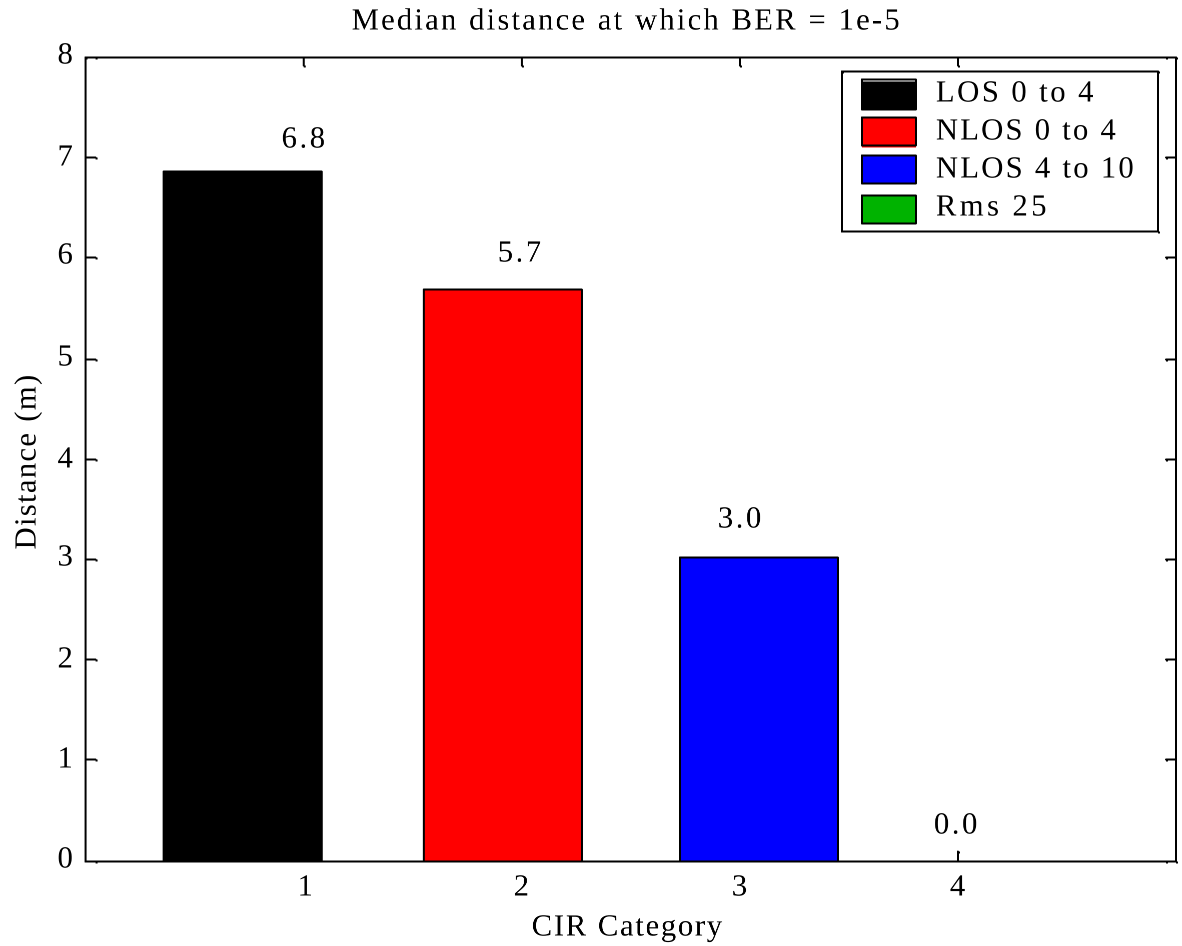

System Performance
128.4Mb/s – Two Rake Teeth

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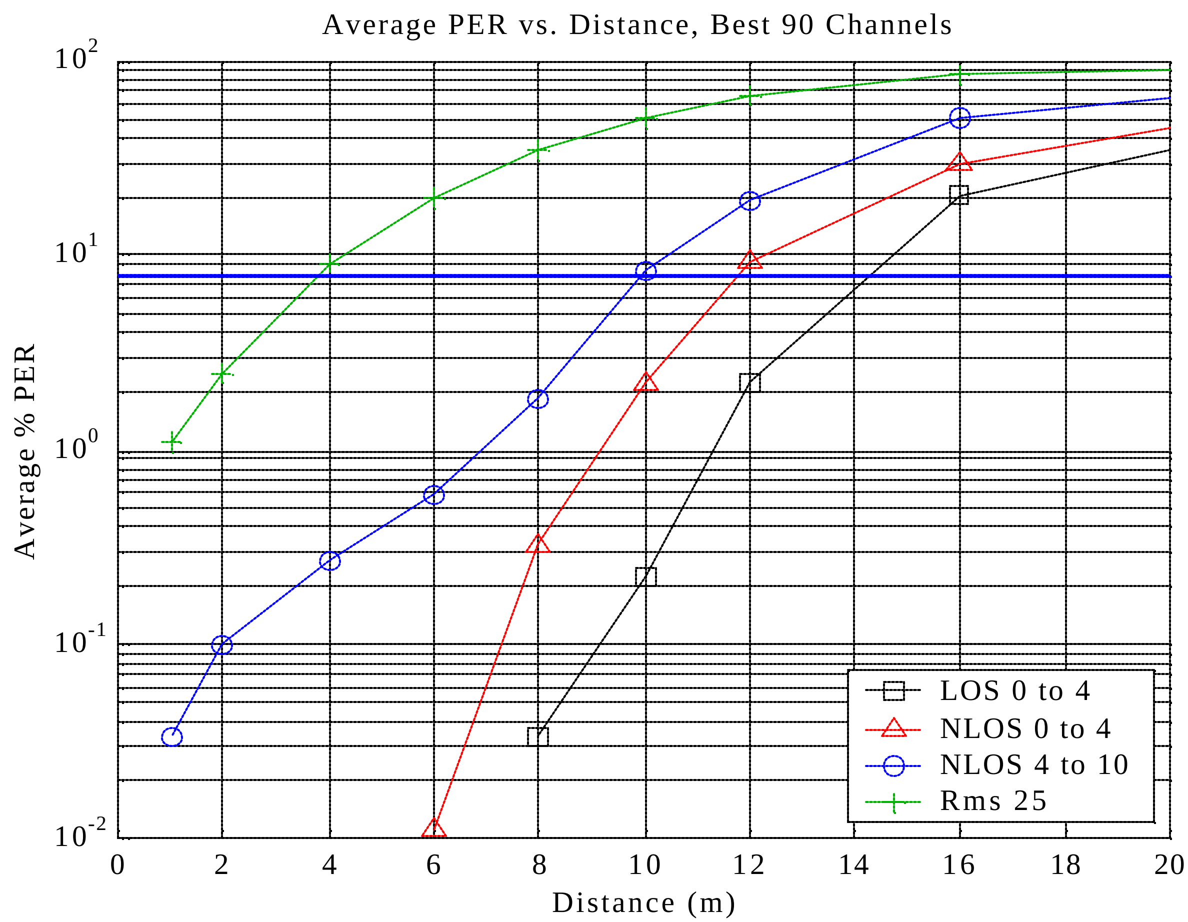

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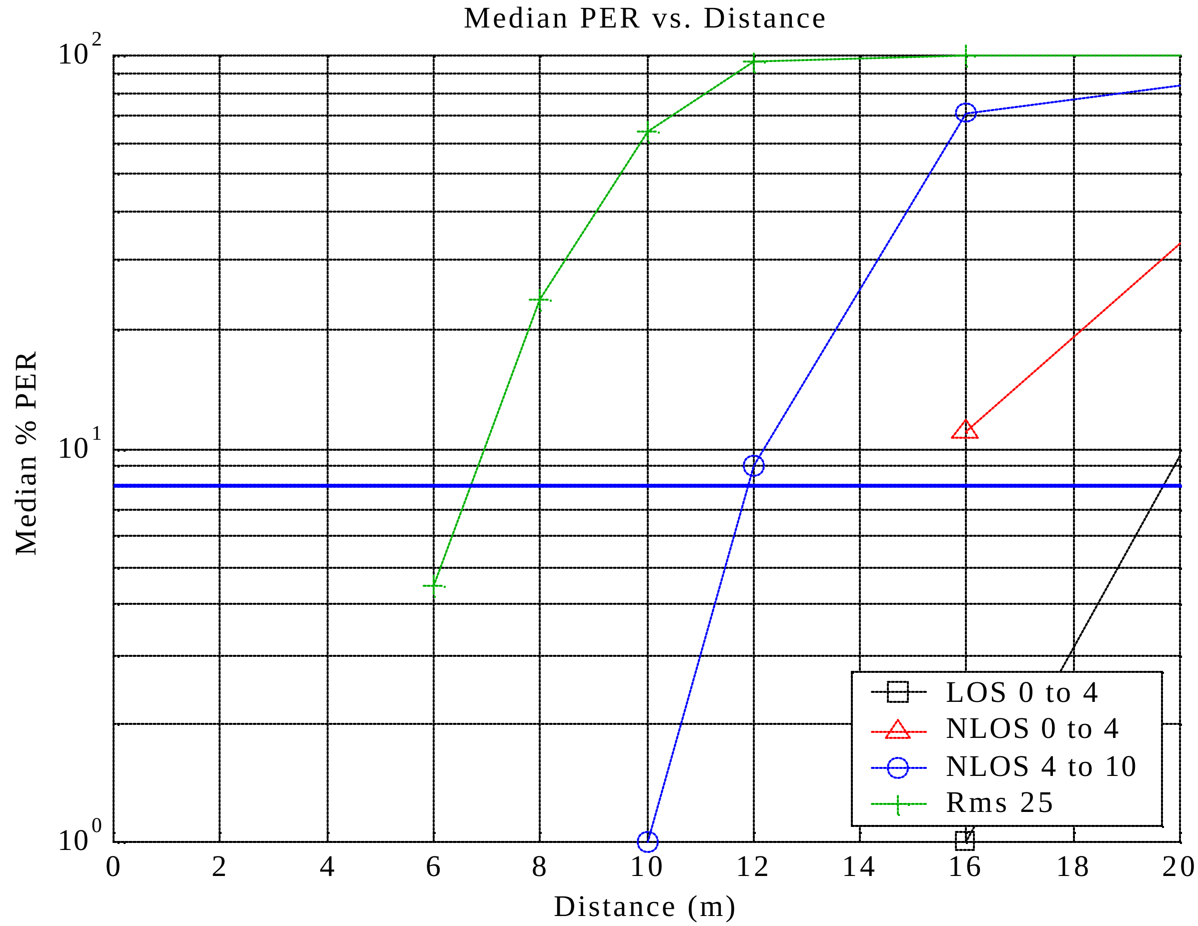

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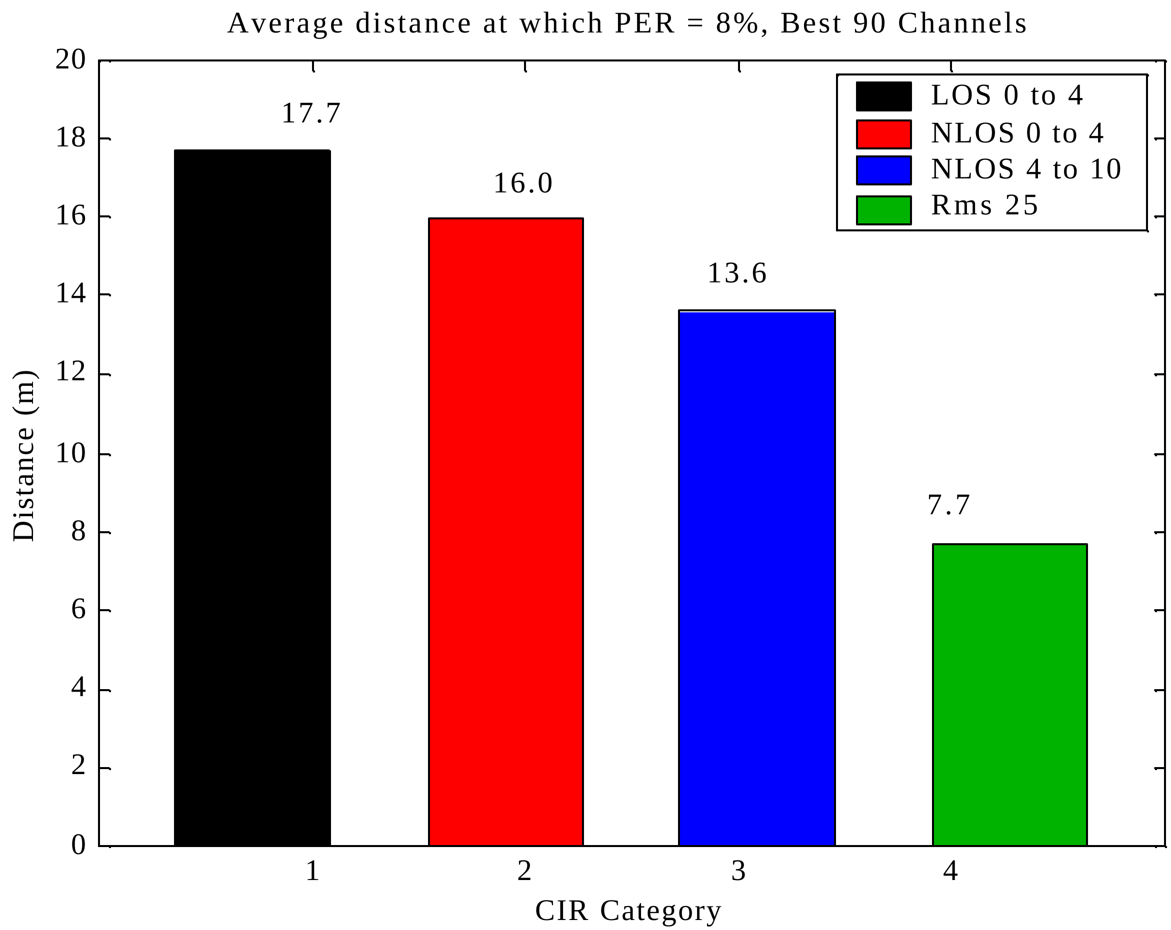

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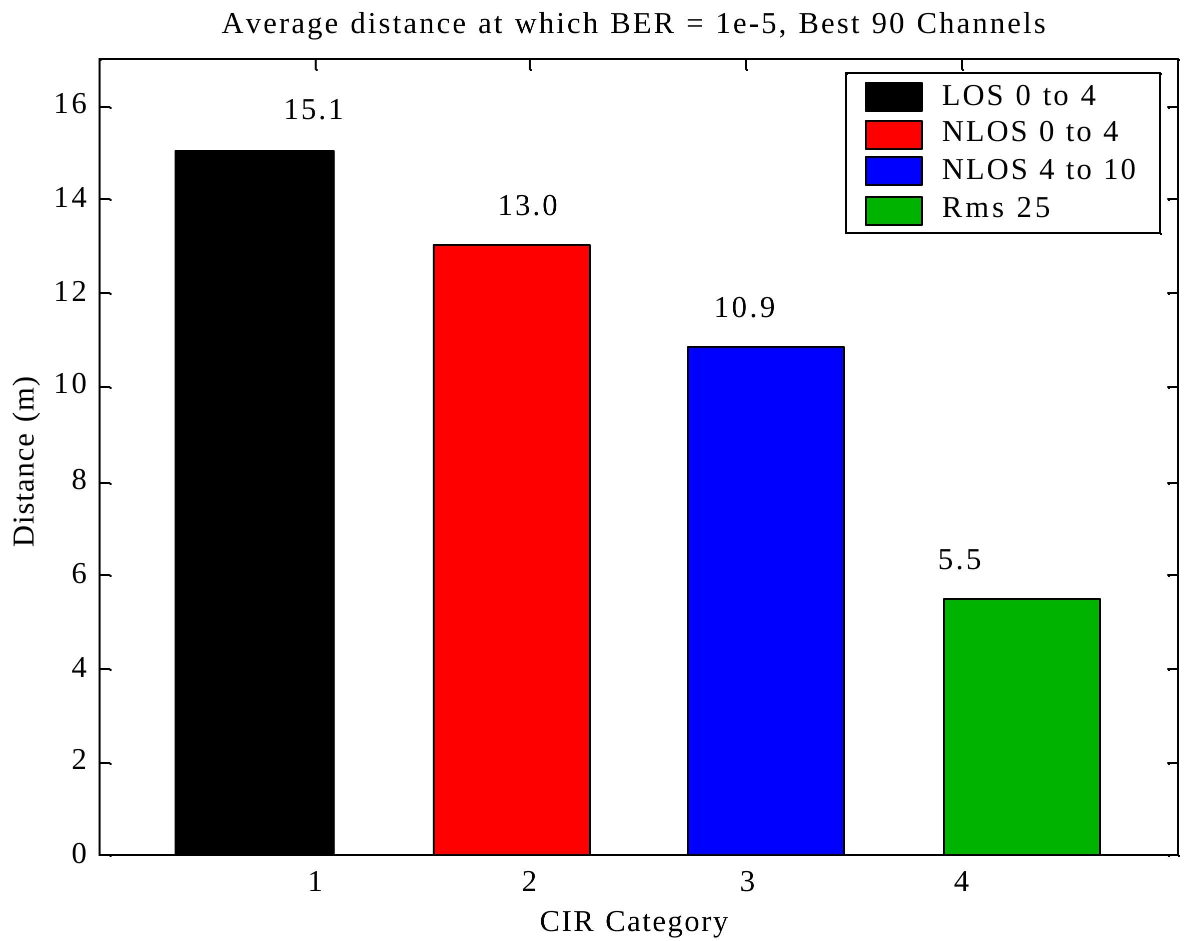

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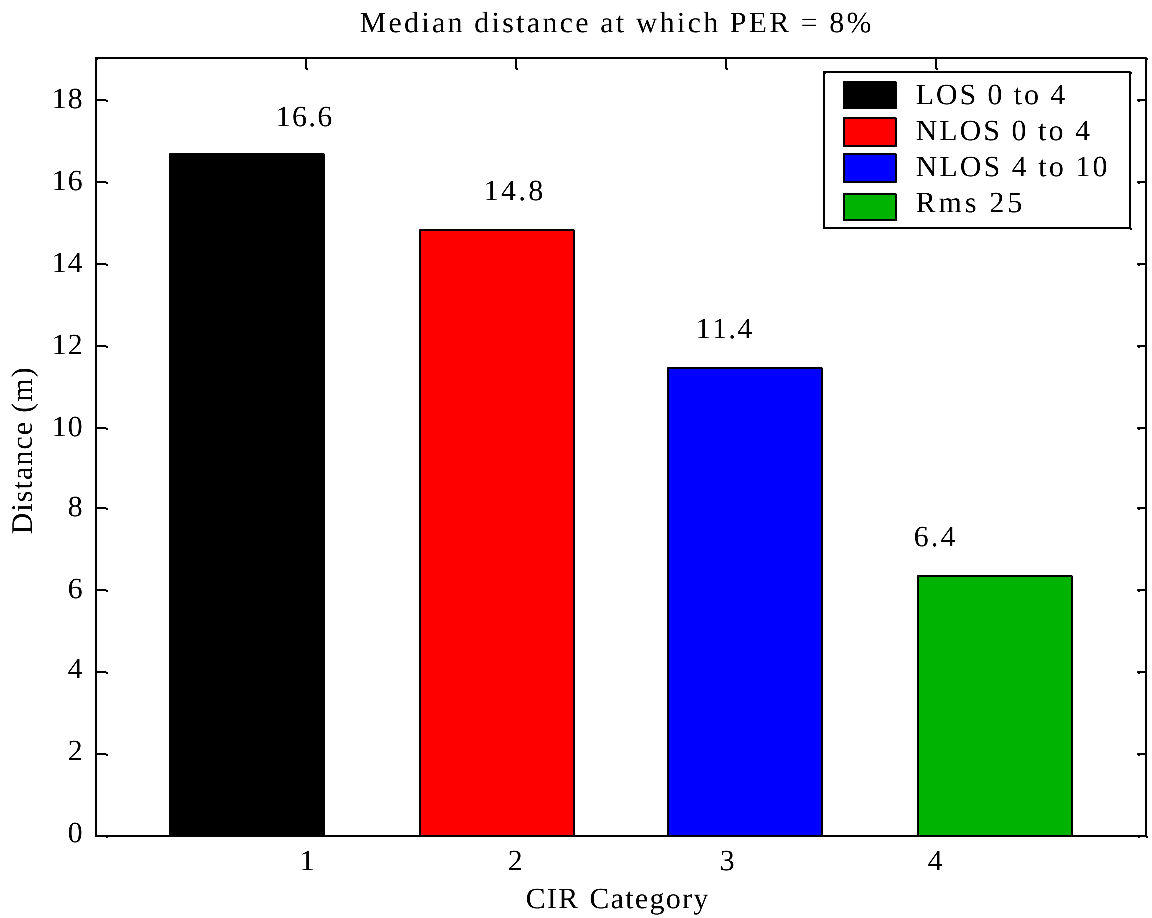

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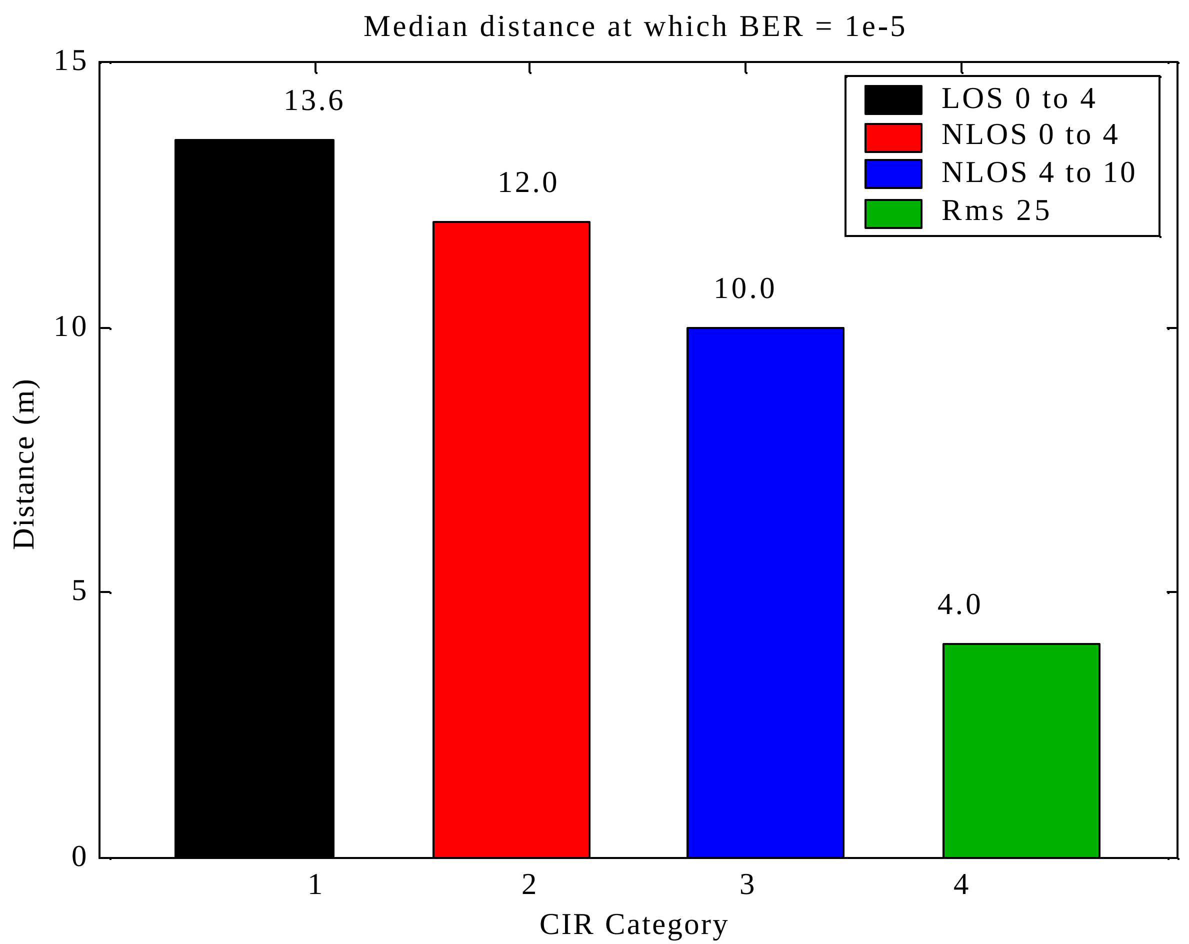

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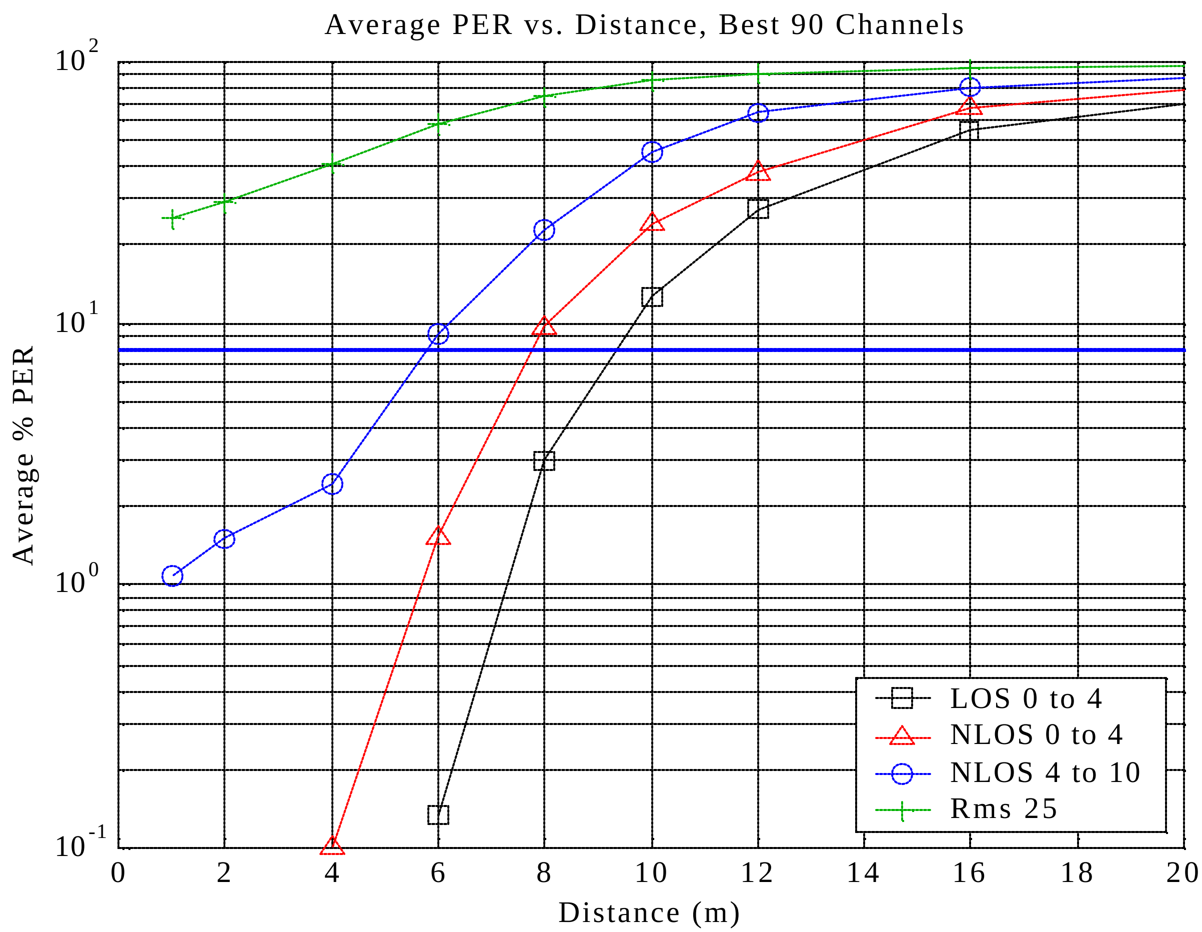

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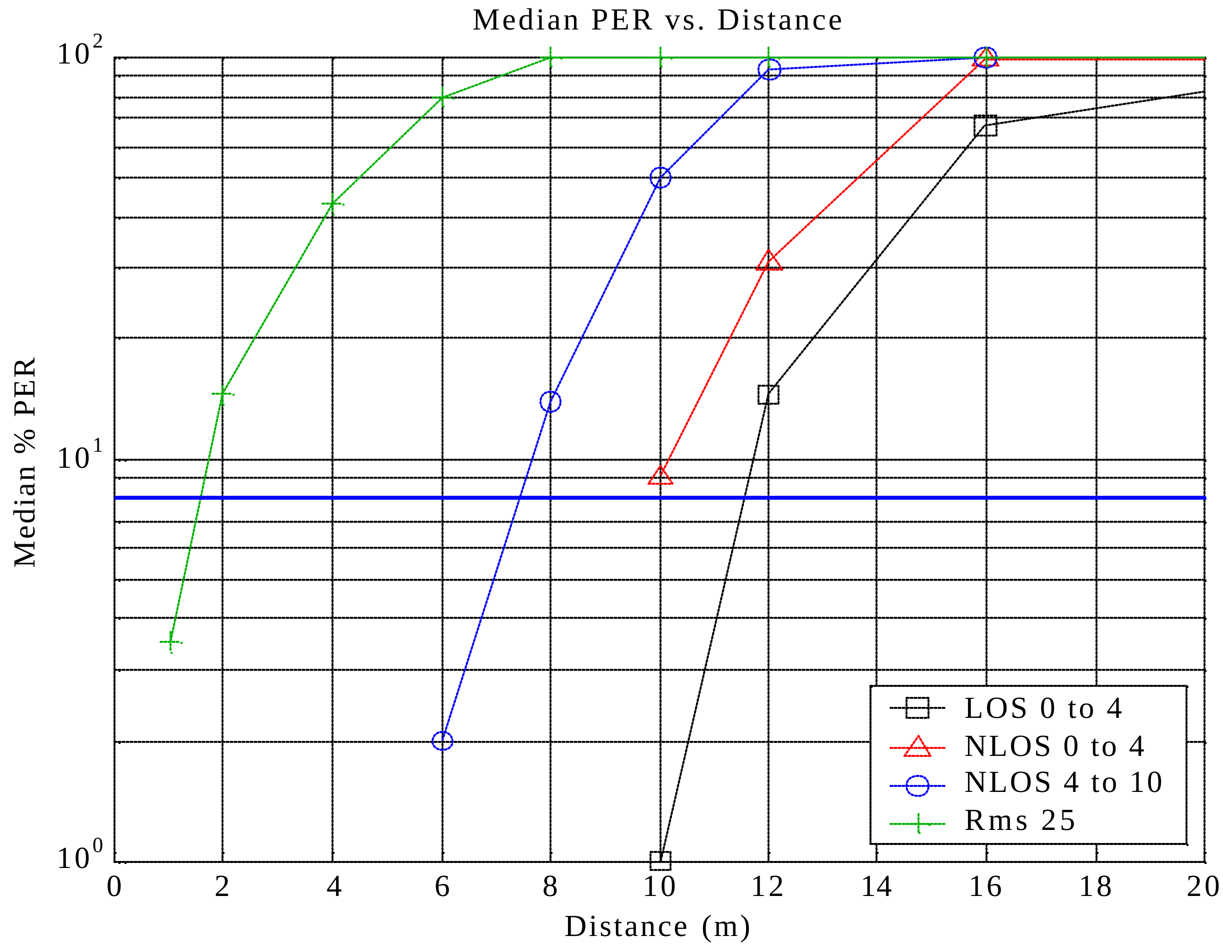

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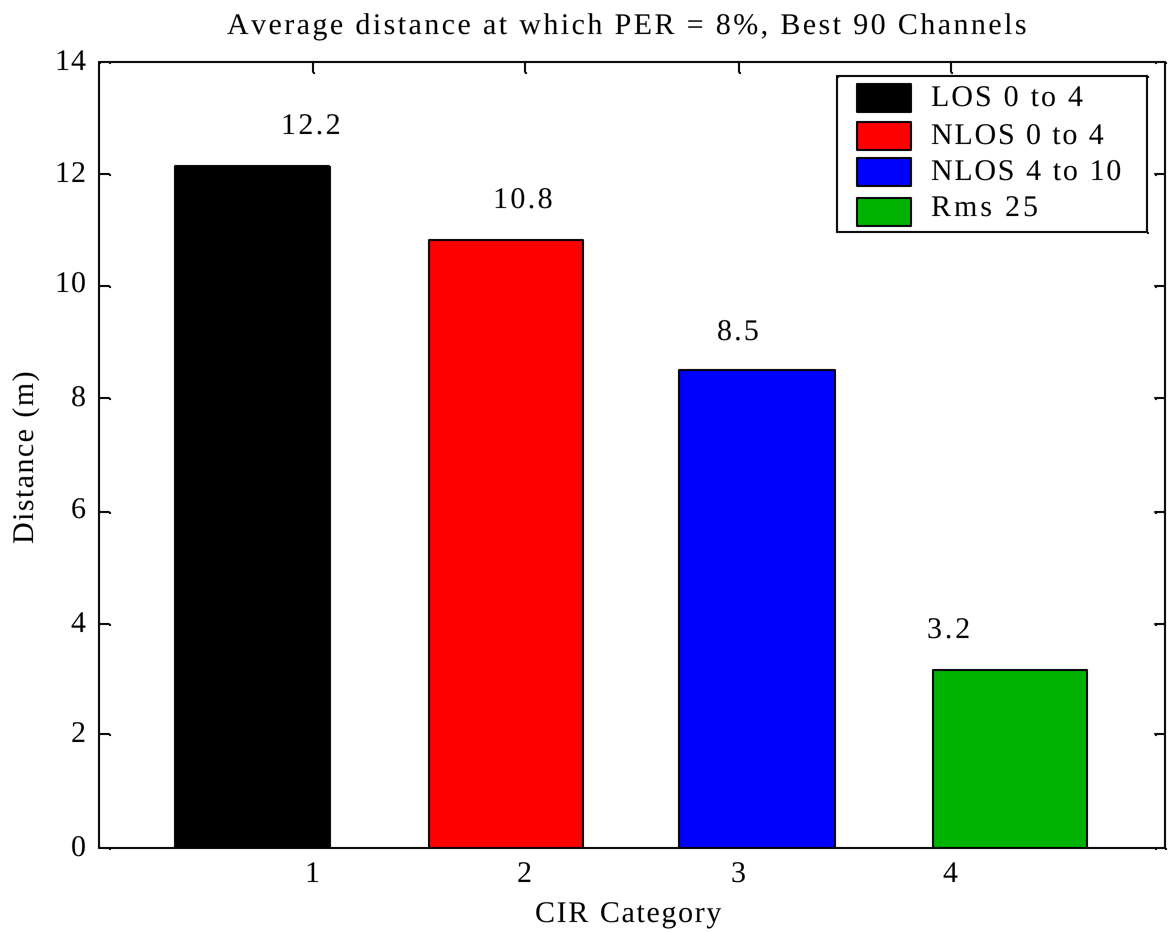

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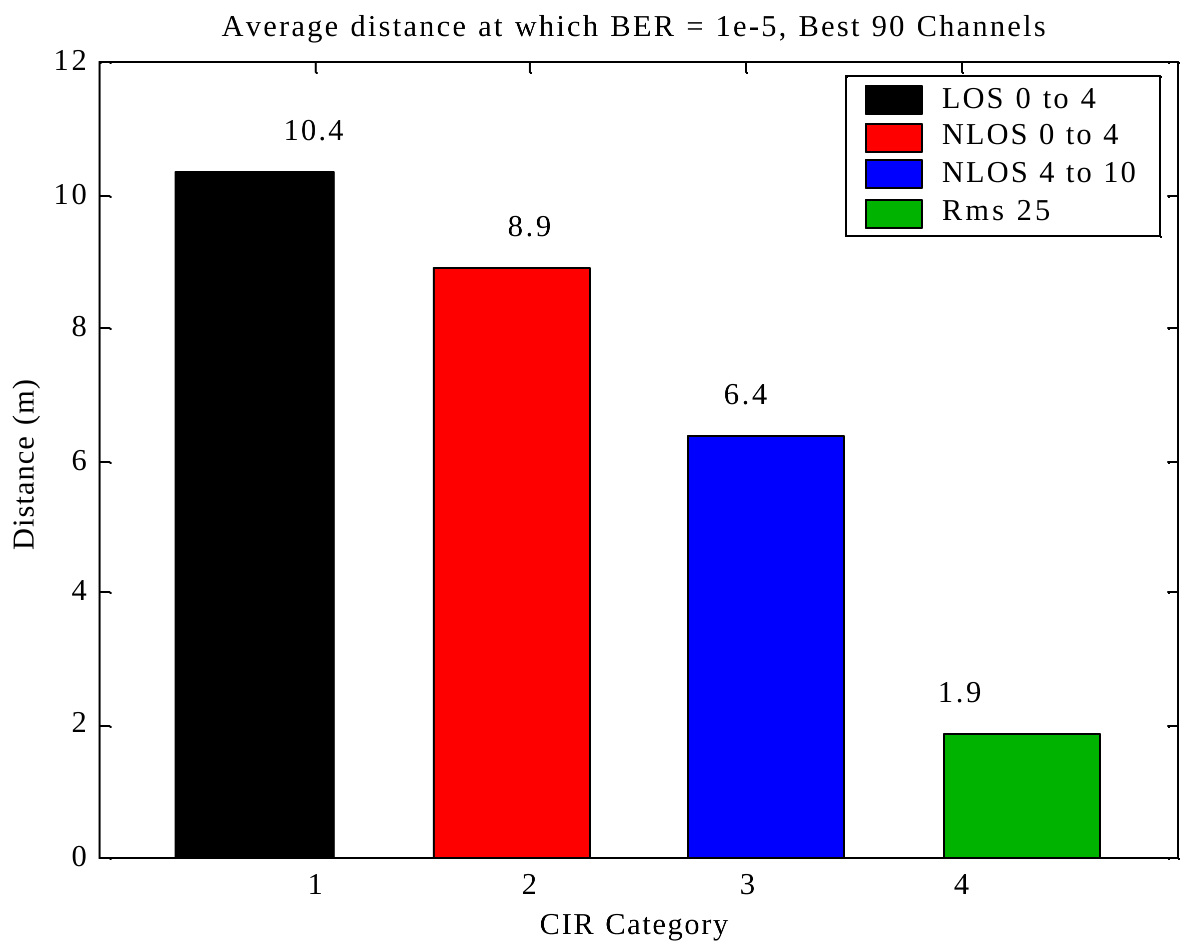

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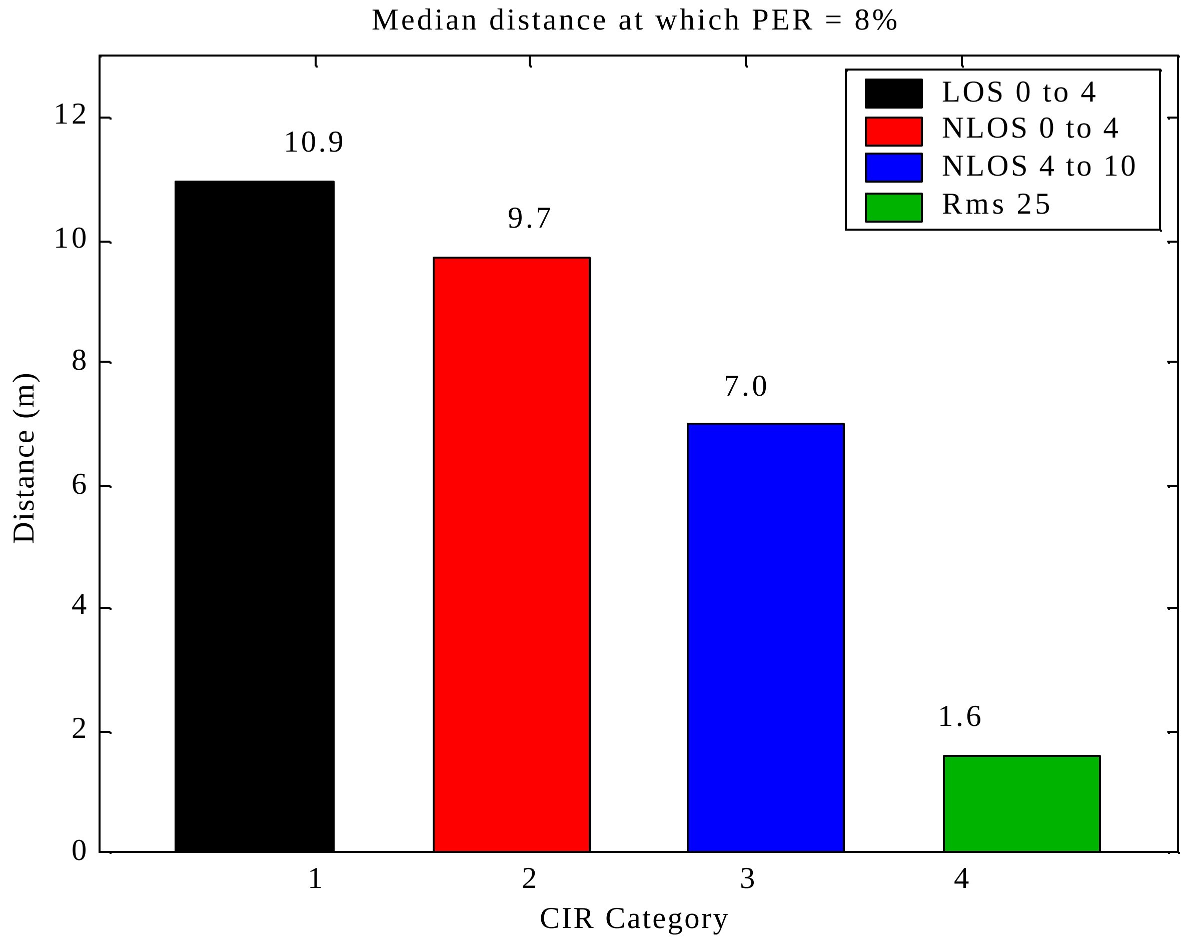

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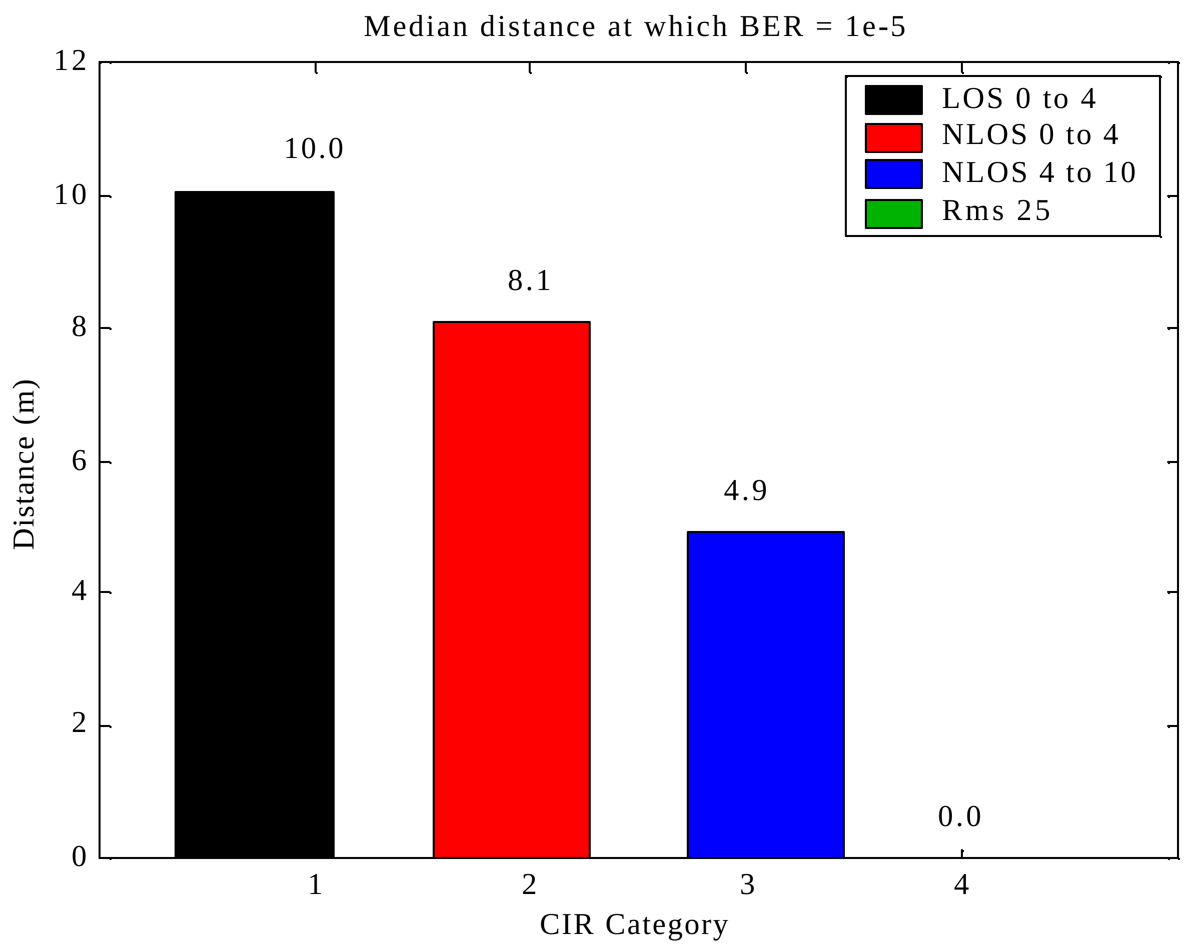
- QPSK, ½-rate FEC
- 2 Rake teeth



Comparison of 1- and 2-fingered RAKE performance

Average Distance (in meters) At Which 8% PER is Attained

	128.4 Mb/s		256.7 Mb/s	
	1 finger	2 fingers	1 finger	2 fingers
CM1	15.3	17.7	9.9	12.2
CM2	13.3	16.0	8.1	10.8
CM3	10.7	13.6	5.2	8.5
CM4	5.3	7.7	1.1	3.2

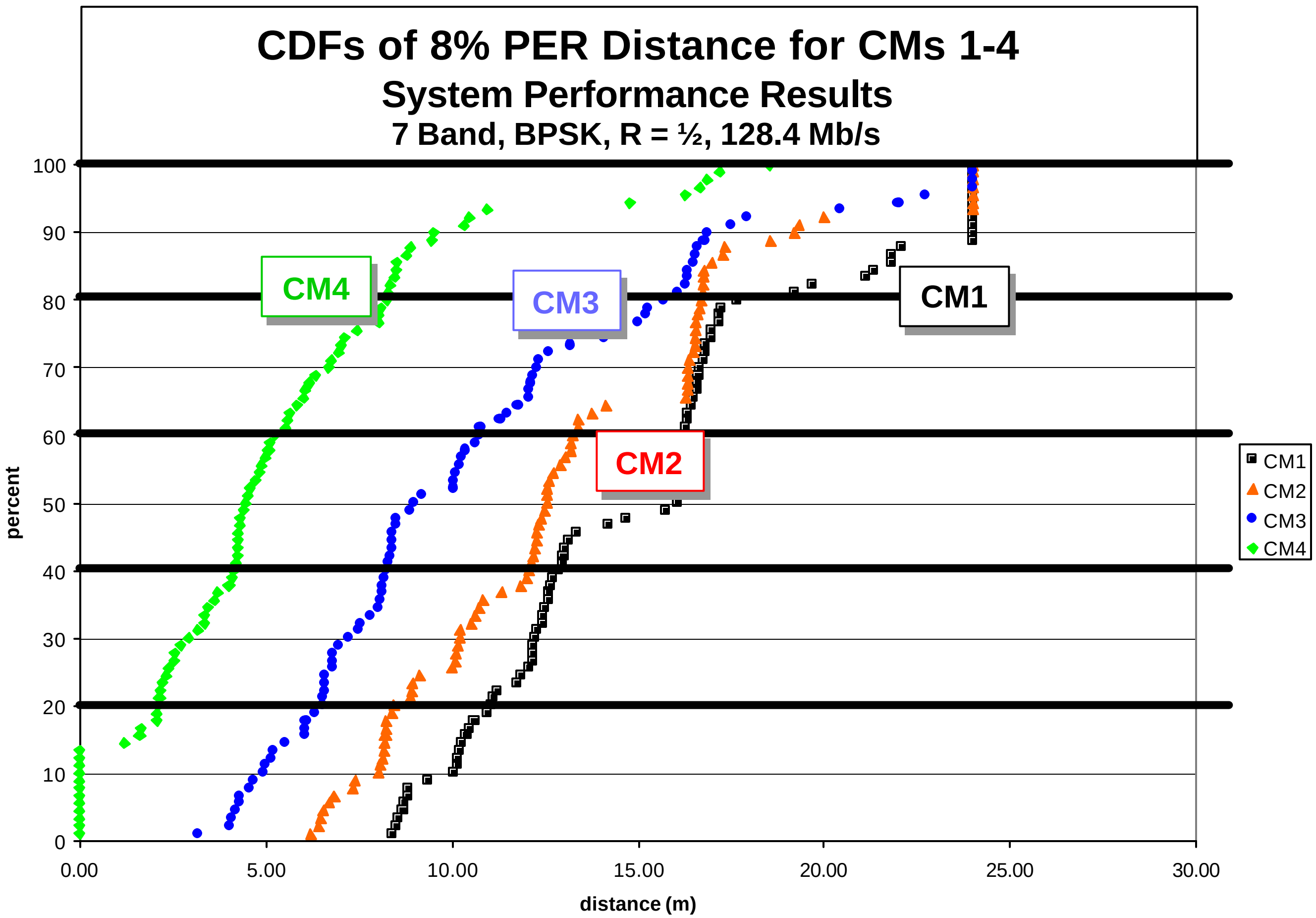
Simultaneously Operating Piconets

- **Goal is to evaluate uncoordinated piconet channelization in multipath**
- **Evaluation on-going**
- **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 this 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

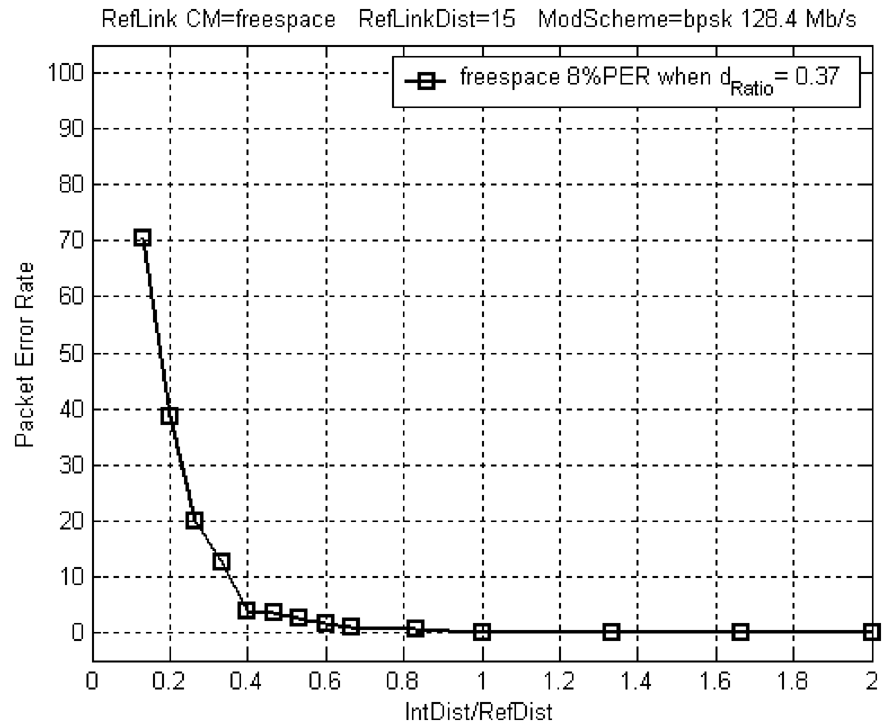


Simultaneously Operating Piconets

- **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 (thus giving us 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.**

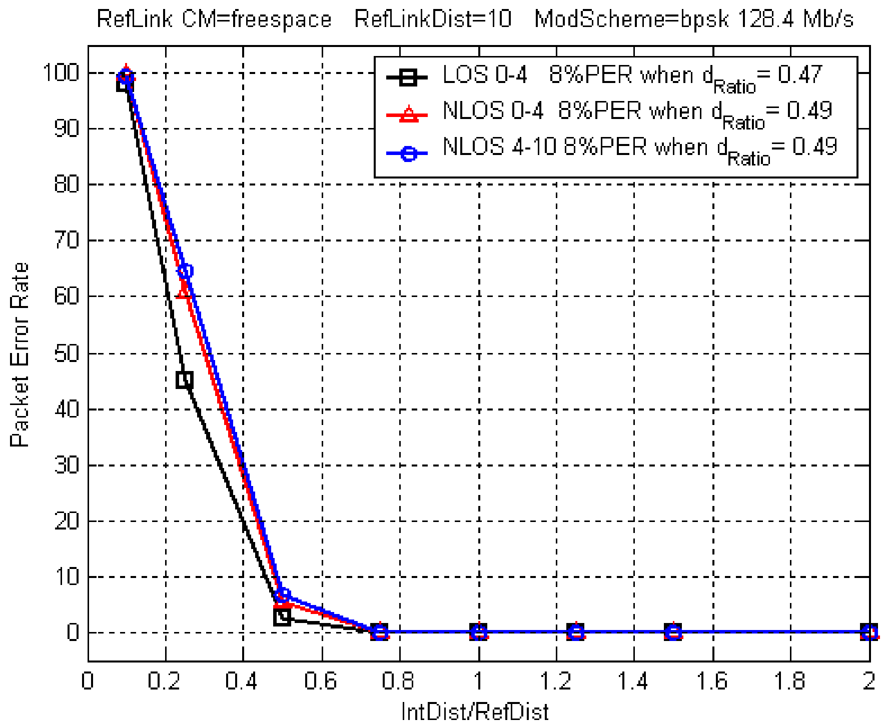
Simultaneously Operating Piconets
N = 1 interferer

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

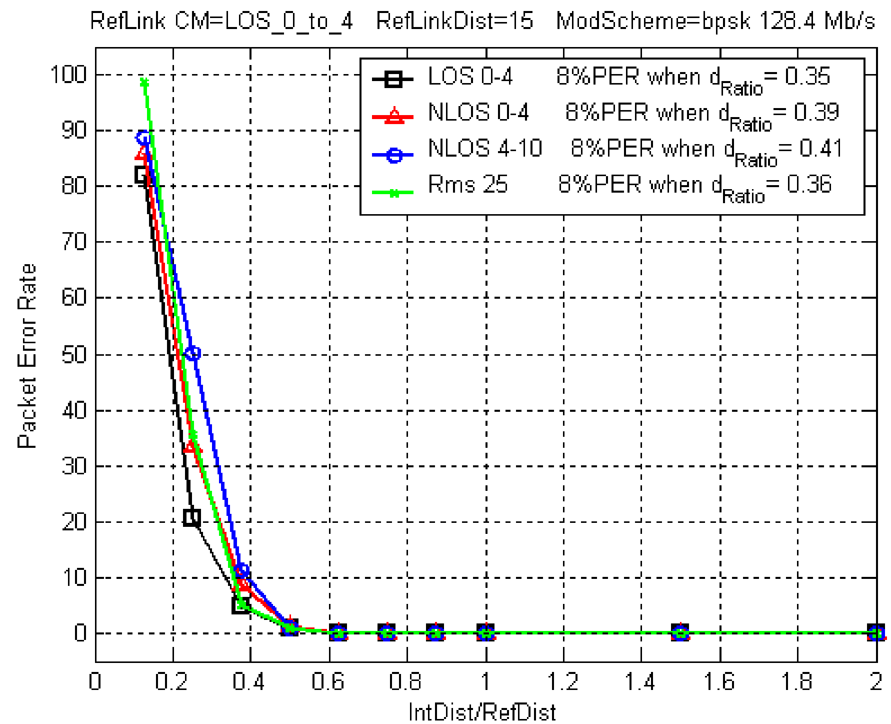
Num. Bands	**7**
Modulation	**BPSK, ½-rate FEC**
Data Rate	**128.5 Mb/s**
Reference Link	**Freespace, 10 m**
Interfering Links	**All CIRs in CMs 1-3**



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**

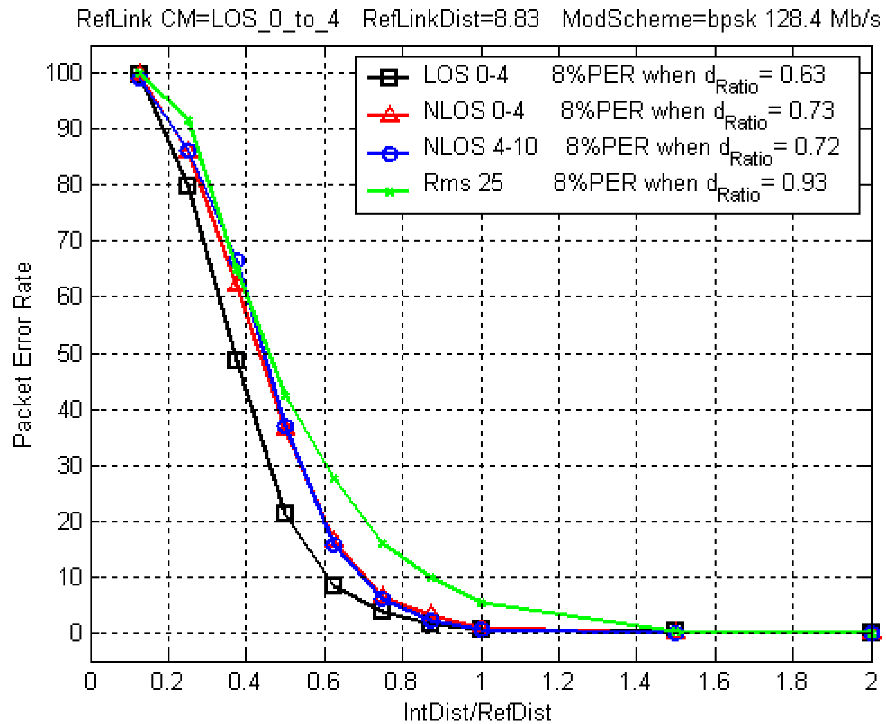


100th percentile System Performance CIR

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**

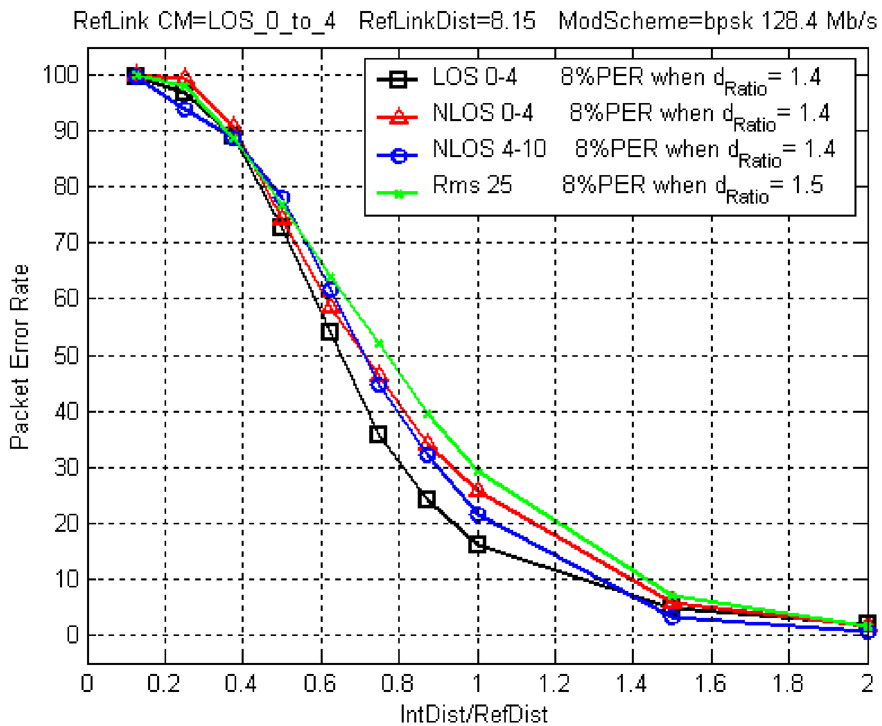


80th percentile System Performance CIR

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	**CM1, CIR 83**
Interfering Links	**CMs 1-4, CIRs 1-15**

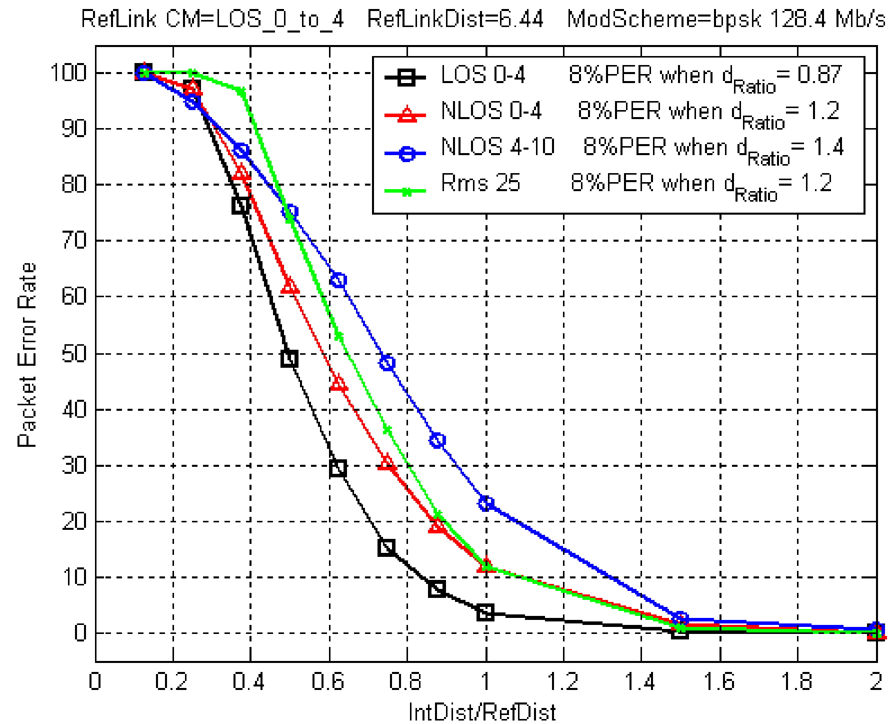


60th percentile System Performance CIR

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	**CM1, CIR 81**
Interfering Links	**CMs 1-4, CIRs 11-2!**

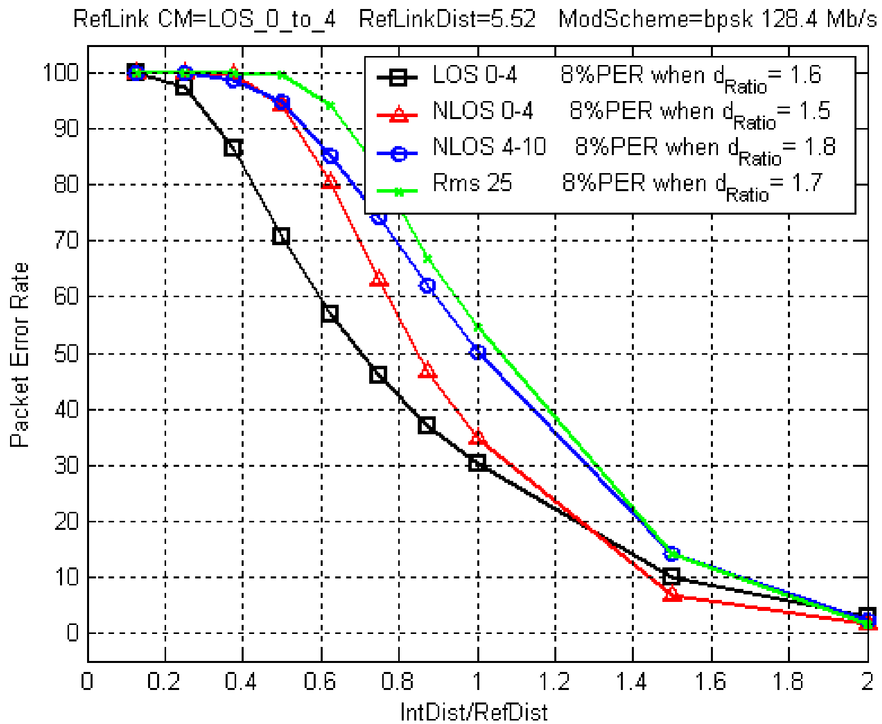


40th percentile System Performance CIR

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 40**
Interfering Links	**CMs 1-4, CIRs 81-95**

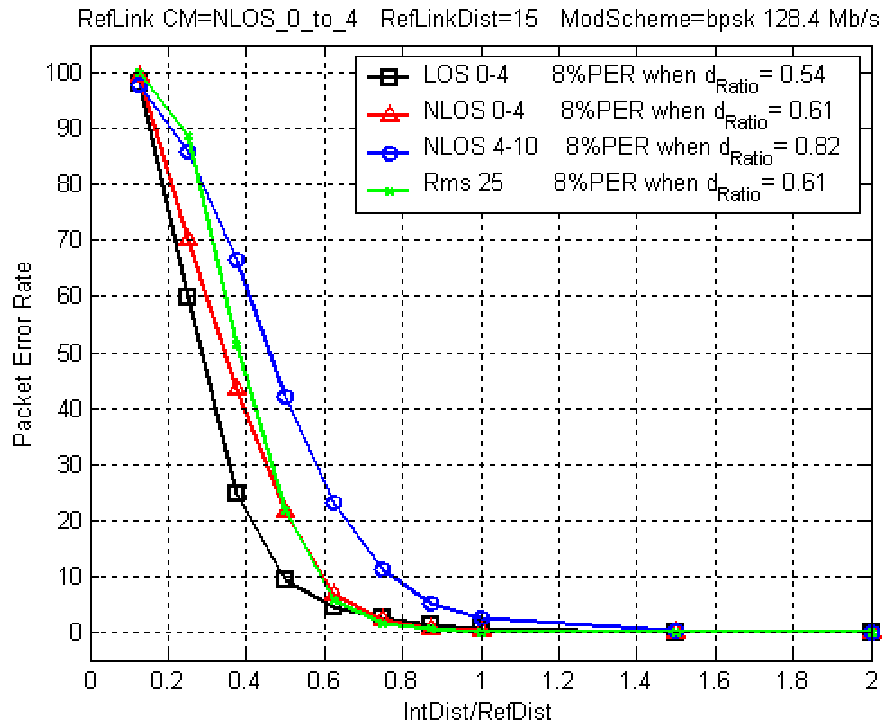


20th percentile System Performance CIR

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

Simultaneously Operating Piconets N = 1 interferer

Num. Bands	**7**
Modulation	**BPSK, ½-rate FEC**
Data Rate	**128.5 Mb/s**
Reference Link	**CM2, CIR 8**
Interfering Links	**CMs 1-4, CIRs 11-25**

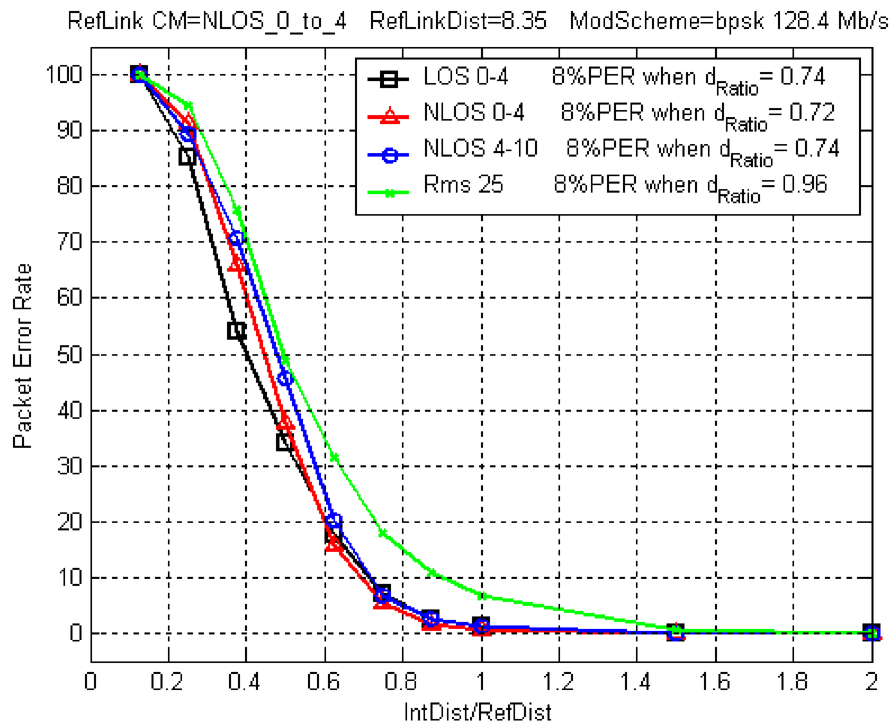


100th percentile System Performance CIR

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	**CM2, CIR 56**
Interfering Links	**CMs 1-4, CIRs 1-15**

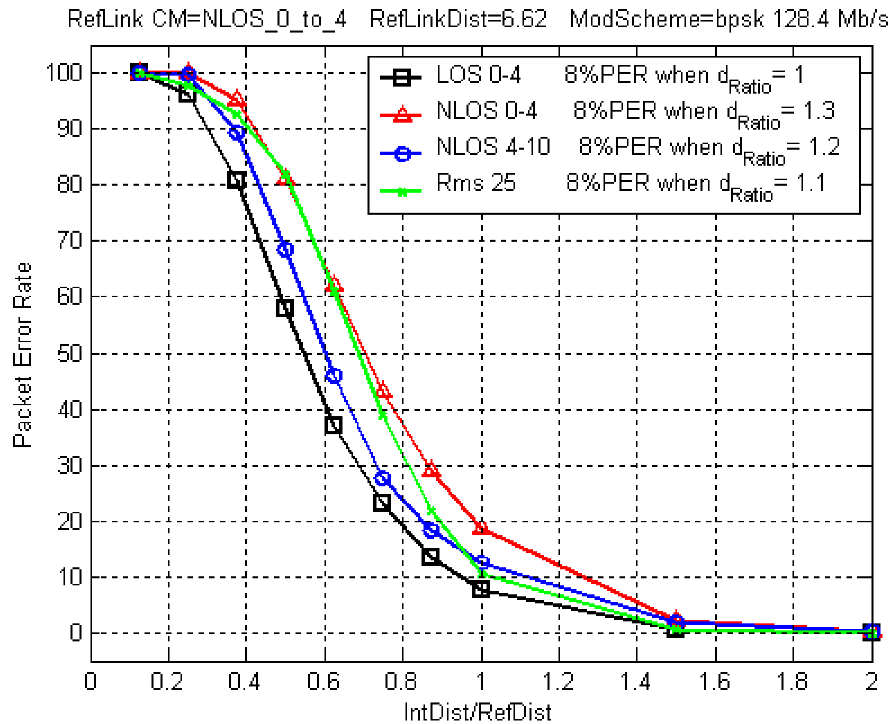


80th percentile System Performance CIR

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	**CM2, CIR 42**
Interfering Links	**CMs 1-4, CIRs 51-65**

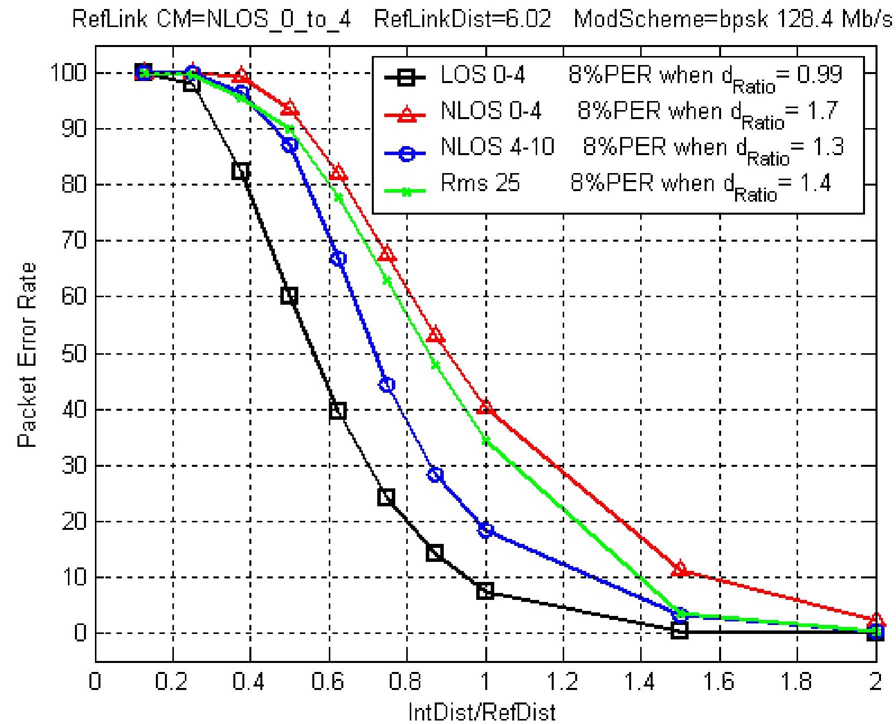


60th percentile System Performance CIR

Average performance in CMs 1-4, CIRs 51-65

Simultaneously Operating Piconets
N = 1 interferer

Num. Bands	**7**
Modulation	**BPSK, ½-rate FEC**
Data Rate	**128.5 Mb/s**
Reference Link	**CM2, CIR 31**
Interfering Links	**CMs 1-4, CIRs 51-65**

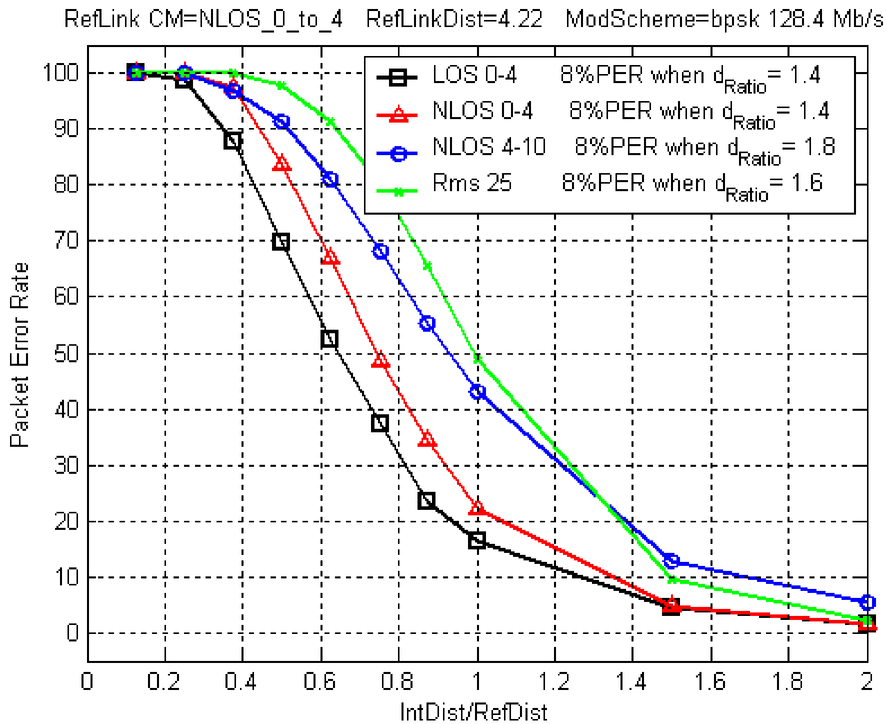


40th percentile System Performance CIR

Average performance in CMs 1-4, CIRs 51-65

Simultaneously Operating Piconets
N = 1 interferer

Num. Bands	**7**
Modulation	**BPSK, ½-rate FEC**
Data Rate	**128.5 Mb/s**
Reference Link	**CM2, CIR 58**
Interfering Links	**CMs 1-4, CIRs 81-95**

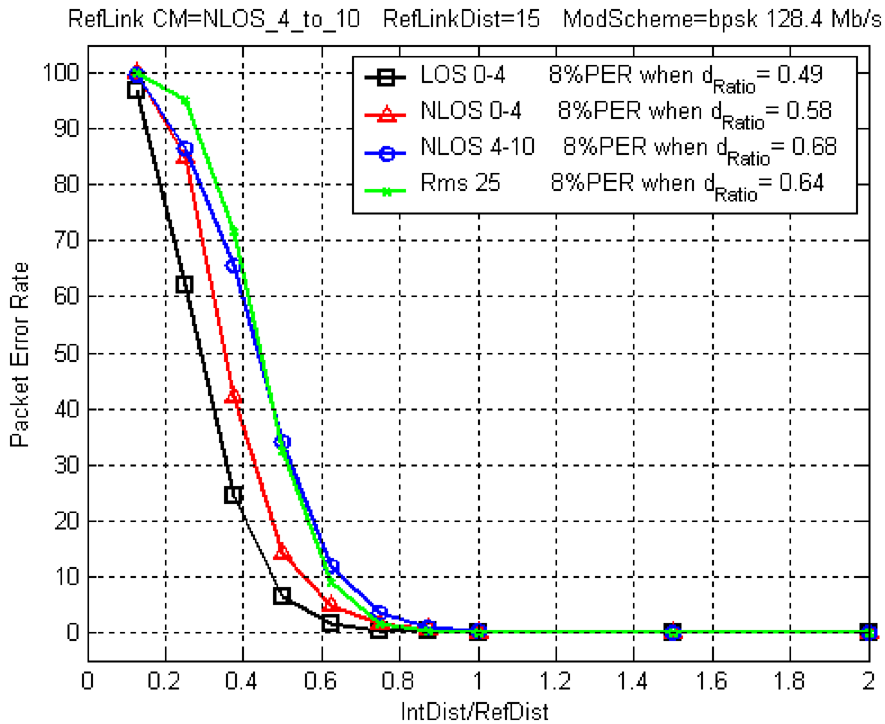


20th percentile System Performance CIR

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

Simultaneously Operating Piconets
N = 1 interferer

Num. Bands	**7**
Modulation	**BPSK, ½-rate FEC**
Data Rate	**128.5 Mb/s**
Reference Link	**CM3, CIR 26**
Interfering Links	**CMs 1-4, CIRs 81-95**

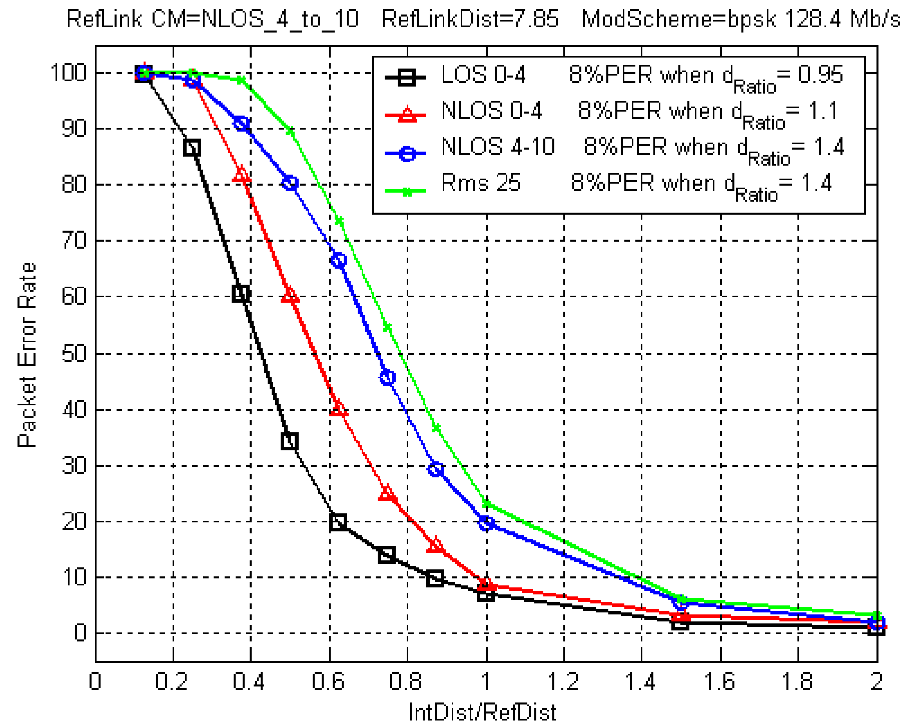


100th percentile System Performance CIR

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

Simultaneously Operating Piconets
N = 1 interferer

Num. Bands	**7**
Modulation	**BPSK, ½-rate FEC**
Data Rate	**128.5 Mb/s**
Reference Link	**CM3, CIR 39**
Interfering Links	**CMs 1-4, CIRs 81-95**

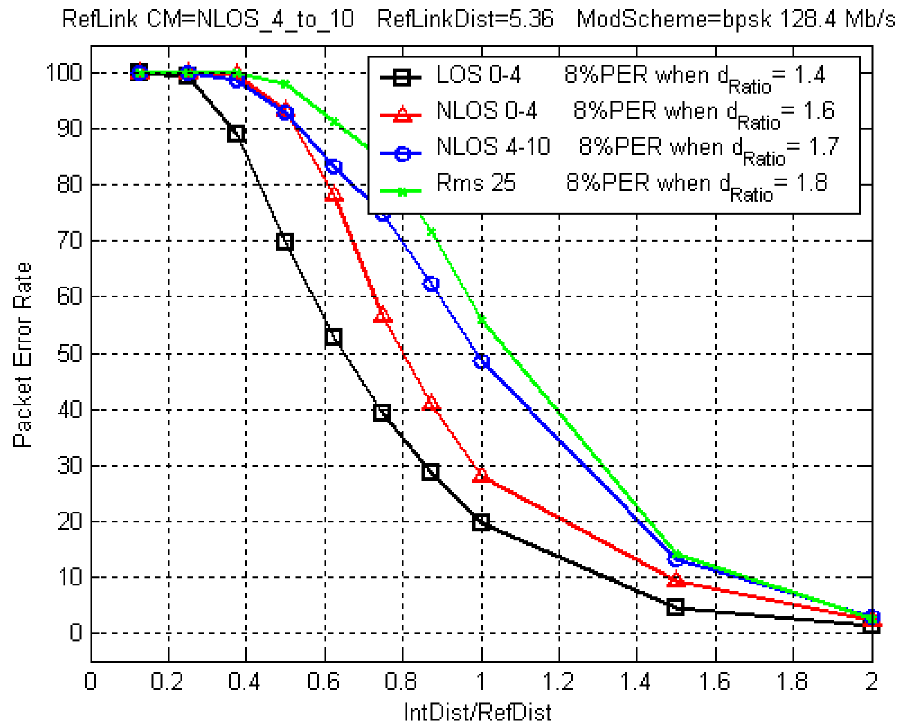


80th percentile System Performance CIR

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

Simultaneously Operating Piconets
N = 1 interferer

Num. Bands	**7**
Modulation	**BPSK, ½-rate FEC**
Data Rate	**128.5 Mb/s**
Reference Link	**CM3, CIR 11**
Interfering Links	**CMs 1-4, CIRs 81-95**

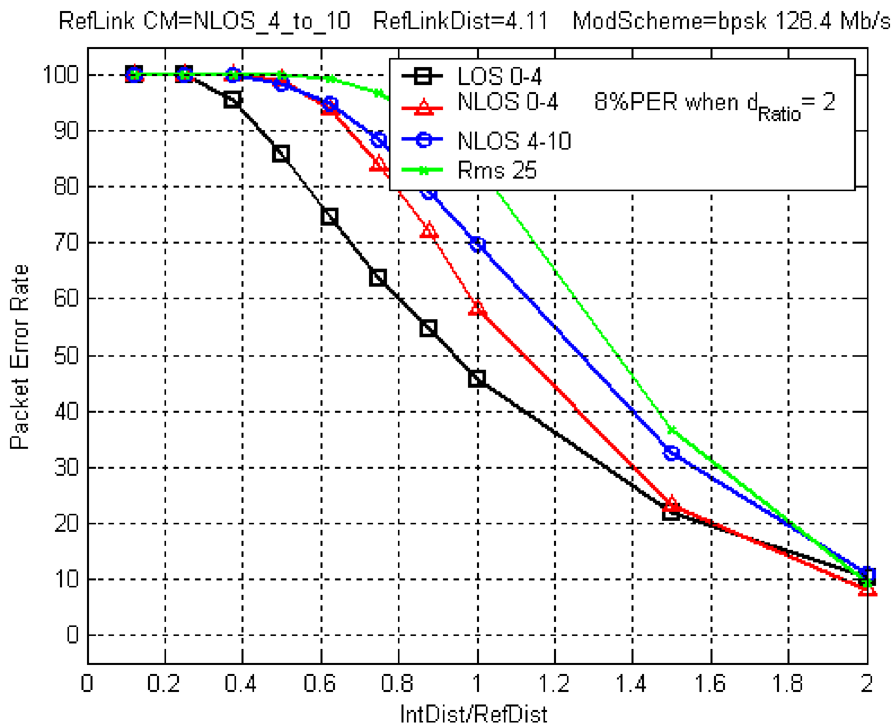


60th percentile System Performance CIR

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

Simultaneously Operating Piconets
N = 1 interferer

Num. Bands	**7**
Modulation	**BPSK, ½-rate FEC**
Data Rate	**128.5 Mb/s**
Reference Link	**CM3, CIR 60**
Interfering Links	**CMs 1-4, CIRs 81-95**

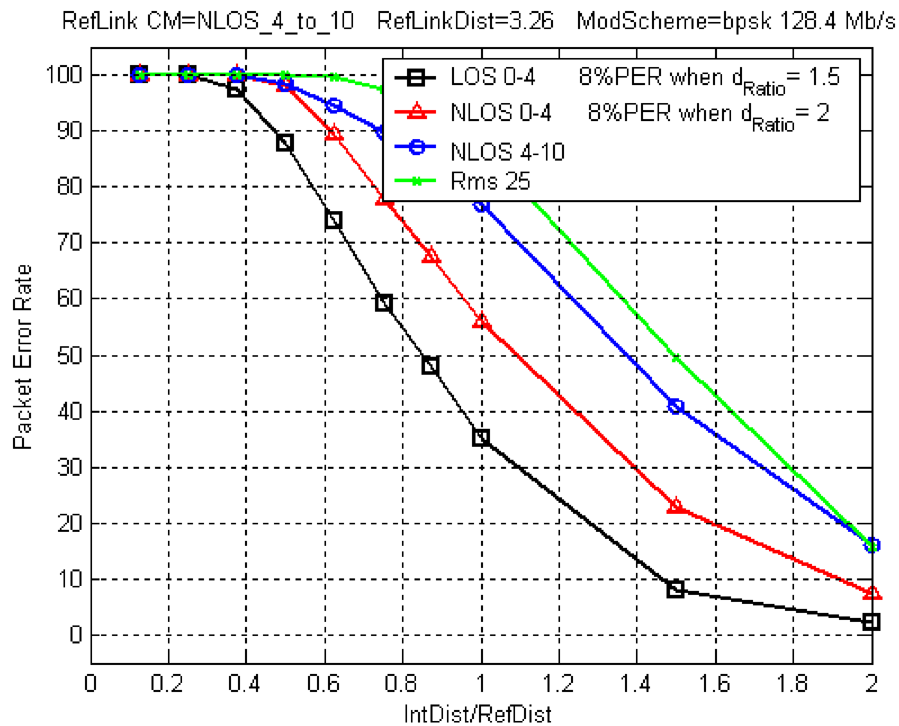


40th percentile System Performance CIR

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

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	----

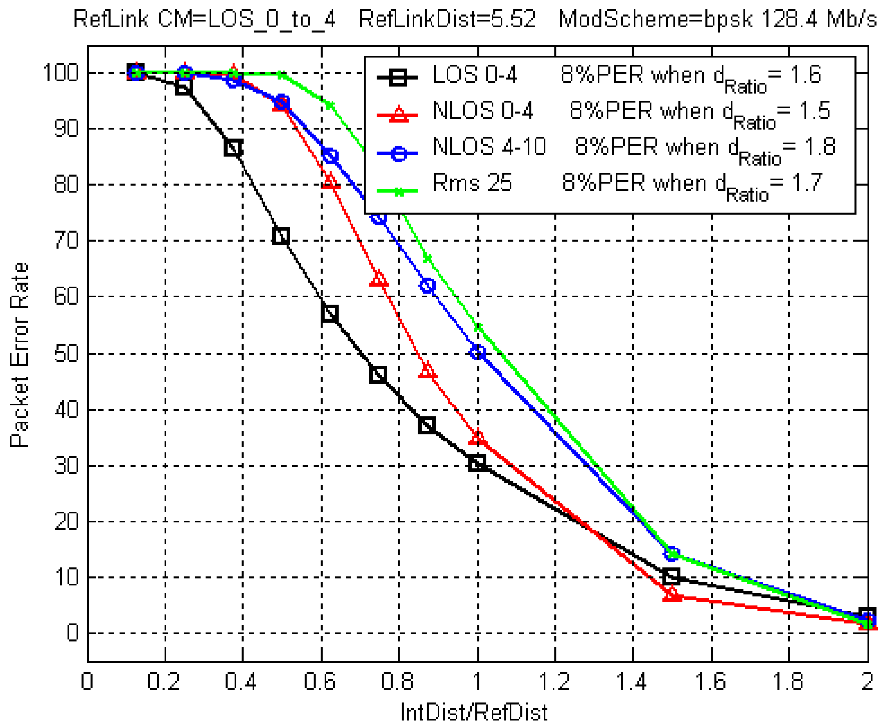
- This suggests mitigation strategies…

Strategies for Enhanced Channelization in Harsh Environments

- If there is significant fading on several bands, simply dropping the faded bands is an option
- For very severe multipath and/or near-far scenarios, use FDMA option
- Both strategies can 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**

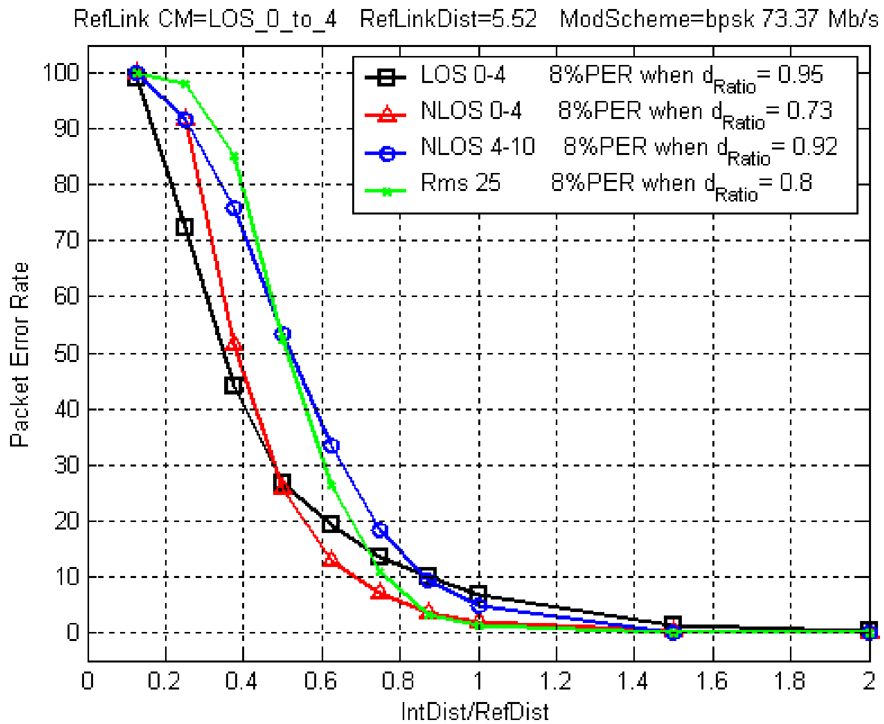


20th percentile System Performance CIR

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)**



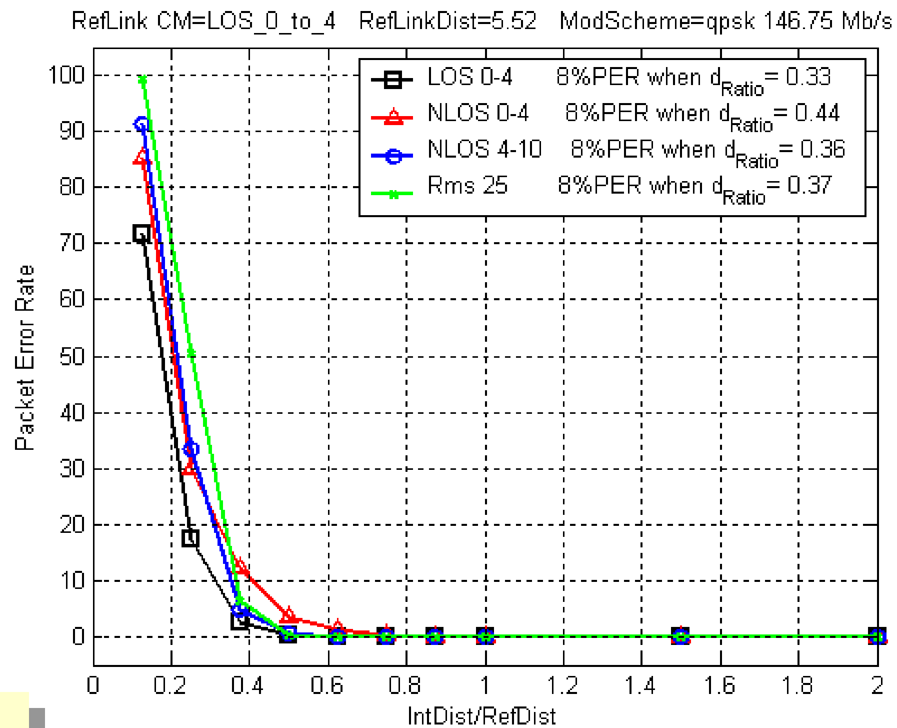
20th percentile System Performance CIR

- 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

SOP Summary

- TFMA as implemented provides 8-10 dB of isolation (17-dB coding isolation, reduced by rectified cosine envelope, 437-MHz band spacing, etc.) between piconets in freespace.
- Multipath will decrease piconet isolation.
- TFMA can be enhanced by dropping severely faded bands in a multipath environment.
- FDMA techniques will be utilized in severe near/far cases.

Signal Acquisition

Acquisition Thresholding Algorithm

- During Threshold Timeout and Coarse Optimize the time-frequency space is searched serially while the Barker rotation space is searched in parallel
- During Threshold Timeout energy is calculated at each search location for ALL possible rotations of the Barker sequence
- Transition from Threshold Timeout to Coarse Optimize is made when the threshold equation is satisfied

$$\frac{\text{Max Energy from all Barker rotations}}{\text{Average Energy from other Barker rotations}} > \text{Threshold}$$

Signal Acquisition

Acquisition Thresholding Algorithm

- During Coarse Optimize the entire time frequency sequence is searched to find the location and Barker rotation which maximizes energy
- During Fine Optimize one chip time interval around the Coarse Optimize maximum energy location is searched using only the Coarse Optimize winning Barker rotation

Signal acquisition

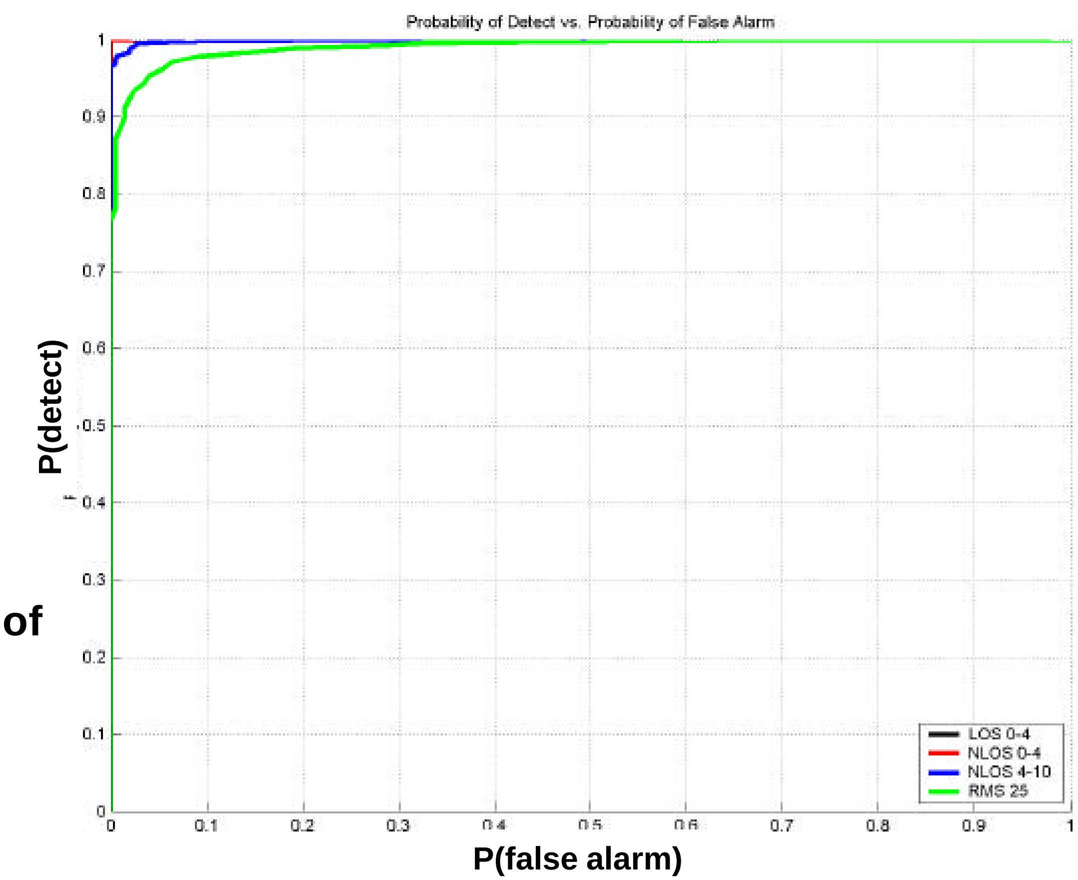
P(detect) vs. P(false alarm): multipath channels
link distance = 10 meters

Num. Bands **7**

Reference Link **10 m**

Path Loss Exponent **2 for all CIRs**

Channel Models **All 400 CIRs from CMs 1-4. Average of best 90 from each CM.**



Signal acquisition

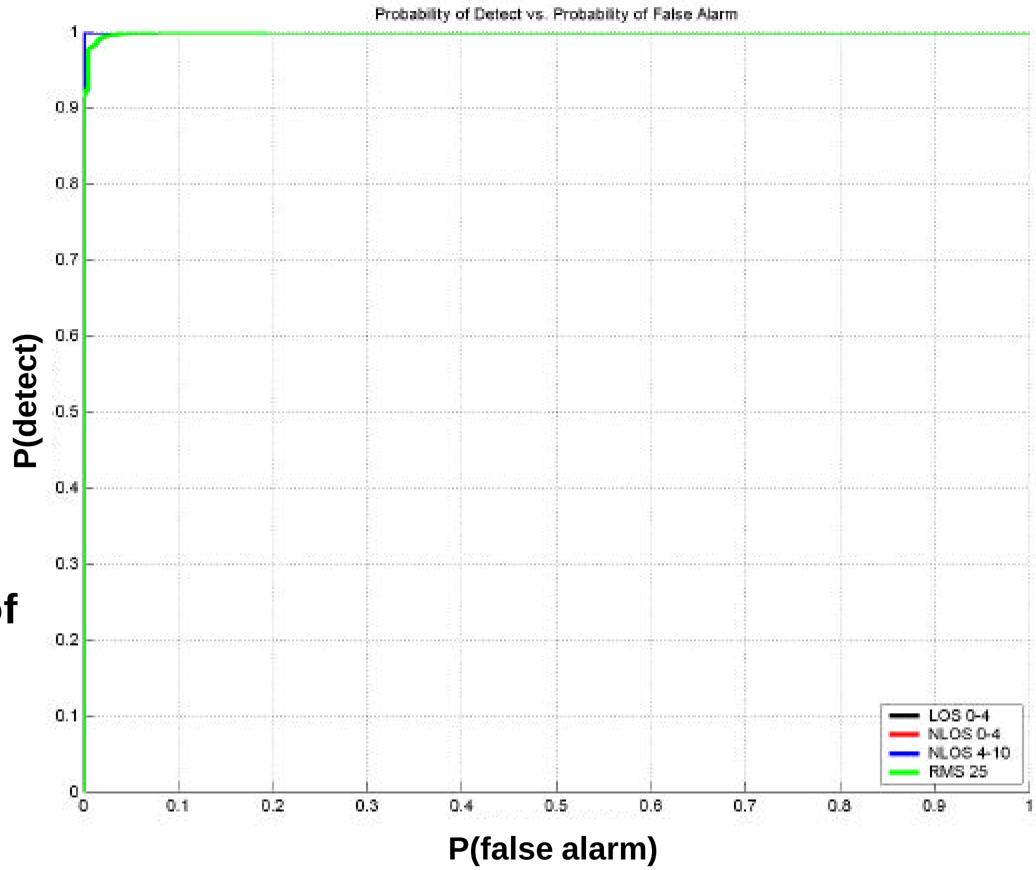
P(detect) vs. P(false alarm): multipath channels
link distance = 4 meters

Num. Bands **7**

Reference Link **4 m**

Path Loss Exponent **2 for all CIRs**

Channel Models **All 400 CIRs from CMs 1-4. Average of best 90 from each CM.**



Coexistence

- **UWB impact on 802.11a, 802.11b, 802.15.1, 802.15.3, and 802.15.4 assessed.**
- **AWGN analysis**
  - **UWB device appears noise-like to victim receiver**
- **Determined “802.15.3a Coexistence Mask”**
  - **Emission limits necessary to meet “minimum” and “desired” coexistence criteria from Selection Criteria document.**
- **Assessed filtering required for our waveforms to meet coexistence mask**
- **Banded approach naturally reduces emissions in the selected bands thereby reducing the additional filtering needs in the 802.15.3a radio implementation**

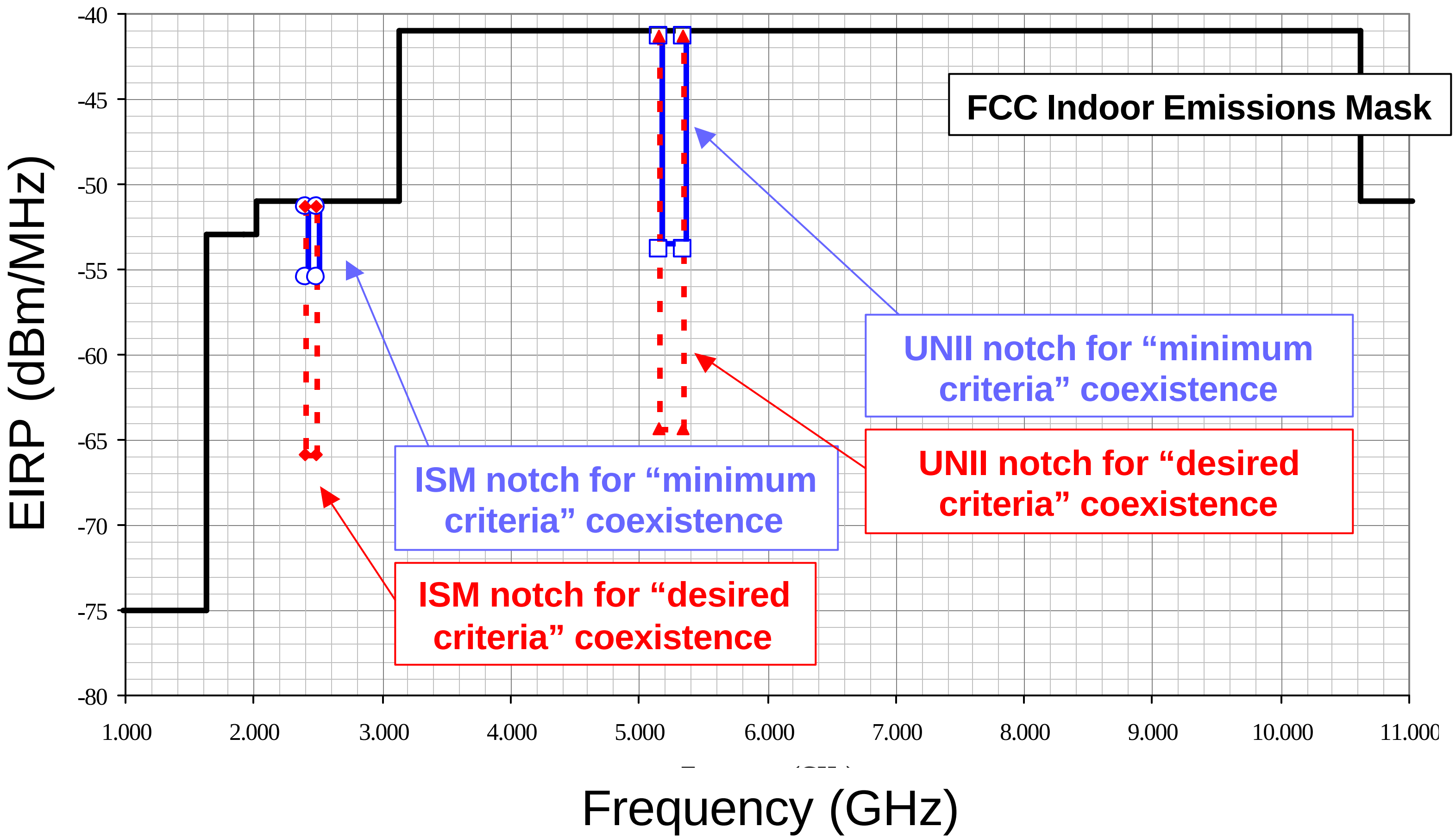
Coexistence Calculations

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:

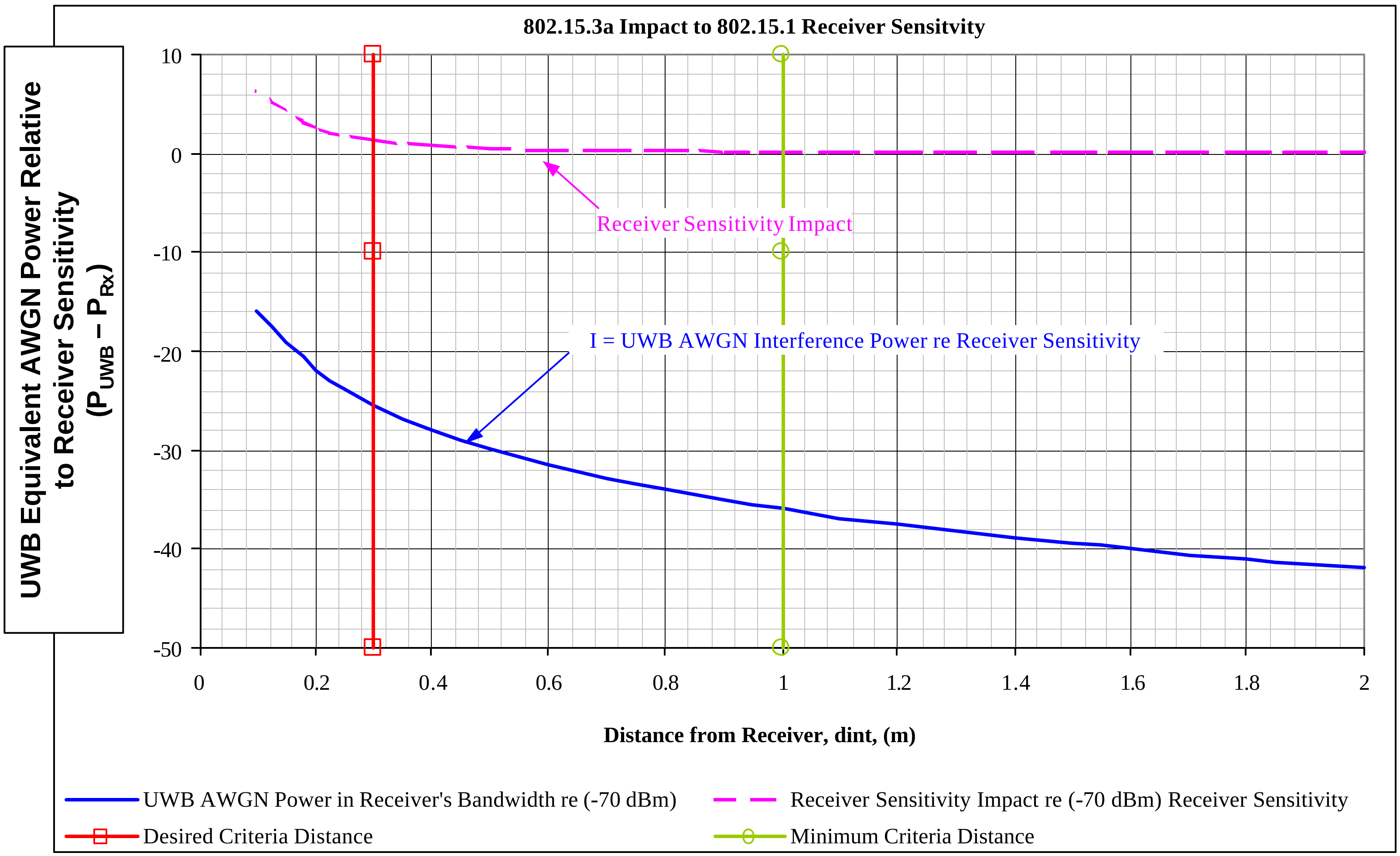
*1) The EIRP density values are the smallest values of a comparison between the FCC handheld limit and the individual wireless service coexistence calculations.

Coexistence Mask



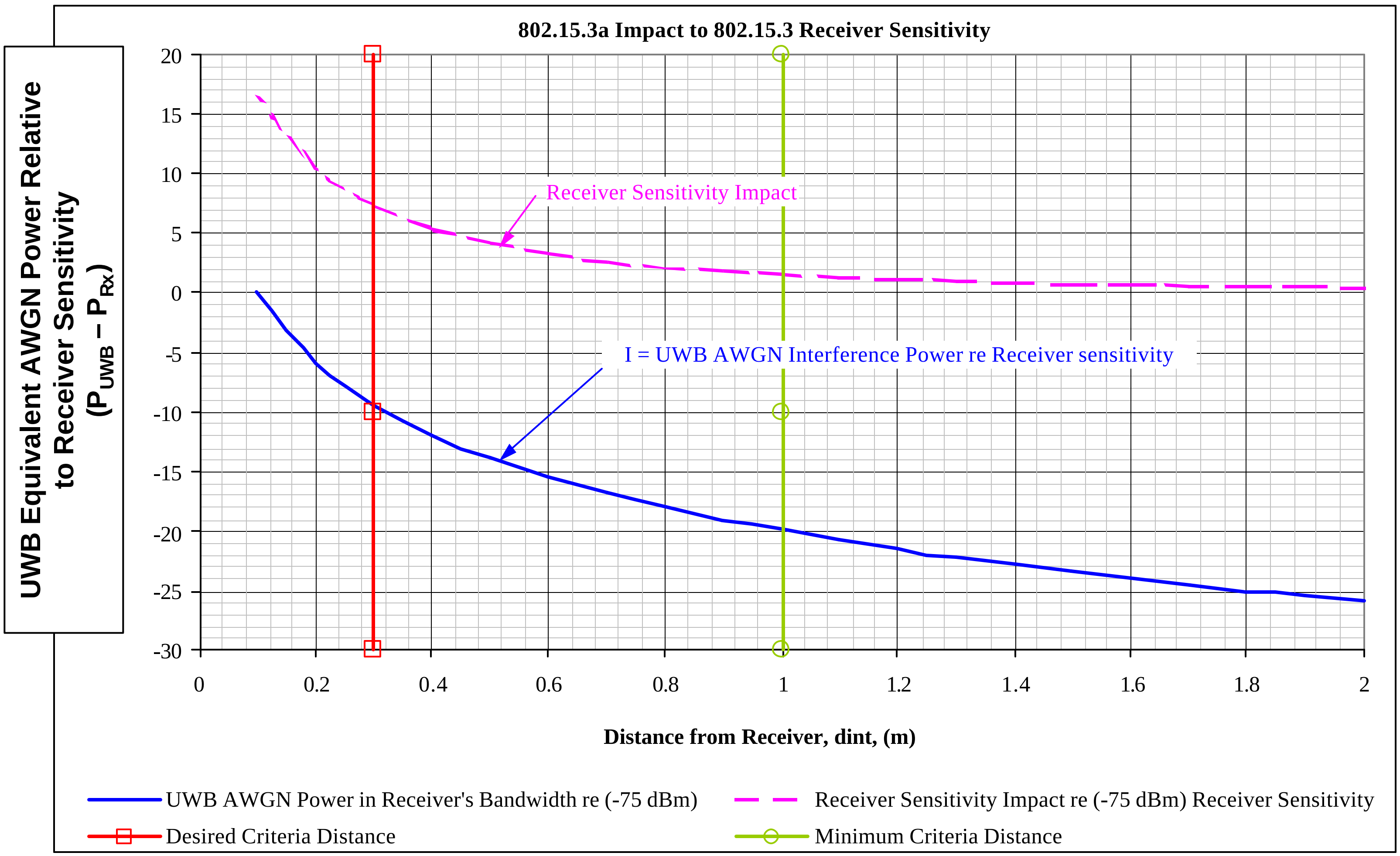
Coexistence

Bluetooth IEEE 802.15.1



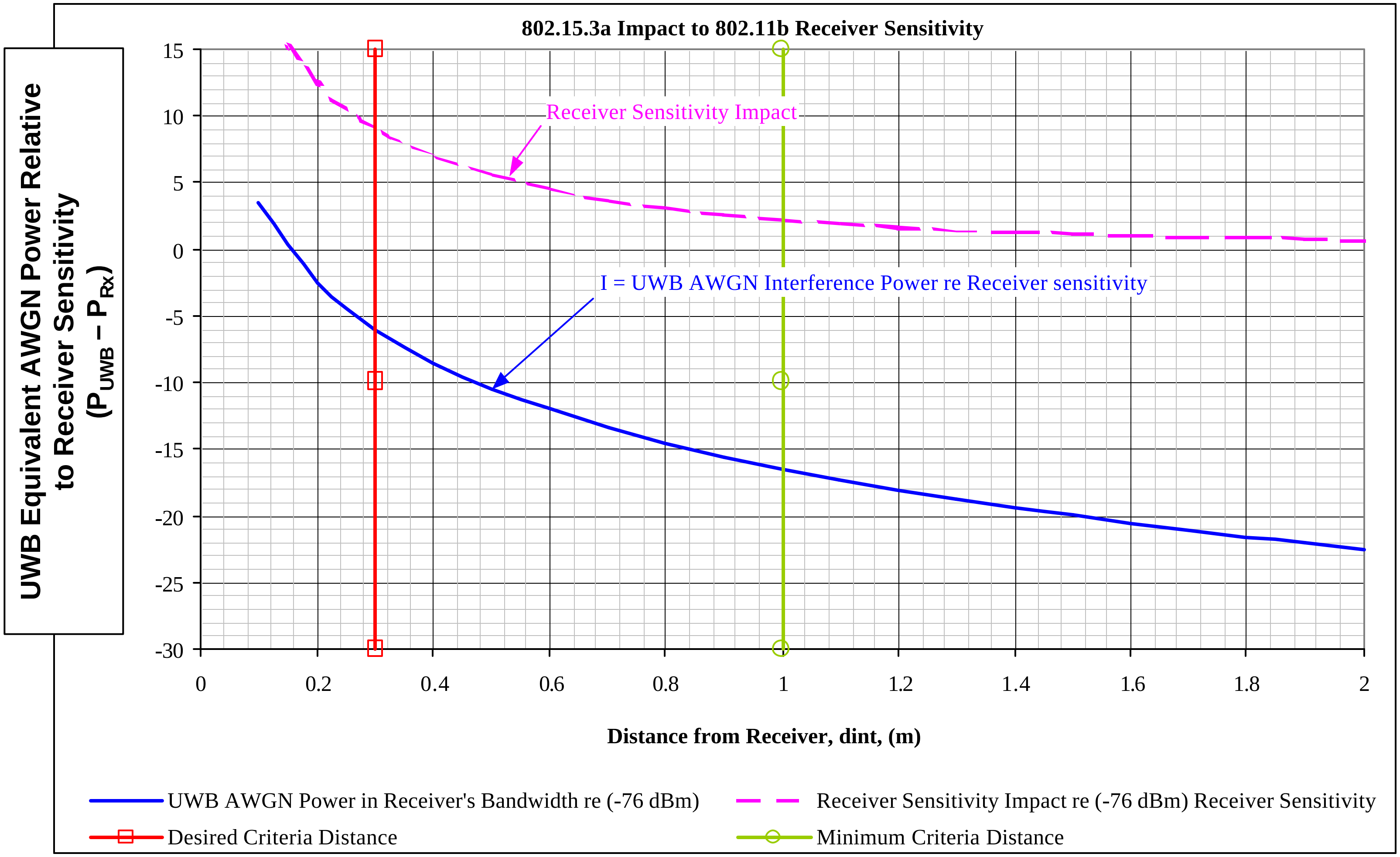
Coexistence

IEEE 802.15.3



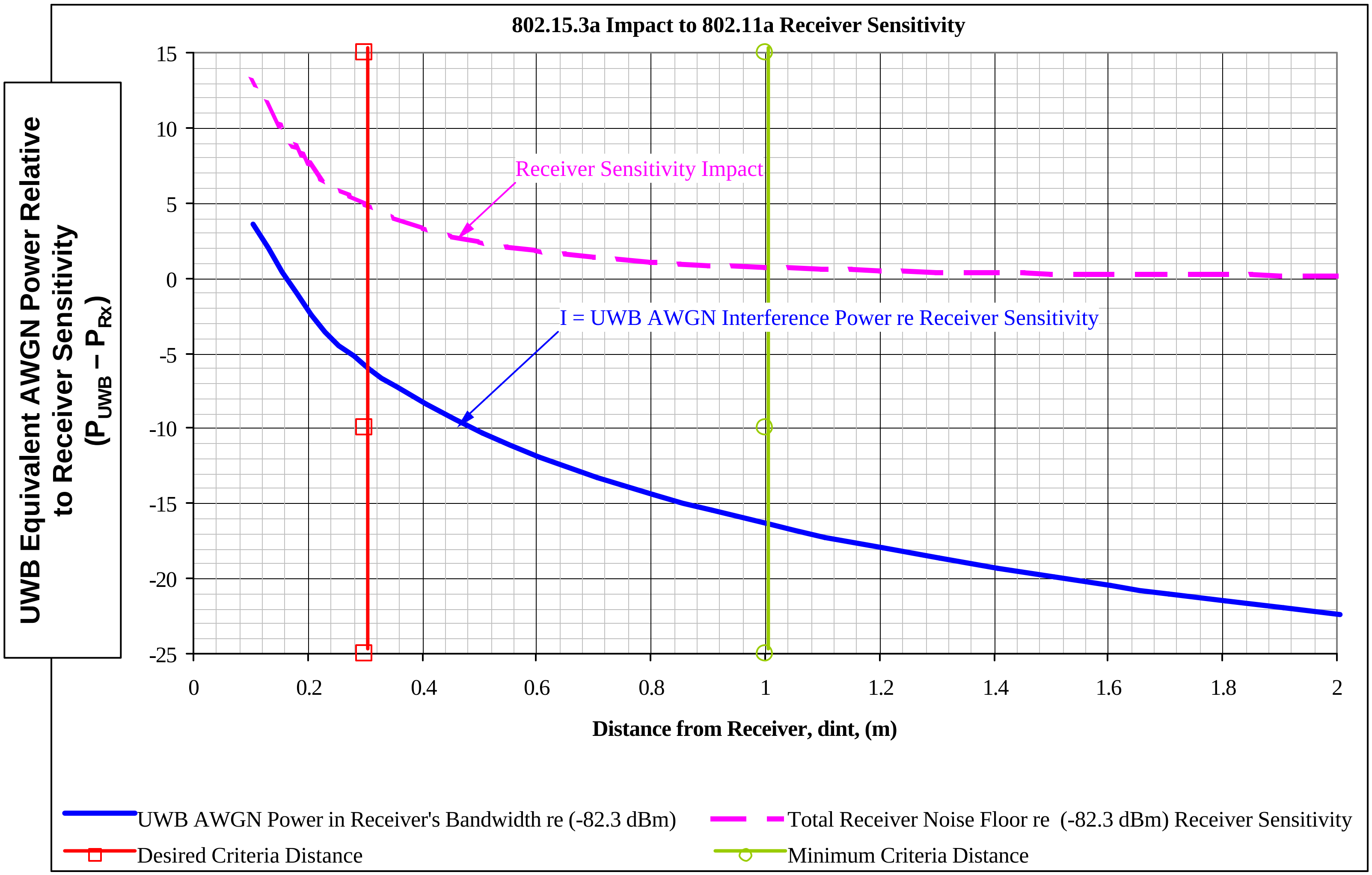
Coexistence

IEEE 802.11b



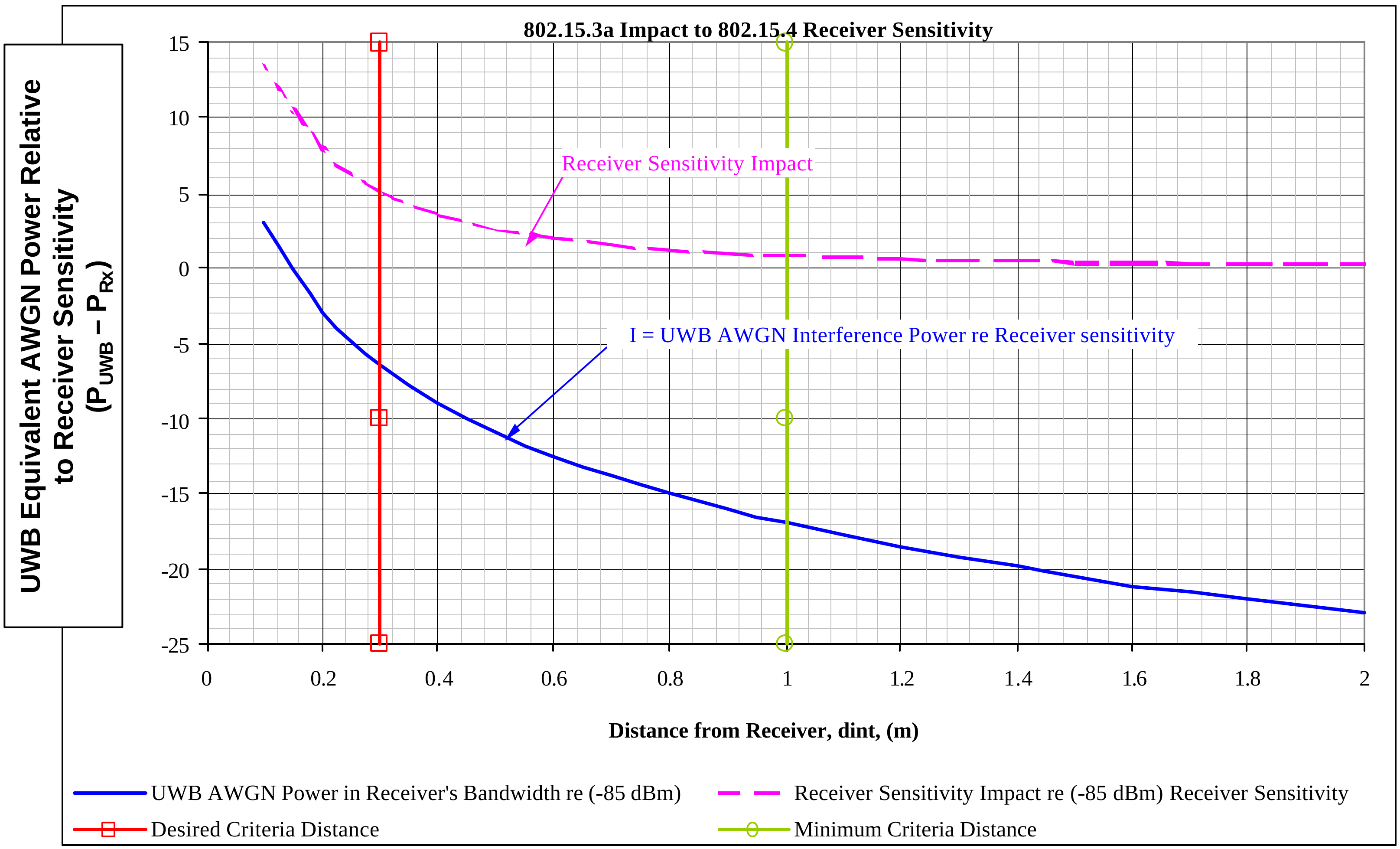
Coexistence

IEEE 802.11a



Coexistence

IEEE 802.15.4



Coexistence

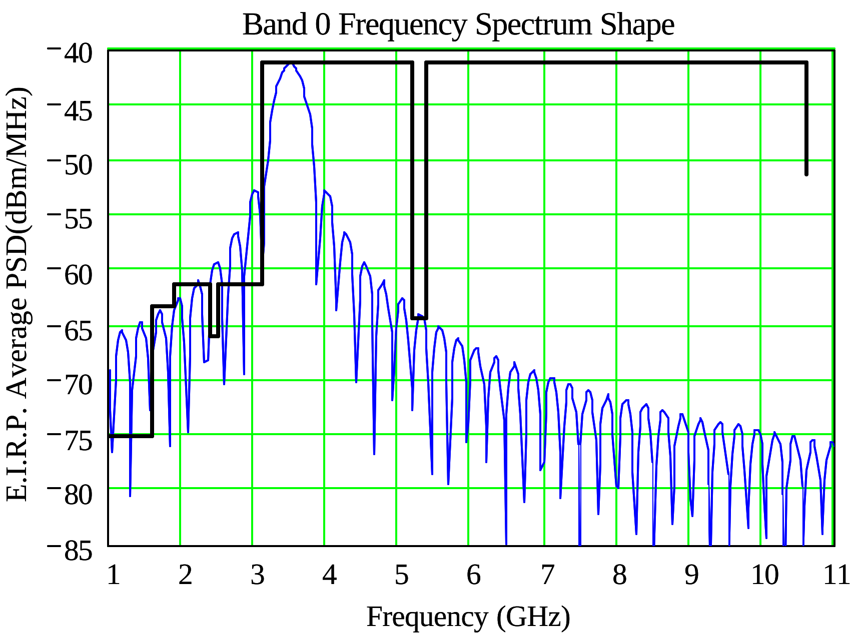
Microwave Oven as Victim Receiver

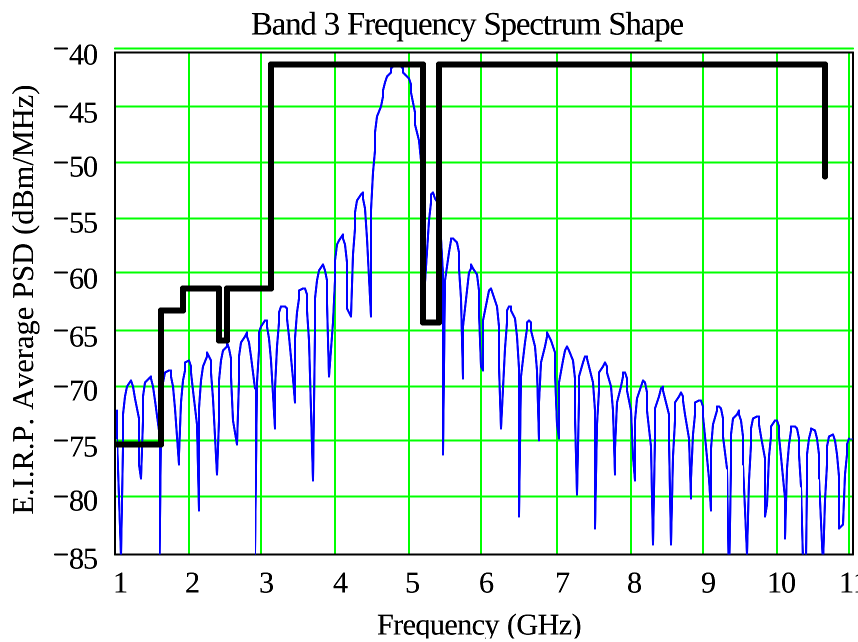
Popcorn prepared with UWB transmitter 0.1 meters from microwave.

Popcorn prepared with UWB transmitter 100 meters from microwave.

Research staff determined that both bags popped nicely and tasted great.

Filtering Required in Band Plan to Meet All Coexistence Criteria





- Less than 15 dB of additional attenuation needed in ISM and UNII to meet all coexistence criteria.
- Filtering necessary only to attenuate band side-lobes.
- Negligible effect on link budget performance.

Interference Susceptibility Analysis

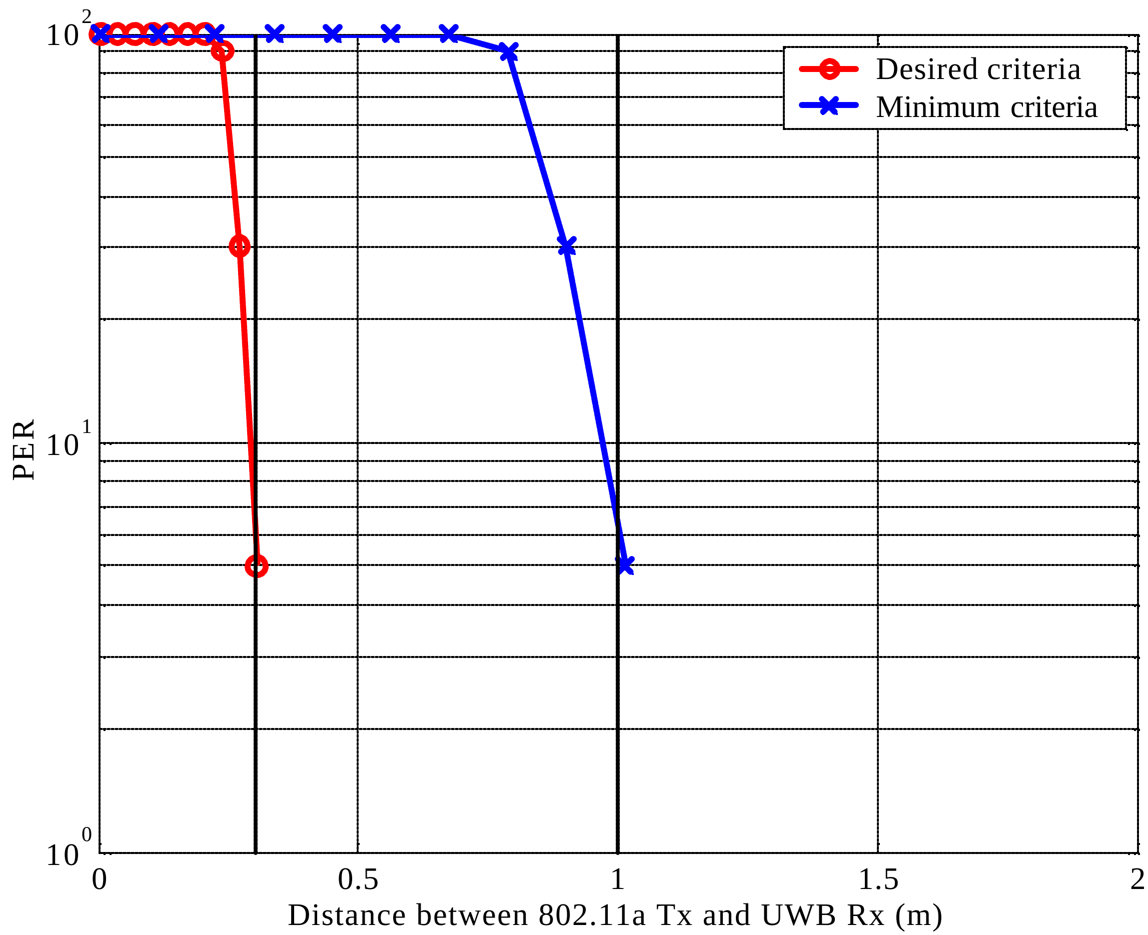
- **Susceptibility to interference from the following devices assessed:**
  - IEEE 802.11 a, IEEE 802.11 b, IEEE 802.15.4, Bluetooth, Microwave oven, Generic In-Band Tone and Modulated Interferers.
- **Analysis method for non-generic interferers**
  - **Interference models were incorporated into the simulator and RF 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 RF front-end filter and with mixer limitations will be presented in May**
- **Analysis method for generic 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

IEEE 802.11a Interferer

Attenuation requirements for the RF Front-End:

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

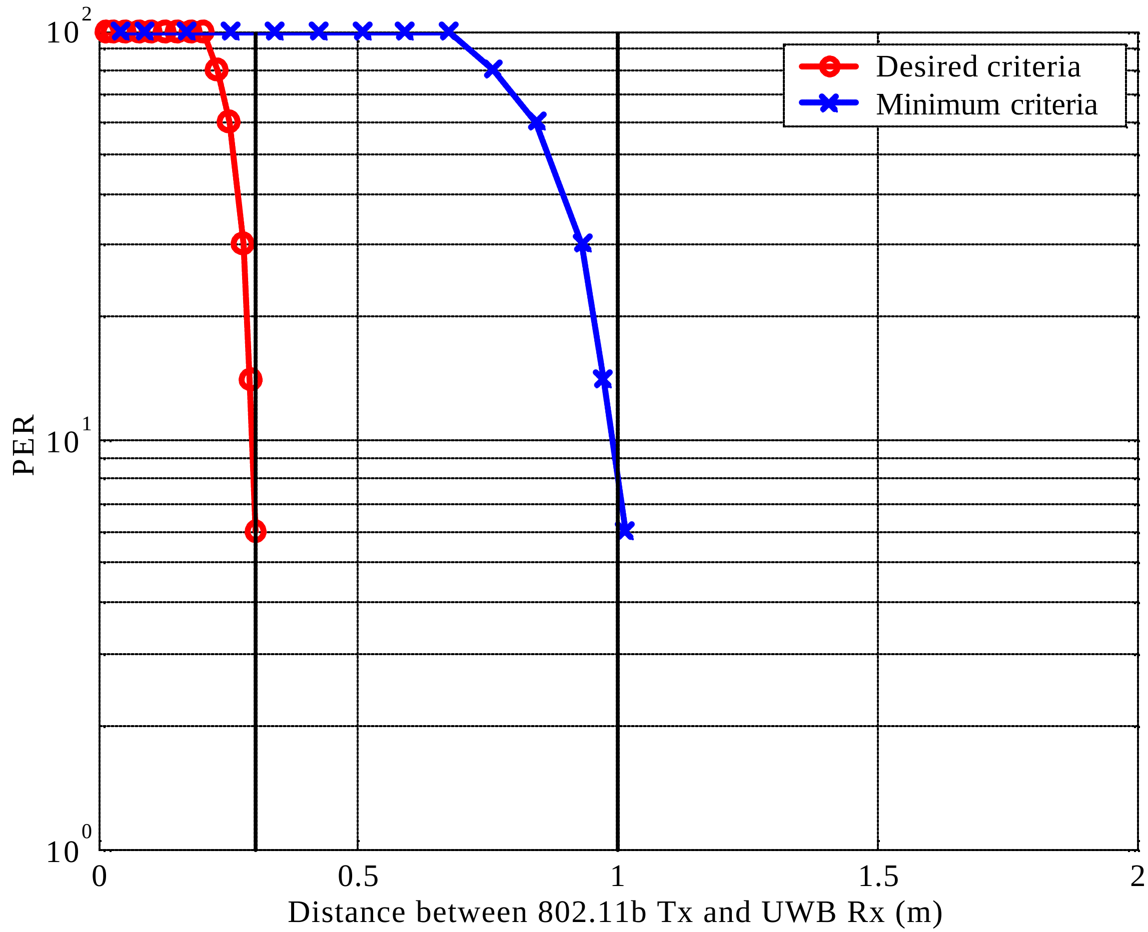


Interference Susceptibility

IEEE 802.11b Interferer

Attenuation requirements for the RF Front-End:

- 27.6 dB for Minimum criteria
- 38 dB for Desired criteria



Interference Susceptibility

Attenuation requirements for the RF Front-End

1. Microwave Oven Interferer
    - Minimum Criteria: 27 dB
2. Bluetooth/ IEEE 802.15.1 Interferer
    - Minimum criteria: 6.5 dB
    - Desired criteria: 16.9 dB

Interference Susceptibility

IEEE 802.15.4 Interferer

Attenuation requirements for the RF Front-End

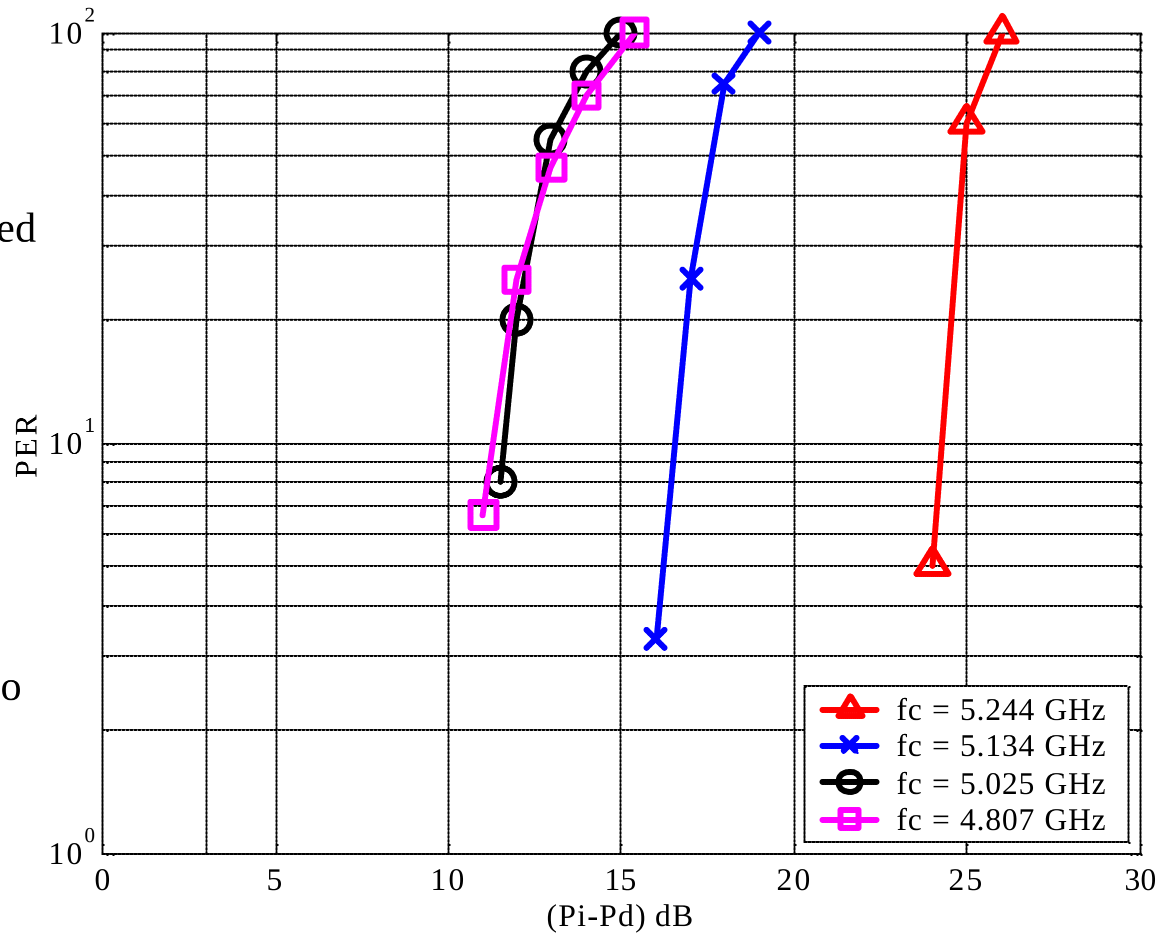
1. 802.15.4 a:
    - Minimum criteria: 12 dB
    - Desired criteria: 22.4 dB
2. 802.15.4 b:
    - Minimum criteria: 13.6 dB
    - Desired criteria: 24.0 dB
3. 802.15.4 c:
    - Minimum criteria: 7.3 dB
    - Desired criteria: 17.7 dB

Interference Susceptibility

Generic In-band Tone Interferer

Test Case

- Sub-band at 5.244 GHz not used



Comments:

- Performance depends on center frequency of interferer
- f_c = 4.807 GHz corresponds to case where the overlapping sub-band is not dropped

Interference Susceptibility

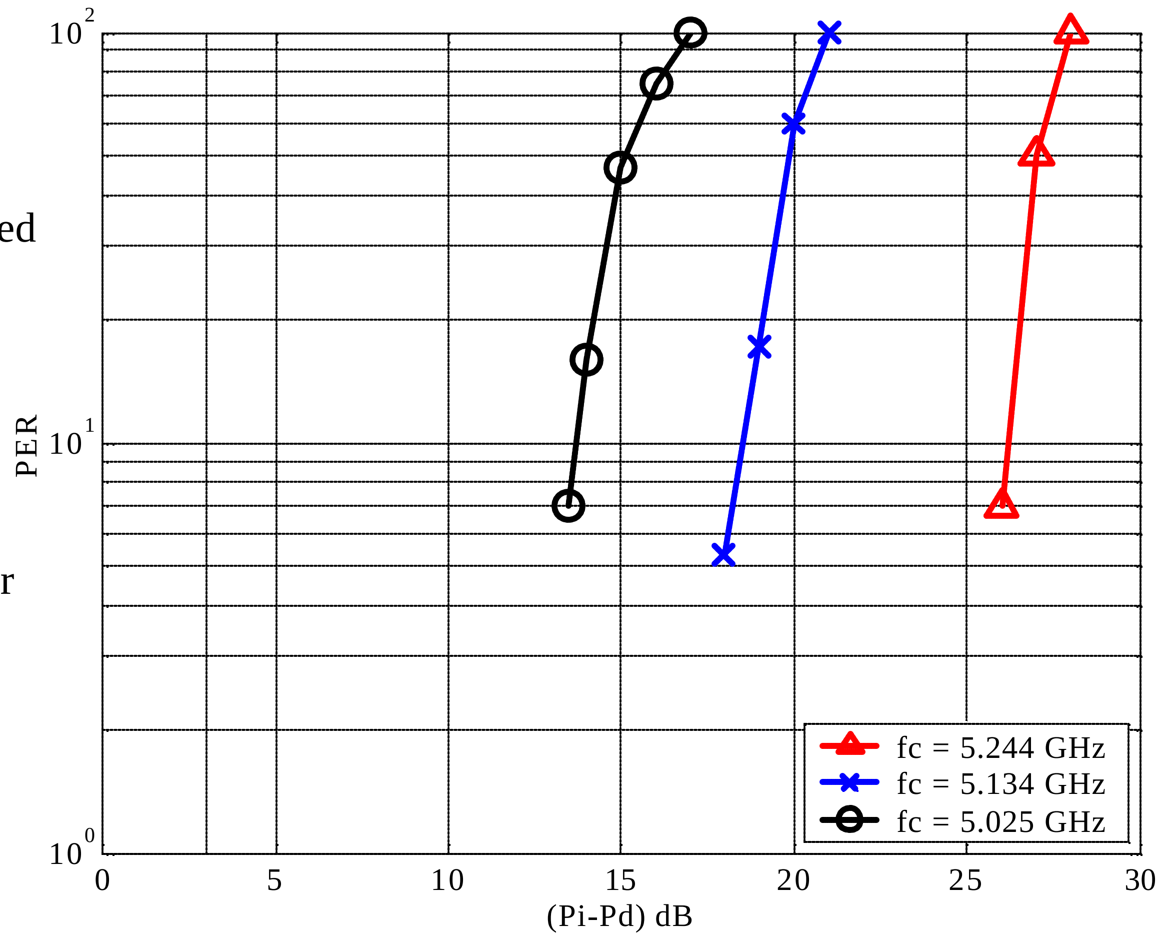
Generic In-band Modulated Interferer

Test Case

- Sub-band at 5.244 GHz not used

Comments

- Performance depends on center frequency of interferer



Location awareness

- Ranging accuracy in any UWB system is determined by how reproducibly the leading edge of an arriving signal can be determined.
- The envelope of the arriving carriers in this proposal will have a rising edge of (at most) 2 nanoseconds.

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Power Management

- The proposed Multi-band Alt-PHY will support the power-save modes of 802.15.3
  - Device States
    - AWAKE
    - SLEEP
  - Power Save Modes
    - ACTIVE
    - PS
    - SPS
    - HIBERNATE

Power Consumption: Discussion

- Power consumption estimates are based on SPECTRE™ analysis of circuits implementing the proposed design.
- There are numerous opportunities for power savings by degrading performance; however this increases packet re-transmissions and increases power consumed.
- The best power saving strategy is to establish a reliable link, move the data, then turn the radio off.

Power Consumption

ACTIVE State Modes: Idle, Tx/Rx Prep, Active Rx, Active RX, Active Tx, CCA

SLEEP State Mode: Power save

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 (with ½-rate FEC)	275 mW
Active RX	Receiving @ 257 Mbit/sec (with ½-rate FEC)	325 mW
Active Tx	Transmitting (any data rate)	190mW
CCA	Clear channel assessment	225 mW
Power save	Power save mode	20 mW

Power Consumption Roadmap

Power to Receive at 128 Mbit/sec
7-Band Radio

	SiGe Power	CMOS Power	Total power
2003: 120 GHz SiGe & .13u CMOS	195 mW	80 mW	275 mW
2005: advanced SiGe & 90 nm CMOS	130 mW	80 mW*	210 mW

* CMOS power consumption is unlikely to improve with the 90 nm process

Power Consumption

- “Milliwatts consumed” is not the whole story. The appropriate metric is power per megabit transferred.
- The above metric is observed by the consumer as battery life.
- The next slides give the percentage of battery used for example applications.

Power Consumption
Camera Application

- Put a 375mW radio (including DME & MAC) into a digital camera.
- Take 300 photos (384 MByte of data).
- Download photos over the UWB link to a computer or printer. This is 48 seconds @ 128 Mb/s (allowing 100 % overhead for packet management).
- 48 seconds is 0.6% of the battery life of a pair of AAA cells (at 250 ma current draw).

➔The radio power consumption has an insignificant impact on battery life.

Power Consumption

PDA Application

- Put a 375 mW radio (including DME & MAC) into a PDA.
- Assume a 16 MByte transfer with every hot sync. (very high estimate)
- Assume 20 hot syncs a day (320 MByte of data).
- Use the UWB link for all hot syncs. This is 40 seconds @ 128 Mb/s (allowing 100 % overhead for packet management).
- 40 seconds is 0.5% of the battery life of a pair of AAA cells (at 250 ma current draw).

➔The radio power consumption has an insignificant impact on battery life.

Power Consumption

MP3 Player

- Put a 375mW radio (including DME & MAC) into an MP3 player.
- Assume a 256 MByte transfer (4 hours of music @ maximum sound quality)
- Use the UWB link for 32 seconds @ 128 Mb/s (allowing 100 % overhead for packet management).
- 32 seconds is 0.4% of the battery life of a pair of AAA cells (at 250 ma current draw).

➔The radio power consumption has an insignificant impact on battery life.

Power Consumption
Digital Video Recorder

- Put a 375mW radio (including DME & MAC) into a Digital video recorder.
- Assume a 1 GByte CompactFlash card
- Use the UWB link to download the entire CF card. This is 2 minutes @ 128 Mb/s (allowing 100 % overhead for packet management).
- 2 minutes @ 100 ma is 0.4% of the battery life of a typical 7.2 volt Lithium rechargeable

➔The radio power consumption has an insignificant impact on battery life.

Summary of Applications

Application	Data transfer	Battery assumption	battery life decrease
Digital still camera	384 Mbyte *300 photos*	2 AAA cells	**0.6%**
MP3 player	256 Mbyte *4hrs of music*	2 AAA cells	**0.4%**
PDA	320 Mbyte *20 hot-synchs*	2 AAA cells	**0.5%**
Digital video recorder	1 Gbyte *Largest CF made*	7.2 V Lithium rechargeable	**0.4%**

Complexity - PHY

- The Multi-band approach is implemented using conventional radio techniques
- The implementation challenges have to do with managing the wide dynamic range of signals at the antenna and are common to all UWB systems

Size and Form Factor

Development path

- Standalone radio approx. 1.5”x3.5”x3/8”
- Laptop-friendly design; 1.5” x 2” radio module, flexible connection to 1.5” sq antenna
- Memory stick / Compact flash radio
- SDIO radio

Form Factor	Generation 1	Generation 2	Generation 3
PC Card	v	v	v
Compact Flash	v	v	v
Memory Stick		v	v
SD Memory			v

Complexity – Silicon Processes

- Phy processes & critical features
  - Digital portion
    - 0.13 micron CMOS
  - Analog portion
    - 120 GHz SiGe
  - Off-Chip Filters
    - LTCC

Complexity – Gate Count

- Gate count estimate
  - Digital: 200 to 300k gates
- Transistor Count
  - Analog: 2k

Complexity – External Components

- Only two significant off-chip components are required for the PHY
  - Reference oscillator
    - Cheap/easy
  - RF filter
    - LTCC or equivalent
    - Better performance
    - Higher yield

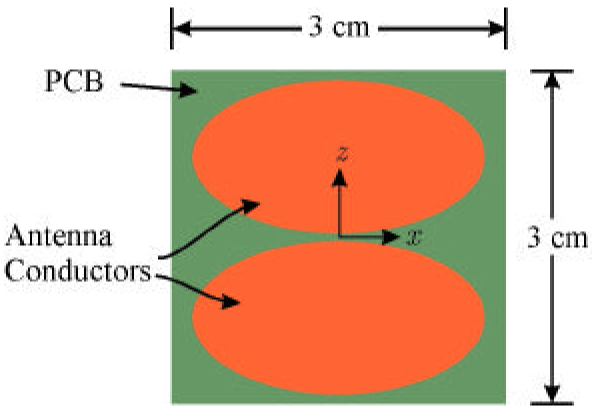
Complexity - Die Size

- 4.5mm x 4.5mm for combined analog and digital functions in silicon
- 5 mm x 5mm for passive filter

Complexity – MAC Enhancements

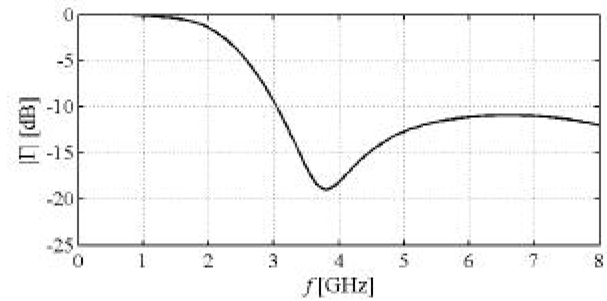
- Proposed enhancements have little impact on the MAC implementation
  - Few additional commands
  - New IEs and PIBs have minimal impact on MAC memory requirements
  - Biggest impact will be MAC speed required to support the data rate capabilities

Antenna Practicality

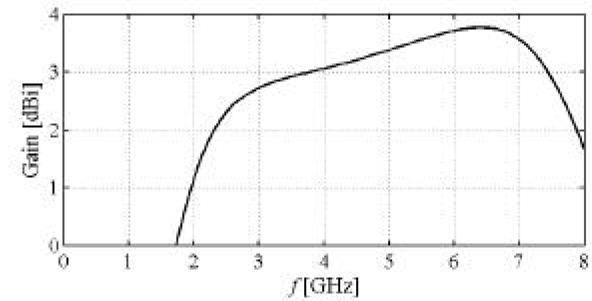


4-band radio (bands 0,1,2,3)

Match



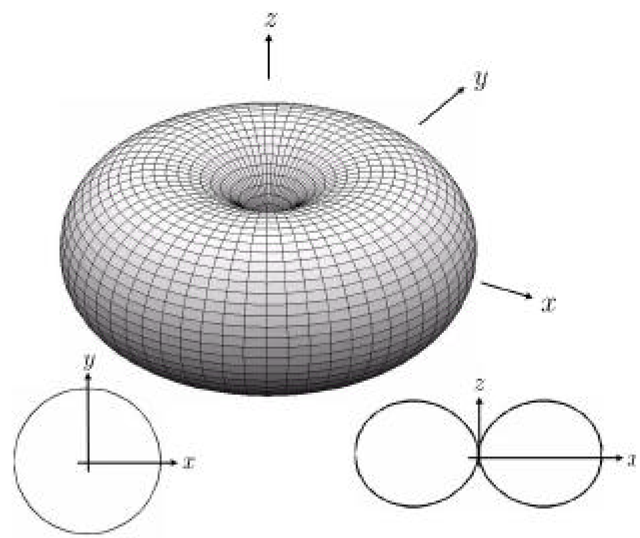
Gain



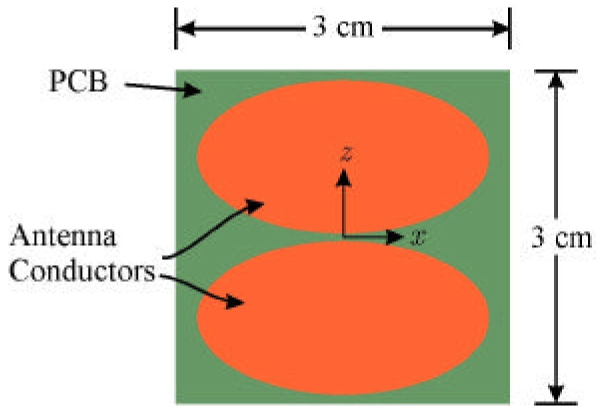
Design Specifications

Design criteria	Parameter
Size	Approximately 3 cm x 3 cm
Frequency Range	3.2 GHz – 5.1 GHz
Match	Return loss > 10 dB
Gain	> 0 dBi
Integration on Board	The antenna can be embedded in the PCB of the radio
PCB Material	FR4

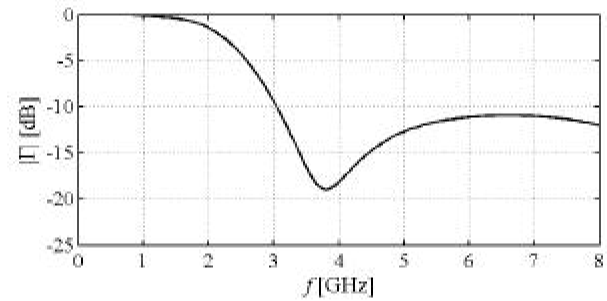
Pattern



Antenna Practicality

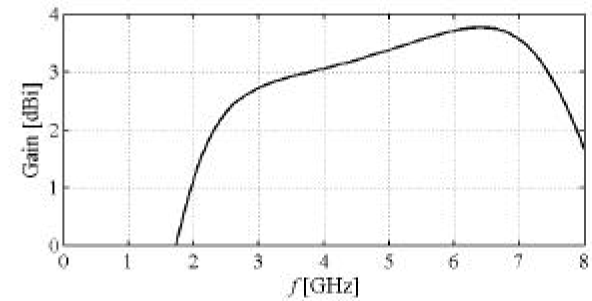


Match



7-band radio
(bands 0,1,2,3,5,6,7)

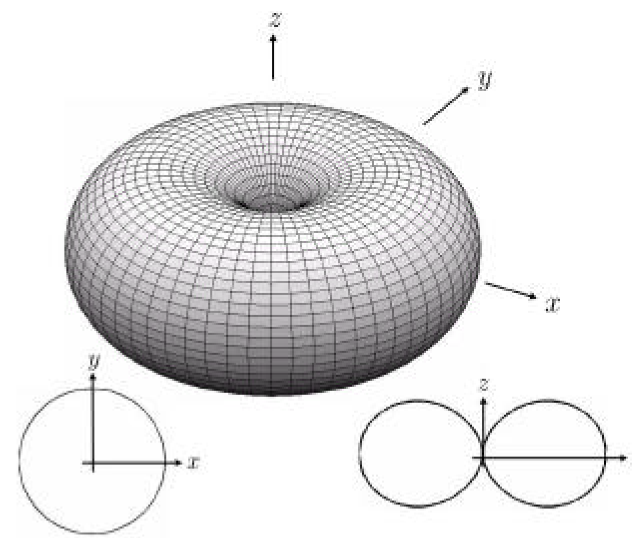
Gain



Design Specifications

Design criteria	Parameter
Size	Approximately 3 cm x 3 cm
Frequency Range	3.2 GHz – 6.8 GHz
Match	Return loss > 10 dB
Gain	> 0 dBi
Integration on Board	The antenna can be embedded in the PCB of the radio
PCB Material	FR4

Pattern



Time To Market

- Implemented using current available silicon technologies that are mature and cost-effective.
- No impediments to timely development.
- PHY chipsets available within nine to twelve months of approval of standard.

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.

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Verification Cross-Reference Table

Selection Criteria Section Number	Title	Slide numbers
3.	General Solution Criteria	
3.1	Unit Manufacturing Cost/Complexity	
3.2	Signal Robustness	
3.2.2	Interference and Susceptibility	
3.2.3	Coexistence	
3.3	Technical Feasibility	
3.3.1	Manufacturability	
3.3.2	Time to Market	
3.3.3	Regulatory Impact	
3.4	Scalability	
3.5	Location Awareness	
4.	Mac Protocol Supplements	
4.1	Alternate PHY Required MAC Enhancements and Modifications	

Verification Cross-Reference Table pg 2

Selection Criteria Section Number	Title	Slide numbers
5.	PHY Layer Criteria	
5.1	Size and Form Factor	
5.2	PHY-SAP Payload Bit Rate and Data Throughput	
5.2.1	Fpayload Bit Rates	
5.2.2	Packet Overhead	
5.2.3	PHY-SAP Throughput	
5.3	Simultaneously Operating Piconets	
5.4	Signal Acquisition	
5.5	System Performance	
5.6	Link Budget	
5.7	Sensitivity	
5.8	Power Management Modes	
5.9	Power Consumption	
5.10	Antenna Practicality	
6.0	Self-Evaluation Matrix	

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Appendices

- Self-Evaluation
- Frame Definition

General Solution Criteria

CRITERIA	***REF.***	***IMPORTANCE LEVEL***	***PROPOSER RESPONSE***
Unit Manufacturing Complexity (UMC)	3.1	B	+
Signal Robustness			
Interference And Susceptibility	3.2.2	A	+
Coexistence	3.2.3	A	+
Technical Feasibility			+
Manufacturability	3.3.1	A	+
Time To Market	3.3.2	A	+
Regulatory Impact	3.3.3	A	+
Scalability (i.e. Payload Bit Rate/Data Throughput, Channelization – physical or coded, Complexity, Range, Frequencies of Operation, Bandwidth of Operation, Power Consumption)	3.4	A	+
Location Awareness	3.5	C	0

PHY Protocol Criteria

CRITERIA	***REF.***	***IMPORTANCE LEVEL***	***PROPOSER RESPONSE***
Size And Form Factor	5.1	B	+
PHY-SAP Payload Bit Rate & Data Throughput			
Payload Bit Rate	5.2.1	A	+
PHY-SAP Data Throughput	5.2.2	A	+
Simultaneously Operating Piconets	5.3	A	+
Signal Acquisition	5.4	A	+
Link Budget	5.5	A	+
Sensitivity	5.6	A	+
Multi-Path Immunity	5.7	A	+
Power Management Modes	5.8	B	+
Power Consumption	5.9	A	0
Antenna Practicality	5.10	B	+

MAC Protocol Enhancement Criteria

CRITERIA	***REF.***	***IMPORTANCE LEVEL***	***PROPOSER RESPONSE***
MAC Enhancements And Modifications	4.1.	C	+

PHY Header Definition

- 2-octets –equivalent to 2.4-GHz PHY
  - 2.4-GHz PHY bits for data rate equated to modulation for the Multi-band PHY

Proposed Multi-band Alt-PHY Header

Bits	Content	Description
b1-b0	Reserved for seed Identifier	Selects seed for data scrambler (if needed)
b4-b2	Frame body modulation	Selects 1 of 8 modulation settings
b15-b5	Payload length	Payload length in octets (limit of 2048)

HCS is sent in the same manner as the rest of the frame, with LSB first.

Data Rate Calculations

Payload Bit Rate

Payload Bit Rate = Bits_per_Symbol/(Chip_Duration*Chips_per_Symbol)

Bits_per_Symbol

Frequency Integration		No Frequency Integration	
BPSK	QPSK	BPSK	QPSK
Coding_Rate/ Time_Integrate	2*Coding_Rate/ Time_Integrate	Num_Bands*Coding_Rate/ Time_Integrate	2*Num_Bands*Coding_Rate/ Time_Integrate

PHY-SAP Throughput relation to frame component durations

Multi-frame - 5 consecutive, No-ACK frames:

PHY_SAP_Throughput = 5*Frame_Body_bits /[T_Initial_Preamble+T_SIFS + 4*(T_Continuous_Preamble+T_MIFS) + 5*(T_Frame_Body+T_MACHDR + T_PHYHDR+T_HCS+T_FCS)]

Single-frame:

PHY_SAP_Throughput = Frame_Body_bits /[T_Initial_Preamble+T_SIFS + T_Frame_Body+T_MACHDR + T_PHYHDR+T_HCS+T_FCS)]