

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

Submission Title: [DS-UWB Responses to TG3aVoter NO Comments]

Date Submitted: [January 2005]

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Re: []

Abstract: [Response to NO voter comments and feedback regarding the DS-UWB (Merger #2) Proposal]

Purpose: [Provide technical information to the TG3a voters regarding DS-UWB (Merger #2) Proposal]

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Roadmap

- Comment summary
 - 26 unique sets of No comments submitted
 - Representative comments are presented here with comment resolution details
 - MAC support
 - DS-UWB performance
 - OOB emissions and regulatory compliance
 - Complexity
 - Proposal summary

MAC Support: CCA

- Comment (in part):
 - “...the DS-UWB proposal is NOT capable of adequately supporting CSMA/CA (e.g., the 15.3 MAC CAP) as described by our selection criteria. In the absence of any credible engineering work in advance of the next meeting, I believe DS-UWB proposers should concede that their proposal is not able to meet the CCA criteria.”
- What is the “CCA Criteria”? Section 5.4 Signal Acquisition of 03/031r9
 - “...Target acquisition times, reflecting what is specified in the proposed IEEE 802.15.3 Standard, are <6 μ s for piconet CCA (referenced to the beginning of the preamble) and <20 μ s for acquisition from the beginning of the preamble to the beginning of the header. Additional information concerning how well the acquisition process scales with payload bit rate would be beneficial. “
- What is required by MB-OFDM proposal?
 - Section 1.6.2 of 04/493r0: “The start of a valid OFDM transmission at a receiver level equal to or greater than the minimum 53.3 Mb/s sensitivity (-84 dBm) shall cause CCA to indicate busy with a probability > 90% within 4.6875 ms. If the preamble portion was missed, the receiver shall hold the carrier sense (CS) signal busy for any signal 20 dB above the minimum 53.3 Mb/s sensitivity (i.e. -64 dBm).”

MAC Support: CCA

- Response: As we see in the requirements from 03/031r9: the proposal must support <6 usec CCA referenced to beginning of packet. The DS-UWB proposal meets this requirement.
- Is there a need for additional requirements above 031r9 to work with 15.3 MAC as the commenter claims?
 - Most modes in the 15.3 MAC do not require CCA: CTA, MCTA
 - The CAP requires CCA
 - For most situations, a device will need to monitor the channel during all of CAP in order to participate, therefore the CCA requirement in 03/031r9 is adequate to ensure good CAP performance
 - The commenter's concern seems to be for some pathological case (during CAP) where the beginning-of-preamble-only CCA causes a degradation in piconet performance, such as a packet collision due to a previously undetected collision earlier in the same CAP
 - Our conclusion is that this case is of very low probability and therefore not required to support the MAC beyond the requirements in 03/031r9
- Portions of 15.3 MAC that use CSMA are appropriate for non-QoS (bursty) traffic and typically have lower throughput performance
- Scalability of these CAP modes to high rate applications and throughput is problematic and is being enhanced as part of the 15.3b project

Performance at Very High Rates

- Comments:
 - “Video links, the primary potential application for link speeds greater than 1Gb are very sensitive to data loss. Claims of high throughput achieved by obscuring the reliability problem are extremely flawed. The willingness of this proposer to put the customer at risk in this manner is highly disturbing. I wish to see the proposer describe their system in terms of usable bandwidth. Below 1Gb, applications can frequently tolerate higher packet error rates stated in the evaluation criteria. Above 1Gb, applications shift to video and need measurements in terms of a 1% packet error rate. To state a 15% rate is absurd and must be stopped.”
 - I am concerned that the emphasis of the DS-UWB proposal on Gbps data rates has detracted from the original TG3a technical requirements in P802.15-03/030r0. I believe that the DS-UWB proponents have tried to move the TG3a discussion and comparison of proposals to data rates and ranges that are closer to an ultra-high-rate "near field" communications system than the original intent to provide a 10m radius wireless PAN solution at 110Mbps (and 4m at 200Mbps).

Performance at Very High Rates

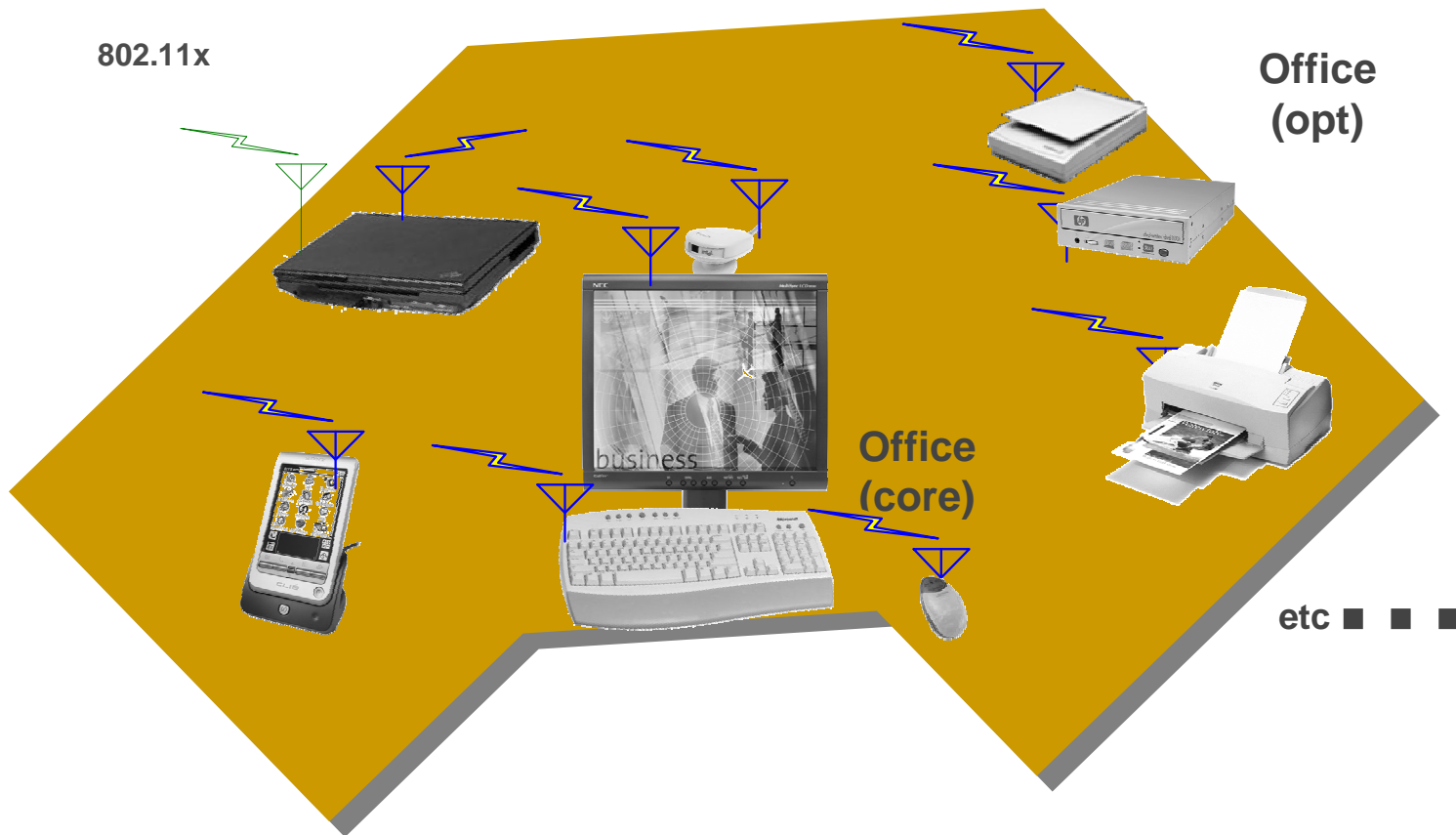
- My skepticism about the practicality of the unprotected 1Gbps data rate has been confirmed by recently published simulation results e.g. in 802.15-04-0483r5. For example, CM1 range for low band 1000Mbps on slide 24. Even in the case of no interferers, the packet error rate could not be shown to drop below 39% at any distance. Therefore, the authors have a way to go before they have convincingly shown a path to robust transfer of Gigabytes of information in a real world environment. If this system is to rely on ARQ as has been suggested, then the total system throughput has to be demonstrated in the context of the 15.3MAC MIFS and SIFS times, the bandwidth allocated to ARQ retries, the impact of multiple piconet interference, etc. If such an overall system analysis for Gbps data rates were presented in a convincing way, I would consider changing my no vote to a yes.

Performance at High Rates (1+ Gbps)

- Assertions of commenters:
 - Uncompressed video links require lower PER than other forms of data
 - High rate video or other applications should not be addressed in TG3a
- We do not agree with these assertions
- Packet losses typically leads to retransmission, not to data loss
- UWB applications requiring 1 Gbps identified in multiple documents
 - Initially identified in a SG3a CFA presentation by Chuck Brabenac of Intel (document 02/139r0) – up to 1000 Mbps desired data BW
 - Also identified in CFA response from Sony (02/043r0) - “Non-encoded Video (>1 Gbps)” & high speed file transfer in <10 seconds
 - CFA response from TI (M. Duval, “High Rate WPAN for Video”, 02/047r0) indentifies 3D computer game apps. using XGA & SXGA
- The TG3a Requirements Document also clearly indicates UWB applications that require up to 1 Gbps (document 03/030r0).
- In addition, the “Download Application” section of 03/030r0 states:
 - “These are minimum download rates for an initial implementation. Consumer desire is always that faster downloads are better and thus significant importance is attached to the ability of the proposed technology to significantly increase download rates in the future.”

Future Office (from 02/139r0)

Notebook PC - native devices



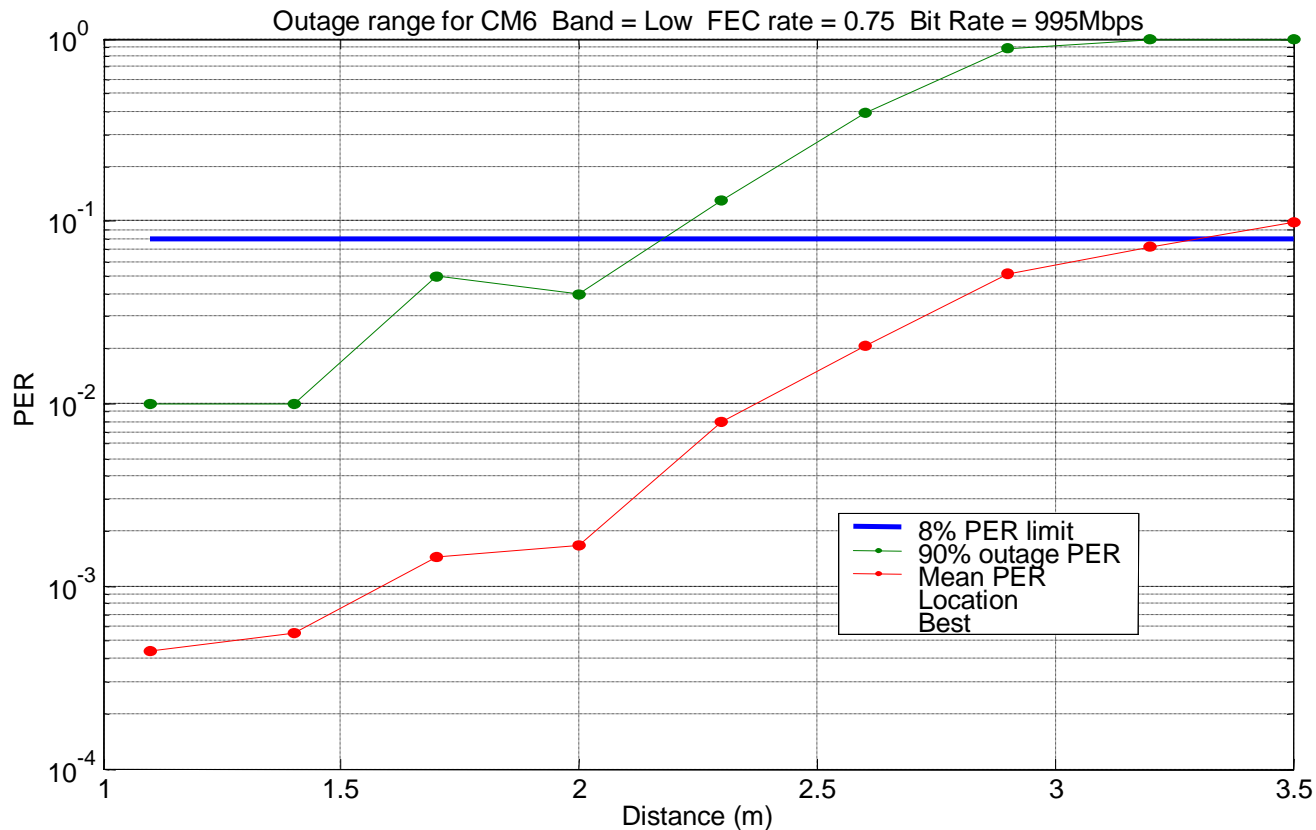
Performance at High Rates (1 Gbps)

- DS-UWB has multiple modes (with FEC) supporting 1+ Gbps (2 bands)
- Simulations in different AWGN and multipath channel conditions
- This is the only proposal considered by TG3a that has demonstrated the capability to satisfy this 1 Gbps requirement from the SG3a CFAs & TG3a Requirements Document
 - No MIMO or higher order modulation (e.g. 16-QAM) is required

Environment	Range	Criteria
AWGN	5.3 m	Mean
Low band CM1	1.7 m	85% Outage
Low band CM1	2.7 m	90% Mean
Low band CM 6* (3 ns RMS delay spread)	2.2 m 3.3 m	90% Outage 90% Mean
High band CM1	2 m	90% Outage
High band CM2	1 m	90% Outage

*CM 6 is a modification of CM1 with 3 ns RMS delay spread – see next slide

Performance at High Rates (1 Gbps)



- *CM 6 is not a part of the TG3a channel model set, but was developed to quantify performance in channels with lower delay spread than CM1
 - 100 realizations, 3 ns RMS delay spread with 3 dB shadowing standard deviation
 - Intermediate between AWGN channel and CM1 channel (5 ns RMS delay spread)
 - Designed to represent a channel of roughly 0-2 meters with LOS conditions

DS-UWB Performance

- Comment:
 - If the DS-UWB camp could provide a convincing proof of its ability to provide a robust NLOS 110Mbps link operating over 10m within the FCC part15f emissions limits, without the aid of directional antennas, I would consider changing my no vote to a yes. At this stage of the game, after several iterations of DS-UWB silicon, it should be possible to provide this as a practical demonstration. Although IEEE rules may not permit this as part of a formal session, the DS-UWB proponents' history of providing interference "demonstrations" leads me to believe that the logistics could be managed, if the technology were there.
- Response:
 - The Selection Criteria do not require a proposal to be fully demonstrated in silicon before selection of the baseline draft. Numerous simulation results have been presented to the TG that were performed according to the procedures described in the Selection Criteria.
 - Nevertheless, multiple public demonstrations have been made of integrated devices that have been certified by the FCC under Part 15f emission limits and that show robust performance in multipath channels.

DS-UWB Performance

- Comments:
 - The equalizer will have error propagation and there will be error floor in performance
 - I would need to see simulation results, architectures, and have a comfortable feeling regarding merge proposal #2s capabilities to scale in data rate and range, as described in the 802.15.3a selection criteria. Then: Unfortunately the no vote response presentation did not provide ample detail to resolve my concerns; I hope to see simulation results, architectures, etc...

DS-UWB Performance

- Comments resolved:
 - System-level simulations (see 04/483r3 for detailed results and specific architectural parameters) demonstrate equalizer performance in end-to-end impaired simulations
 - See detailed discussion of equalizer effects in document 04/504r1, slides 2-11
 - Error floors were shown in simulations performed by the authors of Merged proposal #1 in their simulations of MBOK (04/449r0), but their implementation was sub-optimal and only included an equalizer for MB-OFDM, not for MBOK
 - Our simulations show that although error propagation is present, it does not significantly reduce the range achieved by DS-UWB

DS-UWB Performance

- Comment:
 - A reasonable complexity, multipath immune receiver architecture has not been shown for DS-UWB. OFDM modulation should be used to provide inherent multipath immunity in all implementations, thereby reducing the variance on quality of IEEE 802.15.3a compliant products and thereby doing a service to the end consumer
- Response:
 - DS-UWB has been shown to provide superior performance to MB-OFDM with a lower complexity implementation
 - This comment seems to imply that this voter will only consider OFDM-based solutions and is not open to non-OFDM solutions
 - The TG should select the proposal that best meets the PAR and requirements
 - Arbitrarily restricting consideration to only OFDM technology is not reasonable and will lead to an inferior standard and products

DS-UWB Performance at High Rates

- A comparison of MB-OFDM and DS-UWB at higher data-rates has not been consistent with the information presented by DS-UWB for the 90% outage range (at 500 Mbps, 3.0 m for CM1 and 1.9 m for CM2 in DS-UWB, while at 480 Mbps, 2.9 m for CM1 and 2.6 m for CM2 in MB-OFDM). I hereby question if the DS-UWB comments such as "eDS-UWB takes full advantage of UWB propagation, and DS-UWB performance excels as speed goes up. Performance difference is natural consequence of channel physics." f as given in the DS-UWB proposal, have any technical ground. A convincing explanation is required before ever reconsidering my NO vote.

Range for 500 and 660 Mbps

Channel Model	500Mbps 90% outage range	660Mbps 90% outage range
AWGN	8.5m	9.1m
CM1	4.6m	4.2m
CM2	3.7m	3.2m

Range for 500 and 660 Mbps

Channel Model	500Mbps mean range	660Mbps mean range
AWGN	8.5m	9.1m
CM1	5.6m	5.3m
CM2	5.0m	4.5m

90% Outage Comparison Mandatory Rates

Channel Model	DS-UWB 110Mbps	MBOFDM 110Mbps	DS-UWB advantage	DS-UWB 220Mbps	MBOFDM 220Mbps	DS-UWB advantage
CM1	14	12	17%	9.7	7.4	31%
CM2	11.9	11.4	4%	8.1	7.1	14%
CM3	12.4	12.3	1%	7.9	7.5	5%
CM4	11.8	11.3	4%	7.4	6.6	12%

90% Outage Comparison High Rates

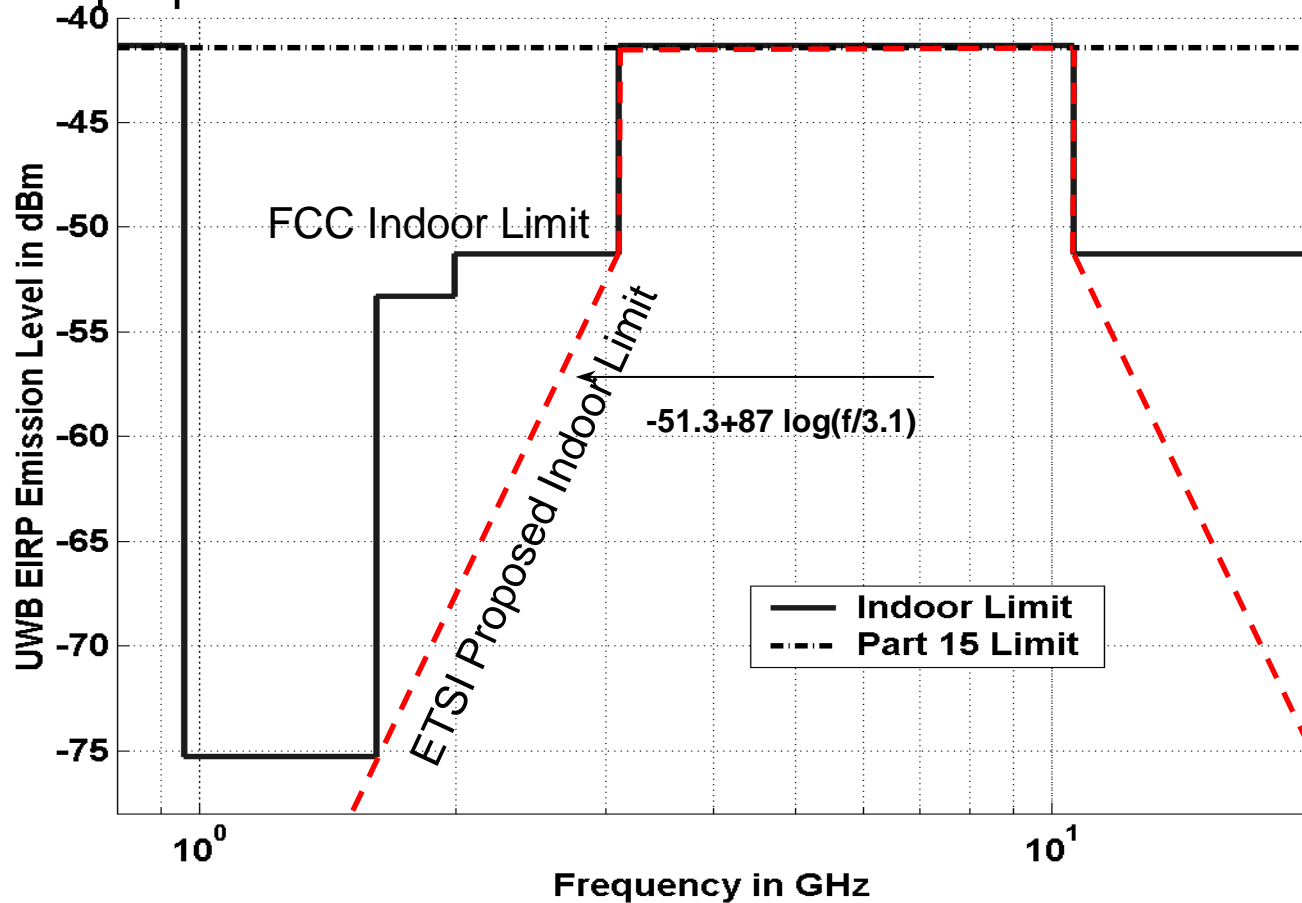
Channel Model	DS-UWB 500Mbps	MBOFDM 480Mbps	DS-UWB advantage	DS-UWB 660Mbps	MBOFDM 480Mbps	DS-UWB advantage
CM1	4.6	3.2	44%	4.2	3.2	31%
CM2	3.7	3	23%	3.2	3	23%

Out-of-band Emissions

- I would like you to quantify the impact on the DS-UWB system of having to meet strict out of band emissions requirements for services such as IMT-2000 etc. corresponding to proposed protection levels being discussed in ITU-R, etc.
- Lack of an effective mechanism to solve out-of-band and in-band interference for incumbent and future radio service operators is a serious disadvantage with the DS-UWB technology. MBOA has proposed MB-OFDM as a solution to meet both performance and interference mitigation; at present, it is the only one UWB technology that provides a mechanism to coexist with other radio services. As being discussed at ITU-R, CEPT and other regulatory meetings, UWB interference is a global issue, and industry needs a standard solution that meets both performance and interference mitigation. Techniques proposed from DS-UWB in the past either accompany an excessive performance drop or lack technical feasibility. Without an effective technical remedy for DS-UWB, it is extremely difficult to reconsider my NO vote.

Example Mask Proposed by ETSI to ITU

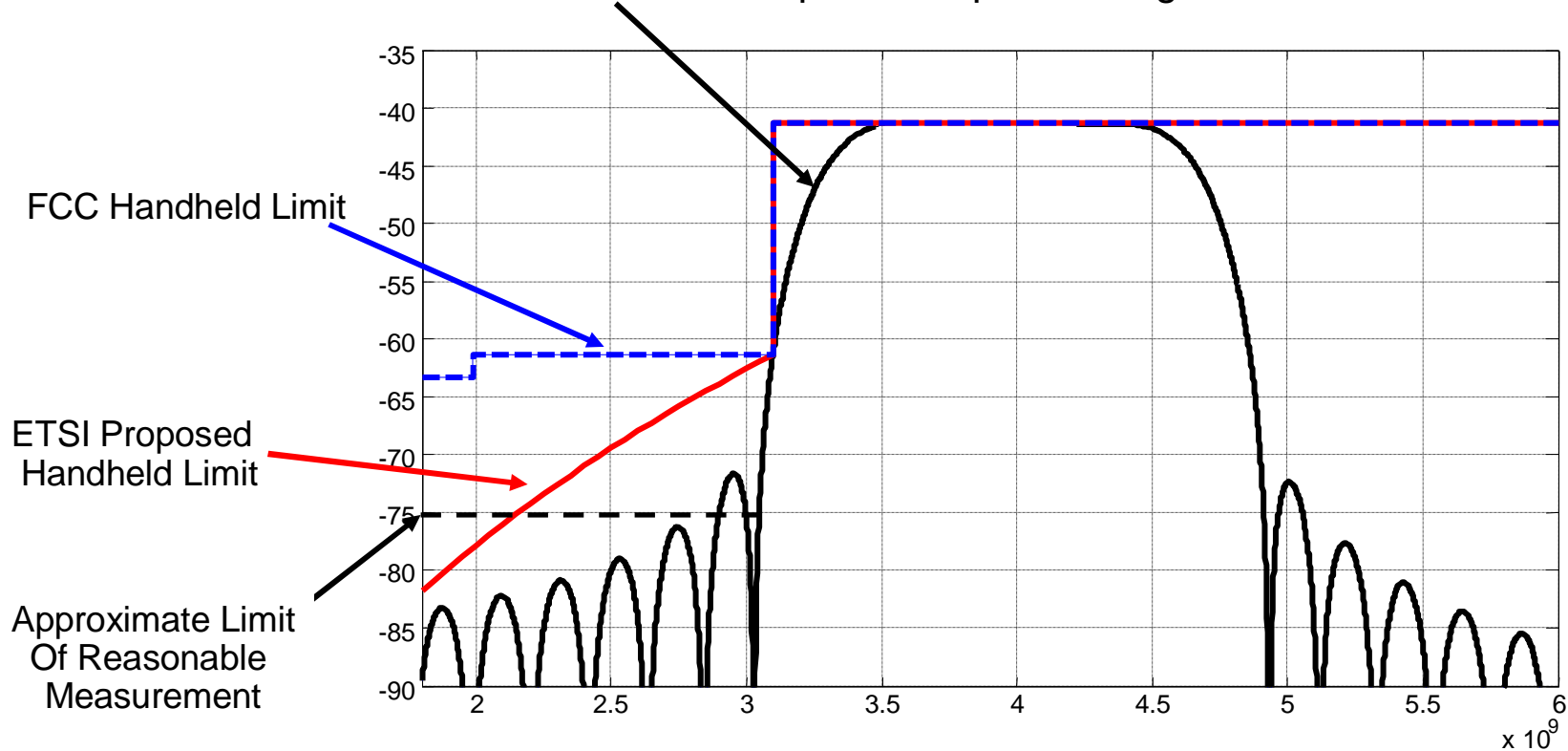
Note that the US is not supporting this indoor limit proposed by ETSI
USA has proposed that ITU use the FCC's mask



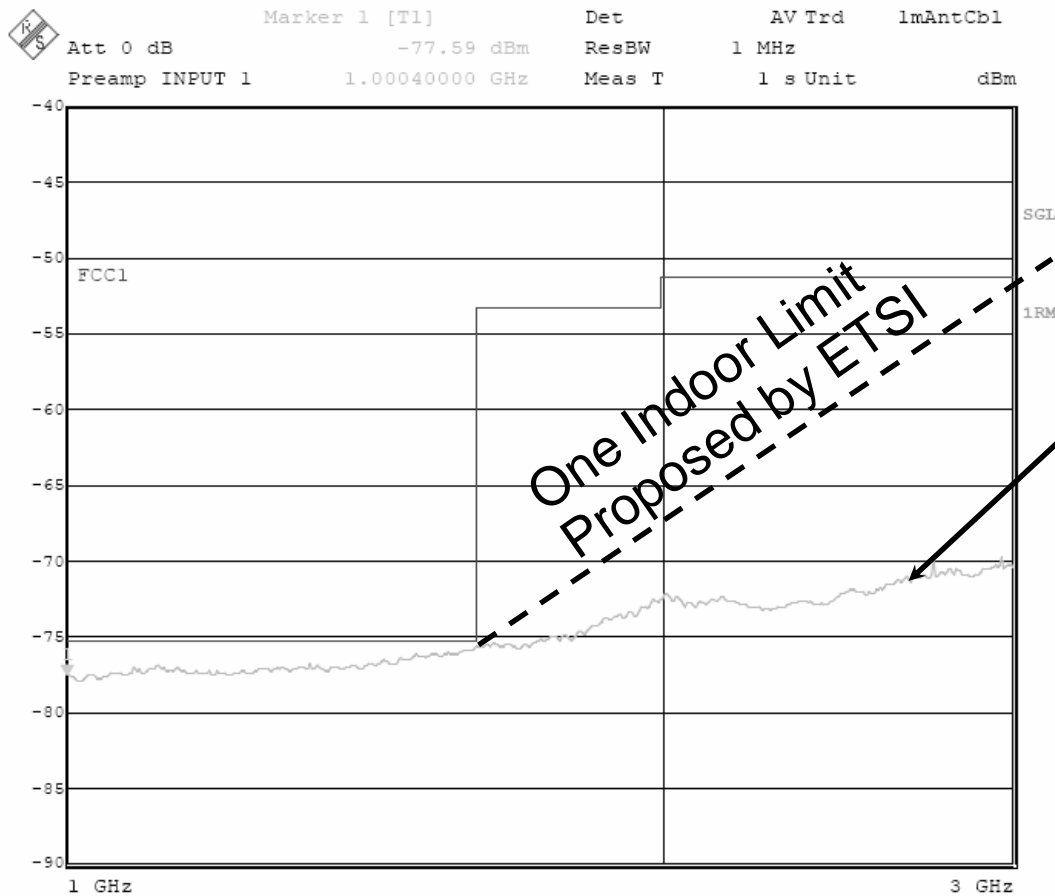
DS-UWB Out-of-band Emissions

- Natural pulse shape of RRC rolls-off quickly outside operating band
- Further control of emissions for co-located applications is possible

Theoretical Root-Raised Cosine pulse shape showing OOB roll-off



OOB Emissions: Measurement From FCC Certification Test Document



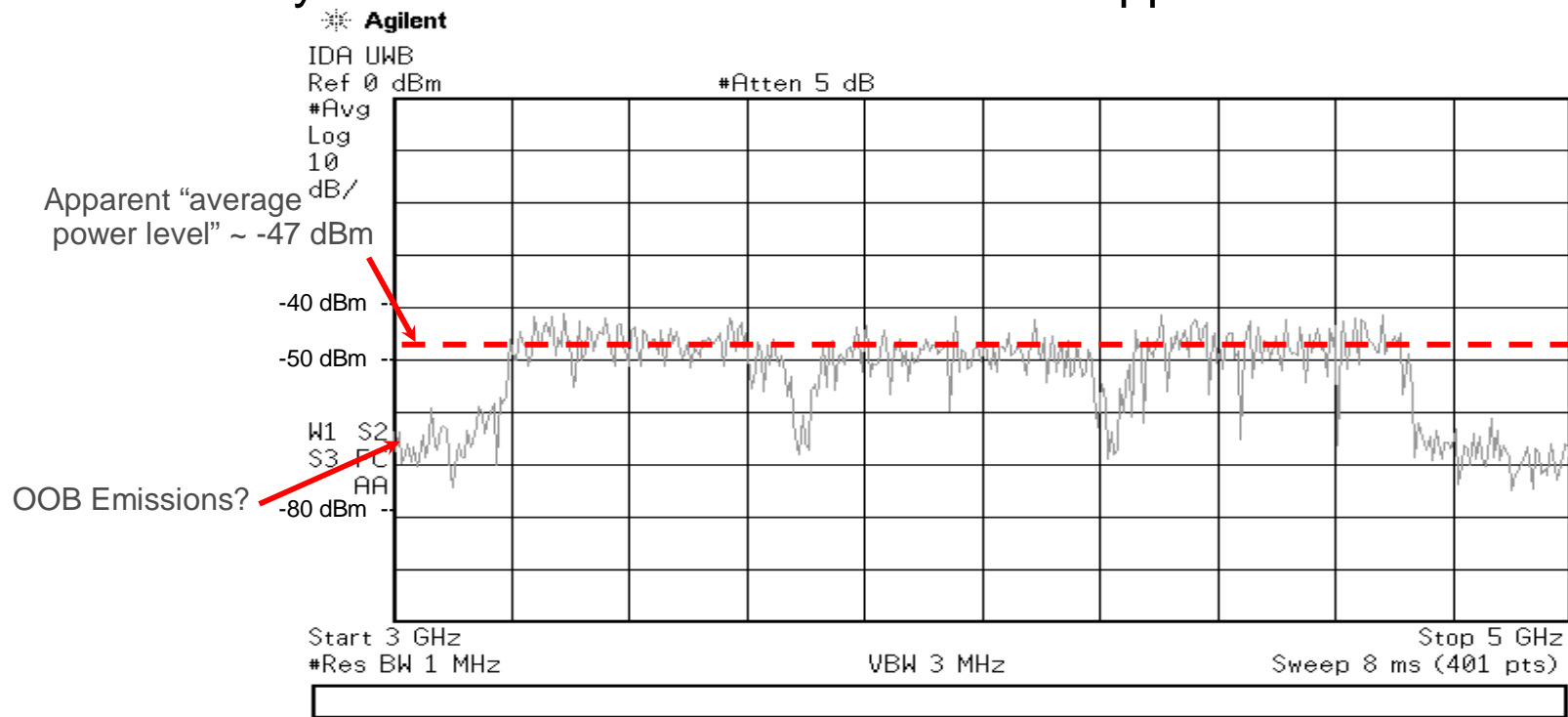
Notes:

- This curve is directly on top of the measurement of the instrument noise floor!
- The Freescale DS-UWB radio emissions are actually lower

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OOB Emissions: Measurements of MB-OFDM

- Commenter indicates that only MB-OFDM can meet OOB emission levels required to coexist with other systems
- Publicly released measurements do not support this conclusion



MB-OFDM UWB Transmitter – Additional Information

Figure B-1 below is a spectral plot of the output of the Staccato SC1000D MB-OFDM UWB transmitter captured directly from an Agilent E4407B spectrum analyzer. An RMS detector and a resolution bandwidth (RBW) of 1MHz were used. The plot, which begins at 3GHz and stops at 5GHz, shows the three OFDM bands that make up the signal. Note that the maximum power spectral density of the signal is around -41dBm/MHz.

“Spectral Flexibility”

- The DS-SS system proposed does not meet the easy frequency adaptability (adaptable emissions mask) that will be necessary for a world wide deployment of a single implementation. Specifically, the current direct of the development of European and Japanese UWB regulations is to provide greater protection to some services (frequency bands) within the UWB operating band. While I understand that steps can be taken to notch out frequencies from the transmitted signal, I believe that the added complexity will increase cost so as to limit this UWB approach to high end products.

Same Spectral Flexibility as OFDM

- I still consider the spectral flexibility of OFDM is essential for a worldwide standard that may have to accommodate spectral mask cutouts in different regulatory regimes than the US. I would change my no vote to a yes if DS-UWB could demonstrate the same level of spectral flexibility as provided by an OFDM approach in a cost-effective and practical manner. This would preferably be by means of a real-time demo, showing on a spectrum analyzer how notches can be created and moved to the desired locations.

World-wide Compliance Topic Fully Resolved

- The only regulations that exist in the world are those of the FCC
- The Freescale implementation of the DS-UWB proposal has already been certified by the FCC (No Waiver Required!)
- Therefore, the DS-UWB proposal is proven to be world-wide compliant
- Neither the PAR nor the Criteria Document requires the proposal to be compliant with non-existing regulations
 - A device cannot be non-compliant or compliant with a document that does not exist

Future World-Wide Regulations Are Easier To Get With DS-UWB

- The key requirement to obtain world-wide regulations is to minimize the potential for interference
- It was difficult to get simple FCC regulations even with all UWB parties working together
- Both proposers have made presentations that show DS-UWB is less interfering than MB-OFDM
- As a result, it will be easier to get world-wide regulations passed for DS-UWB
 - Objectors to UWB will only accept the lowest interfering form of UWB i.e. DS-UWB

There Are Good Reasons For World Wide Regulatory Efforts To Avoid Notching

- There is an extensive technical record justifying the FCC's regulations
- Many applications fail if spectral notching is required
 - especially safety of life and industrial, such as UWB imaging & ranging
- Communications systems are both degraded and made more expensive by notching
- For these reasons, the US position in international regulatory bodies is the FCC's rules

World Wide Efforts are Coalescing Around the FCC Rules & No Notches

- Other nations are working hard to have a global standard largely based on the FCC rules
 - Example is the ETSI proposal to the ITU
No notching is required
 - Recent reports by OFCOM (UK) and EU indicate that mask based on FCC in-band limits is desirable
- None are considering dynamic notching as a requirement for UWB operation
- The desired regulatory outcome is a global standard that would preclude the need for special modes for different regions

Even If Notching Were Ever Required DS-UWB Has Simple Spectral Control Capabilities

- DS-UWB has multiple powerful techniques to control its spectrum
- Any mechanism, static or dynamic, that modifies the pulse shape or code, can be used
 - Small, low-cost filters are already used for front-end protection
 - These also control the emitted spectrum
 - The low-pass RRC filter illustrated in doc 153
 - This filter operates with a bandwidth of $\frac{1}{2}$ the PRF (~700 MHz)
 - A dynamically controlled 700 MHz BW notch filter could be built
 - .18u CMOS is completely adequate
 - Even off the shelf op-amps that have to drive external pins can do this
 - Analog linear pulse combination – e.g., in document 03/111r0
 - DAC based designs - Digital pulse shaping techniques

Even If Notching Were Ever Required DS-UWB Is Simpler Than MB-OFDM

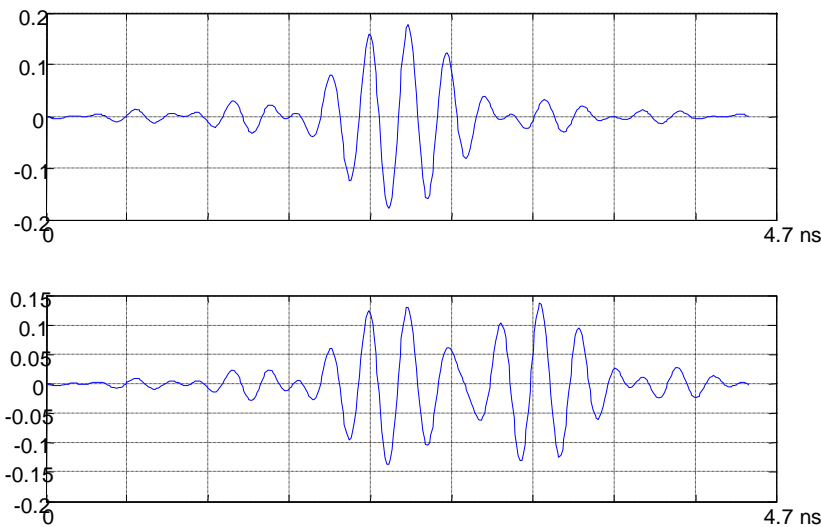
- No detailed results showing feasibility of MB-OFDM notching have ever been presented to TG3a
 - Research indicates issues with spectral ripples induced by nulling tones
- No MAC/Protocol changes are required
 - The notched spectrum can be used without Tx-Rx negotiation protocols
 - Spectral control based on pulse shape does not require changing the preamble sequence as does MB-OFDM
- The DS-UWB receiver is backward compatible
 - It is insensitive to the transmitted pulse shape
 - Only the chipping rates and center frequencies need to match
 - The exact frequency of a narrow notch has little effect
 - The exact frequency for the edge of the pass-band has little effect
 - While power loss cannot be compensated, the existing equalizer will mitigate the ISI

ICI due to Pulse Shaping

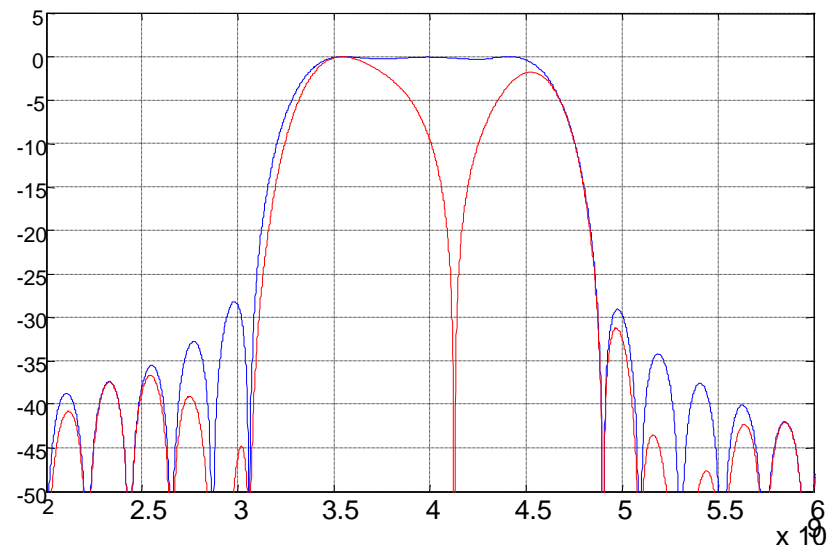
- Comments
 - Any attempt to change the spectrum will generate ISI which will make the equalizer problem even worse
 - Spectral shaping of DSSS introduces ICI and rapidly degrades performance
 - This pulse shaping will also severely degrade the performance
- Response:
 - Pulse shaping lengthens the pulse only marginally
 - A well-designed receiver is already designed to tolerate channel dispersion of 50+ ns and is relatively insensitive to pulse shape – the notch looks like part of the channel
 - Conclusion: Pulse shaping does not cause unmanageable ICI or ISI

Simple Example of Pulse Shaped to Create a Notch

RRC pulse before and after two-tap delay line



RRC pulse spectrum and with notch



- Pulse shaping lengthens the pulse only marginally
- A well-designed receiver is already designed to tolerate channel dispersion of 50+ ns and is relatively insensitive to pulse shape – the notch looks like part of the multipath channel
- Conclusion: Pulse shaping does not cause unmanageable ISI

ADC Complexity

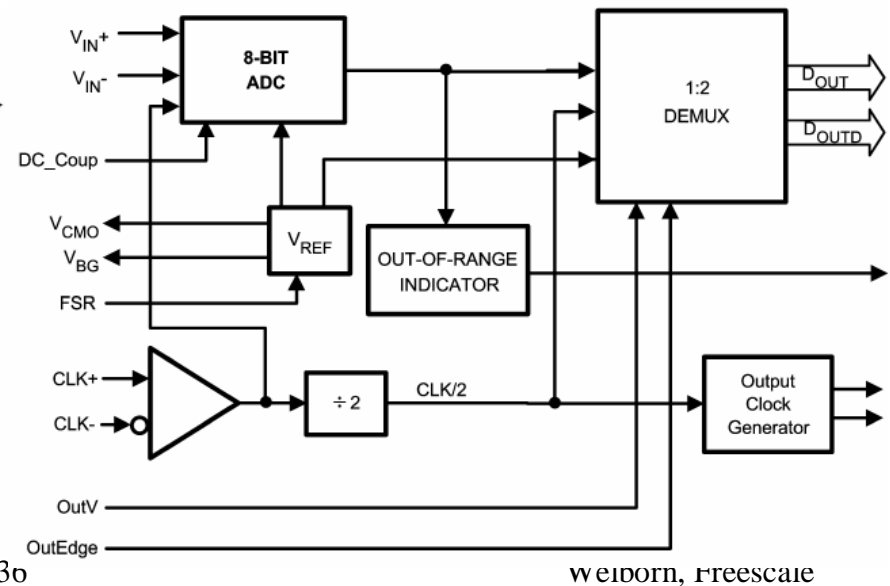
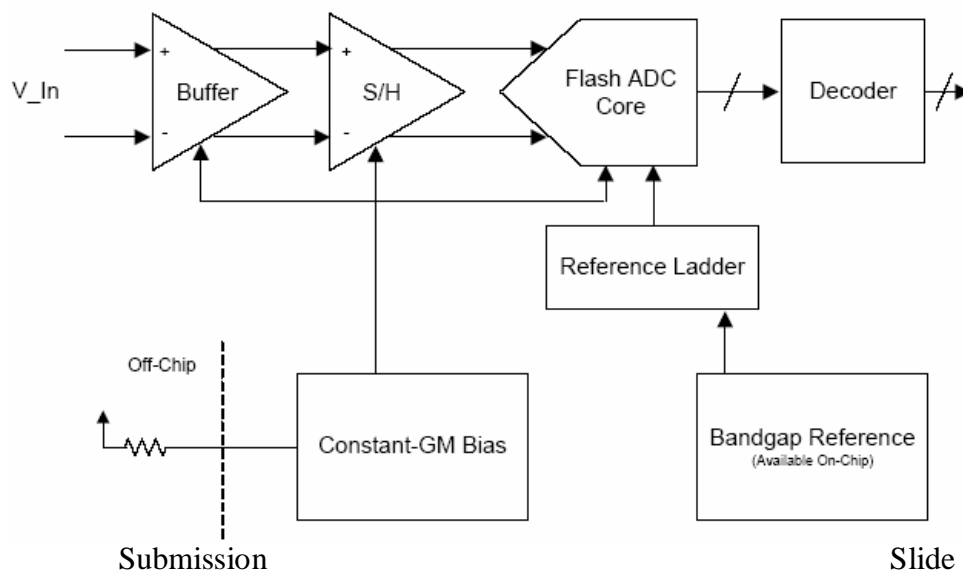
- Comment:
 - The ADC speed and amplifier quality seem to dictate implementation in an exotic process, which in my humble opinion would place a significant damper on adoption. Selecting a standard with significant adoption hurdles will encourage fragmentation of the medium, as lower-cost, higher performance technologies pass by the standard.
- Resolution:
 - ADCs at speeds and quality requires for DS-UWB are already available in commercial products

ADC in 0.13 CMOS ~ 50mw 3-bits 2.5 Gsps

Snowbush Microelectronics ADC8005

- 6-bits - ENOB: 5.2 bits at Nyquist
- DNL at +/- 0.5 LSB, INL at +/- 1.0 LSB
- Input dynamic range: +/-0.4V differential
- Analog bandwidth: 5GHz
- Single 1.2V power supply
- Power dissipation: 500mW
- Input capacitance: 150fF single-ended
- Sophisticated digital error correction
- Designed in a 0.13um TSMC CMOS process

- ## National Semi ADC081000
- 8-Bit, 1 GSPS A/D .18 CMOS
 - ENOB @ 500 MHz Input 7.5 Bits (typ)
 - Operating 1.45 W (typ)
 - Scale to 3-bits ~ 45mw
 - Power Down Mode 9 mW (typ)
 - Single +1.9V ±0.1V Operation
 - Guaranteed No Missing Codes
 - DNL ±0.25 LSB (typ)



ADC Power Requirements & Scaling

- ADC complexity is a function of both sample rate *and* bit width
- Concerns of comments seem to be that ADC requirements are much higher for DS-UWB than for alternative approaches (e.g. MB-OFDM) because clock rate is higher
- ADC power consumption is roughly proportional to clock rate and also scales exponentially with the bit width
 - 2x clock speed = 2x power consumption
 - 1 bit increase in sample width = 2x power increase
- This agrees with ADC scaling estimates based on MB-OFDM-proposed methodology
 - Available in IEEE Document 03/343r1 describing MB-OFDM complexity and power consumption
- DS-UWB digital receiver architecture can use a fixed bit width for all data rates up to 1.326 Gbps
- MB-OFDM proposes to use 4-5 bits at 528 MHz

ADC Relative Complexity & Bounds

- Relative complexity (power)
 - 528 MHz @ 4 bits \approx 0.8x 1326 MHz @ 3 bits
 - 528 MHz @ 5 bits \approx 1.6x 1326 MHz @ 3 bits
- Both approaches can likely scale to lower resolution ADCs with some sacrifice in performance
- ADCs are already commercially available to exceed the requirements needed for DS-WB implementations

PAR Deficiency

- Comment:
 - The TG3a PAR evidently does not require a cognitive radio. I believe this was shortsighted on the part of P802.15.
- Response:
 - As the commenter states, the PAR does not require cognitive radio (CR) capabilities
 - Neither CFA responses nor the TG3a requirements nor the selection criteria even mention CR capabilities
 - There are no UWB regulations anywhere that use CR
 - Getting even simple UWB regulations has proven to be the most contentious proceedings in history for regulatory agencies
 - This fact argues that attempting to get cognitive UWB regulations in place is highly unlikely

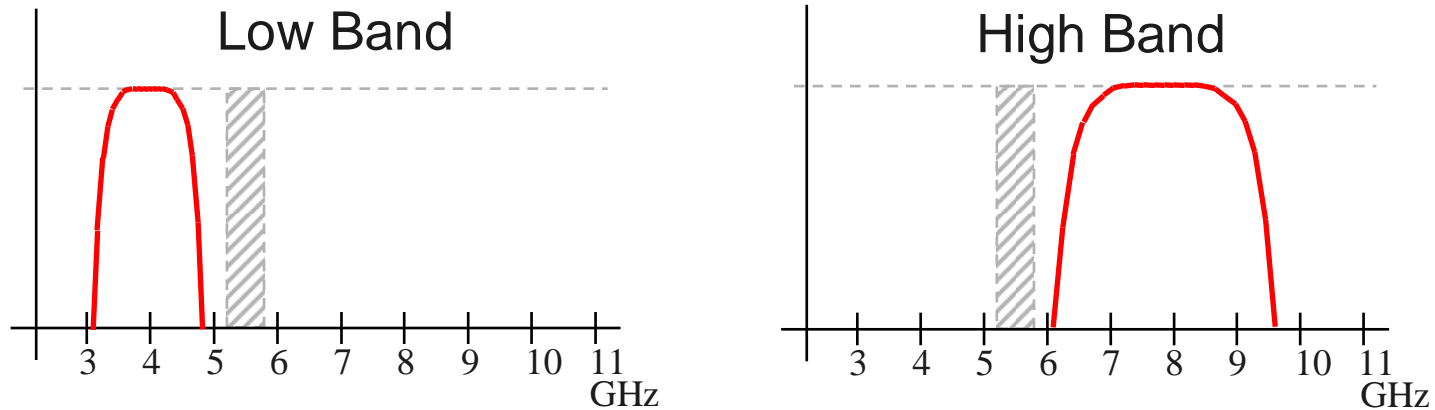
Proposal Summary

- A review of the history of the Merger#2 proposal
- A clear summary presentation of the DS-UWB proposal
- Consistent & complete performance and complexity results

Key Features of DS-UWB

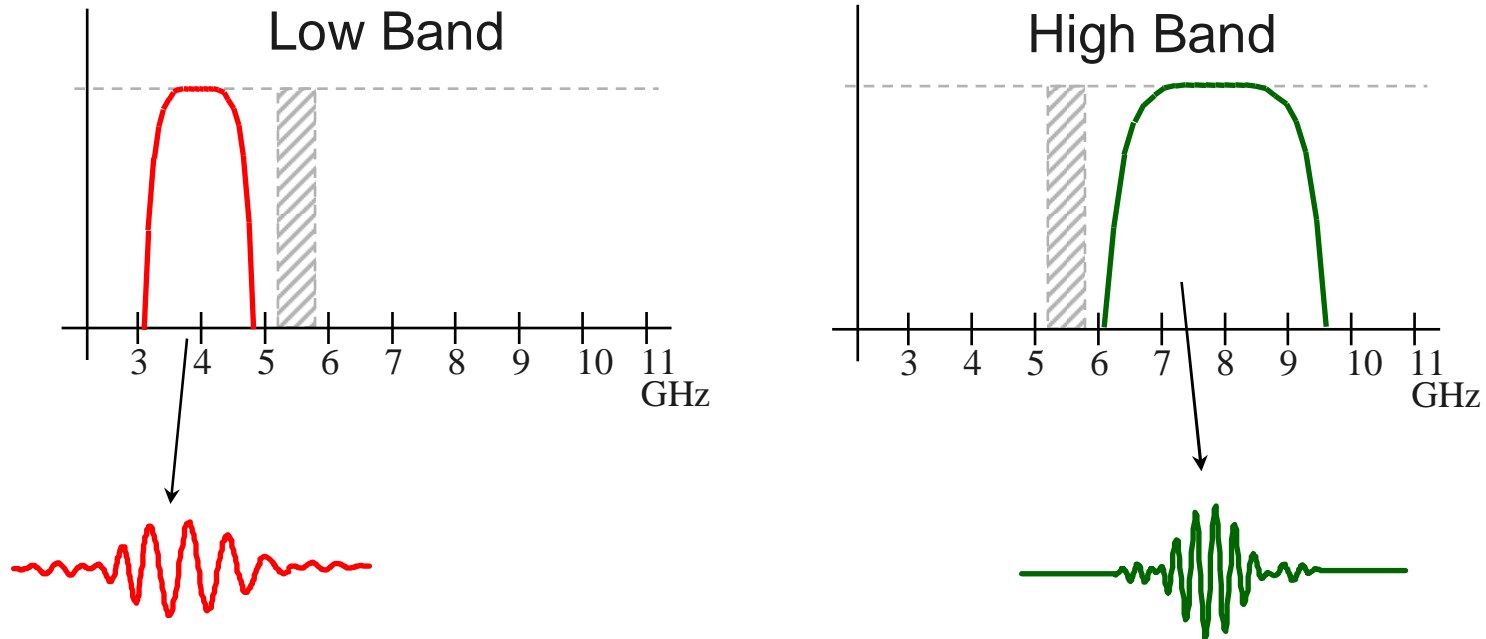
- Based on true Ultra-wideband principles
 - Large fractional bandwidth signals in two different bands
 - Benefits from low fading due to wide bandwidth (>1.5 GHz)
- An excellent combination of high performance and low complexity for WPAN applications
 - Support scalability to ultra-low power operation for short range (1-2 m) very high rates using low-complexity or no coding
 - Performance exceeds the Selection Criteria in all aspect
 - Better performance and lower power than any other proposal considered by TG3a

DS-UWB Operating Bands



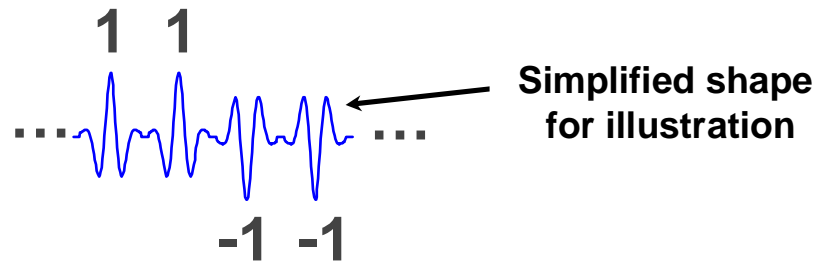
- Each piconet operates in one of two bands
 - Low band (below U-NII, 3.1 to 4.9 GHz) – Required to implement
 - High band (optional, above U-NII, 6.2 to 9.7 GHz) – Optional
- Different “personalities”: propagation & bandwidth
- Both have ~ 50% fractional bandwidth

DS-UWB Pulse Shapes

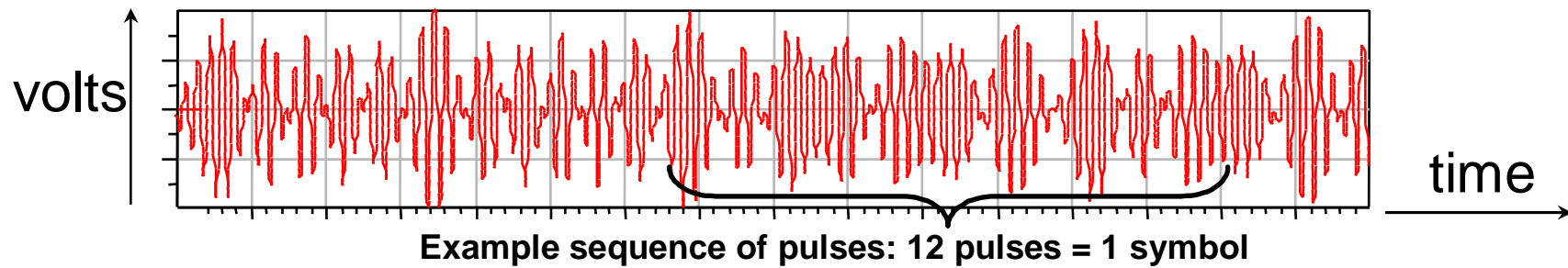


- Integer relationship between chip rate and center frequency
 - Center frequency is always 3x the chip rate
 - Results in a pulse shape that always has the same phase relationship between carrier and pulse

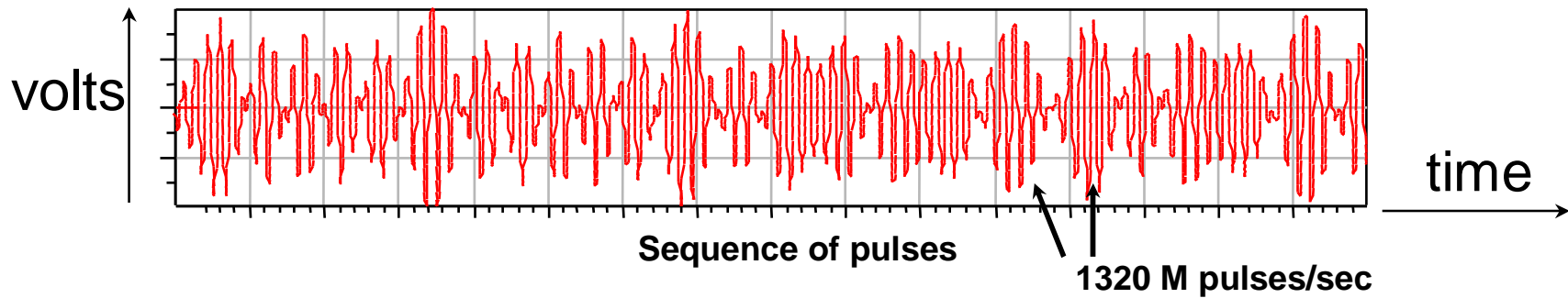
DS-UWB Spreading Codes



- Pulses are transmitted in sequences
 - “Ternary” sequences – elements are +/-1 or 0
- Bits are transmitted by sending a sequence of pulses for each bit
 - Different sequence lengths = different bit or “symbol” lengths
 - Sequences range from length 24 down to length 1
 - Leads to longer or shorter or longer symbols



Achieving Different Data Rates



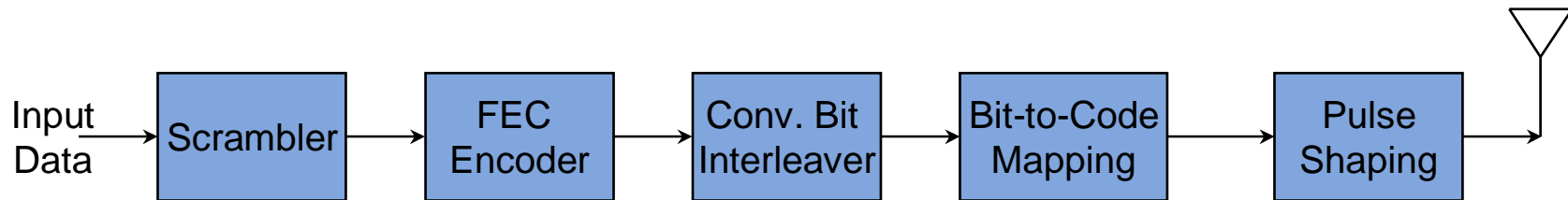
- Pulses or “gaps” are sent at a fixed chip rate
 - “Nominal” chip rate is 1320 MHz
 - Actual chip rates slightly offset for different piconets
- Data modes use different codes, same chip rate
 - Example: $1320 \text{ MHz} / 24 \text{ chips} = 55 \text{ M symbols/sec}$

Data Rates Supported by DS-UWB

Data Rate	FEC Rate	Code Length	Symbol Rate
28 Mbps	$\frac{1}{2}$	24	55 MHz
55 Mbps	$\frac{1}{2}$	12	110 MHz
110 Mbps	$\frac{1}{2}$	6	220 MHz
220 Mbps	$\frac{1}{2}$	3	440 MHz
330 Mbps	$\frac{1}{2}$	2	660 MHz
500 Mbps	$\frac{3}{4}$	2	660 MHz
660 Mbps	1	2	660 MHz
1000 Mbps	$\frac{3}{4}$	1	1320 MHz

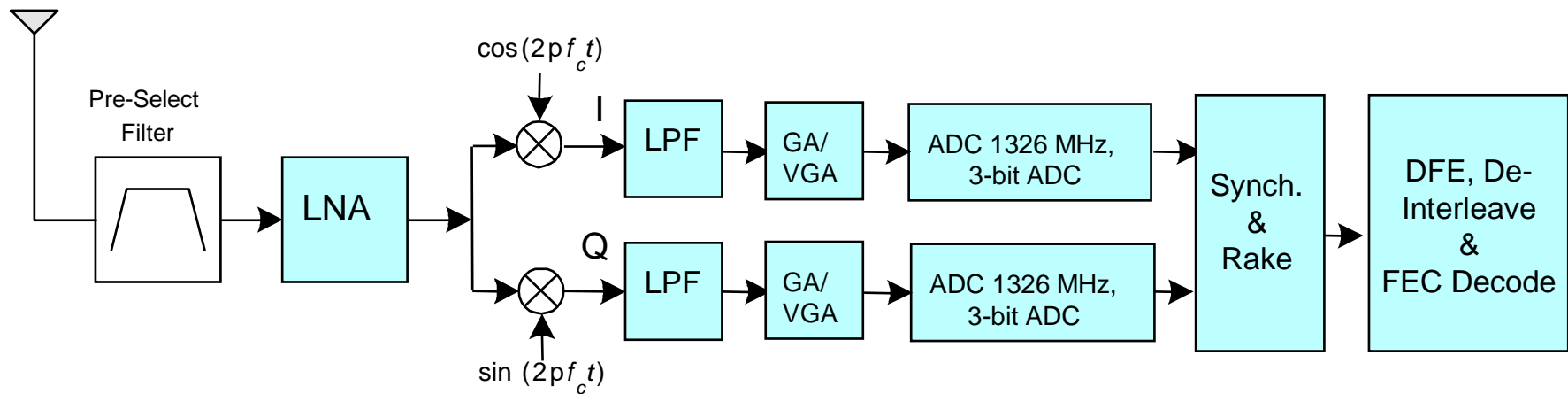
Similar Modes defined for high band

DS-UWB Transmit Chain



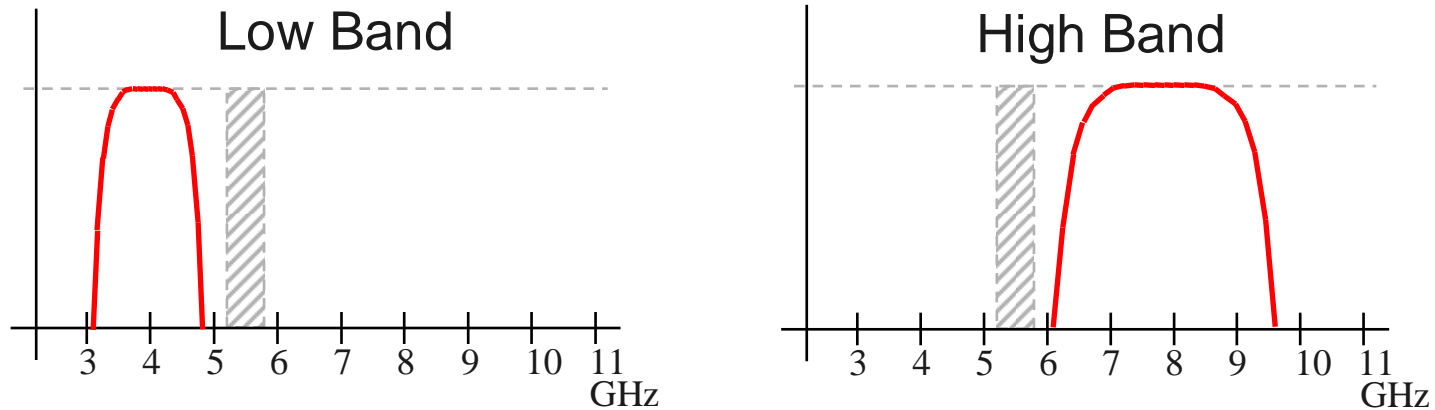
- Transmitter supports both k=6 and k=4 convolutional FEC encoders
 - Both are rate $\frac{1}{2}$ codes that can be punctured to rate $\frac{3}{4}$
 - Adding a second encoder adds significant flexibility
 - Adding a second encoder adds insignificant complexity
 - k=4 code can be used at higher rates (for low complexity implementation)
 - k=4 code can also be used to support iterative decoding (CIDD)

DS-UWB Digital Rake Receiver



- Example architecture specifics
 - Front-end filter + LNA
 - I&Q sampling using 3-bit ADCs
 - 16-finger rake (typical) with 3-bit complex rake taps
 - Decision feedback equalizer (DFE) at symbol rate
 - Viterbi decoder for k=6 convolutional code

DS-UWB Support for Multiple Piconets

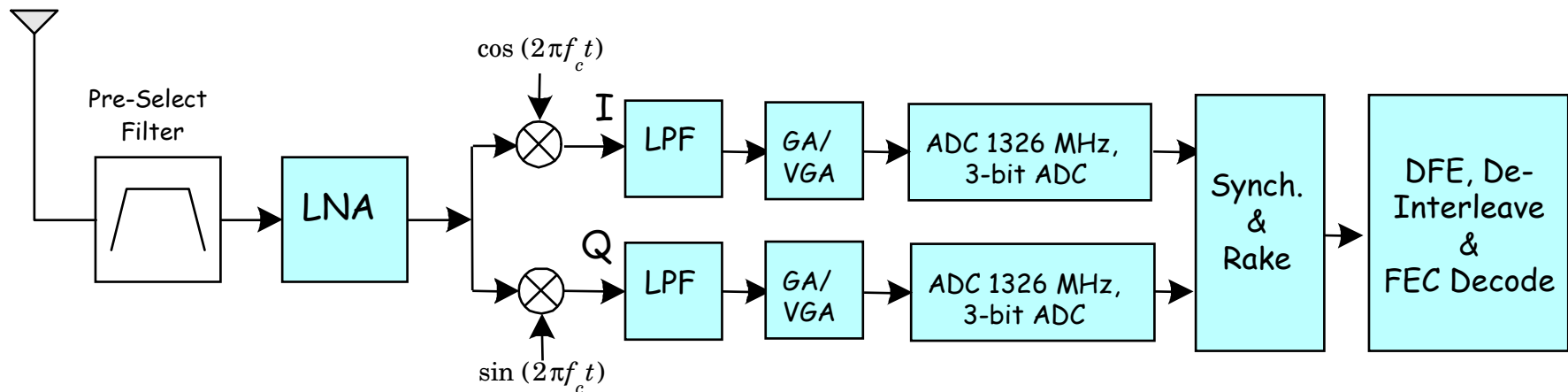


- Each piconet operates in one of two bands
- Each band supports up to 6 different piconets
 - Mandatory: only 4 center frequencies in low band
- Piconet separation through low cross-correlation signals
 - Piconet chip rates are offset by ~1% (13 MHz) for each piconet
 - Piconets use different code word sets

UWB System Complexity & Power Consumption

- Two primary factors drive UWB complexity & power consumption
 - Processing needed to compensate for multipath channel
 - Modulation requirements (I.e. low-order versus high-order)
- DS-UWB designed to use simple BPSK modulation for all rates
 - Receiver functions (Rake & EQ) operate at the symbol rate
- DS-UWB can use lower complexity FEC due to relatively low multipath fading

Complexity For a Rake Receiver

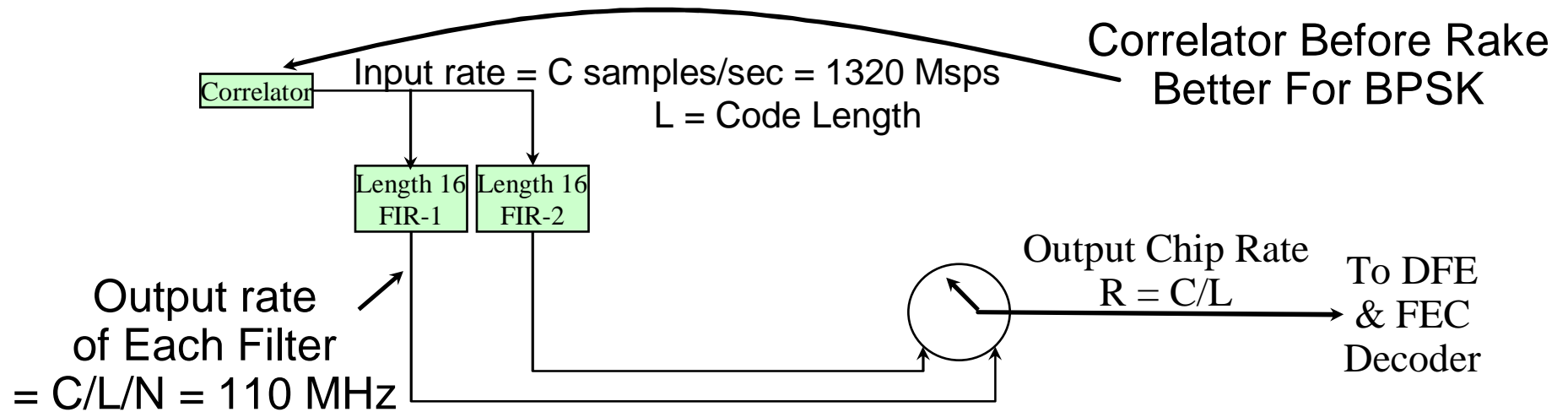


- Architecture assumptions
 - Front-end filter + LNA
 - I&Q sampling using 3-bit ADCs
 - 16-finger rake (at 110 Mbps) with 3-bit complex rake taps
 - Decision feedback equalizer at symbol rate
 - Viterbi decoder for k=6 convolutional code
- Performance results summarized earlier (full details in 04/483r3)

Example Rake Is Based On 2 Parallel Branches, 3-bit A/D, Symbol Rate Output

Parallel N=2 filters so each can run slower by a factor of 2

$$1320/L/2 = 1320/6/2 = 110 \text{ MHz}$$

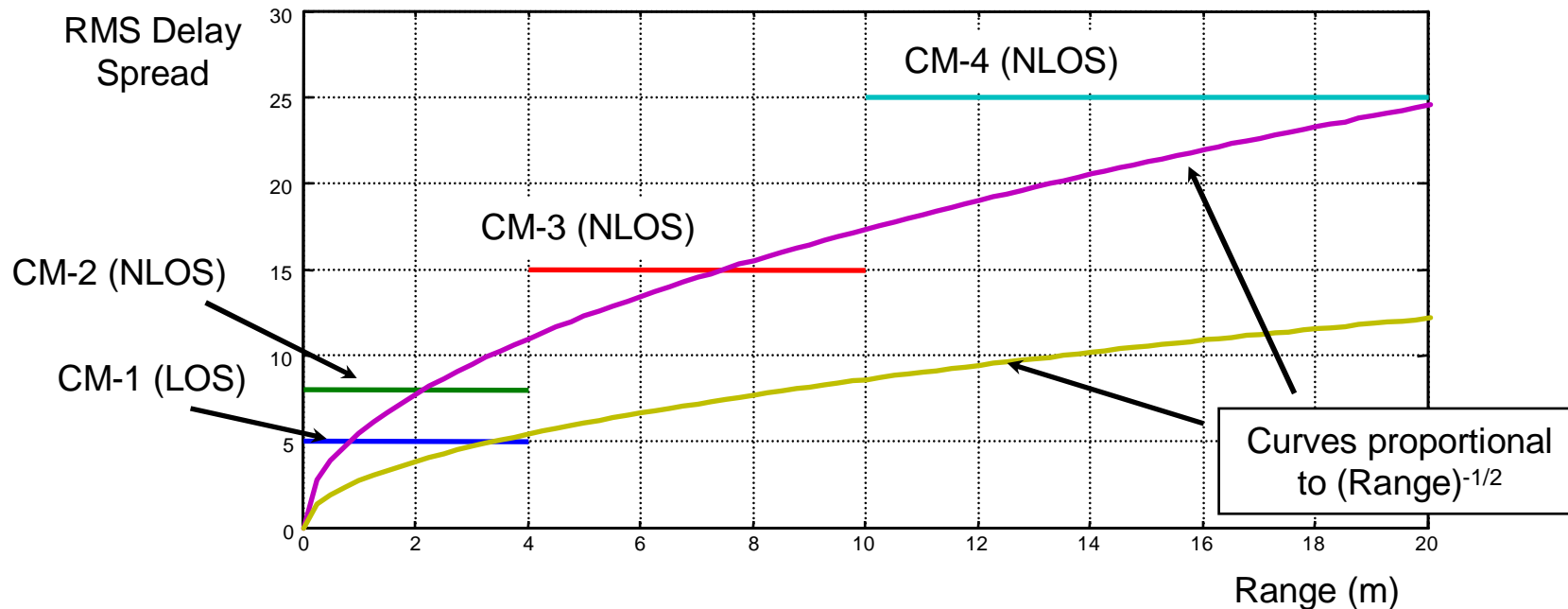


NEW PROPOSAL CHANGES TO

$$\text{Complexity} = (16 \text{ multipliers}) * (N=2 \text{ branches}) * (400 \text{ gates per 3-bit mult}) * \frac{(110 \text{ MHz})}{85.5 \text{ MHz}}$$

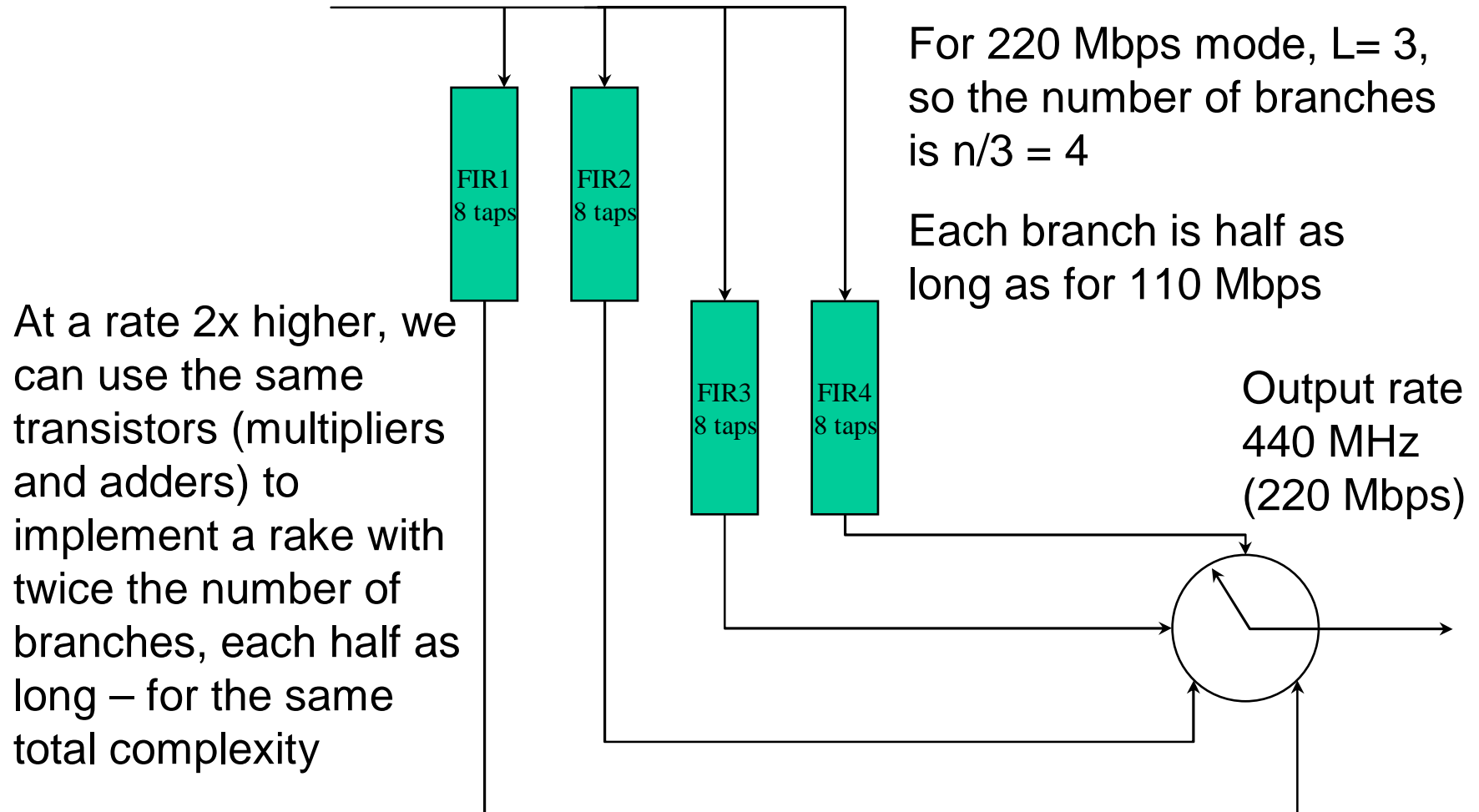
$$= 26k \text{ Gates (including adders and overhead)}$$

DS-UWB Can Use Variable Rake Terms to Match Multipath & Save Power



- Multipath delay spread increases with range
 - High rate modes operate at shorter ranges – few taps
 - Lower rate modes operate at longer ranges – more taps
 - In AWGN, only one tap is needed

How can the Rake Adapt to Speed?



Complexity Scaling for Simulated Modes

- Complexity scaling of 16-finger rake and DFE
 - Assumes 16 finger rake desired at highest supported rate
 - Can also use adaptive rake design
 - Rake size is a complexity/performance trade-off
 - DFE assumes scaling to operate at symbol rate
- Gates counts are given below in terms of gates normalized to 85 MHz (for comparison)

Data Rate (Mbps)	110	220	500	660 (1)	660 (2)	1000
16-finger rake gates	26000	44000	63000	63000	120000	120000
DFE gates	24000	30000	35000	35000	50000	50000

Notes: 660 (1) = length-2 code with no FEC & 660 (2) = length-1 code with k=6 FEC

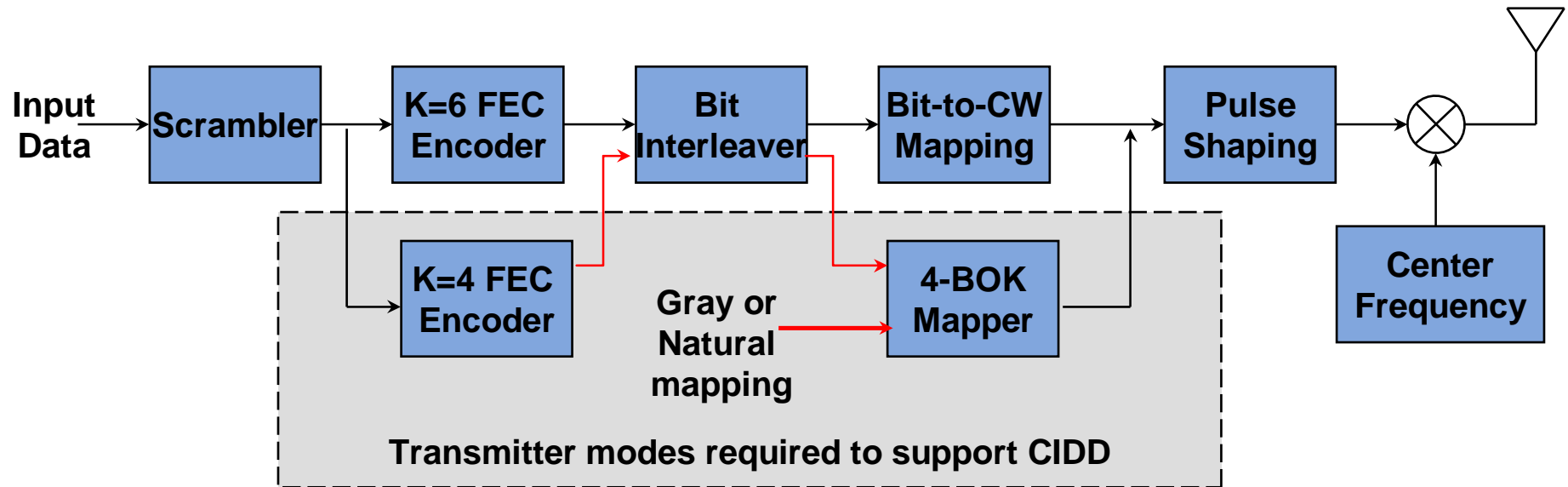
Power Consumption for DS-UWB PHY

Process Node	Rate (Mbps)	Transmit (mW)	Receive (mW)	CCA (mW)
90 nm	110	61	129	101
	220	64	140	101
	500	67	152	101
	660 (1)	67	128	101
	660 (2)	76	163	101
	1000	76	151	101
130 nm	110	75	164	121
	220	80	183	121
	500	85	201	121
	660 (1)	85	163	121
	660 (2)	99	217	121
	1000	99	199	121

Notes: (1) 660 (1) = length-2 code with no FEC & 660 (2) = length-1 code with k=6 FEC
 (2) Estimates include analog and digital portions of system

- Back-up Slides

DS-UWB Transmit Chain (with options)



- Transmitter supports both k=6 and (optional k=4) FEC encoders
 - Adding a second encoder adds significant flexibility
 - Adding a second encoder adds insignificant complexity
 - k=4 code can be used at higher rates (for low complexity implementation)
 - k=4 code can also used to support iterative decoding (CIDD)