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

Submission Title: [The Scalability of UWB PHY Proposals]
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Abstract: [The scalability of UWB PHY designs depends on the fundamental approaches used for UWB signal design.Two primary aspects of this include signal bandwidth and modulation choices. This submission examines how these choice can drive complexity and power consumption for some key UWB applications.]

Purpose: [Technical contribution to help the TG3a members understand the scalability of TG3a PHY proposal to different UWB applications]

Outline

- Review UWB application requirements
- Fundamental factors that drive complexity
- Scalability of UWB systems to high rates (~ Gbps)

UWB Consumer Electronics Applications

Four Primary Usage Scenarios

- Wireless in-room A/V distribution
  - Media center, media PC, set-top box & access points
  - Flat panel displays
    - Plasma display panel (PDP), Liquid crystal display (LCD), Digital light processing (DLP)
- Mobile devices applications
  - Streaming A/V
    - Digital video camcorder (DVC), media player
  - Content transfer (large file upload/download)
    - Media player, portable storage, MP3, digital still camera (DSC), smartphone/PDA

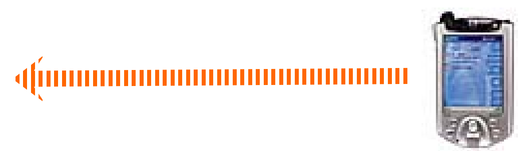
Content Streaming for Mobile Devices

- Applications
  - Digital video camcorder (DVC)
  - Smartphone/PDS, Media player
- Requirements
  - Range is in view of display (< 5m)
  - DV Format 30 Mbps with QoS
  - MPEG 2 at 12-20Mbps
  - Power budget < 500 mW


Stream DV or MPEG to display

Channel surf and PIP to handheld

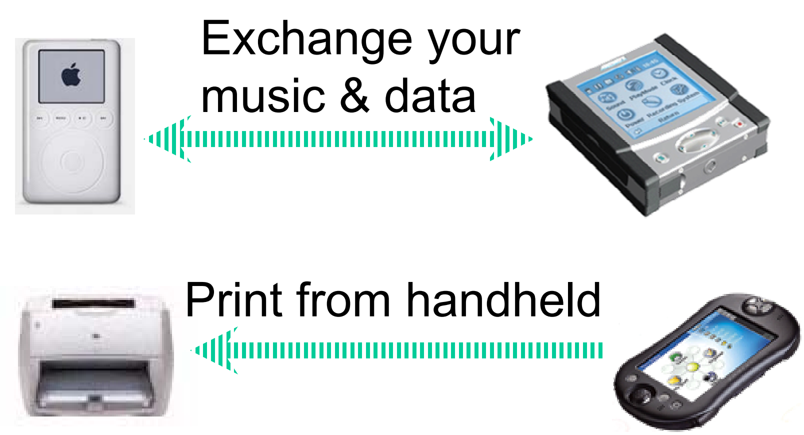




Stream presentation from Smartphone/PDA to projector

Content Transfer for Mobile Devices

- Applications
  - Smartphone/PDA, MP3, DSC
  - Media Player, Storage, display
- Requirements
  - Mobile device storage sizes
    - Flash 5, 32, 512, 2048 … MB
    - HD +4 GB
  - Range is near device (< 2m)
  - User requires transfer time < 10 sec



UWB Power profile compared to Bluetooth

size (MB)	Transfer time (sec)			Energy (Joules)			Power Ratio	
	BT	DS-220	DS-1Gbps	BT joules	DS-220	DS-1Gbps	BT/220	BT/1Gbps
5	58.1	1.3	1.1	5.8	0.6	0.5	9.1	11.0
32	366.7	2.8	1.3	36.7	1.4	0.7	26.4	54.7
512	5852.4	29.4	6.5	585.2	14.7	3.2	39.8	181.2

- Conclusions: Mobile application requirements are only met with low power, high-speed UWB radios, and
- Rates need to reach 1 Gbps for acceptable session time

Model Parameters:

- Flash Storage of 5 MB, 32 MB, 512 MB
- DS-UWB (total solution MAC/BB/PHY) is 500 mW
- Bluetooth (Note BT xmit output power can be 1 to 100 mw) of 100 mW
- Includes Overhead for preambles, headers etc.
- Assumes 1 sec to wake, scan, pass security, & associate
- UWB throughput rates used are 220 Mbps & 1.32 Gbps tx/rvc rates after r=3/4 FEC

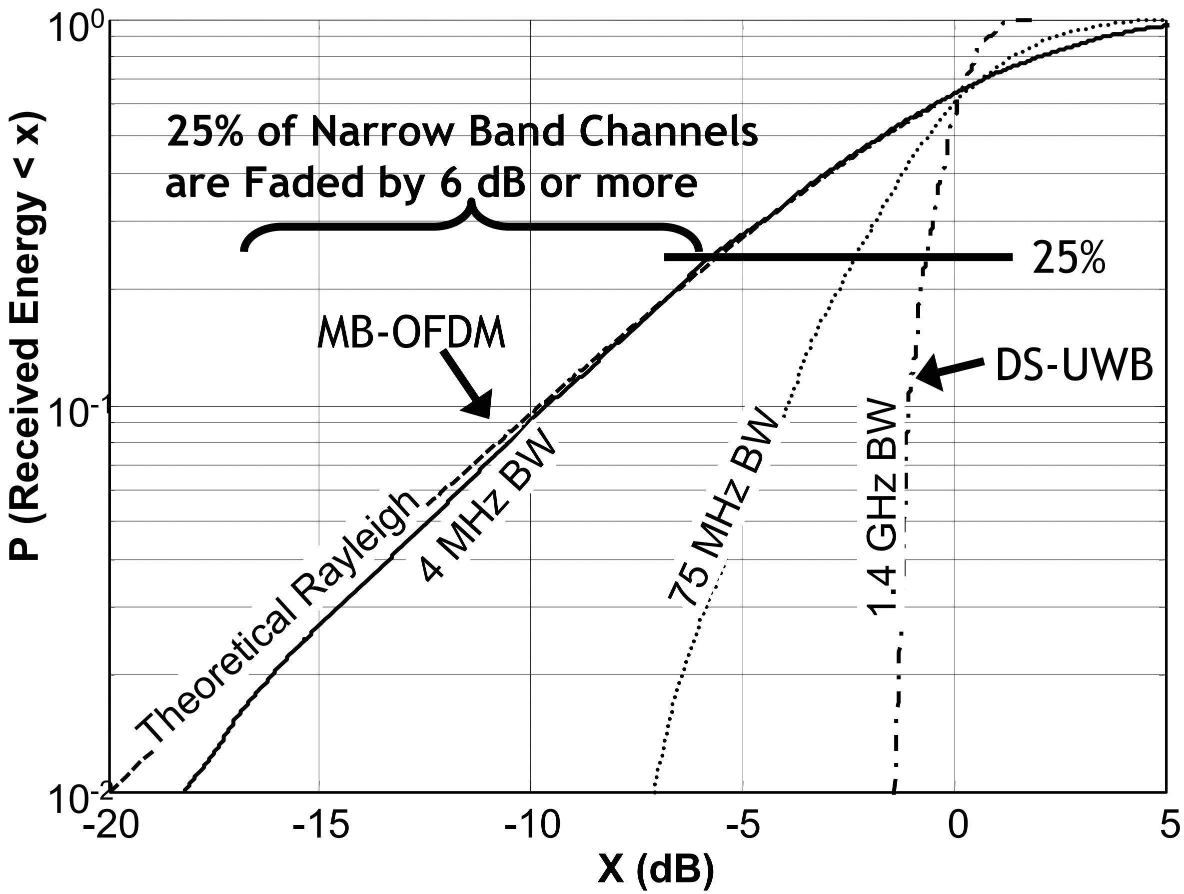
UWB System Complexity & Power Consumption

- 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 operate at the symbol rate
  - Optional 4-BOK has same complexity and BER performance
- MB-OFDM operates at fixed 640 Mbps (raw) using QPSK
  - Designed to operate at higher bit rate, then use carrier diversity and/or strong FEC to combat the multipath fading
  - Diversity not used above 200 Mbps

Fundamental Design Approach Differences

- ***Signal bandwidth*** leads to different operating regimes
  - DS-UWB uses 1.326 GHz bandwidth
  - MB-OFDM data BW is 412.5 MHz (100 tones x 4.125 MHz/tone)
- ***Modulation bandwidth*** induces different fading statistics
  - DS-UWB (single carrier UWB) results in frequency-selective fading with relatively low power fluctuation (variance)
  - MB-OFDM (multi-carrier) creates a bank of parallel channels that experience flat fading with a Rayleigh distribution (deep fades)
- Motivations for different choices
  - Different energy capture mechanism (rake vs. FFT)
  - Different ISI compensation (time vs. frequency domain EQ)
- These fundamental differences affect both complexity & flexibility
  - Significant impact on implementation, especially at high rates

Many MB-OFDM Tones Suffer Heavy Fading



- DS-UWB experiences frequency–selective fading – only a few dB of fading
- MB-OFDM does not coherently combine the multipath energy
- MB-OFDM tones suffer significant fading

Compensating for Multipath Fading

- Strong FEC used to help offset severe fading effects
  - MB-OFDM FEC complexity is relatively high
    - K=7 code required even for high data rates
  - Required Eb/No still higher in Rayleigh fading than in AWGN
    - 1-6 dB, depending on FEC/diversity mode
    - Puncturing of FEC required to reach higher rates
- Diversity
  - Operate receiver at high raw data rate (640 Mbps)
  - 2-tone diversity helps mitigate fading at low rates
  - No diversity can be used for higher rates
- For DS-UWB, multipath fading is relatively modest
  - Worst fades are a few dB
  - Can operate without FEC with minor impact on link budget

Data-Rate-to-Bandwidth Ratio Determines Modulation Options

- Signal-space is sized by the “dimensions-per-second”
  - One Hertz = two “dimensions” per second
- DS-UWB operates with 1326 MHz of bandwidth
  - 2 dimensions x 1326 M = 2652 M dimensions/sec for signaling
- MB-OFDM uses 100 data carriers of 4.125 MHz each
  - Result is data bandwidth of 412.5 MHz
  - MB-OFDM operates at ~78% duty cycle to allow time for multipath ring-down & hopping the front-end (242.4 ns / 312.5 ns)
  - Result is (412.5 x 2 dimensions x 78%) = 640 M dimensions/sec
  - Roughly 4:1 difference (excluding effects of FEC)
- MB-OFDM also uses FEC to compensate for fading
  - Highest rate code proposed is r=3/4
  - With ¾ FEC overhead, MB-OFDM has 480 M dimensions/sec available for data

MB-OFDM Modulation Choices to Achieve More than 480 Mbps

1. Increase the bits-per-dimension by using high-order modulation
2. Increase signal bandwidth (i.e. get more dimensions per second), or
3. Use higher-rate FEC (or no FEC), or

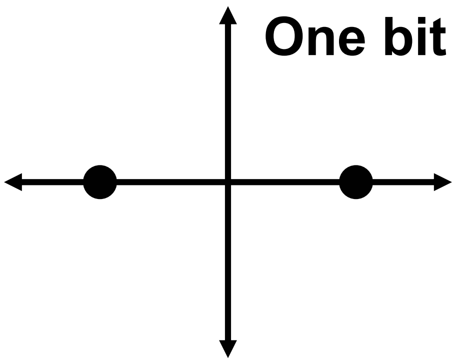
Scaling MB-OFDM > 480 Mbps Requires Increased Complexity

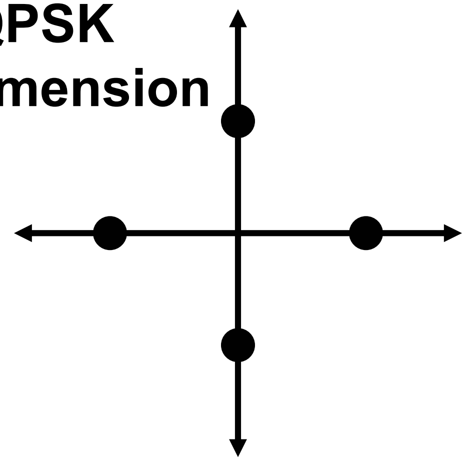
- **Three proposals by MB-OFDM authors to achieve > 480 Mbps***
  1. Shift from QPSK to 16-QAM in order to reach 960 Mbps
     - 3.9 dB higher Eb/No (in AWGN- worse in faded channel) for same BER performance
     - Requires higher precision ADC and FFT processing
  2. Use MIMO techniques to reach higher data rates
     - Requires two Rx & Tx chains (at least 2x the complexity)
     - Assumes uncorrelated RF channels at short range for MIMO gain
  3. Use all three bands simultaneously (“channel bonding”)
     - Eliminates frequency hopping → impacts SOP capability
     - 3x more ADCs or ADC at 3x clock
     - Approximately 4x or more increased FFT complexity
- **All approaches require k=7 Viterbi decoder to run at >1 GHz to combat narrowband (Rayleigh) multipath fading**

***Not in current proposal – based on EETimes, May 17**

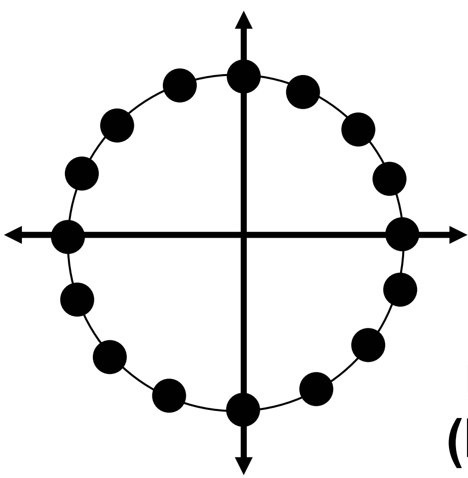
High-Order Signaling Constellations

BPSK & QPSK
One bit per dimension



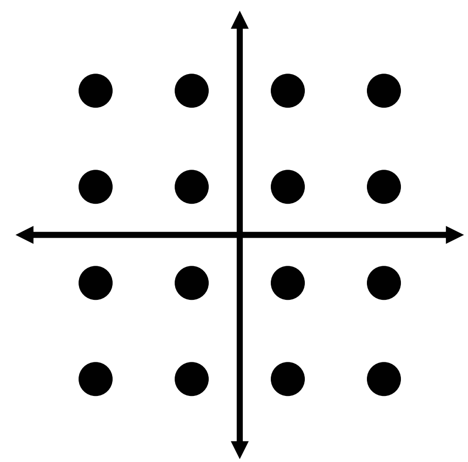


- **DS-UWB uses BPSK**
- **MB-OFDM uses QPSK for (<=480 Mbps) rates**
- **Both have same power efficiency**

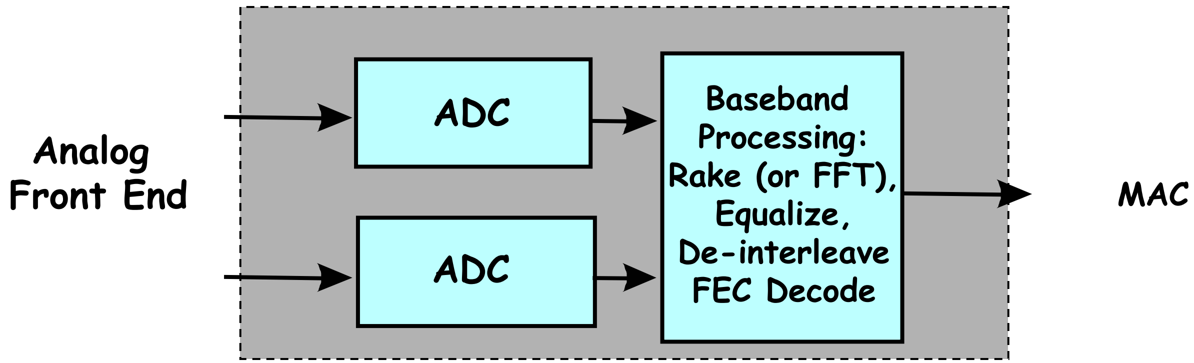


16-PSK or 16-QAM
2 bits per dimension

Trade-off is larger Eb/No requirement for given BER (I.e. Lower power efficiency)



Comparison of DS-UWB to MB-OFDM for Physical Layer Scaling to High Rates

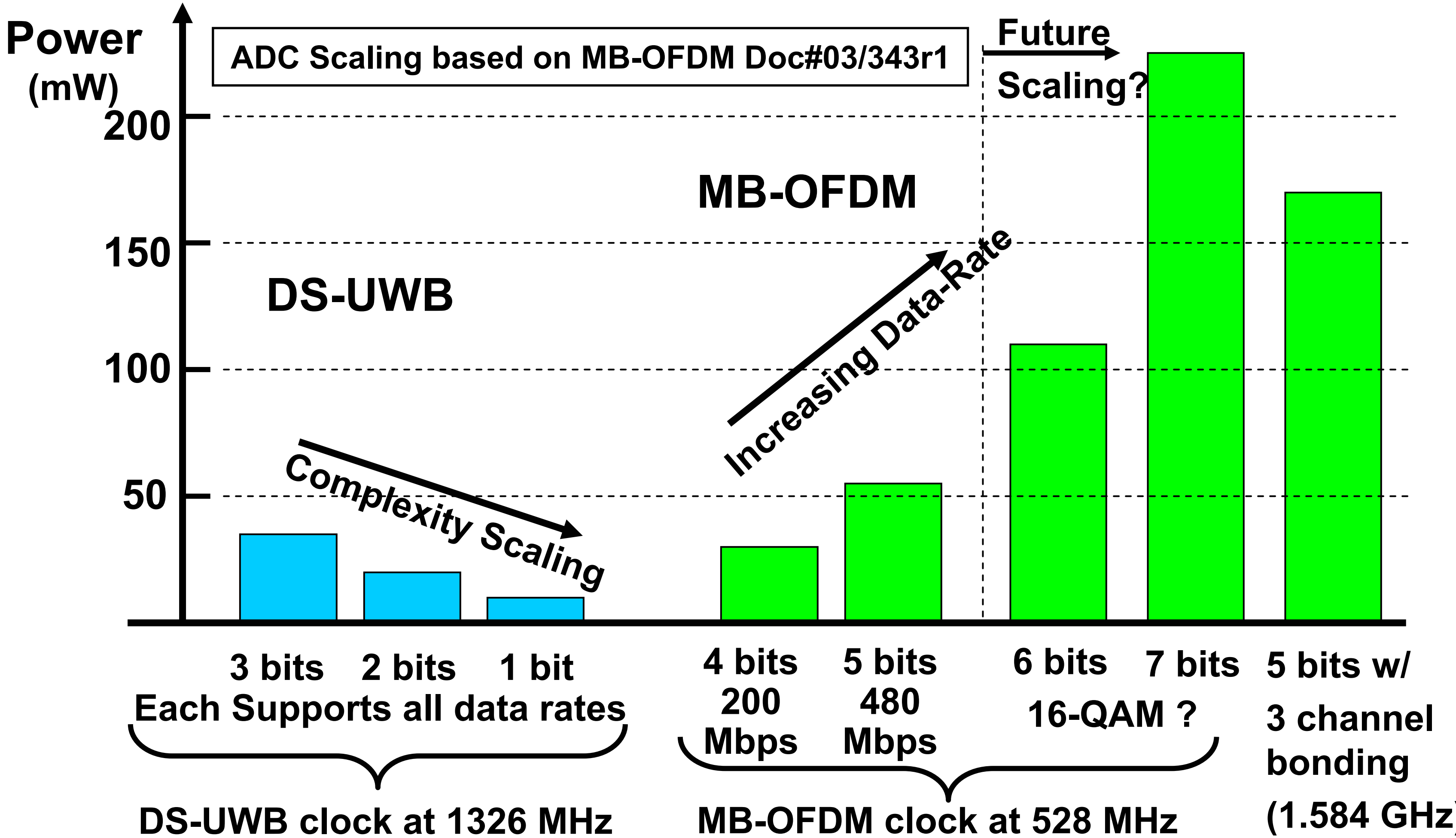


- Analog front ends for both approaches are somewhat independent of data rate
  - (except for MIMO & channel bonding of MB-OFDM)
- Fundament system approaches drive significant scaling differences for ADC and baseband complexity

ADC Power Requirements & Scaling

- 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 requires more ADC bit-width for higher data rates
  - 4 bit ADCs for 110/200 Mbps (IEEE Document 03/449r2)
    - Can scale to 3-bit ADCs for lower complexity implementation
  - 5 bit ADCs for 480 Mbps (IEEE Document 03/268r3)
  - 6-7 bits (estimated) for 16-QAM operation (proposed for >480 Mbps operation)
    - Higher resolution based on higher Eb/No requirement for 16-QAM
      - Other issues (AGC, linearity, clipping) require higher sample resolution for 16-QAM
    - MB-OFDM submissions state that 64-QAM OFDM (802.11a) requires 9-bit ADCs @ 80 MHz (e.g. >4x over-sampled) (03/343r1,p.83)
  - High rate implementation will likely need to use high resolution ADCs even for low rate modes – not cost-effective to turn bits off

ADC Power Requirements & Scaling

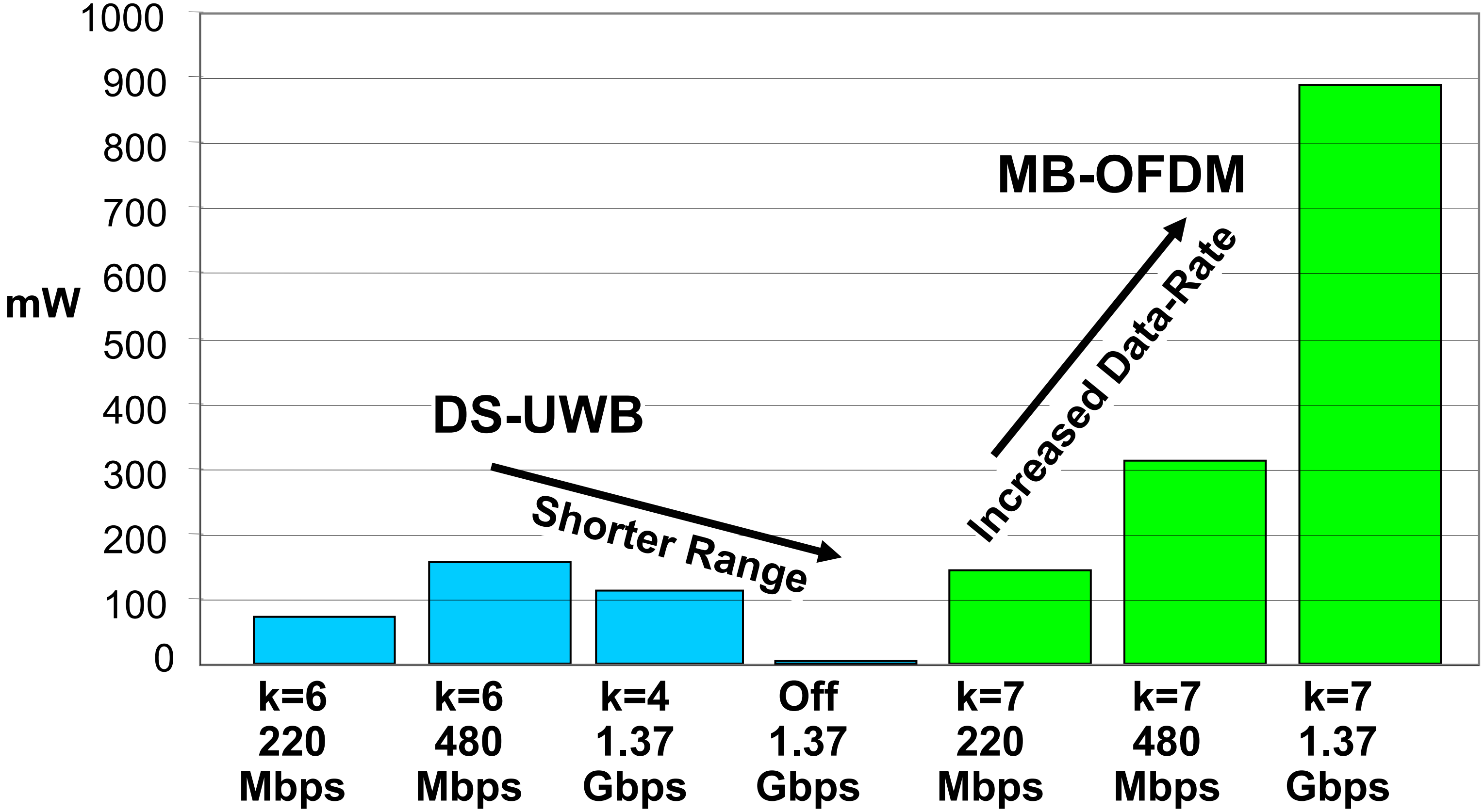


- Downstream processing complexity grows with ADC bit-width
- Bit-width growth = downstream processing growth too!

FEC Power Requirements & Scaling

Power ~ $2^k * f$

Assumes 90nm CMOS -- scaled from Viterbi operating in .18µ



Comparison of DS-UWB to MB-OFDM Digital Complexity for PHY Scaling to High Rates

- Gate count estimates are based on MB-OFDM proposal team methodology detailed in IEEE Document 03/449r2
  - All gate counts converted to common clock speed (85.5 MHz) for comparison
- Explicit MB-OFDM gates counts have been reported by proposers for a 110/200 Mbps implementation
  - Other estimates of MB-OFDM Viterbi decoder and FFT engine are provided in IEEE Document 03/343r0
- Estimates for MB-OFDM 480 Mbps mode complexity are based on scaling of FFT engine, equalizer and Viterbi decoder
  - MB-OFDM estimates of 480 Mbps power consumption available in 03/268r3
  - Details available in IEEE Document 04/164r0
- Estimates for MB-OFDM 960 Mbps mode details are based on linear scaling of decoder and FFT engine to 960 Mbps
  - Assumes 6-bit ADC for 16-QAM operation
    - MB-OFDM team reports 801.11a requires 9-bit/80 MHz ADC for 64-QAM (03/343)
- DS-UWB gate estimates are detailed in IEEE Document 03/099r4
  - Methodology for estimating complexity of 16-finger rake, equalizer and channel est., etc. blocks are per MB-OFDM methodology

DS-UWB & MB-OFDM Digital Baseband Complexity

Component	MB-OFDM (Doc 03/268r3 or 03/343r1) 110 Mbps	DS-UWB 16-Finger Rake 110 Mbps 3-Bit ADC	DS-UWB 32-Finger Rake 110 Mbps 3-Bit ADC
Matched filter Rake [DS] or FFT [OFDM]	100K	26K	45K
Viterbi decoder	108K	54K	54K
Synchronization	247K (Freq Domain)	30K	30K
Channel estimation		24K	24K
Other Miscellaneous including RAM		30K	30K
Equalizer		20K	20K
Total gates @ 85.5 MHz	455K*	184K	203K

- Gate counts are normalized to 85.5 MHz clock speeds to allow comparison
  - Based on methodology presented by MB-OFDM proposal team (03/449r3)
  - Other details of gate count computations are available in Document 04/099

*Equivalent to 295K gates at 132 MHz as reported in 03/268r3

Digital Baseband Complexity Comparison at ~1 Gbps

Component	MB-OFDM 960 Mbps using 16-QAM	DS-UWB 2-Finger Rake 1.326 Gbps 3-bit ADC width	DS-UWB 5-Finger Rake 1.326 Gbps 3-bit ADC width
Matched filter [rake] or FFT	225K	26K	45K
Viterbi decoder	432K	0K*	0K*
Synchronization	297K (Freq Domain)	30K	30K
Channel estimation		24K	24K
Other Miscellaneous including RAM		30K	30K
Equalizer		50K	50K
Total gates @ 85.5 MHz	954K	160K	179K

Assumptions: MB-OFDM using 6-bit ADC, FFT is 2.25x & Viterbi is 4x of low rate.
*DS-UWB operating with no FEC at 1.362 Gbps

Conclusions

- Mobile CE devices are a critical UWB application
  - Requires extremely low power with very high data rates
  - File-synch – e.g. Transfer an MPEG-4 movie (500MB) in < 6 sec
- DS-UWB scales to these mobile applications
  - DS-UWB provides scalable rake processing and can operate without FEC
- MB-OFDM does not scale
  - ADCs for high rate MB-OFDM modes require more bits & significant power consumption
  - Baseband processing is much more intensive for MB-OFDM, requires high-complexity FEC and FFT engine that grows in complexity with ADC bit width