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[特別招待論文]Ultra Wide-Band Solution by Multiband OFDM (MB-OFDM)
－マルチバンドOFDM　UWB　通信技術－

山口　博久

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あらまし　デジタル家電、PCのための近距離ワイアレス接続技術として、3.1 - 10.6 GHz帯域を用いて100+ MBps (10 m)を実現する新技術の標準化がIEEE802.15.3aで進められている。MB-OFDM方式は最も有力な候補として多くのデジタル家電、半導体メーカーの支持を得ているものである。本稿では完全CMOS(90um)によりUWBデバイスとして求められる技術基準、小消費電力、低コストを実現するMB-OFDM方式の概要について論ずる。
キーワード　UWB、ウルトラワイドバンド、マルチバンドOFDM、IEEE802.15.3a、ワイアレスPAN

Ultra Wide-Band Solution by Multiband OFDM (MB-OFDM)
－IEEE802.15.3a draft standard for future consumer electronics and PC－

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Abstract　New wireless PAN technology called Ultra Wide-Band (UWB) that generally utilizes the frequency band 3.1 – 10.6 GHz achieves over 100 Mbps information data-rate at the distance over 10 m. Multiband OFDM (MB-OFDM) has been proposed at IEEE802.15.3a as the draft standard, and received strong support from major CE, and SC manufacturers. Emphasizing the basic CE/PC UWB advantages in cost and power, his paper focuses on the full (RF and DBB) CMOS implementation of MB-OFDM in 90 nm technology.
Keywords　UWB, Ultra Wide-Band, Multiband OFDM, IEEE802.15.3a, wireless PAN

1.　まえがき

Ultra Wide-Band (UWB)技術に関しては2002年のFCCの規制緩和以降、各方面で活発な議論が進められている[1]。 UWBは従来の2.4 GHz、5 GHz帯のunlicensed bandの開放と異なり、既に主要なサービスに用いられているバンドをまたいで送受信を行う。このための基本規制としては平均電力（-3.1 – 10.6 GHz内で-41.25 dBm）ならびにピーク電力がFCCおよびCEPT/ETSIにより検討されている。わが国の将来のデジタル家電製品へのUWB技術の応用はcamcoder, DSC, デジタルTV, ホームシアターを始めとして広い範囲にわたるものと予想される。このため現在IEEE802.15.3a委員会において進められているPHY標準化に対して産業界から多大な関心が寄せられている。

UWBを実現する技術は、当初は、キャリア変調を用いず直接パルスの送受を行う方式[2]が主流であった。その後、全帯域を500MHz以上のバンドに分割し、変調したパルスを各バンドを使ってホッピングさせるマルチバンド方式、さらにその後、周波数利用効率ならびにマルチパス環境における信号電力効率の双方に優れるOFDMをマルチバンドと組み合わせたマルチバンドOFDM（MB-OFDM[3]）が提案され、これが現在、UWBの標準方式の有力候補として検討されている。

以下では、MB-OFDMの特長、マルチパス環境での性能を論ずるとともに、CMOSによりデバイス化した場合の想定されるチップサイズ、消費電力に関する見通しを述べる。

文　献

[1] 例えば、２００３年６月、７月、８月発行の日経エレクトロニクス誌など

[2] 例えば、M.Win and R.Scholtz, “Ultra-Wide Bandwidth Time Hopping Spread-Spectrum Impulse Radio for Wireless Multiple-Access Communications,” IEEE Trans. on Comm., vol.48 No.4, April 2002

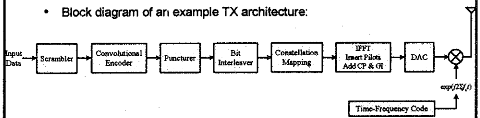
[3] IEEE802.15.3a Singapore meeting document 03-0343-01: Multi-band OFDM Sep03 presentation

Overview of Multi-band OFDM

- Basic idea: divide spectrum into several 528 MHz bands.
- Information is transmitted using OFDM modulation on each band.
  - OFDM carriers are efficiently generated using an 128-point IFFT/FFT.
  - Internal precision is reduced by limiting the constellation size to QPSK.
- Information bits are interleaved across all bands to exploit frequency diversity and provide robustness against multi-path and interference.
- 60.6 ns cyclic prefix provides robustness against multi-path even in the worst channel environments.
- 9.5 ns guard interval provides sufficient time for switching between bands.

Multi-band OFDM: TX Architecture

- Block diagram of an example TX architecture:



- Architecture is similar to that of a *conventional* and *proven* OFDM system. Can leverage existing OFDM solutions for the development of the Multi-band OFDM physical layer.
- For a given superframe, the time-frequency code is specified in the beacon by the PNC. The time-frequency code is changed from one superframe to another in order to randomize multi-piconet interference.

Multi-band OFDM System Parameters

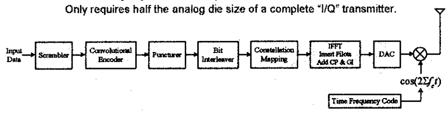
- System parameters for mandatory and optional data rates:

Info. Data Rate	55 Mbps*	80 Mbps**	110 Mbps*	160 Mbps**	200 Mbps*	320 Mbps**	480 Mbps**
Modulation/Constellation	OFDM/QPSK	OFDM/QPSK	OFDM/QPSK	OFDM/QPSK	OFDM/QPSK	OFDM/QPSK	OFDM/QPSK
FFT Size	128	128	128	128	128	128	128
Coding Rate (K=7)	R = 11/32	R = 1/2	R = 11/32	R = 1/2	R = 5/8	R = 1/2	R = 3/4
Spreading Rate	4	4	2	2	2	1	1
Information Tones	25	25	50	50	50	100	100
Data Tones	100	100	100	100	100	100	100
Info. Length	242.4 ns	242.4 ns	242.4 ns	242.4 ns	242.4 ns	242.4 ns	242.4 ns
Cyclic Prefix	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns
Guard Interval	9.5 ns	9.5 ns	9.5 ns	9.5 ns	9.5 ns	9.5 ns	9.5 ns
Symbol Length	312.5 ns	312.5 ns	312.5 ns	312.5 ns	312.5 ns	312.5 ns	312.5 ns
Channel Bit Rate	640 Mbps	640 Mbps	640 Mbps	640 Mbps	640 Mbps	640 Mbps	640 Mbps
Multi-path Tolerance	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns

* Mandatory information data rate, ** Optional information data rate

Simplified TX Analog Section

- For rates up to 200 Mb/s, the input to the IFFT is forced to be conjugate symmetric (for spreading gains ≥ 2).
  - Output of the IFFT is REAL.
- The analog section of TX can be simplified when the input is real:
  - Need to only implement the "I" portion of DAC and mixer.
  - Only requires half the analog die size of a complete "I/Q" transmitter.



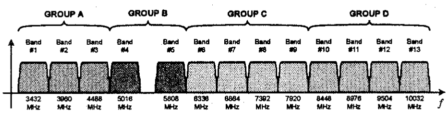
- For rates > 200 Mb/s, need to implement full "I/Q" transmitter.

More Details on the OFDM Parameters

- By using a contiguous set of orthogonal carriers, the transmit spectrum will always occupy a bandwidth greater than 500 MHz.
- Total of 128 tones:
  - 100 data tones used to transmit information (constellation: QPSK).
  - 12 pilot tones used for carrier and phase tracking.
  - 10 user-defined pilot tones.
  - Remaining 6 tones including DC are NULL tones.
- User-defined pilot tones:
  - Carry no useful information.
  - Energy is placed on these tones to ensure that the spectrum has a bandwidth greater than 500 MHz.
  - Can trade the amount of energy placed on tones for relaxing analog filtering specifications.
  - Ultimately, the amount of energy placed on these tones is left to the implementer. Provides a level of flexibility for the implementer.

Band Plan (1)

- Group the 528 MHz bands into 4 distinct groups.



- Group A: Intended for 1st generation devices (3.1 – 4.9 GHz).
- Group B: Reserved for future use (4.9 – 6.0 GHz).
- Group C: Intended for devices with improved SOP performance (6.0 – 8.1 GHz).
- Group D: Reserved for future use (8.1 – 10.6 GHz).

Band Plan (2)

- The relationship between the center frequency f_c and the band number n_b is:

$$f_c(n_b) = 2904 + 528 \times n_b \quad (n_b = 1,2,3,4)$$
$$3168 + 528 \times n_b \quad (n_b = 5,\ldots,13)$$

BAND_ID (n_b)	Lower Frequency (f_l)	Center Frequency (f_c)	Higher Frequency (f_h)	BAND_ID (n_b)	Lower Frequency (f_l)	Center Frequency (f_c)	Higher Frequency (f_h)
1	3168 MHz	3432 MHz	3696 MHz	8	7128 MHz	7392 MHz	7656 MHz
2	3696 MHz	3960 MHz	4224 MHz	9	7656 MHz	7920 MHz	8184 MHz
3	4224 MHz	4488 MHz	4752 MHz	10	8184 MHz	8448 MHz	8712 MHz
4	4752 MHz	5016 MHz	5280 MHz	11	8712 MHz	8976 MHz	9240 MHz
5	5544 MHz	5808 MHz	6072 MHz	12	9240 MHz	9504 MHz	9768 MHz
6	6072 MHz	6336 MHz	6600 MHz	13	9768 MHz	10032 MHz	10296 MHz
7	6600 MHz	6864 MHz	7128 MHz				

Multi-mode Multi-band OFDM Devices (1)

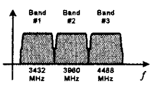
- Having multiple groups of bands enables multiple modes of operations for multi-band OFDM devices.
- Different modes for multi-band OFDM devices are:

Mode	Frequency of Operation	Number of Bands	Mandatory / Optional
1	Bands 1–3 (A)	3	Mandatory
2	Bands 1–3, 6–9 (A,C)	7	Optional

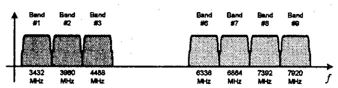
- Future expansion into groups B and D will enable an increase in the number of modes.

Multi-mode Multi-band OFDM Devices (2)

- Frequency of operation for a Mode 1 device:

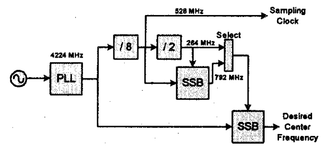


- Frequency of operation for a Mode 2 device:



Frequency Synthesis (1)

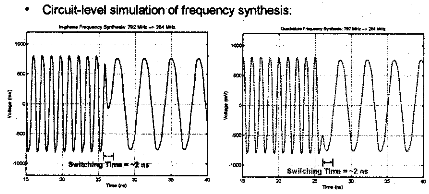
- Example: frequency synthesis for Mode 1 (3-band) device:



- A single PLL can also be used to generate the center frequencies for a Mode 2 (7-band) device.

Frequency Synthesis (2)

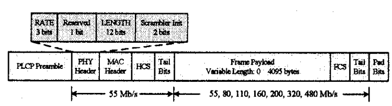
- Circuit-level simulation of frequency synthesis:



- Nominal switching time = ~2 ns.
- Need to use a slightly larger switching time to allow for process and temperature variations.

Multi-band OFDM: PLCP Frame Format

- PLCP frame format:



- Rates supported: 55, 80, 110, 160, 200, 320, 480 Mb/s.
  - Support for 55, 110, and 200 Mb/s is mandatory.
- **Mode 1** (3-band):
  - Preamble + Header length = 11.56 μs. Burst preamble + Header length = 4.69 μs.
- **Mode 2** (7-band):
  - Preamble + Header length = 14.06 μs. Burst preamble + Header length = 7.19 μs.
- Header is sent at an information data rate of 55 Mb/s.
- Maximum frame payload supported is 4095 bytes.

Multiple Access

- Multiple piconet performance is governed by the bandwidth expansion factor.
- Bandwidth expansion can be achieved using any of the following techniques or combination of techniques:
  - Spreading, Time-frequency interleaving, Coding
  - Ex: Multi-band OFDM obtains its BW expansion by using all 3 techniques.
- Time Frequency Codes:

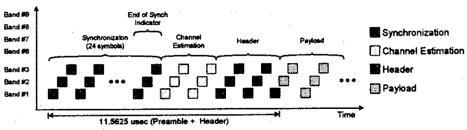
Channel Number	Preamble Pattern	Mode 1 DEV: 3-band Length 6 TFC						Mode 1 DEV: 7-band Length 7 TFC						
1	1	1	2	3	1	2	3	1	2	3	4	5	6	7
2	2	1	3	2	1	3	2	1	7	6	5	4	3	2
3	3	1	1	2	2	3	3	1	4	7	3	6	2	5
4	4	1	1	3	3	2	2	1	3	5	7	2	4	6

PLCP Preamble (1)

- Multi-band OFDM preamble is composed of 3 sections:
  - Packet sync sequence: used for packet detection.
  - Frame sync sequence: used for boundary detection.
  - Channel estimation sequence: used for channel estimation.
- Packet and frame sync sequences are constructed from the same hierarchical sequence.
- Correlators for hierarchical sequences can be implemented efficiently:
  - Low gate count.
  - Extremely low power consumption.
- Sequences are designed to be the most robust portion of the packet.

PLCP Preamble (2)

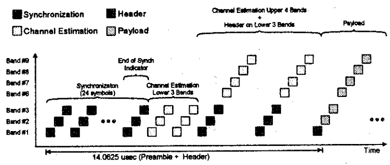
- Preamble needs to be designed to allow both Mode 1 (3-band) and Mode 2 (7-band) devices to operate in the same piconet.
  - All devices in the same piconet must be able to detect the preamble and demodulate PHY/MAC header.
- Preamble structure for Mode 1 (3-band) device:



- End of synchronization pattern $[p_1,p_2,p_3]$ is used to indicate that the interleaving sequence remains constant throughout the packet.

PLCP Preamble (3)

- Preamble structure for Mode 2 (7-band) device:



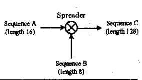
- Preamble/header are transmitted on bands 1–3 using length 6 interleaving sequences, so Mode 1 (3-band) devices can correctly decode the header.
- End of synchronization pattern $[p_4,p_5,p_6]$ is used to indicate the transition to length 7 interleaving sequence.

PLCP Preamble (4)

- In the multiple overlapping piconet case, it is desirable to use different hierarchical preambles for each of the piconets.
- Basic idea: define 4 hierarchical preambles, with low cross-correlation values.
- Preambles are generated by spreading a length 16 sequence by a length 8 sequence.

Preamble Pattern	Sequence A															
1	1	1	1	1	-1	-1	-1	1	-1	1	-1	1	1	-1	1	1
2	-1	1	1	-1	1	-1	-1	-1	-1	1	1	1	-1	1	1	1
3	-1	1	1	1	1	1	-1	-1	1	1	-1	1	-1	1	1	-1
4	1	-1	-1	1	1	-1	1	-1	1	-1	-1	-1	-1	-1	-1	1

Preamble Pattern	Sequence B							
1	1	1	-1	1	1	-1	-1	-1
2	-1	1	-1	-1	1	1	1	-1
3	-1	1	-1	-1	1	1	1	-1
4	1	1	-1	1	1	-1	-1	-1



Link Budget and Receiver Sensitivity

- Assumption: **Mode 1 DEV** (3-band), AWGN, and 0 dBi gain at TX/RX antennas.

Parameter	Value	Value	Value
Information Data Rate	110 Mb/s	200 Mb/s	480 Mb/s
Average TX Power	-10.3 dBm	-10.3 dBm	-10.3 dBm
Total Path Loss	64.2 dB (@ 10 meters)	56.2 dB (@ 4 meters)	50.2 dB (@ 2 meters)
Average RX Power	-74.5 dBm	-66.5 dBm	-60.5 dBm
Noise Power Per Bit	-93.6 dBm	-91.0 dBm	-87.2 dBm
CMOS RX Noise Figure	6.6 dB	6.6 dB	6.6 dB
Total Noise Power	-87.0 dBm	-84.4 dBm	-80.6 dBm
Required Eb/N0	4.0 dB	4.7 dB	4.9 dB
Implementation Loss	2.5 dB	2.5 dB	3.0 dB
Link Margin	6.0 dB	10.7 dB	12.2 dB
RX Sensitivity Level	-80.5 dBm	-77.2 dBm	-72.7 dB

Link Budget and Receiver Sensitivity

- Assumption: **Mode 2 DEV** (7-band), AWGN, and 0 dBi gain at TX/RX antennas.

Parameter	Value	Value	Value
Information Data Rate	110 Mb/s	200 Mb/s	480 Mb/s
Average TX Power	-6.6 dBm	-6.6 dBm	-6.6 dBm
Total Path Loss	66.6 dB (@ 10 meters)	58.6 dB (@ 4 meters)	52.6 dB (@ 2 meters)
Average RX Power	-73.2 dBm	-65.2 dBm	-59.2 dBm
Noise Power Per Bit	-93.6 dBm	-91.0 dBm	-87.2 dBm
CMOS RX Noise Figure	8.6 dB	8.6 dB	8.6 dB
Total Noise Power	-85.0 dBm	-82.4 dBm	-78.6 dBm
Required Eb/N0	4.0 dB	4.7 dB	4.9 dB
Implementation Loss	2.5 dB	2.5 dB	3.0 dB
Link Margin	5.3 dB	10.0 dB	11.5 dB
RX Sensitivity Level	-78.5 dBm	-75.2 dBm	-70.7 dB

System Performance (Mode 1: 3-band)

- The distance at which the Multi-band OFDM system can achieve a PER of 8% for a 90% link success probability is tabulated below:

Range*	AWGN	CM1	CM2	CM3	CM4
110 Mbps	20.5 m	11.5 m	10.9 m	11.6 m	11.0 m
200 Mbps	14.1m	6.9 m	6.3 m	6.8 m	5.0 m
480 Mbps	7.8 m	2.9 m	2.6 m	N/A	N/A

* Includes losses due to front-end filtering, clipping at the DAC, ADC degradation, multi-path degradation, channel estimation, carrier tracking, packet acquisition, etc.

Simultaneously Operating Piconets (1)

- Assumptions:
  Mode 1 DEV (3-band) operating at a data rate of 110 Mbps.
- Simultaneously operating piconet performance as a function of the multipath channel environments (see further update in ref.[3]):

Channel Environment	1 piconet	2 piconet	3 piconet
CM1 (d_{int}/d_{ref})	0.91	1.18	1.45
CM2 (d_{int}/d_{ref})	0.83	1.24	1.47
CM3 (d_{int}/d_{ref})	0.94	1.21	1.46
CM4 (d_{int}/d_{ref})	1.15	1.53	1.85

- Results incorporate SIR estimation at the receiver.

Simultaneously Operating Piconets (2)

- Assumptions:
  Mode 2 DEV (7-band) operating at a data rate of 110 Mbps.
- Simultaneously operating piconet performance as a function of the multipath channel environments (see further update in ref.[3]):

Channel Environment	1 piconet	2 piconet	3 piconet
CM1 (d_{int}/d_{ref})	0.47	0.65	0.86
CM2 (d_{int}/d_{ref})	0.43	0.64	0.80
CM3 (d_{int}/d_{ref})	0.49	0.66	0.81
CM4 (d_{int}/d_{ref})	0.61	0.84	1.01

- Results incorporate SIR estimation at the receiver.

Signal Robustness/Coexistence

- Assumption: Received signal is 6 dB above sensitivity.
- Value listed below are the required distance or power level needed to obtain a PER δ 8% for a 1024 byte packet at 110 Mb/s and a Mode 1 DEV (3-band).

Interferer	Value
IEEE 802.11b @ 2.4 GHz	d_{int} # 0.2 meter
IEEE 802.11a @ 5.3 GHz	d_{int} # 0.2 meter
Modulated interferer	SIR τ -9.0 dB
Tone interferer	SIR τ -7.9 dB

- Coexistence with 802.11a/b and Bluetooth is relatively straightforward because these bands are completely avoided.

PHY-SAP Throughput

- Assumptions:
  MPDU (MAC frame body + FCS) length is 1024 bytes.
  SIFS = 10 Πs.
  MIFS = 2 Πs.

Number of frames	Throughput @ 110 Mb/s	Throughput @ 200 Mb/s	Throughput @ 480 Mb/s
1	Mode 1: 84.8 Mb/s Mode 2: 82.7 Mb/s	Mode 1: 130.4 Mb/s Mode 2: 125.4 Mb/s	Mode 1: 211.4 Mb/s Mode 2: 198.6 Mb/s
5	Mode 1: 94.8 Mb/s Mode 2: 92.1 Mb/s	Mode 1: 155.6 Mb/s Mode 2: 148.5 Mb/s	Mode 1: 286.4 Mb/s Mode 2: 263.4 Mb/s

- Assumptions:
  MPDU (MAC frame body + FCS) length is 4024 bytes.

Number of frames	Throughput @ 110 Mb/s	Throughput @ 200 Mb/s	Throughput @ 480 Mb/s
1	Mode 1: 102.3 Mb/s Mode 2: 101.5 Mb/s	Mode 1: 175.9 Mb/s Mode 2: 173.5 Mb/s	Mode 1: 362.4 Mb/s Mode 2: 352.4 Mb/s
5	Mode 1: 105.7 Mb/s Mode 2: 104.8 Mb/s	Mode 1: 186.3 Mb/s Mode 2: 183.6 Mb/s	Mode 1: 409.2 Mb/s Mode 2: 396.5 Mb/s

Complexity (1)

- Unit manufacturing cost (selected information):
  - Process: CMOS 90 nm technology node in 2005.
  - CMOS 90 nm production will be available from all major SC foundries by early 2004.
- Die size for Mode 1 (3-band) device:

	Complete Analog*	Complete Digital
90 nm	2.7 mm²	1.9 mm²
130 nm	3.0 mm²	3.8 mm²

* *Component area.*

- Die size for Mode 2 (7-band) device:

	Complete Analog*	Complete Digital
90 nm	2.9 mm²	1.9 mm²
130 nm	3.2 mm²	3.8 mm²

* *Component area.*

Complexity (2)

- Active CMOS power consumption for Mode 1 (3-band) and Mode 2 (7-band) devices:

Block	Mode1: 90 nm	Mode 2: 90 nm	Mode 1: 130 nm	Mode 2: 130 nm
TX AFE (110, 200 Mb/s)	76 mW	133 mW	91 mW	160 mW
TX Digital (110, 200 Mb/s)	17 mW	17 mW	26 mW	26 mW
TX Total (110 Mb/s)	93 mW	150 mW	**117** mW	186 mW
RX AFE (110, 200 Mb/s)	101 mW	155 mW	121 mW	187 mW
RX Digital (110 Mb/s)	54 mW	54 mW	84 mW	84 mW
RX Digital (200 Mb/s)	68 mW	68 mW	106 mW	106 mW
RX Total (110 Mb/s)	155 mW	209 mW	**205** mW	271 mW
RX Total (200 Mb/s)	169 mW	223 mW	227 mW	293 mW
Deep Sleep	15 ΠW	15 ΠW	18 ΠW	18 ΠW

Complexity (3)

- Manufacturability:
  - Leveraging standard CMOS technology results in a straightforward development effort.
  - OFDM solutions are mature and have been demonstrated in ADSL and 802.11a/g solutions.
- Scalability with process:
  - Digital section complexity/power scales with improvements in technology nodes (Moore's Law).
  - Analog section complexity/power scales slowly with technology node.
- Time to market: the earliest complete CMOS PHY solutions would be ready for integration is 2005.
- Size: Solutions for PC card, compact flash, memory stick, SD memory in 2005.

Scalability of Multi-band OFDM

- Data rate scaling: from 55 Mb/s to 480 Mb/s.
- Frequency scaling:
  - Mode 1 (3-bands) and optional Mode 2 (7-band) devices.
  - Guaranteed interoperability between different mode devices.
- Complexity scaling:
  - Mandatory data rates (≤ 200 Mbps) require only a single DAC and mixer for the TX chain reduced complexity.
  - Digital section will scale with future CMOS process improvements.
  - Implementers could always trade-off complexity for performance.
- Power scaling:
  - A half-rate Pulse Repetition Frequency (PRF) approach can increase the off time to enable power saving modes of operation (see back-up slide).
  - Implementers could always trade-off power consumption for range and information data rate.

Comparison of OFDM Technologies

- Qualitative comparison between Multi-band OFDM and IEEE 802.11a OFDM:

Criteria	Multi-band OFDM Strong Advantage	Multi-band OFDM Slight Advantage	Neutral	802.11a Slight Advantage	802.11a Strong Advantage
PA Power Consumption	YES				
ADC Power Consumption	YES (3)				
FFT Complexity			YES (1)	YES (2)	
Viterbi Decoder Complexity				YES	
Band Select Filter Power Consumption		YES			
Band Select Filter Area		YES			
ADC Precision	YES				
Digital Precision		YES			
Phase Noise Requirements	YES				
Sensitivity to Frequency/Timing Errors	YES				
Design of Radio	YES				
Power / Mbps	YES				

1. Assumes a 256-point FFT for IEEE 802.11a device.
2. Assumes a 128-point FFT for IEEE 802.11a device.
3. Even though the Multi-band OFDM ADC runs faster than the IEEE 802.11a ADC, the bit precision requirements are significantly smaller, therefore the Multi-OFDM ADC will consume much less power.

Summary

- The proposed system is specifically designed to be a *low power, low complexity all CMOS solution.*
- Expected range for 110 Mb/s (90% link success probability): 20.5 meters in AWGN, and greater than 11 meters in multipath environments for a Mode 1 device.
- Expected power consumption for 110 Mb/s using 130 nm CMOS process:
  - **Mode 1** DEV: 117 mW (TX), 205 mW (RX), 18 ΠW (deep sleep).
  - **Mode 2** DEV: 186 mW (TX), 271 mW (RX), 18 ΠW (deep sleep).
- Multi-band OFDM is coexistence friendly and complies with world-wide regulations.
- Multi-band OFDM offers multi-mode devices (scalability).
- Multi-band OFDM offers the best trade-off between the various system parameters.
- Multi-band OFDM is FCC compliant (see document 03/274).