Achieving High Speed Wireless Communications Using a Multi-Band OFDM UWB System

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Outline

- Motivation for Ultra-wideband Systems.

- Challenges for Designing Ultra-wideband Systems:
  - Overlay of UWB spectrum with licensed and unlicensed bands.
  - Operating bandwidth for initial devices.
  - Worldwide compliance.

- Overview of Multi-band OFDM:
  - Band plan and frequency synthesis.
  - Transmitter and receiver architectures.
  - Systems parameters and system details.
  - Link budget and system performance.
  - Complexity.

- Multi-band Advantages and Conclusions.
Exploiting Shannon’s Theorem To Achieve High Data Rates (1)

- Shannon’s Theorem: \( C = W \log_2(1 + S/N) \)

- For the high \( S/N \) regime: \( C \approx W \log_2(S/N) \)
  - Capacity (\( C \)) is linearly related to the Bandwidth (\( W \)).
  - Capacity (\( C \)) is logarithmically related to \( S/N \).

- For the low \( S/N \) regime: \( C \approx W (S/N) \)
  - Capacity (\( C \)) is linearly related to both \( S/N \) and Bandwidth (\( W \)).
  - More bang for your buck!

- Two mechanisms for achieving higher data rates:
  - Increasing effective \( S/N \): decreasing the range of the system, or adding an advanced FEC code.
  - Increasing bandwidth.
Exploiting Shannon’s Theorem To Achieve High Data Rates (2)

- For bandwidth constrained system using a single antenna, the only way to achieve higher data rates is to increase the effective $S/N$:
  - Increasing the effective $S/N \Rightarrow$ larger constellation sizes can be supported.
  - Can add advanced FEC codes, but at the expense of increased complexity.
  - Can decrease the range of the system (no one wants this).

- For an average PSD limited system that operates in the low $S/N$ regime, the only way to achieve higher data rates is to increase the bandwidth:
  - By restricting the average PSD, the received power $S$ is essentially constrained at a given distance $d$.
  - The typical operating $S/N$ is low, on the order of 0 dB, for these systems.
  - Increasing bandwidth is a relatively easy way to achieve higher data rates.
  - Can also add advanced FEC codes by increasing complexity.

- The relative easy of increasing BW has generated a push to explore the potential of Ultra-wideband Systems.
Promise of UWB

- Data rates:
  - Scalable data rates from 55 Mb/s to 480 Mb/s.
  - 110 Mb/s at 10 meters in realistic multi-path environments.
  - 200 Mb/s at greater than 4 meters in realistic multi-path environments.
  - 480 Mb/s at 2 meters in realistic multi-path environments.

- Low cost solutions.

- Low power solutions (PHY: TX ≤ 130 mw, RX ≤ 160 mW).

- Integrated CMOS solution ⇒ Single chip solutions.

- Small form factors.

- Coexistence with current and future devices.

- Quality of Service – can support multimedia applications.
Challenges for Design of UWB Systems


- Unprecedented allocation of spectrum.

- Indoor and handheld devices must operate in the frequency band 3.1 – 10.6 GHz.

- The challenge when designing a system is that the UWB spectrum allocation cuts across previously allocated spectrum; both licensed and unlicensed.
What Operating Bandwidth to Use?

- Given that we have 7.5 GHz to use, what should the operating bandwidth be?

- Look at Received Power = TX Power – Path Loss, as a function of upper frequency.

- Assume that the TX signal occupies the BW from $f_L$ to $f_U$.
  - Assume that $f_L$ is fixed at 3.1 GHz. Vary upper frequency $f_U$ between 4.8–10.6 GHz.
  - Assume that the transmit spectrum is flat over entire bandwidth.
  - TX power = $-41.25$ dBm $+ 10\log_{10}(f_U - f_L)$.

- IEEE 802.15.3a has specified a free-space propagation model:
  \[
  P_L(d) = 20\log_{10}\left[\frac{4\pi f_g d}{c}\right] \text{ (dB)}
  \]
  - $f_g$ is the Geometric mean of lower/upper frequencies (10-dB points)
  - $d$ is the UWB transmitter-receiver separation distance (assume $d = 10$ m)
  - $c$ is the speed of light
Small Gains From Increasing Upper Frequency

- Increasing the upper frequency to 7.0 GHz (10.5 GHz) gives at most a 2.0 dB (3.0 dB) advantage in total received power.

- On the other hand, increasing the upper frequency, results in an increased noise figure:
  - For $f_u = 7.0$ GHz, by at least 1.0 dB.
  - For $f_u = 10.5$ GHz, by at least 2.0 dB.

- **Result:** using frequencies larger than 4.8 GHz increases the overall link margin by *at most* 1.0 dB with the current RF technology, but at the cost of higher complexity and higher power consumption.

- **Conclusion:** only minimal gains can be realized in the link budget by using frequencies above 4.8 GHz. Link budget translate directly into range.

- **Note:** using larger operating bandwidth is useful from a multiple access point of view.
The Benefits of OFDM

- OFDM was invented almost 50 years ago.
- OFDM is a mature technology
- Currently used in several products available today:
  - ADSL, 802.11a/g, 802.16, European Digital TV, Digital Audio Broadcast
- OFDM is also being considered in the following technologies:
  - 4G, 802.11n, 802.16a, 802.20
- High spectral efficiency
- Excellent robustness against multi-path
- Robustness against narrowband interferers
Worldwide Compliance

- By using OFDM, small and narrow bandwidths can easily be protected by turning off tones near the frequencies of interest.

- In addition, tones can be dynamically turned on and off via software in order to comply with changing world-wide regulations.

- For example, consider the radio-astronomy bands allocated in Japan. Only need to zero out a few tones in order to protect these services.

![Channel #1 - Typical OFDM waveform](image1)

![Channel #1 - Waveform with Japanese radioastronomical bands protected.](image2)
Overview of Multi-band OFDM
Authors and Supporters of Multi-band OFDM
Overview of Multi-band OFDM

- Basic idea: divide the spectrum into bands that are 528 MHz wide.
- Interleave OFDM symbols across all bands to exploit frequency diversity and provide robustness against multi-path and interference.
- Transmitter and receiver process smaller bandwidth signals (528 MHz).
- Prefix provides robustness against multi-path even in the worst case channel environments.
- Insert a guard interval between OFDM symbols in order to allow sufficient time to switch between channels.
Band Plan

- Group the 528 MHz bands into 5 distinct groups.

- Band Group #1: Intended for 1st generation devices (3.1 – 4.9 GHz).
- Band Group #2 – #5: Reserved for future use.

Because of path loss, the range that is supported by each Band Group will be different, i.e.,

\[ R_{\text{max},1} > R_{\text{max},2} > R_{\text{max},3} > R_{\text{max},4} > R_{\text{max},5} \]

- Range differential turns out to be an advantage!
  - Can use range differential to help address multiple access.
  - Example: for applications, such as DVD to HDTV, use Band Group #1 or #2.
  - Example: for applications, such as DSC to laptop, use Band Group #3 or #4.
Frequency Synthesis (1)

- Center frequencies for the sub-bands:
  - $f_1 = 4224 - 792 = 3432$ MHz
  - $f_2 = 4224 - 264 = 3960$ MHz
  - $f_3 = 4224 + 264 = 4488$ MHz

- Example: Frequency synthesis circuit for Band Group #1:
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 Transmitter Architecture

- Block Diagram:

- Architecture is similar to that of a conventional and proven OFDM system.
- Major Differences:
  - Time-Frequency kernel specifies the frequency for next OFDM symbol.
  - Constellation size is limited to QPSK (limits size of IFFT/FFT, DAC/ADC).
  - For rates less than 80 Mb/s, we force the input to the IFFT to be conjugate symmetric.
    - Need to only implement the “I” portion of TX analog chain.
    - As a result, only half the analog die size of a full “I/Q” transmitter is needed.
  - Zero-padded prefix limits power back at the transmitter.
Multi-band OFDM Receiver Architecture

- **Block diagram:**

- 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.
Multi-band OFDM System Parameters

- System parameters for mandatory and optional data rates:

<table>
<thead>
<tr>
<th>Info. Data Rate</th>
<th>55 Mbps</th>
<th>80 Mbps</th>
<th>110 Mbps</th>
<th>160 Mbps</th>
<th>200 Mbps</th>
<th>320 Mbps</th>
<th>400 Mbps</th>
<th>480 Mbps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation/Constellation</td>
<td>OFDM QPSK</td>
<td>OFDM QPSK</td>
<td>OFDM QPSK</td>
<td>OFDM QPSK</td>
<td>OFDM QPSK</td>
<td>OFDM QPSK</td>
<td>OFDM QPSK</td>
<td>OFDM QPSK</td>
</tr>
<tr>
<td>FFT Size</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>Coding Rate (K=7)</td>
<td>R = 11/32</td>
<td>R = 1/2</td>
<td>R = 11/32</td>
<td>R = 1/2</td>
<td>R = 5/8</td>
<td>R = 1/2</td>
<td>R = 5/8</td>
<td>R = 3/4</td>
</tr>
<tr>
<td>Frequency-domain Spreading</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Time-domain Spreading</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Data Tones</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Zero-padded Prefix</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
</tr>
<tr>
<td>Guard Interval</td>
<td>9.5 ns</td>
<td>9.5 ns</td>
<td>9.5 ns</td>
<td>9.5 ns</td>
<td>9.5 ns</td>
<td>9.5 ns</td>
<td>9.5 ns</td>
<td>9.5 ns</td>
</tr>
<tr>
<td>Symbol Length</td>
<td>312.5 ns</td>
<td>312.5 ns</td>
<td>312.5 ns</td>
<td>312.5 ns</td>
<td>312.5 ns</td>
<td>312.5 ns</td>
<td>312.5 ns</td>
<td>312.5 ns</td>
</tr>
<tr>
<td>Channel Bit Rate</td>
<td>640 Mbps</td>
<td>640 Mbps</td>
<td>640 Mbps</td>
<td>640 Mbps</td>
<td>640 Mbps</td>
<td>640 Mbps</td>
<td>640 Mbps</td>
<td>640 Mbps</td>
</tr>
<tr>
<td>Multi-path Tolerance</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
</tr>
</tbody>
</table>

* Mandatory information data rate, ** Optional information data rate
Convolutional Encoder

- Assume a mother convolutional code of $R = 1/3$, $K = 7$. Having a single mother code simplifies the decoder implementation.

- Generator polynomial: $g_0 = [133_8]$, $g_1 = [165_8]$, $g_2 = [171_8]$.

- Higher rate codes are achieved by optimally puncturing the mother code. Code rates supported via puncturing are: $11/32$, $1/2$, $5/8$, $3/4$. 
Bit Interleaver

- Bit interleaving is performed across the bits within an OFDM symbol and across six OFDM symbols.
  - Exploits frequency diversity.
  - Randomizes any interference $\Rightarrow$ interference looks nearly white.
  - Latency is less than 2 $\mu$s.

- Bit interleaving is performed in three stages:
  - Initially, $(6/T_{SF})N_{CBPS}$ coded bits are grouped together.
  - First stage: the coded bits are interleaved using $N_{CBPS} \times (6/T_{SF})$ block symbol interleaver.
  - Second stage: the output bits from 1st stage are interleaved using $(N_{CBPS} / 10) \times 10$ block tone interleaver.
  - The end results is that the data is spread across 6 on-air OFDM symbols; spanning three different frequency bands.

- If there are less than $(6/T_{SF})N_{CBPS}$ coded bits, the data is padded out to align with the interleaver boundary.
Bit Interleaver

- Ex: Second stage (symbol interleaver) for a data rate of 110 Mbps ($T_{SF} = 2$).

- Ex: Third stage (tone interleaver) for a data rate of 110 Mbps.
Zero-Padded Prefix (1)

- In conventional OFDM system, a cyclic prefix is added to provide multi-path protection.

- Cyclic prefix introduces structure into the transmitted waveform ⇒ structure in the transmitted waveform produces ripples in the PSD.

- In an average power-limited system, any ripples in the transmitted waveform will result in back-off at the transmitter (reduction in range).

- Ripple in the transmitted spectrum can be eliminated by using a zero-padded prefix.
  - Zero-padded prefix eliminates redundancy in the transmitted waveform.
  - Results in almost no ripple in PSD.
  - Provides the same multi-path protection if a cyclic prefix were present.

- Using a zero-padded (ZP) prefix instead of a cyclic prefix is a well-known and well-analyzed technique.
Zero-Padded Prefix (2)

- A Zero-Padded Multi-band OFDM has the same multi-path robustness as a system that uses a cyclic prefix (60.6 ns of protection).

- The receiver architecture for a zero-padded multi-band OFDM system requires ONLY a minor modification (less than < 200 gates).

- Added flexibility to implementer: multi-path robustness can be dynamically controlled at the receiver, from 1.9 ns up to 60.6 ns.
Multi-band OFDM: PLCP Frame Format

- PLCP frame format:

- Rates supported: 55, 80, 110, 160, 200, 320, 400, 480 Mb/s.
  - Support for 55, 110, and 200 Mb/s is mandatory.

- Preamble + Header = 13.125 ms.

- Burst preamble + Header = 9.375 ms.

- 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:

<table>
<thead>
<tr>
<th>Channel Number</th>
<th>Preamble Pattern</th>
<th>Mode 1 DEV: 3-band Length 6 TFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1 2 3 1 2 3</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1 3 2 1 3 2</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>1 1 2 2 3 3</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1 1 3 3 2 2</td>
</tr>
</tbody>
</table>
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)

- 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.

<table>
<thead>
<tr>
<th>Preamble Pattern</th>
<th>Sequence A</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 1 1 1 -1 -1 1 1 -1 -1 1 -1 1 1 1 1</td>
</tr>
<tr>
<td>2</td>
<td>1 -1 -1 -1 -1 -1 1 -1 1 -1 -1 1 -1 1 -1 1</td>
</tr>
<tr>
<td>3</td>
<td>1 1 -1 -1 -1 1 -1 -1 -1 -1 1 -1 1 -1 1 1</td>
</tr>
<tr>
<td>4</td>
<td>1 -1 -1 -1 -1 -1 1 -1 -1 -1 -1 1 -1 1 -1 1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Preamble Pattern</th>
<th>Sequence B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 -1 -1 -1 -1 -1 1 -1 -1 -1 -1 -1 -1 -1 -1 1</td>
</tr>
<tr>
<td>2</td>
<td>1 -1 1 1 -1 -1 -1 -1 1 -1 1 -1 1 -1 1</td>
</tr>
<tr>
<td>3</td>
<td>1 1 -1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 1</td>
</tr>
<tr>
<td>4</td>
<td>1 1 1 -1 -1 -1 1 -1 -1 -1 -1 -1 -1 -1 -1 1</td>
</tr>
</tbody>
</table>

Sequence A (length 16) | Sequence B (length 8) | Sequence C (length 128)
Link Budget and Receiver Sensitivity

- Assumption: 3-band Device, AWGN, and 0 dBi gain at TX/RX antennas.

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

<table>
<thead>
<tr>
<th>Range*</th>
<th>AWGN</th>
<th>LOS: 0 – 4 m CM1</th>
<th>NLOS: 0 – 4 m CM2</th>
<th>NLOS: 4 – 10 m CM3</th>
<th>RMS Delay Spread: 25 ns CM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>110 Mbps</td>
<td>20.5 m</td>
<td>11.4 m</td>
<td>10.7 m</td>
<td>11.5 m</td>
<td>10.9 m</td>
</tr>
<tr>
<td>200 Mbps</td>
<td>14.1 m</td>
<td>6.9 m</td>
<td>6.3 m</td>
<td>6.8 m</td>
<td>4.7 m</td>
</tr>
<tr>
<td>480 Mbps</td>
<td>8.9 m</td>
<td>2.9 m</td>
<td>2.6 m</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

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

- Assumption: Received signal is 6 dB above sensitivity.

- Values listed below are the required distance or power level needed to obtain a PER ≤ 8% for a 1024 byte packet at 110 Mb/s and operating in Band Group #1.

<table>
<thead>
<tr>
<th>Interferer</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE 802.11b @ 2.4 GHz</td>
<td>( d_{int} \geq 0.2 \text{ meter} )</td>
</tr>
<tr>
<td>IEEE 802.11a @ 5.3 GHz</td>
<td>( d_{int} \geq 0.2 \text{ meter} )</td>
</tr>
<tr>
<td>Modulated interferer</td>
<td>SIR ( \geq -9.0 \text{ dB} )</td>
</tr>
<tr>
<td>Tone interferer</td>
<td>SIR ( \geq -7.9 \text{ dB} )</td>
</tr>
</tbody>
</table>

- Coexistence with IEEE 802.11b and Bluetooth is relatively straightforward because they are out-of-band.

- Multi-band OFDM is also coexistence friendly with both GSM and WCDMA.
  - MB-OFDM has the ability to tightly control OOB emissions.
## PHY-SAP Throughput

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

<table>
<thead>
<tr>
<th>Number of frames</th>
<th>Throughput @ 110 Mb/s</th>
<th>Throughput @ 200 Mb/s</th>
<th>Throughput @ 480 Mb/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mode 1: 83.2 Mb/s</td>
<td>Mode 1: 126.8 Mb/s</td>
<td>Mode 1: 194.9 Mb/s</td>
</tr>
<tr>
<td>5</td>
<td>Mode 1: 97.8 Mb/s</td>
<td>Mode 1: 150.5 Mb/s</td>
<td>Mode 1: 257.2 Mb/s</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Number of frames</th>
<th>Throughput @ 110 Mb/s</th>
<th>Throughput @ 200 Mb/s</th>
<th>Throughput @ 480 Mb/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mode 1: 101.3 Mb/s</td>
<td>Mode 1: 174.4 Mb/s</td>
<td>Mode 1: 354.9 Mb/s</td>
</tr>
<tr>
<td>5</td>
<td>Mode 1: 104.6 Mb/s</td>
<td>Mode 1: 184.6 Mb/s</td>
<td>Mode 1: 399.6 Mb/s</td>
</tr>
</tbody>
</table>
Complexity

- Unit manufacturing cost (selected information):
  - CMOS 90 nm production will be available from all major SC foundries by early 2004.

- Die size for a device operating in Band Group #1:

<table>
<thead>
<tr>
<th>Process</th>
<th>Complete Analog*</th>
<th>Complete Digital</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 nm</td>
<td>3.0 mm²</td>
<td>1.9 mm²</td>
</tr>
<tr>
<td>130 nm</td>
<td>3.3 mm²</td>
<td>3.8 mm²</td>
</tr>
</tbody>
</table>

  * Component area.

- Active CMOS power consumption for a device operating in Band Group #1:

<table>
<thead>
<tr>
<th>Process</th>
<th>TX (55 Mb/s)</th>
<th>TX (110, 200 Mb/s)</th>
<th>RX (55 Mb/s)</th>
<th>RX (110 Mb/s)</th>
<th>RX (200 Mb/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 nm</td>
<td>85 mW</td>
<td>128 mW</td>
<td>147 mW</td>
<td>155 mW</td>
<td>169 mW</td>
</tr>
<tr>
<td>130 nm</td>
<td>104 mW</td>
<td>156 mW</td>
<td>192 mW</td>
<td>205 mW</td>
<td>227 mW</td>
</tr>
</tbody>
</table>
Comparison of OFDM Technologies

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

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Multi-band OFDM</th>
<th>Multi-band OFDM</th>
<th>Neutral</th>
<th>802.11a</th>
<th>802.11a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strong Advantage</td>
<td>Slight Advantage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PA Power Consumption</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADC Power Consumption</td>
<td>✓ ³</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FFT Complexity</td>
<td></td>
<td>✓ ¹</td>
<td>✓ ²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viterbi Decoder Complexity</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Band Select Filter Power Consumption</td>
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<td></td>
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</tr>
<tr>
<td>Band Select Filter Area</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADC Precision</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Digital Precision</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase Noise Requirements</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity to Frequency/Timing Errors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design of Radio</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power / Mbps</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

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.
Multi-band OFDM - Advantages

- Inherent robustness to multi-path in all expected environments.
- Excellent robustness to U-NII and other generic narrowband interference.
- Ability to comply with worldwide regulations:
  - Channels and tones can be turned on/off dynamically to comply with changing regulations.
- Enhanced coexistence with current and future services:
  - Channels and tones can be turned on/off dynamically to coexist with other devices.
- Scalability:
  - More channels can be added as RF technology improves and as capacity requirements increase.
  - Multi-band OFDM is digital heavy. Digital section complexity and power scales with improvements in technology node (Moore’s Law).
Conclusion

- The proposed system is specifically designed to be a low power, low complexity CMOS solution.

- Expected range for a device operating in Band Group #1 and transmitting at 110 Mb/s:
  - 20.5 meters in AWGN.
  - Nearly 11 meters in heavy multi-path environments.

- Expected power consumption for a device operating in Band Group #1 and transmitting at 110 Mb/s (90 nm CMOS process):
  - TX = 128 mW
  - RX = 155 mW
  - Deep Sleep = 15 µW

- Multi-band OFDM is coexistence friendly and can comply with worldwide regulations.

- Multi-band OFDM provides the best trade-off among the various system parameters.