WiFi for IoT: RF Systems & Architecture
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• **Currently: Sr. Director at NXP,** Responsible for RF and Analog development within the Secure Transactions and Identification Business Line

• **Sr. Director, Engineering at Atmel,** where he led development of multiple WiFi-, Bluetooth-, and Zigbee-enabled Wireless MCUs for IoT, including (at the time) the world’s smallest and lowest power production BLE devices, BTLC1000 and SAMB11.

• **Founder and Vice President of Engineering at Newport Media, Inc.,** a fabless semiconductor company acquired by Atmel for $140M in 2014. At Newport, he oversaw 15 Mass production tapeouts in 7 years, resulting in cumulative shipments of over 350 Million wireless devices

• **Principal Engineer at Skyworks Solutions,** where he worked on Cellular Transceivers for AMPs, CDMA, GSM, and WCDMA; primarily in Frequency Synthesizer and Transmitters.

• **BSEE and BSNE,** both from UC Berkeley. MSEE from UCLA.

• **21 issued U.S. patents**
What is WiFi? (or, Why WiFi Is the way it is)

• WiFi was developed circa 2000, when the main use cases were email, web surfing, IM, etc. Target devices were laptops.
  • Occasional packets of data
  • Few or 10s of devices
  • Robustness was main concern, throughput was next concern.
  • 1W of power considered small.

• With time, enhancements have been made to support new, bandwidth hungry use cases (ie Video Streaming) and devices (Smartphones)
  • Introduction of 40, 80, and 160MHz channels (802.11n/ac)
  • MIMO: 2x2, 4x4, 8x8....never ending.
  • 256QAM, 1024 QAM

• BUT:
  • Network Still Collapses as more devices associate to an AP
  • Power in the 100s of mW is still Acceptable
What is Internet of Things?

- Internet did not make sense until a large numbers of PCs had proliferated ("2\textsuperscript{nd} Tectonic Shift")
  - Introduction of Cellphones/mobile computing (third shift) increased connections to several Billion
- The next shift, IoT, is expected (required?) to connect to 100s of Billions or Trillions of devices.
- How can 7 billion people benefit from 1 trillion connected devices?
- **Answer: THINGS.** Especially small things.
  - 1 Trillion (or even 100 Billion) cellphone-like devices are not economically feasible and not beneficial.
  - But, 1 Trillion connected lights, doors, windows, appliances etc. could be another story.
- This is the realm of MCUs: low power, low cost devices.

**BUT: Huge number of low power nodes is NOT what WiFi was made for!**
Why WiFi for IoT?

• Despite these challenges, there is still strong rationale to using WiFi for IoT Devices.
  • WiFi Access points are widely deployed
    • Zigbee and LPWAN techniques require new infrastructure.
    • Everyone already has a WiFi access point.
  • WiFi offers a direct, primary connection to the internet.
    • Other technologies, like BLE, mainly link to a (nearby) cell phone.
    • Cannot reach such devices when you are away.

• With clever engineering, WiFi devices can overcome both the limitations of the 802.11 standards and challenges of IoT Devices.
Example Device
Amazon Dash Button

- Button Programmed with WiFi Router Information via app on Smartphone, then goes to Deep Sleep.
- When pressed, device wakes up, connects to AP, and sends request to Amazon Servers for product to be delivered.
  - Extremely low activity (once per day/week)
  - Extremely simple/cost sensitive

Two Revisions of product:
- 1st Revision introduced Early 2015
- 2nd Revision Introduce Mid 2016

-> Investigate and compare both versions
First Look Inside – Original Version

- Product area and volume dominated by battery
  - Smaller batteries cannot deliver peak currents required for WiFi Transmitters
- Since only 1 AAA can fit, additional Power management circuitry is required.
  - AAA battery is 1.5V and WiFi PA requires 3V
- Expensive Lithium AAA Battery is used
  - Battery has enormous impact on Device
Comparison: 1\textsuperscript{st} and 2\textsuperscript{nd} (Current) Version

Original Version

Current Version

• One significant improvement in new version of button -- New Version uses commodity AAA battery – \textit{3x cost savings}

• What is needed to make this change possible?
Comparison: Lithium vs. Alkaline AAA battery

- Main Difference between Lithium and Alkaline batteries is capacity at high discharge rates
  - Note: Stepping up voltage via Boost Converter *more than doubles device current, and battery discharge rate*

- New revision must consume *2–3x less* power or have 2–3x lower peak currents

![Graph comparing the capacity of AAA Lithium vs. AAA Alkaline batteries](image-url)
1. WiFi SoC and MCU Changed on Second version
2. BLE Added to Second Version
3. Both versions have plenty of unused board space. No 5GHz.
4. Each Radio in 2nd Version has it’s own antenna.
Observations

1. Boost Converter present, as expected. No Change between versions.

2. Both Devices have a Microphone (!?)
   - Strange...button does not have voice recognition capability.
Microphone, BLE, and Provisioning

- The Microphone and BLE both serve the same purpose: Provisioning
  - Router specifics (i.e. network name and password) must be entered into the Button.

- Button itself has no keyboard or screen, so a smartphone is used.

- In the First Version of Device, smartphone speaker sent provisioning info via ultrasound signals to the Button Microphone (!)
  - Unreliable, expensive, and requires un-provisioned button to be “always listening”

- Second Version of Device uses BLE
  - Added cost of BLE is very small.
  - Much simpler to do the provisioning
  - Microphone was kept in second version for backward compatibility
    - Eventually (currently?) removed when most phones have BLE.
Power Consumption Comparison

• Peak Power Consumption of both devices is comparable
  • Current version actually consumes slightly higher active current.

• However, Energy consumed by Current version is **3x less**.
  • This enables use of alkaline battery, and explains the switch from WICED platform to ATWINC1500B

Source: https://mpetroff.net/2016/07/new-amazon-dash-button-teardown-jk29lp/
Concluding Remarks

• Battery and Power Management are key drivers of overall device cost and lifetime.
• IoT WiFi Applications often benefit substantially from BLE
• Optimization of Transaction *Energy* matters more than raw device power consumption.
WiFi Power Modes for IoT
• WiFi has provisions for power save modes.
  • **Beacon Monitoring**: Commonly used today; allows full BW communication.
  • **Use of PS Poll packets**: Less common; allows ~10x less power consumption, at expense of much longer latency and throughput
  • **Shutoff and Reconnect**: Mainly for Event-Driven devices (i.e. button)
Beacon Monitoring Mode: High Activity Devices

- Normal Operation when device is a WiFi STA connected to AP.
- After associating to AP, devices goes to sleep until next Beacon
- Can Receive or Transmit data any time via TIM/DTIM
  - As receive or transmit data increases, current increases
- **If WiFi SoC is well designed:** Receive Power consumptions Dominates
  - For IoT focused devices (low data rates) and low lithography CMOS (40nm and below), RF Power consumption is often significantly more than digital.
- **If WiFi SoC is poorly designed:** sleep current (in between beacons) dominates.
Beacon Monitoring: What not to do, 1

- Overall Beacon Monitor Current is 22.5 mA!
- 90% is standby power.
Beacon Monitoring: What not to do, 2

- Here standby power is much better, but overall Beacon Monitoring Current is still 8mA.
- In this case, the Active time is longer than necessary.
Beacon Monitoring Mode: Optimized for IoT

- Receiver dominates power consumption
- Power in between beacons is minimal
- Average of 3ms @ 80mA every 300ms ~\(1\text{mA}\) average current
  - Increases to \(3\text{mA}\) for 100ms Beacons
- However, even this improvement only enables 700 hour (=1 month) lifetime from 2x AAA batteries
- Traditional Beacon monitoring mode mainly applicable for plugged-in IoT applications (e.g. Thermostat) or Large Li-Ion batteries.
Use of Beacon Monitoring in IoT Application

- Put IoT Device in Beacon Monitoring mode.
- Thermostat can be set any time; Temperature can be read any time (~100’s of ms latency)
For moderate activity devices, it is possible to reduce power further

A special packet (Null packet with PS Poll bit set to 1) is sent to AP once every 60s.
  - This keeps the device associated to the AP

After sending, device goes to sleep and does not listen to beacons.

Device does not receive or Transmit data until it sends another packet to the AP. Then, device will temporarily go to beacon monitoring mode.

Benefit: No need to re-associate to the AP, no need to resume TCP & SSL connections when communication is needed.
PS Poll: Moderate Activity Devices

- Dominant current: Oscillators, Bandgap/LDOs, Memory Leakage
- Power can be reduced to ~100μA
- Extends life to ~10 months for 2 AAA batteries.
  - Still not good enough for many applications
Use of PS Poll in IoT Application

- Periodically Upload Data from IoT device to Server
- Data only flows from IoT Device to Server, not the other way around.

1. Start upload timer, go into PS Poll Mode
2. Timer Expires. Enter Beacon Monitoring mode and upload data
Shut Off and Re-Connect: Low Activity Devices

• For low activity and especially event-driven devices, it is possible to reduce power further

• Simply re-connect to AP when data needs to be transmitted.

• Here, power consumption is mainly dominated by energy used during wakeup and re-connection to AP.

• Data rates must be very low for this to make sense (eg Dash Button, doorbell, fire alarm, )
Shut OFF and Reconnect

- Time for AP Association, Authentication, and DHCP are Critical
- Power consumption carefully planned during each phase of wakeup and Association.
- Average of 80ms @ 80mA for Secure AP
- 2 AAA batteries last 7 years for one event every 20 minutes.
802.11 Overview & System Analysis
• System Analysis requires a combination of Standard compliance, Regulatory compliance, and (often most importantly) Technical Marketing.
  • Competitive offering must generally exceed the spec.
  • Knowing which parameters matter most is critical.

• In what follows we go through each of these in turn to determine final product requirements.
General Signal Properties

- 802.11 a/g/n are OFDM based.
  - Center Subcarrier is always null – alleviates DC offset removal in RX chain
  - 312.5kHz Subcarriers.
  - 64 bin IFFT creates signal. 52 subcarriers used in 802.11a/g; 56 used in 802.11n

- OFDM has very high Peak to Average of ~10dB.
  - Makes PA design significantly more challenging.

52 Carriers (+ Null) in 802.11g=16.6MHz

56 Carriers (+ Null) in 802.11n=17.87MHz
Data Rates

- Variety of Data rates are supported.
  - Starting from very robust, BPSK rate ½ to very high throughput 64QAMR5/6
  - Only one change in modulation between 802.11a/g and 802.11n
    - 802.11g BPSK3/4 mode replaced in 802.11n 64QAM5/6 mode
- For IoT, lower data rates are more suitable.
  - In 802.11g, higher data rate modes were optional.
  - But starting in 802.11n devices must support all modes

### 802.11a/g Data Rates

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Coding rate (R)</th>
<th>Coded bits per subcarrier (N_{bpsk})</th>
<th>Coded bits per OFDM symbol (N_{bop})</th>
<th>Data rate (Mb/s) 10 MHz channel spacing</th>
<th>Data rate (Mb/s) 20 MHz channel spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>1/2</td>
<td>1</td>
<td>48</td>
<td>24</td>
<td>6</td>
</tr>
<tr>
<td>BPSK</td>
<td>3/4</td>
<td>1</td>
<td>48</td>
<td>36</td>
<td>9</td>
</tr>
<tr>
<td>QPSK</td>
<td>1/2</td>
<td>2</td>
<td>96</td>
<td>48</td>
<td>12</td>
</tr>
<tr>
<td>QPSK</td>
<td>3/4</td>
<td>2</td>
<td>96</td>
<td>72</td>
<td>18</td>
</tr>
<tr>
<td>16-QAM</td>
<td>1/2</td>
<td>4</td>
<td>192</td>
<td>96</td>
<td>24</td>
</tr>
<tr>
<td>16-QAM</td>
<td>3/4</td>
<td>4</td>
<td>192</td>
<td>144</td>
<td>36</td>
</tr>
<tr>
<td>64-QAM</td>
<td>2/3</td>
<td>6</td>
<td>288</td>
<td>192</td>
<td>48</td>
</tr>
<tr>
<td>64-QAM</td>
<td>3/4</td>
<td>6</td>
<td>288</td>
<td>216</td>
<td>54</td>
</tr>
</tbody>
</table>

### 802.11n 1x1 Data Rates

<table>
<thead>
<tr>
<th>MCS Index</th>
<th>Modulation</th>
<th>R</th>
<th>N_{bpsk}/3</th>
<th>N_{g} G</th>
<th>N_{g}</th>
<th>N_{c}</th>
<th>N_{g}aps</th>
<th>Data rate (Mb/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>BPSK</td>
<td>1/2</td>
<td>1</td>
<td>52</td>
<td>4</td>
<td>52</td>
<td>26</td>
<td>6.5</td>
</tr>
<tr>
<td>1</td>
<td>QPSK</td>
<td>1/2</td>
<td>2</td>
<td>52</td>
<td>4</td>
<td>104</td>
<td>52</td>
<td>13.0</td>
</tr>
<tr>
<td>2</td>
<td>QPSK</td>
<td>3/4</td>
<td>2</td>
<td>52</td>
<td>4</td>
<td>104</td>
<td>78</td>
<td>19.5</td>
</tr>
<tr>
<td>3</td>
<td>16-QAM</td>
<td>1/2</td>
<td>4</td>
<td>52</td>
<td>4</td>
<td>208</td>
<td>104</td>
<td>26.0</td>
</tr>
<tr>
<td>4</td>
<td>16-QAM</td>
<td>3/4</td>
<td>4</td>
<td>52</td>
<td>4</td>
<td>208</td>
<td>156</td>
<td>39.0</td>
</tr>
<tr>
<td>5</td>
<td>64-QAM</td>
<td>2/3</td>
<td>6</td>
<td>52</td>
<td>4</td>
<td>312</td>
<td>208</td>
<td>52.0</td>
</tr>
<tr>
<td>6</td>
<td>64-QAM</td>
<td>3/4</td>
<td>6</td>
<td>52</td>
<td>4</td>
<td>312</td>
<td>234</td>
<td>58.5</td>
</tr>
<tr>
<td>7</td>
<td>64-QAM</td>
<td>5/6</td>
<td>6</td>
<td>52</td>
<td>4</td>
<td>312</td>
<td>260</td>
<td>65.0</td>
</tr>
</tbody>
</table>

**NOTE:** Support of 400 ns GI is optional on transmit and receive.

802.11a/g Data Rates

802.11a/g Data Rates

802.11a/g Data Rates

802.11n 1x1 Data Rates

802.11n 1x1 Data Rates

802.11n 1x1 Data Rates
### 802.11a/b/g/n Standard Comparison: RX

<table>
<thead>
<tr>
<th></th>
<th>.11a</th>
<th>.11g</th>
<th>.11n</th>
<th>.11b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Band</td>
<td>5GHz ISM</td>
<td>2.4GHz ISM</td>
<td>2.4 &amp; 5 GHz ISM</td>
<td>2.4GHz ISM</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Identical to .11a</td>
<td>Essentially Identical to: .11a (5GHz) .11g (2.4GHz)</td>
<td>-76dBm</td>
<td></td>
</tr>
<tr>
<td>Adjacent Channel</td>
<td>See Next Slide</td>
<td>Identical to .11a (25MHz spacing)</td>
<td>35dB</td>
<td></td>
</tr>
<tr>
<td>Alternate Channel</td>
<td>No Requirement</td>
<td>No Requirement</td>
<td>No Requirement</td>
<td></td>
</tr>
<tr>
<td>Maximum Input</td>
<td>-30dBm</td>
<td>-20dBm</td>
<td>-10dBm</td>
<td></td>
</tr>
</tbody>
</table>

- .11a and .11g identical except for Alternate channel requirement and max signal level.
- .11n is equivalent to .11a and g, with different bitrates/more subcarriers.
- .11b is mostly easier and naturally covered by .11a/g/n. Will not discuss further.
802.11a/g: Key Receiver Specifications

- Standard Sensitivity based on 10dB Noise Figure and 5dB Implementation loss
- Not appropriate for product definition
- Competitive Devices require ~4 dB NF and ~1dB Implementation loss—> 10dB lower sensitivity than standard.

<table>
<thead>
<tr>
<th>Data Rate (Mbps)</th>
<th>Modulation</th>
<th>SNRMIN* (dB)</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>BPSK 1/2</td>
<td>4</td>
<td>-82</td>
</tr>
<tr>
<td>9</td>
<td>BPSK 3/4</td>
<td>5</td>
<td>-81</td>
</tr>
<tr>
<td>12</td>
<td>QPSK 1/2</td>
<td>7</td>
<td>-79</td>
</tr>
<tr>
<td>18</td>
<td>QPSK 3/4</td>
<td>9</td>
<td>-77</td>
</tr>
<tr>
<td>24</td>
<td>16QAM 1/2</td>
<td>13</td>
<td>-74</td>
</tr>
<tr>
<td>36</td>
<td>16QAM 3/4</td>
<td>16</td>
<td>-70</td>
</tr>
<tr>
<td>48</td>
<td>64QAM 2/3</td>
<td>20.5</td>
<td>-66</td>
</tr>
<tr>
<td>54</td>
<td>64QAM 3/4</td>
<td>22</td>
<td>-65</td>
</tr>
</tbody>
</table>

*SNRMIN values are from simulation (1dB implementation loss) They are not a part of the 802.11 standard.

- Adjacent channel requirements are defined such that Receiver dynamic range (SNR + Protection ratio) is a constant ~21dB
  - Alternate channel Protection ratio is always 16dB higher than Adjacent channel.
  - Target 6dB margin to these specs. Just need to meet spec with margin.
802.11a/b/g/n Standard Comparison: TX

<table>
<thead>
<tr>
<th></th>
<th>.11a</th>
<th>.11g</th>
<th>.11n</th>
<th>.11b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Band</td>
<td>5GHz ISM</td>
<td>2.4GHz ISM</td>
<td>2.4 &amp; 5 GHz ISM</td>
<td>2.4GHz ISM</td>
</tr>
<tr>
<td>TX Frequency Accuracy</td>
<td>+/-20ppm</td>
<td>+/-25ppm</td>
<td>Identical to .11a (5GHz)</td>
<td>Identical to .11n</td>
</tr>
<tr>
<td>EVM</td>
<td>Table 17-12</td>
<td>Identical to .11a</td>
<td>Identically to .11a</td>
<td>&lt;35%</td>
</tr>
<tr>
<td>Spectral Mask</td>
<td>Next Slide</td>
<td>Identical to .11a</td>
<td>Next Slide</td>
<td>Next Slide</td>
</tr>
<tr>
<td>LO Feedthrough</td>
<td>-15dBc</td>
<td>Identical to .11a</td>
<td>-20dBc</td>
<td>Identical to .11a</td>
</tr>
</tbody>
</table>

- .11b requirements in general subset of .11a/g/n
- Target LO feedthrough spec of -20dBc set by .11n
- Target EVM requirements of 802.11n (has 1 mode more difficult than .11n)
- **Main Challenge is transmitting high enough Output power while meeting EVM (high data rates) or ACPR (low data rates)**
• 802.11n requirements 5dB more difficult beyond 30MHz.
• Adopt this as the target, generally not a major issue.
• FCC Requirements mainly revolve around -41dBm/MHz noise floor
  • These requirements mainly impact the TX
  • Below this level, FCC looks at it as if nothing is there.

• Main Challenge:
  • **Harmonics.** For +20dBm output 20MHz signal, spec translates to $48\text{dBc } HD_N$
  • **Channels at the edge of the ISM band.** Here ACPR is limiting. Generally back off fundamental for these channels.

• For IoT, pre-certified modules dramatically simplify customer’s life.

<table>
<thead>
<tr>
<th>Emission Type</th>
<th>FCC Limit</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental Power</td>
<td>+30dBm</td>
<td>Assumes &lt;6dBi antenna</td>
</tr>
<tr>
<td>Harmonic Power</td>
<td>-41dBm/MHz</td>
<td>All Harmonics</td>
</tr>
<tr>
<td>Restricted Bands</td>
<td>-41dBm/MHz</td>
<td>Includes Edge of 2.4GHz ISM band (2310-2390 and 2483.5-2500)</td>
</tr>
</tbody>
</table>
Coexistence Requirements

• WiFi Radio must coexist with other wireless standards.
• These “Coexistence” requirements are often the most difficult, but vary greatly from product to product.
• Example:
  • For Integration in a Cell Phone, WiFi radio must de-sense less than 1dB for -15dBm Cellular blocker.
  • This Translates to +72dBm cascaded IIP₂
• Many WiFi devices were designed with Cellular requirements in mind.
• IoT devices do not have such requirements.
Analysis below is for IoT device in presence of a cell phone.

- Similar analysis can be done for various other scenarios.
- Below is a representative example.

Target is to be able to handle such interferers with $\leq 3$dB de-sense.

**Diagram:***

- Phone Transmits $+23$dBm Band 7 LTE signal
- Path loss: 41dB
- Antenna Gain: $-3$dBi (@ Band 7)
- IoT Device Receives $-21$dBm Blocker
- Phone 1m away from IoT Device
Transmitter Coexistence Requirements

- In TX mode, opposite concern arise – Emissions of WiFi device desensitizing Cell phone
- Target is for WiFi emissions to cause $\leq 3\text{dB}$ desense to other receivers

Phone Band 7 Cellular RX noise floor is $-171\text{dBm/Hz}$

IoT Device TX Emissions in Band 7 must be below $-127\text{dBm/Hz}$

Free-Space Path loss: 41dB

Antenna Gain: -3dBi (@ Band 7)

Phone 1m away from IoT Device
### Summary of Cascaded Receiver Requirements

<table>
<thead>
<tr>
<th></th>
<th>Spec</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensitivity</strong></td>
<td>10dB Margin to 802.11a</td>
<td>e.g. -75dBm for 64QAMR¾ Implies 4dB NF.</td>
</tr>
<tr>
<td><strong>Maximum Input Signal</strong></td>
<td>-10dBm</td>
<td>Set by .11b. Little impact on cost/power.</td>
</tr>
<tr>
<td><strong>Out-of-band Blocker</strong></td>
<td>-21dBm</td>
<td>Set by coexistence with cellular blockers</td>
</tr>
<tr>
<td><strong>Adjacent Channel block</strong></td>
<td>6dB margin to 802.11a</td>
<td>e.g. +5dB Protection ratio for 64QAMR¾</td>
</tr>
<tr>
<td><strong>Alternate Channel Blocker</strong></td>
<td>6dB margin to 802.11a</td>
<td>e.g. +21dB Protection ratio for 64QAMR¾ Only required if supporting 5GHZ ISM band</td>
</tr>
<tr>
<td><strong>Power Consumption</strong></td>
<td><strong>Minimize</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td><strong>Minimize</strong></td>
<td></td>
</tr>
</tbody>
</table>
### Cascaded Transmitter Requirements

<table>
<thead>
<tr>
<th>Spec</th>
<th>Spec</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX Output Power</td>
<td>+18dBm for 64QAMR¾</td>
<td>Lower data rates expected to have higher output power. Based on competitive analysis.</td>
</tr>
<tr>
<td>EVM</td>
<td>3dB Margin to 802.11n at P&lt;sub&gt;MAX&lt;/sub&gt;</td>
<td>e.g. -31dB evm for 64QAMR¾</td>
</tr>
<tr>
<td>ACPR</td>
<td>3dB Margin to 802.11n at P&lt;sub&gt;MAX&lt;/sub&gt;</td>
<td>Typically matters at lower data rates</td>
</tr>
<tr>
<td>LO Feedthrough</td>
<td>-20dBc</td>
<td>Set by .11n</td>
</tr>
<tr>
<td>Spectral Emissions</td>
<td>&lt;121dBm/Hz</td>
<td>In all 3GPP Cellular bands. Includes DAC alias.</td>
</tr>
<tr>
<td>Harmonic Distortion</td>
<td>&lt;48dBc</td>
<td>Per FCC</td>
</tr>
<tr>
<td>Frequency Accuracy</td>
<td>+/-20ppm</td>
<td>Can be relaxed in 2.4GHz only is used.</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>Minimize</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>Minimize</td>
<td></td>
</tr>
</tbody>
</table>
• Given the previous high-level, modulated signal specifications, we can derive basic noise, linearity, filtering, and dynamic range specs.

• For Receiver:
  • Noise Figure
  • $\text{IIP}_2$
  • Anti-aliasing
  • ADC dynamic range

• For Transmitter:
  • I/Q imbalance
  • Integrated Phase Noise
  • TX OIP3
  • DAC Anti-Aliasing
• Required Noise Figure is calculated from the Target sensitivity with the Demodulator SNR_{MIN}:

\[ P_{SENS} = -174\text{dBm/Hz} + 10\log_{10}[\text{BW}] + \text{NF} + \text{SNR}_{\text{MIN}} \]

• For 64QAM rate ¾, target sensitivity is -75dBm, and demod SNR_{MIN} is 22dB. Required NF is then

\[ -75\text{dBm} + 174\text{dBm/Hz} - 10\log_{10}[20\text{M}] - 22\text{dB} = 4\text{dB} \]

*In practice, the achievable NF (often 3dB) determines sensitivity, not vice versa...*
Out-of-Band Blocker

• Out-of-band Blocker determines both IIP₂ and Far-out Phase noise spec
  • Evenly allocate between the two impairments such that together they give 3dB de-sense
  • Thermal Noise in 20MHz (w/3dB NF)= -98dBm
  • Total Noise allowed with Cellular Blocker present: -95dBm
  • => Target IM₂ level: -101dBm
  • => Target Reciprocal Mixing power: -101dBm
Out-of-Band Blocker: $IIP_2$

- For $IIP_2$ analysis, treat blocker as two tones of 3dB less power.
- Then Power of IM2 product can be calculated using:

$$IIP_2 = P_{in} + \Delta p$$

$$IIP_2 = -24\text{dBm} + 77\text{dB}$$

$$IIP_2 = +53\text{dBm}$$
Out-of-Band Blocker: Reciprocal Mixing

- Phase noise is calculated by first converting noise power to noise density: -101dBm - 73dBHz = -174dBm/Hz.
- Noise density is then referenced to blocker power to get dBc/Hz:
  - -174dBm/Hz + 21dBm = -153dBc/Hz
- This spec should be used at 100MHz offset and beyond.
ADC Anti-Aliasing

- Required Anti-Aliasing is equal to Protection Ratio+SNR+Margin
  - In this case, we use the Alternate channel Protection Ratio.
  - Target 6dB margin on protection ratio, and additional 6 to leave room for other impairments.
- Wifi protection ratio decreases as required signal SNR increases.
- Sum is roughly constant: ~22dB for Adjacent channel and ~38dB for Alternate Channel.
  - Eg: $SNR_{MIN}$ for 64QAM$r^{3/4}$ is 23dB, Adjacent Protection ratio is -1dB
- Required Anti-Aliasing is $38+12=50$dB

<table>
<thead>
<tr>
<th>Data Rate (Mbps)</th>
<th>$SNRMIN^*$ (dB)</th>
<th>Adjacent Protection Ratio</th>
<th>Alternate Protection Ratio</th>
<th>SNR+PR</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>4</td>
<td>16</td>
<td>32</td>
<td>20</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>15</td>
<td>31</td>
<td>20</td>
</tr>
<tr>
<td>12</td>
<td>7</td>
<td>13</td>
<td>29</td>
<td>20</td>
</tr>
<tr>
<td>18</td>
<td>9</td>
<td>11</td>
<td>27</td>
<td>20</td>
</tr>
<tr>
<td>24</td>
<td>13</td>
<td>8</td>
<td>24</td>
<td>21</td>
</tr>
<tr>
<td>36</td>
<td>16</td>
<td>4</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>48</td>
<td>20.5</td>
<td>0</td>
<td>16</td>
<td>20.5</td>
</tr>
<tr>
<td>54</td>
<td>22</td>
<td>-1</td>
<td>15</td>
<td>21</td>
</tr>
</tbody>
</table>
ADC Dynamic Range

- Minimum ADC dynamic range is equal to SNR + Peak-Average + Margin.
  - This assumes ideal AGC and all blockers removed.
- Since protection ratios for high data rates are low (-1dB per standard; +5dB target), we can slightly increase required dynamic range and push channel select filtering to digital.
- Then ADC dynamic range required is:
  - SNR + P-A + Protection ratio + margin=23dB+10+6+10=49dB
  - Note: must ensure that filtering attenuates alternate blockers to similar protection ratio.
    - As alternate blockers are 16dB higher, need at least 16dB of Alternate channel filtering.
    - If alternate filtering falls short, can increase ADC dynamic range to compensate.
• Integrated Phase noise, I/Q imbalance, and non-linearity all rms sum to give TX EVM.
  • Allow non-linearity to dominate the EVM budget, as this allows for highest PA efficiency.
• Target is for 3dB margin to standard at maximum Pout (+18dBm for high data rates)
• Budget must then sum to -28dB for 64QAM

<table>
<thead>
<tr>
<th></th>
<th>Budget</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>I/Q imbalance</td>
<td>-40dB</td>
<td>Achievable without calibration</td>
</tr>
<tr>
<td>PLL Phase Noise</td>
<td>-37dBc</td>
<td>Must meet this with PA Pulling of VCO</td>
</tr>
<tr>
<td>Non-Linearity (OIM3)</td>
<td>-29dB</td>
<td>Should be dominated by PA. Note this is in-band non-linearity (harder)</td>
</tr>
<tr>
<td>Total</td>
<td>-28dB</td>
<td>In-line with Target</td>
</tr>
</tbody>
</table>

Table 17-12—Allowed relative constellation error versus data rate

<table>
<thead>
<tr>
<th>Relative constellation error (dB)</th>
<th>Modulation</th>
<th>Coding rate (R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5</td>
<td>BPSK</td>
<td>1/2</td>
</tr>
<tr>
<td>-8</td>
<td>BPSK</td>
<td>3/4</td>
</tr>
<tr>
<td>-10</td>
<td>QPSK</td>
<td>1/2</td>
</tr>
<tr>
<td>-13</td>
<td>QPSK</td>
<td>3/4</td>
</tr>
<tr>
<td>-16</td>
<td>16-QAM</td>
<td>1/2</td>
</tr>
<tr>
<td>-19</td>
<td>16-QAM</td>
<td>3/4</td>
</tr>
<tr>
<td>-22</td>
<td>64-QAM</td>
<td>2/3</td>
</tr>
<tr>
<td>-25</td>
<td>64-QAM</td>
<td>3/4</td>
</tr>
</tbody>
</table>
TX ACPR

- Two tone test can approximate ACPR fairly accurately
- With this assumption, TX ACPR directly translates to OIP_3: \( OIP_3 = P_{out} + \Delta P/2 \)
- For \( P_{out} = +20\text{dBm} \) (=17dBm each tone) and \( \Delta P = 27\text{dBc} \) (3dB margin) we have
  - \( OIP_3 = +30.5\text{dBm} \)
- Note this is easier than the linearity required for EVM at high data rates, but more difficult for low data rates.
• TX Emissions requirement translates to a DAC Anti-Aliasing Requirement:
  • TX Emissions spec of -127dBm/Hz translates to -54dBm in 20MHz.
  • Assuming +20dBm TX output signal, this implies 74dBc DAC Anti-Aliasing.
  • With Margin, we need 80dBc

• However, can relax this with frequency planning.

• If Alias is placed at frequency that does not interfere with cellular, spec relaxes to -28dBm in 20MHz (FCC)
Transceiver Architecture
• Receive 2.4-2.5GHz
• Single ended RX input, differential Transmitter
• Integrated PA with +26dBm saturated output power
• Integrated T/R Switch
  • By carefully managing PA on /LNA off interaction, we can integrate T/R Switch
  • Elimination of T/R switch allows us to degrade NF and output power by 1dB
Receiver Overview

- 20MHz signal bandwidths RF input frequencies from 2.4-2.5GHz
- Single-Ended LNA followed by passive mixer
- Self Contained RF AGC loop followed by Digital AGC
- Quadrature LO Generated by ÷2 of PLL output
- Filtering, DC offset correction, and I/Q imbalance correction in digital domain.

<table>
<thead>
<tr>
<th>Spec</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>NF</td>
<td>3dB (+1dB T/R SW)</td>
</tr>
<tr>
<td>IIP2</td>
<td>+53dBm</td>
</tr>
<tr>
<td>LO Spot Phase</td>
<td>-153dBc/Hz @ 100MHz offset</td>
</tr>
<tr>
<td>Noise</td>
<td></td>
</tr>
<tr>
<td>ADC DR</td>
<td>49dB</td>
</tr>
<tr>
<td>AA Filtering</td>
<td>50dB</td>
</tr>
</tbody>
</table>
Single Ended vs. Differential LNAs

- For IoT, Single ended LNAs have major advantages with respect to differential LNAs.
  - 2x Lower Power for a given Noise figure
  - Less pins
  - No need for external baluns

- Main advantage is that Differential LNA enables Differential mixer
  - Differential Mixer has significantly improved $IIP_2$
  - $IIP_2$ specs are challenging if WiFi needs to Coexist with Cellular Signals.
  - WiFi Receiver must only de-sense 1dB when subjected to a -20dBm Cellular blocker at ~100MHz offset
  - This translates to +65dBm cascaded $IIP_2$

- For IoT Devices, Cellular Coexistence is not typically required.
  - Level of Cellular blockers is significantly lower.

- As a result, single ended LNA is more suited to IoT WiFi.
LNA + RX Mixer + BB AMP Specifications

- Quasi-Differential LNA-Mixer. Upconverted Impedance to give minimum 12dB filtering of OOB blockers.
- Two sets of Differential Quadrature outputs, combined by ADC gm
- Wideband match required due to integration of T/R switch
- *Power down mode such that PA swing does not damage LNA transistors.*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Spec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Gain</td>
<td>15dB</td>
</tr>
<tr>
<td>Gain Step Size</td>
<td>3dB</td>
</tr>
<tr>
<td>IIP3 @ Max gain</td>
<td>-10dBm</td>
</tr>
<tr>
<td>IIP2 @ Max Gain</td>
<td>+53dBm</td>
</tr>
<tr>
<td>OOB filtering @ LNA output</td>
<td>&gt;12dB</td>
</tr>
<tr>
<td>Power Down current</td>
<td>&lt;10uA</td>
</tr>
<tr>
<td>RX turn-on Time</td>
<td>3ms</td>
</tr>
</tbody>
</table>
ADC and 1\textsuperscript{st} Decimation

- Differential 8 bit 160MHz SAR ADC
- 2 Passive poles ahead of ADC at ~15MHz for blocker filtering/anti-aliasing
- Final CIC can be 2\textsuperscript{nd} order for 20MHz signals.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Spec</th>
</tr>
</thead>
<tbody>
<tr>
<td># Physical bits</td>
<td>8 bits</td>
</tr>
<tr>
<td>Sampling</td>
<td>160MS/s</td>
</tr>
<tr>
<td>ENOB in 20MHz</td>
<td>9 bits</td>
</tr>
<tr>
<td>Nominal BW</td>
<td>Two poles @ 15MHz</td>
</tr>
<tr>
<td>OIM3(adjacent)</td>
<td>+50dBc</td>
</tr>
<tr>
<td>Total Current</td>
<td>4mA</td>
</tr>
<tr>
<td>Power Down Current</td>
<td>&lt;1\mu \text{A}</td>
</tr>
</tbody>
</table>
Channel Selection Filter

- 802.11g Single-side BW is 8.3MHz
- 802.11n SSBW is 8.935MHz (worst Case)

**Spec Passband at 9MHz**

**Conservative Stop band: 10MHz**
- Allows Narrowband blocker like BT right at WiFi Band edge
- Minimum Stop band: 11MHz (assumes adjacent channel .11n blocker).

- Stop band attenuation: For 64QAM we spec 30dB SNR and 20dB protection ratio, giving **50dB stopband attenuation**.

- Ripple: +/-0.5dB

- **Channel Selection Performed in Digital Domain. Prefer IIR Implementation to save area and power.**

56 Carriers in 802.11n=17.87MHz

52 Carriers in 802.11g=16.6MHz
Transmitter Architecture

- Direct Conversion Transmit Architecture
- Gain control in PA and DAGC
- 8 or 16x Oversampled Nyquist DAC.
- **Differential PA is critical for low-cost packages**
- **PA Digital pre-distortion.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Spec</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA Gain</td>
<td>24dB</td>
</tr>
<tr>
<td>Gain Step Size</td>
<td>3dB</td>
</tr>
<tr>
<td>Psat @ Max Gain</td>
<td>+26dBm</td>
</tr>
<tr>
<td>EVM@+18dBm</td>
<td>-28dB</td>
</tr>
<tr>
<td>ACPR @+18dBm</td>
<td>-28dB</td>
</tr>
<tr>
<td>Output OOB noise @+18dBm</td>
<td>-123dBm/Hz</td>
</tr>
<tr>
<td>I/Q phase balance</td>
<td>&lt;0.2º</td>
</tr>
<tr>
<td>TX 10-90 turn-on Time</td>
<td>2ms</td>
</tr>
</tbody>
</table>
Impact Of DPD: Single Tone

![Graph showing the impact of DPD (Discrete Power Detector) on output power versus power back off (dB). The graph compares DPD Enabled and DPD Disabled scenarios.](image-url)
Impact of DPD: Modulated signals

**DPD Disabled**

<table>
<thead>
<tr>
<th>Burst:</th>
<th>Min</th>
<th>Mean</th>
<th>Limit</th>
<th>Max</th>
<th>Limit</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVM All Carr.</td>
<td>5.29</td>
<td>5.48</td>
<td>5.62</td>
<td>5.82</td>
<td>5.62</td>
<td>%</td>
</tr>
<tr>
<td>EVM Data Carr.</td>
<td>-25.37</td>
<td>-25.27</td>
<td>-25.00</td>
<td>-25.16</td>
<td>-25.00</td>
<td>dB</td>
</tr>
<tr>
<td>EVM Pilot Carr.</td>
<td>5.48</td>
<td>5.54</td>
<td>5.62</td>
<td>5.61</td>
<td>5.62</td>
<td>%</td>
</tr>
<tr>
<td>EVM Pilot Carr.</td>
<td>-25.22</td>
<td>-25.13</td>
<td>-25.00</td>
<td>-25.02</td>
<td>-25.00</td>
<td>dB</td>
</tr>
<tr>
<td>IQ Offset</td>
<td>4.11</td>
<td>4.20</td>
<td>39.81</td>
<td>4.30</td>
<td>39.81</td>
<td>%</td>
</tr>
<tr>
<td>Gain Imbalance</td>
<td>0.38</td>
<td>0.40</td>
<td>0.44</td>
<td>0.44</td>
<td>0.44</td>
<td>%</td>
</tr>
<tr>
<td>Quadrature Err</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>dB</td>
</tr>
<tr>
<td>Freq. Err</td>
<td>-0.72</td>
<td>-0.69</td>
<td>-0.68</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Symb Clock Err</td>
<td>-16632.17</td>
<td>-16640.37</td>
<td>± 60300</td>
<td>-16649.52</td>
<td>± 60300</td>
<td>Hz</td>
</tr>
<tr>
<td>Crest Factor</td>
<td>7.41</td>
<td>7.41</td>
<td>7.41</td>
<td>7.41</td>
<td>7.41</td>
<td></td>
</tr>
</tbody>
</table>

**DPD Enabled**

<table>
<thead>
<tr>
<th>Burst:</th>
<th>Min</th>
<th>Mean</th>
<th>Limit</th>
<th>Max</th>
<th>Limit</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVM All Carr.</td>
<td>5.20</td>
<td>5.28</td>
<td>5.62</td>
<td>5.34</td>
<td>5.62</td>
<td>%</td>
</tr>
<tr>
<td>EVM Data Carr.</td>
<td>-25.68</td>
<td>-25.54</td>
<td>-25.00</td>
<td>-25.44</td>
<td>-25.00</td>
<td>dB</td>
</tr>
<tr>
<td>EVM Pilot Carr.</td>
<td>5.29</td>
<td>5.38</td>
<td>5.62</td>
<td>5.43</td>
<td>5.62</td>
<td>%</td>
</tr>
<tr>
<td>EVM Pilot Carr.</td>
<td>-25.53</td>
<td>-25.39</td>
<td>-25.00</td>
<td>-25.30</td>
<td>-25.00</td>
<td>dB</td>
</tr>
<tr>
<td>IQ Offset</td>
<td>4.83</td>
<td>4.00</td>
<td>39.81</td>
<td>4.17</td>
<td>39.81</td>
<td>%</td>
</tr>
<tr>
<td>Gain Imbalance</td>
<td>0.29</td>
<td>0.34</td>
<td>0.42</td>
<td>0.42</td>
<td>0.42</td>
<td>%</td>
</tr>
<tr>
<td>Quadrature Err</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>dB</td>
</tr>
<tr>
<td>Freq. Err</td>
<td>-1.02</td>
<td>-0.98</td>
<td>-0.94</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Symb Clock Err</td>
<td>-16319.89</td>
<td>-16324.68</td>
<td>± 60300</td>
<td>-16331.73</td>
<td>± 60300</td>
<td>Hz</td>
</tr>
<tr>
<td>Burst Power</td>
<td>18.64</td>
<td>18.64</td>
<td>18.65</td>
<td>18.65</td>
<td>18.65</td>
<td>dBm</td>
</tr>
<tr>
<td>Crest Factor</td>
<td>7.27</td>
<td>7.31</td>
<td>7.34</td>
<td>7.34</td>
<td>7.34</td>
<td></td>
</tr>
</tbody>
</table>

→ DPD enhances EVM Compliant Output power by 4dB

+14.7dBm

+18.6dBm
DAC and Digital Interface

- Differential 12-bit Current steering DAC
- 2 Passive poles at DAC output at 15MHz for anti-aliasing/OOB noise filtering
  - Much Less critical in IoT! No cellular coexistence to worry about.
- Last Stage of Interpolation can be performed by custom logic in legacy CMOS (eg 65nm)
  - Can/Should be done entirely on Digital side in 28nm...
  - Final CIC can be 2nd order for 20MHz signals. 1st AA filter comes free from ZOH

**Parameter Spec**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Spec</th>
</tr>
</thead>
<tbody>
<tr>
<td># bits</td>
<td>12</td>
</tr>
<tr>
<td>Sampling</td>
<td>480-500GS/s</td>
</tr>
<tr>
<td>Nominal BW</td>
<td>Two poles @ 15MHz</td>
</tr>
<tr>
<td>OIM$_3$ @500mVpp se</td>
<td>50dB</td>
</tr>
<tr>
<td>Output Noise @ 200MHz</td>
<td>&lt;2nV/rt(Hz)</td>
</tr>
<tr>
<td>Anti-Aliasing</td>
<td>80dB</td>
</tr>
<tr>
<td>Max o/p</td>
<td>&gt;700mVppse</td>
</tr>
<tr>
<td>Total Current</td>
<td>&lt;20mA</td>
</tr>
<tr>
<td>Power Down Current</td>
<td>&lt;10uA</td>
</tr>
</tbody>
</table>
LO & Clock PLL Architecture

- Synthesize 4x the required LO to mitigate VCO pulling by PA
  - Required LO is 2.412-2.480. With margin we design for 2.4-2.5
Looking Forward
802.11ah is the Future of IoT WiFi
  • Standard is Optimized for IoT devices
  • Uses 900MHz ISM band for ~3x range
  • MAC enhancements to allow huge number of low duty cycle devices

UPDATE: 802.11ax is the Future of WiFi
  • 802.11 working group cleverly included enhancements for IoT in a mainstream (read: Cell Phone) amendment
BACKUP
Aside: Coin Cell Battery

- Although Coin cell is naturally 3V it’s capacity under high discharge and internal resistance make it unsuitable for most WiFi chips/applications.
- Even 10mA loads cause a significant drop across battery IR

**Specifications**

- **Classification:** "Lithium Coin"
- **Chemical System:** Lithium / Manganese Dioxide (Li/MnO₂)
- **Designation:** ANSI / NEDA-5004LC, IEC-CR2032
- **Nominal Voltage:** 3.0 Volts
- **Typical Capacity:**
  - 240 mAh (to 2.0 volts)
  - (Rated at 15K ohms at 21°C)
- **Typical Weight:** 3.0 grams (0.10 oz.)
- **Typical Volume:** 1.0 cubic centimeters (0.06 cubic inch)
- **Typical IR:** 10,000 - 40,000 mΩ
- **Max Rev Charge:** 1 microampere
- **Energy Density:** 198 milliWatt hr/g, 653 milliWatt hr/cc
- **Typical Li Content:** 0.109 grams (0.0038 oz.)
- **UL Listed:** MH29980
- **Operating Temp:** -30°C to 60°C
- **Self Discharge:** ~1% / year