WiFi for IoT: RF Systems & Architecture

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About the Author: Edward Youssoufian

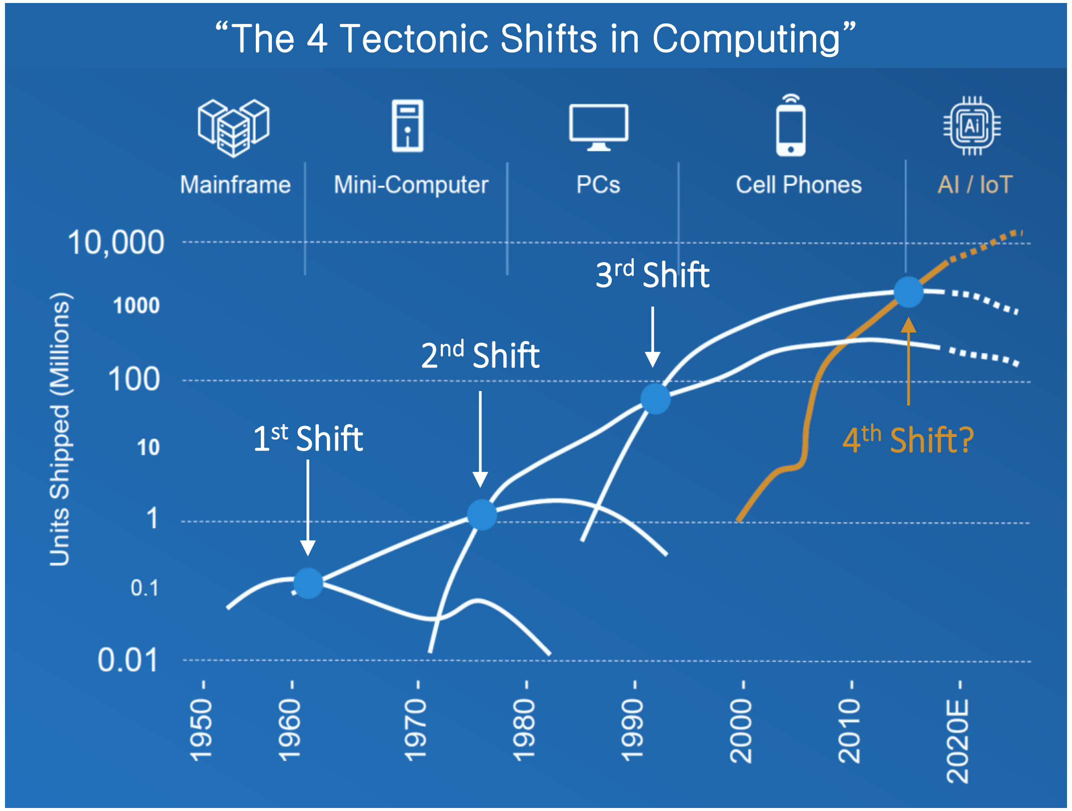
- **Currently: *Sr. Director at NXP,*** Responsible for RF and Analog development within the Secure Transactions and Identification Business Line
- ***Sr. Director, Engineering at Atmel***, where he led development of multiple WiFi-, Bluetooth-, and Zigbee-enabled Wireless MCUs for IoT, including (at 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 (“2nd 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.



Source: Jeffries, NXP

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: 1st and 2nd (Current) Version

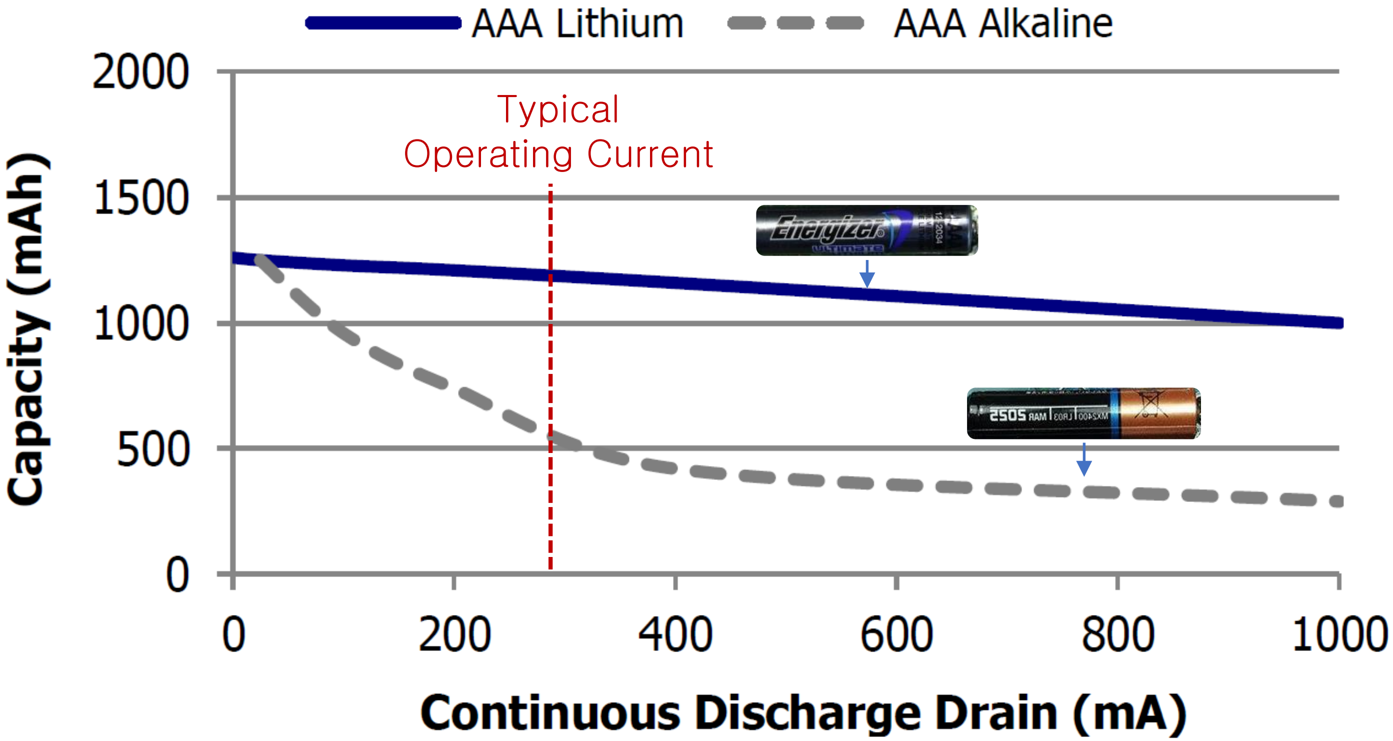
Original Version

Current Version

- One significant improvement in new version of button –– New Version uses commodity AAA battery – *3x cost savings*
- What is needed to make this change possible?

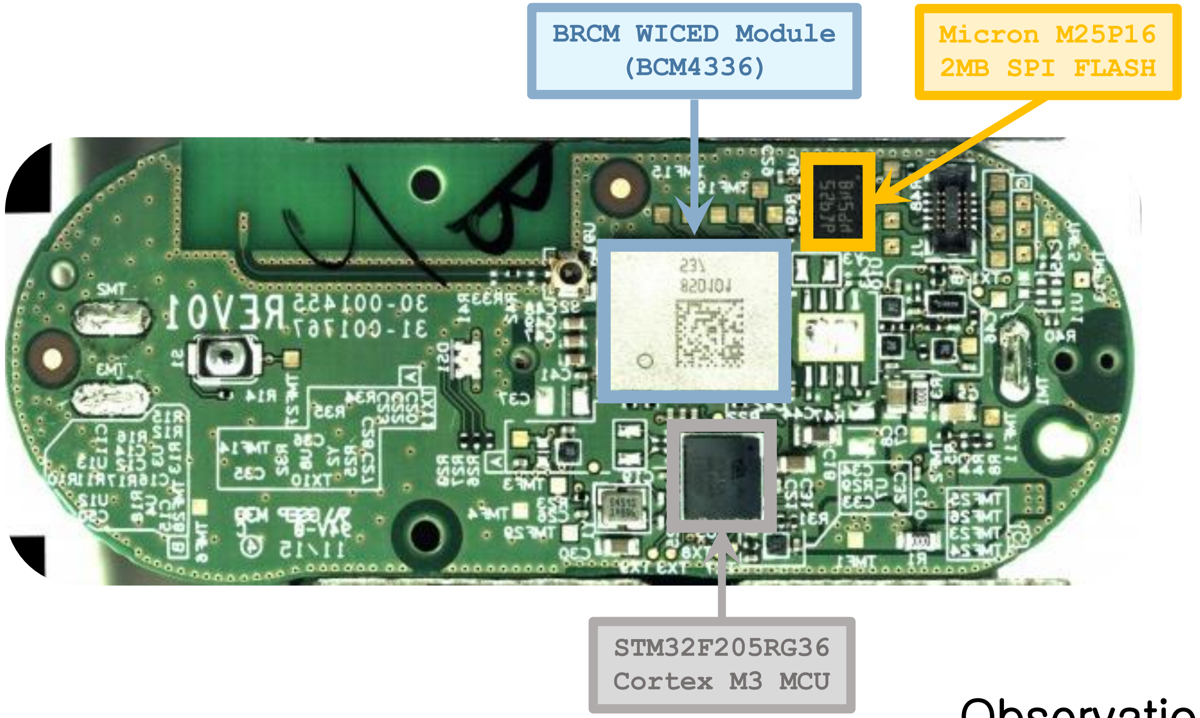
Comparison: Lithium vs. Alkaline AAA battery

- 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



PCB Bottom

Original Version

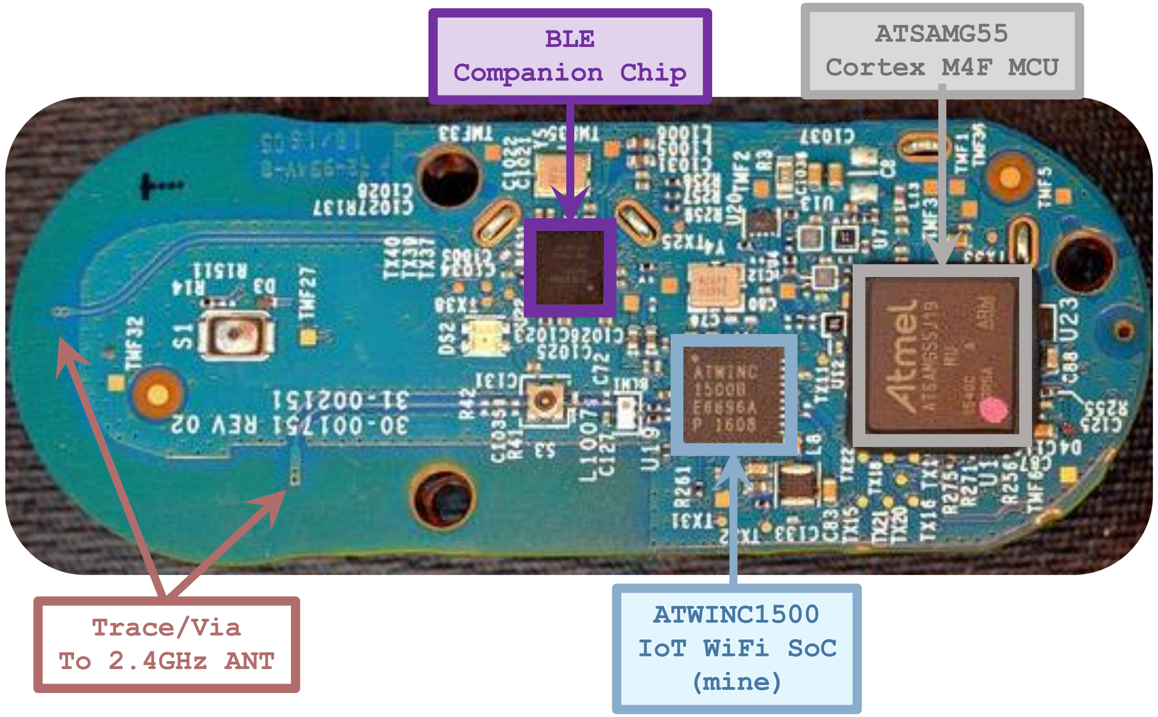


BRCM WICED Module (BCM4336)

Micron M25P16 2MB SPI FLASH

STM32F205RG36 Cortex M3 MCU

Current Version



BLE Companion Chip

ATSAMG55 Cortex M4F MCU

Trace/Via To 2.4GHz ANT

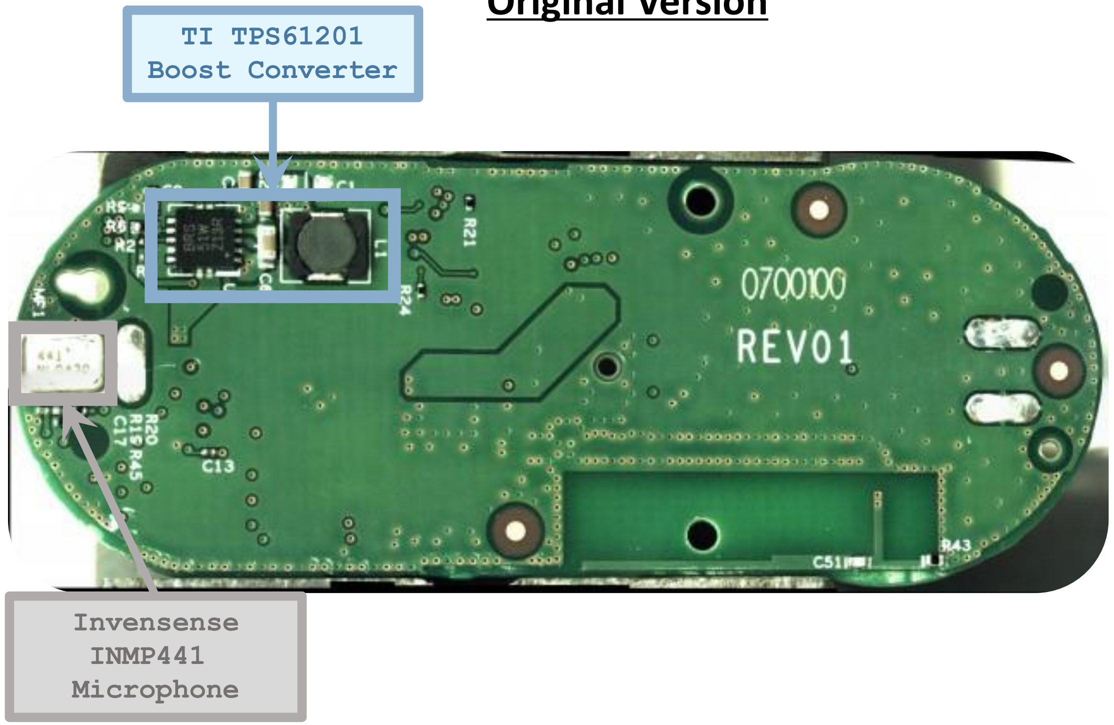
ATWINC1500 IoT WiFi SoC (mine)

Observations

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.

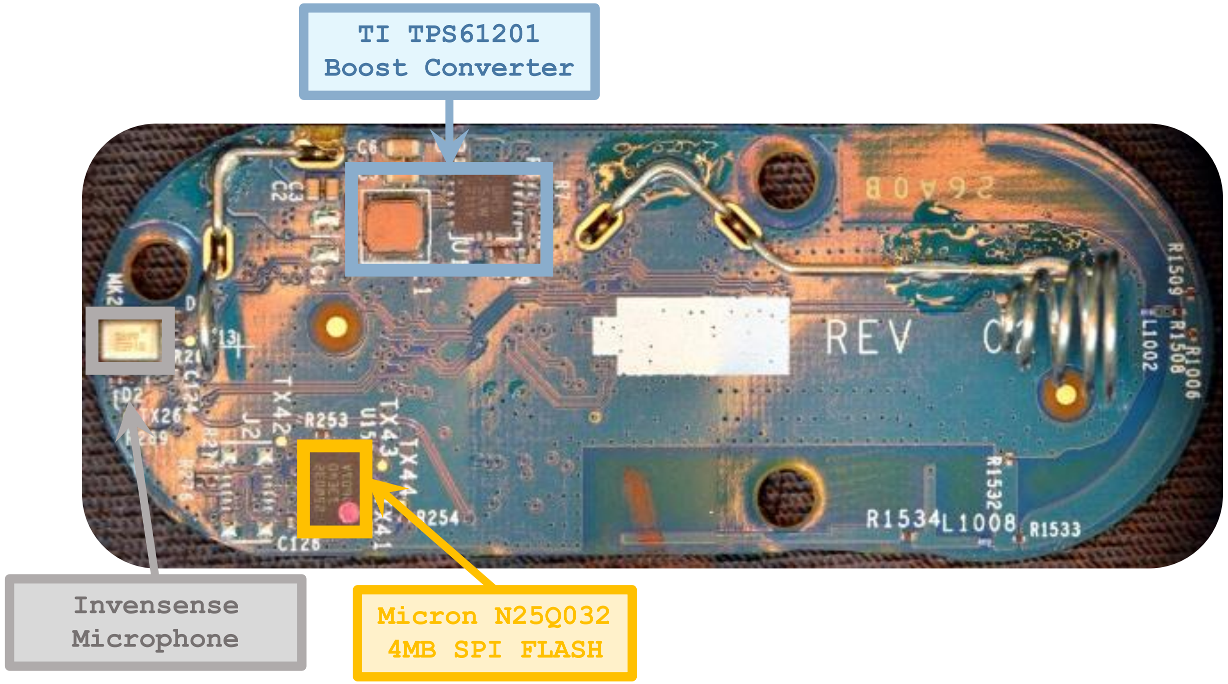
PCB Top

Original Version


TI TPS61201 Boost Converter

Invensense INMP441 Microphone

Current Version


TI TPS61201 Boost Converter

Invensense Microphone

Micron N25Q032 4MB SPI FLASH

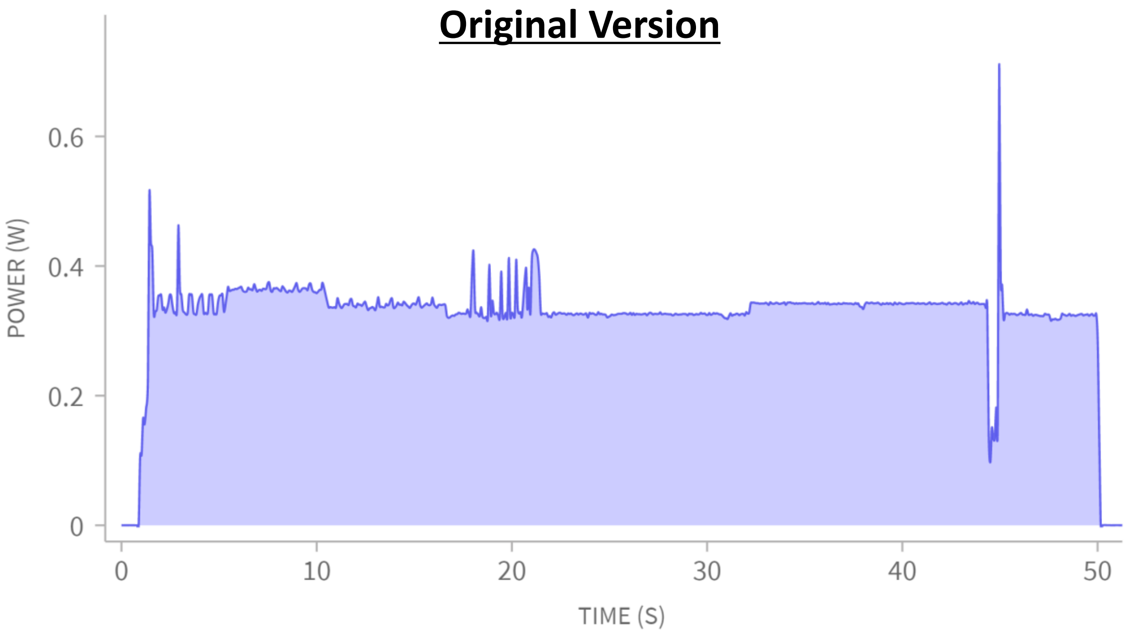
Observations

1. Boost Converter present, as expected. No Change between versions.
2. Both Devices have a Microphone (!?)
    - Strange…button does not have voice recognition capability.

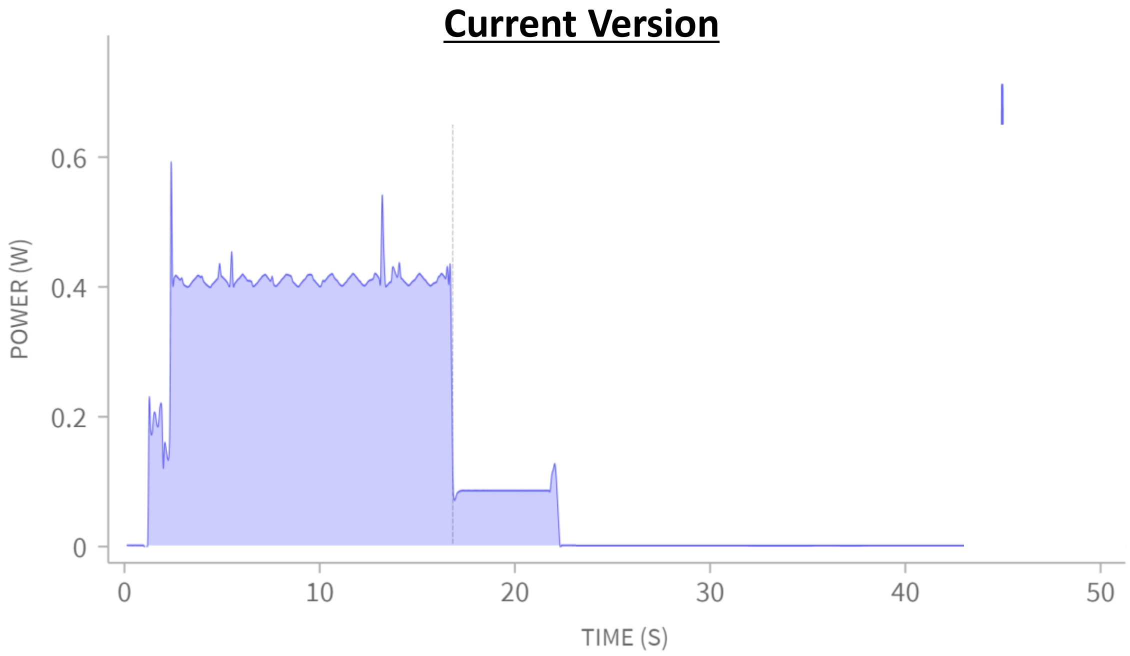
Microphone, BLE, and Provisioning

- 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



Original Version



Current Version

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

- Peak Power Consumption of both devices is comparable
  - Current verson 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

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.

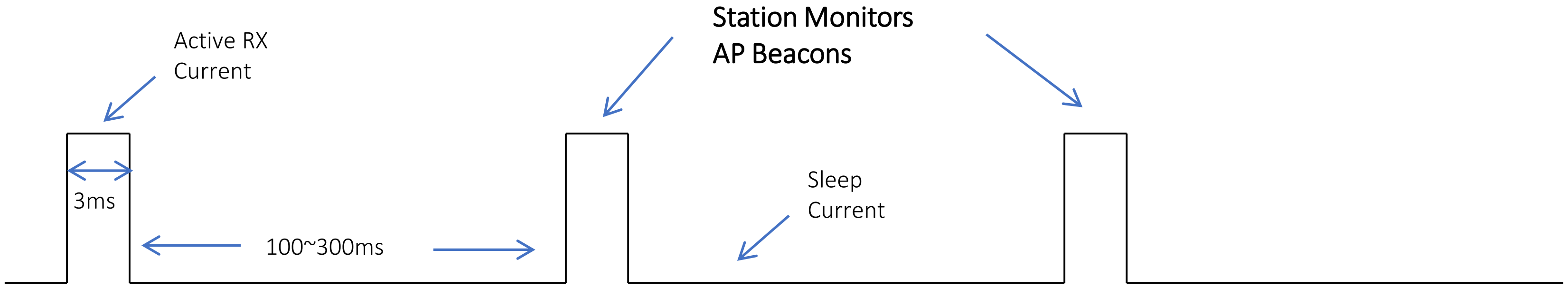
WiFi Power Modes for IoT

Power Modes

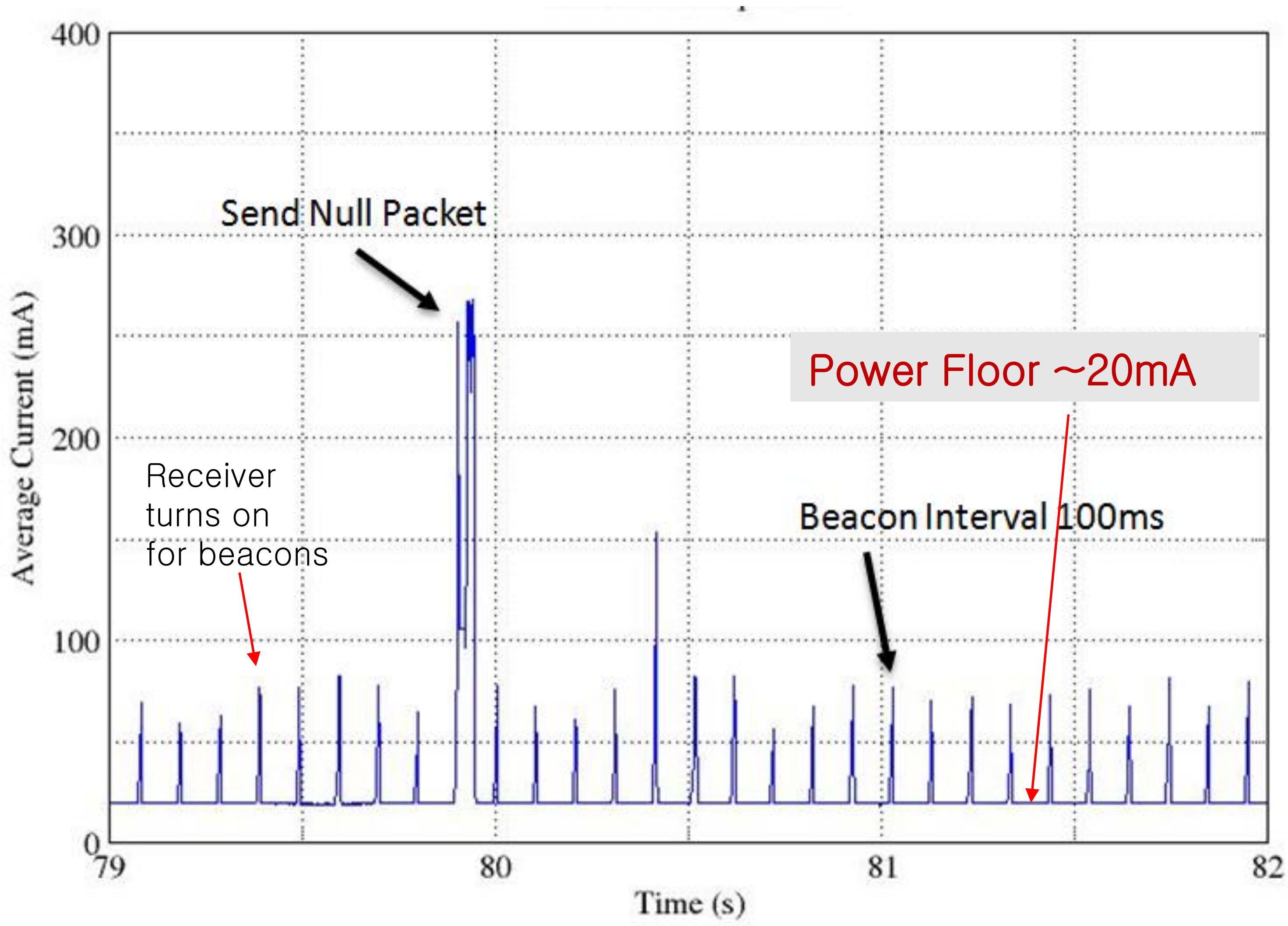
- WiFi has provisions for power save modes.
  - **Beacon Monitoring**: Commonly used today; allows full BW communication.
  - **Use of PS Poll packets**: Less common; allows ~10x less power consumption, at expense of much longer latency and throughput
  - **Shutoff and Reconnect**: Mainly for Event-Driven 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



Send Null Packet

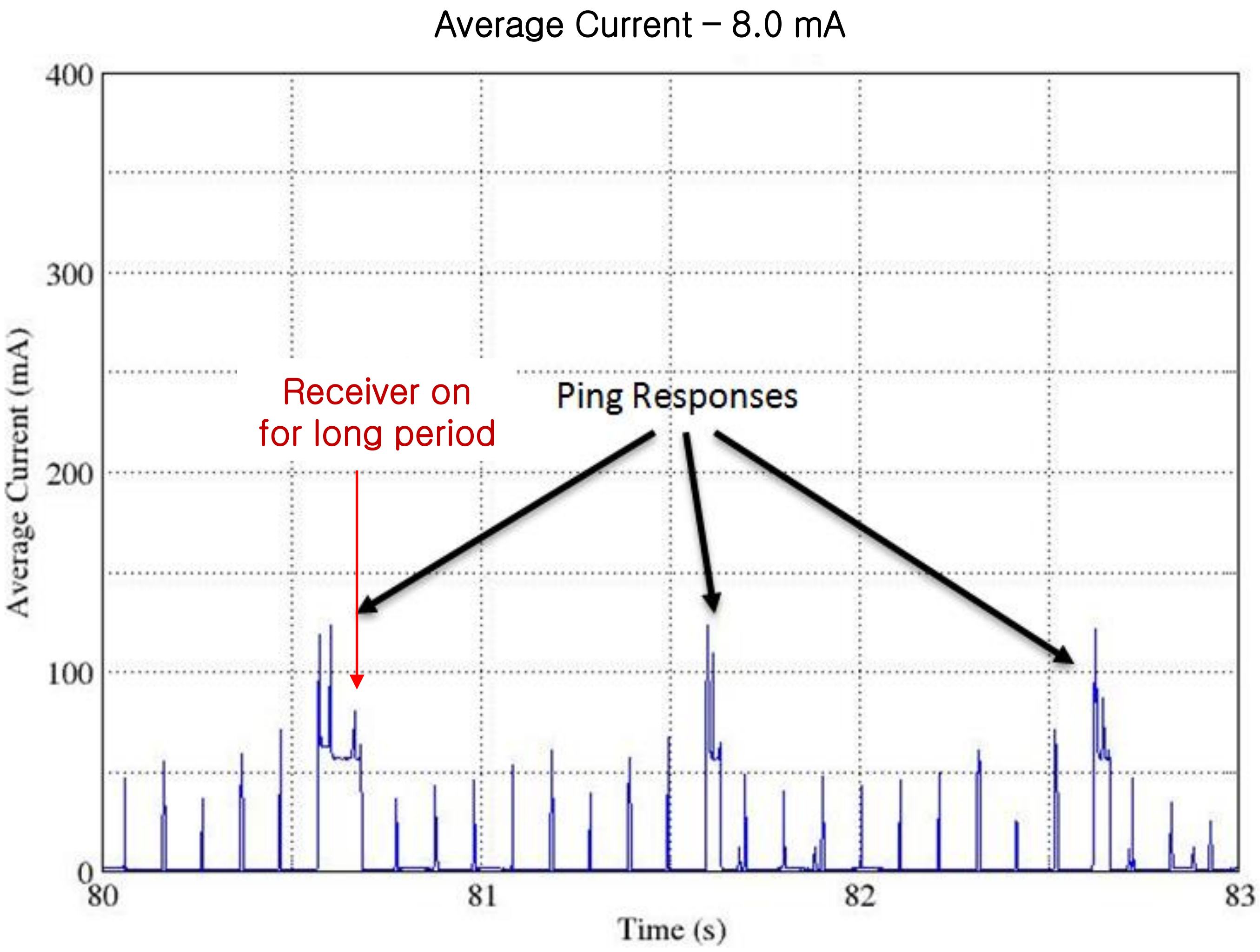
Power Floor ~20mA

Receiver turns on for beacons

Beacon Interval 100ms

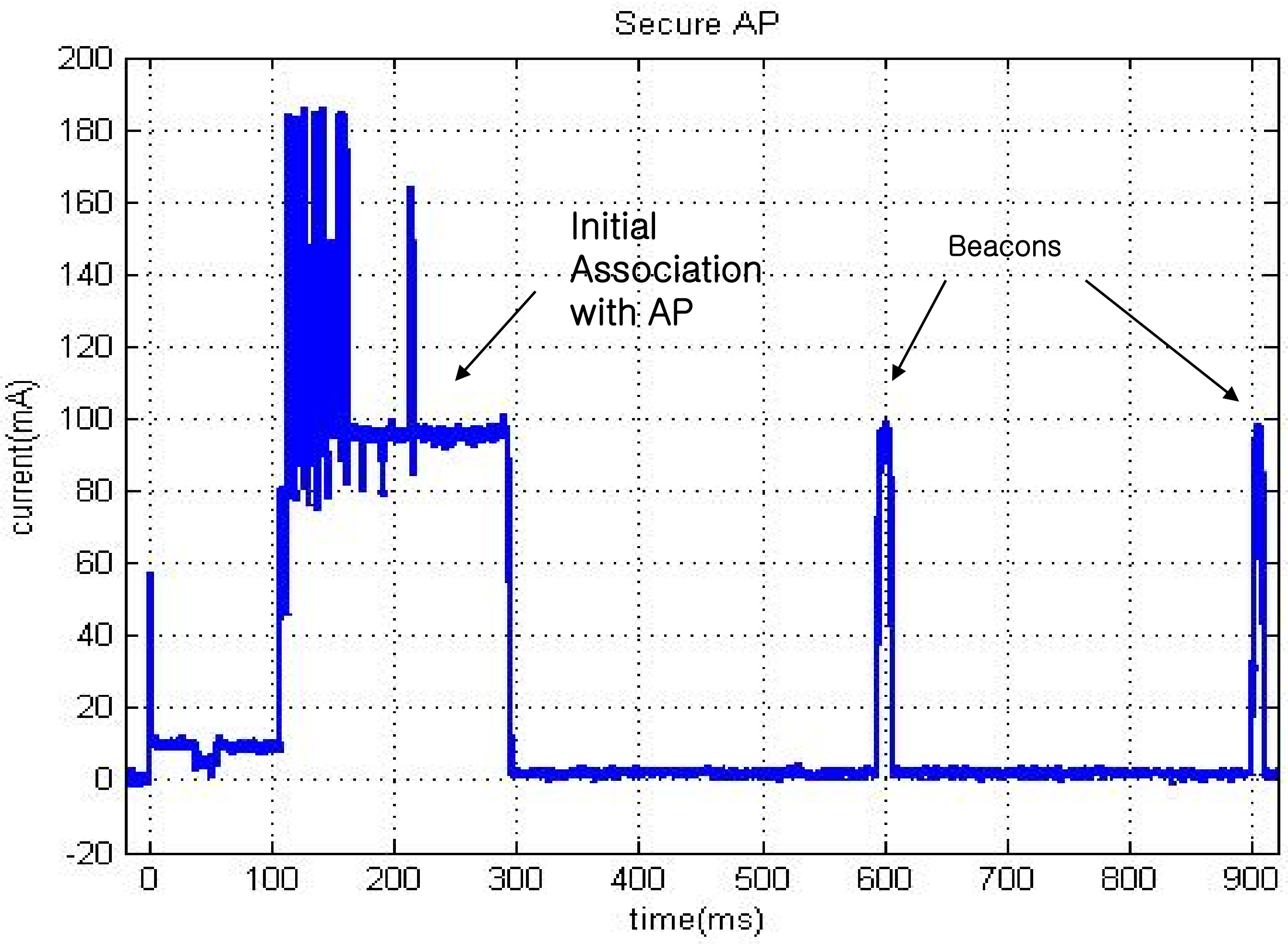
- Overall Beacon Monitor Current is 22.5 mA!
- 90% is standby power.

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

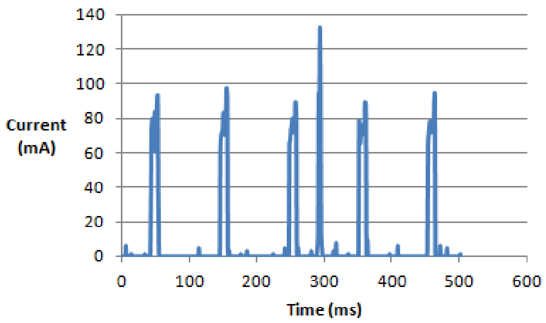
Beacon Monitoring Mode: Optimized for IoT



- Receiver dominates power consumption
- Power in between beacons is minimal
- Average of 3ms @ 80mA every 300ms ~1mA average current
  - Increases to 3mA 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

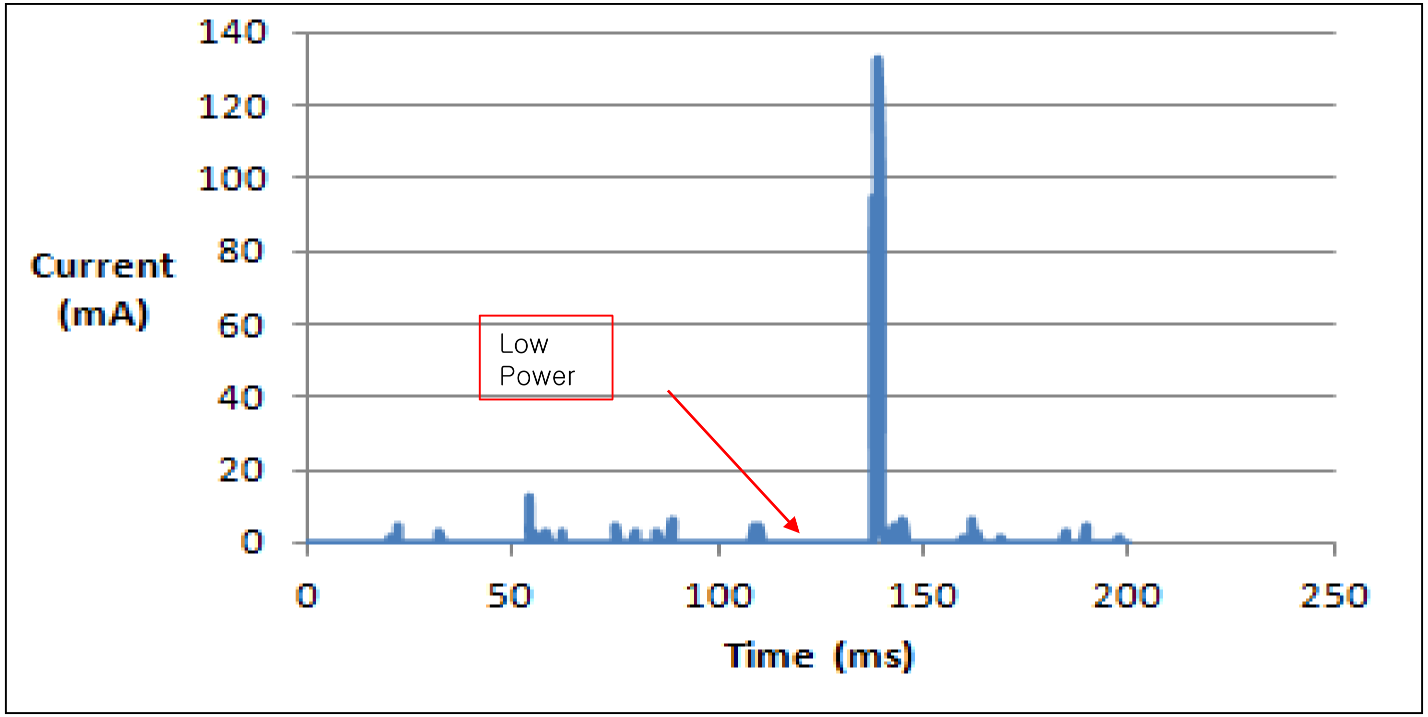
- Put IoT Device in Beacon Monitoring mode.
- Thermostat can be set any time; Temperature can be read any time (~100’s of ms latency)



PS Poll: Moderate Activity Devices

- 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

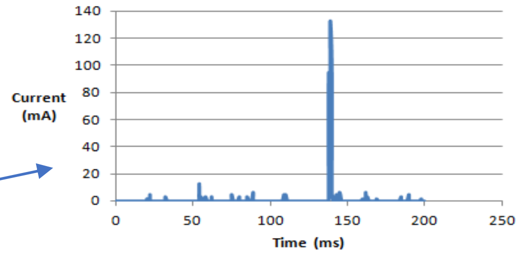


- Dominant current: Oscillators, Bandgap/LDOs, Memory Leakage
- Power can be reduced to ~100uA
- Extends life to ~10 months for 2 AAA batteries.
  - Still not good enough for many applications

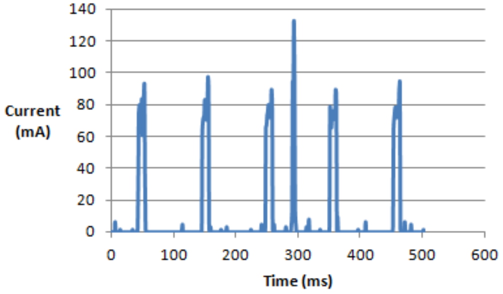
Use of PS Poll in IoT Application

- 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

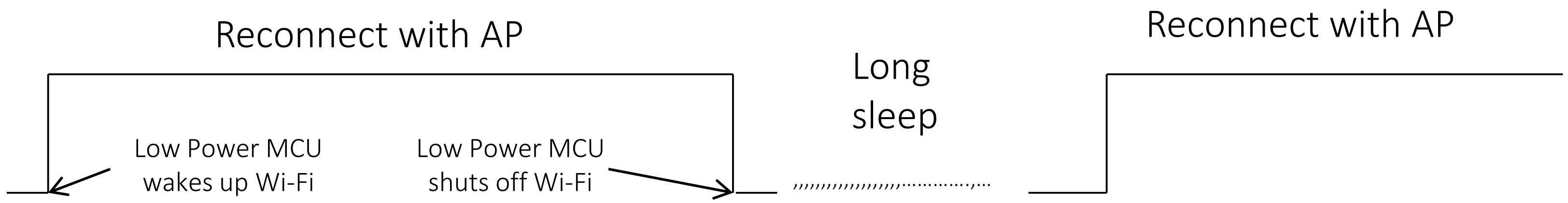


2. Timer Expires. Enter Beacon Monitoring mode and upload data

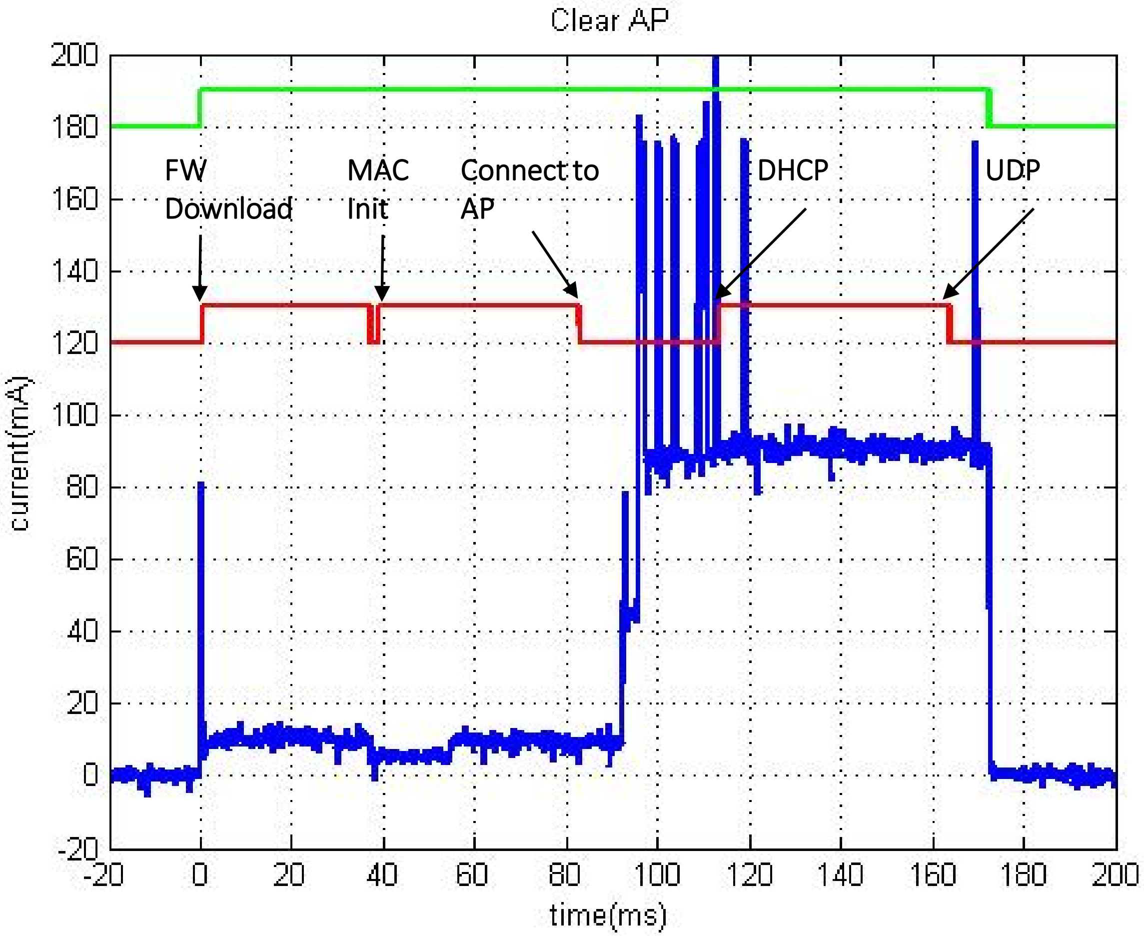


Shut Off and Re-Connect: Low Activity Devices

- 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

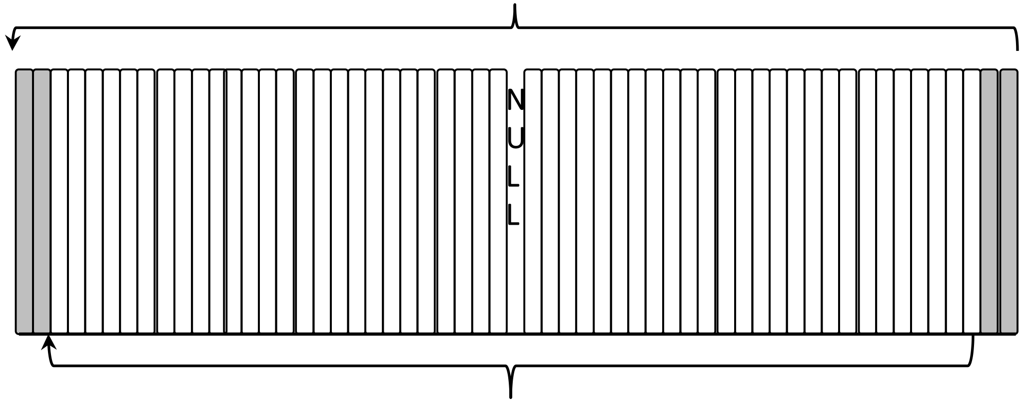
Strategy

- 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.

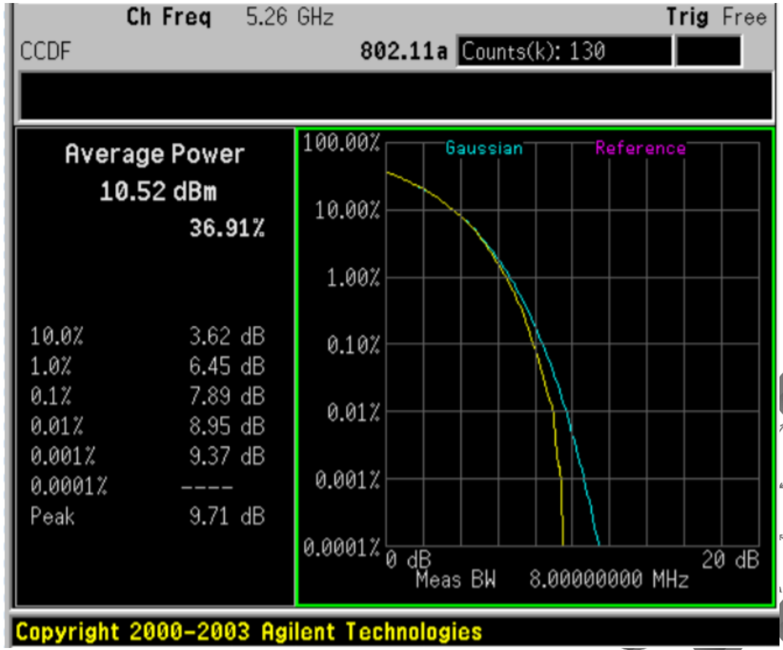
General Signal Properties

- 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.

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



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



```
Ch Freq    5.26 GHz                              Trig Free
CCDF                        802.11a Counts(k): 130

Average Power
10.52 dBm
        36.91%

10.0%        3.62 dB
1.0%         6.45 dB
0.1%         7.89 dB
0.01%        8.95 dB
0.001%       9.37 dB
0.0001%      ----
Peak         9.71 dB

Meas BW      8.00000000 MHz
```

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

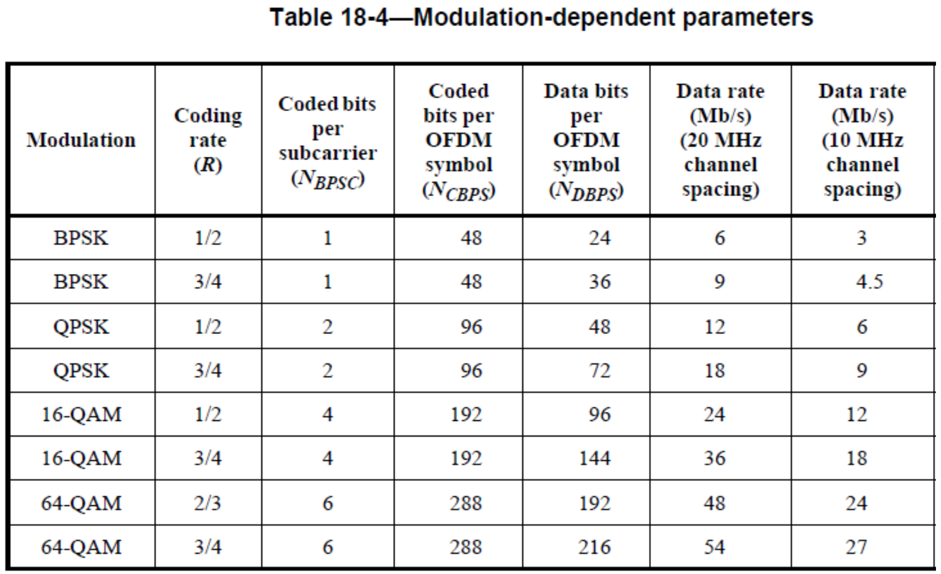


Table 18-4—Modulation-dependent parameters

Modulation	Coding rate (R)	Coded bits per subcarrier (N_{BPSC})	Coded bits per OFDM symbol (N_{CBPS})	Data bits per OFDM symbol (N_{DBPS})	Data rate (Mb/s) (20 MHz channel spacing)	Data rate (Mb/s) (10 MHz channel spacing)
BPSK	1/2	1	48	24	6	3
BPSK	3/4	1	48	36	9	4.5
QPSK	1/2	2	96	48	12	6
QPSK	3/4	2	96	72	18	9
16-QAM	1/2	4	192	96	24	12
16-QAM	3/4	4	192	144	36	18
64-QAM	2/3	6	288	192	48	24
64-QAM	3/4	6	288	216	54	27

802.11n 1x1 Data Rates

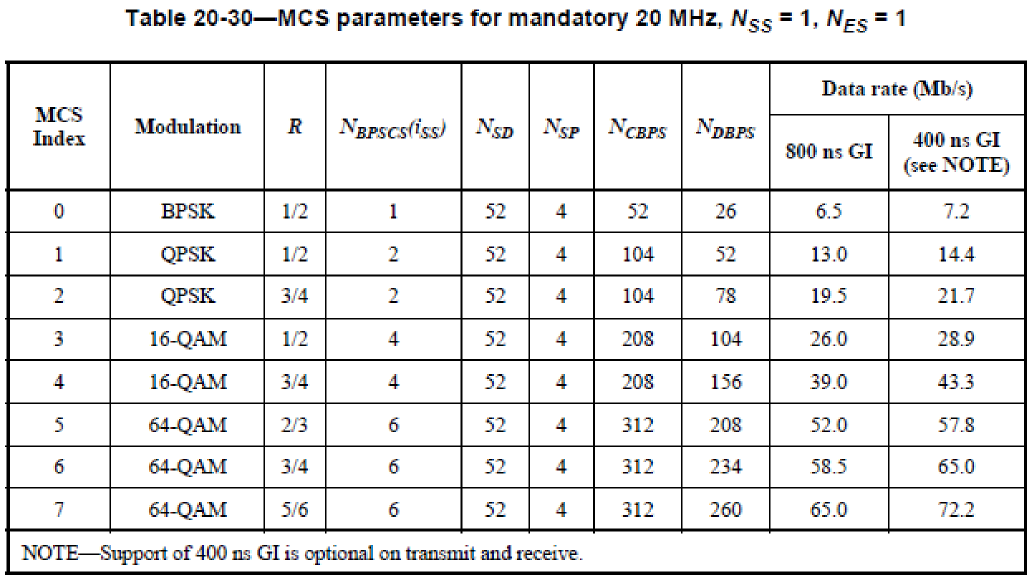


Table 20-30—MCS parameters for mandatory 20 MHz, N_{SS} = 1, N_{ES} = 1

MCS Index	Modulation	R	$N_{BPSCS}(i_{SS})$	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	Data rate (Mb/s) 800 ns GI	Data rate (Mb/s) 400 ns GI (see NOTE)
0	BPSK	1/2	1	52	4	52	26	6.5	7.2
1	QPSK	1/2	2	52	4	104	52	13.0	14.4
2	QPSK	3/4	2	52	4	104	78	19.5	21.7
3	16-QAM	1/2	4	52	4	208	104	26.0	28.9
4	16-QAM	3/4	4	52	4	208	156	39.0	43.3
5	64-QAM	2/3	6	52	4	312	208	52.0	57.8
6	64-QAM	3/4	6	52	4	312	234	58.5	65.0
7	64-QAM	5/6	6	52	4	312	260	65.0	72.2

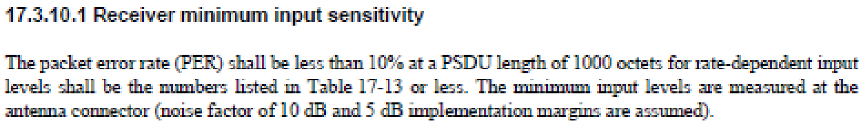
NOTE—Support of 400 ns GI is optional on transmit and receive.

802.11a/b/g/n Standard Comparison: RX

	.11a	.11g	.11n	.11b
Frequency Band	5GHz ISM	2.4GHz ISM	2.4 & 5 GHz ISM	2.4GHz ISM
Sensitivity	See Next Slide	Identical to .11a	Essentially Identical to: .11a (5GHz) .11g (2.4GHz)	-76dBm
Adjacent Channel		Identical to .11a (25MHz spacing)		35dB
Alternate Channel		No Requirement		No Requirement
Maximum input	-30dBm	-20dBm		-10dBm

- .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



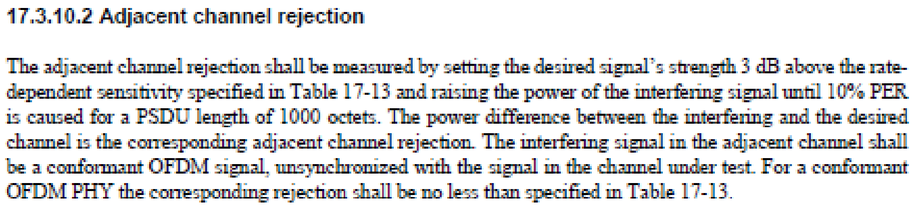
17.3.10.1 Receiver minimum input sensitivity

The packet error rate (PER) shall be less than 10% at a PSDU length of 1000 octets for rate-dependent input levels shall be the numbers listed in Table 17-13 or less. The minimum input levels are measured at the antenna connector (noise factor of 10 dB and 5 dB implementation margins are assumed).

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

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

- 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.



17.3.10.2 Adjacent channel rejection

The adjacent channel rejection shall be measured by setting the desired signal's strength 3 dB above the rate-dependent sensitivity specified in Table 17-13 and raising the power of the interfering signal until 10% PER is caused for a PSDU length of 1000 octets. The power difference between the interfering and the desired channel is the corresponding adjacent channel rejection. The interfering signal in the adjacent channel shall be a conformant OFDM signal, unsynchronized with the signal in the channel under test. For a conformant OFDM PHY the corresponding rejection shall be no less than specified in Table 17-13.

Data Rate (Mbps)	Modulation	SNRMIN* (dB)	Adjacent Protection Ratio	Alternate Protection Ratio	SNR+PR
6	BPSK 1/2	4	16	32	20
9	BPSK 3/4	5	15	31	20
12	QPSK 1/2	7	13	29	20
18	QPSK 3/4	9	11	27	20
24	16QAM 1/2	13	8	24	21
36	16QAM 3/4	16	4	20	20
48	64QAM 2/3	20.5	0	16	20.5
54	64QAM 3/4	22	-1	15	21

*SNRMIN values are from simulation (1dB implementation loss)

- 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

	.11a	.11g	.11n	.11b
Frequency Band	5GHz ISM	2.4GHz ISM	2.4 & 5 GHz ISM	2.4GHz ISM
TX Frequency Accuracy	+/-20ppm	+/-25ppm	Identical to: .11a (5GHz) .11g (2.4GHz)	Identical to .11g
EVM	Table 17-12	Identical to .11a	Essentially Identical to .11a	<35%
Spectral Mask	Next Slide	Identical to .11a	Next Slide	Next Slide
LO Feedthrough	-15dBc	Identical to .11a	**-20dBc**	Identical to .11a

802.11a/g

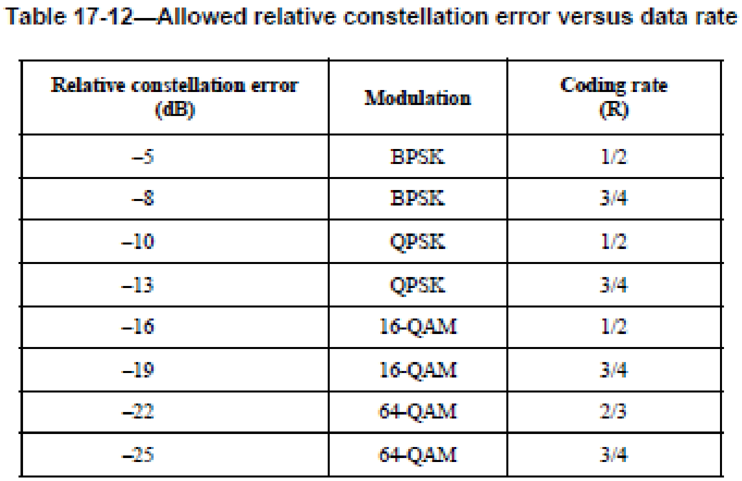


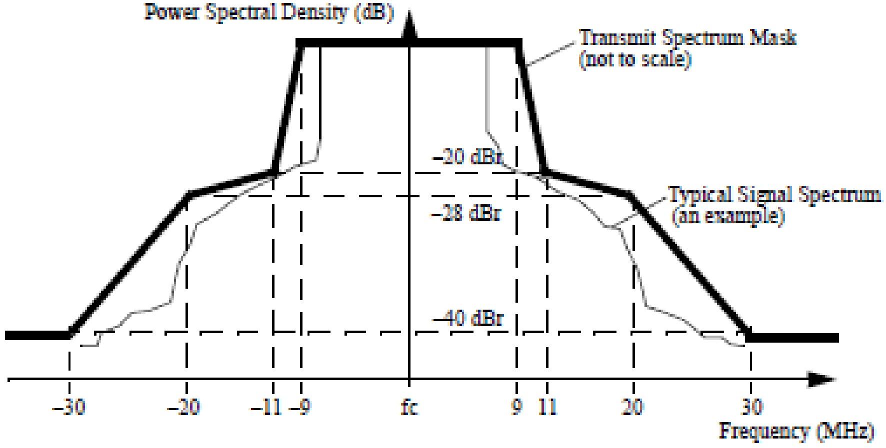
Table 17-12—Allowed relative constellation error versus data rate

Relative constellation error (dB)	Modulation	Coding rate (R)
–5	BPSK	1/2
–8	BPSK	3/4
–10	QPSK	1/2
–13	QPSK	3/4
–16	16-QAM	1/2
–19	16-QAM	3/4
–22	64-QAM	2/3
–25	64-QAM	3/4

- .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)

Spectral Masks

802.11a/g



802.11n

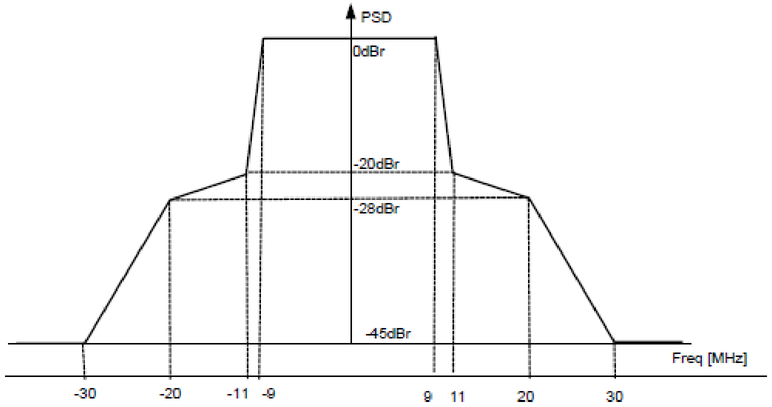


Figure 20-17—Transmit spectral mask for 20 MHz transmission

802.11b

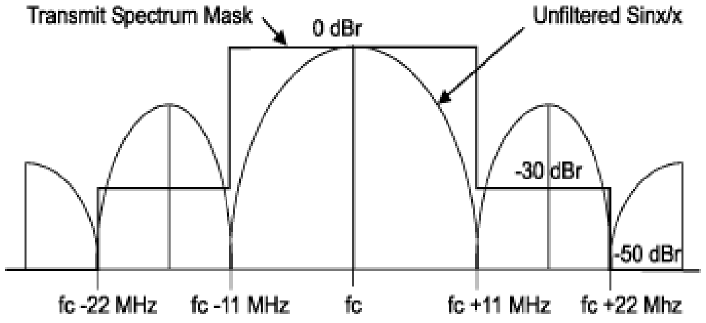


Figure 18-19—Transmit spectrum mask

- .11n requirements 5dB more difficult beyond 30MHz.
- Adopt this as the target, generally not a major issue.

FCC

- 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 48dBc 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.

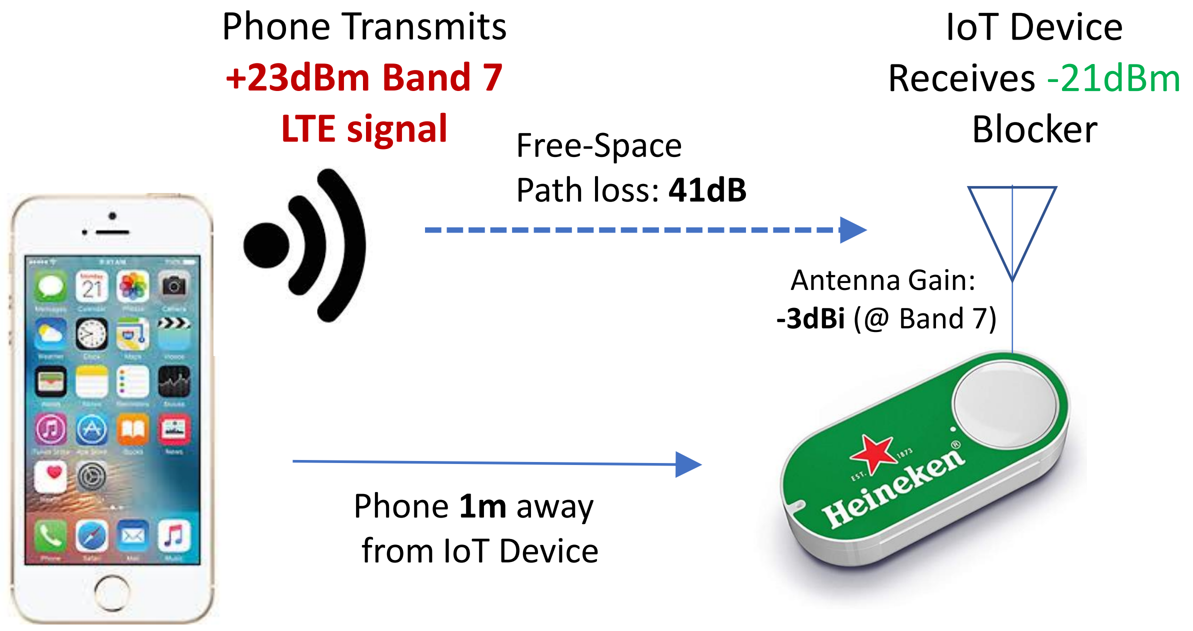
Emission Type	FCC Limit	Comment
Fundamental Power	+30dBm	Assumes <6dBi antenna
Harmonic Power	-41dBm/MHz	All Harmonics
Restricted Bands	-41dBm/MHz	Includes Edge of 2.4GHz ISM band (2310-2390 and 2483.5-2500)

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 IIP_2
- Many WiFi devices were designed with ***Cellular*** requirements in mind.
- IoT devices do not have such requirements.

Receiver Coexistence 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 <=3dB de-sense



Phone Transmits
+23dBm Band 7
LTE signal

Free-Space
Path loss: **41dB**

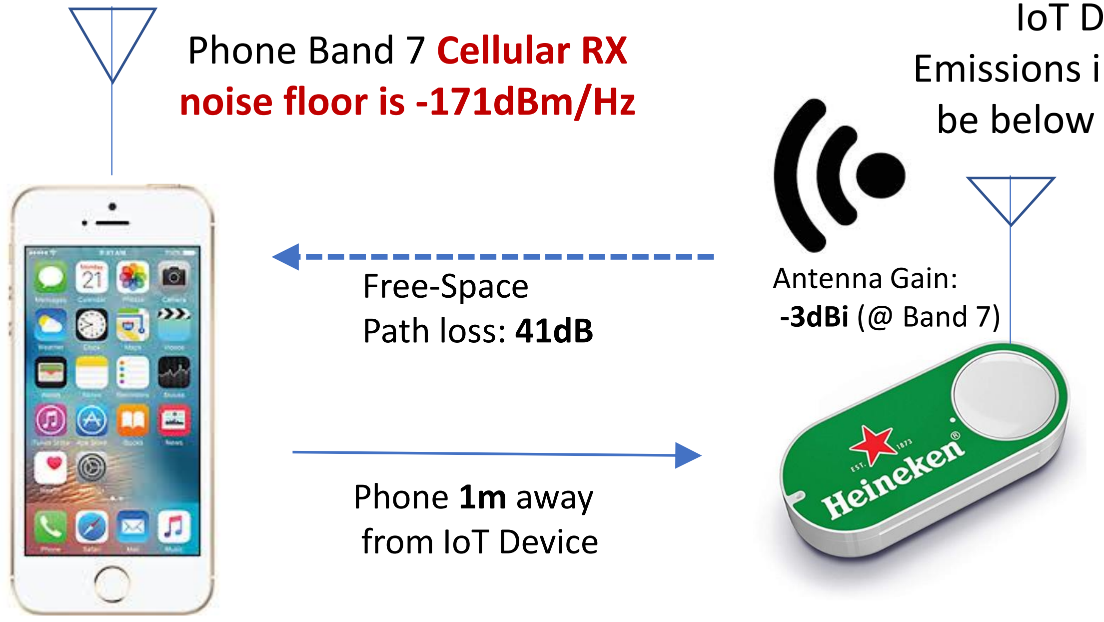
IoT Device
Receives -21dBm
Blocker

Antenna Gain:
-3dBi (@ Band 7)

Phone **1m** away
from IoT Device

Transmitter Coexistence Requirements

- In TX mode, opposite concern arise – Emissions of WiFi device de-sensitizing Cell phone
- Target is for WiFi emmissions to cause <=3dB de-sense to other receivers



Phone Band 7 **Cellular RX noise floor is -171dBm/Hz**

IoT Device TX
Emissions in Band 7 must
be below **-127dBm/Hz**

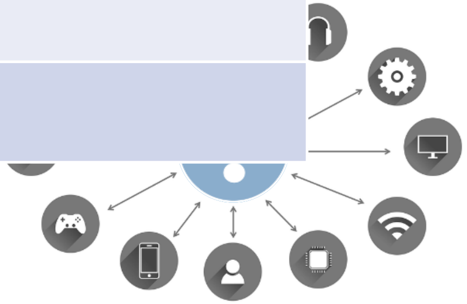
Free-Space
Path loss: **41dB**

Antenna Gain:
-3dBi (@ Band 7)

Phone **1m** away
from IoT Device

Summary of Cascaded Receiver Requirements

	Spec	Comment
Sensitivity	10dB Margin to 802.11a	e.g. -75dBm for 64QAMR¾ Implies 4dB NF.
Maximum Input Signal	-10dBm	Set by .11b. Little impact on cost/power.
Out-of-band Blocker	-21dBm	Set by coexistence with cellular blockers
Adjacent Channel blocker	6dB margin to 802.11a	e.g. +5dB Protection ratio for 64QAMR¾
Alternate Channel Blocker	6dB margin to 802.11a	e.g. +21dB Protection ratio for 64QAMR¾ Only required if supporting 5GHZ ISM band
Power Consumption	**Minimize**	
Cost	**Minimize**	



Cascaded Transmitter Requirements

	Spec	**Comment**
TX Output Power	+18dBm for 64QAMR¾	Lower data rates expected to have higher output power. Based on competitive analysis.
EVM	3dB Margin to 802.11n at P_{MAX}	e.g. -31dB evm for 64QAMR¾
ACPR	3dB Margin to 802.11n at P_{MAX}	Typically matters at lower data rates
LO Feedthrough	-20dBc	Set by .11n
Spectral Emissions	<-121dBm/Hz	In all 3GPP Cellular bands. Includes DAC alias.
Harmonic Distortion	<-48dBc	Per FCC
Frequency Accuracy	+/-20ppm	Can be relaxed in 2.4GHz only is used.
Power Consumption	**Minimize**	
Cost	**Minimize**	

Translation

- Given the Previous high-level, modulated signal specifications, we can derive basic noise, linearity, filtering, and dynamic range specs.
- For Receiver:
  - Noise Figure
  - IIP_2
  - Anti-aliasing
  - ADC dynamic range
- For Transmitter:
  - I/Q imbalance
  - Integrated Phase Noise
  - TX OIP3
  - DAC Anti-Aliasing

Receiver Noise Figure

- Required Noise Figure is calculated from the Target sensitivity with the Demodulator SNR_{MIN} :

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

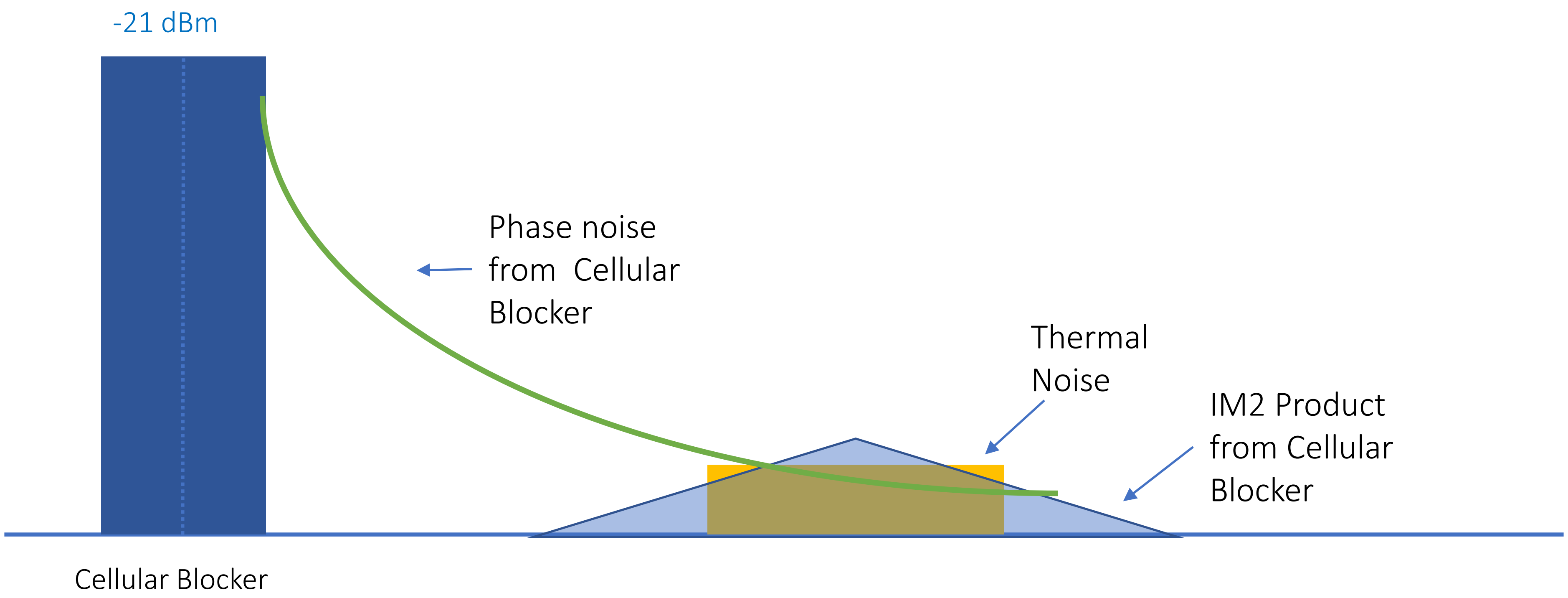
- For 64QAM rate ¾, target sensitivity is -75dBm, and demod SNR_{MIN} is 22dB. Required NF is then

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

In practice, the achievable NF (often 3dB) determines sensitivity, not vice versa…

Out-of-Band Blocker

- Out-of-band Blocker determines both IIP_2 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 IM_2 level: -101dBm
  - =>Target Reciprocal Mixing power: -101dBm



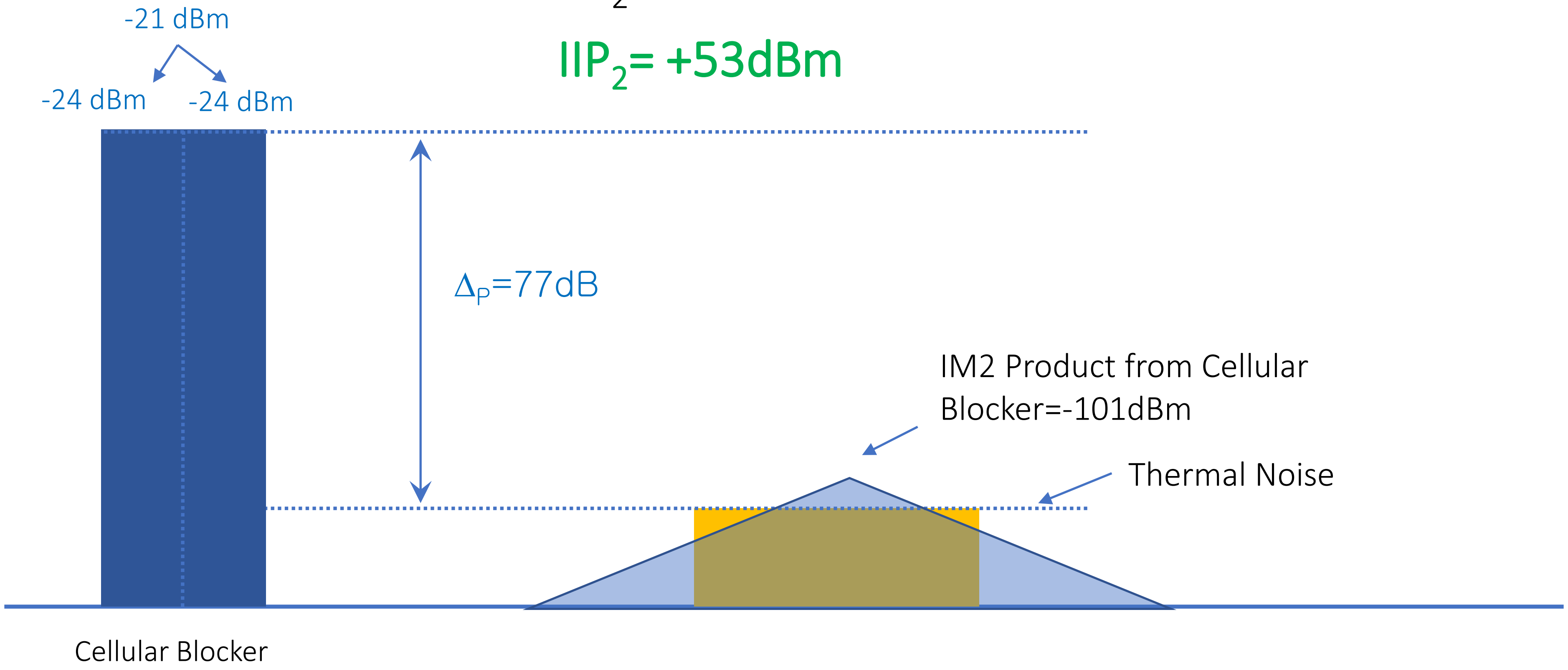
Out-of-Band Blocker: IIP_2

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

$$IIP_2 = P_{in} + \Delta_P$$

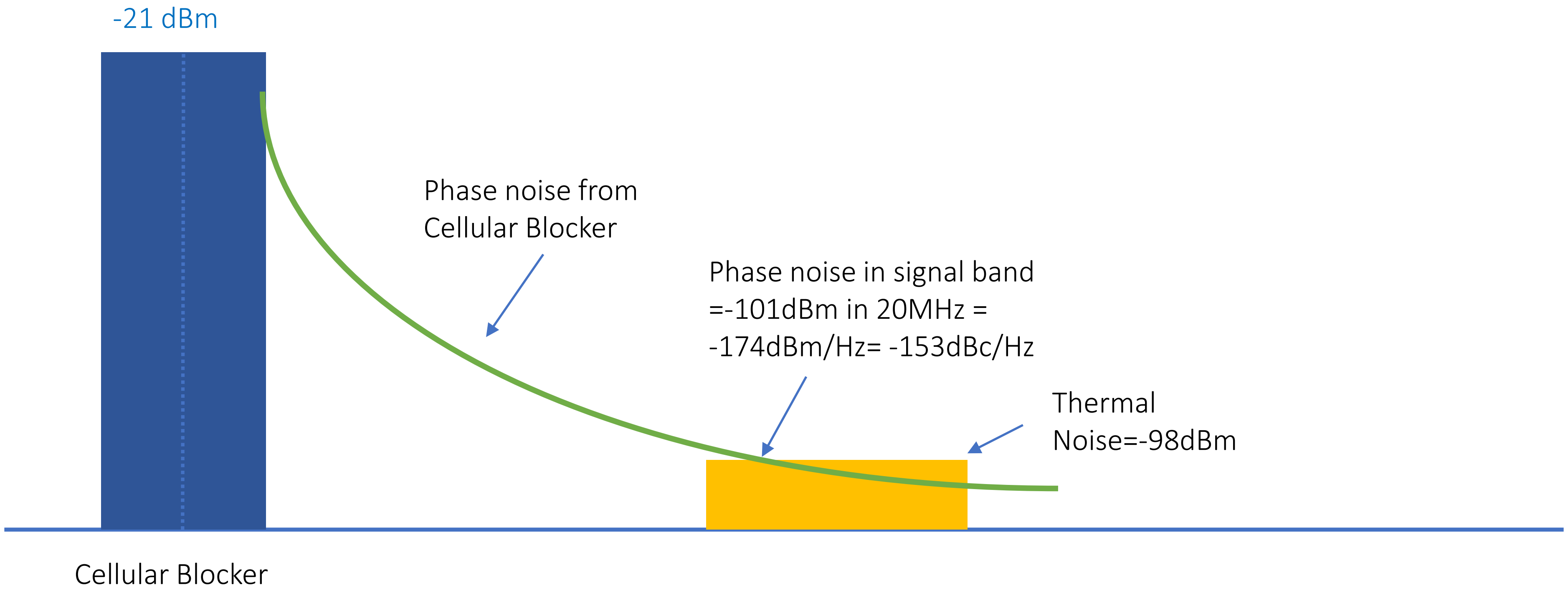
$$IIP_2 = -24dBm + 77dB$$

$$IIP_2 = +53dBm$$



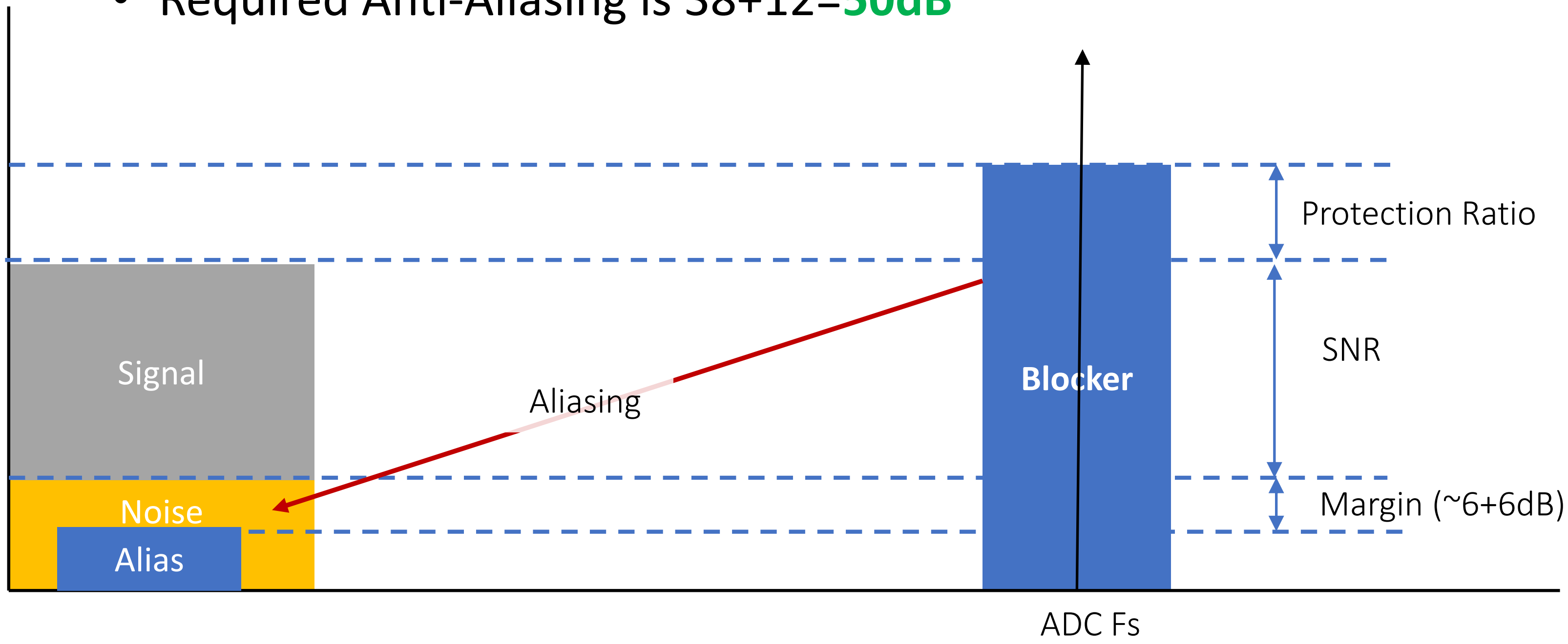
Out-of-Band Blocker: Reciprocal Mixing

- 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.

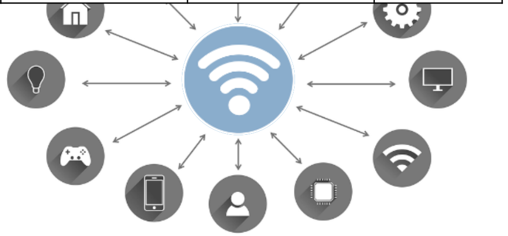


ADC Anti-Aliasing

- 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 64QAMr¾ is 23dB, Adjacent Protection ratio is -1dB
- Required Anti-Aliasing is 38+12=**50dB**



Data Rate (Mbps)	SNRMIN* (dB)	Adjacent Protection Ratio	Alternate Protection Ratio	SNR+PR
6	4	16	32	**20**
9	5	15	31	**20**
12	7	13	29	**20**
18	9	11	27	**20**
24	13	8	24	**21**
36	16	4	20	**20**
48	20.5	0	16	**20.5**
54	22	-1	15	**21**



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.

TX EVM

- 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 64QAMR¾

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

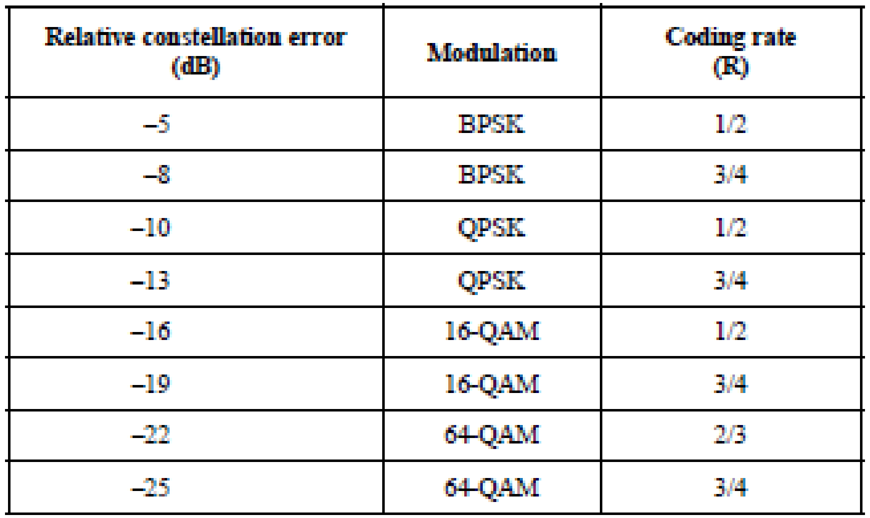


Table 17-12—Allowed relative constellation error versus data rate

Relative constellation error (dB)	**Modulation**	**Coding rate (R)**
–5	BPSK	1/2
–8	BPSK	3/4
–10	QPSK	1/2
–13	QPSK	3/4
–16	16-QAM	1/2
–19	16-QAM	3/4
–22	64-QAM	2/3
–25	64-QAM	3/4

TX ACPR

- Two tone test can approximate ACPR farily accurately
- With this assumption, TX ACPR directly translates to OIP_3: $OIP_3 = P_{out} + \Delta P/2$
- For Pout=+20dBm (=17dBm each tone)and ΔP=27dBc (3dB margin) we have
  - OIP3=+30.5dBm
- Note this is easier than the linearity required for EVM at high data rates, but more difficult for low data rates.

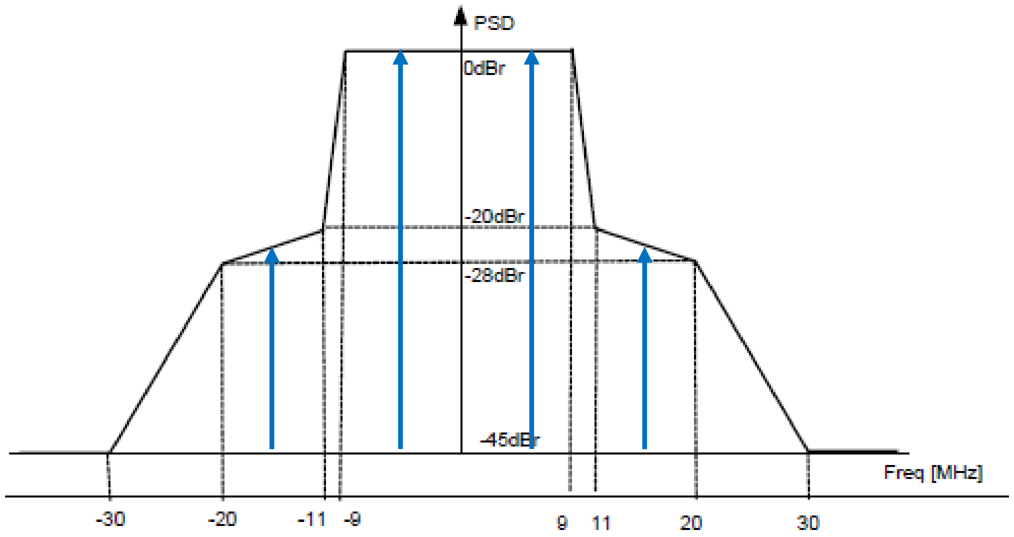
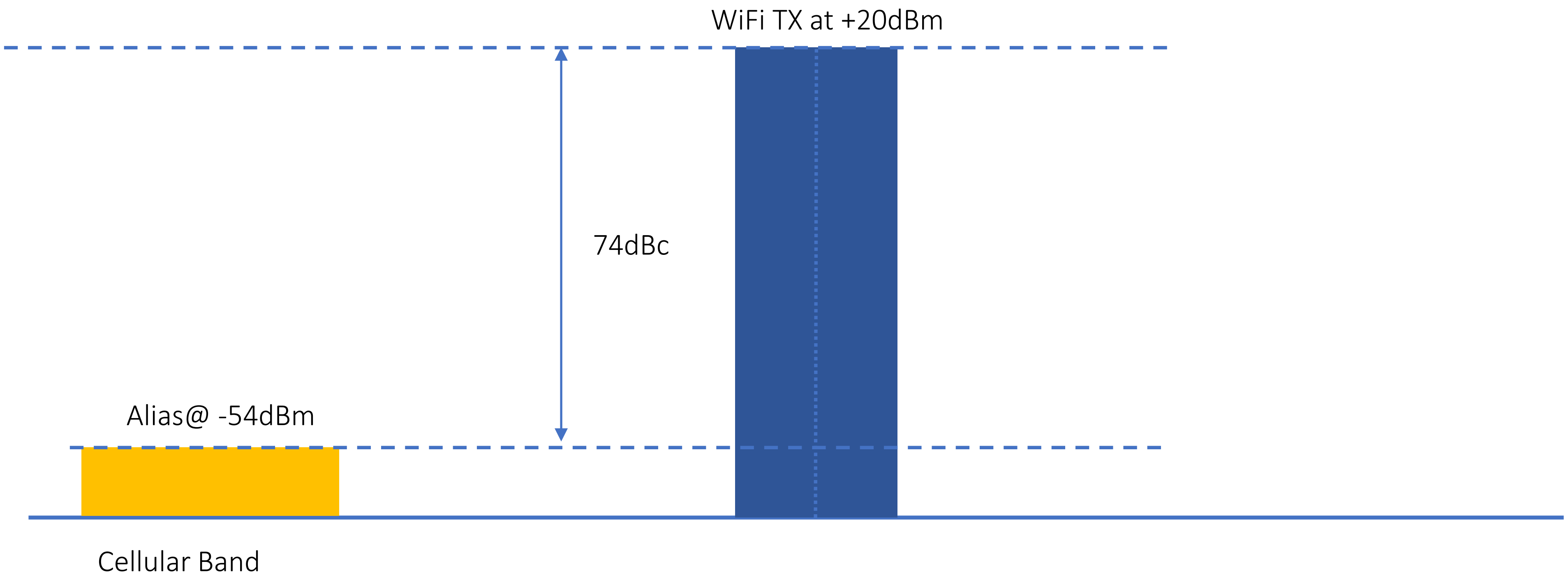


Figure 20-17—Transmit spectral mask for 20 MHz transmission

DAC Anti-Aliasing

- 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)



WiFi TX at +20dBm

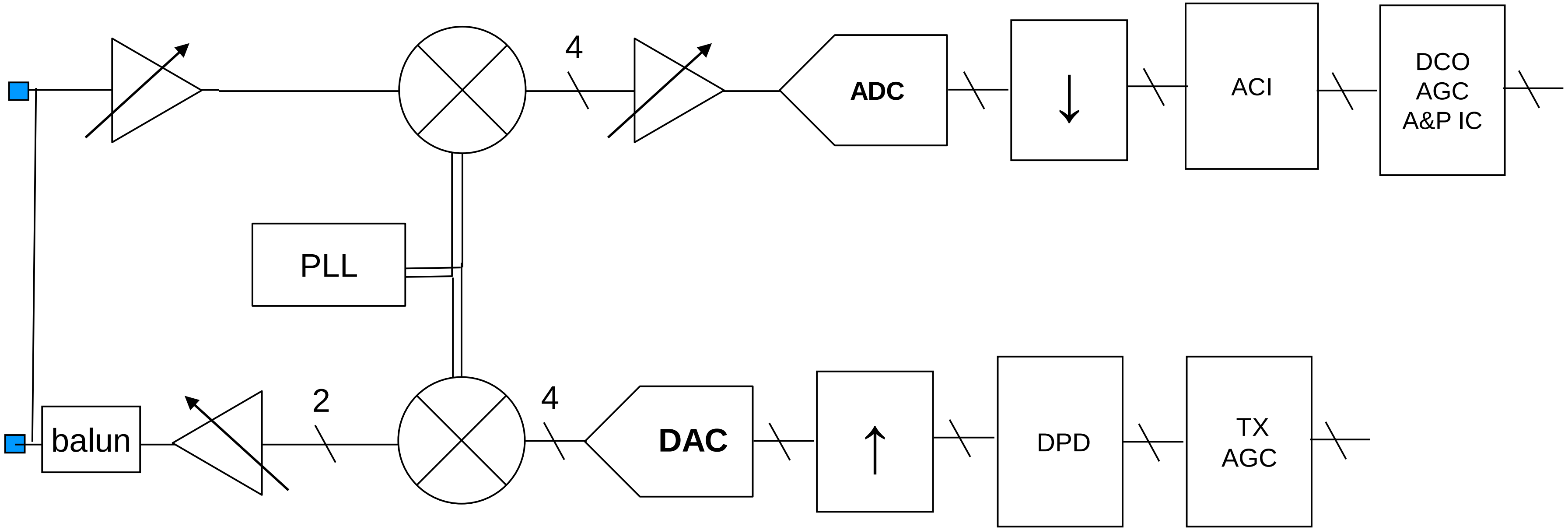
74dBc

Alias@ -54dBm

Cellular Band

Transceiver Architecture

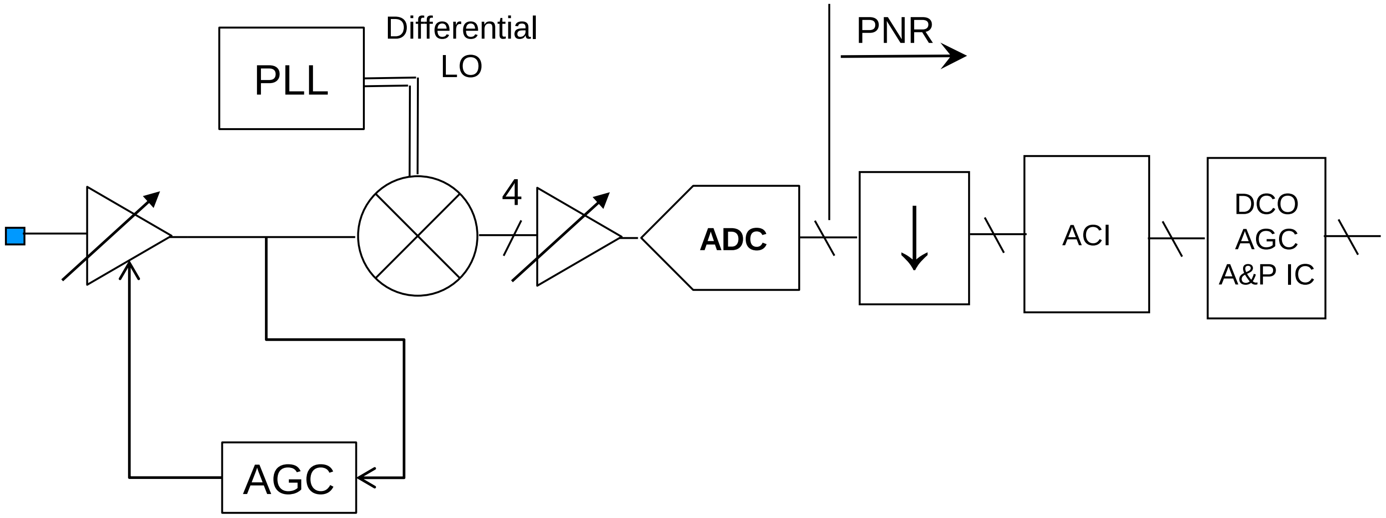
Architecture



- 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.



Spec	Target
NF	3dB (+1dB T/R SW)
IIP2	+53dBm
LO Spot Phase Noise	-153dBc/Hz @ 100MHz offset
ADC DR	49dB
AA Filtering	50dB

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

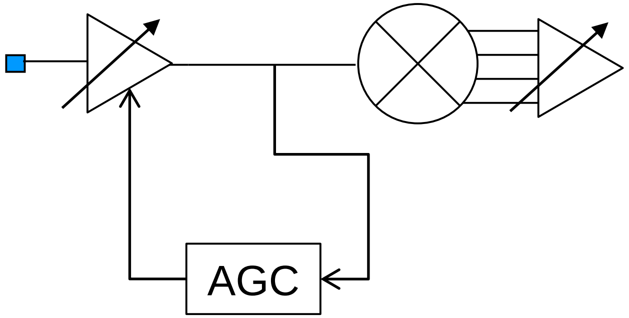
- Main advantage is that Differential LNA enables Differential ***mixer***
  - Differential Mixer has significantly improved IIP_2
  - IIP_2 specs are challenging if WiFi needs to Coexist with Cellular Signals.
  - WiFi Receiver must only de-sense 1dB when subjected to a -20dBm Cellular blocker at ~100MHz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

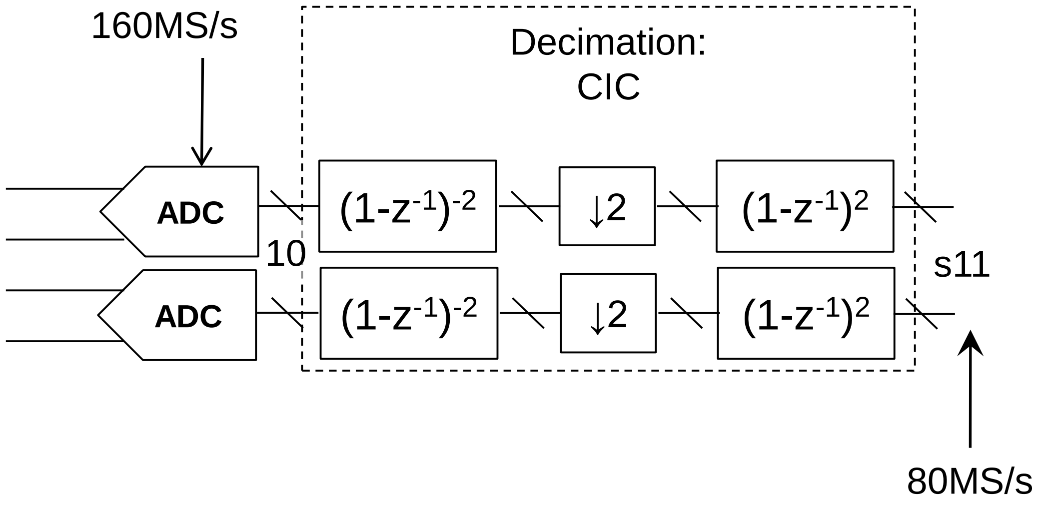
- Quasi-Differential LNA-Mixer. Upconverted Impedance to give minimum 12dB filtering of OOB blockers.
- Two sets of Differential Quadrature outputs, combined by ADC gm
- Wideband match required due to integration of T/R switch
- *Power down mode such that PA swing does not damage LNA transistors.*



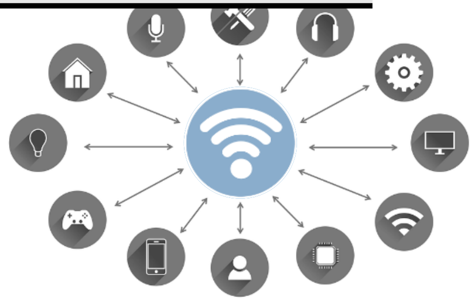
Parameter	Spec
Max Gain	15dB
Gain Step Size	3dB
IIP3 @ Max gain	-10dBm
IIP2@ Max Gain	+53dBm
OOB filtering @ LNA output	>12dB
Power Down current	<10uA
RX turn-on Time	3ms

ADC and 1st Decimation

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

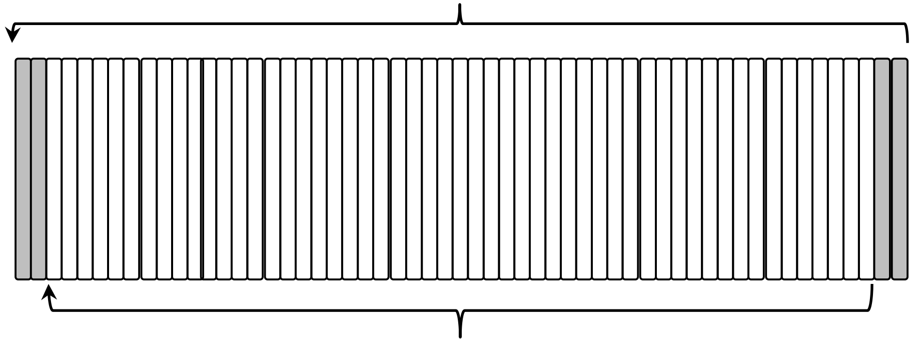


Parameter	Spec
# Physical bits	8 bits
Sampling	160MS/s
ENOB in 20MHz	9 bits
Nominal BW	Two poles @ 15MHz
OIM3(adjacent)	+50dBc
Total Current	4mA
Power Down Current	<1uA



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.***



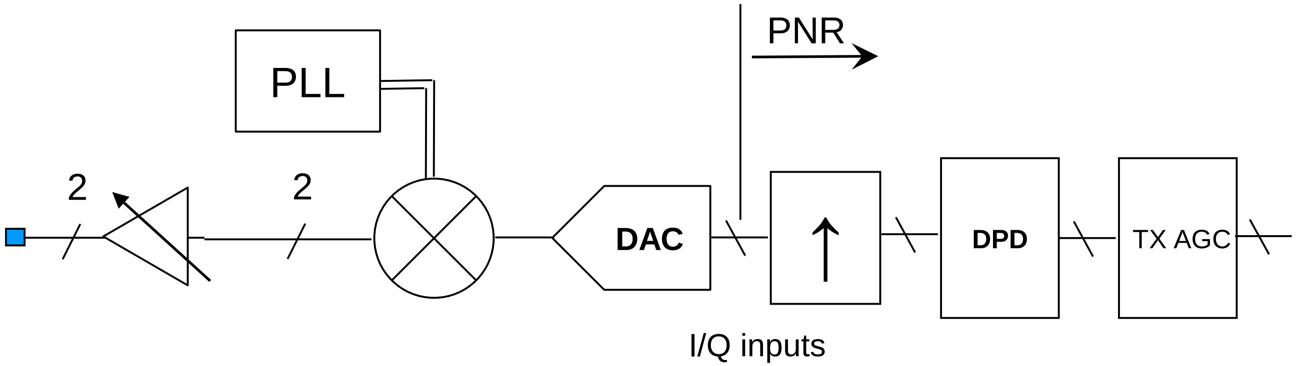
56 Carriers in 802.11n=17.87MHz

52 Carriers in 802.11g=16.6MHz

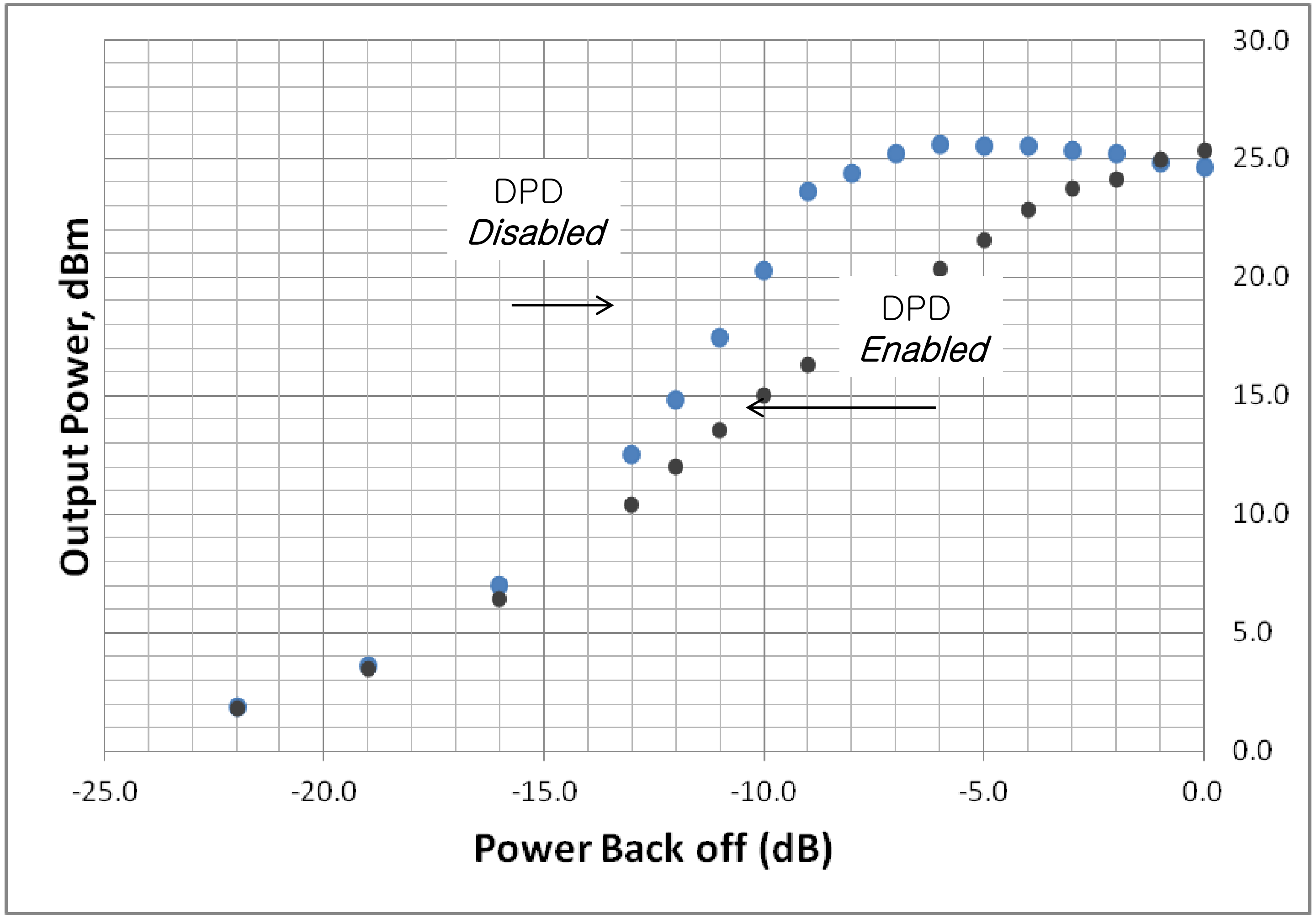
Transmitter Architecture

- 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.*

Parameter	Spec
PA Gain	24dB
Gain Step Size	3dB
Psat @ Max Gain	+26dBm
EVM@+18dBm	-28dB
ACPR @+18dBm	-28dB
Output OOB noise @+18dBm	-123dBm/Hz
I/Q phase balance	<0.2º
TX 10-90 turn-on Time	2ms

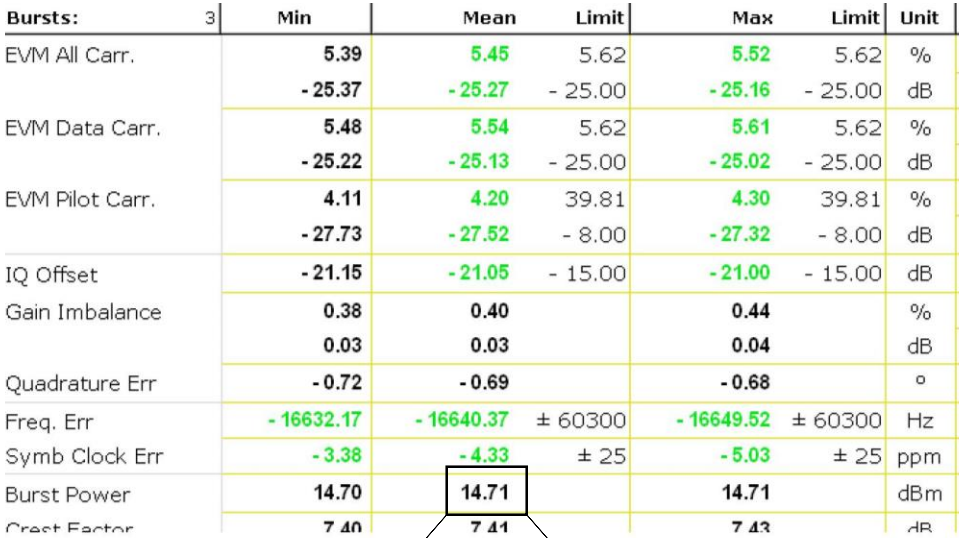


Impact Of DPD: Single Tone



Impact of DPD: Modulated signals

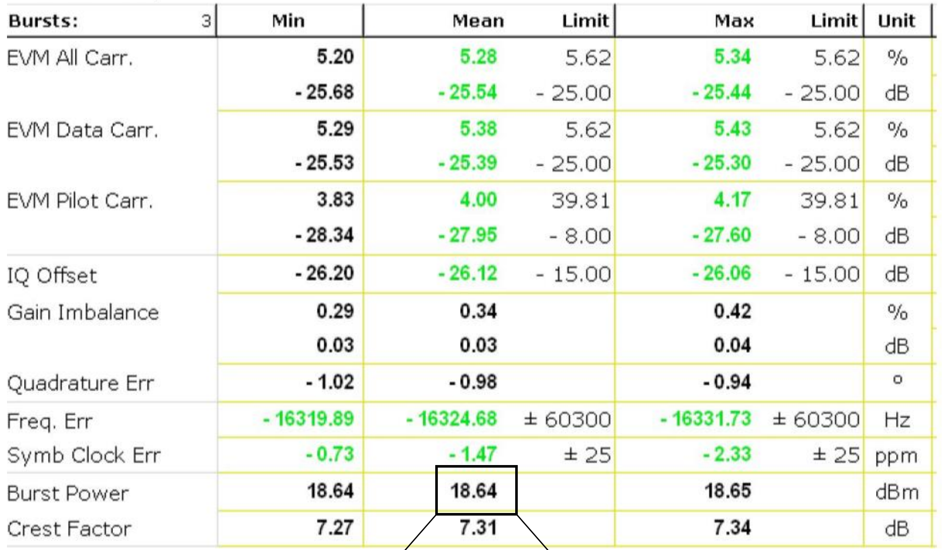
DPD Disabled



Bursts: 3	Min	Mean	Limit	Max	Limit	Unit
EVM All Carr.	5.39	5.45	5.62	5.52	5.62	%
	-25.37	-25.27	-25.00	-25.16	-25.00	dB
EVM Data Carr.	5.48	5.54	5.62	5.61	5.62	%
	-25.22	-25.13	-25.00	-25.02	-25.00	dB
EVM Pilot Carr.	4.11	4.20	39.81	4.30	39.81	%
	-27.73	-27.52	-8.00	-27.32	-8.00	dB
IQ Offset	-21.15	-21.05	-15.00	-21.00	-15.00	dB
Gain Imbalance	0.38	0.40		0.44		%
	0.03	0.03		0.04		dB
Quadrature Err	-0.72	-0.69		-0.68		°
Freq. Err	-16632.17	-16640.37	± 60300	-16649.52	± 60300	Hz
Symb Clock Err	-3.38	-4.33	± 25	-5.03	± 25	ppm
Burst Power	14.70	14.71		14.71		dBm
Crest Factor	7.40	7.41		7.43		dB

+14.7dBm

DPD Enabled



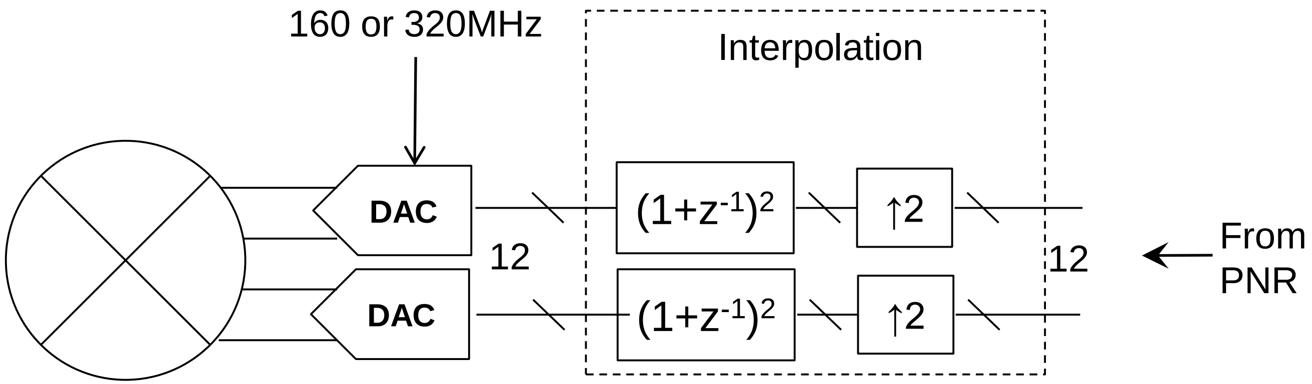
Bursts: 3	Min	Mean	Limit	Max	Limit	Unit
EVM All Carr.	5.20	5.28	5.62	5.34	5.62	%
	-25.68	-25.54	-25.00	-25.44	-25.00	dB
EVM Data Carr.	5.29	5.38	5.62	5.43	5.62	%
	-25.53	-25.39	-25.00	-25.30	-25.00	dB
EVM Pilot Carr.	3.83	4.00	39.81	4.17	39.81	%
	-28.34	-27.95	-8.00	-27.60	-8.00	dB
IQ Offset	-26.20	-26.12	-15.00	-26.06	-15.00	dB
Gain Imbalance	0.29	0.34		0.42		%
	0.03	0.03		0.04		dB
Quadrature Err	-1.02	-0.98		-0.94		°
Freq. Err	-16319.89	-16324.68	± 60300	-16331.73	± 60300	Hz
Symb Clock Err	-0.73	-1.47	± 25	-2.33	± 25	ppm
Burst Power	18.64	18.64		18.65		dBm
Crest Factor	7.27	7.31		7.34		dB

+18.6dBm

→ *DPD enhances EVM Compliant Output power by 4dB*

DAC and Digital Interface

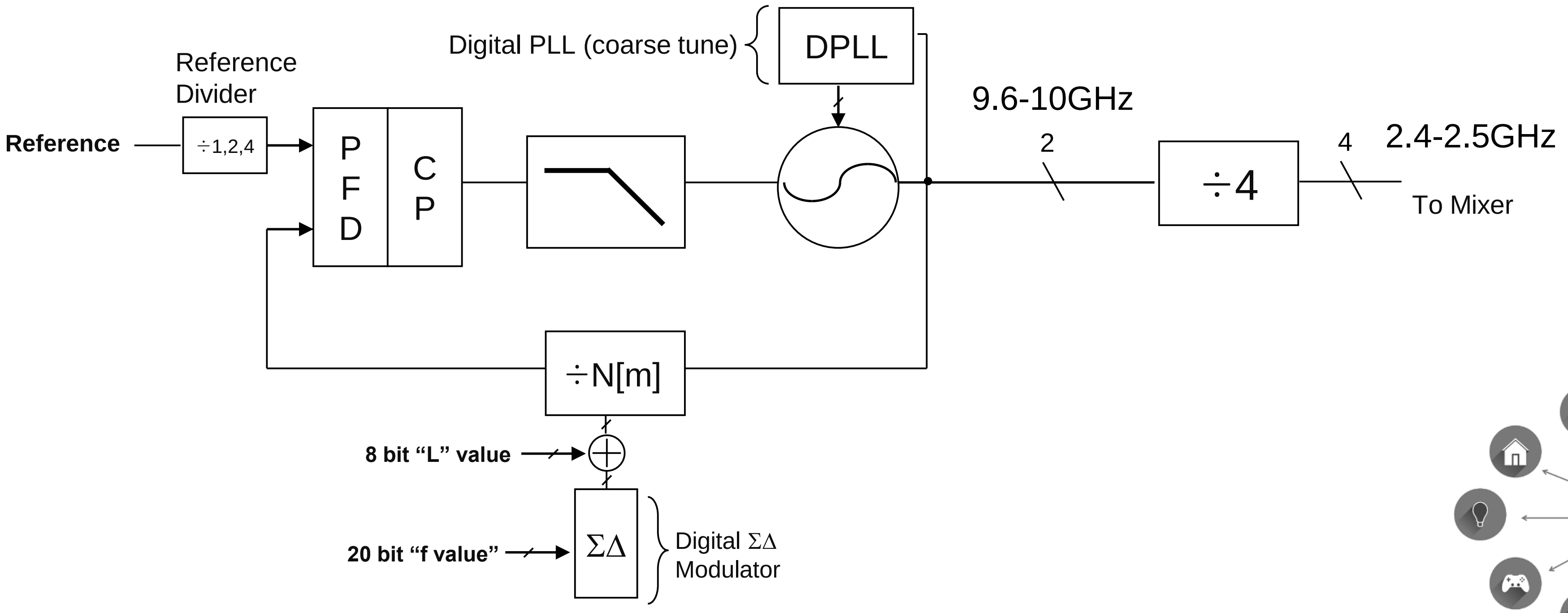
- Differential 12-bit Current steering DAC
- 2 Passive poles at DAC output at 15MHz for anti-aliasing/OOB noise filtering
  - Much Less critical in IoT! No cellular coexistence to worry about.
- Last Stage of Interpolation can be performed by custom logic in legacy CMOS (eg 65nm)
  - Can/Should be done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



Parameter	Spec
# bits	12
Sampling	480-500GS/s
Nominal BW	Two poles @ 15MHz
OIM$_3$ @500mVpp se	50dB
Output Noise @ 200MHz	<2nV/rt(Hz)
Anti-Aliasing	80dB
Max o/p	>700mVppse
Total Current	<20mA
Power Down Current	<10uA

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

The Future

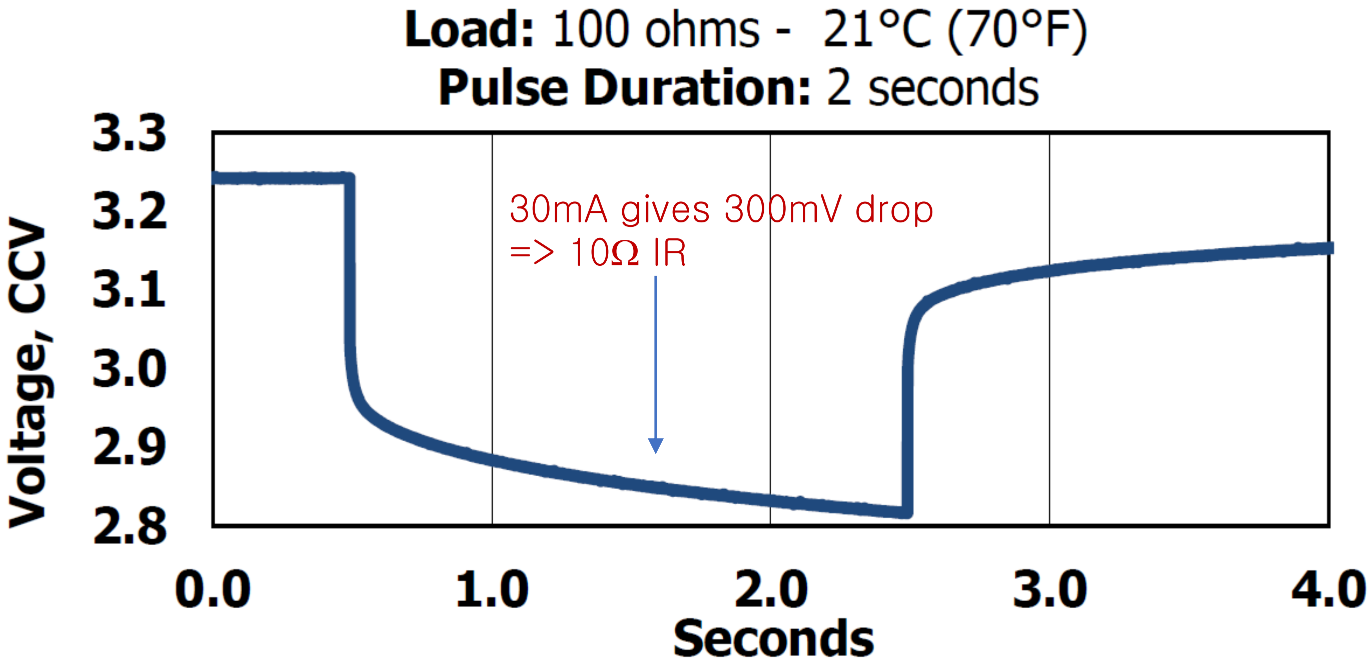
- ~~802.11ah is the Future of IoT WiFi~~
  - Standard is Optimized for IoT devices
  - Uses 900MHz ISM band for ~3x range
  - MAC enhancements to allow huge number of low duty cycle devices

- 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 signficant drop across battery IR



30mA gives 300mV drop
=> 10Ω IR

ENERGIZER CR2032

Specifications

Classification:	"Lithium Coin"
Chemical System:	Lithium / Manganese Dioxide (Li/MnO_2)
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:	-30C to 60C
Self Discharge:	~1% / year