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5 GHz Wi-Fi Transmit Network Tuning

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Overview

This coop term I worked on optimizing Wi-Fi 5GHz network for maximum transmit performance. Wi-Fi transmit performance measurements include Transmit (TX) power, Error Vector Magnitude (EVM), and spectral mask compliance. The performance is measured for 5 example channels in the 5 GHz band across the lowest and highest data rates for 802.11a and n.

EVM is a measure of how accurately a radio is transmitting symbols within its constellation. EVM is a measure of signal quality, which is a function of noise, interfering signals, nonlinear distortion and the load of the radio [1]. EVM is part of the 802.11 IEEE standard which has become industry standard for phones, television and Wi-Fi. It essentially is shows linearity transmitter accuracy, and how well it can represent the symbol of amplitude phase point in the constellation. This indirectly translates to supporting higher data rates and higher EVM number can support new generation of Wi-Fi.

Table 1 shows the Wi-Fi Transmit Specification Table that needs to be met by Thunderchild product. Table 1 includes the power level and EVM for various Wi-Fi versions with different data rates and modulation. These specs should be met by products for optimal Wi-Fi performance.

Technology	Data rate	MCS	Modulation	Coding	Power (dBm)	EVM max (dB)
802.11g	6Mbps		BPSK	1/2	13	-5
802.11g	54Mbps		64-QAM	3/4	11	-25
802.11n	7.2Mbps	HT20 MCS0	BPSK	1/2	13	-5
802.11n	72.2Mbps	HT20 MCS7	64-QAM	5/6	9	-27
802.11n	7.2Mbps	HT40 MCS0	BPSK	1/2	12	-5
802.11n	72.2Mbps	HT40 MCS7	64-QAM	5/6	9	-27

Table 1:Wi-Fi 5 GHz TX Spec Table

Objective

The overall objective for this project was to match Thunderchild boards' Wi-Fi TX performance with Wi-Fi TX specifications as shown in Table 1, which are consist with the Qualcomm development board QCA402x.

Wi-Fi RF Schematic and Layout

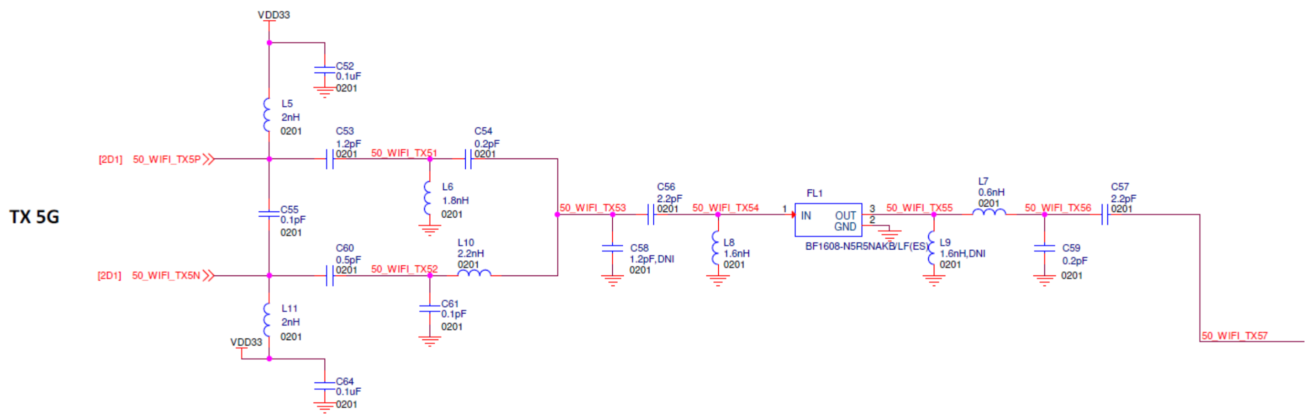


Figure 1: Wi-Fi 5GHz TX Schematic Connected to RF Switch

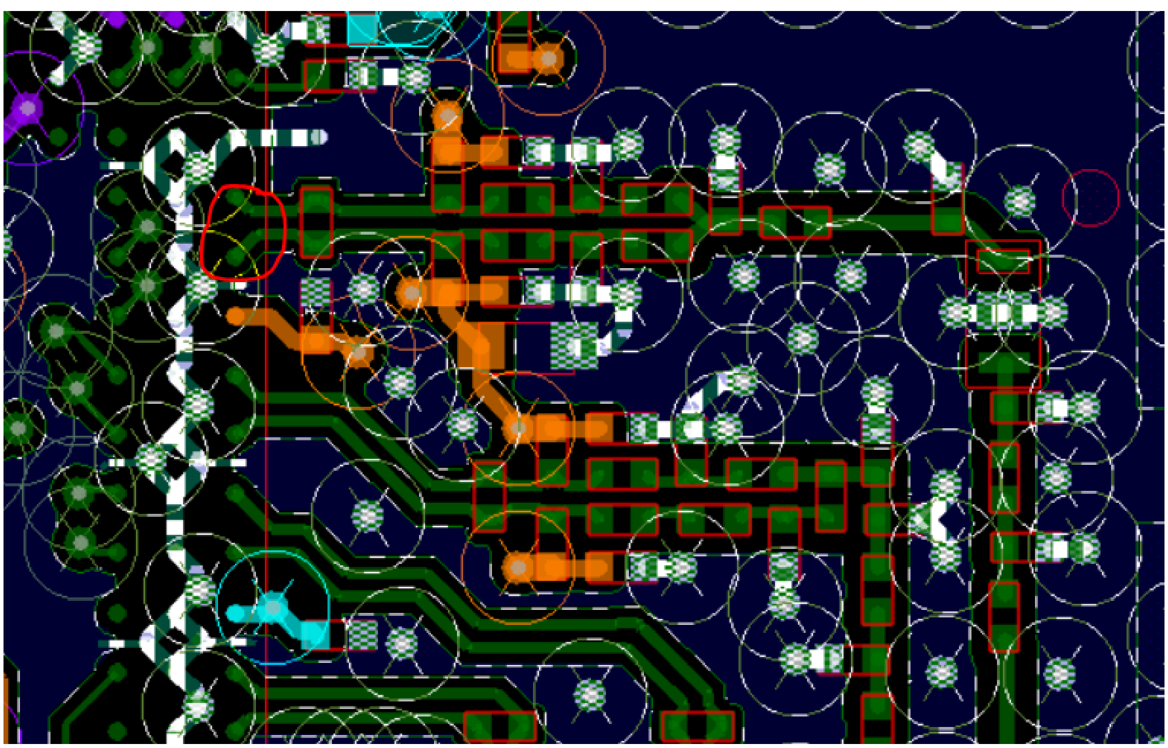


Figure 2: PCB Layout of 5GHz Wi-Fi TX Path from Chip circled in Red

The original design as shown in the above schematic Figure 1 was drawn from the reference design from Qualcomm. This design was used in current board but did not provide good results with failing EVM and low power level.

The optimal way to increase the 5GHx Tx performance is by analyzing the topology, components and corresponding values. Since topology was mainly fixed on this version of the board shown in PCB layout Figure 2, the components and associated values needed to be changed.

The general topology of RF matching network consists of the following blocks coming from the chip:

- Balun- provides single-ended to differential conversion.
- Lowpass filter section- supresses harmonics and spurious emissions.
- Impedance transformation section- matches correct impedance to antenna feed.

The tuning exercise was limited by the information presented in layout guidelines from Qualcomm. This included the original topology selection, trace width selection, use of microstrip/co-planar, layer thickness, geometry, and track length matching of the nets. Results from advanced simulation software (ADS, HFSS, etc.) or internal chip design details from Qualcomm were not shared with us for this project as well.

Tuning using QUACS Simulation and Trial-Error

Simulation 1: Balun

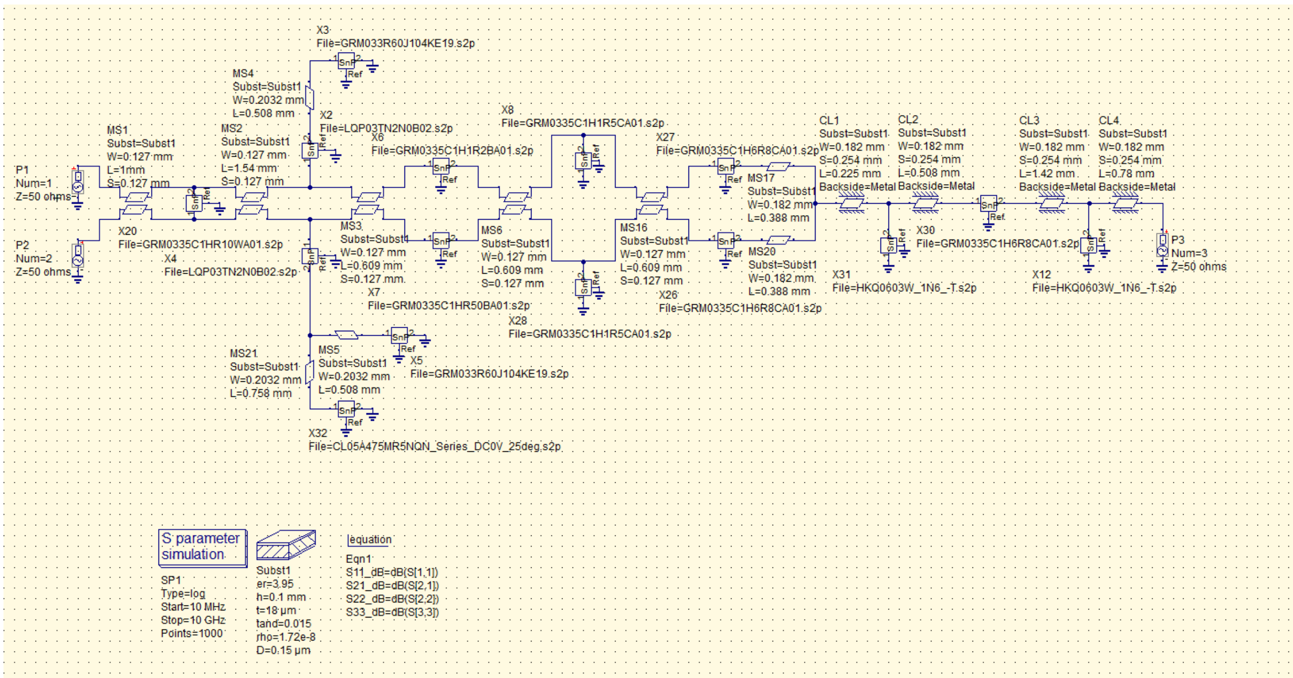


Figure 3: Balun Simulation Topology in QUACS

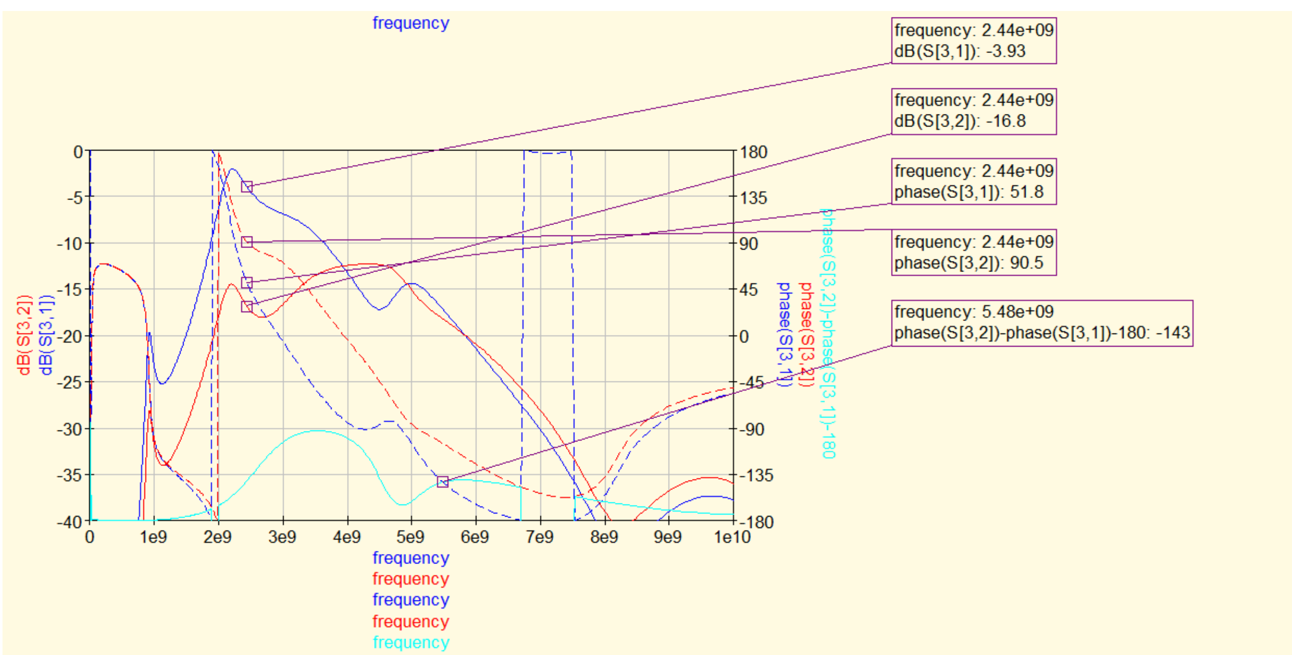


Figure 4: Balun Frequency Response

The simulation that was done in Figure 3 is for the balun, which consist of high and low pass filters which is initial guide where changes should be applied. This is good starting point since its closest to the input pins of the chip, thus having the greatest impact. The balun is selected to provide a single-ended to differential conversion function with minimal insertion loss over the frequency band of interest. The simulation is for the PCB layout of the balun consists of input and output ports with impedance values, component S-parameter values, co-planar track width/space/length values, and substrate value. Using open-source free QUACS software, an accurate layout of the balun was created and simulated. As seen in the frequency (GHz) vs power(dB) plot in Figure 4, there is not much to learn from simulation since the correct port impedance values are unknown, making it very difficult to match to. The optimum impedance at the various points along the track is also not known as that information is not provided by the Qualcomm documentation. The reason for doing the entire balun simulation was to compare the frequency response match for the high pass and low pass arms. Theoretically, the upper arm is supposed to have +90 degree phase shift and the lower arm with -90 degree phase shift. The difference between phase shifts of the arms is expected to be 180 degree. As shown in Figure 4, at frequency 5.48 GHz, the phase is -143 degrees, which is not consistent with the balun topology. The only important line in the plot is the s31 and s32, which is the loss from the positive pin to the 50 ohm port and the negative pin to the 50 ohm port. The plots just show very high loss, which cannot be used to determine changes to any component values. The plot results turned out to be very random and so the result cannot be actionable changes. The problem is that the real port impedance is not 50 ohms which is why the simulation does not work. One of the caveats with doing simulation is that the impedance at the ports are not known. Port 3 (RF Switch which connects to the antenna) should be 50 ohms but there is no information available on the impedance values of port 1 and port 2 inside the chip to match to. Port 1 and 2 are the input TX and RX pins connected to Wi-Fi portion of the Qualcomm chip. Any internal chip simulation results are unknown, making the tuning even more difficult. Thus, this simulation is not useful as the source we are matching to is not 50 ohms. Since source impedance is unknown, there is no way of optimizing the loss very well because mismatch loss is also unknown. An option of getting port 1 and port 2 impedance values is by measuring using two pigtails to find the s11 and s22 of the ports directly. This was not possible since a 6 GHz VNA instrument or RF calibrated probe was not available to us at the time and due to other mechanical constraints of the board. Even with pigtail results, getting the simulation to align with the measurement would be difficult due to high error from parasitic capacitance, inductance of components and pigtail tip interface to the board track changing the values each time. However, this simulation is considered a good starting point in going forward with the rest of tuning steps.

Results shown in Figure 9 and 10 is tuning steps using various component values. The strategy for optimizing the balun was to start replacing component values with 10 percent increment and decrements from left to right on layout. That means components closest to the chip were altered first based on 10 percent change rule and the best measured value was kept. As seen from Figure 9, at tune step 18, we were able to match the balun to highest possible power level and EVM while keeping current under 220 mA. The power level was at an average of 8.6 dBm, -28.2 EVM and 170 mA current. This was achieved through sheer hard work of trial and error while keeping simulations results in mind.

Simulation 2 : Band Pass Filter Section

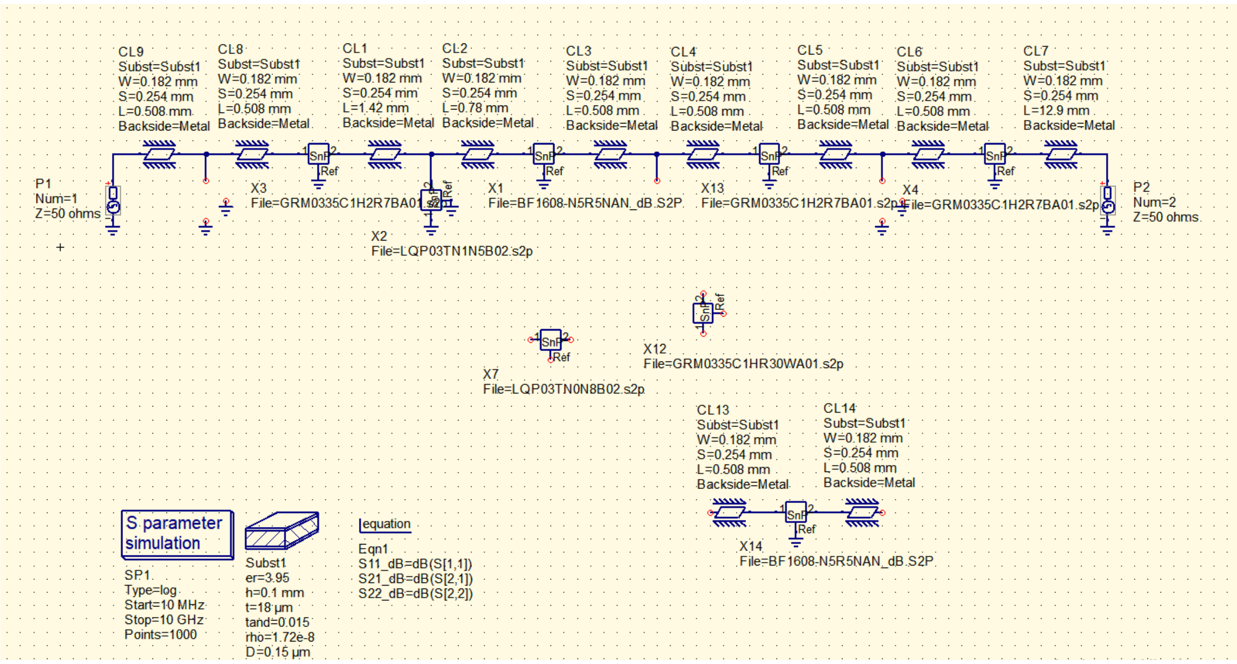


Figure 5: Original Band Pass Filter Section Topology in QUACS

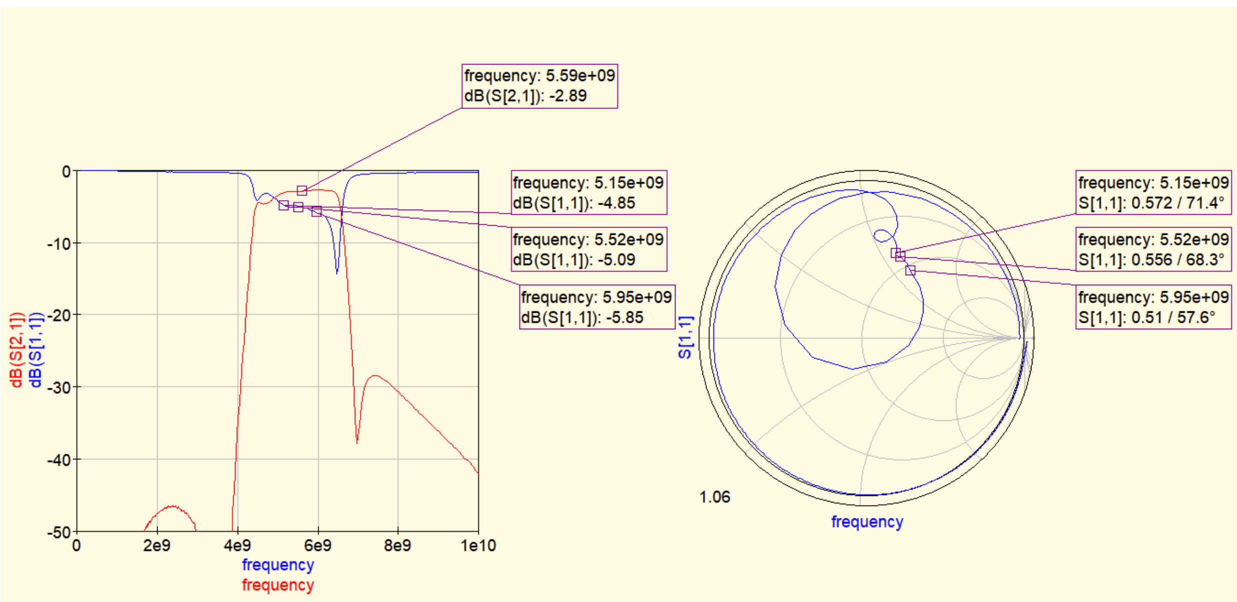


Figure 6: Frequncy Response and Smith Chart for Band Pass Filter Section

After correcting the balun, the next section to optimize is the filtering section shown in Figure 5. The lowpass filter network is designed to attenuate the TX harmonics and spurious emissions below the level required to meet applicable regulatory standards. If the selected filter provides acceptable attenuation of the harmonic signal energy and reasonable insertion loss, it is a "good" filter [2]. This was started by setting up the simulation of the filtering and impedance matching section of the Wi-Fi TX path. This includes the track from the exit of the balun through the matching filter and out to the 50 ohm RF switch. It is reasonable to assume that the end of balun (Port 1) in the simulation is 50 ohm and the RF switch (Port 2) is 50 ohm impedance since it ends up going to the antenna and at that point matching is typically done.

Figure 6 shows the results of the original filtering topology as per schematic diagram. As seen from the plots, the s11 is around -5 dB and s21 is -2.89 dB, which shows that the throughput loss / reflection is minimized. However, the Smith Chart shows that this topology is not matched to 50 ohm characteristic impedance since the s11 frequency points are not clustered at the centre.

In order to try to cluster the frequency points to centre of Smith Chart, further simulation was performed by removing shunt inductor L8. The simulation showed adding a shunt inductor moves the current point on the Smith Chart in counter-clockwise direction along the Ycircle. Smith Chart in Figure 6 shows the clustered points are in top-right side and so removing the shunt inductor would mean shifting the clustered points towards the centre in a clockwise direction along the Ycircle.

Simulation 3: Shunt Inductor

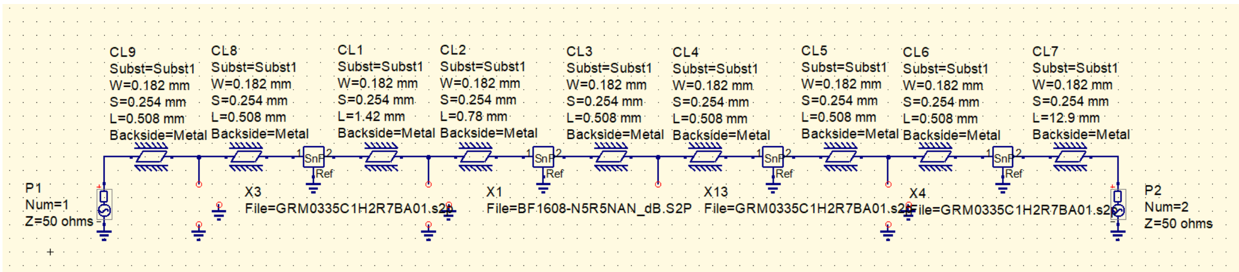


Figure 7: Band Pass Filter ith no Shunt Components

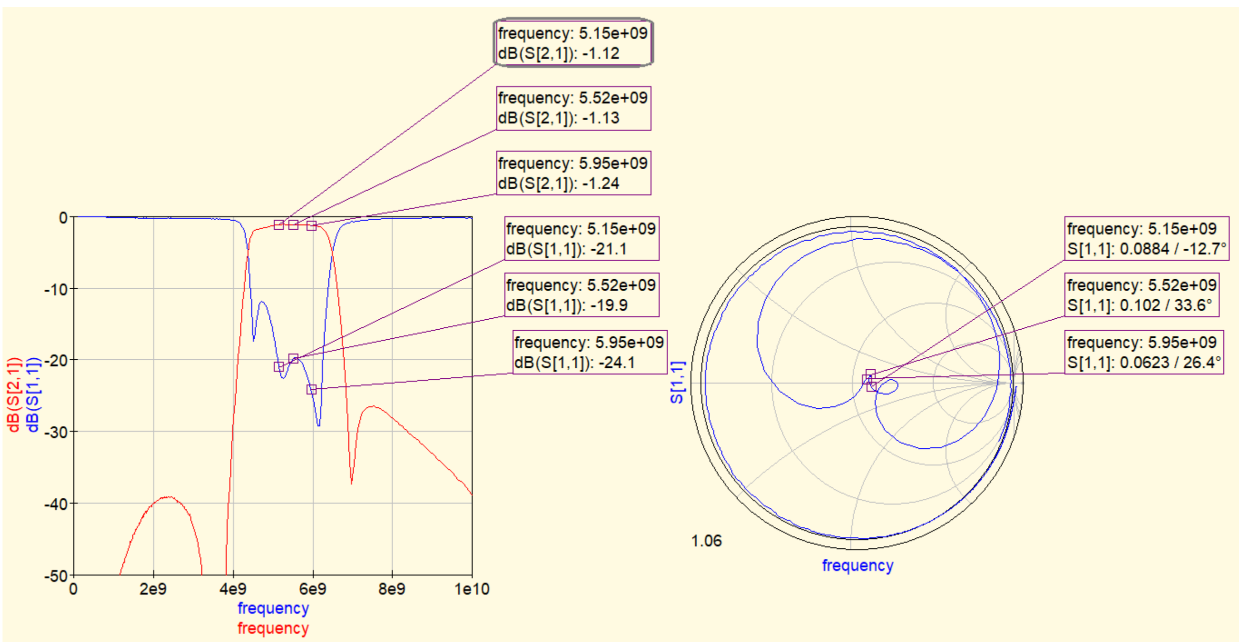


Figure 8: Frequncy Response and Smith Chart for Band Pass Filter Section with no Shunt Components

The goal of simulation in Figure 7 was to centre the clustered points on Smith Chart. This is shown by optimizing s11 and s22, which means minimum s11 and maximum s21 values in the frequency plot, indicating good performance of the Wi-Fi PA at all frequencies. This was achieved in simulation by removing shunt inductor component as described in previous section of this report. As seen in Figure 8 plot, the reflection is -20 dB and pass through loss is -1dB, which is pretty good since the band pass filter (BPF-1608) itself has about 1 dB loss as per data sheet. Furthermore, the power level is flat across the 5GHz band which means it is a good match.

Tuning with Trial Error

Simulation from Figure 7 suggested that this topology and components should be tested on the Thunderchild board. At tune step 57 from Figure 10, we had implemented the above topology and found the results opposing. As seen in step 57, at low frequencies there was poor EVM and power was also not a fit. The measured performance of this topology and components did not match the simulation results. At the low frequencies, there was failing EVM (-23 dB) and high end EVM became reasonable value (-30 dB), creating a large slope across the band. This proved that the impedance from end of balun at port 1 is not 50 ohms since it did not improve the performance and the EVM is not flat across the frequency range. Port 1 was determined to have a large complex component that varies with frequency and it was determined to add the shunt inductor back in after coplanar line (CL1) as per guidelines from Qualcomm design. In this stage after tune step 57, we wanted to make sure that results were flat, good or bad. Based on further simulation and analysing the s21, s11from frequency plots and Smith chart clustered points, it was deduced that the Wi-Fi TX path was designed for inductive load.

Since the source impedance is unknown, the result was starting point for systematic tuning. Ultimately, it was left to trial error of various components from end of balun to RF switch so there is no significant slope in EVM which can lead to current spikes and Wi-Fi spurious emissions.

Trial and error led to final tuning at step 64 shown in Figure 10 and Figure 11, where the results matched closest to Wi-Fi TX specs and Qualcomm development boards. At tune step 64, the average results are power level at 9.4 dBm, -30 dB for EVM, current at 164 mA, and spectral mask passing across all frequencies in the band. This topology and component changes were tested across various boards, which showed very similar results, as indicated in green rows, with tune step 64 labelled in Figure 10.

"T" = Taiyo-Yuden

Board	Tune step	L5L11	C55	C52	C53	C60	L6	C61	C54	L10	C58	C56	L8	L9	L7	C59	C57	Data rate	Power (dE AVG	EVM (dB) AVG	MaskPass All	Current (n AVG	Power 5190	Power 5510	Power 5795	EVM 5190	EVM 5510	EVM 5795	MaskPass 5190	MaskPass 5510	MaskPass 5795	Current 5190	Current 5510	Current 5795
YB617_1D0649		2n0	1p0	0u1	1p0	0p5	1n6	0p1	0p2	2n2	DNI	2p2	1n6	DNI	0n6	0p2	2p2	RATE_MCS_7_40																
YB209_1D0117		1n5	0p1	1u	1p0	0p5	1n8	0p1	0p2	2n2	0p1	0R	1n6	1n6	0n6	0p2	2p2	RATE_MC	9.2	-28.7	TRUE	260.8	8.921	9.36	9.407	-25.927	-30.322	-29.881	TRUE	TRUE	TRUE	260.27662	253.88745	268.15097
YB209_1D0445		1n5	0p1	1u	1p0	0p5	1n8	0p1	0p2	2n2	0p1	0R	1n6	1n6	0n6	0p2	2p2	RATE_MC	9	-28.8	TRUE	255.7	9.293	9.127	8.713	-25.133	-30.032	-31.148	TRUE	TRUE	TRUE	257.88689	249.08709	260.16568
D46	0	2n0	0p1	0u1	1p2	0p5	1n8T	0p1	0p2	2n2T	DNI	2p2	1n6T	DNI	0n6	0p2	2p2	RATE_MC	9.2	-29.5	TRUE	166.5	9.567	9.337	8.72	-30.765	-26.665	-31.197	TRUE	TRUE	TRUE	165.70952	168.84076	164.94161
D46	1	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n2T	DNI	2p2	1n6T	DNI	0n6	0p2	2p2	RATE_MC	8.9	-29.1	TRUE	166.7	9.04	8.947	8.767	-29.127	-26.763	-31.26	TRUE	TRUE	TRUE	165.55742	168.26355	166.23675
D46	2	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n2	DNI	2p2	1n6T	DNI	0n6	0p2	2p2	RATE_MC	8.8	-28.8	TRUE	165.8	9	8.963	8.48	-30.275	-26.149	-30.028	TRUE	TRUE	TRUE	163.98949	168.43917	164.84200
D46	3	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n0	DNI	2p2	1n6T	DNI	0n6	0p2	2p2	RATE_MC	9	-28.6	TRUE	168	8.837	9.524	8.616	-29.263	-26.552	-29.93	TRUE	TRUE	TRUE	165.40997	171.62043	166.93758
D46	4	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	1n8	DNI	2p2	1n6T	DNI	0n6	0p2	2p2	RATE_MC	9	-28	TRUE	167.8	8.827	9.394	8.667	-27.595	-26.863	-29.419	TRUE	TRUE	TRUE	167.37216	168.28984	167.83563
D46	5	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n4	DNI	2p2	1n6T	DNI	0n6	0p2	2p2	RATE_MC	9.4	-28	TRUE	167.8	9.113	9.713	9.287	-28.166	-25.665	-30.106	TRUE	TRUE	TRUE	165.69307	170.91303	166.75895
D46	6	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n0	DNI	2p2	1n6	DNI	0n6	0p2	2p2	RATE_MC	9.1	-30	TRUE	166.5	9.07	9.34	8.824	-32.578	-26.463	-30.831	TRUE	TRUE	TRUE	162.40216	170.13956	167.04870
D46	7	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	9	-29.5	TRUE	166.3	9.19	8.967	8.763	-31.195	-27.165	-30.225	TRUE	TRUE	TRUE	164.40245	167.79168	166.79841
D46	8	1n8	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	9.3	-26.8	TRUE	170.6	9.35	9.677	8.943	-25.297	-26.232	-28.966	TRUE	TRUE	TRUE	173.69947	169.52927	168.49302
D46	9	2n2	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	8.8	-27.9	TRUE	165.6	8.45	9.163	8.76	-27.731	-25.833	-30.025	TRUE	TRUE	TRUE	158.74102	170.40007	167.65666
D46	10	2n0	DNI	0u1	1p2	0p5	1n8	0p1	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	9.2	-25.5	TRUE	180	9.048	9.33	9.354	-23.9	-25.4	-27.164	TRUE	TRUE	TRUE	185.277	173.18967	181.67305
D46	11	2n0	0p2	0u1	1p2	0p5	1n8	0p1	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	8.7	-27.6	TRUE	165.2	8.584	8.77	8.61	-25.349	-26.998	-30.364	TRUE	TRUE	TRUE	159.33191	168.21810	167.93211
D46	12	2n0	0p1	1p5	1p2	0p5	1n8	0p1	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	8.8	-28.4	TRUE	167.8	8.827	8.88	8.794	-28.656	-27.065	-29.494	TRUE	TRUE	TRUE	167.13572	167.59086	168.74696
D46	13	2n0	0p1	1p5	1p5	0p5	1n8	0p1	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	7.2	-30.8	TRUE	168.5	8.5	8.89	4.259	-26.593	-26.829	-38.942	TRUE	TRUE	TRUE	170.90630	168.92290	165.61816
D46	14	2n0	0p1	0u1	1p0	0p5	1n8	0p1	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	9.2	-28.6	TRUE	168.9	9.25	9.47	8.86	-29.365	-27.164	-29.294	TRUE	TRUE	TRUE	167.33020	170.15516	169.25775
D46	15	2n0	0p1	0u1	0p8	0p5	1n8	0p1	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	9.3	-28.7	TRUE	169.1	8.837	9.557	9.637	-30.161	-26.524	-29.325	TRUE	TRUE	TRUE	164.56712	169.92833	172.81417
D46	16	2n0	0p1	0u1	1p0	0p4	1n8	0p1	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	8.8	-28.2	TRUE	168.8	9.25	8.69	8.573	-25.1	-29.095	-30.501	TRUE	TRUE	TRUE	175.68643	164.00620	166.60615
D46	17	2n0	0p1	0u1	1p0	0p6	1n8	0p1	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	9.3	-28.9	TRUE	168.6	9.1	9.51	9.157	-31.412	-25.995	-29.16	TRUE	TRUE	TRUE	164.22986	171.54820	170.07917
D46	18	2n0	0p1	0u1	1p0	0p5	1n6	0p1	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	8.6	-28.2	TRUE	169.9	8.727	8.564	8.55	-27.829	-27.175	-29.661	TRUE	TRUE	TRUE	170.74446	168.75558	170.24400
D10	0	2n0	0p1	0u1	1p2	0p5	1n8T	0p1	0p2	2n2T	DNI	2p2	1n6T	DNI	0n6	0p2	2p2	RATE_MC	9.2	-30	TRUE	166.9	9.154	9.47	8.83	-29.422	-27.764	-32.748	TRUE	TRUE	TRUE	166.16146	169.09320	165.55252
D10	19	2n0	0p1	0u1	1p0	0p5	2n0	0p1	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	8.9	-30.3	TRUE	167.9	8.96	8.96	8.631	-29.032	-28.729	-33.061	TRUE	TRUE	TRUE	168.55156	168.2008	167.09052
D10	14	2n0	0p1	0u1	1p0	0p5	1n8	0p1	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	8.6	-30.5	TRUE	168.3	8.847	8.583	8.48	-29.965	-28.754	-32.928	TRUE	TRUE	TRUE	168.17783	168.41234	168.4331
D10	20	2n0	0p1	0u1	1p0	0p5	2n2	0p1	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	8.7	-28.1	TRUE	169.1	8.773	8.327	8.857	-30.028	-29.464	-24.76	TRUE	TRUE	TRUE	165.59506	166.19187	175.58606
D10	21	2n0	0p1	0u1	1p0	0p5	2n0	0p1	0p2	2n4	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	8.9	-30.1	TRUE	167.7	8.773	9.108	8.803	-29.966	-27.095	-33.09	TRUE	TRUE	TRUE	166.88535	169.40305	166.92895
D10	22	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	8.8	-30	TRUE	169.2	8.834	8.639	9.027	-29.462	-29.727	-30.955	TRUE	TRUE	TRUE	168.96743	167.10667	171.42850
D10	22 tightened	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	9	-30.9	TRUE	165.7	8.88	9.097	8.947	-30.323	-29.717	-32.598	TRUE	TRUE	TRUE	164.40930	165.49777	167.22562
D10	23	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p3	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	8.9	-27.2	TRUE	173.5	8.29	9.572	8.7	-28.952	-27.163	-25.495	TRUE	TRUE	TRUE	162.08746	174.40386	184.00905
D10	24	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p1	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	9.3	-29.1	TRUE	170.2	9.177	9.57	9.026	-25.533	-29.781	-31.958	TRUE	TRUE	TRUE	179.22636	165.44630	166.01805
D10	25	2n0	0p1	0u1	1p0	0p5	2n0	0p3	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	9.1	-29.7	TRUE	166.8	8.67	9.333	9.207	-29.57	-30.857	-28.564	TRUE	TRUE	TRUE	163.62966	165.42690	171.44255
D10	26	2n0	0p1	0u1	1p0	0p5	2n0	0p3	0p3	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	8.9	-25.8	TRUE	174.2	8.317	9.487	8.913	-28.549	-26.927	-22.067	TRUE	TRUE	TRUE	165.85427	176.66334	180.03141
D10	27	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	1p8	1n5	DNI	0n6	0p2	2p2	RATE_MC	8.9	-30.9	TRUE	165.4	8.573	9.419	8.677	-29.795	-29.631	-33.136	TRUE	TRUE	TRUE	164.39641	166.19420	165.65729
D10	28	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n6	0p2	2p2	RATE_MC	9.3	-30.4	TRUE	167	9.153	9.513	9.23	-30.033	-29.55	-31.624	TRUE	TRUE	TRUE	163.37706	167.00147	170.65475
D10	29	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	0p1	2p7	1n5	DNI	0n6	0p2	2p2	RATE_MC	9.2	-30.1	TRUE	166.8	9.023	9.04	9.463	-29.423	-28.663	-32.097	TRUE	TRUE	TRUE	161.82428	168.44150	170.27329
D10	30	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	0p2	2p7	1n5	DNI	0n6	0p2	2p2	RATE_MC	9.1	-29.7	TRUE	168.9	8.978	9.457	8.883	-30.455	-27.366	-31.332	TRUE	TRUE	TRUE	164.73822	173.46670	168.55175
D10	31	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	3n9	2p7	1n5	DNI	0n6	0p2	2p2	RATE_MC	9.3	-30.1	TRUE	169.4	9.57	9.37	8.88	-25.999	-31.644	-32.651	TRUE	TRUE	TRUE	176.64745	164.35524	167.12982
D10	32	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	3n3	0n6	0p2	2p2	RATE_MC	9.2	-30.4	TRUE	166.1	9.216	9.417	8.96	-29.729	-29.986	-31.576	TRUE	TRUE	TRUE	165.15713	165.27496	167.98646
D10	33	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	2n2	0n6	0p2	2p2	RATE_MC	9.1	-30.6	TRUE	165.5	8.9	9.527	8.923	-29.949	-29.897	-31.952	TRUE	TRUE	TRUE	164.44156	164.98786	166.95862
D10	34	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	1n5	0n6	0p2	2p2	RATE_MC	9.2	-30.4	TRUE	167.7	9.083	9.458	9.159	-30.197	-29.894	-31.047	TRUE	TRUE	TRUE	165.58501	166.44443	170.93011
D10	35	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n8	0p2	2p2	RATE_MC	9.2	-30.6	TRUE	166.6	9.141	9.174	9.17	-30.397	-29.959	-31.484	TRUE	TRUE	TRUE	165.45762	165.03264	169.40316
D10	36	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	1n0	0p2	2p2	RATE_MC	9.6	-30.4	TRUE	171.6	9.71	9.49	9.473	-30.533	-30.033	-30.489	TRUE	TRUE	TRUE	170.48691	168.7303	175.56185
D10	37	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0R	0p2	2p2	RATE_MC	8.9	-30.4	TRUE	166.8	8.881	8.93	8.957	-29.907	-29.898	-31.444	TRUE	TRUE	TRUE	166.26995	165.44225	168.62873
D10	38	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	2p7	0p2	2p2	RATE_MC	8.8	-30	TRUE	169.3	8.977	8.77	8.65	-27.866	-29.298	-32.963	TRUE	TRUE	TRUE	171.86641	168.25155	167.89624
D10	39	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	2p2	0p2	2p2	RATE_MC	9.1	-29.4	TRUE	171.3	8.916	9.367	8.964	-27.666	-28.832	-31.555	TRUE	TRUE	TRUE	173.09636	171.59177	169.22827
D10	40	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n8	0p1	2p2	RATE_MC	9	-30.7	TRUE	166.1	9.087	8.96	8.897	-29.33	-30.622	-32.181	TRUE	TRUE	TRUE	165.93052	164.01295	168.25727
D10	41	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n8	0p3	2p2	RATE_MC	9.3	-30.4	TRUE	166.6	9.49	9.137	9.173	-30.767	-29.095	-31.439	TRUE	TRUE	TRUE	166.15826	166.36877	167.34796
D10	42	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n8	Best(0p1)	1p8	RATE_MC	9.4	-30.8	TRUE	168.1	8.92	9.81	9.72	-30.346	-30.664	-30.822	TRUE	TRUE	TRUE	165.44956	166.83733	172.33751
D10	43	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n8	Best(0p1)	2p7	RATE_MC	9	-30.7	TRUE	166.4	9.057	9.3	8.7	-28.771	-30.732	-32.742	TRUE	TRUE	TRUE	166.31203	164.37594	168.48026
D30	7	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	9.2	-31.1	TRUE	177.1	9.24	9.123	9.264	-31.172	-30.133	-31.851	TRUE	TRUE	TRUE	178.14130	177.16547	175.87665
D30	7shld	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2	RATE_MC	9.1	-31.6	TRUE	177.3	8.638	9.364	9.194	-32.195	-30.976	-31.691	TRUE	TRUE	TRUE	176.47198	177.70643	177.73343
D30	42	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n8	Best(0p1)	1p8	RATE_MC	9	-31.1	TRUE	177	8.887	9.107	9.087	-31.041	-31.203	-31.124	TRUE	TRUE	TRUE	178.33971	174.91414	177.79968
D30	35	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n8	0p2	2p2	RATE_MC	8.6	-30.3	TRUE	173	8.72	8.68	8.547	-28.863	-30.81	-31.245	TRUE	TRUE	TRUE	176.87795	169.94451	172.14586
D30	35newcable	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n8	0p2	2p2	RATE_MC	8.8	-29.9	TRUE	172.8	8.9	8.74	8.62	-28.963	-30.196	-30.484	TRUE	TRUE	TRUE	176.71261	169.79487	171.79054
D30	35flippedind	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n8	0p2	2p2	RATE_MC	9.2	-30.9	TRUE	173.9	8.593	9.583	9.317	-31.095	-30.395	-31.164	TRUE	TRUE	TRUE	173.20012	172.86965	175.69816
D30	44	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n8	0p2	1p8	RATE_MC	8.8	-31.5	TRUE	173.7	8.48	8.89	8.901	-31.281	-31.912	-31.197	TRUE	TRUE	TRUE	174.01181	172.46948	174.66018
D30	45	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n8	0p2	1p5	RATE_MC	8.8	-30.4	TRUE	173.8	8.773	9.047	8.513	-31.527	-30.376	-29.205	TRUE	TRUE	TRUE	175.04051	173.01808	173.26796
D30	46	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n8	0p2	2p7	RATE_MC	8.7	-31.7	TRUE	172.4	8.587	8.75	8.833	-31.419	-33.129	-30.422	TRUE	TRUE	TRUE	173.16966	170.27651	173.85146
D30	47	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n8	0p2	3p3	RATE_MC	8.9	-30.9	TRUE	174.2	8.484	9.127	9.017	-31.069	-31.271	-30.459	TRUE	TRUE	TRUE	174.15636	173.66986	174.70303
D30	48	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n8	0p1	2p2																	
	3A BOM 0.8	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n2	DNI	2p2	1n5	DNI	0n6	0p2	2p2																	
	Tuned - 64	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	0n6	DNI	2p7																	

Figure 9: Tuning Results till Step 48 [3]

"T" = Taiyo-Yuden

Board	Tune step	L5L11	C55	C52	C53	C60	L6	C61	C54	L10	C58	C56	L8	L9	L7	C59	C57	Data rate	Power (dE AVG	EVM (dB) AVG	MaskPass All	Current (n AVG	Power 5190	Power 5310	Power 5510	Power 5710	Power 5795	EVM 5190	EVM 5310	EVM 5510	EVM 5710	EVM 5795	MaskPass 5190	MaskPass 5310	MaskPass 5510	MaskPass 5710	MaskPass 5795	Current (n 5190	Current (n 5310	Current (n 5510	Current (n 5710	Current (mA) 5795
YB209_1D0117		1n5	0p1	1u	1p0	0p5	1n8	0p1	0p2	2n2	0p1	0R	1n6	1n6	0n6	0p2	2p2	RATE_MC	9.4	-28.4	TRUE	261.5	9.054	9.27	9.813	9.685	9.33	-25.767	-27.68	-29.856	-29.614	-29.26	TRUE	TRUE	TRUE	TRUE	TRUE	262.6754	257.8729	255.2215	262.4724	269.3677
YB209_1D0445		1n5	0p1	1u	1p0	0p5	1n8	0p1	0p2	2n2	0p1	0R	1n6	1n6	0n6	0p2	2p2	RATE_MC	9.4	-28.6	TRUE	256.6	9.147	9.41	9.503	9.92	9.09	-24.532	-28.294	-29.299	-29.912	-30.723	TRUE	TRUE	TRUE	TRUE	TRUE	257.4153	252.5720	250.9444	260.1149	262.0474
D10	43?	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n8	0p1	2p7	RATE_MC	9.2	-31.6	TRUE	165.8	9.094	9.12	9.245	9.383	9.074	-30.466	-31.755	-30.893	-32.89	-32.188	TRUE	TRUE	TRUE	TRUE	TRUE	165.0245	163.8921	163.6449	166.6061	169.6907
D10	42	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n8	0p1	1p8	RATE_MC	9.1	-31.1	TRUE	166.3	8.91	8.732	9.203	9.497	8.98	-30.252	-31.929	-29.801	-32.465	-30.96	TRUE	TRUE	TRUE	TRUE	TRUE	165.7680	163.3731	165.3098	167.1269	169.9151
D30	42?	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n8	0p1?	1p8?	RATE_MC	8.7	-31.1	TRUE	170.8	8.4	8.923	8.683	8.943	8.753	-30.419	-29.165	-33.074	-31.498	-31.406	TRUE	TRUE	TRUE	TRUE	TRUE	172.2908	168.4695	169.4091	170.8536	172.9330
D30	42	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n8	0p1	1p8	RATE_MC	8.9	-31	TRUE	171	8.57	8.91	9.183	8.947	8.83	-30.999	-28.893	-31.832	-31.757	-31.484	TRUE	TRUE	TRUE	TRUE	TRUE	172.1720	168.4132	170.7333	170.8791	172.9062
D49	0	2n0	0p1	0u1	1p2	0p5	1n8T	0p1	0p2	2n2T	DNI	2p2	1n6T	DNI	0n6	0p2	2p2	RATE_MC	9.3	-30.2	TRUE	162.5	8.98	8.82	9.893	9.857	9	-28.594	-31.763	-26.633	-30.792	-33.222	TRUE	TRUE	TRUE	TRUE	TRUE	161.7505	160.1013	166.2497	163.2974	161.2321
D49	42	2n0	0p1	0u1	1p0	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	0n8	0p1	1p8	RATE_MC	9.1	-30.1	TRUE	163.9	8.567	8.592	8.923	9.713	9.513	-31.39	-30.427	-29.664	-31.721	-27.217	TRUE	TRUE	TRUE	TRUE	TRUE	158.7095	159.5632	160.8760	164.5634	175.5558
D49	49	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n2	DNI	2p7	1n5	DNI	0n8	0p1	1p8	RATE_MC	9.4	-30	TRUE	162.9	8.97	9.427	9.154	9.61	9.71	-27.3	-31.682	-28.058	-31.763	-30.952	TRUE	TRUE	TRUE	TRUE	TRUE	163.2037	160.9868	162.3572	161.4984	166.6742
D49	50	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n2	DNI	2p7	1n5	DNI	0n8	0p1	1p5	RATE_MC	9.6	-29.8	TRUE	164	9.41	9.333	9.53	9.727	9.863	-26.99	-31.921	-27.866	-30.863	-31.113	TRUE	TRUE	TRUE	TRUE	TRUE	165.3708	161.6597	163.5754	162.5921	166.6253
D49	51	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n2	DNI	2p7	1n5	DNI	0n8	0p1	2p2	RATE_MC	9.1	-30.3	TRUE	161.8	9.09	9.267	9.144	9.077	8.813	-26.698	-32.041	-28.465	-31.897	-32.6	TRUE	TRUE	TRUE	TRUE	TRUE	164.3241	160.8529	161.0697	160.4121	162.4299
D49	52	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n2	DNI	2p7	1n5	DNI	0n8	0p1	2p7	RATE_MC	9.3	-30.2	TRUE	162.6	8.75	9.007	9.417	9.697	9.507	-26.789	-31.771	-28.297	-31.847	-32.097	TRUE	TRUE	TRUE	TRUE	TRUE	162.9161	159.7811	161.4330	162.4698	166.2832
D49	53	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n2	DNI	2p7	1n5	DNI	0n8	0p2	1p8	RATE_MC	9.2	-29.9	TRUE	162.7	9.123	8.959	9.527	9.347	9.267	-26.963	-32.481	-27.467	-31.431	-31.167	TRUE	TRUE	TRUE	TRUE	TRUE	164.2881	160.4004	163.8533	161.2876	163.5222
D49	54	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n2	DNI	2p7	1n5	DNI	0n8	0p3	1p8	RATE_MC	9.3	-29.7	TRUE	164.5	9.337	9.333	8.967	9.523	9.503	-28.067	-30.812	-26.633	-32.3	-30.481	TRUE	TRUE	TRUE	TRUE	TRUE	165.8422	164.1345	164.5892	161.9131	165.8372
D49	55	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n2	DNI	2p7	1n5	1n5	0n8	0p3	1p8	RATE_MC	9.6	-29.2	TRUE	164.5	9.663	9.22	10.444	9.645	9.063	-28.294	-29.866	-25.566	-32.307	-29.865	TRUE	TRUE	TRUE	TRUE	TRUE	164.4750	164.1011	169.6804	160.5979	163.4831
D49	56	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n2	DNI	2p7	1n5	DNI	1n0	0p3	1p8	RATE_MC	9.5	-29.4	TRUE	164.1	9.524	9.317	9.977	9.533	8.953	-28.497	-29.895	-26.199	-31.555	-30.995	TRUE	TRUE	TRUE	TRUE	TRUE	164.5003	165.5474	166.5157	160.4905	163.4116
D49	57	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n2	DNI	2p7	DNI	DNI	0n8	0p3	1p8	RATE_MC	9.5	-26.7	FALSE	186.1	9.64	10.023	9.578	9.604	8.753	-24.092	-23.166	-23.431	-29.929	-32.785	FALSE	FALSE	TRUE	TRUE	TRUE	201.3770	221.7895	180.9610	165.3288	161.0508
D49	58	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n2	DNI	2p7	DNI	DNI	2p7	DNI	2p7	RATE_MC	9.3	-26	TRUE	177.5	9.077	9.202	8.893	10.06	9.5	-25.1	-24.024	-23.264	-27.86	-29.998	TRUE	TRUE	TRUE	TRUE	TRUE	174.6641	189.5926	178.0435	175.7095	169.6713
D49	59	2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n2	DNI	2p7	1n5	DNI	2p7	DNI	2p7	RATE_MC	9.4	-28.5	TRUE	166.9	9.383	9.054	9.663	9.513	9.537	-24.897	-31.342	-27.699	-28.551	-30.167	TRUE	TRUE	TRUE	TRUE	TRUE	170.3476	159.8069	165.6065	168.4567	170.4211
D49	60	2n0	0p1	0u1	1p0	0p5	1n8	0p1	0p2	2n2	DNI	2p7	1n5	DNI	2p7	DNI	2p7	RATE_MC	9.2	-29	TRUE	165.6	9.173	9.003	9.213	9.497	8.993	-24.9	-31.627	-28.132	-29.717	-30.632	TRUE	TRUE	TRUE	TRUE	TRUE	169.6614	159.4819	163.1313	167.9396	167.9049
D49	61	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p7	1n5	DNI	2p7	DNI	2p7	RATE_MC	9.3	-29.4	TRUE	164.7	8.863	9.06	9.683	9.687	9.347	-27.697	-28.998	-28.29	-30.862	-31.307	TRUE	TRUE	TRUE	TRUE	TRUE	163.5732	158.9357	165.0095	167.7548	168.3238
D49	62	2n0	0p1	0u1	1p2	0p5	2n0	0p2	0p2	2n0	DNI	2p7	1n5	DNI	2p7	DNI	2p7	RATE_MC	9.1	-28.7	TRUE	164.2	8.853	8.53	9.227	9.633	9.173	-29.23	-26.961	-29.063	-30.431	-27.862	TRUE	TRUE	TRUE	TRUE	TRUE	160.9178	157.3484	163.9067	168.6028	170.4499
D49	63	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p7	1n5	DNI	0n6	DNI	2p7	RATE_MC	9	-30.6	TRUE	162	8.667	8.533	9.2	9.647	9.027	-30.421	-30.565	-29.498	-31.164	-31.276	TRUE	TRUE	TRUE	TRUE	TRUE	158.8161	157.4337	160.8598	165.3219	167.5123
D49	64	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	0n6	DNI	2p7	RATE_MC	9.3	-30.5	TRUE	162.7	9.434	9.16	9.35	9.447	9.007	-28.433	-31.2	-29.6	-32.195	-31.259	TRUE	TRUE	TRUE	TRUE	TRUE	162.6086	158.7031	161.3419	164.1459	166.5159
D49	65	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	1p8	1n5	DNI	0n6	DNI	2p7	RATE_MC	9.2	-30	TRUE	163.5	9.247	9.484	9.167	9.354	8.973	-26.832	-31.157	-29.565	-31.422	-30.874	TRUE	TRUE	TRUE	TRUE	TRUE	164.9702	161.0692	161.2512	164.0538	166.3686
D49	66	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	1p8	1n5	DNI	0n6	0p1	2p7	RATE_MC	9.4	-29.9	TRUE	164	9.42	9.086	9.323	9.59	9.58	-27.6	-31.07	-27.963	-31.897	-31.219	TRUE	TRUE	TRUE	TRUE	TRUE	164.9711	160.5167	163.4220	164.3166	166.8140
D49	67	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	0n6	0p1	2p7	RATE_MC	9.3	-29.8	TRUE	163.9	9.11	8.993	9.67	9.503	9.31	-28.629	-30.619	-27.163	-30.378	-32.059	TRUE	TRUE	TRUE	TRUE	TRUE	162.7782	160.8546	165.1719	164.1131	166.5679
D49	68	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	0n6	0p2	2p7	RATE_MC	9.3	-29.9	TRUE	163.8	9.34	8.973	9.517	9.02	9.503	-28.567	-30.917	-27.263	-30.512	-31.992	TRUE	TRUE	TRUE	TRUE	TRUE	164.8229	160.5149	165.0593	162.1473	166.4099
D49	69	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	0R	DNI	2p7	RATE_MC	8.8	-30.4	TRUE	161.9	8.974	8.887	8.647	8.654	8.74	-26.649	-32.39	-29.765	-31.607	-31.693	TRUE	TRUE	TRUE	TRUE	TRUE	164.2381	159.0045	159.0356	161.5863	165.4781
D49	70	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	0n8	DNI	2p7	RATE_MC	9.2	-30.2	TRUE	162.8	8.657	9.147	9.68	9.671	9.014	-26.192	-31.989	-29.597	-31.765	-31.528	TRUE	TRUE	TRUE	TRUE	TRUE	162.9550	159.6613	161.0475	163.9843	166.1892
D49	71	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	1n0	DNI	2p7	RATE_MC	9.5	-30	TRUE	163.3	9.41	9.587	9.51	9.85	9.267	-26.597	-30.884	-29.933	-31.871	-30.695	TRUE	TRUE	TRUE	TRUE	TRUE	164.7174	160.6964	159.2421	163.8596	168.0854
D49	72	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p7	1n5	DNI	1n0	DNI	2p7	RATE_MC	9.2	-30.1	TRUE	162.6	8.553	9.233	9.084	9.36	9.687	-26.081	-32.463	-29.782	-31.854	-30.086	TRUE	TRUE	TRUE	TRUE	TRUE	161.5308	160.2127	158.4528	163.0504	169.5294
D49	73	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	1n0	0p2	2p7	RATE_MC	9.4	-31.9	TRUE	167.1	9.118	9.295	9.502	9.285	9.578	-30.879	-32.968	-29.817	-34.338	-31.374	TRUE	TRUE	TRUE	TRUE	TRUE	163.5942	167.4972	164.0192	164.7583	175.3956
D49	74	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	1n0	0p2	2p2	RATE_MC	9.5	-30.2	TRUE	163.5	9.4	8.893	9.643	10.064	9.69	-31.367	-30.997	-28.397	-32.311	-28.165	TRUE	TRUE	TRUE	TRUE	TRUE	160.2172	161.7130	161.4729	162.7300	171.2217
D49	75	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	0n8	0p2	2p7	RATE_MC	9.5	-30.3	TRUE	162.9	9.351	9.137	9.73	9.777	9.457	-28.792	-31.961	-27.9	-32.033	-30.91	TRUE	TRUE	TRUE	TRUE	TRUE	162.4124	160.9639	162.8542	162.0630	166.2732
D49	76	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	1n0	0p1	2p7	RATE_MC	9.4	-29.9	TRUE	162.4	8.857	8.96	9.727	9.83	9.683	-27.895	-31.312	-28.799	-31.225	-30.137	TRUE	TRUE	TRUE	TRUE	TRUE	160.8174	159.6117	161.0141	162.1876	168.2008
D49	77	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	1n0	0p1	2p2	RATE_MC	9.2	-30.6	TRUE	161.5	8.73	8.963	9.583	9.287	9.357	-27.967	-32.293	-28.599	-32.925	-31.192	TRUE	TRUE	TRUE	TRUE	TRUE	160.5751	159.4230	160.8802	160.3470	166.0977
D49	78	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	1n2	0p2	2p7	RATE_MC	9.4	-29.3	TRUE	163.2	9.267	9.07	9.567	9.737	9.537	-28.293	-30.132	-29.295	-31.888	-27.094	TRUE	TRUE	TRUE	TRUE	TRUE	161.6788	161.2818	159.0332	161.9452	172.0962
D49	76 new cable	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	1n0	0p1	2p7	RATE_MC	9.3	-30	TRUE	161.9	8.743	9.08	9.613	9.793	9.23	-27.498	-29.926	-27.788	-32.698	-31.864	TRUE	TRUE	TRUE	TRUE	TRUE	160.7661	159.6025	161.0042	162.1171	166.1086
D49	73 new cable	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	1n0	0p2	2p7	RATE_MC	9.4	-29.9	TRUE	163.3	9.057	9.073	9.713	9.547	9.573	-28.333	-30.339	-27.632	-32.547	-30.405	TRUE	TRUE	TRUE	TRUE	TRUE	162.2407	161.2451	162.7736	162.2001	168.2530
D49	79	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	0p1	2p2	1n5	DNI	1n0	0p2	2p7	RATE_MC	9.3	-29.9	TRUE	164.4	8.713	9.267	9.62	9.643	9.197	-31.695	-28.597	-27.298	-31.339	-30.817	TRUE	TRUE	TRUE	TRUE	TRUE	158.7465	167.1324	164.4458	163.6477	167.9066
D49	64	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	0n6	DNI	2p7	RATE_MC	9.4	-30	TRUE	164.1	9.417	9.903	9.23	9.353	9.307	-27.832	-30.899	-28.06	-32.063	-31.02	TRUE	TRUE	TRUE	TRUE	TRUE	164.3266	162.2408	162.5798	163.5926	167.9326
D10	64	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	0n6	DNI	2p7	RATE_MC	9.1	-30.8	TRUE	166.9	9.357	8.94	9.123	9.377	8.61	-28.963	-32.051	-29.832	-32.098	-31.223	TRUE	TRUE	TRUE	TRUE	TRUE	167.4483	164.6612	166.0139	167.5051	168.6881
D30	64	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	0n6	DNI	2p7	RATE_MC	9	-31.6	TRUE	174.3	8.416	8.737	9.173	9.61	9.1	-29.827	-31.847	-31.917	-33.16	-31.579	TRUE	TRUE	TRUE	TRUE	TRUE	175.6936	170.7833	173.0247	175.3338	176.9097
FINAL		2n0	0p1	0u1	1p2	0p5	1n8	0p1	0p2	2n0	DNI	2p2	1n5	DNI	0n6	0p2	2p2																									
D49	64-noMM	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	0n6	DNI	2p7	RATE_MC	9.3	-30	TRUE	0	8.88	9.003	9.513	9.47	9.433	-29.463	-30.33	-28.3	-30.865	-30.912	TRUE	TRUE	TRUE	TRUE	TRUE	-0.004631	-0.004545	-0.004686	-0.004694	-0.004101
D10	64-noMM	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	0n6	DNI	2p7	RATE_MC	9.2	-31.1	TRUE	0	9.184	8.967	9.35	9.864	8.763	-29.961	-32.349	-29.981	-31.965	-31.16	TRUE	TRUE	TRUE	TRUE	TRUE	-0.002681	-0.002573	-0.004223	-0.002523	-0.001863
D30	64-noMM	2n0	0p1	0u1	1p2	0p5	1n8	0p2	0p2	2n2	DNI	2p2	1n5	DNI	0n6	DNI	2p7	RATE_MC	9	-30.9	TRUE	0	8.87	8.912	8.987	9.26	9.113	-30.694	-31.9	-30.638	-32.068	-29.167	TRUE	TRUE	TRUE	TRUE	TRUE	-0.007002	-0.003887	-0.004897	-0.003740	-0.001672

Figure 10: Tuning Results till Step 64 [3]

WiFi 2GHz HT20	Power (dBm)	EVM (dB)	MaskPass	Current (mA)																				
Rate	AVG	AVG	All	AVG																				
WiFi 2GHz HT40	Power (dBm)	EVM (dB)	MaskPass	Current (mA)																				
Rate	AVG	AVG	All	AVG																				
WiFi 5GHz HT20	Power (dBm)	EVM (dB)	MaskPass	Current (mA)	Power	Power	Power	Power	Power	EVM	EVM	EVM	EVM	EVM	MaskPass	MaskPass	MaskPass	MaskPass	MaskPass	Current	Current	Current	Current	Current
Rate	AVG	AVG	All	AVG	5180	5320	5500	5700	5825	5180	5320	5500	5700	5825	5180	5320	5500	5700	5825	5180	5320	5500	5700	5825
RATE_6Mbps	13.5	-22.3	TRUE	0	14.78	12.837	13.706	13.182	13.044	-22.02	-21.679	-22.858	-22.817	-22.176	TRUE	TRUE	TRUE	TRUE	TRUE	-0.00138654601	-0.00338317226	-0.00473366807	-0.00477526445	-0.00446467815
RATE_54Mbps	11.6	-30.3	TRUE	0	11.67	11.054	11.702	11.7	11.626	-29.616	-29.627	-29.239	-32.432	-30.756	TRUE	TRUE	TRUE	TRUE	TRUE	-0.00408753763	-0.00565433462	-0.00281746149	-0.0023266242	-0.00543248726
RATE_MCS_0_2	13.3	-21.4	TRUE	0	14.472	12.715	13.456	12.948	13.15	-21.279	-20.698	-22.1	-21.8	-21.079	TRUE	TRUE	TRUE	TRUE	TRUE	-0.00403484889	-0.00368821238	-0.0034746843	-0.00445081269	-0.00380468225
RATE_MCS_7_2	9.5	-32.2	TRUE	0	9.746	9.138	9.828	9.424	9.546	-30.098	-34.096	-30.117	-33.397	-33.358	TRUE	TRUE	TRUE	TRUE	TRUE	-0.00683289873	-0.00143368857	-0.00372703567	-0.00419568822	-0.00619231448
WiFi 5GHz HT40	Power (dBm)	EVM (dB)	MaskPass	Current (mA)	Power	Power	Power	Power	Power	EVM	EVM	EVM	EVM	EVM	MaskPass	MaskPass	MaskPass	MaskPass	MaskPass	Current	Current	Current	Current	Current
Rate	AVG	AVG	All	AVG	5190	5310	5510	5710	5795	5190	5310	5510	5710	5795	5190	5310	5510	5710	5795	5190	5310	5510	5710	5795
RATE_MCS_0_4	12.4	-14.5	TRUE	0	12.84	11.85	12.387	12.804	12.23	-14.7	-14.3	-14.9	-14.367	-14.166	TRUE	TRUE	TRUE	TRUE	TRUE	-0.00368543929	-0.00292006589	-0.00590945909	-0.00367989311	-0.00543803345
RATE_MCS_7_4	9.3	-30	TRUE	0	8.88	9.003	9.513	9.47	9.433	-29.463	-30.33	-28.3	-30.865	-30.912	TRUE	TRUE	TRUE	TRUE	TRUE	-0.00463106367	-0.00454509782	-0.00468652551	-0.00469484479	-0.00410140309
Qualcomm reference																								
WiFi 5GHz HT20	Power (dBm)	EVM (dB)	MaskPass	Current (mA)	Power	Power	Power	Power	Power	EVM	EVM	EVM	EVM	EVM	MaskPass	MaskPass	MaskPass	MaskPass	MaskPass	Current	Current	Current	Current	Current
Rate	AVG	AVG	All	AVG	5180	5320	5500	5700	5825	5180	5320	5500	5700	5825	5180	5320	5500	5700	5825	5180	5320	5500	5700	5825
RATE_6Mbps	13.8	-22.7	TRUE	330.8	14.468	13.745	13.732	13.336	13.615	-22.519	-22.879	-23.119	-22.599	-22.24	TRUE	TRUE	TRUE	TRUE	TRUE	346.027671	322.221246	312.480316	332.43145	340.591612
RATE_54Mbps	11.9	-29.8	TRUE	288.4	11.718	11.61	11.976	11.926	12.142	-27.158	-29.994	-30.857	-30.845	-30.231	TRUE	TRUE	TRUE	TRUE	TRUE	290.209632	280.375238	277.586589	294.679344	299.026837
RATE_MCS_0_2	13.6	-21.7	TRUE	328.7	14.178	13.222	13.508	13.272	13.646	-21.659	-22.077	-21.978	-21.499	-21.14	TRUE	TRUE	TRUE	TRUE	TRUE	342.650621	319.723888	311.262923	332.22133	337.476428
RATE_MCS_7_2	9.6	-30.5	FALSE	267.8	9.656	9.491	9.729	9.3	9.88	-27.057	-30.054	-31.855	-32.173	-31.555	TRUE	FALSE	TRUE	TRUE	TRUE	270.559241	264.24207	260.127121	269.920273	274.374489
WiFi 5GHz HT40	Power (dBm)	EVM (dB)	MaskPass	Current (mA)	Power	Power	Power	Power	Power	EVM	EVM	EVM	EVM	EVM	MaskPass	MaskPass	MaskPass	MaskPass	MaskPass	Current	Current	Current	Current	Current
Rate	AVG	AVG	All	AVG	5190	5310	5510	5710	5795	5190	5310	5510	5710	5795	5190	5310	5510	5710	5795	5190	5310	5510	5710	5795
RATE_MCS_0_4	12.7	-14.6	TRUE	321.6	13.037	12.637	12.833	12.977	12.077	-14.733	-14.9	-14.767	-14.467	-14.333	TRUE	TRUE	TRUE	TRUE	TRUE	333.4636	313.053242	307.674331	323.896526	330.065375
RATE_MCS_7_4	9.4	-28.4	TRUE	261.5	9.054	9.27	9.813	9.685	9.33	-25.767	-27.68	-29.856	-29.614	-29.26	TRUE	TRUE	TRUE	TRUE	TRUE	262.675412	257.872927	255.221576	262.472416	269.367787

Figure 11: Tunign Step 64 Passing Results on D49 and Qualcomm Dev Board Test Results [3]

Wi-Fi 5 GHz Band Edge Emission Tests

After the topology and components were finalized, additional tests were conducted to measure power consumption across various data rates, power level in dBm, EVM in dB, current, and mask compliance. Furthermore, band edge testing was conducted using Spectrum Analyzer to make sure that there is no spurious emissions and it would pass FCC levels highlighted in red lines.

Test Mode Power Measurements

D10/D17			AVG			Lo channel		Mid channel		Hi channel	
Radio	**Mode**	**Data rate**	**P(W)**	**Vi(V)**	**I(mA)**	**Vi(V)**	**I(mA)**	**Vi(V)**	**I(mA)**	**Vi(V)**	**I(mA)**
WiFi 5GHz (D10)	TX	11g 6Mbps	0.965	5.002	193.0	5	195	5.005	189	5	195
		11g 54Mbps	0.952	5.004	190.3	5.012	179	5.008	185	4.991	207
		11n HT20 MCS0	0.991	4.998	198.3	5	196	4.994	203	5	196
		11n HT20 MCS7	0.879	5.016	175.3	5.017	174	5.016	175	5.014	177
		11n HT40 MCS0	0.991	4.998	198.3	5	196	5.004	190	4.99	209
		11n HT40 MCS7	0.894	5.013	178.3	5.013	178	5.014	177	5.012	180

Table 2: Test Mode Power Measurements

Wi-Fi 5 GHz Transmit Performance Results

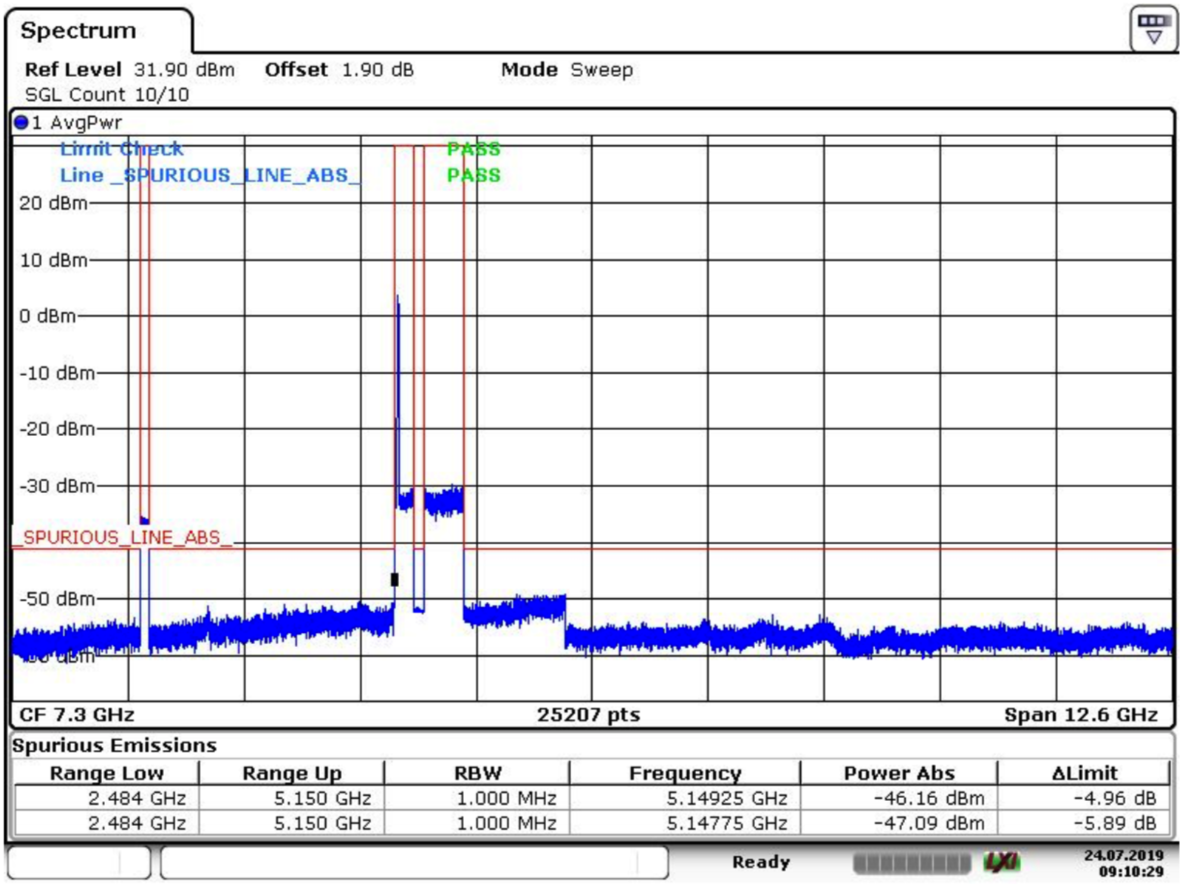
The expected output power ranges from 9 to 14 dBm (dependent on the modulation rate). EVM is required to be compliant with as shown in Table 1. The following results matched with all Wi-Fi TX specs and improved performance significantly than original Qualcomm design. Various boards were also tested to make sure they match specs.

Parameter	Data rate	Chan Avg	5180 5190	5320 5310	5500 5510	5700 5710	5825 5795	Unit
Power	802.11a 6Mbps	13.5	14.8	12.8	13.7	13.2	13.0	dBm
	802.11a 54Mbps	11.6	11.7	11.1	11.7	11.7	11.6	
	802.11n HT20 MCS0	13.3	14.5	12.7	13.5	12.9	13.2	
	802.11n HT20 MCS7	9.5	9.7	9.1	9.8	9.4	9.5	
	802.11n HT40 MCS0	12.4	12.8	11.9	12.4	12.8	12.2	
	802.11n HT40 MCS7	9.3	8.9	9.0	9.5	9.5	9.4	
EVM (dB)	802.11a 6Mbps	-22.3	-22.0	-21.7	-22.9	-22.8	-22.2	dB
	802.11a 54Mbps	-30.3	-29.6	-29.6	-29.2	-32.4	-30.8	
	802.11n HT20 MCS0	-21.4	-21.3	-20.7	-22.1	-21.8	-21.1	
	802.11n HT20 MCS7	-32.2	-30.1	-34.1	-30.1	-33.4	-33.4	
	802.11n HT40 MCS0	-14.5	-14.7	-14.3	-14.9	-14.4	-14.2	
	802.11n HT40 MCS7	-30.0	-29.5	-30.3	-28.3	-30.9	-30.9	
Mask compliance	802.11a 6Mbps	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	
	802.11a 54Mbps	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	
	802.11n HT20 MCS0	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	
	802.11n HT20 MCS7	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	
	802.11n HT40 MCS0	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	
	802.11n HT40 MCS7	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	

Table 3: Board Performance Test Results for Wi-Fi 5 GHz

Wi-Fi 5 GHz Transmit Mode Spurious Emissions

802.11a TX 9Mbps 5180 MHz



Date: 24.JUL.2019 09:10:29

Figure 12: 802.11a TX 9Mbps 5180 MHz

802.11n TX MCS0_20 5180 MHz

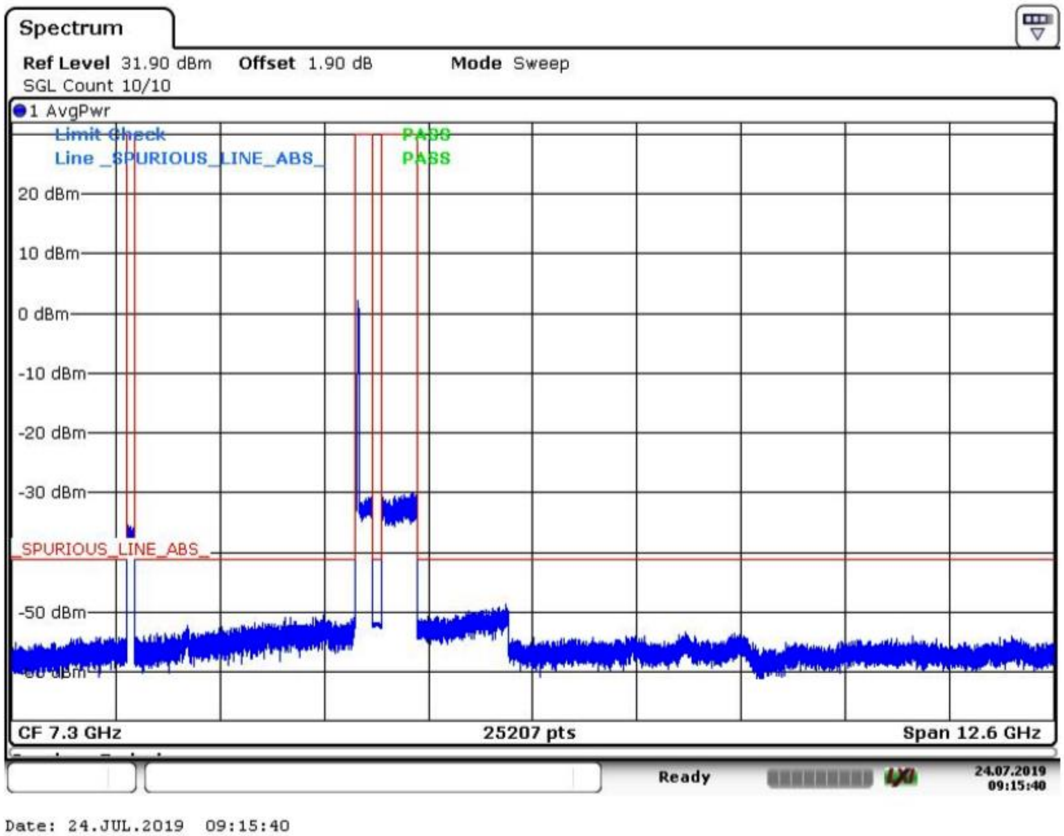


Figure 13: 802.11n TX MCS0_20 5180 MHz

802.11n TX MCS7_20 5180 MHz

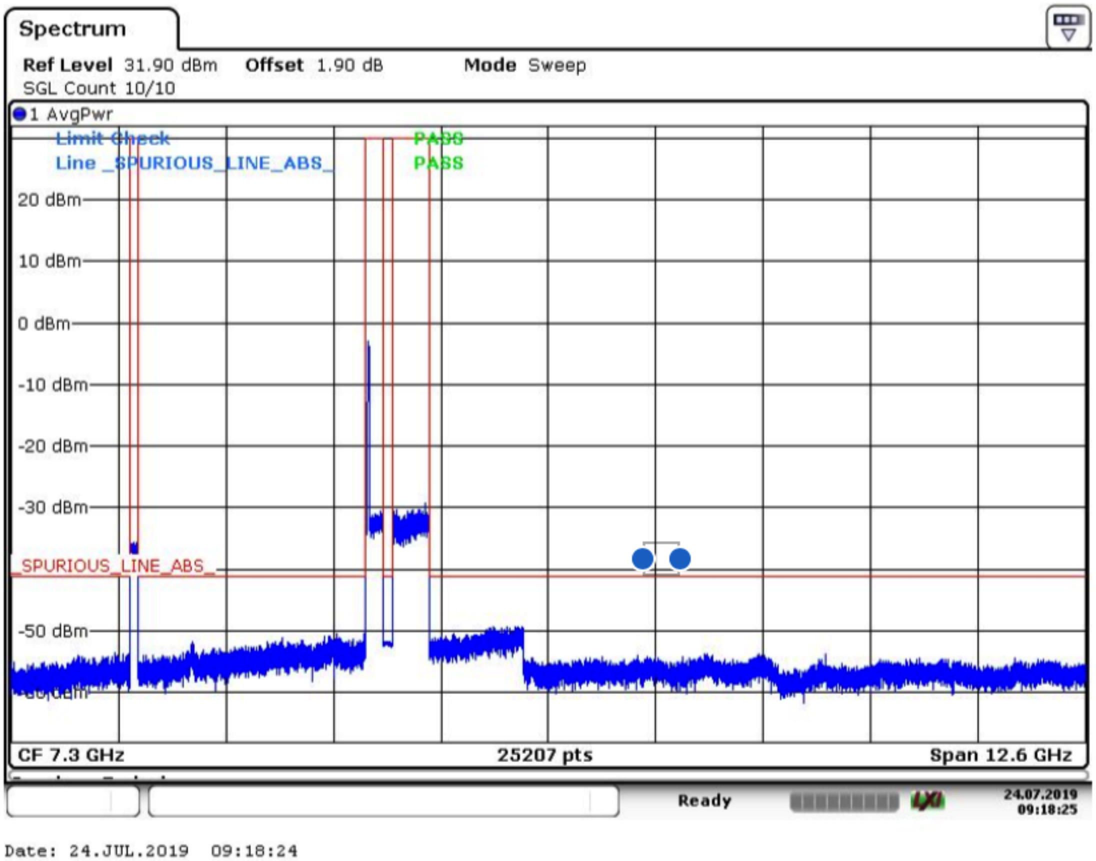


Figure 14: 802.11n TX MCS7_20 5180 MHz

Test Equipment

Table 5 shows all test equipment that were used to conduct the various tests and perform the tuning exercise for 5 GHz Wi-Fi and other testing related to Thunderchild board for internal use. Qualcomm test automation software QSPR was used to gather and process data from Anristu test box and current meters over LAN to pass/fail appropriate tests.

Manufacturer	Model Number	Description	Used for
Rigol	MSO1104Z	4-channel mixed-signal oscilloscope	Voltage rail stability, power-on transients, button testing
Fluke	179	Digital multimeter	Average/instantaneous current/voltage, voltage rail stability
Anritsu	MT8870A	Wireless test set	RF transmit/receive performance
Ramsey	STE3300	Shielded test box	RF receive performance, WLAN benchmarking
Rohde & Schwarz	FSV13	Spectrum analyzer with frequency counting	Spurious emissions, oscillator frequency accuracy
Rohde & Schwarz	ZVL6	Network analyzer	Antenna S11 measurements
TP-LINK	Archer C7	Dual-band AC1750 Gigabit Wi-Fi router	WLAN benchmarking

Table 4: Test Equipments used in Thunderchild Testing

References

[1] Bevelacqua, P. (2019). *EVM - Error Vector Magnitude*. [online] Antenna-theory.com. Available at: http://www.antenna-theory.com/definitions/evm.php [Accessed 12 Aug. 2019].

[2] Silabs.com. (2019). [online] Available at: https://www.silabs.com/documents/public/application-notes/AN923-subGHz-Matching.pdf [Accessed 12 Aug. 2019].

[3]https://docs.google.com/spreadsheets/d/1Dv2STQ9tcgVLb3Lsh9wcvK4a9Gs37ucCxrvmtOsJphI/edit?usp=sharing.