RLAN device-based dynamic power control and exposure time-averaging

V1.3.5

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1 Introduction

To optimize device-based real-time power control while ensuring compliance with SAR limits, future Apple products will support a time-averaged method of Dynamic SAR Averaging (DSA) within the RLAN chipset in 2020+ iPhone, iPad and Mac computers. The purpose of this KDB is to seek FCC acceptance of Apple's DSA implementation of device-based dynamic power control and exposure time-averaging for RLAN transmitters only.

2 Power Limits and Utilization Ratio Limits

Since a device utilizing DSA for RLAN transmitters may be configured with different combinations of antennas, transmitter cores, and related components, each combination is characterized with SAR measurements to determine the maximum power limit P_{lim} allowable for each discrete operating state. These measurements are conducted using standard FCC-approved procedures and the resulting power limits are tabulated in the RLAN power table for the device.

This DSA implementation does not monitor actual output power level, but instead conservatively assumes that RLAN transmitters are operating at the maximum allowable output power for purposes of the average power calculation. For each transmitter, the maximum power for any given operational state can be one of 3 possible values:

- P_{lim} - Measured power limit determined for a discrete operating state during SAR characterization of the device
- P_{opt} – Increased power P_{lim} + *power offset* when optimization mode is active
- P_{dev} – Hardware-limited maximum power applicable when $P_{opt} > P_{dev}$

Since power levels in different bands with different operating states and power limits are not directly comparable, the DSA algorithm instead tracks the ratio of energy contribution relative to the available energy budget for each transmitter. The resulting "utilization ratio" for a particular RLAN transmitter can then be added to the utilization ratios for all the other RLAN transmitters in a device over the same time period to derive the total RLAN system utilization ratio.

Consistent with FCC guidance on compliance with time-averaged exposure limits, the DSA implementation uses the total RLAN utilization ratio over a nominal[1] 60 second time window to manage transmitter power levels. Conservatively, the ~60 second window is used for both $f > 3$ GHz and $f < 3$ GHz. Power is increased to P_{opt} when the total utilization ratio is << 1.0 and decreased to inherently compliant levels (P_{lim}) when it

[1] The actual duration of the averaging window is typically 59.9 seconds (65 monitoring periods, 0.9216 seconds per period) but may vary since the duration of monitoring periods is a multiple of the 802.11 beacon interval. In no case will it exceed 60 seconds. The actual duration of monitoring periods in microseconds is stored within the RLAN chipset to allow validation of the averaging calculations.

approaches 1.0. This technique ensures that the total power budget can never be exceeded when transitioning between bands or operational states since power is always represented in relation to its respective power limit.

2.1 Per-Packet Tracking Enhancement

Certain projects will implement a power tracking enhancement that accounts for per packet power variation. The actual output power (P_{actual}) is measured from the TSSI ADC reading as shown in Figure 1. P_{actual} is reported in the form of Tx duration weighted for Pmax. Please refer to Section 3.5 for further details. This enhancement can be enabled and/or disabled on a per project basis via power table parameter.

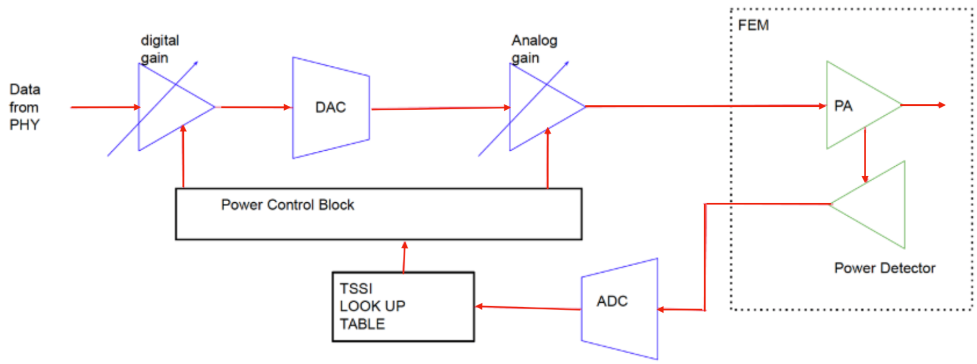

Figure 1. *Block Diagram for TSSI ADC power measurement*

This power measurement process is consistent with that in previously certified projects; please see Table 1 for devices using this implementation to drive the WLAN Tx power control circuit. As in previously certified devices, the TSSI circuit is calibrated on a per unit basis and the overall uncertainty in the Tx power control loop is characterized as +/-1.5 dB. This uncertainty is already considered in the overall uncertainty budget.

Model(s)	FCC ID
A2176	BCG-E3539A
A2398	BCG-E3540A
A2399, A2400, A2401	BCG-E3541A
A2172	BCG-E3542A
A2402	BCG-E3543A
A2403, A2404, A2405	BCG-E3544A
A2341	BCG-E3545A
A2406	BCG-E3546A
A2407, A2408, A2409	BCG-E3547A
A2342	BCG-E3548A
A2410	BCG-E3549A
A2411, A2412, A2413	BCG-E3550A

Table 1.

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3 Functional Description

The RLAN chipset continuously records the maximum allowable output power (P_{lim}, P_{opt}, or P_{dev}) and the actual transmit duration in μsec for each RLAN transmitter. During each monitoring period (every 0.92 seconds), the maximum average power is calculated for each transmitter at each monitoring period by the following equation:

$$P_{mon} = P_{max} \times \sum_{i=1}^{n} T_i \div T_{mon} \qquad \text{(Eq. 1)}$$

Where:

- P_{mon} = Maximum average power of a transmitter within the monitoring period
- P_{max} = Maximum power output of the transmitter within the monitoring period (either P_{lim}, P_{opt}, or P_{dev}); adjusted P_{max} used when PPT enabled (see Eq. 5)
- n = Number of active transmit periods within the monitoring period
- T_i = Duration of the active transmit period (recorded in μsec by the chipset)
- T_{mon} = Duration of the monitoring period

The maximum power levels and durations aggregated over the time-averaging window (the previous ~60 seconds) are then used to calculate a conservative real-time rolling SAR utilization ratio. Since the applicable power limits and actual duration of the time-averaging window vary, the total SAR power budget for each transmitter is recalculated at each monitoring period:

$$Q_{sar} = \left(\sum_{j=1}^{m} P_{lim_j} \times T_j \right) \textit{ where } \sum_{j=1}^{m} T_j = T_{win} \qquad \text{(Eq. 2)}$$

Where:

- Q_{sar} = Per-transmitter power budget for the time-averaging window
- m = Number of power limits applied within the time-averaging window
- P_{lim_j} = Measured power limit determined for a discrete operating state during SAR characterization of the device applicable during T_j
- T_j = Duration of a specific operational state with applicable power limit P_{lim_j} (recorded in μsec by the chipset)
- T_{win} = Duration of the time-averaging window (≤ 60 sec)

Once the power budget for a time-averaging window is known, the maximum average powers and durations for each monitoring period are used to calculate the overall time-averaged utilization:

$$U_{win} = \sum_{k=1}^{p} \left(P_{mon_k} \times T_{mon_k} \right) \div Q_{sar} \qquad \text{(Eq. 3)}$$

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Where:

U_{win} = Per-transmitter utilization of power budget over the time-averaging window
p = Number of monitoring periods within the time-averaging window
P_{mon_k} = Maximum average transmitter power during a specific monitoring period
T_{mon_k} = Duration of the monitoring period
Q_{sar} = Total power budget for transmitter within the time-averaging window

After the utilization ratios for each of the individual RLAN transmitters are calculated, they are summed to derive the overall RLAN system power utilization ratio. This is the metric used by the RLAN chipset to manage power levels over time and ensure that SAR limits are never exceeded. If the system utilization ratio is significantly less than 1.0, the power limit for the active RLAN transmitter is increased by a fixed preset offset to the optimization value (P_{opt}). As the utilization ratio increases to a maximum threshold level (near 1.0), the power limit on the active RLAN transmitter will be reduced to P_{lim}, ensuring that SAR limits are never exceeded. In this implementation, only one RLAN transmitter is actively sending data at any given time; simultaneous dual-band operation is not supported.[2]

[2] While more than one transmitter cannot send data packets at the same time, transmitters in different bands may send IEEE-802.11 Control Frame transmissions (including ACK, Block ACK, CTS and similar messages) while the other transmitter is sending data. Since all radio transmit activity is monitored by the RLAN chipset at each transmitter and aggregated into the power averaging calculations for the entire RLAN system, this ensures that SAR limits are never exceeded.

3.1 Power Optimization Mode

Power optimization mode is the only mechanism used for power control in DSA. When activated, the output power for the active RLAN transmitter is increased to a higher power level (P_{opt}) by a preset amount defined globally for the device by the *power offset* parameter (see Table 1). If P_{opt} is greater than the maximum power output supported by the device hardware, P_{dev}, then $P_{opt} = P_{dev}$. Proprietary algorithms in the chipset determine the optimal levels for the maximum and minimum threshold levels that bound the normal range for the utilization ratio for a given *power offset* value. The operation of power optimization mode over time is shown in Figure 2.

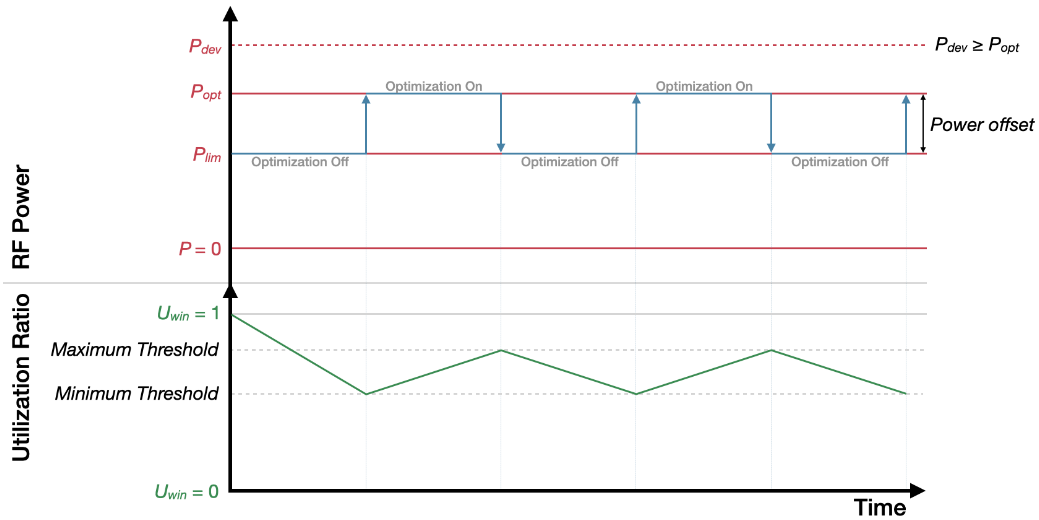

Figure 2. *Operation of Power Optimization Mode*

3.2 Startup Mode

To ensure that no scenario exists where a device could exceed time-averaged SAR limits when it is turned on or reset, the DSA algorithm assumes that the device has been utilizing 100% of the SAR budget for the preceding 60 seconds when it starts up. Optimization mode will not be available until the utilization ratio decreases to the minimum activation threshold level. This is shown in Figure 2.

3.3 Control Parameters

There are only two control parameters for operation of the DSA power optimization function, as summarized in Table 2:

Parameter	Value	Description
Mode	0, 1	Enables or disables power optimization mode
Power offset	0 – 6	Power increase in dB when optimization mode is activated

Table 2. *DSA control parameters*

A specific *Power offset* value is determined for each product to optimize performance of the DSA algorithm, balancing power output and transmit time duration. Both parameters are set in non-volatile memory at the factory and are not user accessible.

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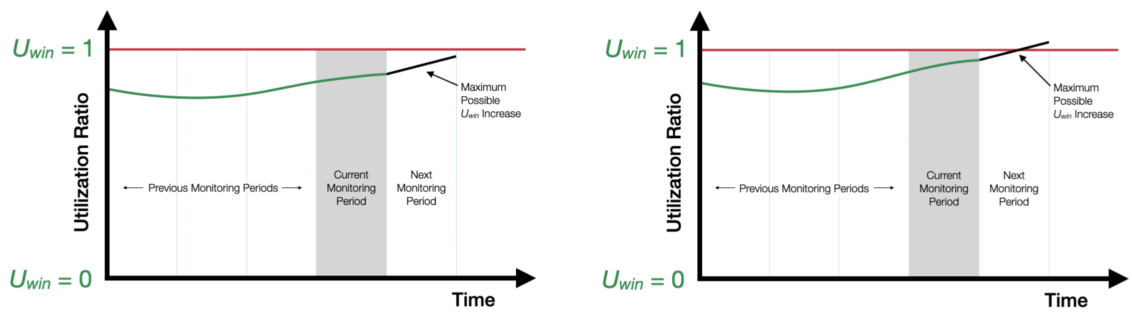
3.4 Protective Power Control

To ensure that maximum time-averaged power limits can never be exceeded while under control of the DSA algorithm, an additional power control function has been implemented. Protective Power Control (PPC) is triggered when the aggregated 60-second average power is close to maximum and the algorithm determines that the limit would be exceeded if all transmitters operate with maximum power and duty cycle during the next (~1 sec) monitoring period. A comparison of conditions where PPC would be triggered or not triggered is shown below:



a) Utilization ratio plus maximum increase below 1.0 at next monitoring period; PPC not triggered

b) Utilization ratio plus maximum increase above 1.0 at next monitoring period; PPC triggered

Figure 3. *Condition triggering PPC activation*

PPC will disable all transmitters until the aggregated average returns to a level where there is no possibility for exceedance during the next monitoring period. Examples of PPC mode being activated and its effect on time-averaged utilization calculations is shown in Appendix C. Even though this scenario is extremely unlikely to occur under typical usage patterns, PPC guarantees that the time-averaged power limit can never be exceeded.

3.5 Per-Packet Tracking Enhancement

For devices with Per-Packet Tracking (PPT) enabled, following every transmission, the RLAN chipset additionally reports measured Tx power (P_{actual}). Using Equation 4, an adjusted transmit duration value normalized relative to P_{max} is calculated.

$$TxDur_{norm} = DC * P_{actual}/P_{max} \quad \text{(Eq. 4)}$$

Where:

$TxDur_{norm}$ = transmit duration normalized to Pmax
DC = Duty Cycle
P_{actual} = Tx power measured from TSSI ADC
P_{max} = Maximum power output of the transmitter within the monitoring period (either P_{lim}, P_{opt}, or P_{dev})

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The RLAN chipset accumulates $TxDur_{norm}$ in per antenna counters. At the end of each monitoring period or upon any change in P_{max}, the $TxDur_{norm}$ value is reported and Utilization calculated as described in Section 3 using adjusted P_{max} value (Equation 5).

$$adjusted\ P_{max} = P_{max} * TxDur_{norm} \quad \text{(Eq. 5)}$$

This feature is an update to the power measurement methodology only with the goal of performing a more accurate Utilization calculation. Please see Appendix E for test data.

4 Compliance and Validation

To validate DSA algorithm implementation for RLAN transmitters, the time-averaging and power control functions of the expected behavior of RLAN transmissions and operating characteristics are compared against power measurement results using power control test sequences that are representative of a range of scenarios.

SAR measurements are performed according to normally required SAR procedures at the maximum time-average power level P_{lim} in all supported RLAN operating conditions for the particular device. SAR reports will present SAR values relative to these P_{lim} values. P_{lim} is the power level that should never be exceeded under any circumstances and the measured SAR is scaled to account for total system tolerance. SAR is measured for RLAN transmitters, in test mode, at P_{lim} with DSA disabled.

To validate the operation of RLAN DSA functions, a set of test scenarios will be defined for each device to characterize DSA operation in both standard use cases and edge-case situations. The specific scenarios will be constructed to validate the operation of the algorithm in all operational states, including transitions between states, and will include the following:

- Connection drop and reacquisition
- Change in channel/band
- Change in antenna
- Change in device state, e.g Cell on/off WiFi power change

Since this DSA implementation does not support full RLAN simultaneous transmit operations and has only one control method, the test scenarios will be fairly simple.

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For each of the test scenarios a transmit test sequence will be created to verify the DSA mechanism. The profile will be modeled using numerical calculation to predict its expected behavior, to establish the expected maximum output power/transmit duration and, by extension, the expected time-averaged SAR utilization ratio over time. The test sequences will then be used to control devices under laboratory test conditions. External measurements of power output from the DUT will be captured alongside real-time data outputs of transmission parameters directly from the RLAN chipset to verify that the results match the expected values. Examples of test scenarios are shown in Appendix C.

FCC input into specific validation scenarios is welcomed.

5 Additional KDB Submittals and Prior KDB Approvals

Dynamic power control and exposure time-averaging for RLAN (DSA) and cellular transmissions (QC-ST) are managed independently within the iPhone.

WWAN and RLAN energy budgets are fixed to maintain compliance considering simultaneous operation. The independent budgets ensure that differences in averaging windows does not impact the overall compliance of the device.

The overall SAR budget for the device is subdivided, with a certain percentage of the budget reserved for RLAN energy and another percentage reserved for WWAN energy. Any other technologies subject to SAR evaluation would likewise be allocated a specific percentage of the budget. The sum of these percentages is, by definition, the total SAR budget for the device. The averaging algorithm applicable to each technology independently calculates the rolling average relative to the apportioned budget for that technology.

The other radio technologies that do not have device-based power control and time-averaging features will each operate independently according to separate power budgets and regulatory requirements. The worst-case Bluetooth maximum output power will be used to determine the exposure ratio for Bluetooth operations.

Separate KDB inquiries have been submitted for approval of cellular device-based dynamic power control and exposure time-averaging using QC-ST (KDB 372448) and approval of numerical simulation for WPT SAR compliance (KDB 839465), also being featured in 2020+ iPhone and iPad products.

Methods described in previously approved KDB inquiries are summarized in Sections 5.1-5.3 will continue to be used in these 2020+ products to establish the maximum output power according to use conditions detected by the device through look-up tables. Since P_{lim} levels for different use conditions are provided by the RLAN power table, the

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selection of different maximum output powers based on device-detected use conditions is transparent to the DSA algorithm.

5.1 WLAN and/or Cellular State Dependent BT Power Table

This is an Apple proprietary feature that determines the state of the WLAN radio and cellular radio and adjusts the output power of the Bluetooth (BT) radio based on that state.

When either RLAN core is transmitting in 5 GHz or cellular transmission is ON or both transmissions are ON at the same time then the BT radio (for a given BT antenna) will transmit at a pre-determined reduced power level, BT $P_{low}1$ or BT $P_{low}2$ or BT $P_{low}3$. When in ULCA mode BT power will be set to the most conservative reduced power state. If the WLAN/cellular state cannot be determined, the BT power will be set to the most conservative reduced power state.

5.2 Cellular State Dependent WLAN Power Table

This is an Apple proprietary feature that determines the state of the cellular radio and cellular antenna to adjust the output power of the RLAN radio.

When cellular transmission is ON then the RLAN radio will transmit at a pre-determined reduced power level, RLAN P_{Low} based on the cellular antenna in use. If cellular transmission is OFF then RLAN radio will start transmitting at the higher power level, RLAN P_{Max}. When in ULCA mode RLAN powers will be set to the most conservative reduced power state. If cellular state cannot be determined, the RLAN power will be set to the most conservative reduced power state.

5.3 Detect Mode Feature

Detect Mode is an Apple proprietary feature that has been approved for use for several generations of iPhone and iPad models which determines if a device is being used against a head, body or stationary non-body surface for the purpose of setting the appropriate conducted output power table.

This feature, which is enabled only during cellular data transmissions, is based on a motion detection algorithm using accelerometer measurements.

In the device, the accelerometer is active and functioning at all times. At the factory, each device goes through an accelerometer calibration and test procedure. If, after calibration, the sensor does not fall in the expected range then the device is discarded. The minimum detectable acceleration is limited by the noise of the sensor.

An example of sensor noise distribution data for the accelerometer in x, y and z axis is shown below:

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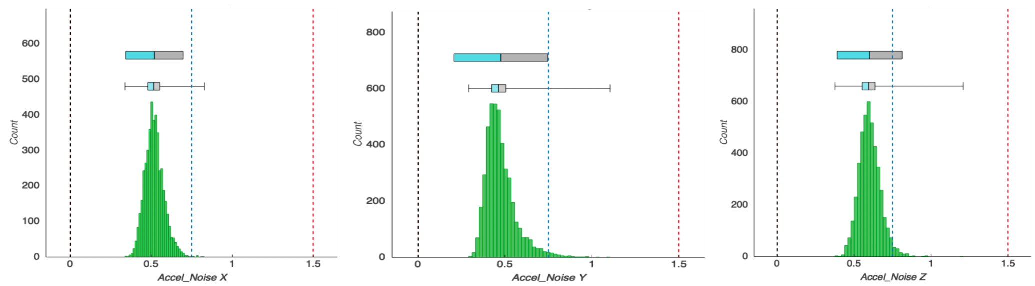

Figure 4. *Accelerometer noise data distributions*

The accelerometer measurements are processed to produce a metric that is sensitive to motion consistent with the device being held by the user or located on a user's body (i.e. in their hands, held against the ear or on their lap). For iPad, the device is declared to be on the body if the computed metric exceeds a priori specified threshold at any point over a finite time interval. If every sample of the metric falls below the threshold during the time interval, the device is declared to be on a stationary object. For iPhone, the off-body case uses the head power table. Therefore, in the power tables there are only two use cases "head" and "body." In the absence of sensor output or detect decision, the device defaults to the failsafe state which is "on body."

The metric threshold is directly dependent on the accelerometer measurement noise characteristics. Every unit from the production line is calibrated and tested to ensure that the sensor of the device meets or exceeds the expected noise characteristics. The length of the time interval monitored for changes in the metric is dependent on a characterization of user motion under a set of use cases involving cellular data transmission.

The algorithm has been tested under practical use cases reviewed and approved by the FCC and applicable to different product types (phone or tablet), including:

A - device resting on a stationary object, both with and without disturbances (i.e. periodic and aperiodic vibrations applied to the stationary object)
B - device being held in the user's hand
C - device resting on the user's lap
D – device being held to the ear

The use cases applicable to each device are specified in the technical description of the certification filing.

Detect Mode algorithm flow-diagram:

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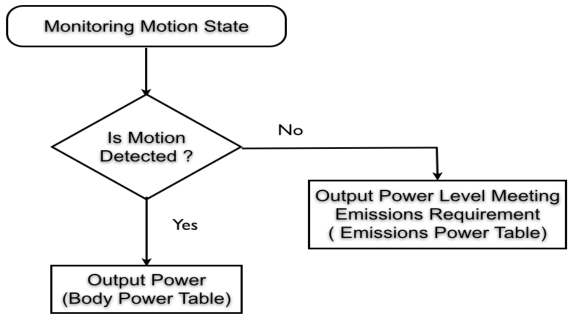

Figure 5. *Process flow diagram for Detect Mode algorithm*

For any given cellular band, *Output Power* level in Body Power Table is always less than the *Output Power* level necessary for meeting emissions requirements for that band (Emissions Power Table).

6 Apple Inquiry

Apple is proposing the methodology described in sections 1-5 above, consistent with the guidance provided by FCC for device-based power averaging. Please confirm that this methodology is acceptable.

Version History

Version	Release Date	Release Notes
1.0	January 8, 2020	Initial Inquiry
1.1.1	March 16, 2020	Incorporates general clarifications and descriptions of previously approved power control methods as requested by FCC, and adds Footnote 2 clarifying how control frame traffic from other RLAN radios is incorporated into the power averaging algorithm.
1.2	June 15, 2020	
1.3	April 14, 2021	Update for Per-Packet Tracking Feature
1.3.1	June 21, 2021	Clarifications for Section 2.1, Section 5. Added Appendix F
1.3.3	July 15, 2021	Update for Appendix F
1.3.4	August 9, 2021	Update for Appendix F
1.3.5	August 17, 2021	Update for Appendix F

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Appendix A: Determining SAR Limits

RLAN DSA power averaging uses empirically derived power levels stored in power tables on each device to calculate power utilization and control power output from RLAN transmitters. RLAN radio systems in different devices may have a variety of configurations, with different bands, transmission cores, antennas, and proximity/use sensing capabilities. Each of these configurations needs to be independently characterized and measured to determine the appropriate power limit (P_{lim}) for each possible set of operating conditions. Since the configurations that need to be characterized are dependent on a specific hardware/software combination, we will use an example to illustrate how the process works.

Consider this 4-core, 2-antenna configuration:

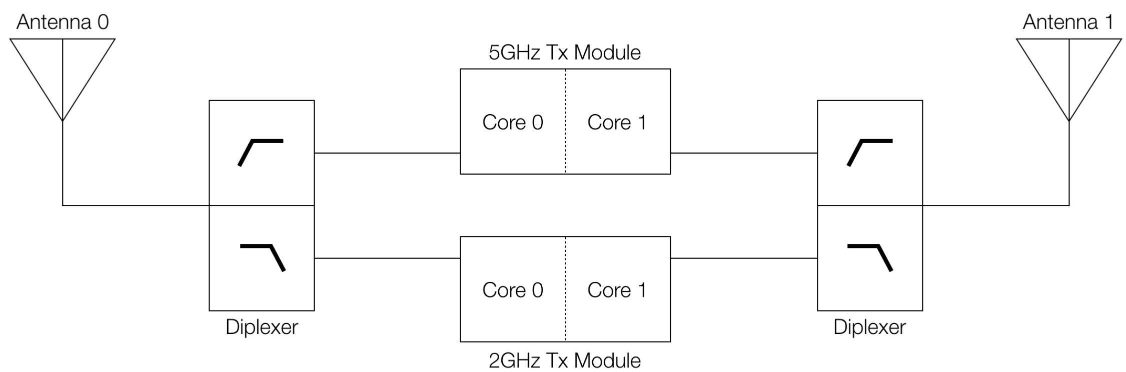

Figure 6. *4-core, 2-antenna RLAN configuration*

Along with this hardware configuration, we will also assume the implementation of a two-state proximity/use detection algorithm that identifies operation of the representative device in one of two different proximity or use states. This combination of hardware and proximity/use detection state results in the following operational decision tree:

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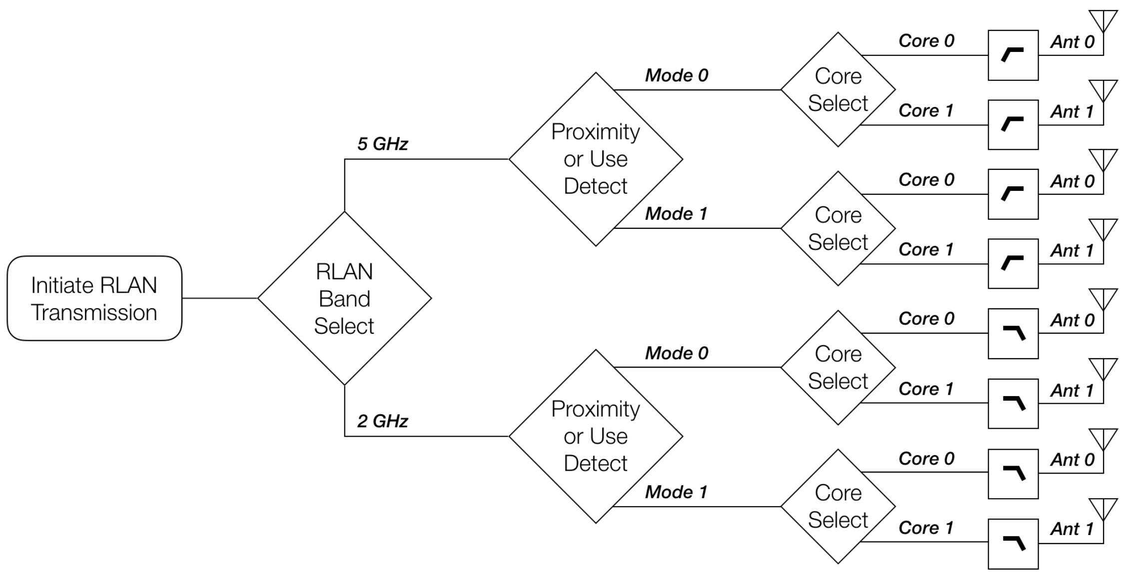

Figure 7. *Operational decision tree in representative RLAN configuration*

From the decision tree, we can derive the eight discrete signal paths that must be characterized with SAR measurements to determine the P_{lim} for each:

Configuration	Band	Proximity/Use	Core	Diplexer	Antenna
1	5 GHz	Mode 0	Core 0	High-pass	Ant 0
2	5 GHz	Mode 0	Core 1	High-pass	Ant 1
3	5 GHz	Mode 1	Core 0	High-pass	Ant 0
4	5 GHz	Mode 1	Core 1	High-pass	Ant 1
5	2 GHz	Mode 0	Core 0	Low-pass	Ant 0
6	2 GHz	Mode 0	Core 1	Low-pass	Ant 1
7	2 GHz	Mode 1	Core 0	Low-pass	Ant 0
8	2 GHz	Mode 1	Core 1	Low-pass	Ant 1

Table 3. *Discrete signal paths in representative RLAN configuration*

A device using this example configuration would then be fully characterized through SAR measurements performed in accordance with the guidance in KDB publication 248227 to determine the maximum power level P_{lim} that will not exceed the SAR limit while operating in each of the eight discrete operational states in Table 3. These power limits would then be compiled into a power table that is loaded into the device-specific firmware controlling the RLAN radios. For devices with different configurations, the identification of discrete operating states and measurement of each state to determine P_{lim} values will be conducted in a similar manner.

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Appendix B: Hardware Implementation

The DSA algorithm is designed to work on Broadcom model 4387 and subsequent RLAN chipsets. A dedicated DSA module in the chipset collects and stores transmit duration and maximum power level data from the microcode radio module. At each monitoring period, supervisor code calculates utilization ratios for each transmitter and aggregates ratios for each antenna over the preceding nominal 60-second time-averaging window. Based on these ratios, the supervisor will communicate with the Media Access Control module to enable or disable Optimized Mode power limits for the next monitoring period. The MAC module then uses these limits and preloaded power tables to manage the transmission parameters of the microcode radio. The host platform provides only high-level configuration parameters to the DSA module on system startup and can access transmission parameter logs from the DSA module database for regulatory compliance and troubleshooting purposes. The relationship between the system functions is detailed in the diagram below:

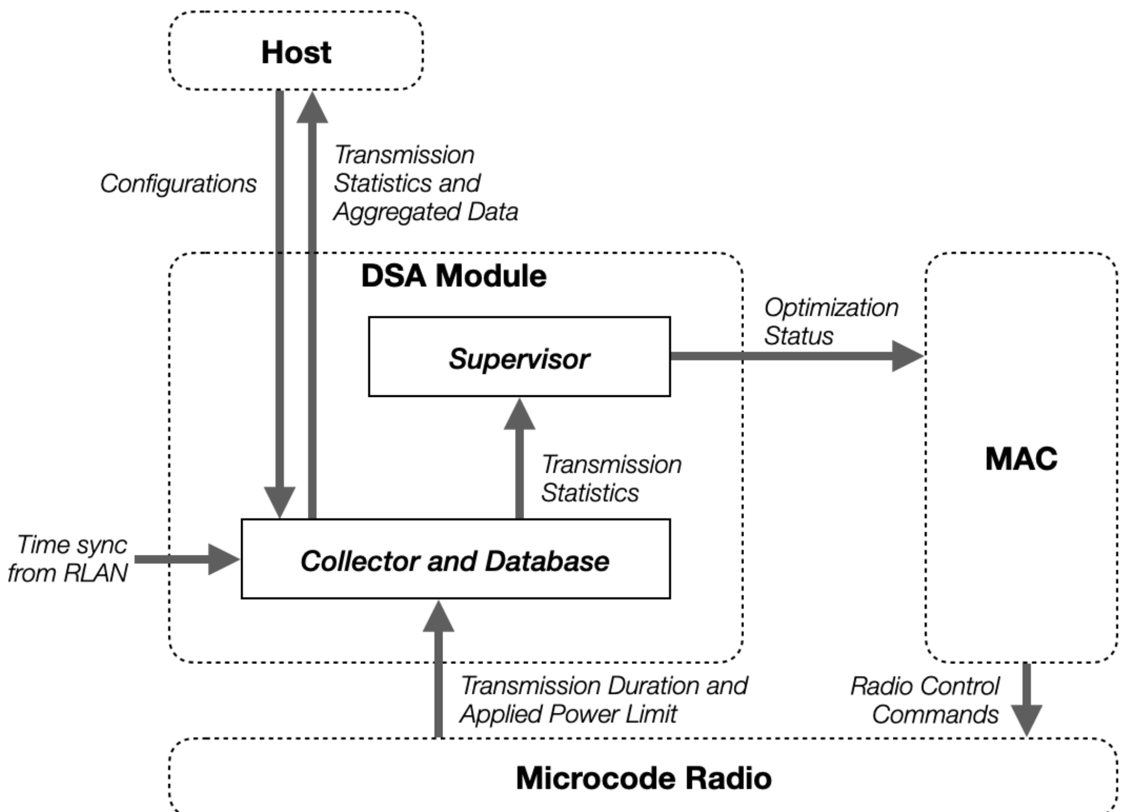

Figure 8. *DSA system diagram*

The microcode radio measures transmit duration in microseconds and those values are stored in the DSA Module database. Time intervals used in DSA calculations are controlled by the RLAN chipset, which in turn is synchronized with an access point when connected. IEEE 802.11 specifications define a basic Time Unit of 1024 µsec, and the standard beacon interval of an access point is set to 100 TU, or 102.4 msec. The

RLAN chipset can perform DSA functions at every third beacon interval (307.2 msec). Monitoring period durations are derived from this clock frequency, so they are typically 921.6 msec (3 intervals) or 1228.8 msec (4 intervals) in duration in order to keep the period as close to 1 second in duration as possible. The duration of the time-averaging window is determined by the aggregate total duration of monitoring periods up to, but not exceeding, 60 seconds.

Note that beacon signals may be skipped during high transmit duty cycle periods and in some cases access points are configured with other beacon interval values, leading to variations in the duration of the monitoring period and, by extension, the nominal 60-second time-averaging window. However, all power averaging calculations are based on actual transmit durations measured and stored by the chipset in microseconds. This, along with the use of utilization ratios to track RF energy contributions, ensures that the DSA algorithm is accurately tracking the overall system utilization ratio independent of the 802.11 beacon frequency.

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Appendix C: DSA Functional Example

To help understand how the DSA algorithm functions under typical operating conditions, the following illustrated example is provided. For this example,

- The P_{lim} power level of a single 5 GHz RLAN transmitter was fixed at 10 dBm
- Power optimization was enabled with 3 dB offset
- Total system utilization ratio at the beginning of the test sequence is at 86%
- A sequence of test transmissions were initiated by the test automation system with varying transmit durations, resulting in the following duty cycle sequence:
    - 30% from 0–20 seconds
    - 60% from 20–65 seconds
    - 30% from 65–120 seconds.

Synchronized operational data was recorded from internal firmware and external power monitors. The data was plotted in two graphs over time relative to a) the utilization limit and b) instantaneous average power level. Tabular data for each graph is shown in the following tables. "Reported" values were output and captured directly from DUT firmware, while "Measured" results were obtained from external power metering. The RLAN chipset in this DUT applies a 1.5 dB uncertainty budget to all power control functions, ensuring that Reported power levels are always higher than Measured values.

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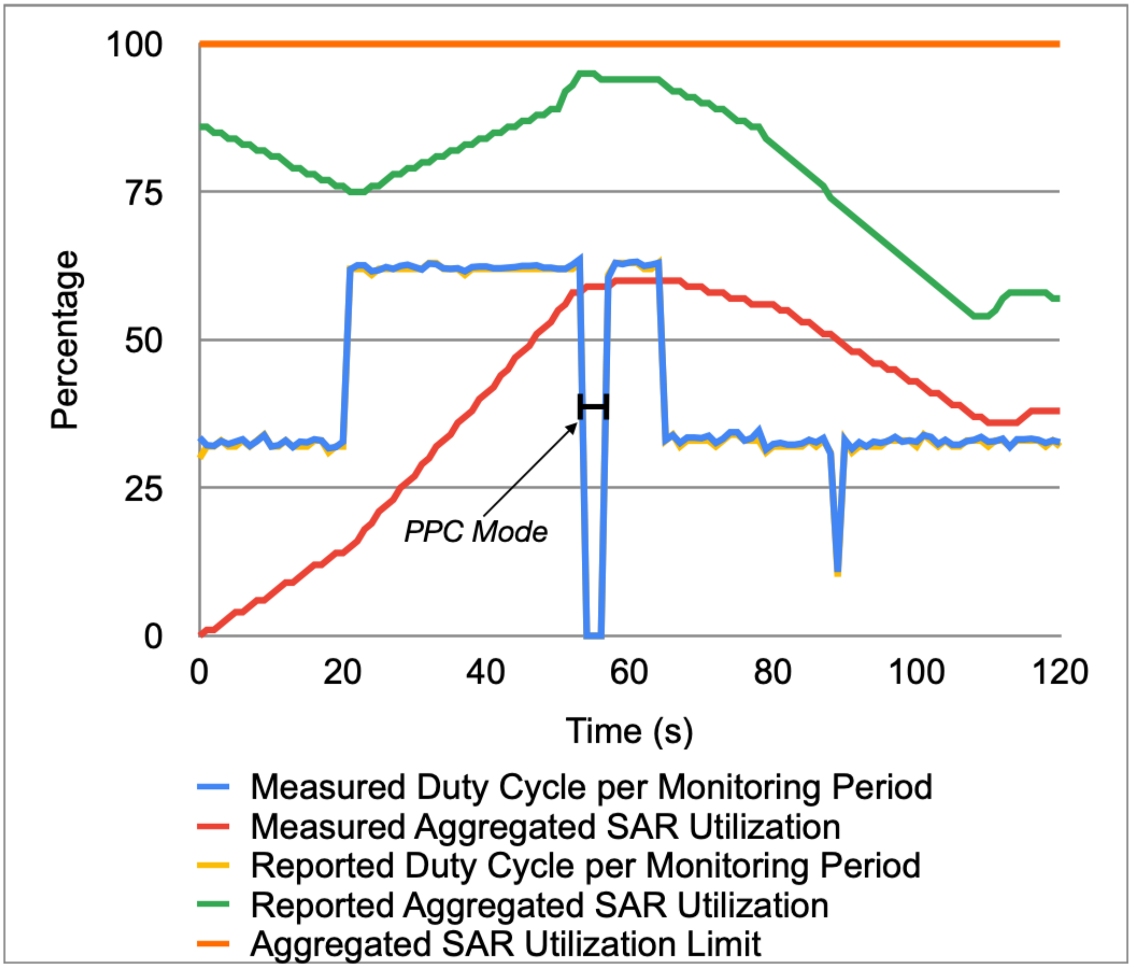

Figure 9. *Aggregated SAR Utilization and Duty Cycle vs. Time, duty cycle sequence*

Figure 9 shows the relationship between the transmit duty cycle and system utilization ratio over time. The orange line represents the utilization ratio limit of 100% for reference. When the test sequence begins at Time=0 s, the measured (blue) and reported (yellow) duty cycle are at the 30% level under the control of test automation. The firmware is reporting 86% utilization ratio (green) to represent an actively operating device with transmission history stored from previous monitoring periods. The measured utilization ratio (red) begins at 0% since the external power meter does not have any stored history.

As time approaches 20 s, the measured utilization increases at a constant rate, while the reported utilization gradually decreases from its initial state. At 20 s, both measured and reported duty cycle increase to 60%, as expected due to the preset test sequence. The change is also reflected in the measured utilization curve, which begins to increase at a faster rate, and the reported utilization curve, which reverses course and begins to increase again.

As the reported utilization curve approaches the 100% limit at around Time=50 s, the DSA algorithm determines that a risk exists for the total utilization ratio to exceed the limit in a future monitoring period and triggers Protective Power Control mode at Time = 54 s. This turns off the RLAN transmitter until the DSA algorithm determines that there is no longer a risk of exceedance, at Time = 57 s. The effect of the PPC activation can be clearly seen in the duty cycle curves as they drop to 0% and in both utilization curves as they reach a plateau. After PPC is deactivated, the duty cycle curves return immediately to 60% but the utilization curves are no longer increasing. This is due to the deactivation of Optimization Mode, which will be discussed in detail in the next graph.

At Time = 65 s, test automation reduces the duty cycle to 30%. This is shown by both duty cycle curves and reflected in the gradual decrease of both measured and reported utilization ratios. Note that the utilization ratio curves are now tracking closely, since after Time = 60 s, both are calculating the time-averaged ratio from the same preceding 60 seconds of transmission history. The delta between the curves is due to a 1.5 dB uncertainty budget included in the reported power data from the firmware, while the measured data is reporting actual power output of the transmitter. The reported data will always be greater than the measured data.

The brief drop in duty cycle at Time = 89 s is normal IEEE-802.11 chipset behavior and is unrelated to the DSA algorithm.

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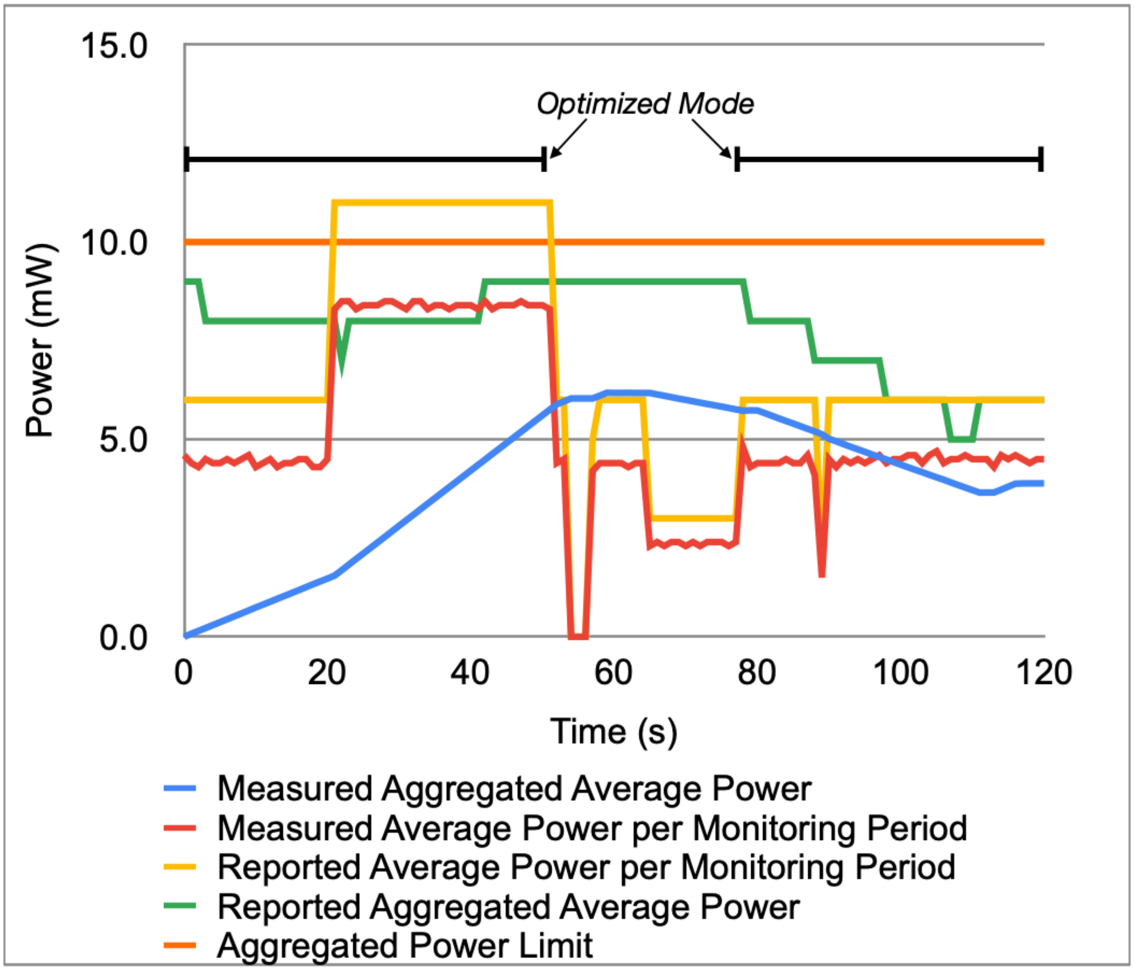

Figure 10. *Average Power vs. Time, duty cycle sequence*

Figure 10 shows the same test scenario over the same time period as in Figure 9, but this instead shows the variation in average power over time. The orange line indicates the P_{lim} value of 10 dBm for this test scenario. The average power over the duration of each monitoring period is shown for both reported (yellow) and measured (red) results. The average power aggregated over the 60-second time-average window is shown in green for reported data and blue for measured data. Power data from this version of firmware was reported in 1 mW increments. The 1.5 dB uncertainty budget described above applies to all power data in this graph.

As seen in the utilization ratio curves in Figure 9, the average power reported by the system over the prior 60 s begins at a high level while the measured power begins at 0. The DSA algorithm has calculated that enough margin in the utilization ratio exits for Optimized Mode to be enabled, so the instantaneous transmit power is allowed to increase to 20 mW. As the duty cycle increases to 60% at Time = 20 s, the average power at each monitoring period increases accordingly and the aggregate average power curves show the change.

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At Time = 52 s, the maximum threshold is reached and the DSA algorithm disables Optimized Mode, causing the monitoring period average powers to drop by 3 dB. As discussed above, this is followed shortly by the activation of PPC mode at Time = 54 s and the complete cessation of transmissions for 3 seconds. Average power returns to non-optimized levels until Time = 65 s, when test automation reduces the transmit duty cycle to 30%. The aggregated power curves gradually begin to decrease.

When the DSA algorithm determines that the utilization ratio is below the minimum threshold level, it reactivates Optimization Mode at Time = 78 s and the monitoring period average power curves increase by 3 dB. The brief transmission interruption mentioned above occurs at Time = 89 s.

The aggregate average power curves track all the power changes as expected, always staying below the 10 mW P_{lim} level.

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Time	*Measured Duty Cycle*	*Measured SAR Utilization*	*Reported Duty Cycle*	*Reported SAR Utilization*	**Time**	*Measured Duty Cycle*	*Measured SAR Utilization*	*Reported Duty Cycle*	*Reported SAR Utilization*
0	33.5	0	30	86	**61**	63.2	60	63	94
1	32.2	1	32	86	**62**	62.5	60	62	94
2	32.1	1	32	85	**63**	62.7	60	62	94
3	32.9	2	33	85	**64**	63	60	63	94
4	32.4	3	32	84	**65**	33.1	60	33	93
5	32.8	4	32	84	**66**	33.9	60	34	92
6	33.2	4	33	83	**67**	32.6	60	32	92
7	32.1	5	32	83	**68**	33.5	59	33	91
8	32.9	6	33	82	**69**	33.5	59	33	91
9	33.9	6	34	82	**70**	33.4	59	33	90
10	32	7	32	81	**71**	33.8	58	33	90
11	32.2	8	32	81	**72**	32.6	58	32	89
12	33	9	33	80	**73**	33.3	58	33	89
13	31.9	9	32	79	**74**	34.4	57	34	88
14	32.8	10	32	79	**75**	34.4	57	34	87
15	32.7	11	32	78	**76**	33	57	33	87
16	33.2	12	33	78	**77**	33.4	56	33	86
17	33	12	33	77	**78**	34.7	56	33	86
18	31.7	13	31	77	**79**	31.5	56	31	84
19	31.9	14	32	76	**80**	32.4	56	32	83
20	32.8	14	32	76	**81**	32.6	55	32	82
21	61.9	15	62	75	**82**	32.3	55	32	81
22	62.6	16	62	75	**83**	32.3	54	32	80
23	62.6	18	62	75	**84**	32.5	53	32	79
24	61.6	19	61	76	**85**	33.1	53	33	78
25	61.8	21	62	76	**86**	32.7	52	32	77
26	62.3	22	62	77	**87**	33.4	51	33	76
27	62	23	62	78	**88**	30.8	51	31	74
28	62.5	25	62	78	**89**	10.8	50	10	73
29	62.7	26	62	79	**90**	33.1	49	33	72
30	62.3	27	62	79	**91**	31.6	48	31	71
31	61.9	29	62	80	**92**	32.7	48	32	70
32	62.9	30	63	80	**93**	32	47	32	69
33	62.8	32	63	81	**94**	32.8	46	32	68
34	62.1	33	62	81	**95**	32.6	46	32	67
35	62	34	62	82	**96**	32.9	45	33	66
36	62.1	36	62	82	**97**	33.6	45	33	65
37	61.6	37	61	83	**98**	32.8	44	33	64
38	62.3	38	62	83	**99**	33	43	33	63
39	62.4	40	62	84	**100**	32.8	43	32	62
40	62.4	41	62	84	**101**	33.9	42	34	61
41	62.1	42	62	85	**102**	33.6	41	33	60
42	62.1	44	62	85	**103**	32.4	41	32	59
43	62.2	45	62	86	**104**	33.1	40	33	58
44	62.3	47	62	86	**105**	32.3	39	32	57
45	62.5	48	62	87	**106**	32.3	39	32	56
46	62.5	49	62	87	**107**	32.9	38	33	55
47	62.6	51	62	88	**108**	33.1	37	33	54
48	62.2	52	62	88	**109**	33.6	37	33	54
49	62.2	53	62	89	**110**	32.8	36	32	54
50	62	55	62	89	**111**	32.9	36	33	55
51	62	56	62	92	**112**	33.3	36	33	57
52	62.7	58	62	93	**113**	31.9	36	32	58
53	63.6	58	63	95	**114**	33.2	36	33	58
54	0	59	0	95	**115**	33.2	37	33	58
55	0	59	0	95	**116**	33.3	38	33	58
56	0	59	0	94	**117**	33.1	38	33	58
57	60.5	59	61	94	**118**	32.6	38	32	58
58	63	60	63	94	**119**	33	38	33	57
59	62.8	60	63	94	**120**	32.7	38	32	57
60	63.1	60	63	94					

Table 4. *Aggregated SAR Utilization and Duty Cycle vs. Time, duty cycle sequence*

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Time	*Measured Aggregated Average Power*	*Measured Average Power per Monitoring Period*	*Reported Average Power per Monitoring Period*	*Reported Aggregated Average Power*	*Time*	*Measured Aggregated Average Power*	*Measured Average Power per Monitoring Period*	*Reported Average Power per Monitoring Period*	*Reported Aggregated Average Power*
0	0.0	4.6	6	9	**61**	6.2	4.4	6	9
1	0.1	4.4	6	9	**62**	6.2	4.3	6	9
2	0.2	4.3	6	9	**63**	6.2	4.4	6	9
3	0.2	4.5	6	8	**64**	6.2	4.4	6	9
4	0.3	4.4	6	8	**65**	6.2	2.3	3	9
5	0.4	4.4	6	8	**66**	6.1	2.4	3	9
6	0.4	4.5	6	8	**67**	6.1	2.3	3	9
7	0.5	4.4	6	8	**68**	6.1	2.4	3	9
8	0.6	4.5	6	8	**69**	6.0	2.4	3	9
9	0.7	4.6	6	8	**70**	6.0	2.3	3	9
10	0.7	4.3	6	8	**71**	6.0	2.4	3	9
11	0.8	4.4	6	8	**72**	5.9	2.3	3	9
12	0.9	4.5	6	8	**73**	5.9	2.4	3	9
13	1.0	4.3	6	8	**74**	5.9	2.4	3	9
14	1.0	4.4	6	8	**75**	5.8	2.4	3	9
15	1.1	4.4	6	8	**76**	5.8	2.3	3	9
16	1.2	4.5	6	8	**77**	5.8	2.4	3	9
17	1.3	4.5	6	8	**78**	5.7	4.8	6	9
18	1.3	4.3	6	8	**79**	5.7	4.3	6	8
19	1.4	4.3	6	8	**80**	5.7	4.4	6	8
20	1.5	4.5	6	8	**81**	5.7	4.4	6	8
21	1.6	8.3	11	8	**82**	5.6	4.4	6	8
22	1.7	8.5	11	7	**83**	5.5	4.4	6	8
23	1.8	8.5	11	8	**84**	5.5	4.5	6	8
24	2.0	8.3	11	8	**85**	5.4	4.4	6	8
25	2.1	8.4	11	8	**86**	5.3	4.4	6	8
26	2.3	8.4	11	8	**87**	5.3	4.6	6	8
27	2.4	8.4	11	8	**88**	5.2	4.1	6	7
28	2.5	8.5	11	8	**89**	5.1	1.5	2	7
29	2.7	8.5	11	8	**90**	5.0	4.5	6	7
30	2.8	8.4	11	8	**91**	5.0	4.3	6	7
31	3.0	8.3	11	8	**92**	4.9	4.5	6	7
32	3.1	8.5	11	8	**93**	4.8	4.4	6	7
33	3.2	8.5	11	8	**94**	4.8	4.5	6	7
34	3.4	8.3	11	8	**95**	4.7	4.4	6	7
35	3.5	8.4	11	8	**96**	4.6	4.5	6	7
36	3.7	8.4	11	8	**97**	4.6	4.6	6	7
37	3.8	8.3	11	8	**98**	4.5	4.4	6	6
38	3.9	8.4	11	8	**99**	4.4	4.5	6	6
39	4.1	8.4	11	8	**100**	4.4	4.5	6	6
40	4.2	8.4	11	8	**101**	4.3	4.6	6	6
41	4.4	8.3	11	8	**102**	4.2	4.6	6	6
42	4.5	8.5	11	9	**103**	4.2	4.4	6	6
43	4.6	8.3	11	9	**104**	4.1	4.6	6	6
44	4.8	8.4	11	9	**105**	4.0	4.7	6	6
45	4.9	8.4	11	9	**106**	4.0	4.4	6	6
46	5.1	8.4	11	9	**107**	3.9	4.5	6	5
47	5.2	8.5	11	9	**108**	3.8	4.5	6	5
48	5.3	8.4	11	9	**109**	3.8	4.6	6	5
49	5.5	8.4	11	9	**110**	3.7	4.5	6	5
50	5.6	8.4	11	9	**111**	3.7	4.5	6	6
51	5.8	8.3	11	9	**112**	3.7	4.5	6	6
52	5.9	4.4	6	9	**113**	3.7	4.3	6	6
53	6.0	4.5	6	9	**114**	3.7	4.6	6	6
54	6.0	0	0	9	**115**	3.8	4.5	6	6
55	6.0	0	0	9	**116**	3.9	4.6	6	6
56	6.0	0	0	9	**117**	3.9	4.5	6	6
57	6.0	4.2	5	9	**118**	3.9	4.4	6	6
58	6.1	4.4	6	9	**119**	3.9	4.5	6	6
59	6.2	4.4	6	9	**120**	3.9	4.5	6	6
60	6.2	4.4	6	9					

Table 5. *Average Power vs. Time, duty cycle sequence*

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Appendix D: Compliance Validation Examples, PPT disabled

The examples in this section show the DSA validation tests proposed to be performed on devices utilizing DSA during certification testing at third-party labs. These tests utilized late-stage DSA firmware on development hardware and the methodology described in Section 4 to demonstrate the proper functioning of the core DSA algorithm in transition scenarios. The final hardware and firmware configurations for certification will be substantially similar to those tested.

Predefined transmit profiles for each test scenario were created in test automation software to control the operation of the DUT while synchronized operational data was recorded from internal firmware and external power monitors. The data was plotted over time relative to the utilization limit to demonstrate that the maximum time-averaged power is never exceeded. "Reported" values were output and captured directly from DUT firmware, while "Measured" results were obtained from external power metering. The RLAN chipset in this DUT applies a 1.5 dB uncertainty budget to all power control functions, ensuring that Reported power levels are always higher than Measured values.

Transmitter power is fixed at 10 dBm for all tests in this Appendix. As previously described, for projects with PPT disabled, the algorithm does not track actual instantaneous transmit power but assumes that all transmitters are operating at the maximum power specified in the applicable power table. For projects with PPT enabled, the algorithm tracks actual instantaneous transmit power and applies a transmit duration factor weighted for P_{max}. In both cases, transmit duration is the variable controlled by the transmit profile to effect changes in utilization ratio during testing, represented as duty cycle in the following plots. The time periods when Power Optimized Mode and PPC Mode are active are also shown on the plots for reference.

In device certification filings, the test plots comparable to Figures 11–18 will be included in the Technical Description (long term confidential) when submitted to the TCB and FCC.

Scenario 1: Change in Antenna

For this test, the effect on the DSA algorithm from a change in the active transmit antenna is shown. The algorithm includes an internal mapping of individual transmitters to specific antennas so that all energy contributions can be properly aggregated. In the case of this specific DUT, Antenna 0 and Antenna 1 are located on opposite sides of the device so their respective power contributions are aggregated independently with no impact on the other.

Figures 11–12 show a switch of 2 GHz transmissions from antenna 0 to antenna 1 at Time = 120 s, while Figures 13–14 show a comparable transition for 5 GHz transmissions. In both cases the test automation is controlling the RLAN radios to

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operate at 100% duty cycle. In both cases the utilization ratio never exceeds 100% and the average transmit power never exceeds the P_{lim} of 10 mW.

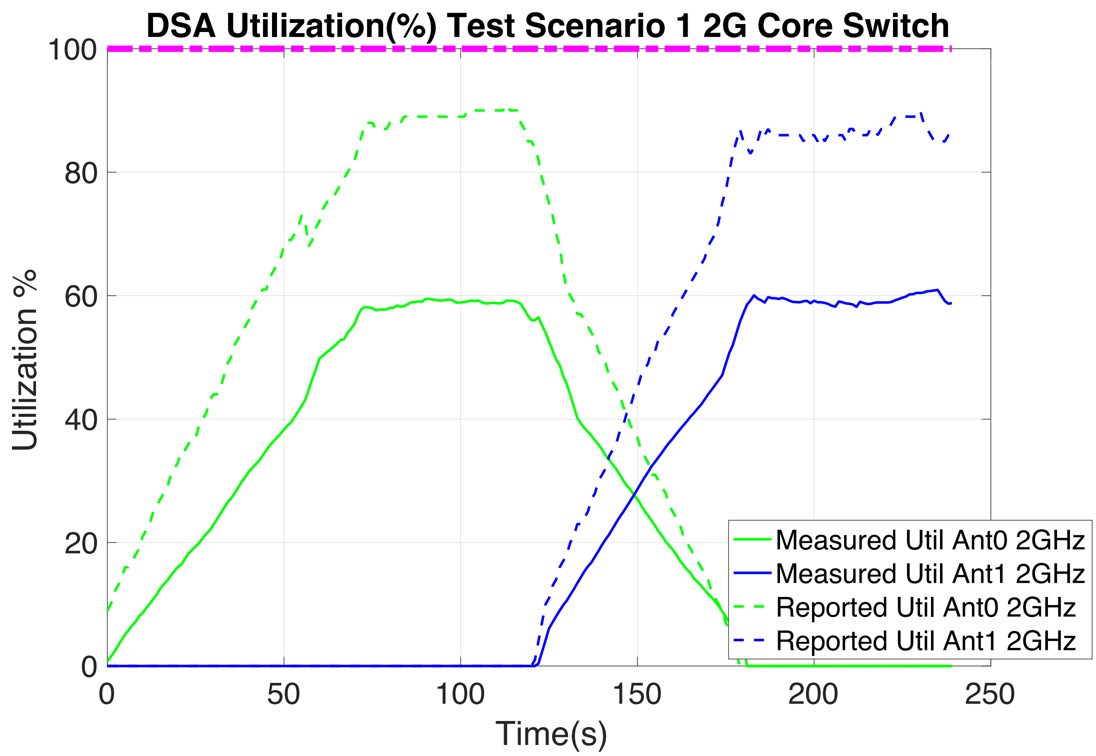

Figure 11. *Aggregated SAR Utilization vs. Time, 2 GHz, PPT disabled*

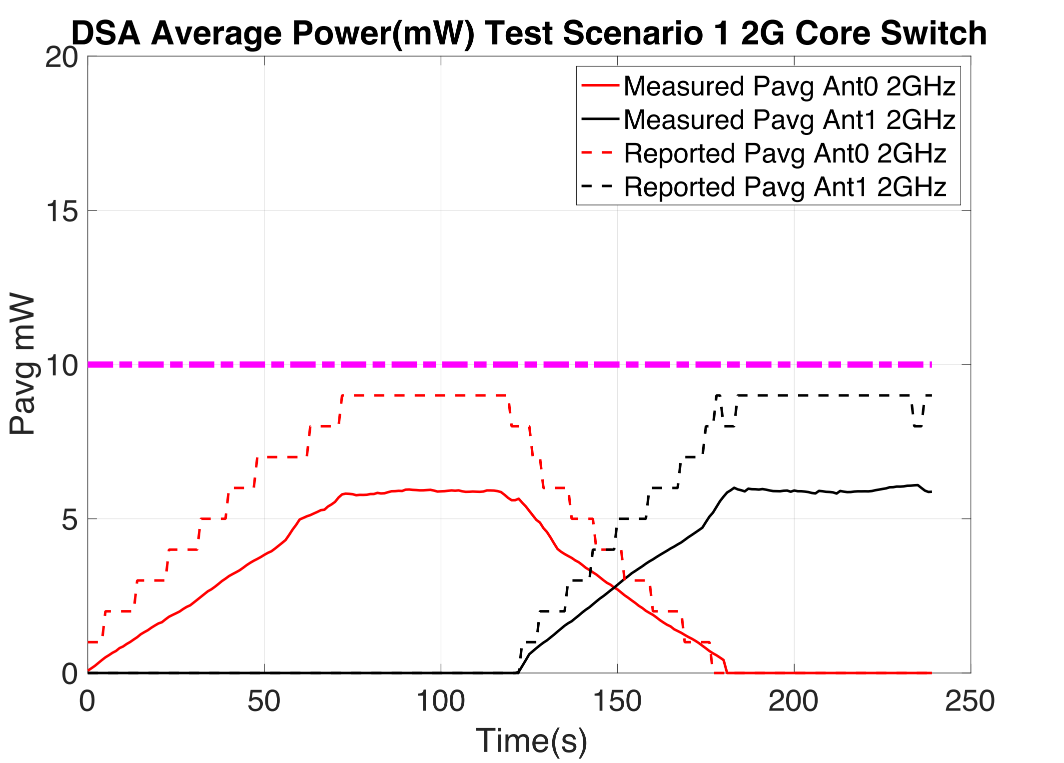

Figure 12. *Average Power vs. Time, 2 GHz, PPT disabled*

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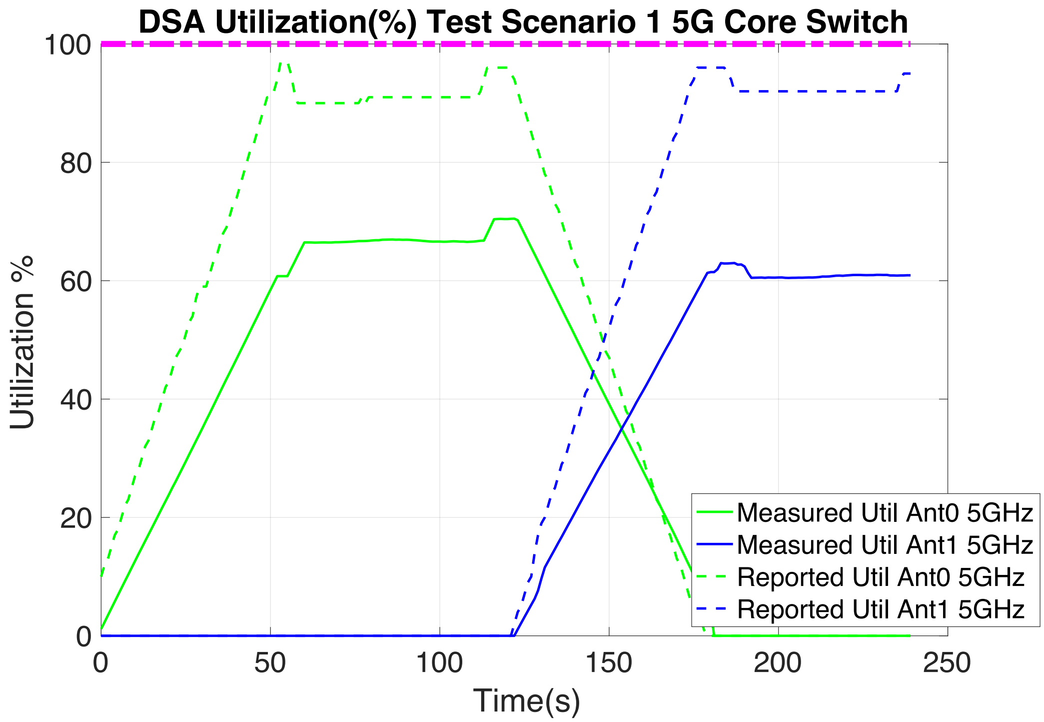

Figure 13. *Aggregated SAR Utilization vs. Time, 5 GHz, PPT disabled*

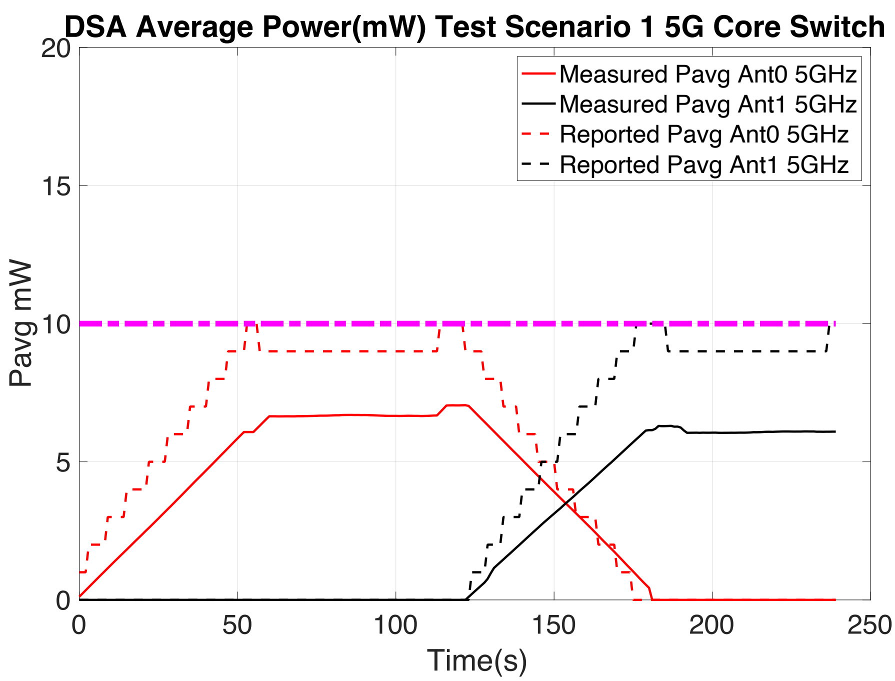

Figure 14. *Average Power vs. Time, 5 GHz, PPT disabled*

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Scenario 2: Change in Channel/Band Test Case (Includes Connection Drop/Reacquisition)

This test demonstrates the efficacy of the DSA algorithm while switching between 2 GHz and 5 GHz RLAN bands. In addition, it shows that the DSA algorithm correctly tracks time-averaged power and system utilization when the active transmitter is disabled and then reconnects.

The 2 GHz RLAN transmitter is active at 100% duty cycle until Time = 120 s. When 2 GHz transmission cease, the 5 GHz transmitter is activated and begins to negotiate a new connection. The measured data from the tests clearly shows the 5 GHz transmitter beginning to transmit and then reaching a plateau while the new connection is negotiated. At Time = 133 s the connection is established and the increase in average transmit power and utilization can clearly be seen.

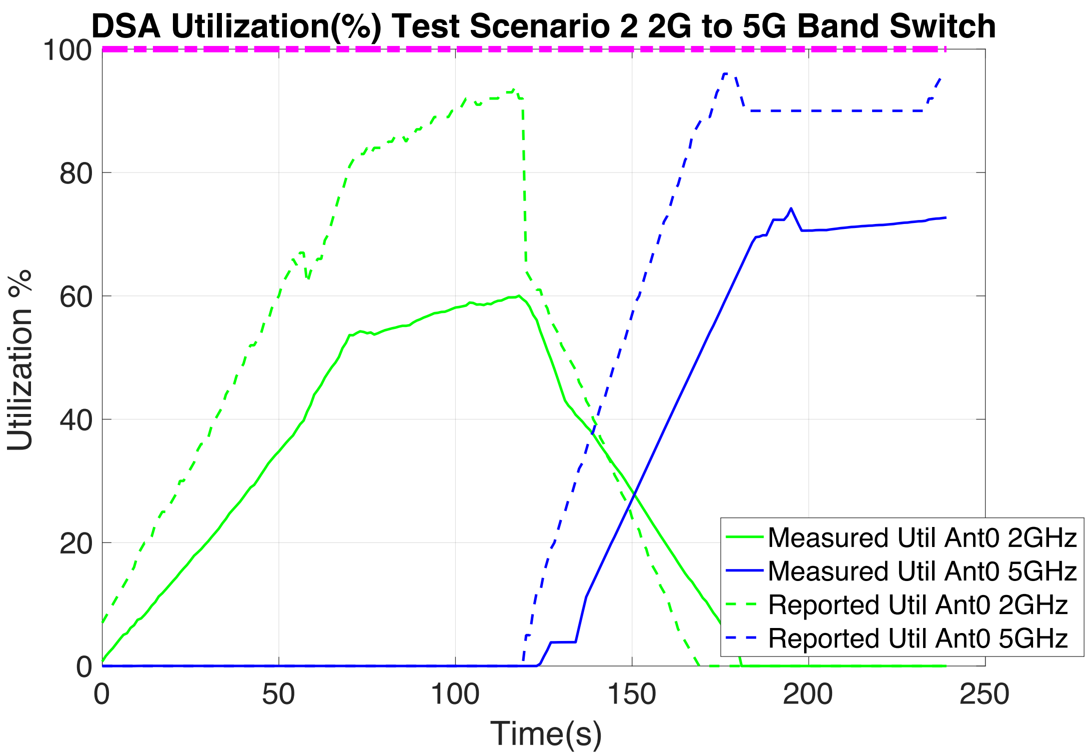

Figure 15. *Utilization vs. Time during Band Switch, 100% duty cycle, PPT disabled*

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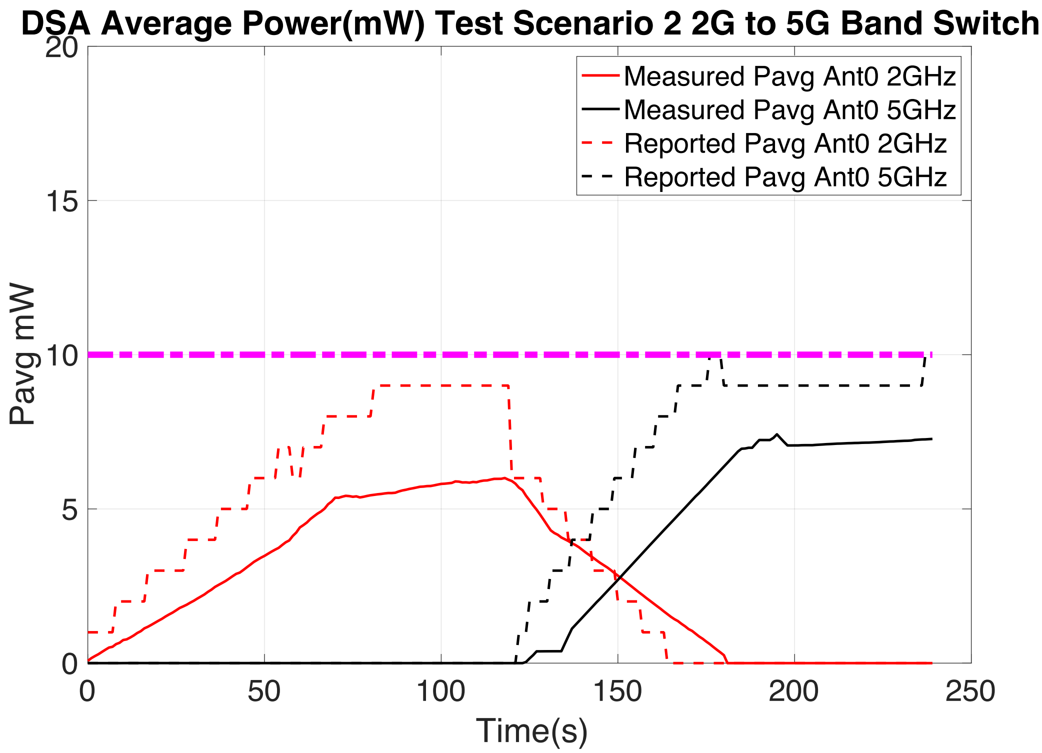

Figure 16. *Average Power vs. Time during Band Switch, 100% duty cycle, PPT disabled*

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Scenario 3: Change in Device State
For this test an external power control trigger is activated, transitioning between cell off and cell on states at Time = 120 s. As shown in Figures 17–18, this change has no discernable impact on the average power or utilization ratio.

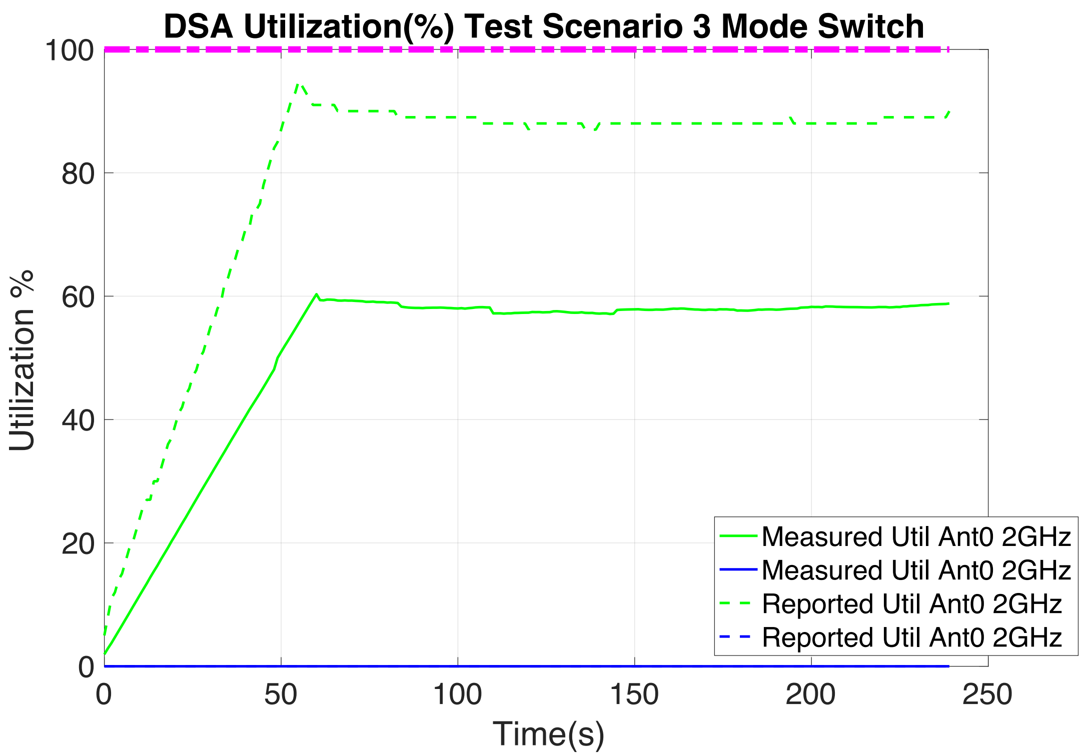

Figure 17. *Utilization vs. Time during Mode Switch, 100% duty cycle, PPT disabled*

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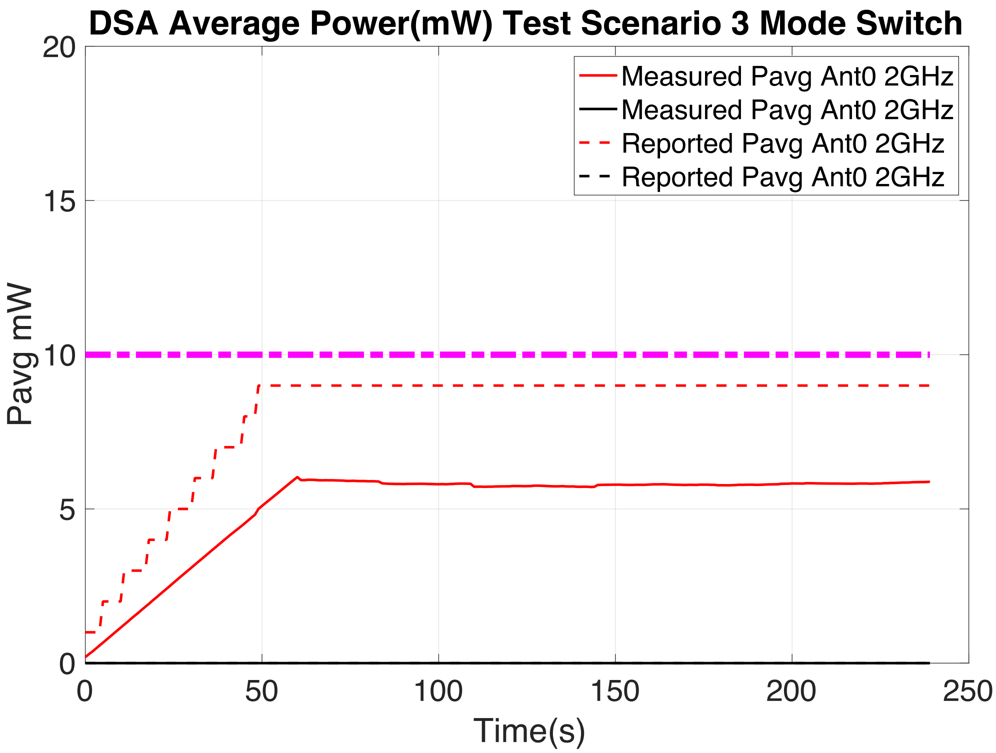

Figure 18. *Average Power vs. Time, duty cycle sequence, PPT disabled*

Appendix E: Compliance Validation Examples, PPT enabled

The examples in this section show Utilization plots with the Per-Packet Tracking feature enabled. The same predefined transmit profiles outlined in Appendix D were performed using development hardware with applicable power levels and late-stage DSA firmware.

The Utilization curves presented in Figures 19-21 closely follow those presented in Appendix D. No discernable change in Utilization is noted between enabling or disabling the PPT feature. Thus, the previously approved validation procedure will be implemented for devices with PPT enabled.

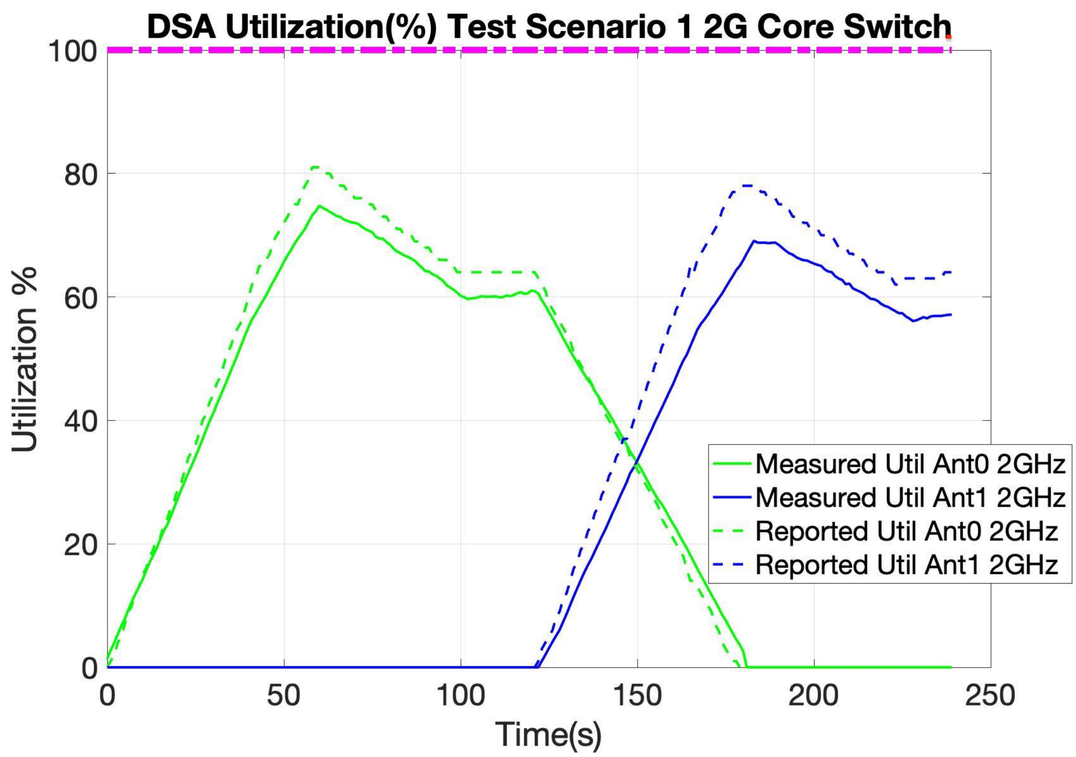

Figure 19. *Aggregated SAR Utilization vs. Time, 2 GHz, PPT enabled*

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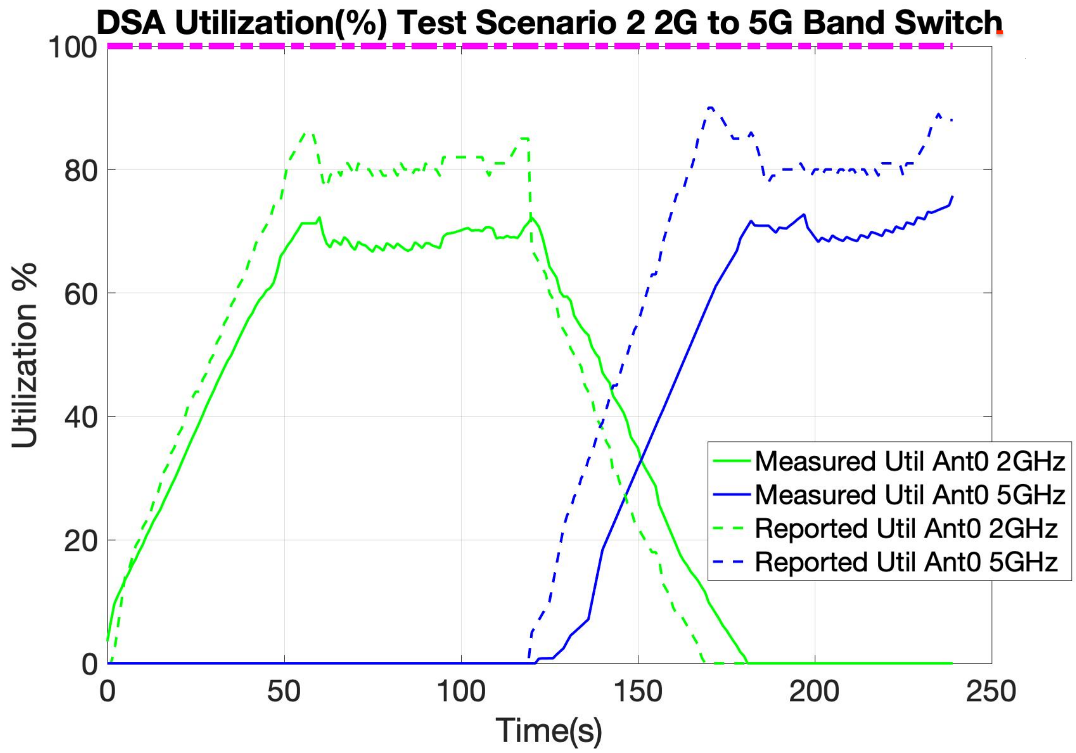

Figure 20. *Utilization vs. Time during Band Switch, 100% duty cycle, PPT enabled*

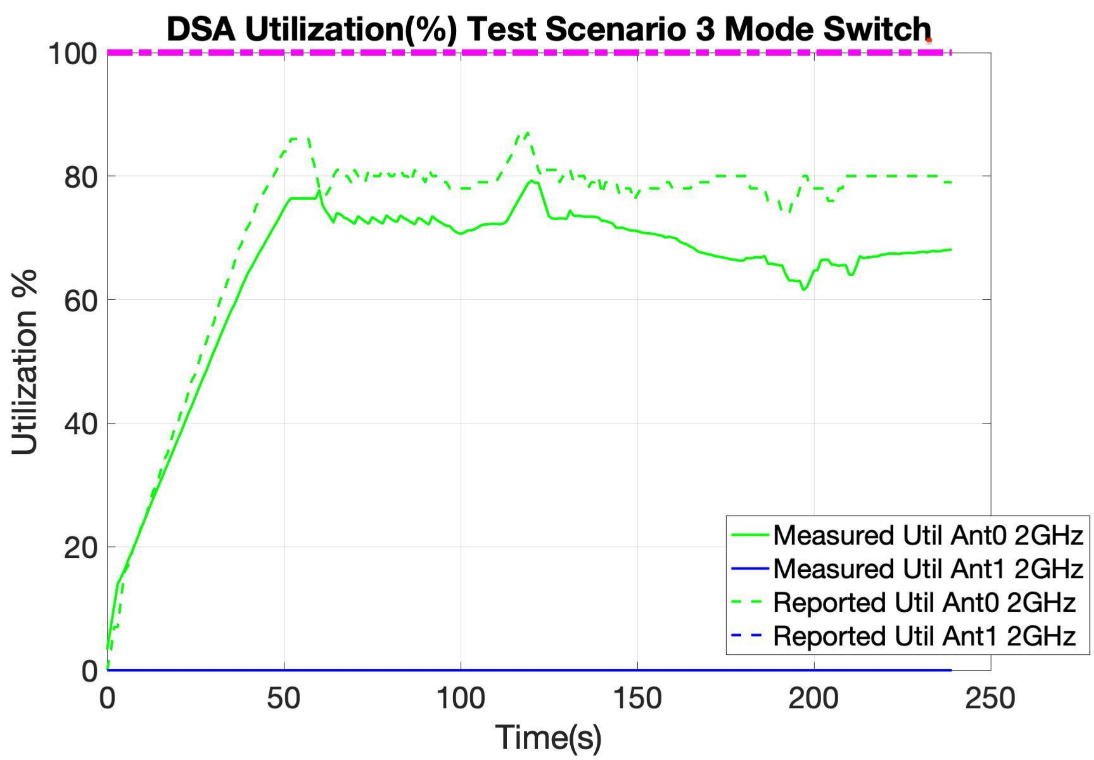

Figure 21. *Utilization vs. Time during Mode Switch, 100% duty cycle, PPT enabled*

Appendix F: FCC Communication

FCC response on 06/10/2021

1) On a somewhat separate but overlapping topic, the following concerns have come to our attention.

For reference, Sec. 5 paras. 1 and 2 of V1.3.0 says:

> Dynamic power control and exposure time-averaging for RLAN (DSA) and cellular transmissions (QT-ST) are managed independently within the iPhone. The overall SAR budget for the device is subdivided, with a certain percentage of the budget reserved for RLAN energy and another percentage reserved for WWLAN energy. Any other technologies subject to SAR evaluation would likewise be allocated a specific percentage of the budget. The sum of these percentages is, by definition, the total SAR budget for the device. The averaging algorithm applicable to each technology independently calculates the rolling average relative to the apportioned budget for that technology.

By the way, seems to have typo error – “WWLAN” ?

Recent concern generally is where WWAN and WLAN within an end-product each use separate “stand-alone” time-averaging control algorithms. For example of regulatory max. window of 100 s, used with WWAN scheme, when 60 s windows are used with WLAN then sampling occurs at 60 s, 120 s, etc. At 100 s, the 60 s scheme is still using the initial 60 s results and won’t be updated until 120 s. Therefore, the 60 s scheme, relative to the 100 s scheme, may not comply with 100 s window requirements if all energy is used up at the beginning of each 60 s duration and it waits until the next segment at 120 s to recover credits. So the concern is that shorter windows applied for longer regulatory window durations (or misaligned windows) could produce non-compliant conditions.

Please provide more details and explanations, further to V1.3.0 Sec. 5 paras. 1 and 2 where appropriate, how compliance is handled with the latter concern.

2) Sec 2.1 of V1.3.0 includes:

> This power measurement process is consistent with that in previously certified projects and is validated independently of DSA algorithm. Pactual is reported in the form of Tx duration weighted for Pmax. …

Of course that begs questions:

> a) what are best illustrative and detailed examples of “previously certified projects”?
> b) what are details of “validated independently of DSA algorithm”?

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Please amend accordingly as appropriate.

Apple response:

1.

Added Sec.5 paragraph 2 of V1.4 saying:

WWAN and RLAN energy budgets are fixed to maintain compliance considering simultaneous operation. The independent budgets ensure that differences in averaging windows does not impact the overall compliance of the device.

Updated Sec.5 paragraph 3 for 'WWLAN' typo:

The overall SAR budget for the device is subdivided, with a certain percentage of the budget reserved for RLAN energy and another percentage reserved for WWAN energy.

2.

Updated Sec. 2.1 of V1.4 saying:

This power measurement process is consistent with that in previously certified projects; please see Table 1 for devices using this implementation to drive the WLAN Tx power control circuit. As in previously certified devices, the TSSI circuit is calibrated on a per unit basis and the overall uncertainty in the Tx power control loop is characterized as +/- 1.5 dB. This uncertainty is already considered in the overall uncertainty budget.

Model(s)	**FCC ID**
A2176	BCG-E3539A
A2398	BCG-E3540A
A2399, A2400, A2401	BCG-E3541A
A2172	BCG-E3542A
A2402	BCG-E3543A
A2403, A2404, A2405	BCG-E3544A
A2341	BCG-E3545A
A2406	BCG-E3546A
A2407, A2408, A2409	BCG-E3547A
A2342	BCG-E3548A
A2410	BCG-E3549A
A2411, A2412, A2413	BCG-E3550A

Table 1.

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FCC response on 08/12/2021

"KDB Technical Description with response - Aug 10 2021, confidential exhibit"

No further comments or concerns at this time for proceeding with implementation and testing.

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