SIL-SK63100 MPE analysis

Coordinate system

For clarity of the following discussion we first define the coordinate system in Figure 1. The antennas are located in the xy plane. y=0 corresponds to the base of the laptop. x=0 corresponds to the center of the antenna array.

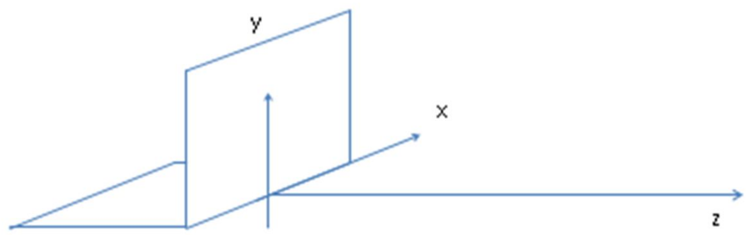

Figure 1: Laptop coordinate axis definition

Problem statement

Determine the maximum power density on or below the plane y=0. This represents the maximum exposure to the user of the laptop. It could be approached by a physical configuration similar to Figure 2. Direct placement of the RX unit at this angle is unlikely. We evaluate this configuration as a worst case operating condition.

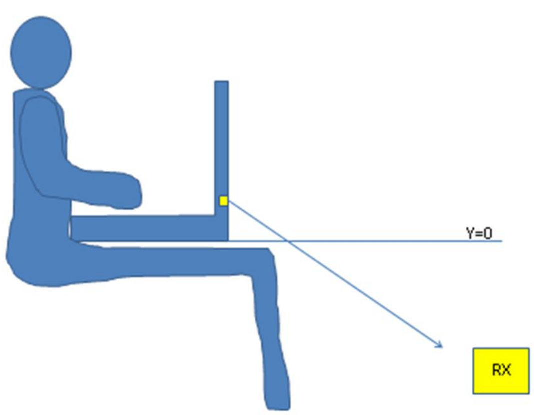

Figure 2: Unlikely but nevertheless possible use case

Mechanical placement

In the portable application, the base of the RF chip is installed inside the laptop lid facing forwards away from the user with y>=33mm or more from the base of the laptop (Figure 3).

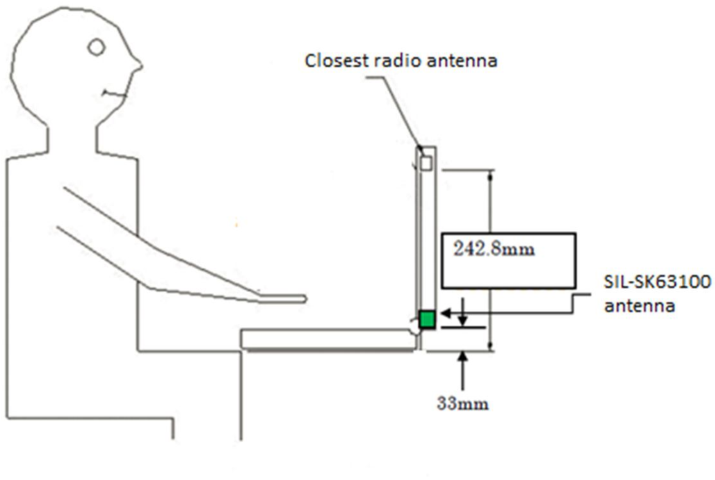

Figure 3: Placement of WVAN module in laptop lid

The preferred orientation of the RF chip is restricted to place the A1 marker located at the top (Figure 4). With this orientation, the TX antennas are a minimum of 6mm from the base of the RF chip (Figure 5) and thus 39mm from the base of the laptop as the TX antennas are located at the top of the package. The peak of the beam formed radiation pattern is expected to occur approximately in line with the middle row of TX antennas (8.2mm above the base of the RF chip) but for the purpose of the analysis that follows we conservatively take the position of the lowest row of TX antennas to represent the position of the antenna array.

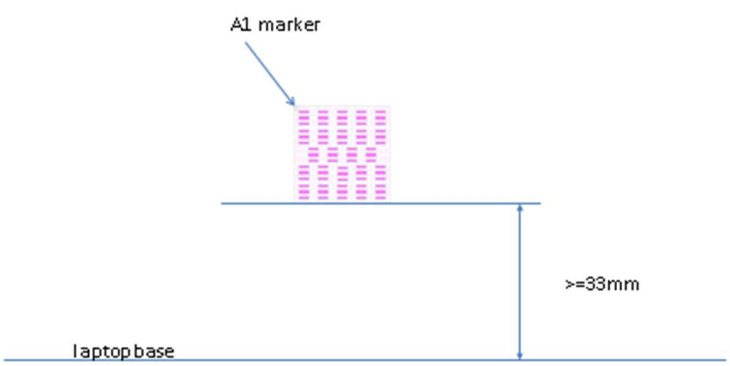

Figure 4: Vertical placement of RF chip relative to laptop base

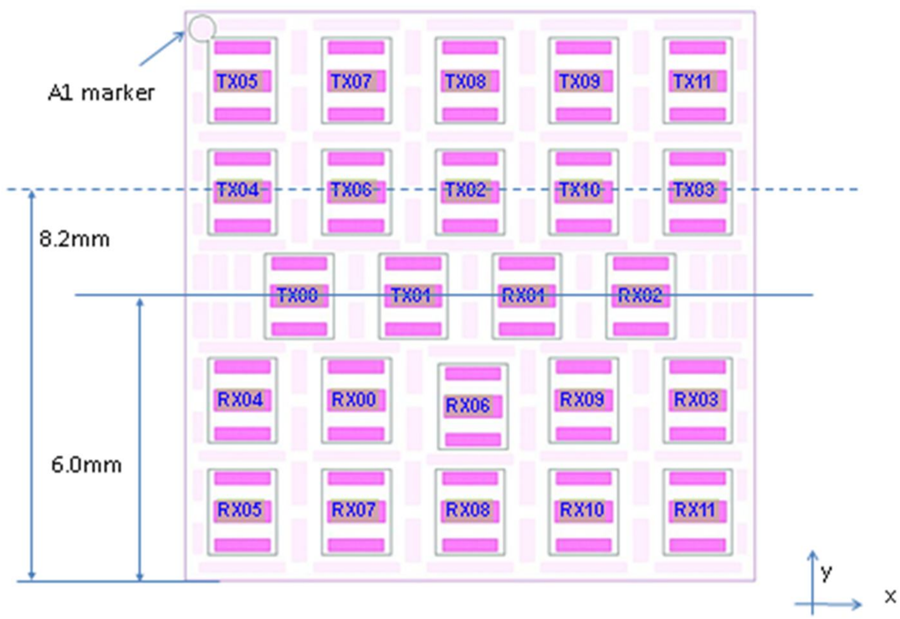

Figure 5: Drawing of package showing location of TX antennas relative to A1 marker dot

For the alternate orientation with A1 marker located at the bottom, we further restrict the distance from the base of the laptop to the edge of the RF chip to be greater than 39mm thus ensuring that in all orientations the lowest TX antenna is at least 39mm from the base of the laptop.

Theory of operation

The transmit antenna array is a phased array with 12 transmit elements and 90° phase resolution on each element with independent phase adjustment for each element. The radiation pattern of the beam is the composite of:

- the radiation pattern of the individual elements (with a theoretical null in the *xy* plane of the antenna)
- the finite resolution of the beam direction arising from quantization of the transmit phase into 90° steps

"Beam search" is the name given to the process used to calculate the set of antenna phases that maximizes the signal strength in the direction of the RX unit. For the purpose of this discussion we assume that the beam search process is capable of finding the optimum set of phase values for the twelve antenna elements.

In normal operation the beam is recalculated continuously by part of the beam search process approximately every 5ms and causes some variation in the strength of the beam: the average beam strength evaluated over a few seconds would typically be approximately 1dB lower than the optimum but we do not depend on this in the analysis or measurements that follow.

Measured beam coverage

The elevation coverage was obtained experimentally as follows. The TX unit was located on a turntable orientated so that elevation is varied as the turntable is rotated (Figure 6). The RX unit placement was fixed. The received signal strength indicator provided by the RX unit was used to record signal strength. The elevation was swept in 5 degrees steps between -90° and 90° by moving the turntable. At each elevation, beam search was allowed to run 20 times and the set of antenna phases giving largest RSSI and the corresponding RSSI value recorded. This result gives the strongest beam that could form with the RX unit at the specified elevation angle.

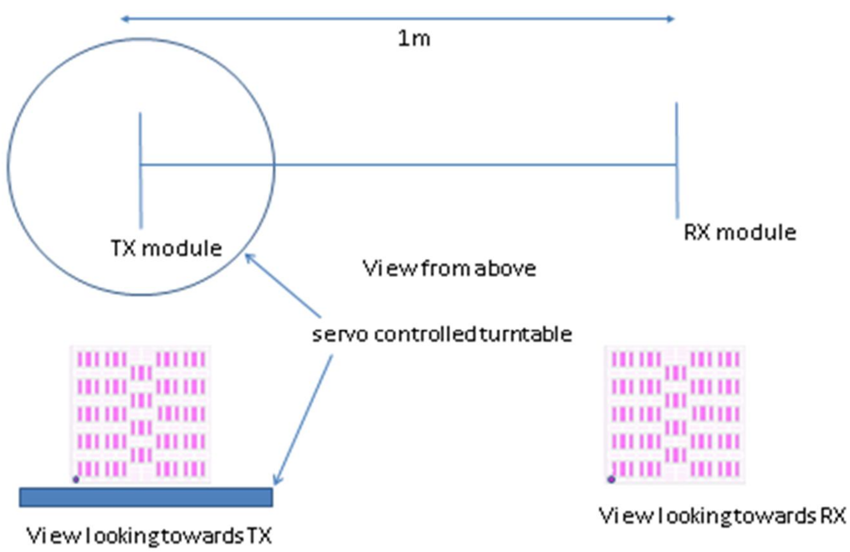

Figure 6: Turntable set up for coverage measurement

The results are plotted in Figure 7 .

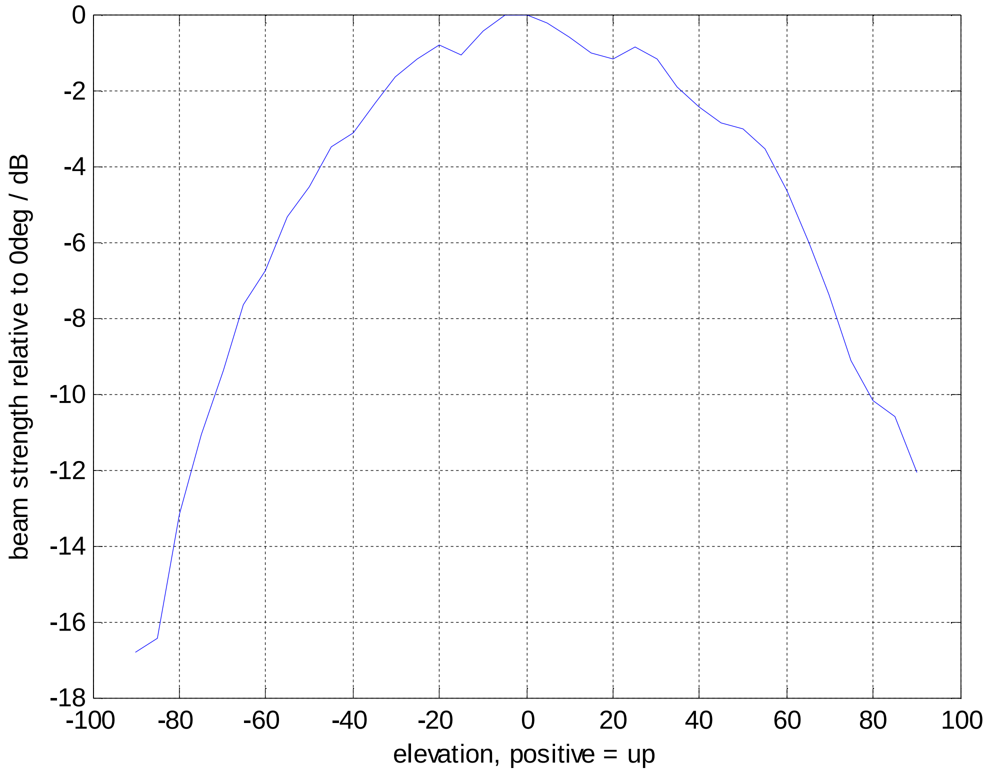

Figure 7: Measured elevation coverage

In a separate experiment, the beam is fixed using the antenna phases obtained during the coverage sweep at a specific elevation angle. For that fixed beam orientation, the TX elevation is again swept over the range -90° to 90°. These results indicate the radiation pattern associated with that particular beam. The results for three representative beams (0° elevation, -55° elevation and -90° elevation) are shown in Figure 8. The beam coverage data from Figure 7 is also overlaid on the same plot. The markers are placed at the angle at which the beam was obtained: note that the beam pattern intersects the beam coverage at those points verifying that these beams represent the strongest beams at those specific elevations. Note also that for a given beam, the angle of maximum radiation is not necessarily the same as the angle at which the RX unit was located. For example, for the beam obtained with the RX unit at -55° the beam maximum occurs at around -40°. For the beam obtained with the RX unit at -90° the beam maximum occurs at around -45°. Also note that the beam coverage is greater than or equal to all of the points on the three example beams shown on the Figure: the beam coverage is the envelope of all possible beam patterns.

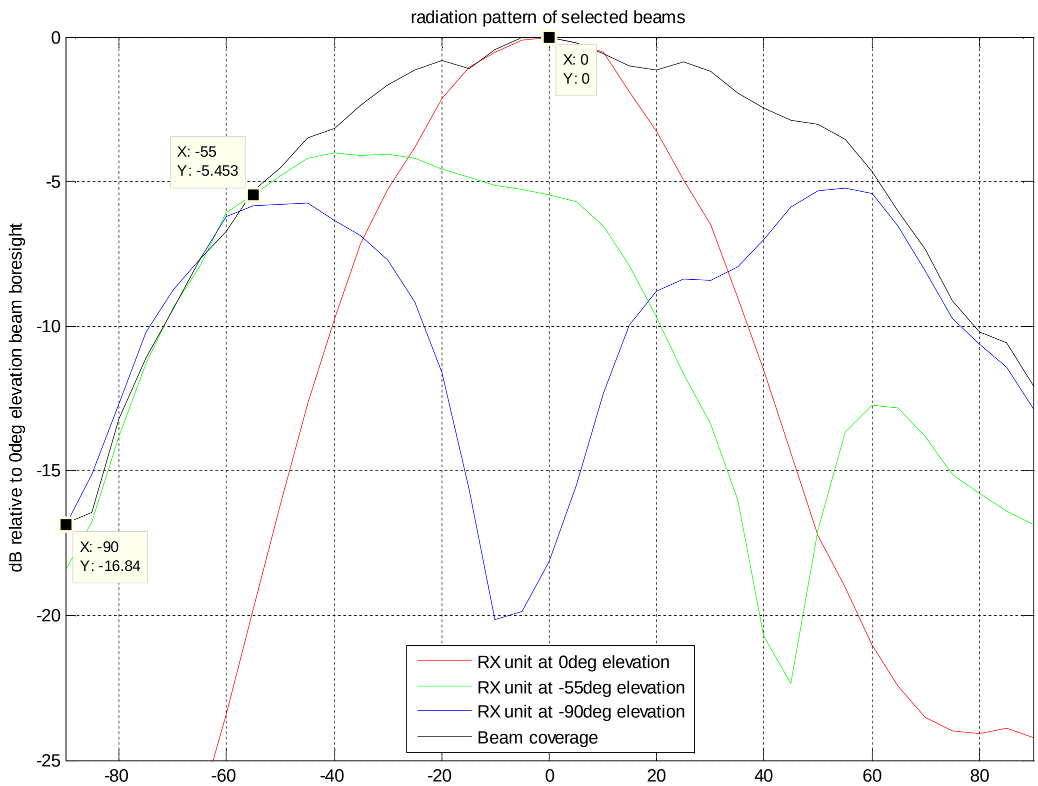

Figure 8: Radiation pattern of representative beams

Predicted power density

The radio used in the laptop has an EIRP of 27dBm in the boresight direction in the highest power operating condition (MRP).

Using the measured data for the elevation beam coverage shown in Figure 7 the power density is computed at each point in space assuming the beam is free to form in the direction that maximizes the power at that point.

- The module is treated as a point source at coordinates (0mm,39mm,0mm)
- The distance to the point source is calculated from the geometry and the path loss calculated under far field assumption.
- The elevation angle to the point source is calculated from the geometry and the experimentally determined elevation coverage used to correct the power density.

This calculation is presented as a contour plot in the *yz* plane (Figure 9) and as a cross section through this data in the line of interest y=0 in the plane of the laptop base (Figure 10). The area in which the power density exceeds the limit is shaded in red; the area in which the power density is below the MPE limit is colored white. All positions along y<=0 are below the limit, and the point of maximum power density in the plane of the laptop base is marked with an asterisk.

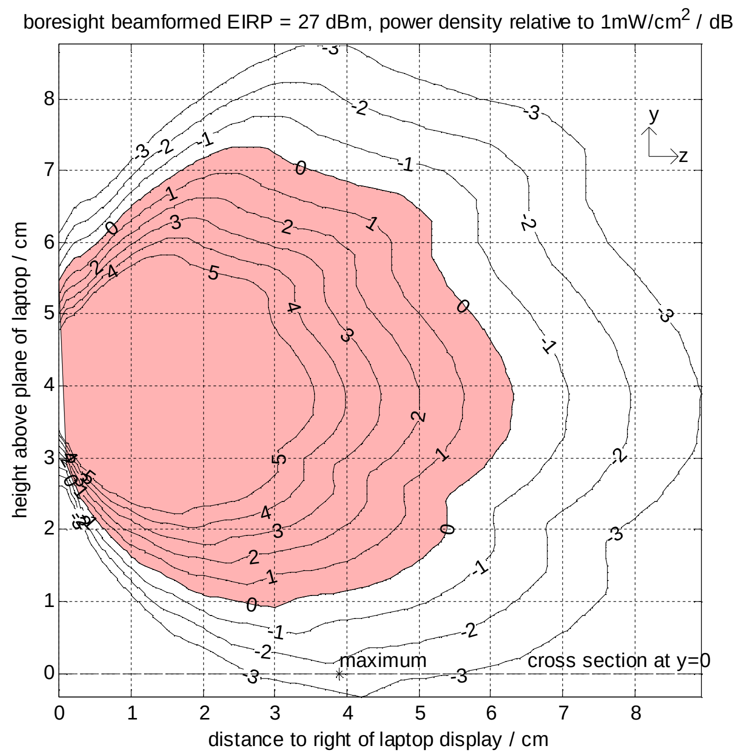

Figure 9: Power density relative to 1mW/cm^2 , boresight EIRP=27dBm, height=39mm

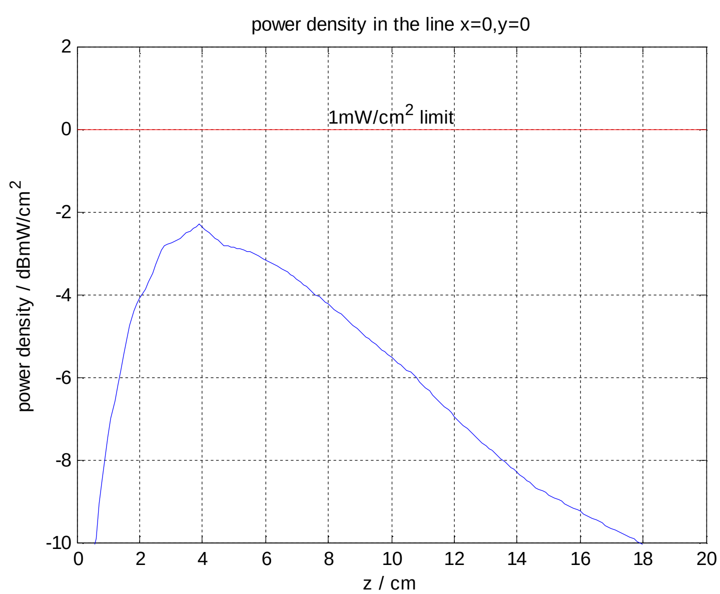

Figure 10: Cross section of maximum power density along the line x=0,y=0

Notice that the distance of minimum physical separation (straight down, -90° elevation) corresponds to a null in the beam coverage and does not give the highest power density. As the elevation angle increases towards boresight, the beam coverage increases but the distance to the plane of the laptop and thus the path loss also increases. There is thus a particular z coordinate that maximizes the power density. As shown in the plot this model predicts 2.3dB of margin at the worst case position in the plane of the laptop which is located at z=3.9cm. The elevation angle at this point is $\tan^{-1}(39/39) = 45°$ and the direct distance to the point source is 55mm. Far field assumption is valid at this distance.

The power density in the plane y=0 as a function of elevation angle may be written as

$$S_0(\theta) = \frac{EIRP}{4\pi y_0^2} f(\theta)\sin^2\theta$$

where f(θ) is the beam elevation coverage from Figure 7 and EIRP is the boresight EIRP. It follows that the particular elevation angle that maximizes the power density in the plane y=0 is a function only of the beam coverage pattern and not of the height of the antenna above the plane y_0. It also follows that the configuration with smallest y_0 will give the highest power density.

It can be seen that the case analyzed above is the configuration with the smallest value of y_0 of the three specific configurations under test in this case (Table 1).

Laptop configuration	Distance to laptop base / mm	y_0 / mm	Distance from TX antenna array to plane y=0 at 45° / mm	A1 orientation
1	33	39	55	top
2	39	45	64	top
3	49	49	69	bottom

Table 1: Laptop configurations under evaluation

Verification of power density

Bore sight measurement of EIRP

Bore sight measurement of EIRP at 5.0cm is performed by fixing the transmit beam straight ahead and optimizing the placement of the probe antenna to maximize received power. The y position of the maximum can readily be observed to be aligned with the middle row of transmit antennas.

This result, together with the separately determined elevation coverage, can be used to make a prediction of the maximum power density in the plane y=0.

But a direct measurement in the plane of the laptop is preferred to verify the analysis.

Direct measurement of maximum power density in plane of the laptop base

The objective is to determine the maximum possible power density in the plane of the base of the laptop (y=0) maximized across the following variables:

1. z position of the probe
2. x position of the probe
3. elevation of the probe
4. beam elevation

The experimental setup allows the angle of the waveguide probe antenna to be fixed to a specific value and the z coordinate of the probe antenna to be adjusted to optimize the power with a translation stage operating along the z axis.

An ideal experimental configuration would provide a rotational adjustment operating about an axis aligned with the end of the waveguide. As a substitute for this we conduct the measurement for several different elevation angles of the probe antenna chosen in the neighborhood of the value suggested by the theoretical analysis above e.g. 35°, 45° and 55°. The probe is first fixed at the selected angle then positioned using a y-axis positioner at the location y=0. Then the z-axis translation stage is used to maximize the power meter reading.

For a fixed physical position of the probe, the beam elevation can be readily adjusted electronically by fixing the antenna phases to those values previously determined during the beam coverage experiment. Using this method, the probe antenna does not obstruct formation of the beam in the direction of measurement.

Results

Silicon Image internal measurements on a bare SIL-SK63100 module recorded a boresight EIRP at 5.0cm of 27.0dBm. When installed inside the laptop according to the mechanical placement described above, the maximum power density measured in the y=0 plane was 0.74mW/cm^2 compared to a requirement of 1mW/cm^2. The maximum power density was obtained at approximately z=4.1cm with a probe angle of 45° and a beam elevation of -65°.

Table 2 compares the power density obtained using the two methods: extrapolation of boresight EIRP vs the direct measurement in the plane of the laptop base. This data was taken using UL-CCS equipment. The two methods are consistent within 0.63dB.

	HR2		HR3		
	HRP	**MRP**	**HRP**	**MRP**	**Units**
Measured boresight Pr at 5cm	-9.55	-8.75	-10.55	-8.91	dBm
Gr	6.53	6.53	6.49	6.49	dBi
Path loss at 5cm	42.06	42.06	42.36	42.36	dB
Boresight EIRP	25.98	26.78	25.32	26.96	dBm
Predicted maximum power density in y=0 at EIRP=27.0dBm (from Figure 10)	-2.3	-2.3	-2.3	-2.3	dBmW/cm^2
Predicted maximum power density in y=0 at measured boresight EIRP	-3.32	-2.52	-3.98	-2.34	dBmW/cm^2
Measured maximum Pr in y=0	-14.5	-13.7	-15.21	-12.99	dBm
Equivalent power density	-3.95	-3.15	-4.31	-2.09	dBmW/cm^2
	0.40	0.48	0.37	0.62	mW/cm^2
Delta, measurement to prediction	-0.63	-0.63	-0.33	0.25	dB

Table 2: Comparison of two methods for verifying power density

Measurement setup diagrams

HRP/MRP

Diagrams of the experimental setup to determine HRP/MRP exposure for the three laptop configurations defined in Table 1 are illustrated in Figure 11, Figure 12 and Figure 13.

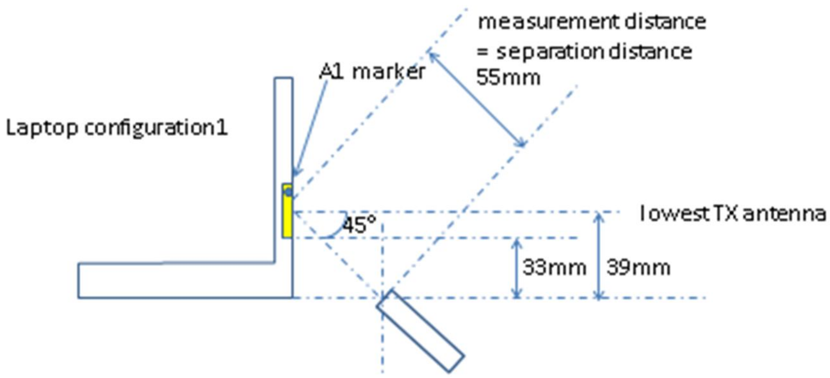

Figure 11: Measurement configuration for HRP/MRP - laptop configuration 1

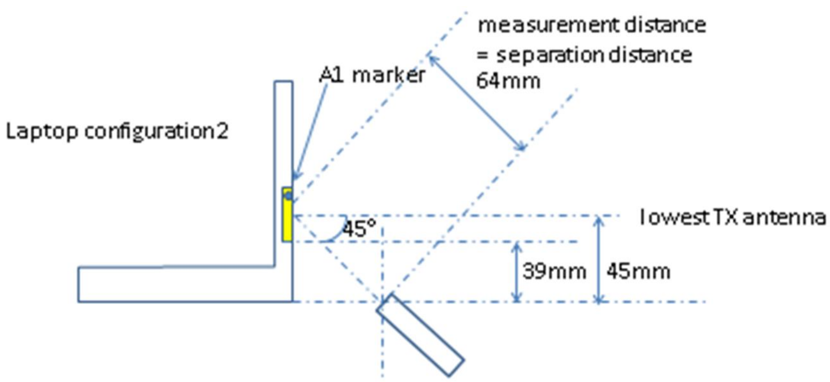

Figure 12: Measurement configuration for HRP/MRP - laptop configuration 2

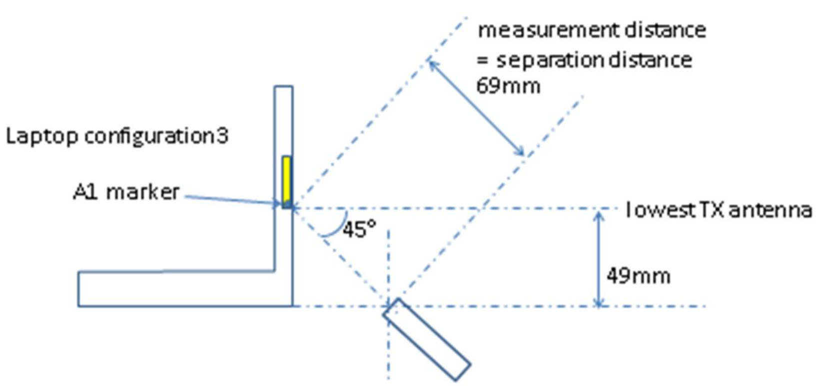

Figure 13: Measurement configuration for HRP/MRP - laptop configuration 3

LRP

The RF exposure calculation for LRP assumes that off-axis power density in all possible directions is equal to the on-axis power density at the same separation distance. The smallest possible separation distance is the distance from the lowest TX antenna to the plane of the laptop base. An on-axis bore-sight EIRP measurement at a fixed distance of 50mm is made and the power density extrapolated to that smallest possible separation distance. The measurement setup for LRP is illustrated in Figure 14 for the example of Laptop Configuration #1.

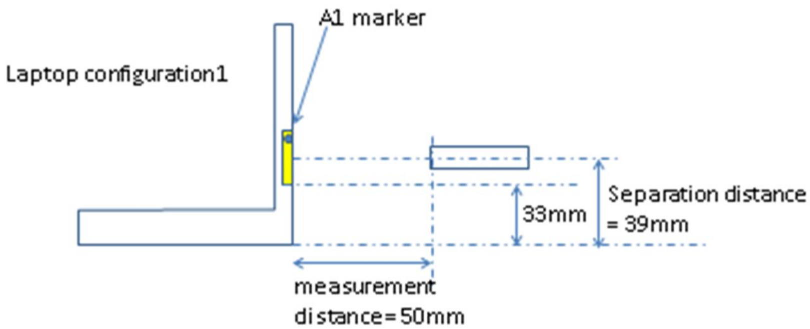

Figure 14: Measurement configuration for LRP