4.3 Summary of Minimum Interference Path Loss Data

Table 4.3-1 summarizes the MIPL shown in Section 4.2. Data in this table were taken from the "All Aircraft" summary rows at the end of each table. In this table, the *minimum MIPL* values displayed are the *lowest* MIPL of all aircraft. Likewise, the *average MIPL* values displayed are the *average* of the MIPL of all aircraft. The minimum MIPL and the average MIPL are used in the later calculations for interference safety margins. The maximum MIPL and the StDev of the MIPL of all aircraft are also shown. The standard deviations were calculated without assigning additional weight to any specific aircraft model or number of measurement points.

Table 4.3-1 shows there can be a large difference in dB between the maximum MIPL and the minimum MIPL. MIPL can vary between 35 dB to 82 dB for LOC and between 30 dB to 84.7 dB for VOR. TCAS system has the smallest MIPL range, 48.2 dB to 69.1 dB, and the lowest MIPL standard deviation value of 5.3 dB.

Table 4.3-1: Summary of Aircraft Minimum IPL (MIPL)

	Min MIPL (dB)	All Aicraft Ave MIPL (dB)	Max MIPL (dB)	StDev (dB)
LOC	35.0	60.0	82.0	10.0
VOR	30.0	62.4	84.7	12.2
VHF	28.7	50.4	76.0	10.9
GS	46.2	59.1	77.0	7.2
TCAS	48.2	57.3	69.1	5.3
SatCom	51.5	59.9	87.0	15.2
GPS	41.0	64.6	82.4	10.6
MLS*	78			

* From DO-199; Note: Average IPL in DO-199 are defined differently than the average MIPL and therefore are not used.

5 Interference Analysis

In this section, receiver susceptibility thresholds are discussed, and the measured interference thresholds are summarized from RTCA/DO-199. In addition, safety margins are calculated from the interference susceptibility thresholds, the path loss data in Section 4, and the emissions from the wireless phones.

5.1 Published Receiver Susceptibility

Of the three elements required for risk assessment (wireless phone emission; aircraft IPL; and receiver interference threshold), receiver interference threshold (to PED interfering signal) is the one element with the least amount of available data. RTCA/DO-199 and RTCA/DO-233 provide the most information on the subject. However, the amount of data available is far from being sufficient to provide a high level of confidence in the figures provided. Except for GPS, the ICAO Annex 10, Vol.1 [24] and receiver MOPS did not properly address the in-band, on-channel interference. Also, spurious signals were too low to cause other types of interference, such as desensitization, addressed in these documents.

5.1.1 RTCA/DO-233

For LOC, RTCA/DO-233 sets four different interference thresholds for in-band, on-channel interference. Signal-to-Interference (*S/I*) ratio for the four interference types can vary between 7 dB to as much as 46 dB depending upon the frequency spacing between the CW interference signal from the 90 Hz or 150 Hz ILS sidebands of the LOC carrier. In addition, a modulated interference signal may result in a different interference threshold than CW interference. Additional information is documented in [1].

RTCA/DO-233 did not provide similar guidance for other systems such as VOR or GS. And unlike RTCA/DO-199, RTCA/DO-233 did not provide data to support their findings and recommendations concerning receiver interference thresholds.

5.1.2 RTCA/DO-199

RTCA/DO-199 is the only publicly available document that provided results from testing of receiver interference thresholds. In RTCA/DO-199, receiver interference levels along with test signal strengths were documented in the form of tables and charts, from which relevant threshold data for LOC, GS, VOR, TCAS, VHF-Com and SatCom were extracted. For a CW interference signal, the official *S/I* ratios were chosen from the typical values, which were valid across most of the channel bandwidth. However, when the interfering signal was such that it mixed with the local carrier to produce a frequency close to the receiver's side band, susceptibility notches could occur. Test results show the *S/I* ratio can be as high as 38 dB for LOC, 35 dB for GS and 46 dB for VOR. Theoretical analysis was also conducted and presented for LOC and VOR.

For CW interference, the disruption threshold tends to vary along with the signal level in such a way that the *S/I* ratio stays constant. As a result, the disruption threshold can only be determined if the test signal is known. In the document, the test signals were set equal to the minimum desired signals at the receivers. These signals were calculated from the minimum desired external field environments within the coverage airspace assuming an isotropic, lossless antenna, and fixed values of cable losses. The minimum desired external field environments were taken from several sources, including the ICAO Annex 10, Vol.1, and FAA National Orders, and others. Additional details on the desired signal strength calculations and the interference criteria unique to each system can be found in RTCA/DO-199.

According to the document, it was very difficult to maintain signal lock at the susceptibility notches to cause undetected interference even if it was intended. The official thresholds were selected, therefore, by ignoring narrowband notches. Table 5.1-1 summarizes the test signal level used, the official disruption threshold, along with the unofficial disruption threshold at the susceptibility notches. The underlined data in this table were used in the safety margin calculations in Section 5.2.

Table 5.1-1: RTCA/DO-199 Interference Thresholds

	LOC	VOR	GS	VHF	GPS	MLS
Desired Signal at Receiver (dBm)	**-88**	**-97**	**-78**	**-89**		
Typical Interference Level (dBm)	**-104**	**-110**	**-93**	**-107**	**-126.5***	**-62**
Signal/Inteference (S/I) Ratio (dB)	16	13	15	18		
Minimum Interference Level (dBm) (at notches)	**-127**	**-143**	**-113**	**-107**		
Signal/Interference ratio (dB)	39	46	35	18		
Theoretical Thresholds (dBm)	**-130**	**-148**	**-120**			
Theoretical S/I Ratio (dB)	42	51	42			

* For GPS, -126.5 dBm minimum interference level is required in GPS receiver MOPS such as DO-208 and DO-229B. DO-199 provides –130 dBm interference level for GPS.

For GPS, the interference threshold was very well defined and was consistent across various standards, Technical Standard Orders (TSOs) and receiver MOPS for airborne navigation equipment. These documents provided the minimum performance standards for stand-alone, satellite-based and ground-based GPS systems and sensors. A few of these documents include: ITU-R M.1477 [28], RTCA/DO-235A [7], RTCA/DO-229B [29], RTCA/DO-253A [30], RTCA/DO-228 [31], and RTCA/DO-208 [32].

These documents show that the lowest interference threshold is **–126.5 dBm** for a GPS system in acquisition mode with CW interference or signals with bandwidth up to 700 Hz. This threshold was specified at the output of a passive antenna, or at the output of an active antenna, but before the pre-amplifier stage. Thus, the active GPS antenna pre-amplification gain must be accounted for in the path loss value in order to use the –126.5 dBm threshold value.

The values provided assume that there is only one interference signal. In the presence of additional interference sources and noise, the threshold values may have to be re-evaluated.

5.2 Safety Margin Calculations

Knowing device emission "A", aircraft minimum path loss "-B", and receiver susceptibility threshold "C", safety margins can be computed using

$$\textit{Safety Margin} = C - (A + B)$$

This section first calculates the interference signal strength at the receiver's antenna port (A +B). Safety margin can then be computed with the knowledge of "C".

Applying the minimum and the average values of MIPL ("-B") in Table 4.3-1 to the emission data ("A") in Table 3.6-1, the resulting interference signals at the receiver ("A+B") are shown in Table 5.2-1. Due to the large range of IPL "-B" values, the results of the calculation (A+B) are presented with only the maximum and the average values that are calculated from the minimum and the average path loss "-B" values.

Table 5.2-1: Interference Signal Strength at Receiver's Antenna Port (A+B). Maximum and Average values in dBm

	Maximum and Average Interference Signal at Receiver (A+B)					
	Cellular-Band Phones		**PCS-Band Phones**		**Laptops/PDA**	
	Max (Min IPL)	**Ave (Ave IPL)**	**Max (Min IPL)**	**Ave (Ave IPL)**	**Max (Min IPL)**	**Ave (Ave IPL)**
LOC	-110.3	-135.3	-111.8	-136.8	-98.3	-123.3
VOR	-105.3	-137.7	-106.8	-139.2	-93.3	-125.7
VHF	-104.0	-125.7	-105.5	-127.2	-92.0	-113.7
GS	-125.7	-138.6	-122.0	-134.9	-104.9	-117.8
TCAS	-112.9	-122.0	-111.5	-120.6	-93.9	-103.0
GPS	-126.8	-150.4	-107.5	-131.1	-96.8	-120.4
SatCom(*)	-137.3	-145.7	-118.0	-126.4	-107.3	-115.7
MLS(**)	-121.8		-141.8		-155.0	

(*) SatCom Band device's emission are assumed to be the same as for the GPS band

(**) from RTCA/DO-199

Comparing the maximum and the average signal strength at the receivers, (A+B), in Table 5.2-1 to the typical and the minimum susceptibility thresholds in Table 5.1-1, safety margins can be calculated. The result for each system is a 2x2 matrix. Deciding which element of the safety margin matrix to use depends upon whether the maximum or the average value for (A+B) was used, and on whether the typical or the minimum interference threshold was used. In the cases where there was only one value for interference threshold, such as GPS, the safety margin results are 2x1 matrices.

Tables 5.2-2 to 5.2-7 report the results of the calculation with the safety margin results highlighted in **bold** for each combination of wireless phone's emissions, MIPL, and interference threshold values. The calculations were conducted for LOC, VOR, VHF Comm, GS, GPS and MLS. To determine safety margins, one simply locates the right combinations of devices (cellular or PCS-band phones), the MIPL values, and interference thresholds on the tables. Thus, the combination of cellular-band phone, minimum MIPL (resulting in the interference signal at receiver of -110.3 dBm), and the minimum LOC interference threshold (-127 dBm) results in –16.7 dB safety margin. A large positive safety margin is desirable, whereas a large negative safety margin indicates a possibility of interference.

Safety margin calculations for TCAS and SatCom were not possible due to the lack of interference threshold data. However, the remaining IPL and spurious emissions data can be used in future calculations once the interference threshold is defined.

Table 5.2-2: LOC Safety Margin (in dB) for Different Combinations of Wireless Phones, MIPL and Interference Thresholds

		Cellular-Band Phones &		**PCS-Band Phones &**		**Laptops/PDAs &**	
		Min MIPL	Ave MIPL	Min MIPL	Ave MIPL	Min MIPL	Ave MIPL
Interference Signal at Receiver (dBm) =		*-110.3*	*-135.3*	*-111.8*	*-136.8*	*-98.3*	*-123.3*
LOC Interference Threshold							
Minimum (dBm)	*-127*	**-16.7**	**8.3**	**-15.2**	**9.8**	**-28.7**	**-3.7**
Typical (dBm)	*-104*	**6.3**	**31.3**	**7.8**	**32.8**	**-5.7**	**19.3**

Table 5.2-3: VOR Safety Margin (in dB) for Different Combinations of Wireless Phones, MIPL and Interference Thresholds

		Cellular-Band Phones &		**PCS-Band Phones &**		**Laptops/PDAs &**	
		Min MIPL	Ave MIPL	Min MIPL	Ave MIPL	Min MIPL	Ave MIPL
Interference Signal at Receiver (dBm) =		*-105.3*	*-137.7*	*-106.8*	*-139.2*	*-93.3*	*-125.7*
VOR Interference Threshold							
Minimum (dBm)	*-143*	**-37.7**	**-5.3**	**-36.2**	**-3.8**	**-49.7**	**-17.3**
Typical (dBm)	*-110*	**-4.7**	**27.7**	**-3.2**	**29.2**	**-16.7**	**15.7**

Table 5.2-4: VHF Safety Margin (in dB) for Different Combinations of Wireless Phone, MIPL and Interference Thresholds

		Cellular-Band Phones &		**PCS-Band Phones &**		**Laptops/PDAs &**	
		Min MIPL	Ave MIPL	Min MIPL	Ave MIPL	Min MIPL	Ave MIPL
Interference Signal at Receiver (dBm) =		*-104*	*-125.7*	*-105.5*	*-127.2*	*-92*	*-113.7*
VHF Interference Threshold (dBm)	*-107*	**-3.0**	**18.7**	**-1.5**	**20.2**	**-15**	**6.7**

Table 5.2-5: GS Safety Margin (in dB) for Different Combinations of WLAN/Radio Devices, MIPL and Interference Thresholds

		Cellular-Band Phones &		**PCS-Band Phones &**		**Laptops/PDAs &**	
		Min MIPL	Ave MIPL	Min MIPL	Ave MIPL	Min MIPL	Ave MIPL
Interference Signal at Receiver (dBm) =		*-125.7*	*-138.6*	*-122.0*	*-134.9*	*-104.9*	*-117.8*
GS Interference Threshold							
Minimum (dBm)	*-113*	**12.7**	**25.6**	**9.0**	**21.9**	**-8.1**	**4.8**
Typical (dBm)	*-93*	**32.7**	**45.6**	**29.0**	**41.9**	**11.9**	**24.8**

Table 5.2-6: GPS Safety Margin (in dB) for Different Combinations of WLAN/Radio Devices, MIPL and Interference Thresholds

		Cellular-Band Phones &		**PCS-Band Phones &**		**Laptops/PDAs &**	
		Min MIPL	Ave MIPL	Min MIPL	Ave MIPL	Min MIPL	Ave MIPL
Interference Signal at Passive Antenna Output (dBm) =		*-126.8*	*-150.4*	*-107.5*	*-131.1*	*-96.8*	*-120.4*
GPS Interference Threshold (dBm)	*-126.5*	**0.3**	**23.9**	**-19.0**	**4.6**	**-29.7**	**-6.1**

Table 5.2-7: MLS Safety Margin (in dB) for Different Combinations of WLAN/Radio Devices, MIPL and Interference Thresholds

		Cellular-Band Phones &		**PCS-Band Phones &**		**Laptops/PDAs &**	
		Min MIPL	Ave MIPL	Min MIPL	Ave MIPL	Min MIPL	Ave MIPL
Interference Signal at Receiver (dBm) =		*-121.8*		*-141.8*		*-155.0*	
MLS Interference Threshold (dBm)	*-62*	**59.8**		**79.8**		**93.0**	

* For MLS both path loss and receiver susceptibility thresholds came from DO-199.

Note that the emissions and safety margins for systems operating in Band 1 (LOC, GS, VHF-Com) are different than in [2], even though the same data are used in both reports. Band 1 in this report covers 105 – 140 MHz, whereas Band 1 in [2] was defined to cover 105 – 120 MHz.

From the tables, interference safety margins can be positive or negative depending upon the combinations of MIPL and receiver interference thresholds used. The wireless phones considered generally have better safety margin than standard laptops and PDAs based on test data in this effort.

The exception is the MLS band. In this band, emissions from the wireless devices are higher than emissions from the laptop computers by at least 13 to 33 dB (emission from the laptop computers were below the measurement noise floor). There appears no cause for concern due to the large positive safety margins. However, the safety margin for MLS seems unusually large. In addition, there was lack of additional data to validate the interference threshold and the IPL data provided in RTCA/DO-199 and used in this analysis. Additional measurement data in the MLS band is needed.

In general, there is a need for better understanding and characterization of receiver's susceptibility thresholds. Additional data on all receiver systems based on measurement and theoretical analysis are highly desirable.

6 Multiple Equipment Cumulative Effects

In dealing with PED interference with aircraft systems, multiple equipment cumulative effects must be addressed. This issue is a concern for both back-door interference (where interference signals couple into system wiring) and front-door interference (where unintended transmissions couple into aircraft exterior antennas to the victim aircraft receiver).

This paper provides a conservative bound on the cumulative effects for several aircraft systems. Similar to the previous sections, this effort only addresses the effects associated with front-door interference. However, the approach can be similarly applied to other types of interference coupling.

6.1 Approach

In simplest form, front-door cumulative effects of multiple PEDs are the ratio of cumulative PED interference powers to the interference power from just one device, all measured at receivers' antenna ports.

For non-coherence sources with equal signal strength, it is often assumed that $P^I_N = N* P^I_1$, where P^I_N and P^I_1 is interference signal power at the receiver for N devices and for one device, respectively. This assumption is often valid for sources that are physically co-located (ideally), or for sources located in such a way that the interference contributions from all sources are nearly equal. For sources not co-located, or if the assumption above is not valid, an individual device's contribution should be adjusted for its path-loss value before being summed. Thus, to study the cumulative effects of multiple PEDs on "front-door" interference, IPL should be factored in the calculations.

This paper utilizes existing IPL data to derive a Multiple Equipment Factor (MEF). The following subsections describe the formulations for calculating MEF.

6.1.1 MEF Formulation

To compute the cumulative effects from multiple devices, the spurious emission value for each device is first weighted proportional to its linear (not dB) interference coupling value, C_i. The results for all devices are summed, and normalized to the single-PED worst-case contribution to arrive at the cumulative effects.

The C_i is computed from the IPL at the same source location using:

$$C_i = 10^{-IPL/10} \quad \text{(Eq. 6.1-1)}$$

Thus, the maximum power, in watts, coupled from seat n to the receiver is simply:

$$P_{rec}^{n} = P_{xmit}^{n} * C_i^{n} \quad \text{(Eq. 6.1-2)}$$

Summing all P_{rec}^{n} and normalizing to the maximum value, $P_{rec}^{\max}$, MEF for N devices is defined as

$$MEF = \left(\sum_N P_{rec}^{n}\right) / \left(P_{rec}^{n}\right)^{max} \quad \text{(Eq. 6.1-3)}$$

$$= \left(\sum_N P_{xmit}^{n} * C_i^{n}\right) / \left(P_{xmit} * C_i\right)^{max} .$$

Note that $\left(P_{xmit} * C_i\right)^{max}$ is the maximum ($P_{xmit}^{n} * C_i^{n}$) for all N values. For the devices with maximum emission located at the minimum path loss location, ($P_{xmit}^{n} * C_i^{n}$) becomes ($P_{xmit}^{\max} * C_i^{\max}$)

If P_{xmit} is the same for all transmitting sources, it can be normalized, and (3) become:

$$MEF = \sum_N \left(C_i^{n} / C_i^{\max}\right) \quad ; \quad \text{for } n=1,\ldots,N \quad \text{(Eq. 6.1-4)}$$

with $C_i^{\max}$ = max (C_i^{n}) for all n values (or simply C_i at the minimum IPL location).

Alternatively, defining the <u>normalized</u> coupling factor $< C_i^{n} >$ and the <u>normalized</u> IPL $< IPL^{n} >$ as

$$< C_i^{n} > = C_i^{n} / C_i^{\max}, \text{ and} \quad \text{(Eq. 6.1-5)}$$

$$< IPL^{n} > = IPL^{n} - IPL^{\min} , \quad \text{(Eq. 6.1-6)}$$

it can be shown that

$$< C_i^{n} > = 10^{-<IPL^{n}>/10}, \quad \text{(Eq. 6.1-7)}$$

$$MEF = \sum_{\mathrm{N}} < C_i^{n} >. \quad \text{(Eq. 6.1-8)}$$

The MEF result is a power ratio. To convert to decibels,

$$MEF_{dB} = 10 \log_{10} (MEF) \quad \text{(Eq. 6.1-9)}$$

6.1.2 Assumptions

This effort provides a reasonable upper bound for the MEF. The following simplifying assumptions are made concerning interference signals and their summing effects to establish the upperbound:

1. There are as many devices as there are passenger seats, and there is one device located at each seat.

2. All interference signals are of the same form, i.e. continuous-wave (CW), or similarly modulated.

3. All devices transmit on the same frequency.

4. Signals are non-coherent, and their summing effects at the victim receivers are additive in power, not in voltage (a reasonable assumption as the devices are operating independently).

5. Interference signals are polarized either vertically or horizontally. The worse case coupling of the two polarizations is used in the calculation. These two polarizations are typically used in IPL measurement.

6. All devices have the same emission level in the aircraft radio bands. As a result, the absolute signal strength is calibrated out. However, the formulation can be easily modified to include devices having different emissions levels.

6.2 Aircraft Path Loss Measurement

Aircraft minimum IPL data are insufficient for MEF calculations since they are usually reported as a single value for each system. Full-aircraft IPL data are much more desirable as they include many possible PED locations within the cabin. The full-aircraft IPL data are usually measured with the transmitting source located at all the windows and the seat locations. Full-aircraft IPL data should also capture the minimum IPL value.

Under a recent effort between United Airlines, Eagle Wings Inc., and NASA LaRC, full-aircraft IPL were collected on two B737 airplanes. For each of the four receiver system considered, measurements were conducted with approximately 160 transmit antenna locations covering the left or right halves of the airplanes. In addition, the transmit antennas were in vertical and horizontal polarizations. As stated in [2], these measurements confirmed that the window measurements indeed captured the minimum IPL for that aircraft.

Due to the large number of transmit antenna locations considered, aircraft resonance and local effects are automatically accounted for in the summation. A mechanical stirrer, typically used to help in collecting the statistics of the reverberating field environment, is not necessary.

Additional details for window measurements are reported in [2]. Full-aircraft measurements are reported in this section. However, only relevant details pertaining to the full-aircraft measurement method, analysis, and results applicable to MEF analysis are reported. Subsections 6.2.1 and 6.2.2 briefly touch on the measurement method and the IPL results for the four systems for which full-aircraft data are available. While full-aircraft IPL are not simple to present graphically, window IPL are shown to provide additional insight into the strength of coupling at different aircraft locations.

6.2.1 Method

Section 4.1 discussed in further details about the measurement methods for conducting IPL measurements on the six B737 aircraft. As discussed, the source antennas used include dipoles for frequencies in the GS band and below, and a dual-ridge horn antenna for the frequencies in the TCAS band and above. No corrections were made to account for (to remove the effects of) the transmit antenna gain. For the MEF calculation, antenna-gain correction is not necessary since the same factor exist in all measurements. These antenna-gains are removed in the normalization as shown in Equation 6.1-3.

As stated, full-aircraft data were collected with the transmit antenna:

1. Positioned at all window locations

2. Scanned along door seams

3. Positioned in all seat locations, at window level

4. Positioned in armrest locations, at window level

5. Positioned in the aisle, one per row of seats, at window level

6. In both vertical and horizontal polarizations

Full-aircraft measurements were performed on four systems. Details concerning spectrum and measurement range are shown in Table 6.2-1.

Table 6.2-1: B737 Full-Aircraft IPL - System Measured and Frequency Bands

Aircraft Systems	Aircraft Antenna Location	Measurement Frequency Range (MHz)	Spectrum (MHz)
VHF-Comm 1	Top	116-138	118 – 137
LOC/VOR	Tail	108-118	LOC: 108.1 – 111.95 VOR: 108 – 117.95
GS	Nose	325-340	328.6 – 335.4
TCAS	Top	1080 – 1100	1090

6.2.2 Measurement Results

Two-dimensional graphical presentations of some of the available full-aircraft data have been previously reported [33]. In addition, window IPL data for the six B737s are repeated here, Figures 6.2-1 to 6.2-4, for the VHF, LOC, GS and TCAS systems.

On these plots, IPL data for each receiver system on each aircraft are represented by two traces for the two vertical and horizontal polarizations of the transmit antennas. The window locations are simply labeled as the n^{th} side window starting from the cockpit. The door locations are labeled as “L1” and “L2” for left side doors; and "EE" for emergency exits. At the doors, a sweep was typically conducted with the transmit antenna scanning along the door seam. A door sweep at L1 is labeled as "L1 Dr Swp".

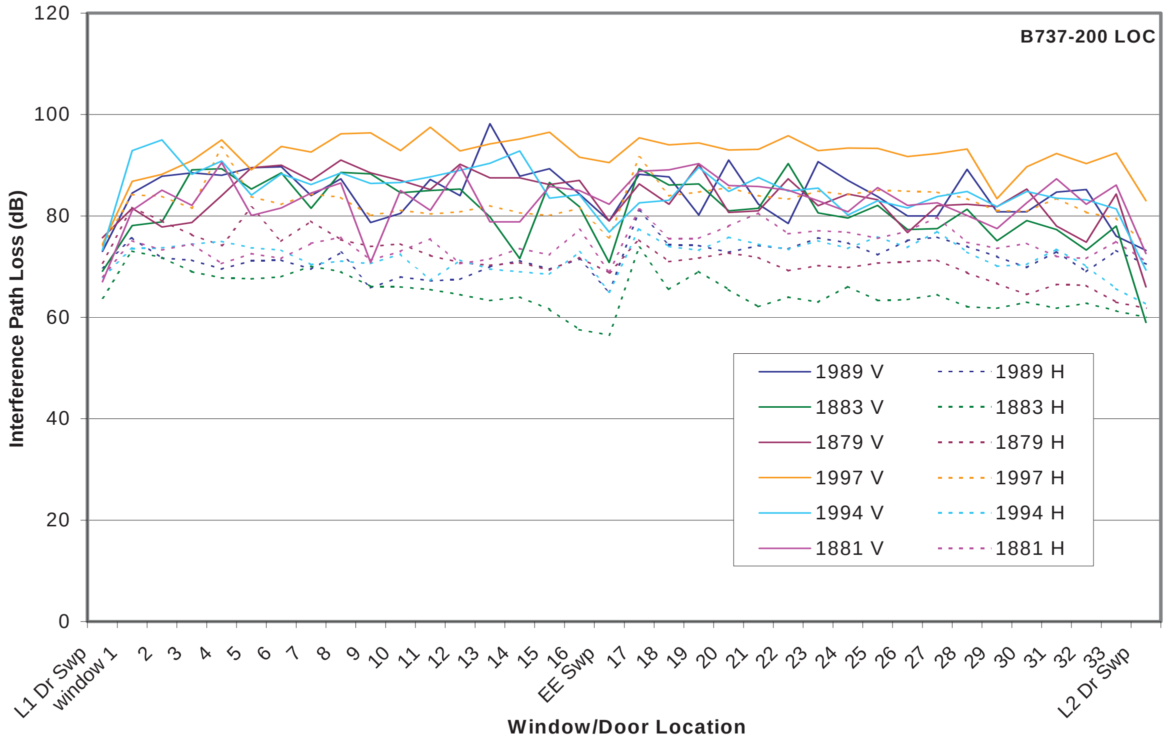

Figure 6.2-1: B737-200 LOC/VOR (Tail) interference path loss. Left windows/doors excitation.

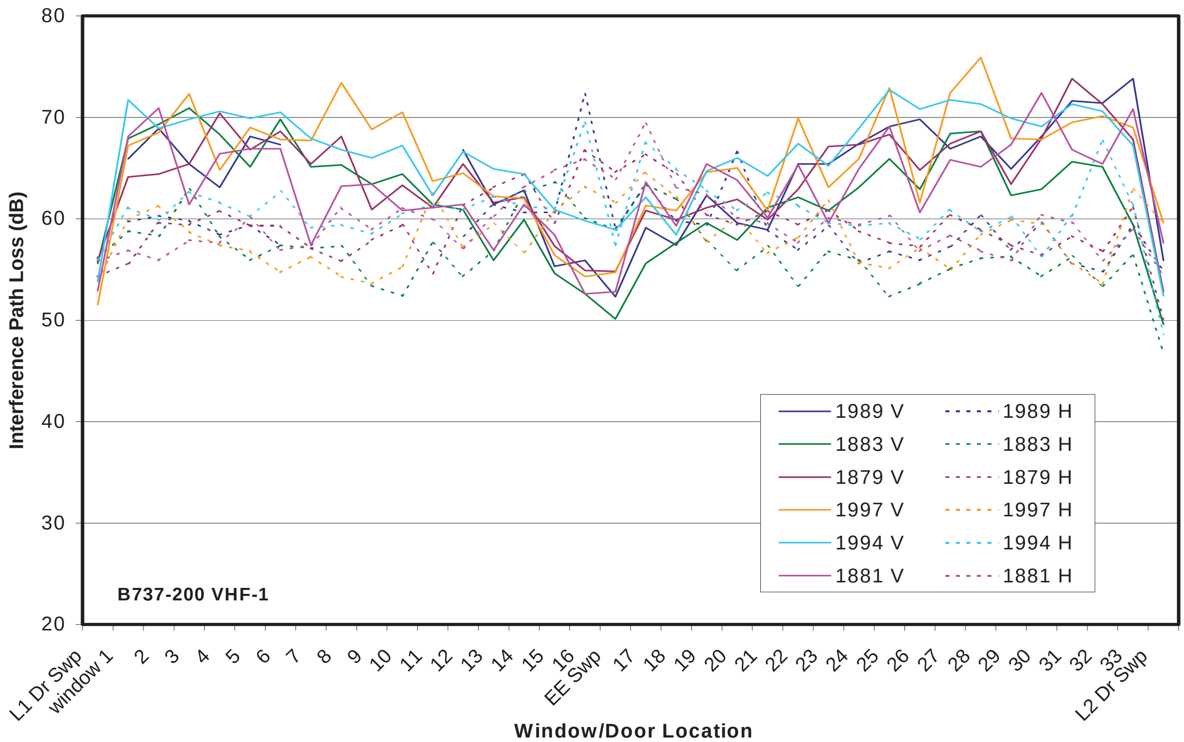

Figure 6.2-2: B737-200 VHF-1 Comm. (Top) interference path loss. Left windows/doors excitation.

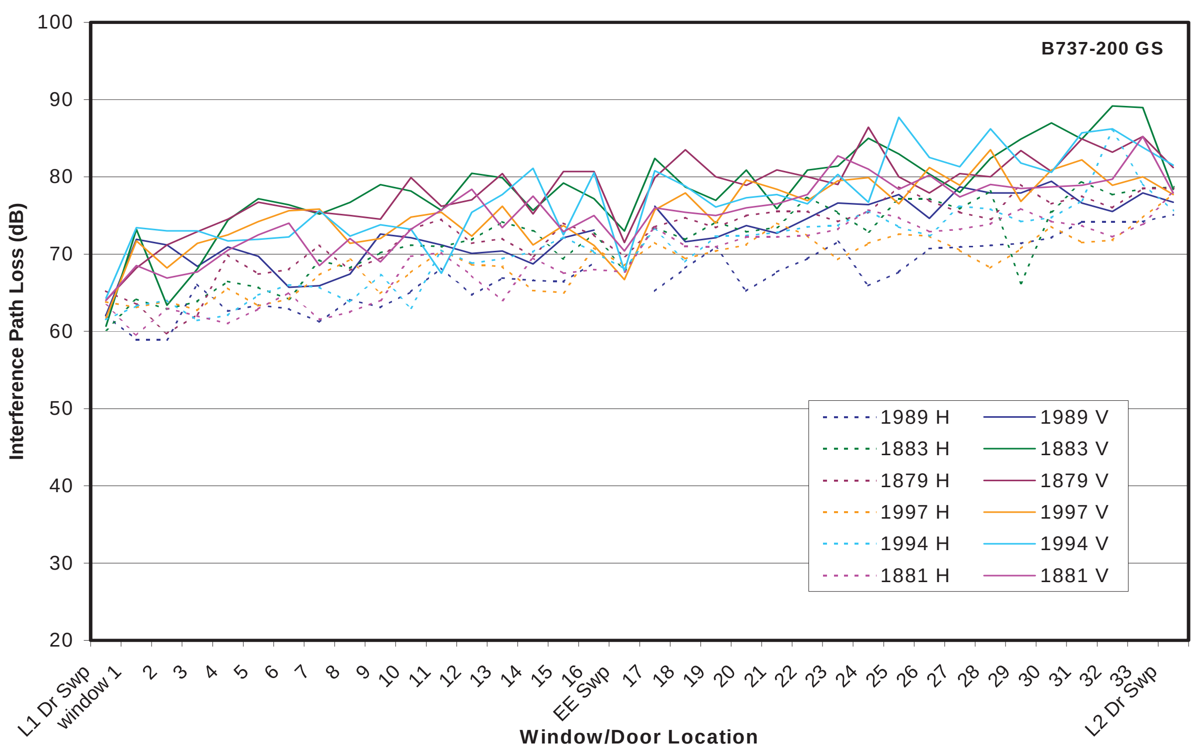

Figure 6.2-3: B737-200 GS (Nose) interference path loss. Left windows/doors excitation. Cockpit windows taped.

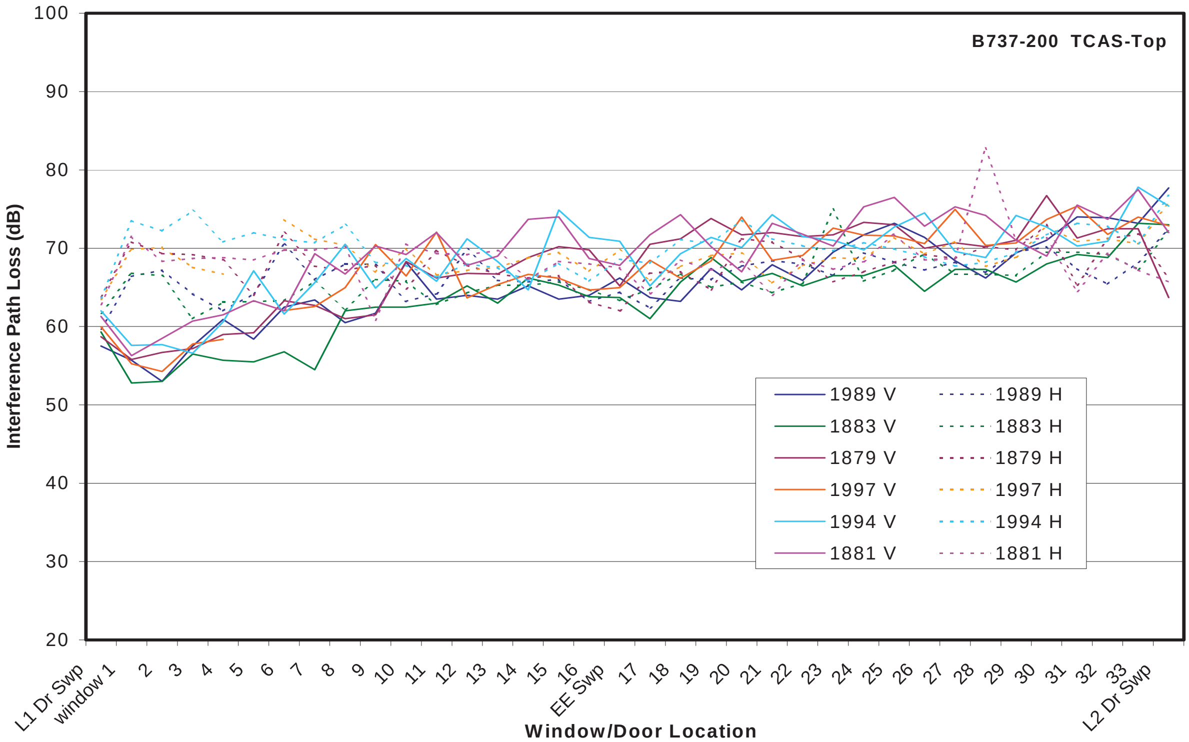

Figure 6.2-4: B737-200 TCAS (Top) interference path loss. Left windows/doors excitation.

6.3 MEF Based on IPL Measurements

As a result of the full-aircraft IPL measurements, there were more data points collected than there were seats. This happened since data were taken at every window (there are more windows than there are number of rows), at every seat, at every armrest position, and also in the aisle. For MEF calculations, the number of data points needs to be reduced to the number of seats or the number of PEDs. To achieve that goal, each seat's IPL is chosen to be the lowest IPL value (maximum coupling) for the vicinity locations. Refering to Figure 6.3-1, the specifics on the data reduction approach are listed below:

1. Seat-A Data: the IPL value is chosen to be the lowest among the Location Set A (LS-A). LS-A includes locations: 1) seat A; and 2) nearest windows and doors. There may be more than one window considered.

2. Seat-B Data: the lowest IPL among the Location Set B (LS-B). LS-B includes locations: 1) in middle of seat B; and 2) arm-rest between seats A and B (Location Set B).

3. Seat-C Data: the lowest IPL among the Location Set C (LS-C). LS-C includes locations: 1) armrest between seats B and C; 2) in the middle of seat C; and 3) the armrest next to the aisle.

4. Aisle Data: the IPL measured in the center of the aisle

5. No First Class: While data were collected on an airplane with first class seating (2 seats per row), this section assumes there are three seats per row for ease of data arrangement in the table format. This is reasonable since many configurations do not include first class seats.

6. All measurement points are considered only once. If a window data point was considered in an earlier row, the same data point cannot be considered in any other row.

Data points near a seat are compared and the minimum IPL (maximum coupling) is chosen for that seat. Table 6.3-1 shows the relationship between seat location and its measurement locations.

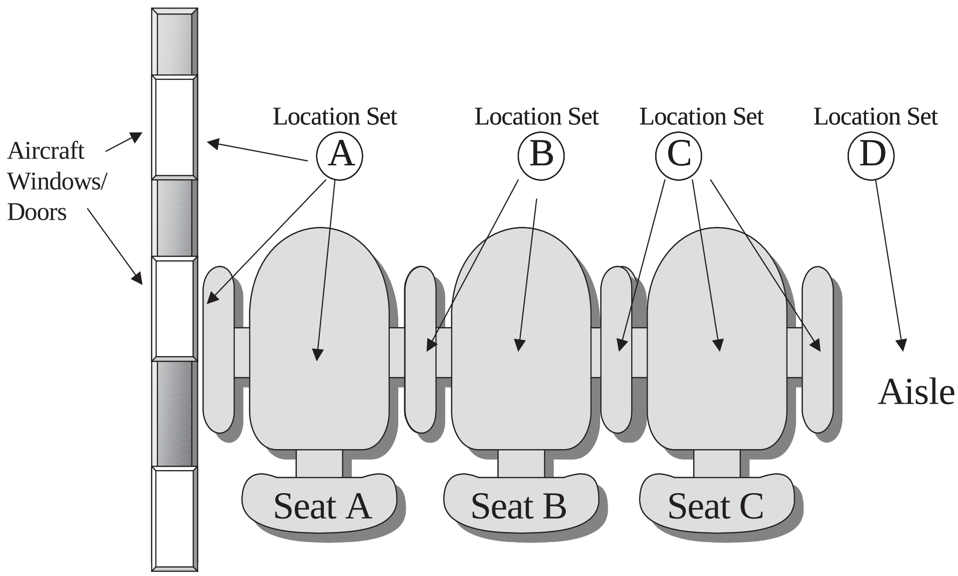

Figure 6.3-1: Seat Locations and Relationship with Measurement Locations.

Table 6.3-1: Explanation of Figure 6.3-1

Seat Location	Data Set
Seat-A	Location Set A (LS-A)
Seat-B	Location Set B (LS-B)
Seat-C	Location Set C (LS-C)
Aisle	Location Set D (LS-D)

6.4 *Results of MEF Calculations*

The minimum IPLs for the four aircraft systems are reported in Table 6.4-1, The same data is also shown for an isotropic transmit test antenna by removing the transmit antenna gain from the minimum IPL, thereby resulting in higher IPL values. Determination of MEF in this section does not require the minimum IPL, however, since it is normalized out in the process. They are provided so that the true IPL can be determined.

As a result of the data reduction process, normalized IPL for different systems are shown in Tables 6.4-2 to 6.4-5. In these tables, the number of IPL data points is approximately equal to the number of aircraft seats. The use of normalized IPL also helps to overcome the problem of having different definitions of IPL, or whether it includes antenna gain. The normalized IPL values in the table remain the same, while the minimum IPL may be scaled to conform to different definitions. The data in the table can also be used to apply to interference sources having different emission levels according to their locations. In this report, however, only sources having the same emissions level are assumed.

Figures 6.4-1 to 6.4-4 show the statistical cumulative distribution as the number of locations (seats) is increased. This process involves sorting and incrementally summing the normalized IPL, starting from the worst case IPL. Equations 6.1-8 and 6.1-9 are used on the incremental sums. Note that the numbers of seats/windows are for **both** sides of the aircraft for the purpose of calculating MEF. Actual number of data points measured is only half if performed on only one side.

In addition, Figures 6.4-1 to 6.4-4 also show the MEF computed using only the window IPLs. It is suspected that there are possible relationships between the MEF using the seats data and the MEF using only the window data. After all, interference signals are assumed to pass through window/door-seams as they propagate to aircraft receiver antennas.

The comparisons show that the MEF calculated using seat-IPL data and window-IPL data are within one dB of one another.

While there are significantly more number of seats than windows, the similar MEF values can be explained in that: 1) There are more windows than number of rows of seats; and 2) Coupling data at the windows are significantly higher than the same data for the inside seats.

Table 6.4-1: Aircraft Systems Minimum IPL

Aircraft Systems	B737-200 UAL Nose No.	Transmit Antenna Type	Free Space Transmit Ant. Gain (dBi)	Minimum IPL (dB)	Minimum IPL (Isotropic Source) (dB)
LOC/VOR	1989	Dipole	0.9	65	65.9
VHF-1 Com (top)	1997	Dipole	2.1	51.5	53.6
TCAS	1997	Dual-Ridge Horn	7.4	54.3	61.7
GS	1997	Dipole	1.9	61.7	63.6

Table 6.4-2: LOC-Tail Normalized IPL- B737 (Nose No. 1989)

Row	Seat-A Data	Seat-B Data	Seat-C Data	Aisle Data	Windows/Doors considered in Seat-A Data
1	4.8	16	14.2	15.5	L1, W1
2	4.5	17.7	16.5	17.5	w1,s2,w3
3	6.2	19.2	18.3	17.7	w5,w6
4	4.5	17.2	15.3	16.7	w7
5	0.8	11.8	13.5	13.2	w8,w9,w10
6	2.2	8	13.5	17.5	w11,w12
7	5	13.7	14.3	16	w13
8	6.2	12.2	14	14.8	w14
9	4.5	9.8	13.5	13	w15
10	6.3	11.5	15	14.2	w16
11	0	17.8	17	16	EE,w17
12	9.3	15.7	15.7	15.7	w18
13	7.8	20.7	17.2	17	w19,w20
14	9.2	17.2	16.8	18.8	w21
15	8.5	18.3	14	16.7	w22,w23,w24
16	7.3	15.5	15.2	15.5	w25,w26,w27
17	4.8	10	11	15.5	w28,w29,w30,w31
18	4	11.5	12.8	11.1	w32,w33,L2

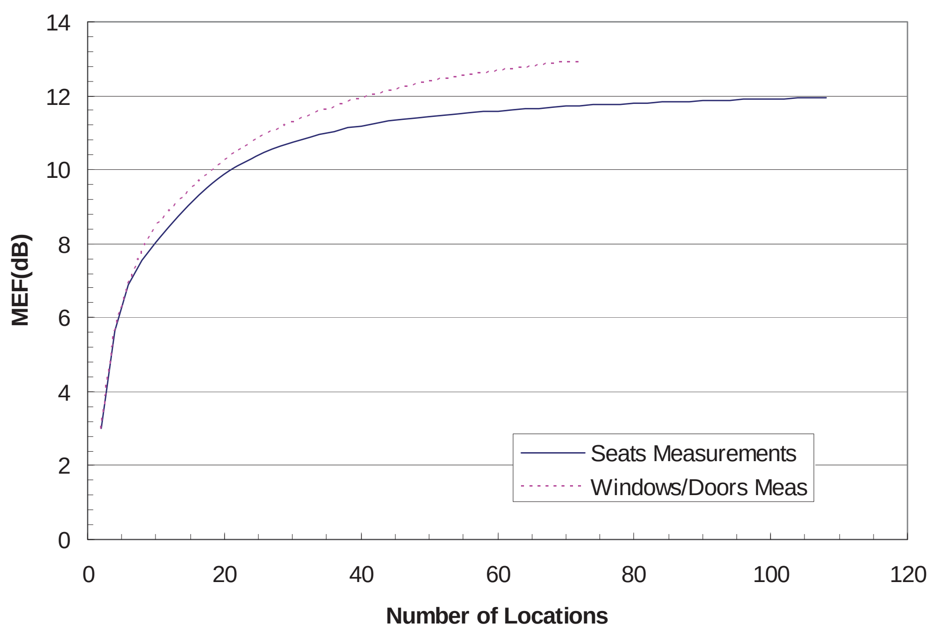

Figure 6.4-1: MEF versus number of locations. B737-Loc-Tail.

Table 6.4-3: VHF-Comm 1 Normalized IPL. B737 (Nose No. 1997)

Seat Row	Seat-A	Seat-B	Seat-C	Aisle	Windows/Doors included in Seat-A Measurements
1	0	13.2	11.8	10	L1, w1
2	5.9	15.7	13.6	16.7	w2,w3,w4
3	3.2	16.3	13.3	12.2	w5,w6
4	2.8	16.8	13.9	15.4	w7,w8
5	2.1	15.9	12.8	12.1	w9,w10
6	5.7	13.7	11.9	13	w11,w12
7	8	14.4	12	11.1	w13
8	4.9	10.8	13	15.4	w14,w15
9	2.8	9.5	9.8	13.8	w16
10	3.2	14.9	10.7	12.5	EE(w16),w17
11	9.3	13.5	10.8	11.2	w18
12	6.2	14	14	12.4	w19,w20
13	5.1	12.9	11.7	15.9	w21
14	6.7	15.3	13.1	17.7	w22,w23
15	3.6	13.2	9.9	14.3	w24,w25
16	5.7	15.1	14.1	15.7	w26
17	3.5	16.6	13.8	16.8	w27,w28
18	8.4	15.2	13.6	13.5	w29
19	4.2	12.1	12.7	16.7	w30,w31
20	2.1	10.3	6.2	13.3	w32
21	8.1	9.9	6.1	9.6	w33,L2

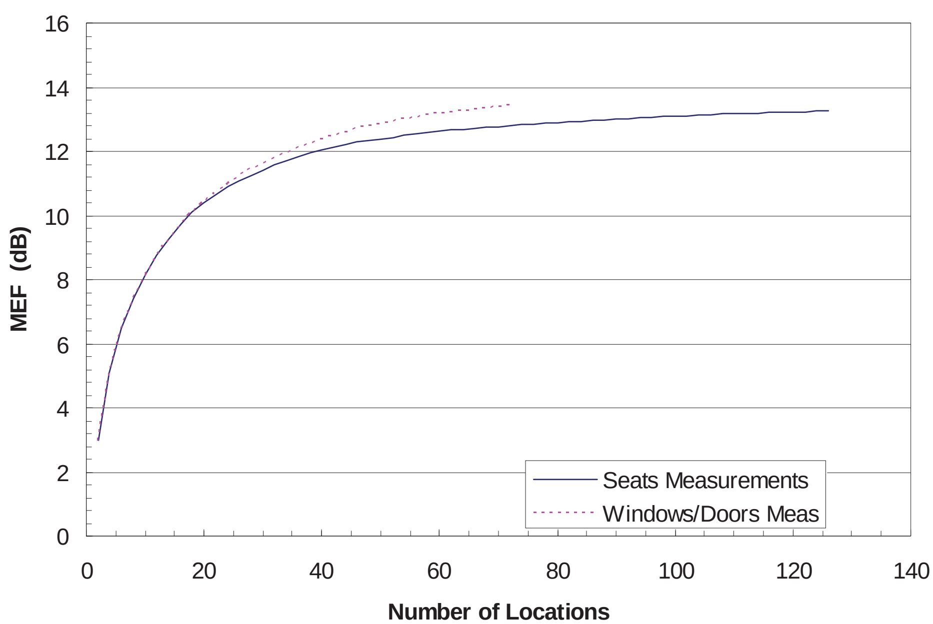

Figure 6.4-2: MEF versus number of locations. B737-VHF-Top.

Table 6.4-4: TCAS-Top- Normalized IPL. B737-1997

Seat Row	Seat-A	Seat-B	Seat-C	Aisle	Windows/Doors included in Seat-A Measurements
1	1	11	13.2	15.4	L1, w1
2	0	9	9.7	12.8	w2,w3,w4
3	7.8	10.3	8.8	14.6	w6
4	8.3	13.1	13.9	13.8	w7,w8
5	12.2	12.9	11.4	19.2	w9,w10
6	9.4	13.6	11.8	17	w11,w12
7	11.1	14.7	13.6	14.9	w13
8	12.4	14.3	13.4	16.1	w14
9	9.5	13.6	13	16.3	w15
10	10.4	13.6	16.2	15.8	w16
11	10.7	13.3	14.8	19.4	EE,w17
12	11.9	14.8	15.7	18	w18
13	12.7	16.3	16.3	13.8	w19,w20
14	11.3	16.3	15.1	17.7	w21
15	13.5	11.3	17.2	18.8	w22,w23
16	14.4	17.3	16.9	19.9	w24,w25
17	15	16.3	19.2	23	w26
18	13.4	16.5	18	16.1	w27,w28
19	14.6	16.4	17	17.5	w29
20	16.6	19.4	20.2	21.1	w30,w31
21	16.9	16.3	19.7	21.2	w32
22	14.8	18.6	17.1	20.3	w33,L2

*Note: Window 5 data not available. Antenna used would not fit due to seat blockage.

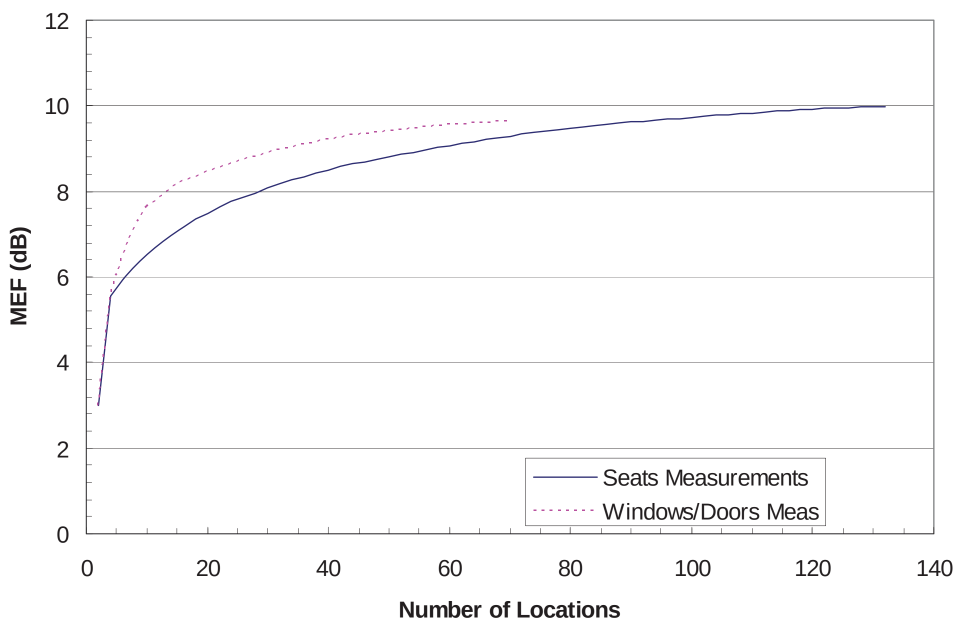

Figure 6.4-3: MEF versus number of locations. B737-TCAS-Top.

Table 6.4-5: Glideslope. B737-1997. Cockpit windows taped

Seat Row	Seat-A	Seat-B	Seat-C	Aisle	Windows/Doors included in Seat-A Measurements
1	0	4	8.7	4.1	L1, w1
2	1	3.1	4.3	6.6	w2,w3,w4
3	1.6	6.8	6	6.3	(w5),w6
4	5.6	7.2	5	5.9	w7,w8
5	3.2	5.3	5.8	7.2	w9,w10
6	6.9	6.6	8.1	8.9	w11,w12
7	5.3	7.4	6.7		w13
8	3.3	7	9.2	14.5	w14,15
9	5	10.7	9	6.8	w16, EE
10	9.8	7.2	7.6	8.4	w17
11	6.3	9.3	6.3	10.3	w18
12	8.6	11.2	6.9	9.7	w19,w20
13	12.3	11.1	11	12.2	w21
14	6.2	9.9	11.5	15.7	w22,w23
15	9.7	11.9	13.5	14.3	w24,w25
16	9.9	11.3	12.1	12.9	w26
17	6.5	15.8	12	14.3	w27,w28
18	9	12.1	13.2	16.8	w29
19	9.8	12	15.2	13.9	w30,w31
20	10.1	15.3	14.9	14.5	w32
21	13	14.9	14.7	15.3	w33

* Note: IPL for window 5 was interpolated from data for the nearby readings.

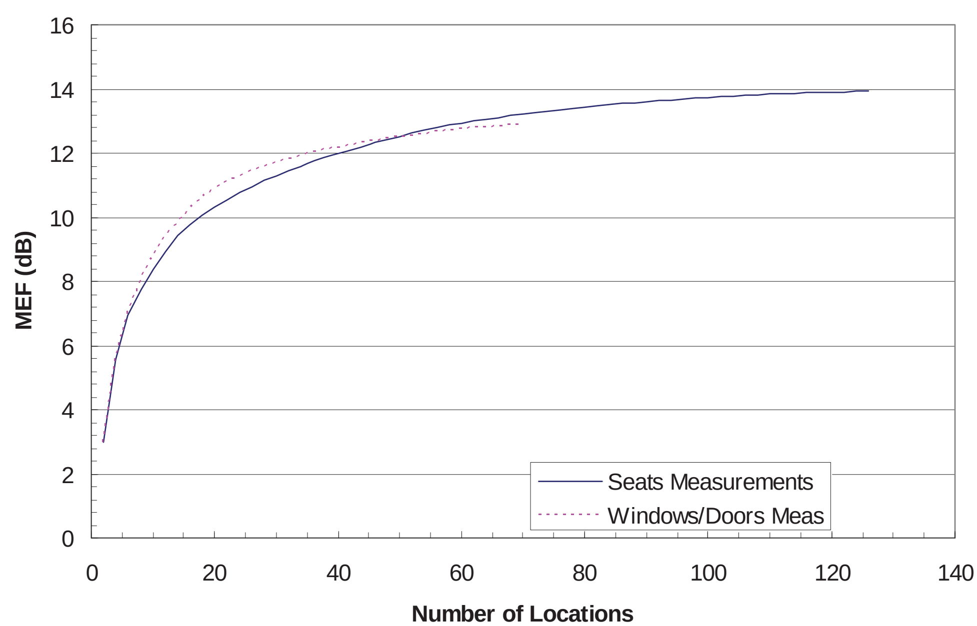

Figure 6.4-4: MEF versus number of locations. B737-GS- Nose. (Cockpit windows taped).

In addition, it is of interest to determine the incremental effects of the seat locations. Using seat-A as the base line, Tables 6.4-6 to 6.4-9 compute the incremental effects as all seat-B data and all seat-C data are added. With the aisle data, incremental effects are also shown as one adds additional inside seats. In this case aisle data are counted only once per row of seat, rather than doubled as the seat data.

As expected, the effects on MEF decrease as the seats are further inward from the windows. The addition of aisle data implies that each additional seat column only adds no more than 0.4 dB to the total MEF, with decreasing effects further inside. For large airplane, this implies that only outside seats should be considered, and that further inside seats contribute little to the overall MEF.

Table 6.4-6: Incremental Effects of Including Additional Seat Locations – LOC/VOR-Tail

Combi nation	Seat Locations Included	MEF (dB)	Incremental Effects (dB)	No. of Locations
1	Seat-A	10.87	0	42
2	Seat-A and Seat-B	12.72	1.85	84
3	Seat-A, Seat-B and Seat-C	<u>13.93</u>	1.21	105
4	Seat-A, Seat-B, Seat-C and Ailse	14.33	0.4	126
5	Windows/ Doors Only (All)	<u>12.90</u>		70

Table 6.4-7: Incremental Effects of Including Additional Seat Locations – VHF-1-Top

Combi nation	Seat Locations Included	MEF (dB)	Incremental Effects (dB)	No. of Locations
1	Seat-A	12.02	0	42
2	Seat-A and Seat-B	12.54	0.52	84
3	Seat-A and Seat-B and Seat-C	<u>13.26</u>	0.72	126
4	Seat-A and Seat-B and Seat-C and Ailse	13.46	0.2	147
5	Windows/ Doors Only (All)	<u>13.41</u>		72

Table 6.4-8: Incremental Effects of Including Additional Seat Locations – TCAS-Top

Combinations	**Seat Locations Included**	**MEF (dB)**	**Incremental Effects (dB)**	**No. of Locations**
1	Seat-A	8.02	0	44
2	Seat-A and Seat-B	9.15	1.13	88
3	Seat-A and Seat-B and Seat-C	9.98	0.83	132
4	Seat-A and Seat-B and Seat-C and Ailse	10.19	0.21	154
5	Windows/ Doors Only (All)	9.64		70

Table 6.4-9: Incremental Effects of Additional Seat Locations – GS-Nose

Combinations	**Seat Locations Included**	**MEF (dB)**	**Incremental Effects (dB)**	**No. of Locations**
1	Seat-A	10.87	0	42
2	Seat-A and Seat-B	12.72	1.85	84
3	Seat-A and Seat-B and Seat-C	13.93	1.21	126
4	Seat-A and Seat-B and Seat-C and Ailse	14.33	0.4	146
5	Windows/ Doors Only (All)	12.9		70

Due to airplane symmetry and that IPL measurements were conducted only on one side of the airplane, contributions from Seats, Windows and Doors to the total cumulative effects are doubled to simulate full configuration. The Aisle measurements are counted only once, however.

6.5 Observations

A few observations can be made from the previous tables and charts:

1. MEF determined using the windows-only IPL data are within one dB of the MEF determined using full-aircraft seat data. This is significant in that only window IPLs are needed if this observation can be further proven for other systems and aircraft. Window IPL data are readily available, while full-aircraft data are more difficult and expensive to collect, especially for large aircraft.

2. The cumulative distribution curves can help to determine the minimum number of measurements to make for the purpose of MEF calculations.

3. The conservative estimates of the bounds for MEF for the systems measured are between 10 dB and 14 dB, depending on systems.

4. The additional seat effects on the MEF diminish rapidly as the seat locations moved away from windows/doors. At the worst case, the addition of seat-B contributes only 2 dB to the MEF. Seat-C and aisle (simulating another column of seats) contribute even less.

A MEF comparison between different aircraft would be of interest. However, that would be difficult since full-aircraft IPLs are time consuming to collect. Alternatively, Appendix C provides an indirect comparison by comparing MEF computed from window IPL data for different airplanes. The validity of this comparison hinges upon further validations of the observation that MEF computed using window IPL and using full-aircraft IPL are similar.

7 Summary and Conclusions

Emission measurements were conducted on 33 wireless phones of various design configurations by different manufacturers. Seventeen of the phones were GSM phones, and most devices were dual-band (a few were tri-band or even quad-band) and had GPRS data capabilities. Likewise, the remaining 16 CDMA phones were mostly dual-band devices and 1xRTT capable. These mobile phones were more representative of those available in today's market place than the mobile phones tested previously by NASA [1]. The following observations were made:

- The 33 wireless phones tested did not generate higher emissions in most aircraft radio bands than standard laptop computers. An exception is the MLS band, where the emissions from the phone exceeded the emissions from the laptop computers. However, the safety margins in this band were positive for all devices. It is noted that operation of non-intentionally transmitting laptop computers is currently allowed during certain parts of flight.

- Spurious emissions from the wireless phones tested were below the aircraft installed equipment emission limits (RTCA/DO-160 Category M). They were also below the FCC Part 15 limits for unintentional transmitters such as laptop computers.

- The calculated safety margins can be negative or positive depending upon the interference thresholds (minimum or typical) and the minimum IPL data (the lowest or the average) used. The safety margins are based on the measured emission data, the existing IPL and interference threshold data.

- It is generally observed that in lower frequency bands (VHF-Com, LOC, VOR and GS), each mobile phone's maximum emissions are similar regardless whether it is operating in the cellular or PCS bands. This is not the case for higher frequency bands (TCAS, DME, GPS or MLS).

- The measured emissions in the voice and data modes are generally similar for any single device (within 2-5 dB) in most cases.

An approach was developed to provide an estimate of the upper bound on the front-door interference effects of multiple PEDs. This approach sums the interference powers at the receivers after scaling each device's emission by the IPL corresponding to its location. Using full-aircraft B737 IPL data, conservative upper bounds were derived for LOC, VHF and TCAS on a B737 airplane. The following observations were made:

- MEF determined using the windows-only IPL data were within one dB of the MEF determined using full-aircraft seat data.

- Conservative bounds for MEF for the systems measured were between 10 dB and 14 dB for LOC, VHF-Com, VOR and GS.

- The effects of additional seats on the MEF calculation diminished rapidly with the increased distance between the seat locations and the windows/doors.

8 Recommended Future Work

- Additional receiver interference threshold data are needed for greater confidence level. Tests on multiple receivers from different manufacturers are recommended. Signal modulation and types should be considered.

- Assessment should be performed for software-defined-radios, active and passive RFID (radio-frequency-identification) tags, and the latest portable music playing devices (non-intentional transmitters).

- Assessment of the potential for emerging radio technologies that overlay existing spectrum (such as Ultra Wideband) to cause interference to aircraft systems.

- Conduct additional IPL measurements on different types of aircraft where minimal data currently exists. Cargo-bay IPL data are also desirable.

- Conduct additional assessment of multiple equipment effects.

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Appendix A: CDMA Phone Test Results

The following charts illustrate each wireless phone's cell data, cell voice, PCS data, and PCS voice mode envelopes. An equivalent measurement noise floor is included in each chart for each band to represent the instrument noise floor. The data in these charts were further reduced to produce the data plotted in charts found in Sections 3.4.1 to 3.4.3.

A.1 Band 1

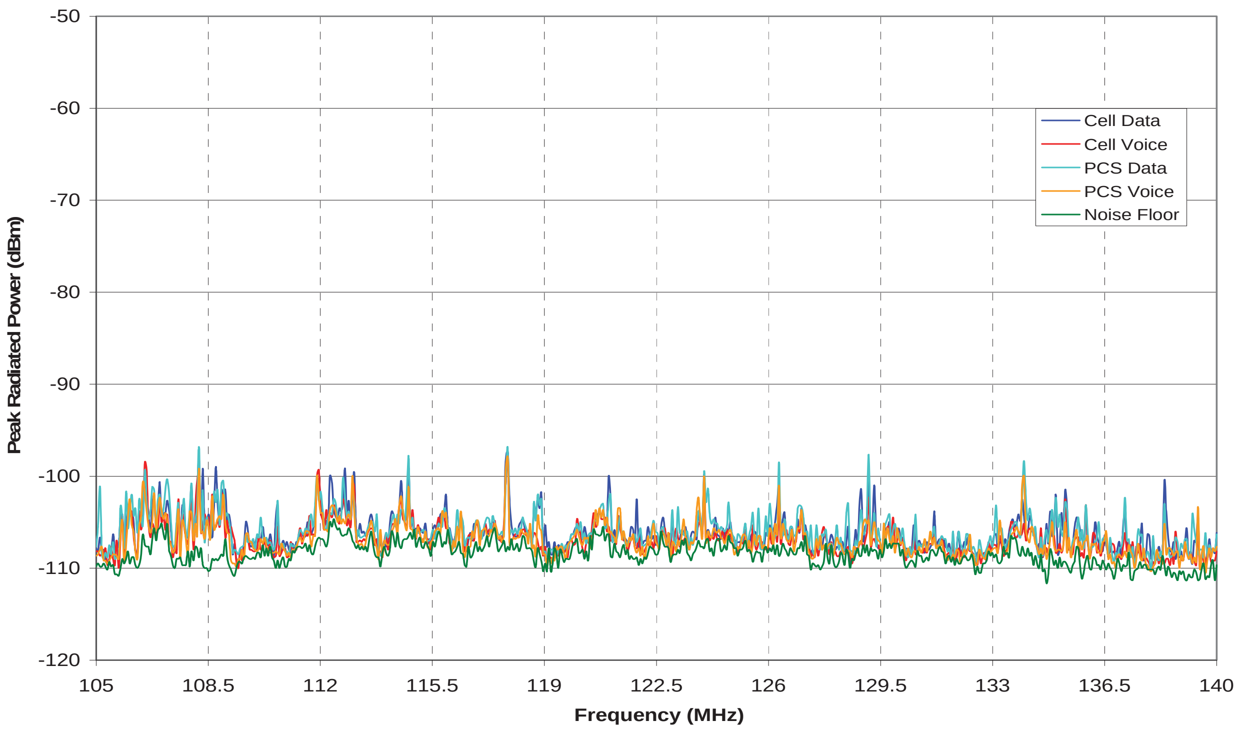


Figure A1: CDM01 four mode envelopes, Band 1.

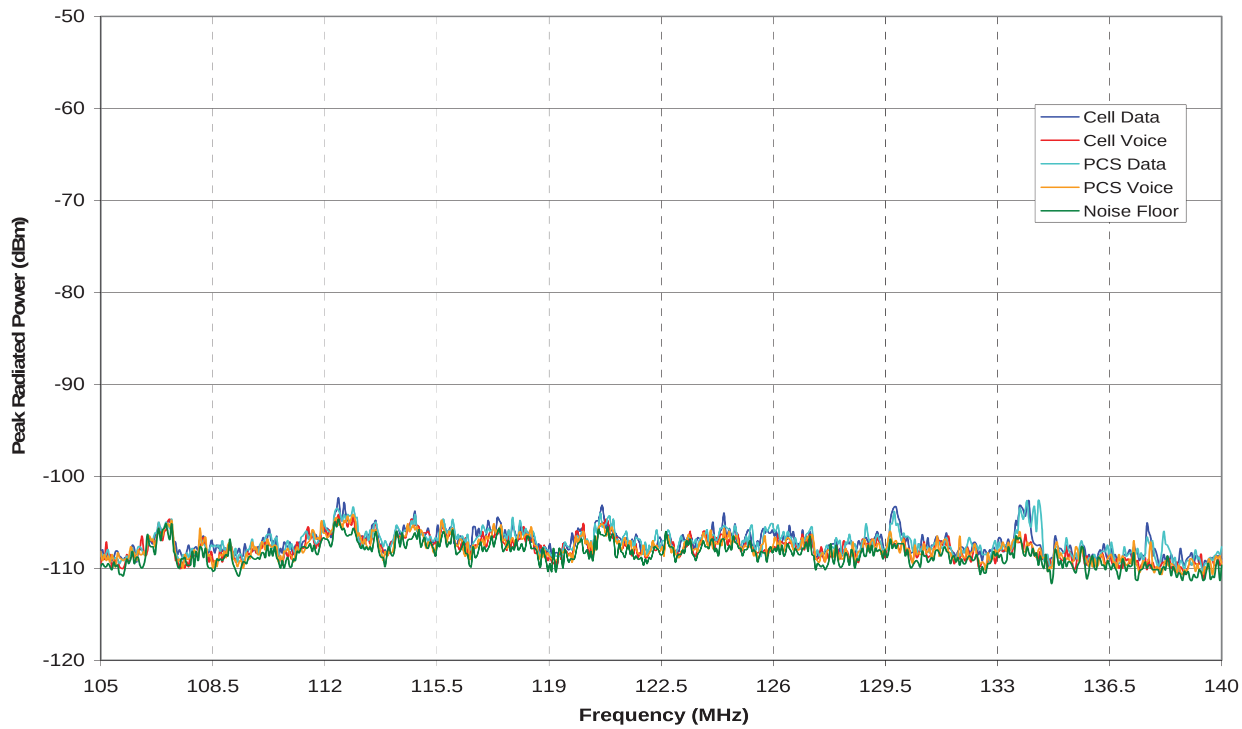


Figure A2: CDM02 four mode envelopes, Band 1.

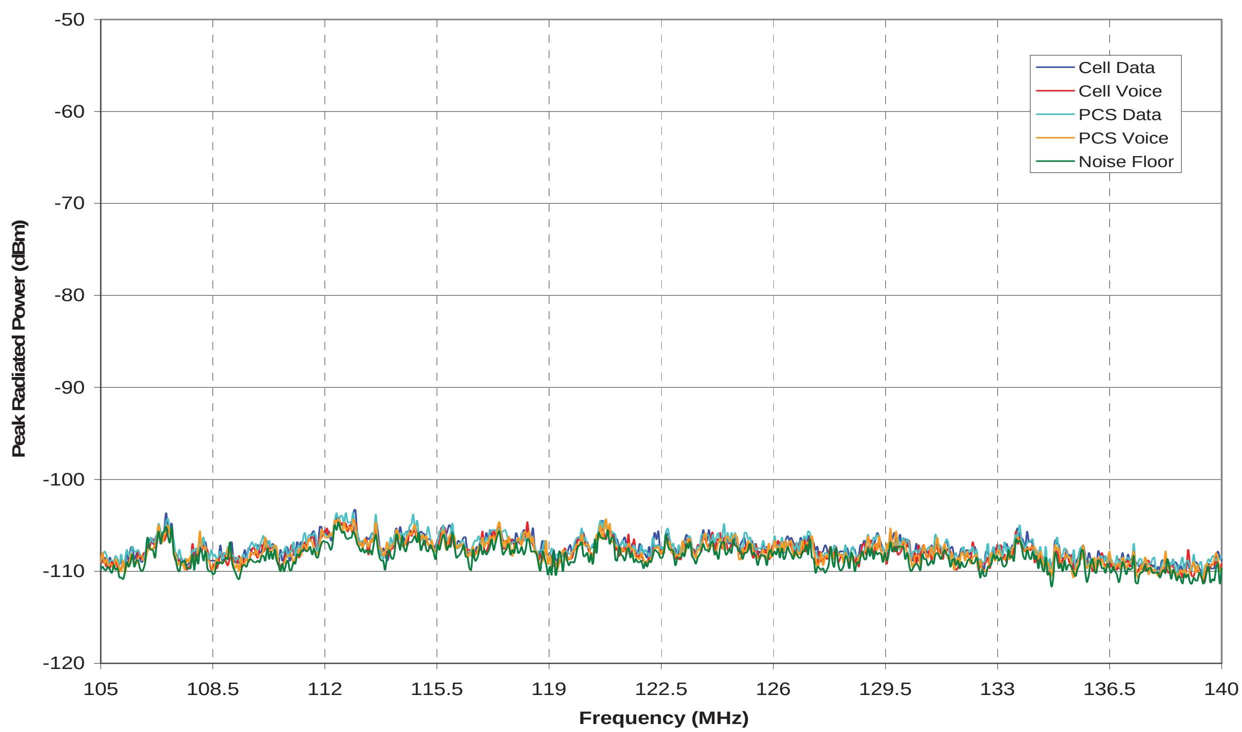


Figure A3: CDM03 four mode envelopes, Band 1.

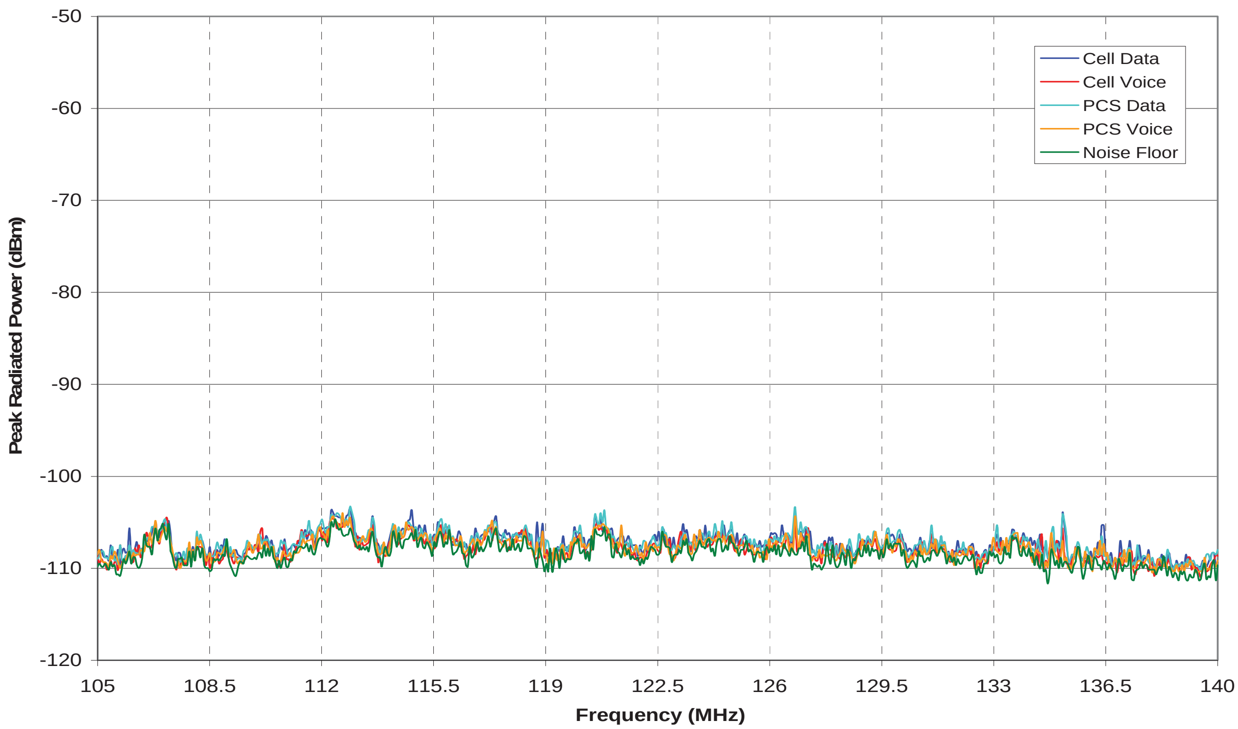


Figure A4: CDM04 four mode envelopes, Band 1.

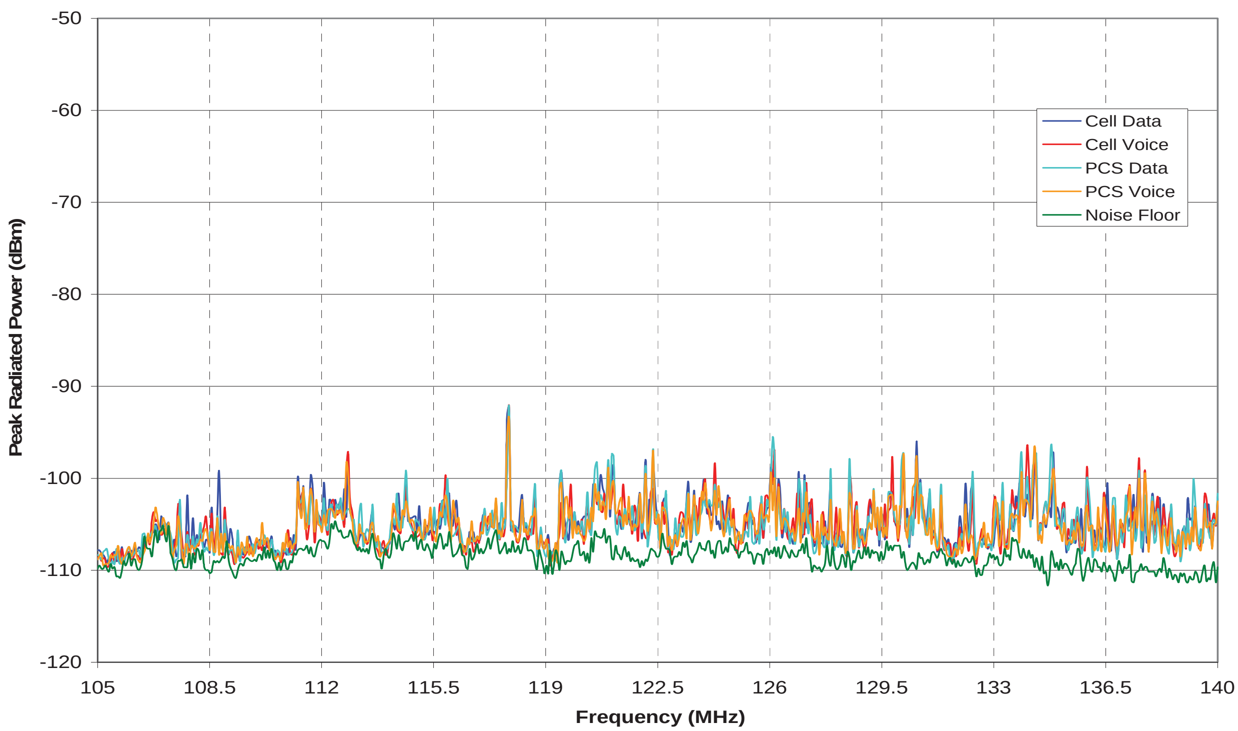


Figure A5: CDM05 four mode envelopes, Band 1.

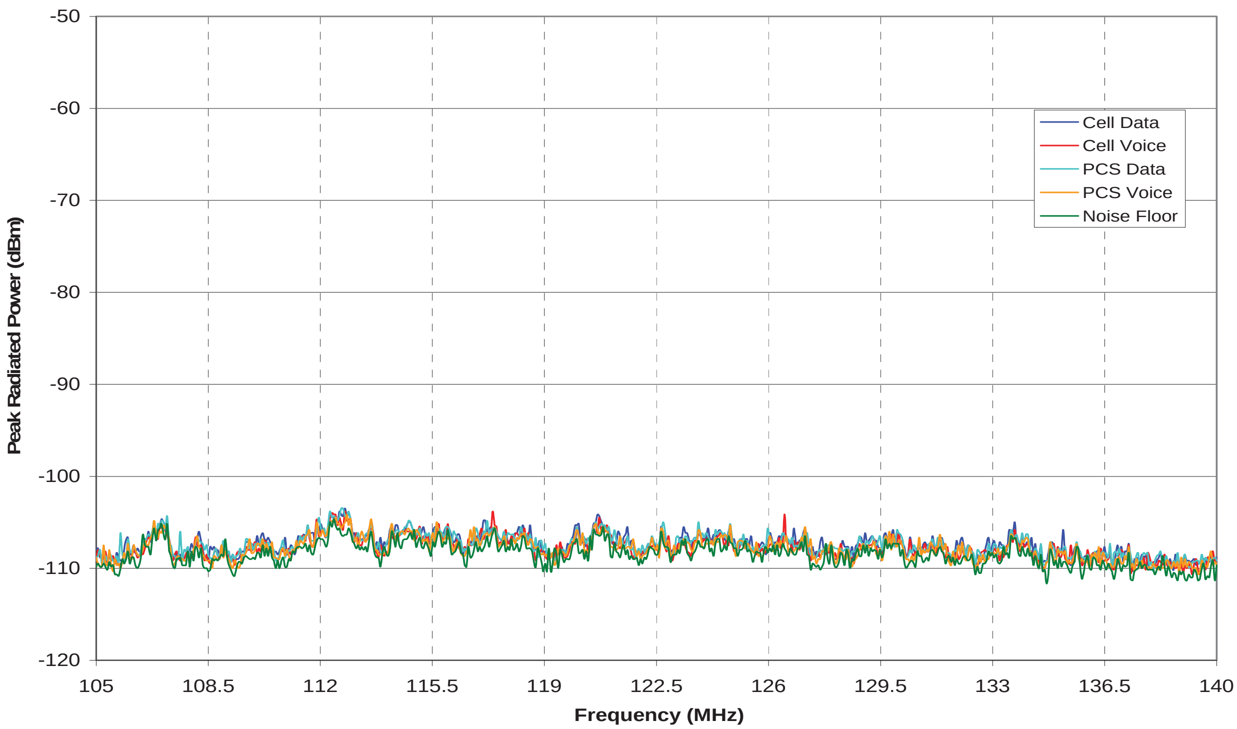


Figure A6: CDM06 four mode envelopes, Band 1.

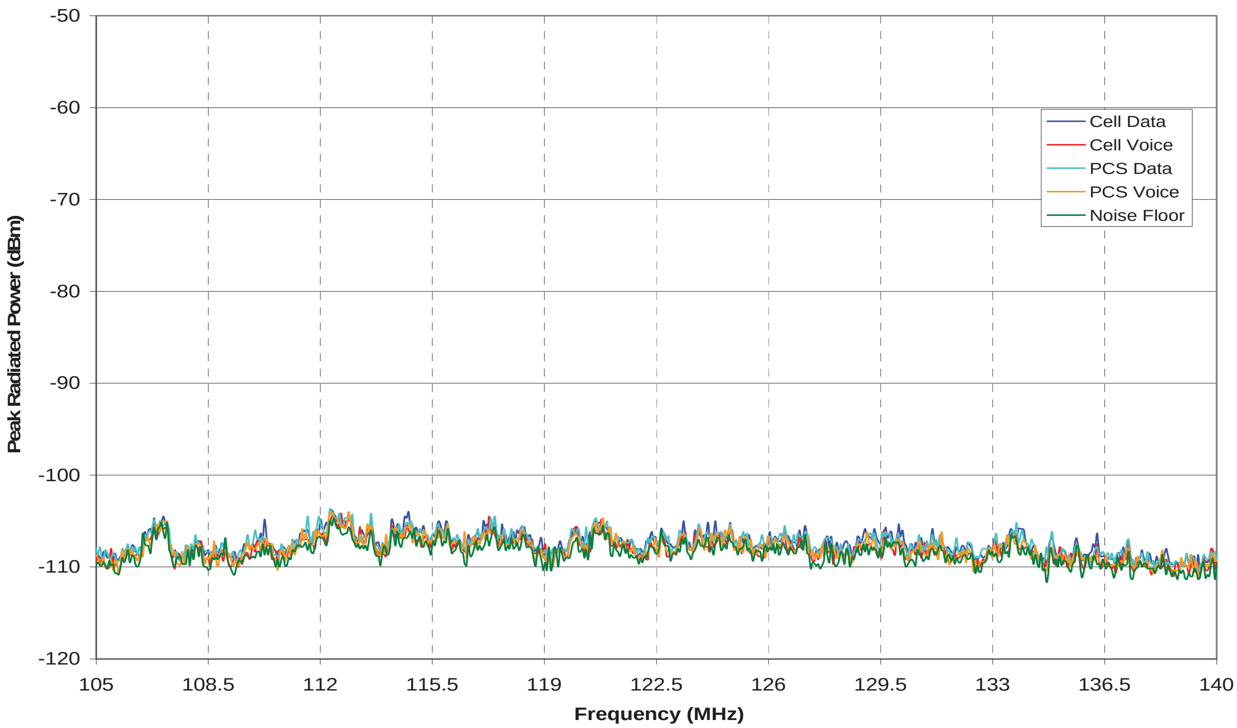


Figure A7: CDM07 four mode envelopes, Band 1.

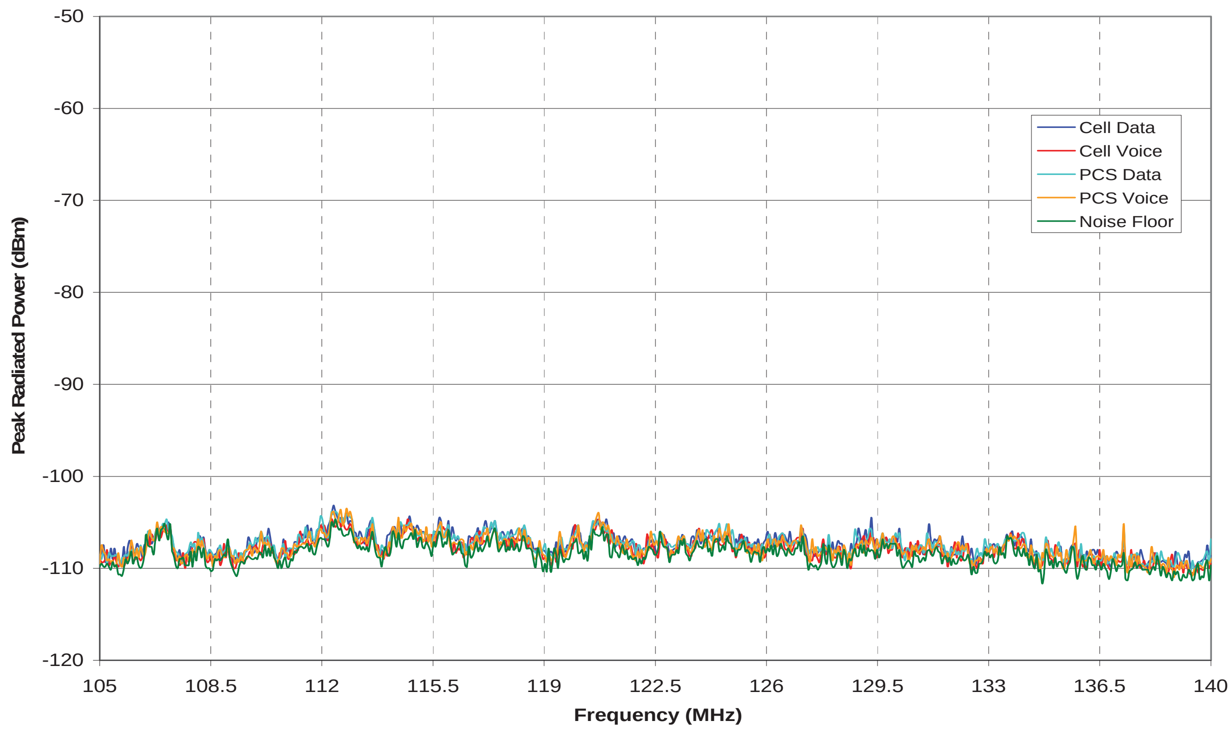


Figure A8: CDM08 four mode envelopes, Band 1.

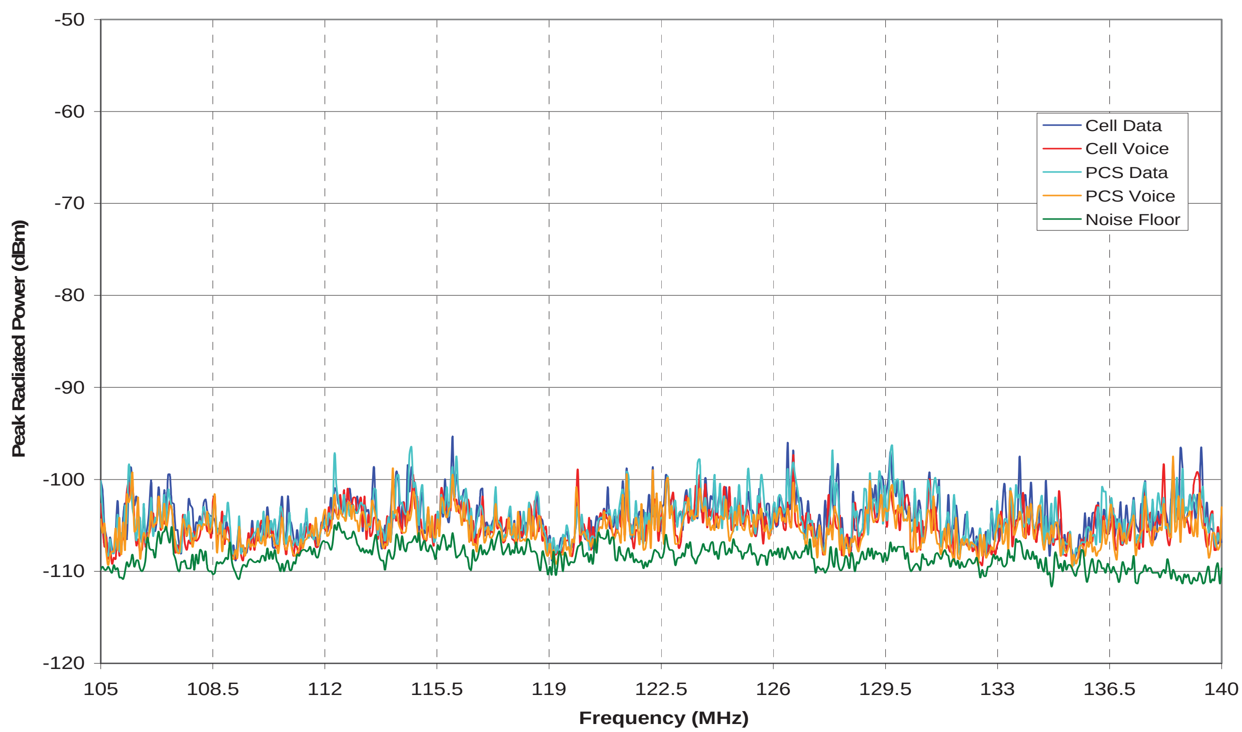


Figure A9: CDM09 four mode envelopes, Band 1.

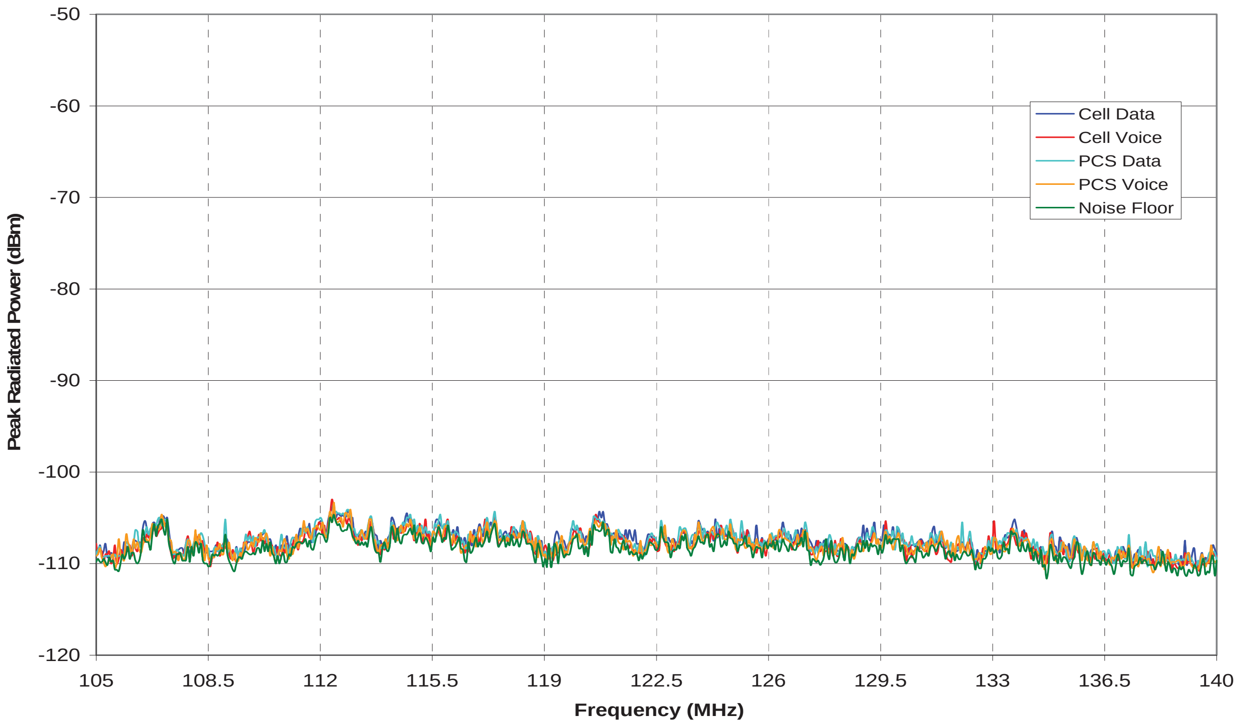


Figure A10: CDM10 four mode envelopes, Band 1.

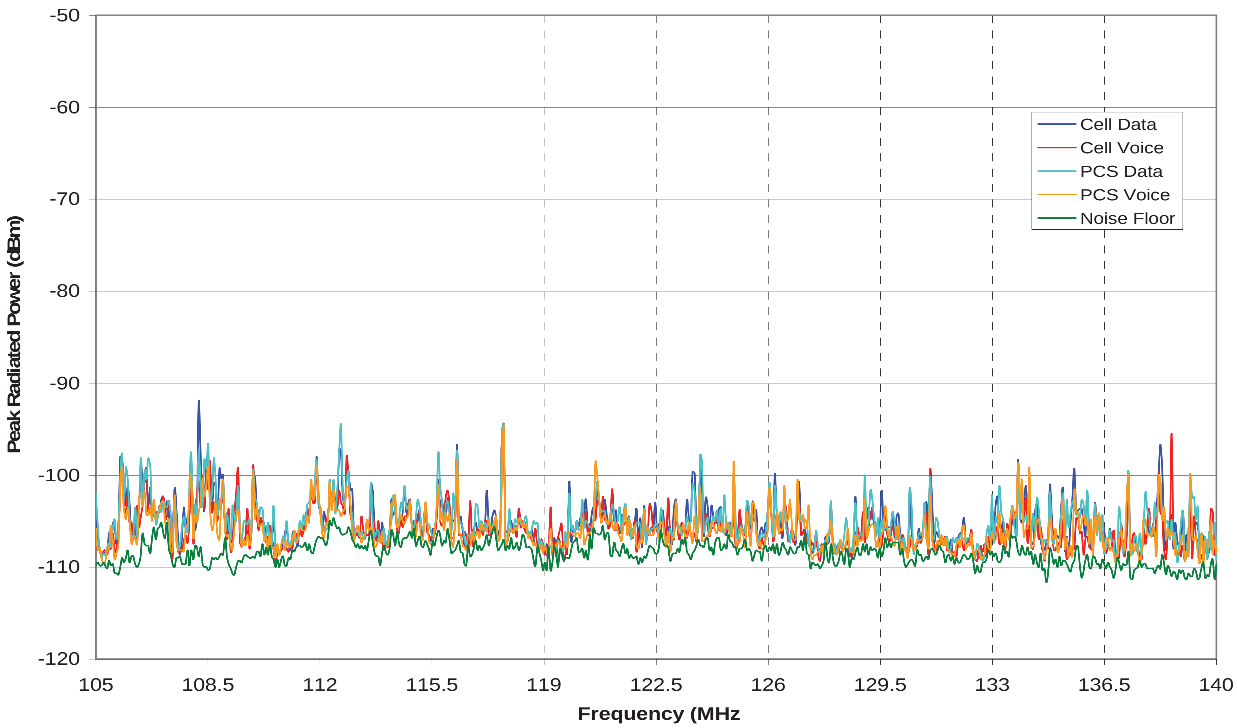


Figure A11: CDM11 four mode envelopes, Band 1.

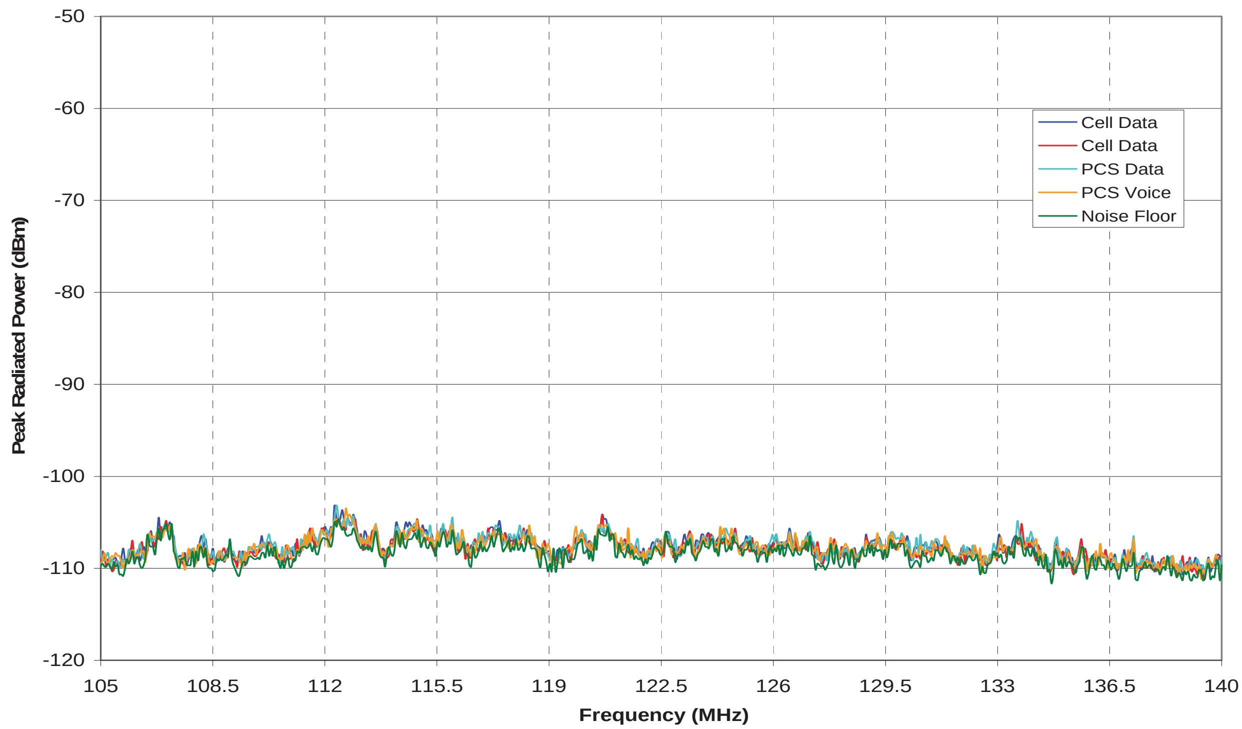


Figure A12: CDM12 four mode envelopes, Band 1.

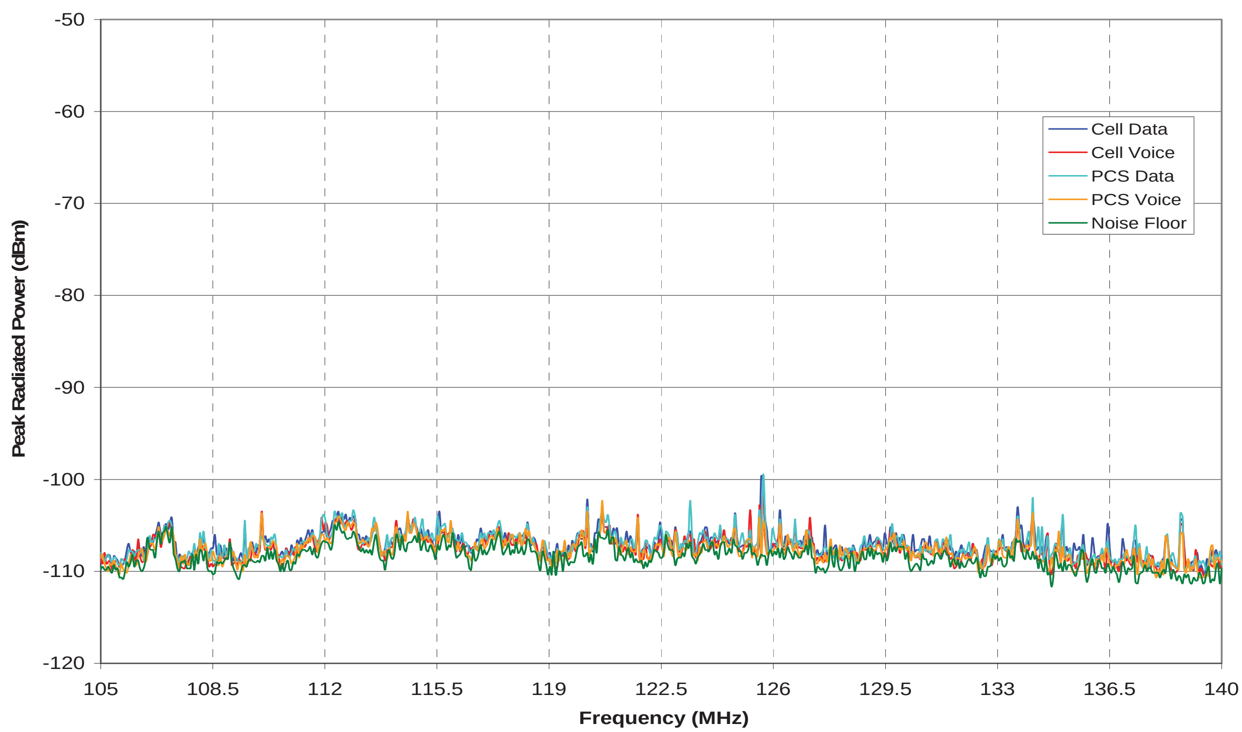


Figure A13: CDM13 four mode envelopes, Band 1.

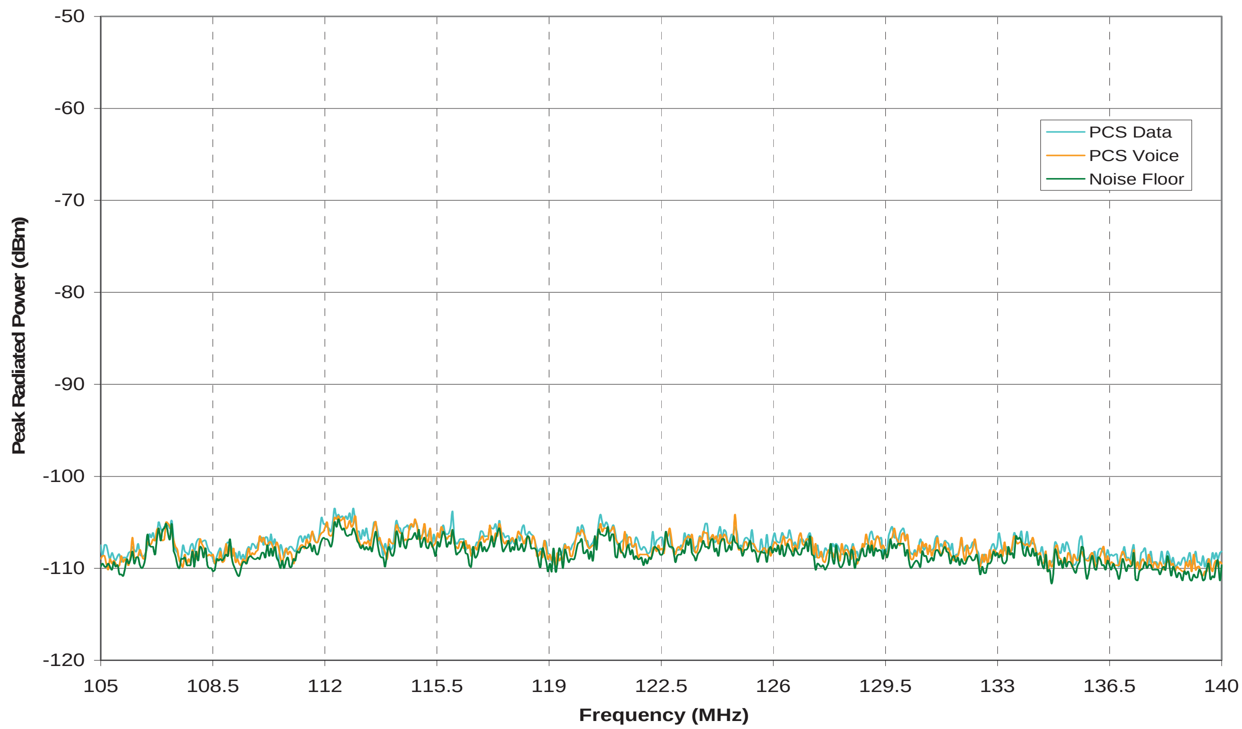


Figure A14: CDM14 two mode envelopes, Band 1.

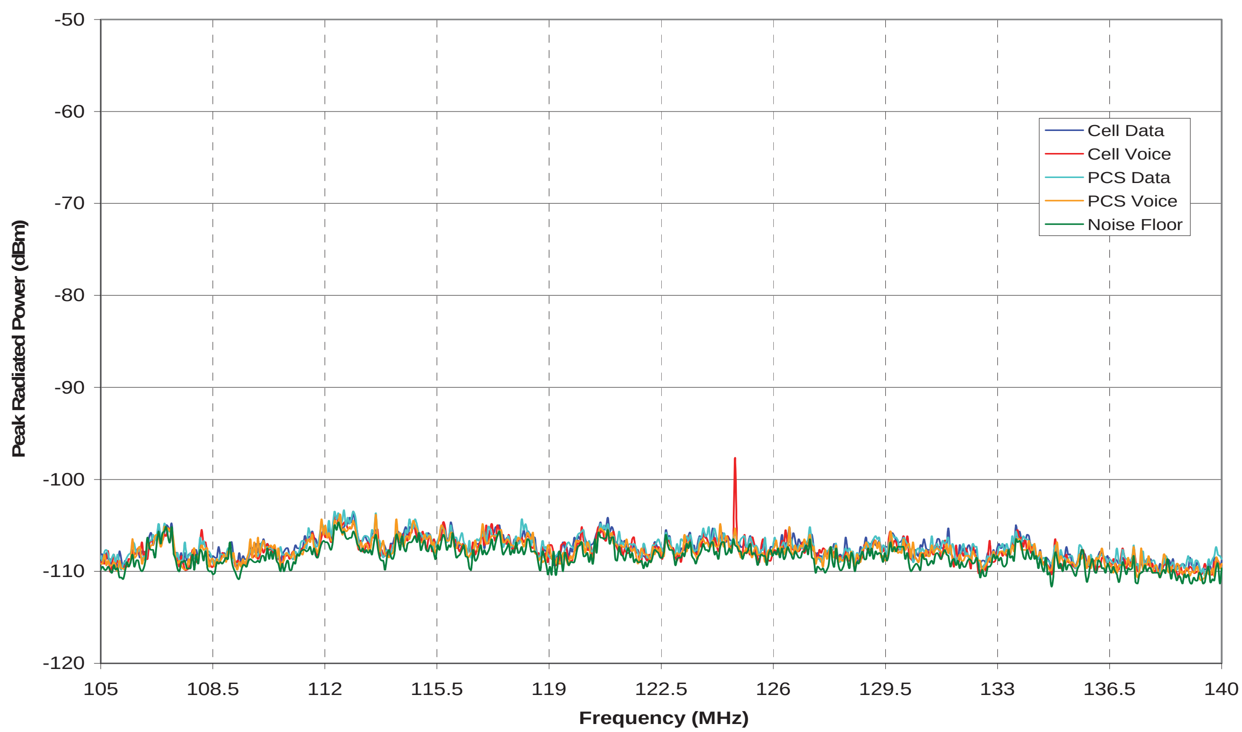


Figure A15: CDM15 four mode envelopes, Band 1.

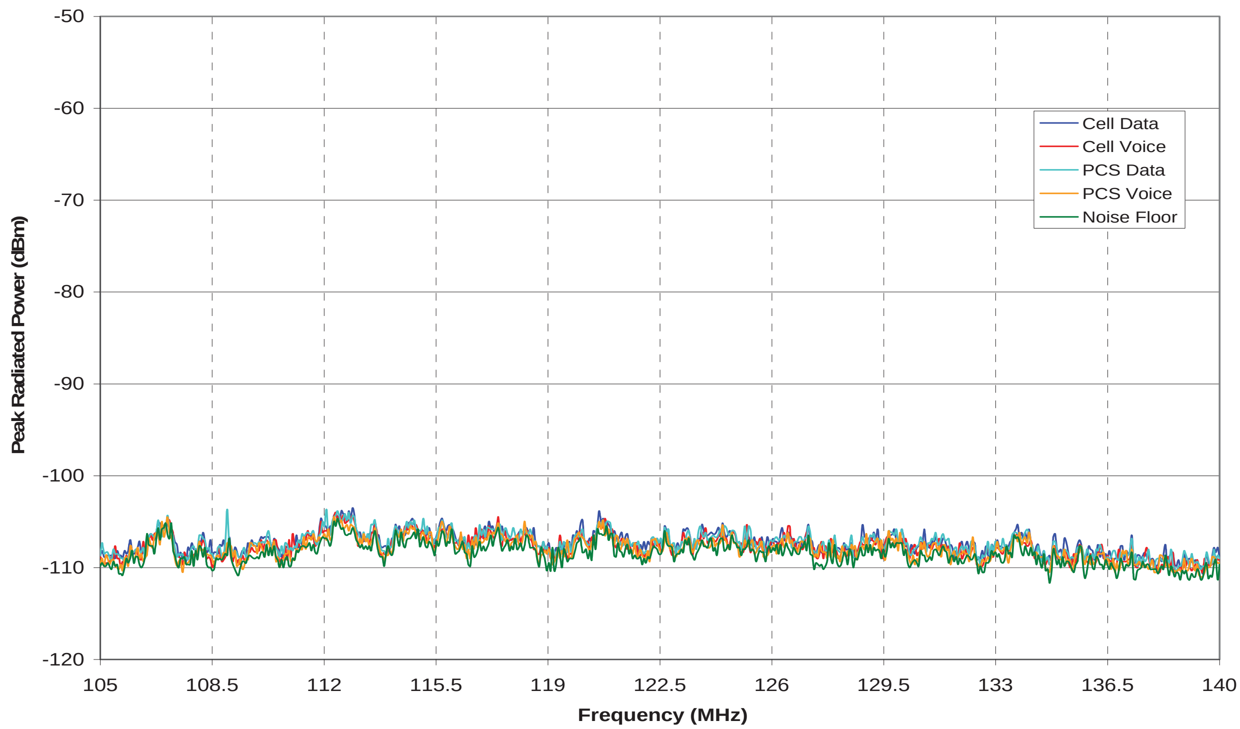


Figure A16: CDM16 four mode envelopes, Band 1.

A.2 Band 2

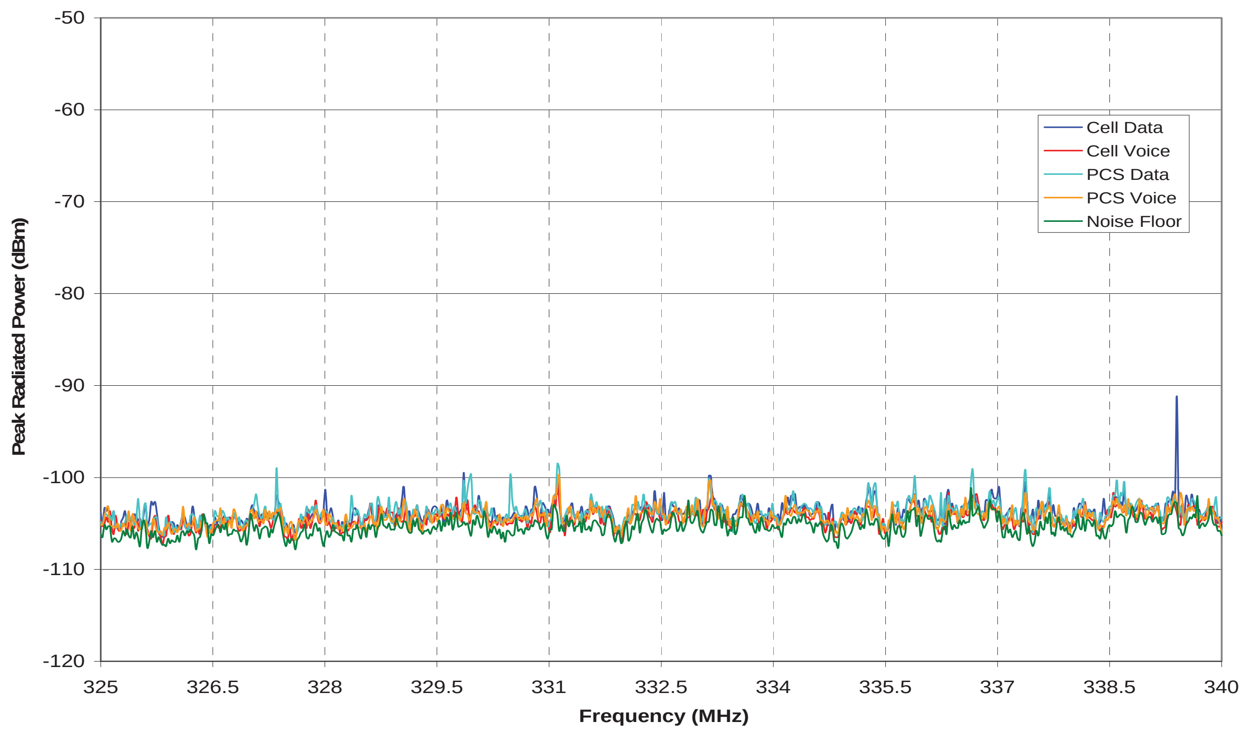


Figure A17: CDM01 four mode envelopes, Band 2.

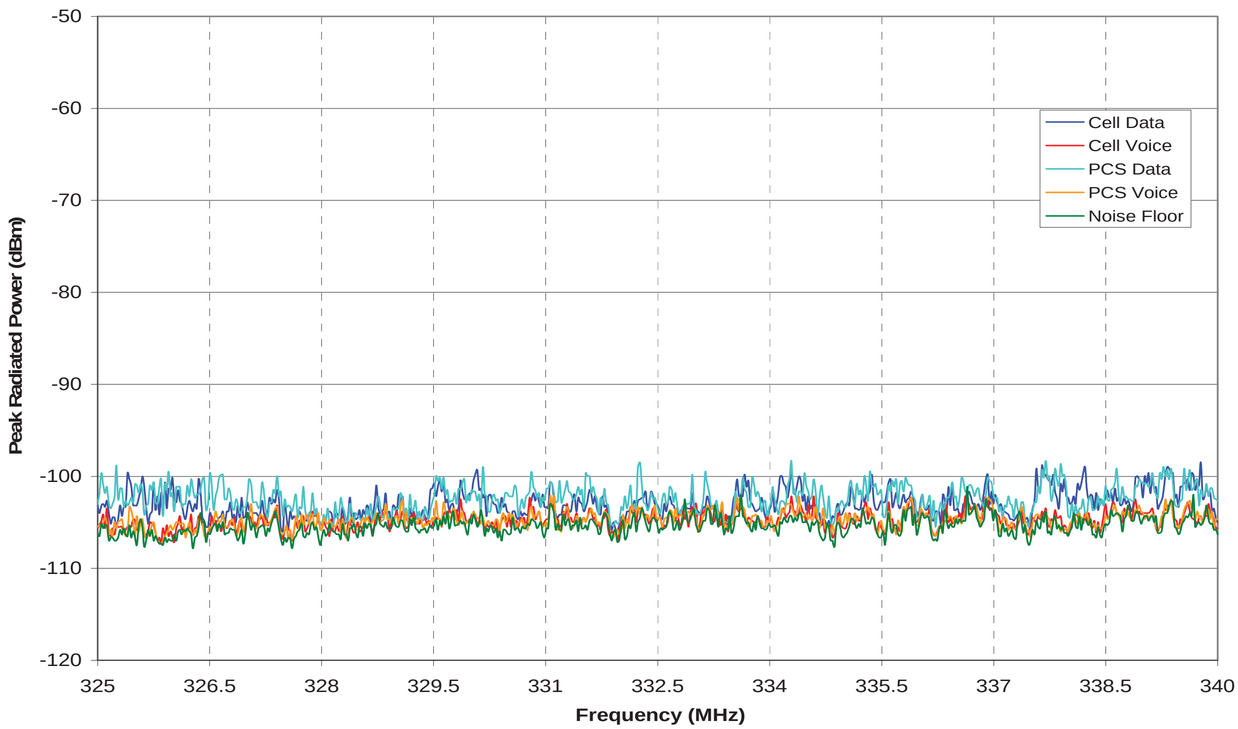


Figure A18: CDM02 four mode envelopes, Band 2.

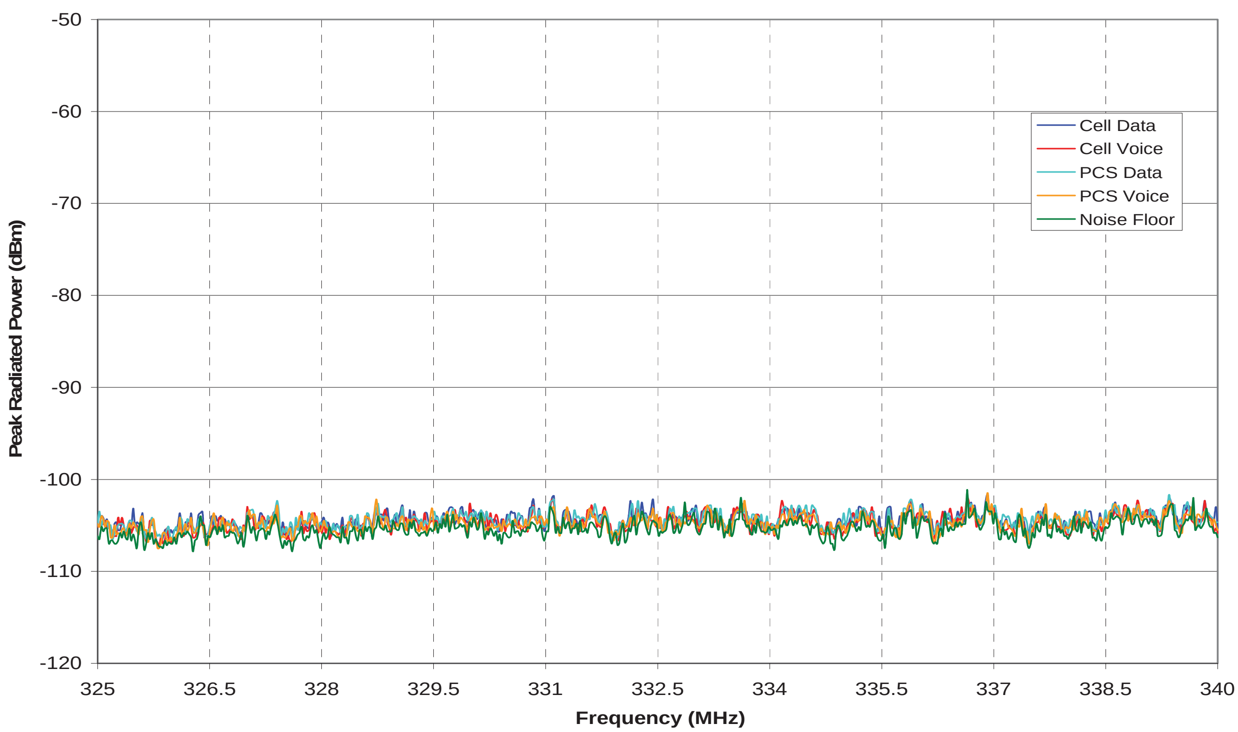


Figure A19: CDM03 four mode envelopes, Band 2.

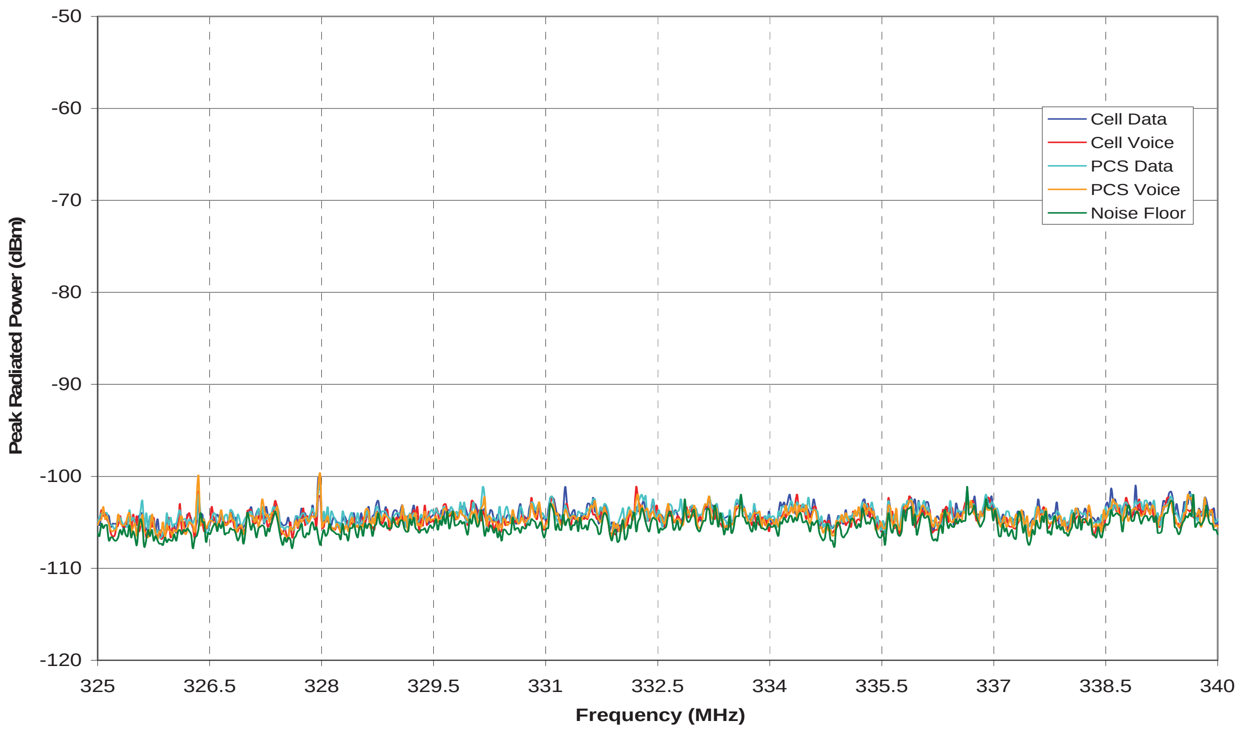


Figure A20: CDM04 four mode envelopes, Band 2.

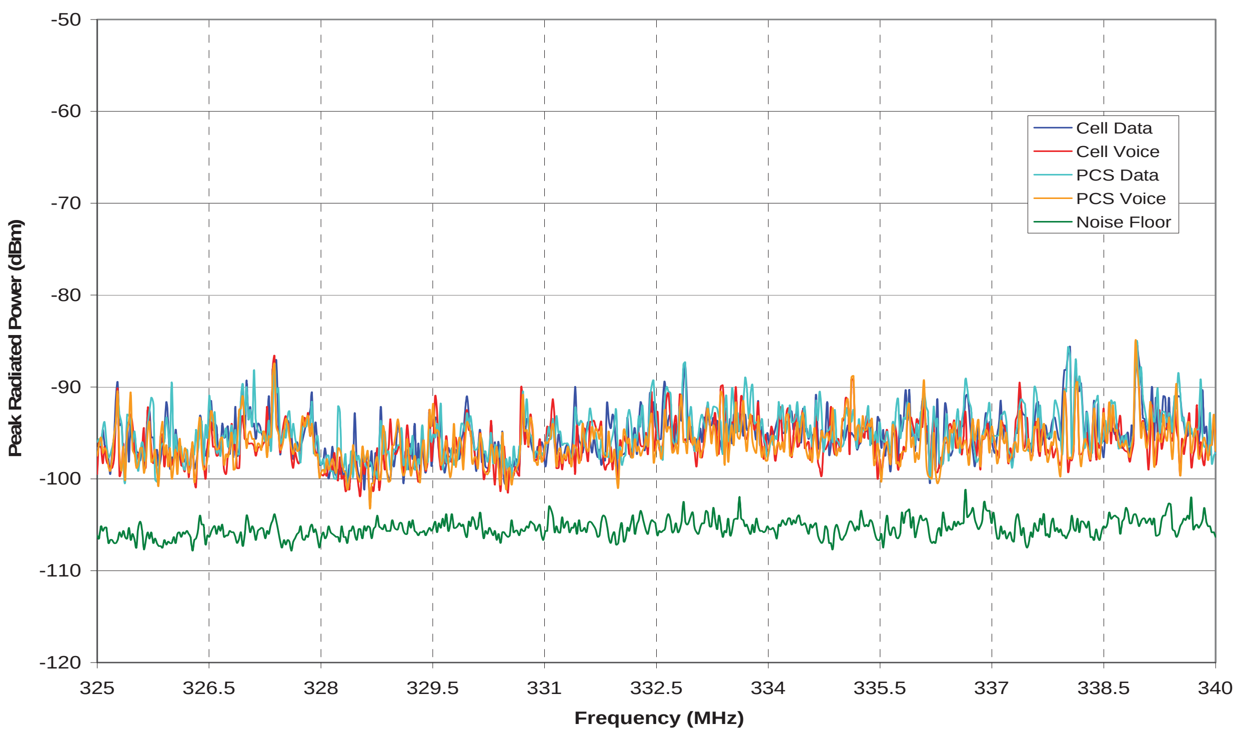


Figure A21: CDM05 four mode envelopes, Band 2.

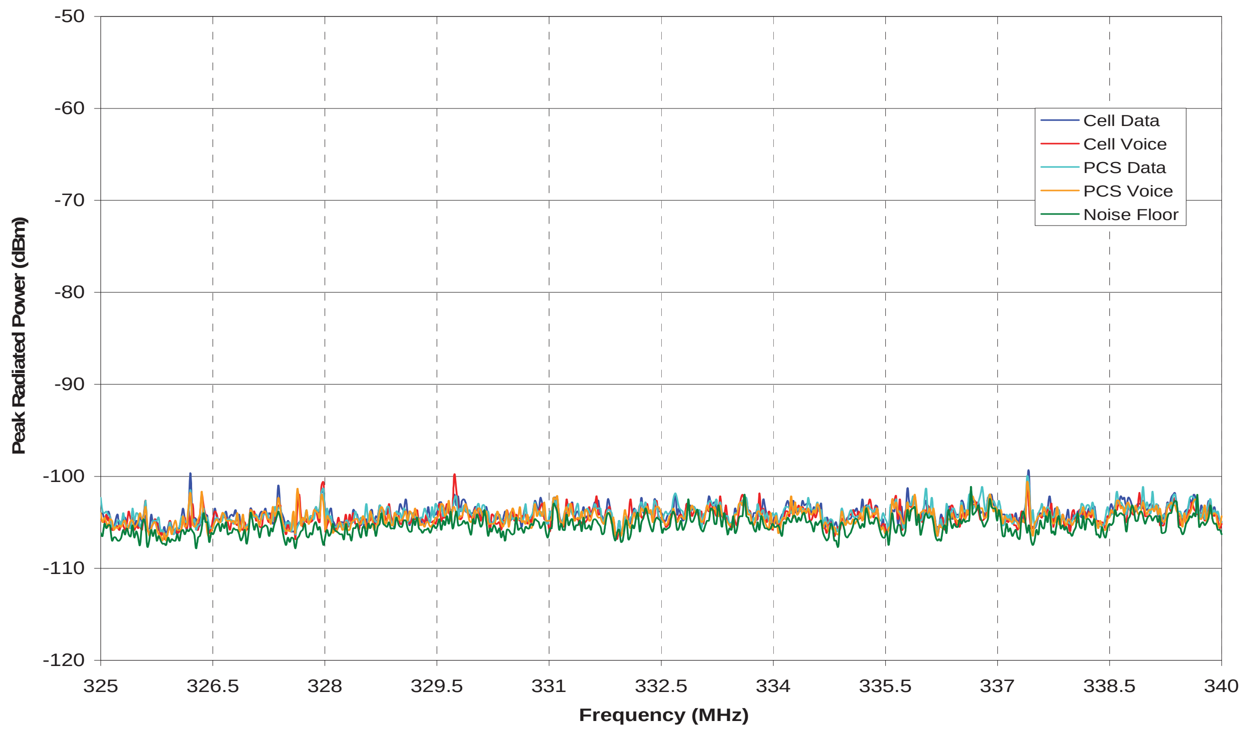


Figure A22: CDM06 four mode envelopes, Band 2.

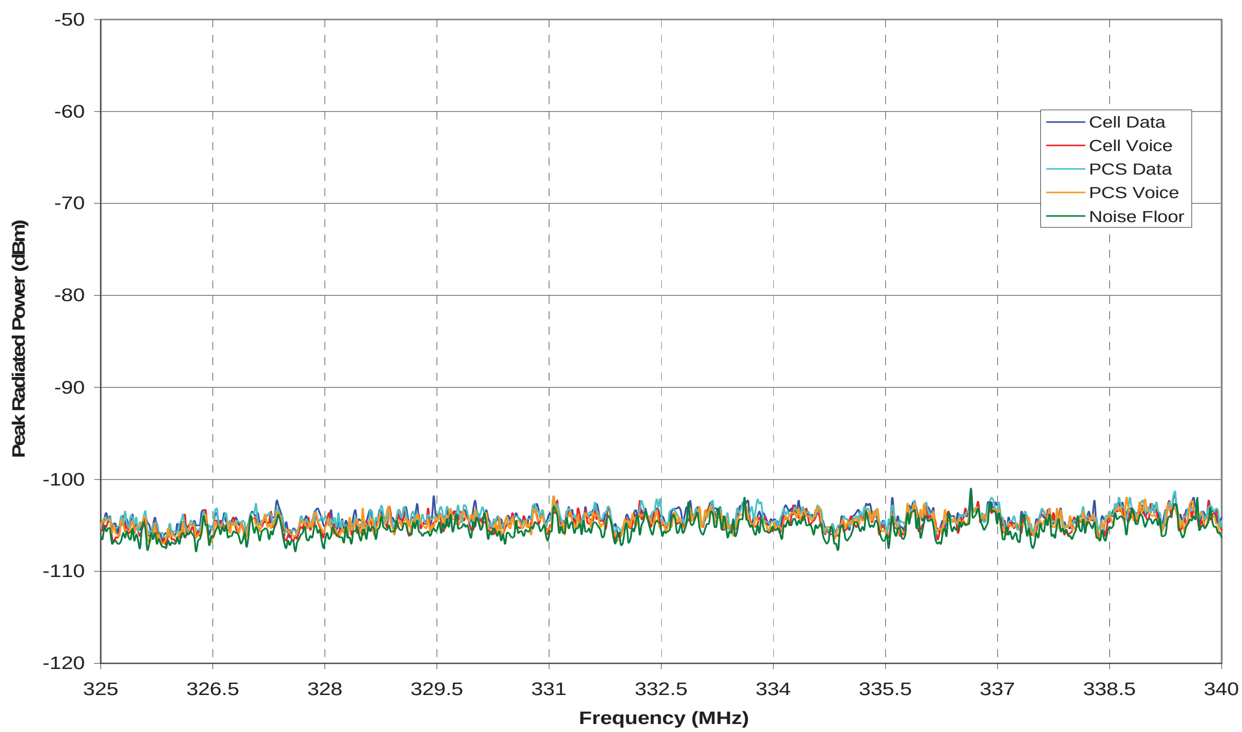


Figure A23: CDM07 four mode envelopes, Band 2.

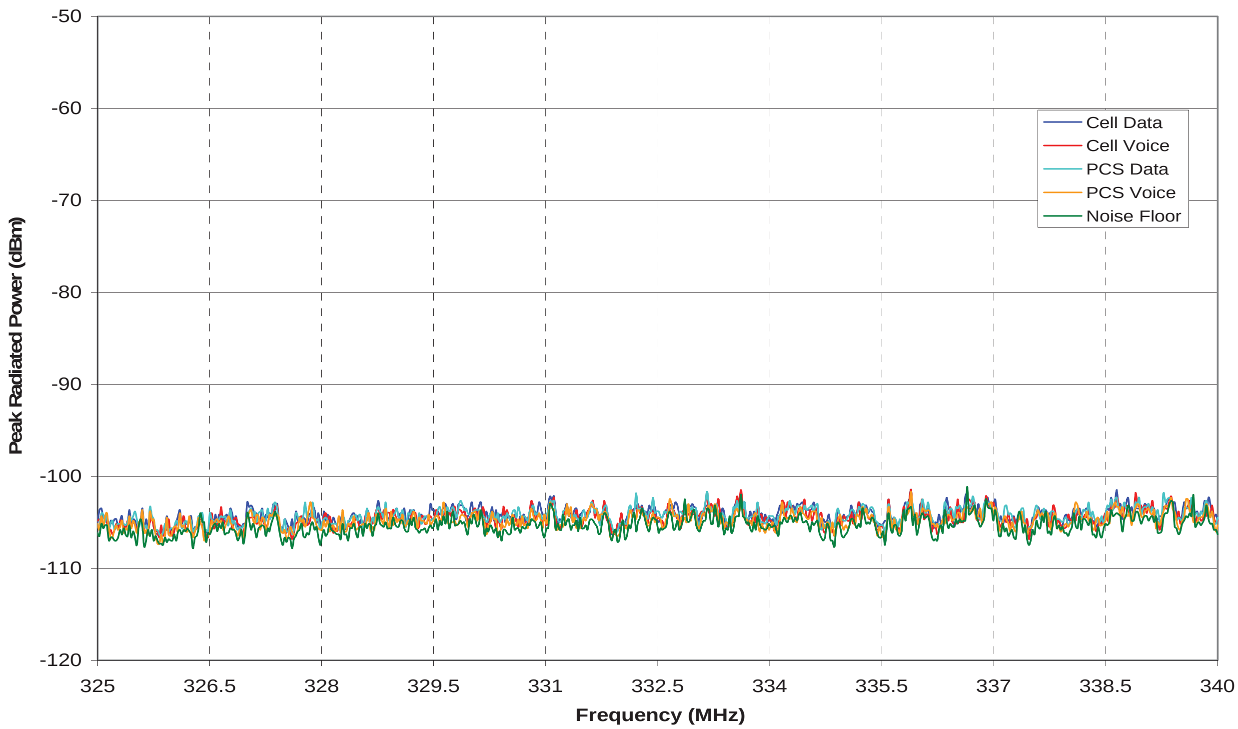
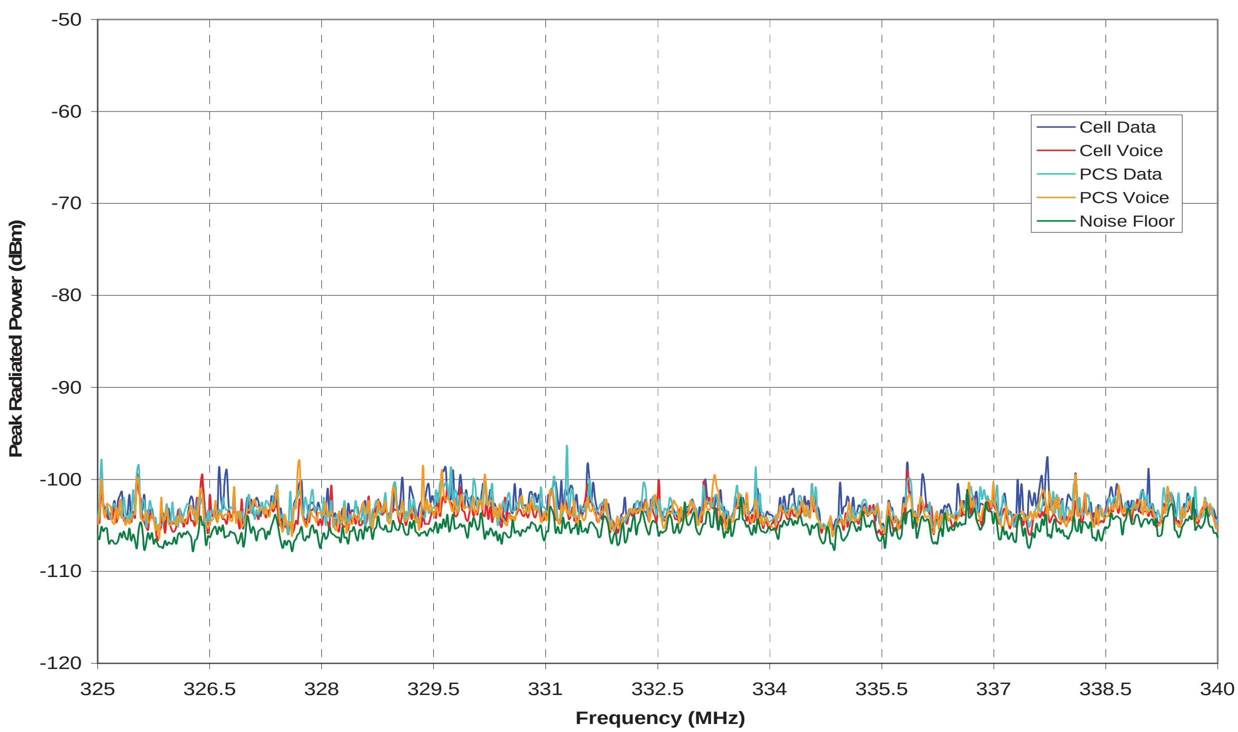


Figure A24: CDM08 four mode envelopes, Band 2.



FigureA25: CDM09 four mode envelopes, Band 2.

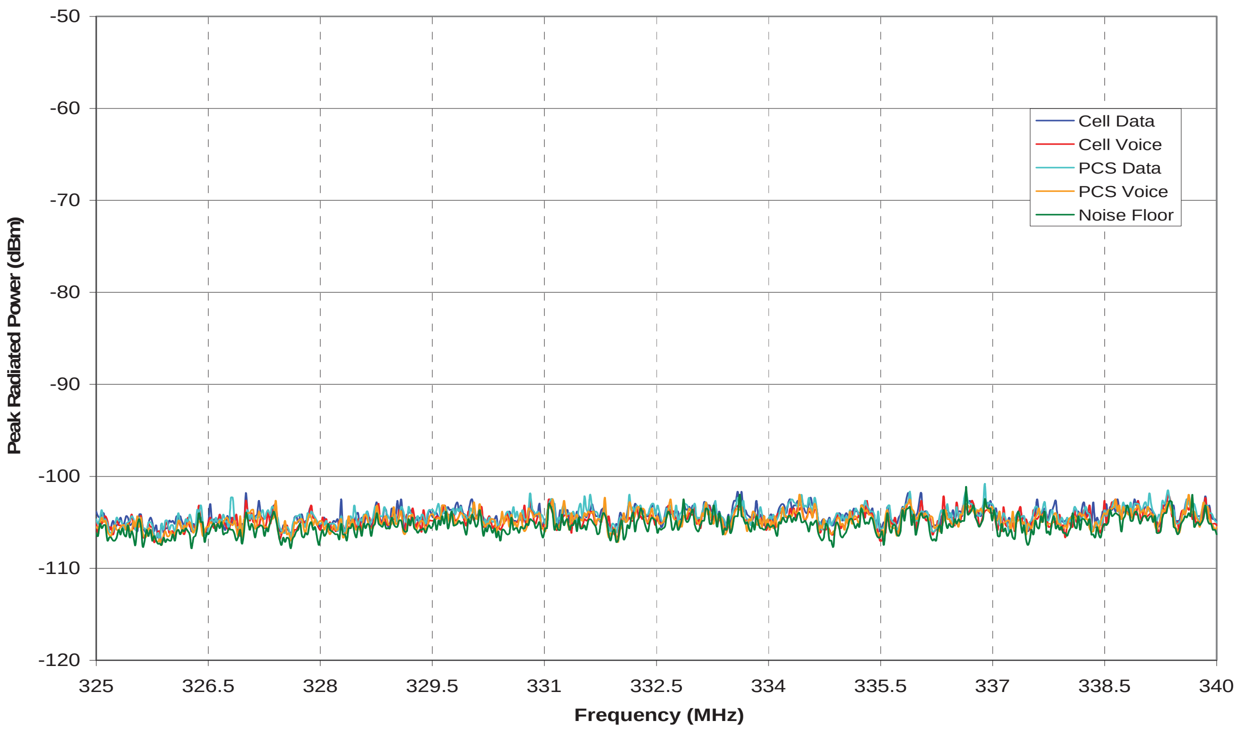


Figure A26: CDM10 four mode envelopes, Band 2.

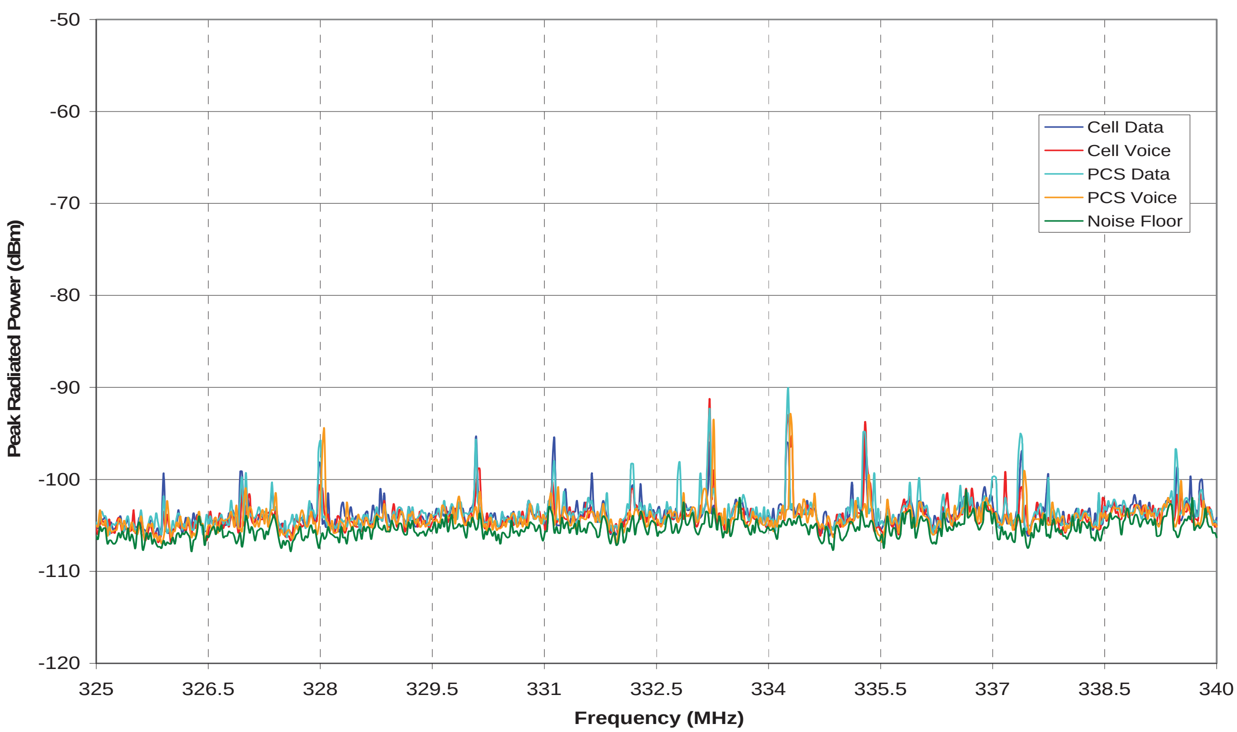


Figure A27: CDM11 four mode envelopes, Band 2.

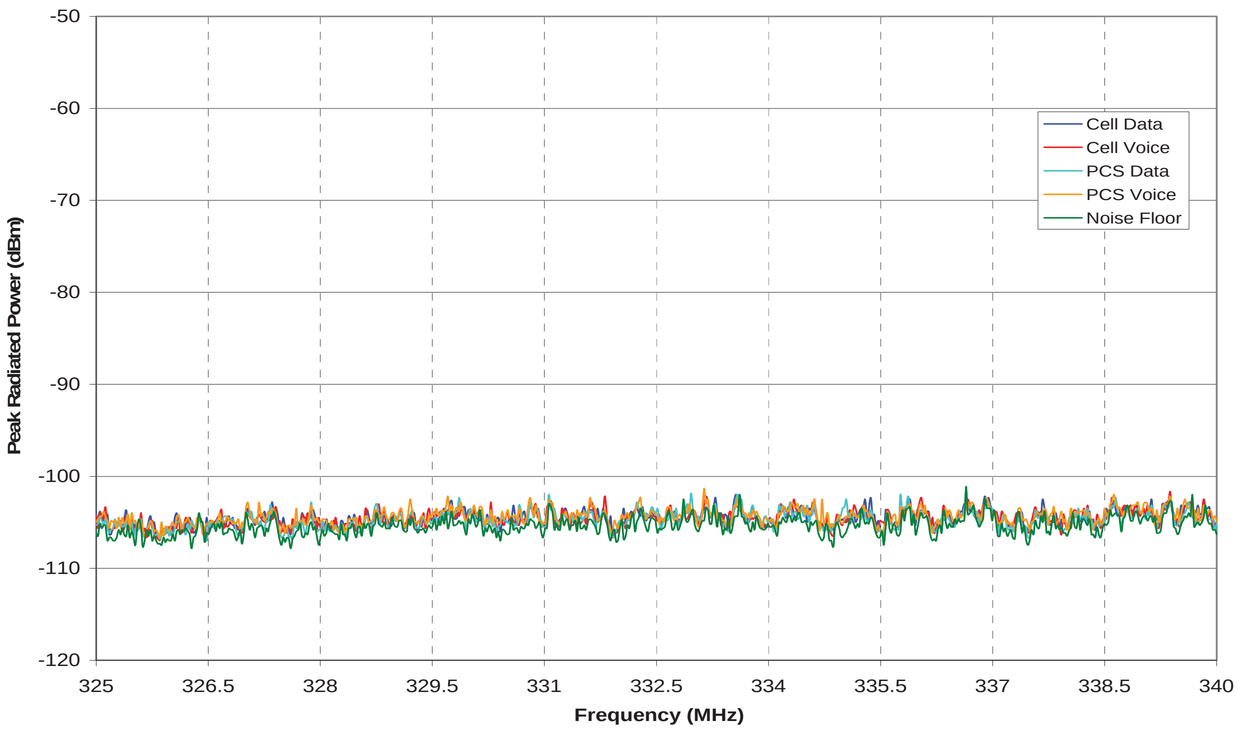


Figure A28: CDM12 four mode envelopes, Band 2.

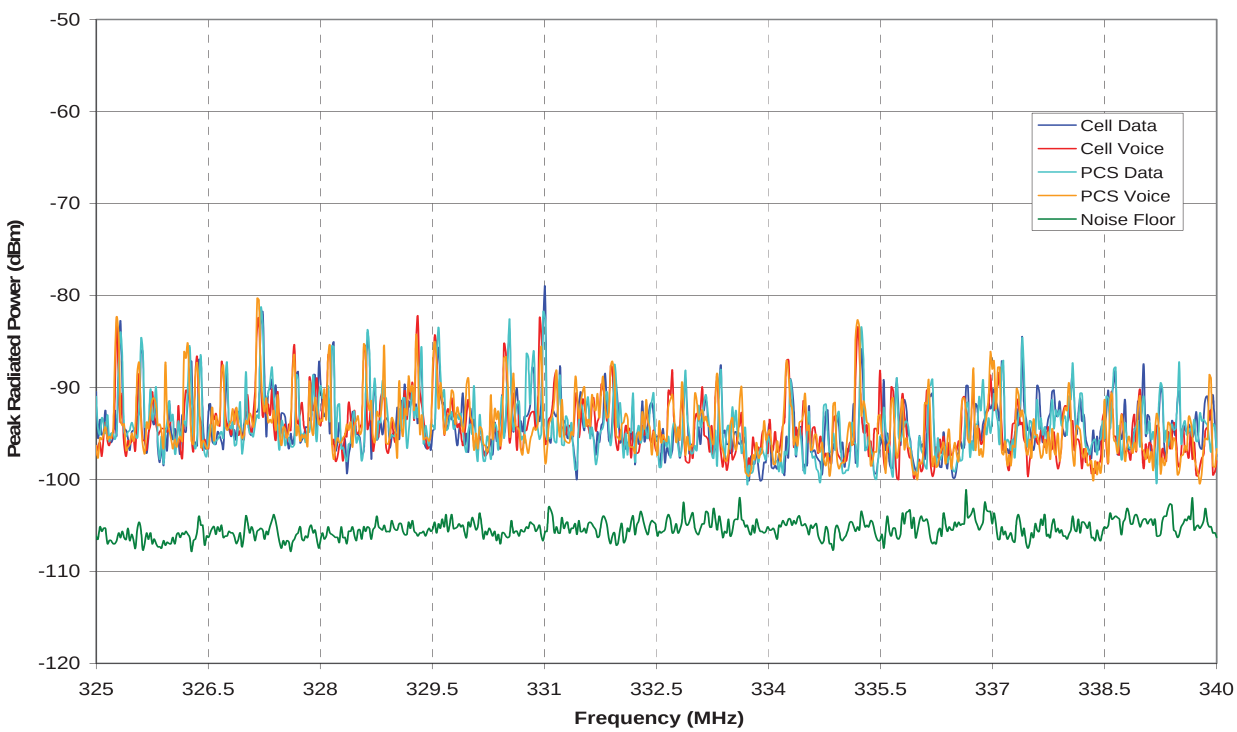


Figure A29: CDM13 four mode envelopes, Band 2.

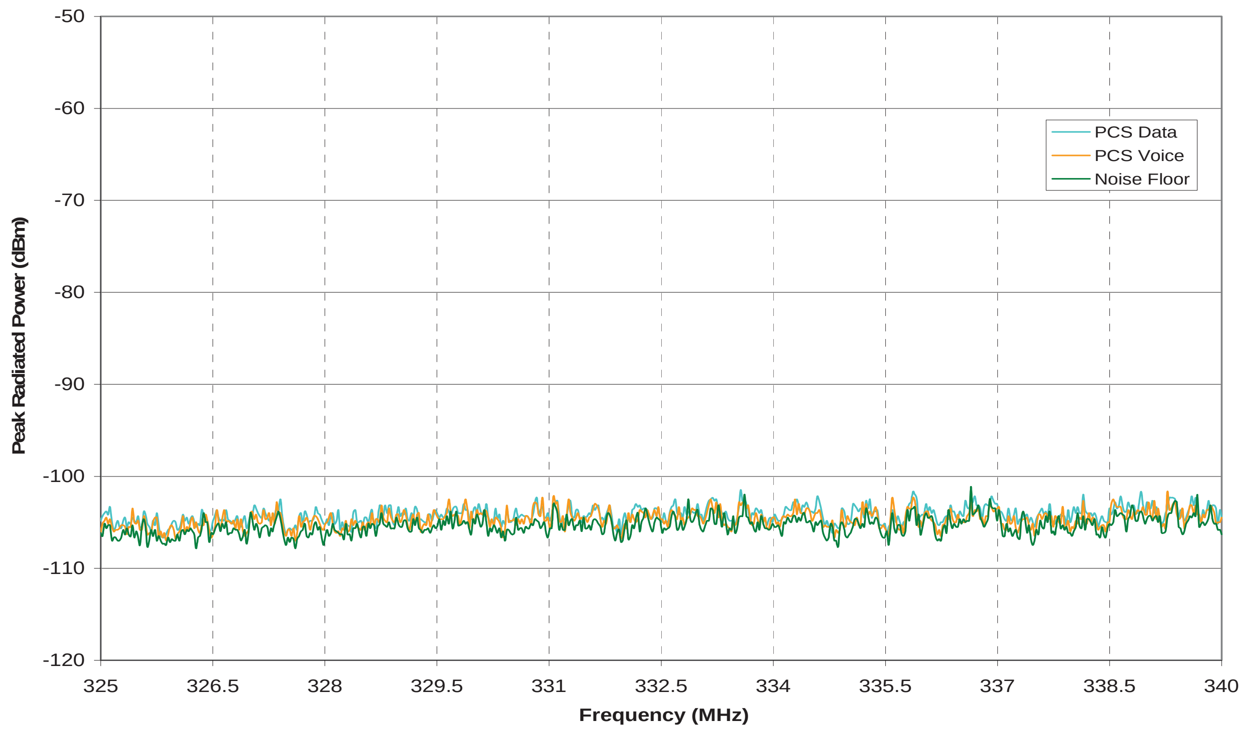


Figure A30: CDM14 two mode envelopes, Band 2.

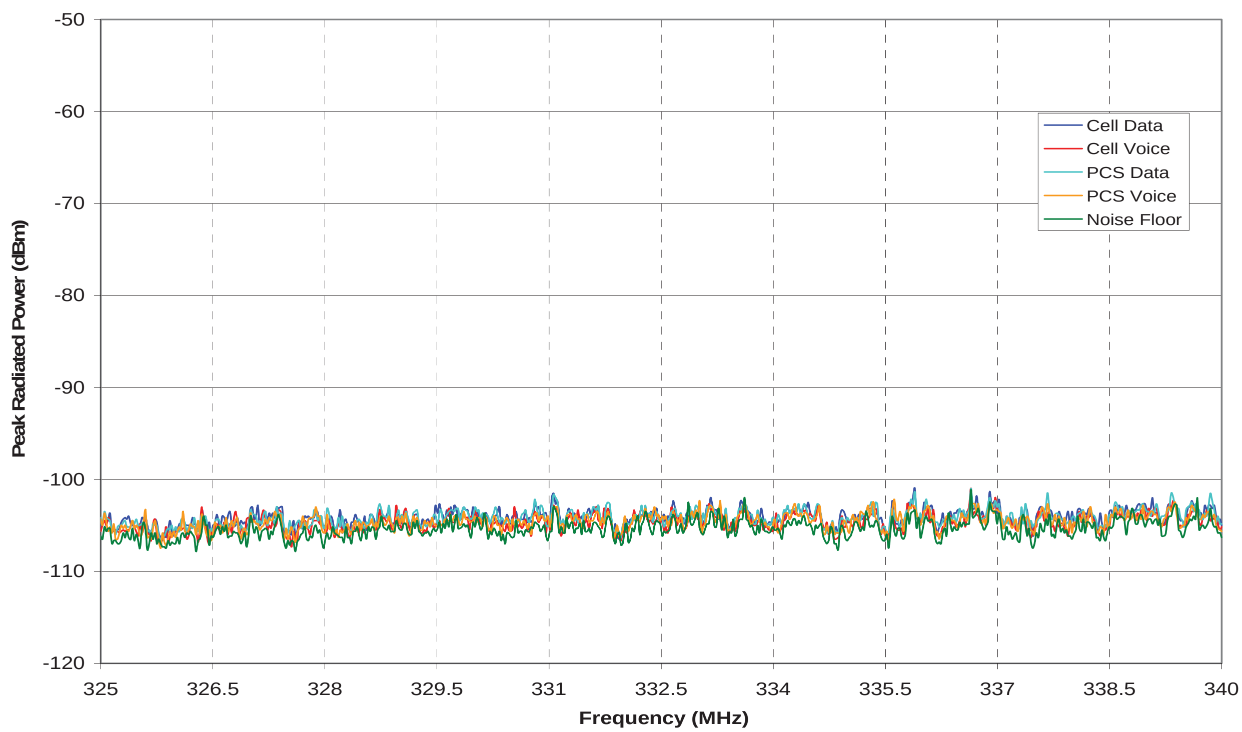


Figure A31: CDM15 four mode envelopes, Band 2.

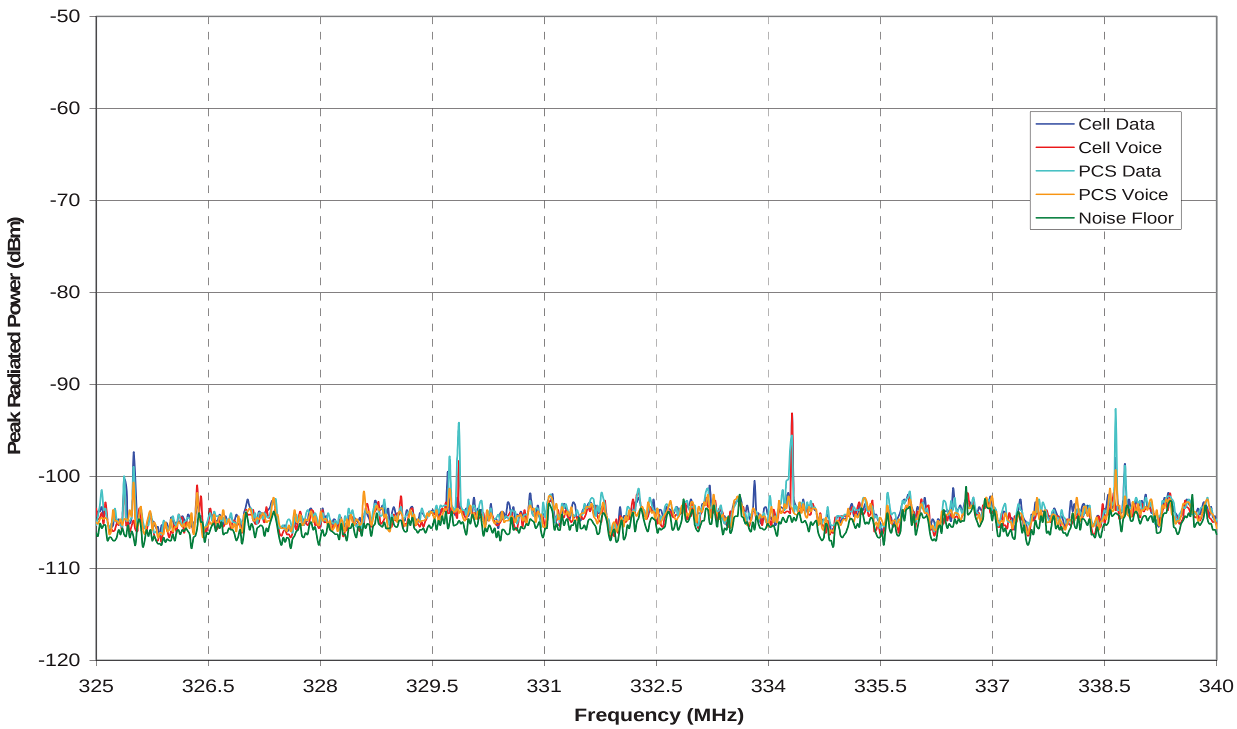


Figure A32: CDM16 four mode envelopes, Band 2.

A.3 Band 3

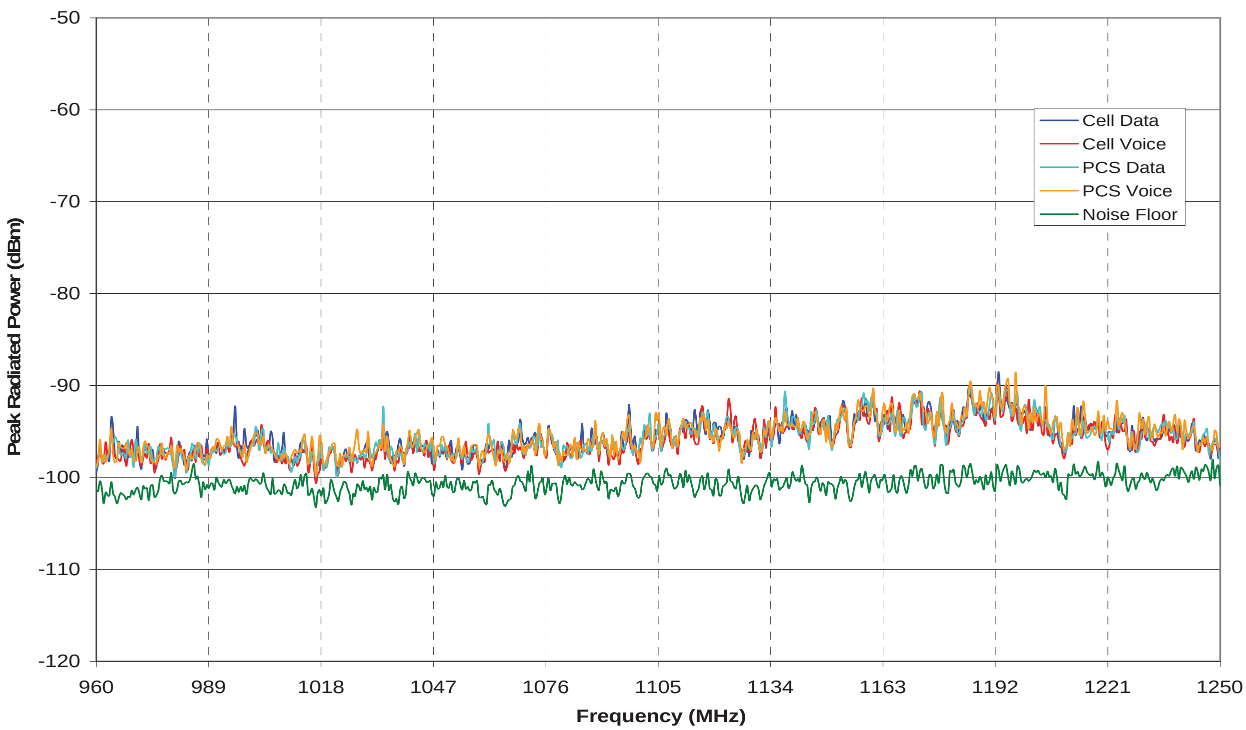


Figure A33: CDM01 four mode envelopes, Band 3.

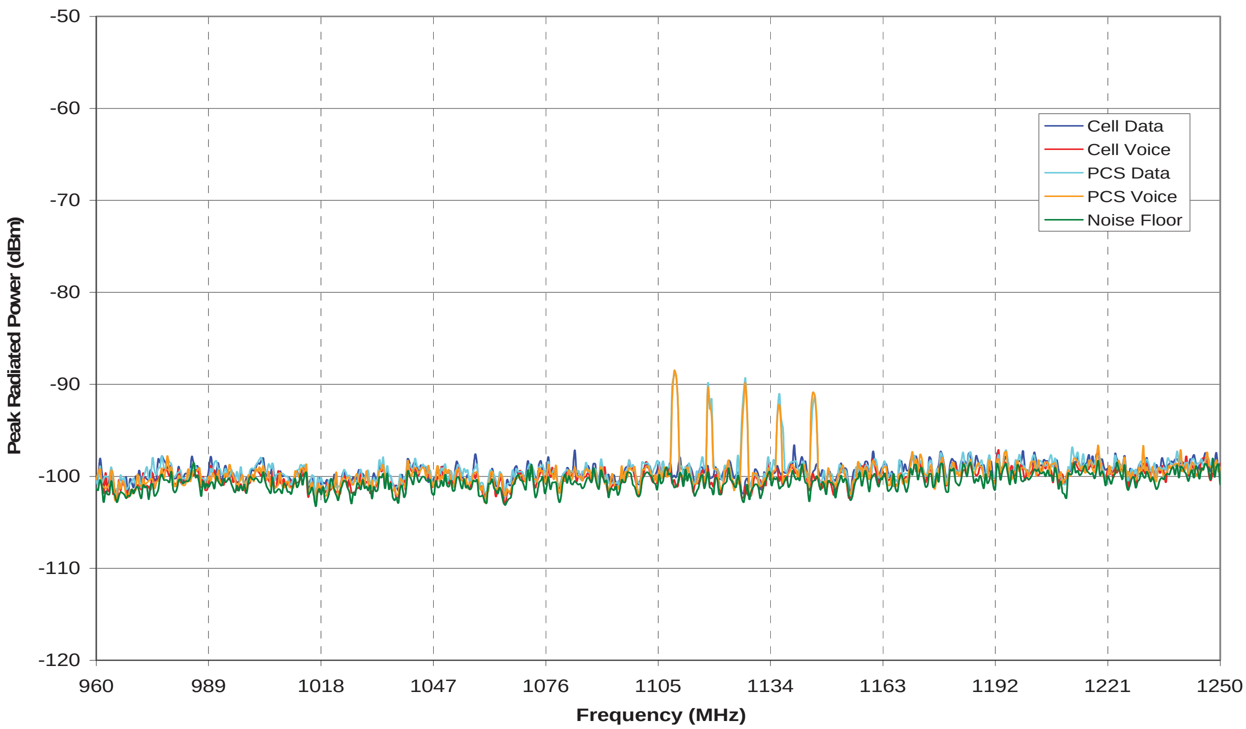


Figure A34: CDM02 four mode envelopes, Band 3.

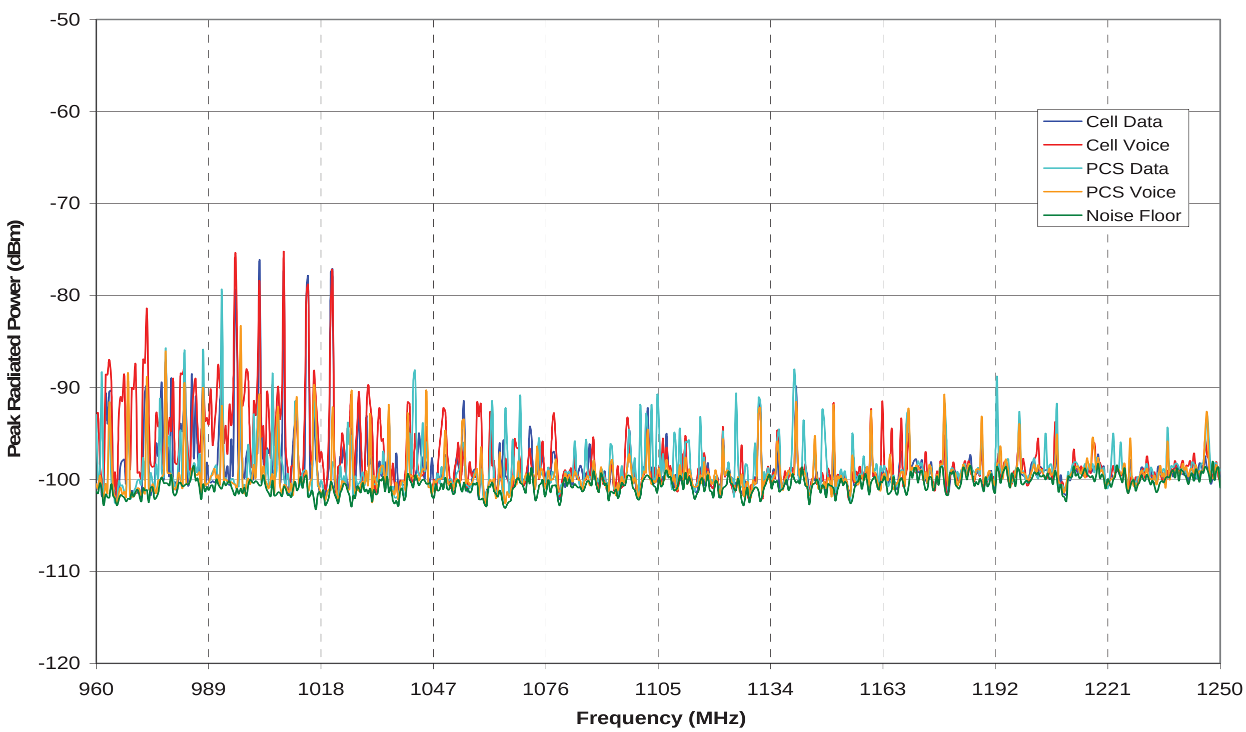


Figure A35: CDM03 four mode envelopes, Band 3.

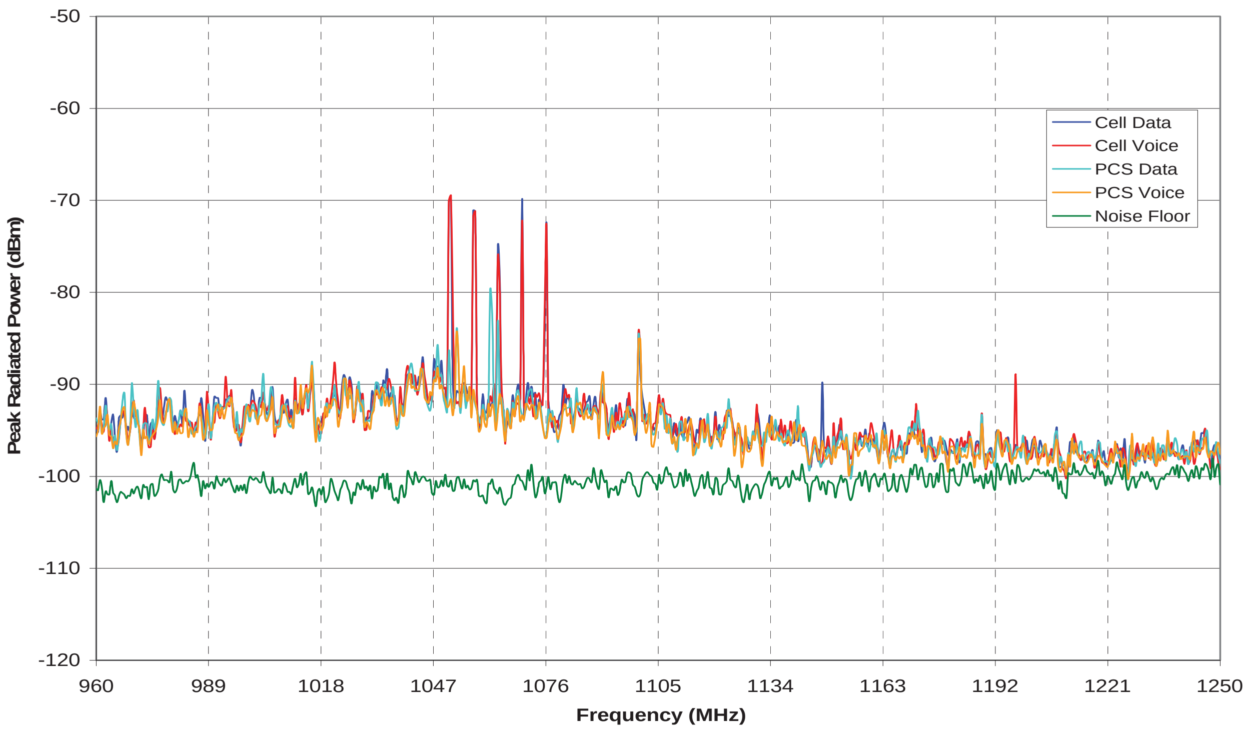


Figure A36: CDM04 four mode envelopes, Band 3.

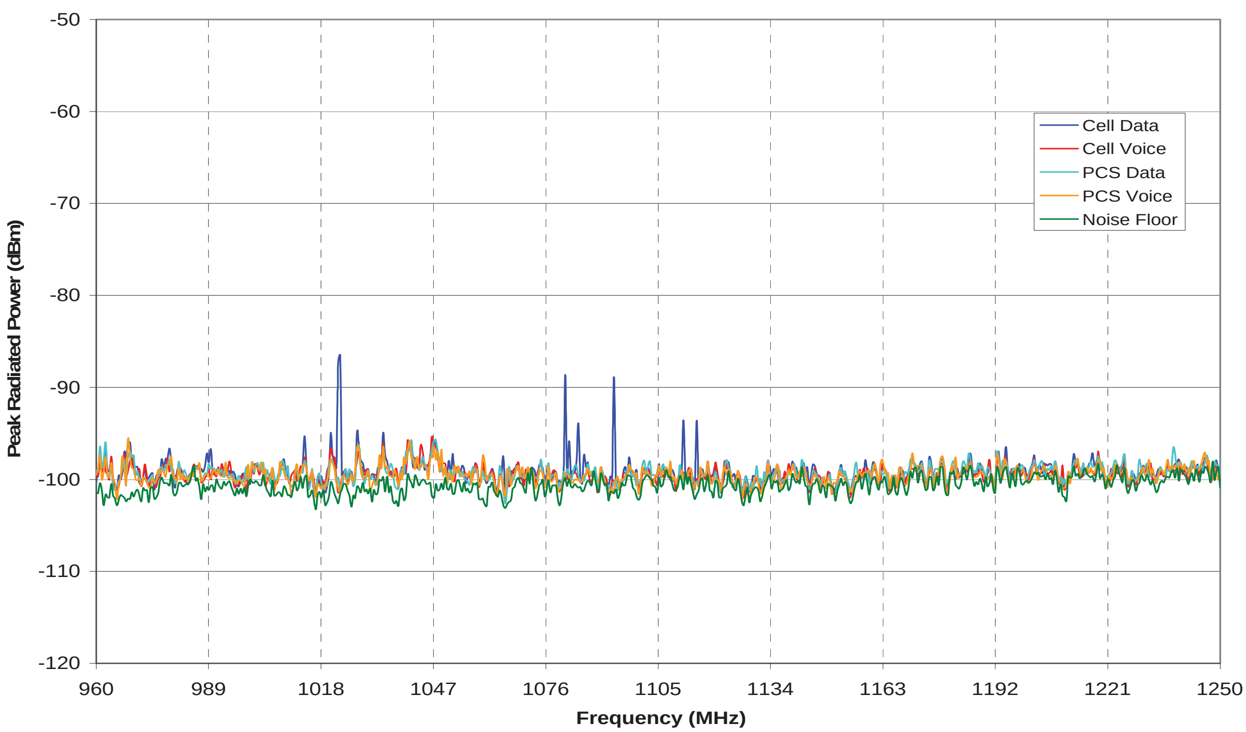


Figure A37: CDM05 four mode envelopes, Band 3.

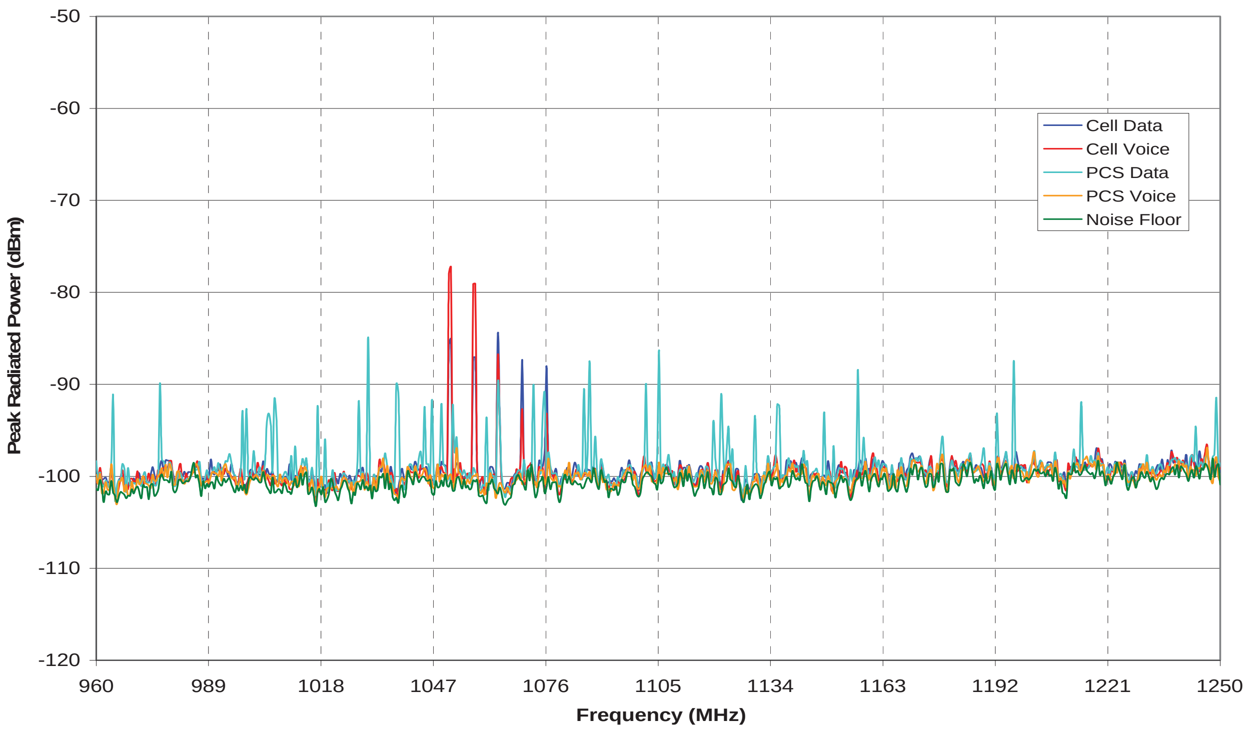


Figure A38: CDM06 four mode envelopes, Band 3.

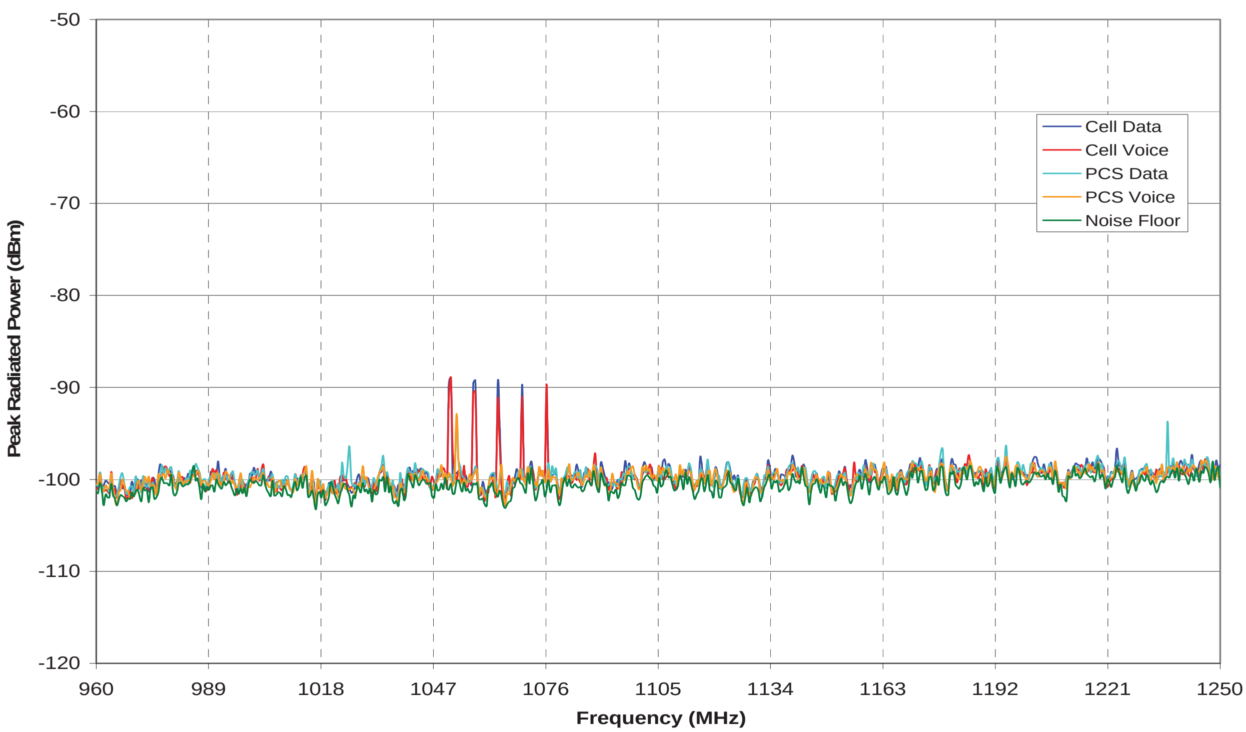


Figure A39: CDM07 four mode envelopes, Band 3.

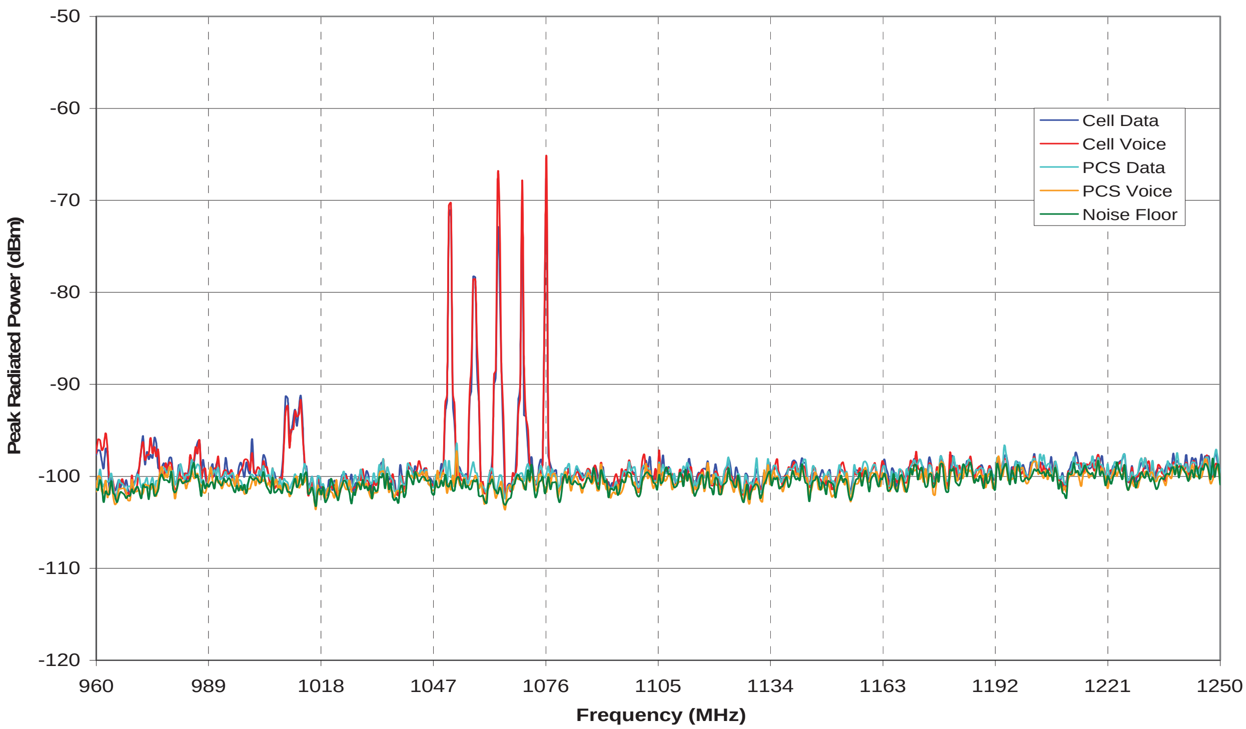


Figure A40: CDM08 four mode envelopes, Band 3.

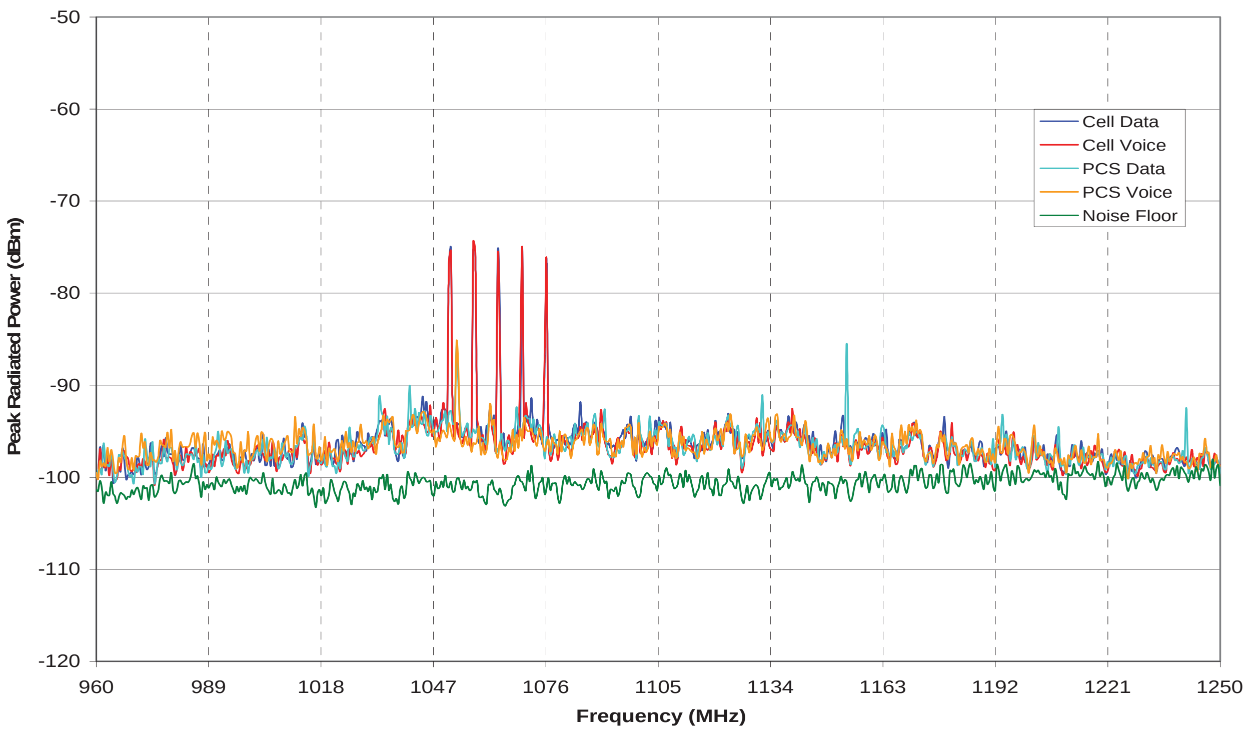


Figure A41: CDM09 four mode envelopes, Band 3.

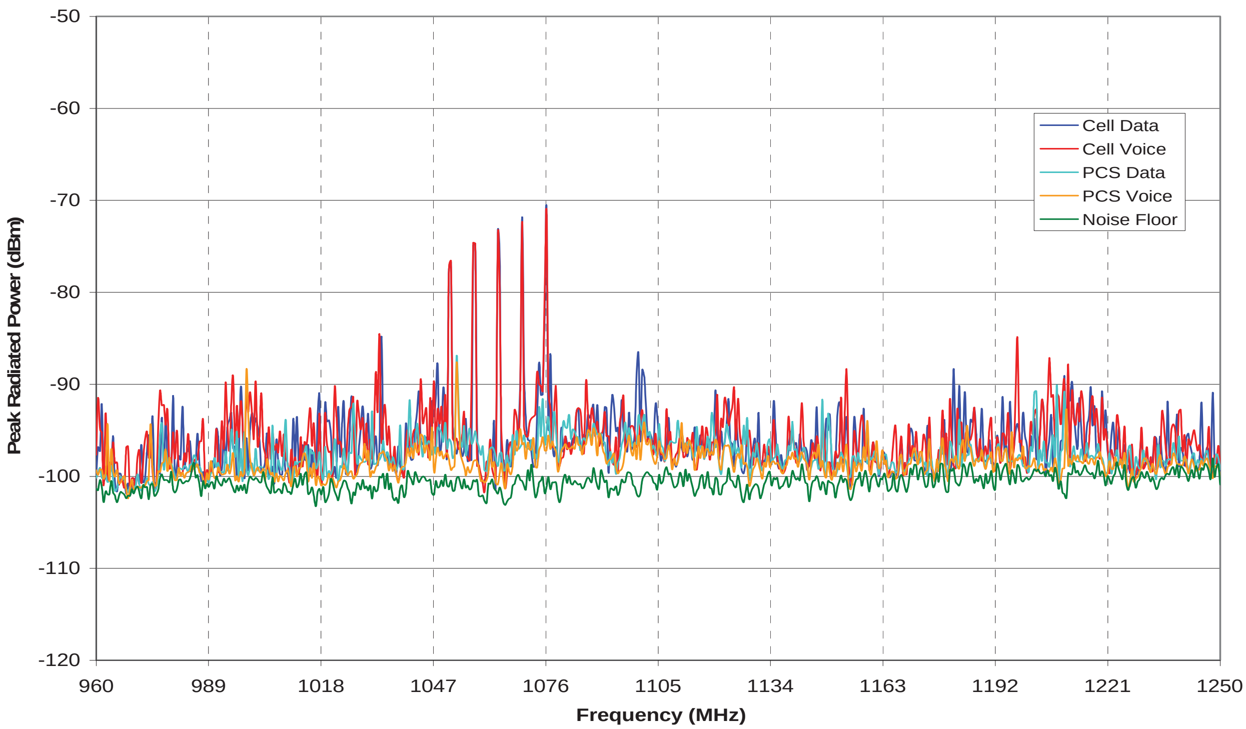


Figure A42: CDM10 four mode envelopes, Band 3.

Figure A43: CDM11 four mode envelopes, Band 3.

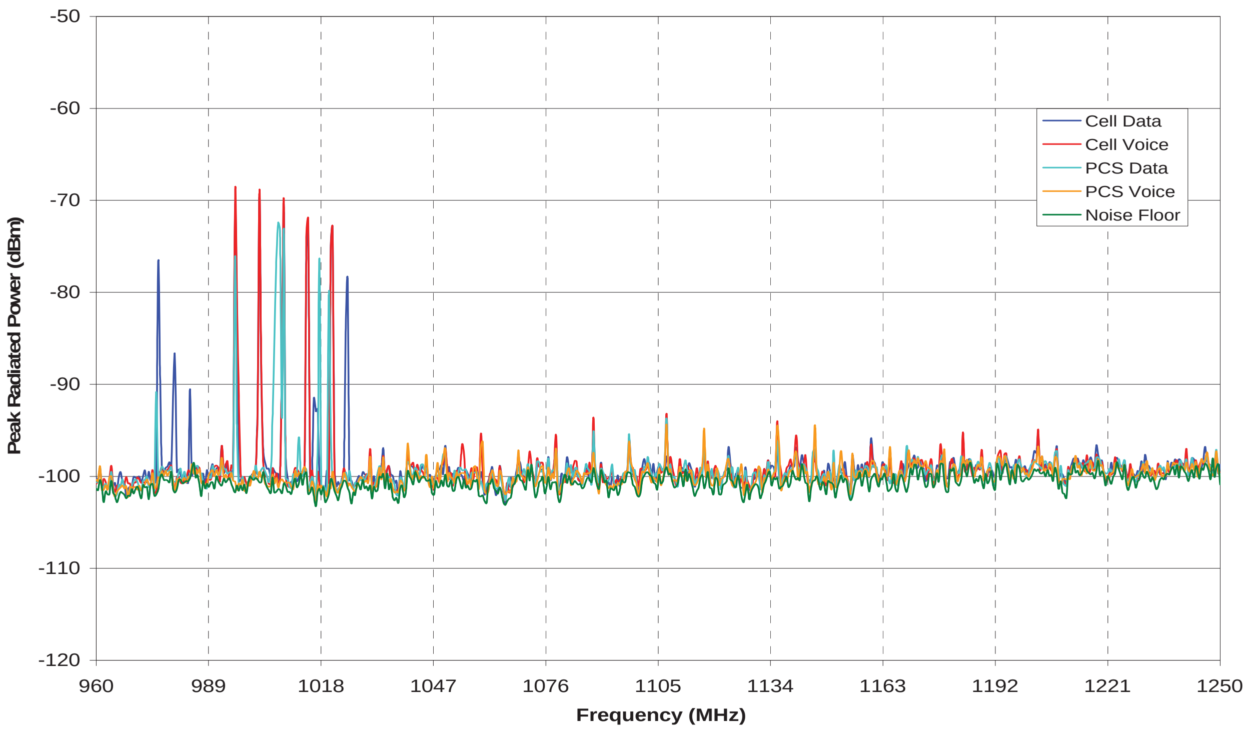


Figure A44: CDM12 four mode envelopes, Band 3.

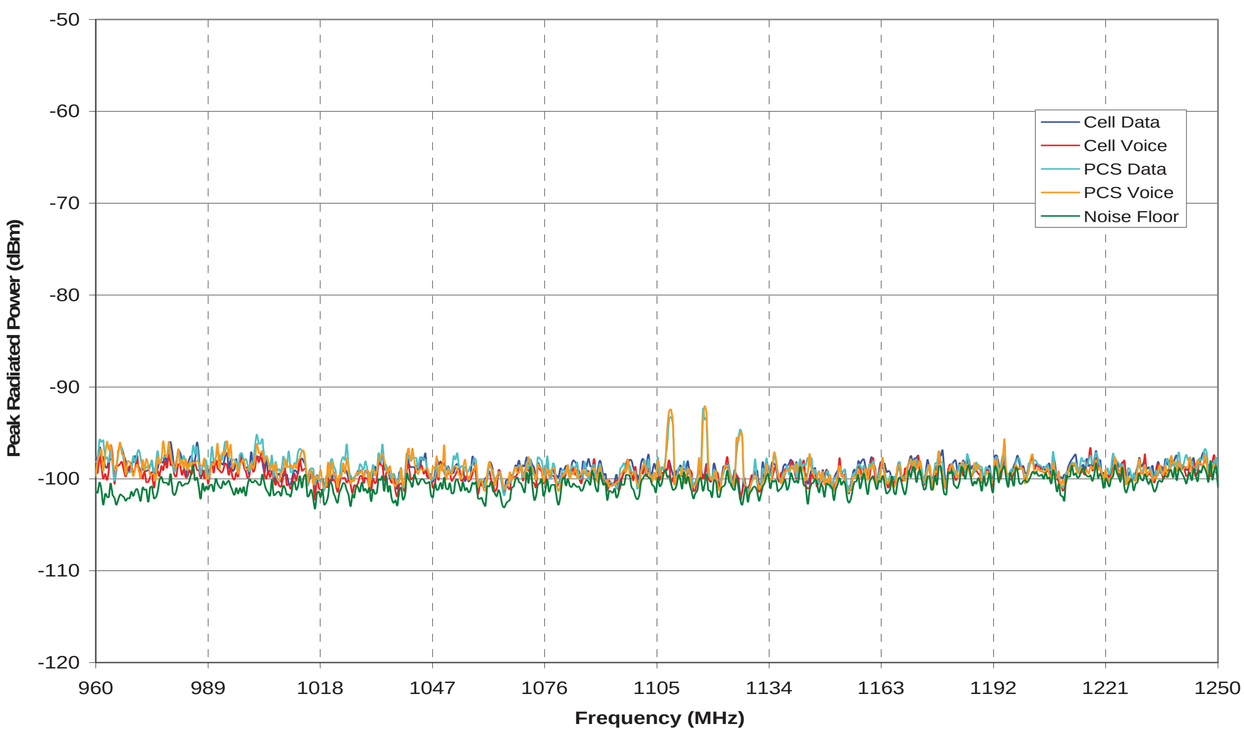


Figure A45: CDM13 four mode envelopes, Band 3.

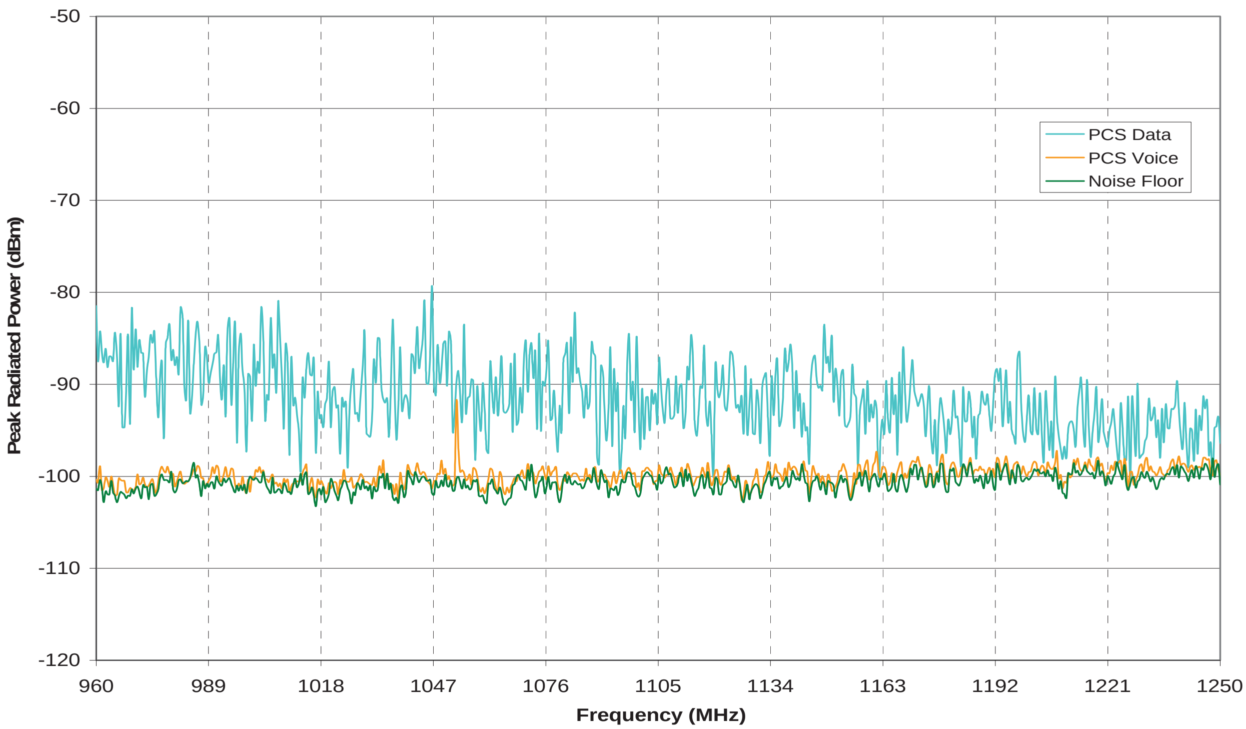


Figure A46: CDM14 two mode envelopes, Band 3.

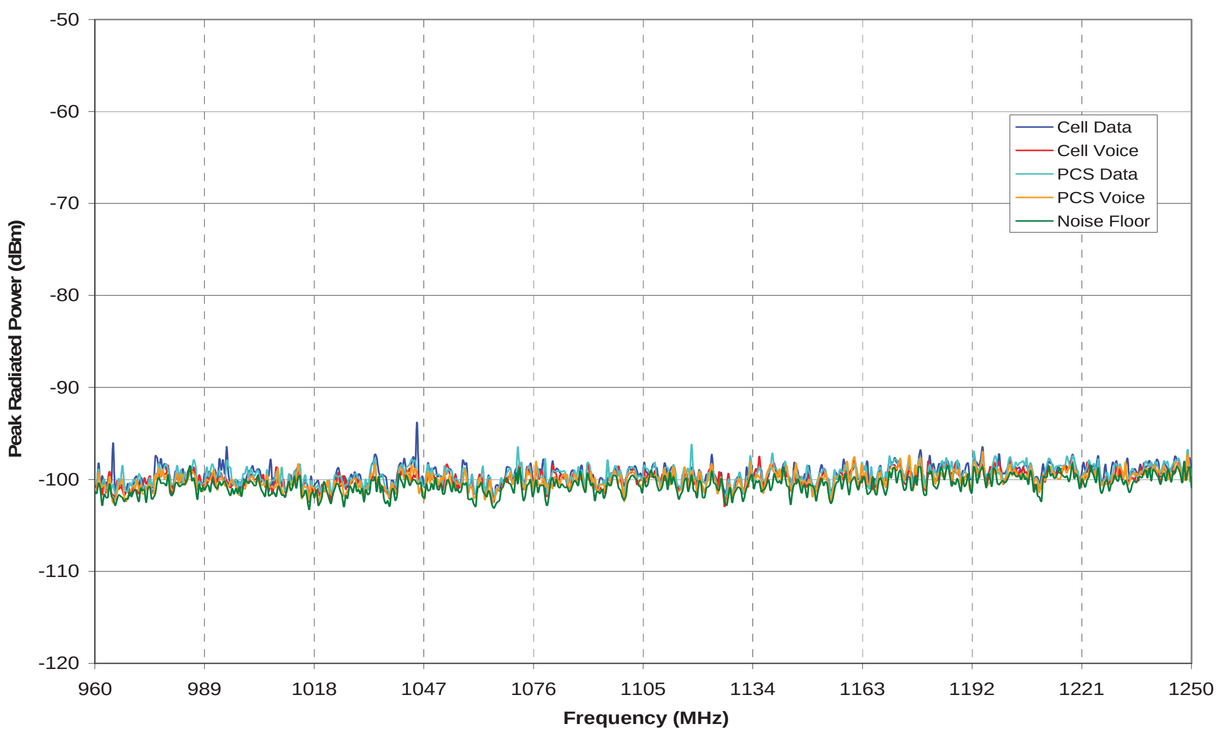


Figure A47: CDM15 four mode envelopes, Band 3.

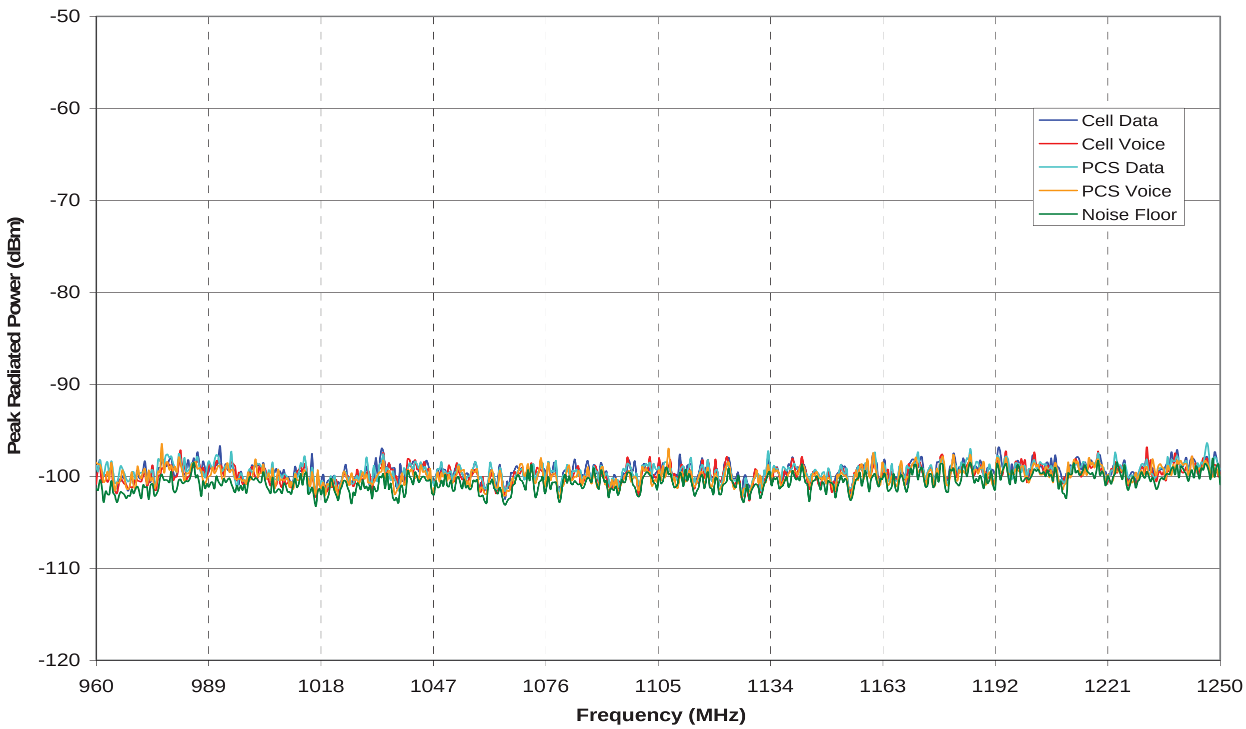


Figure A48: CDM16 four mode envelopes, Band 3.

A.4 Band 4

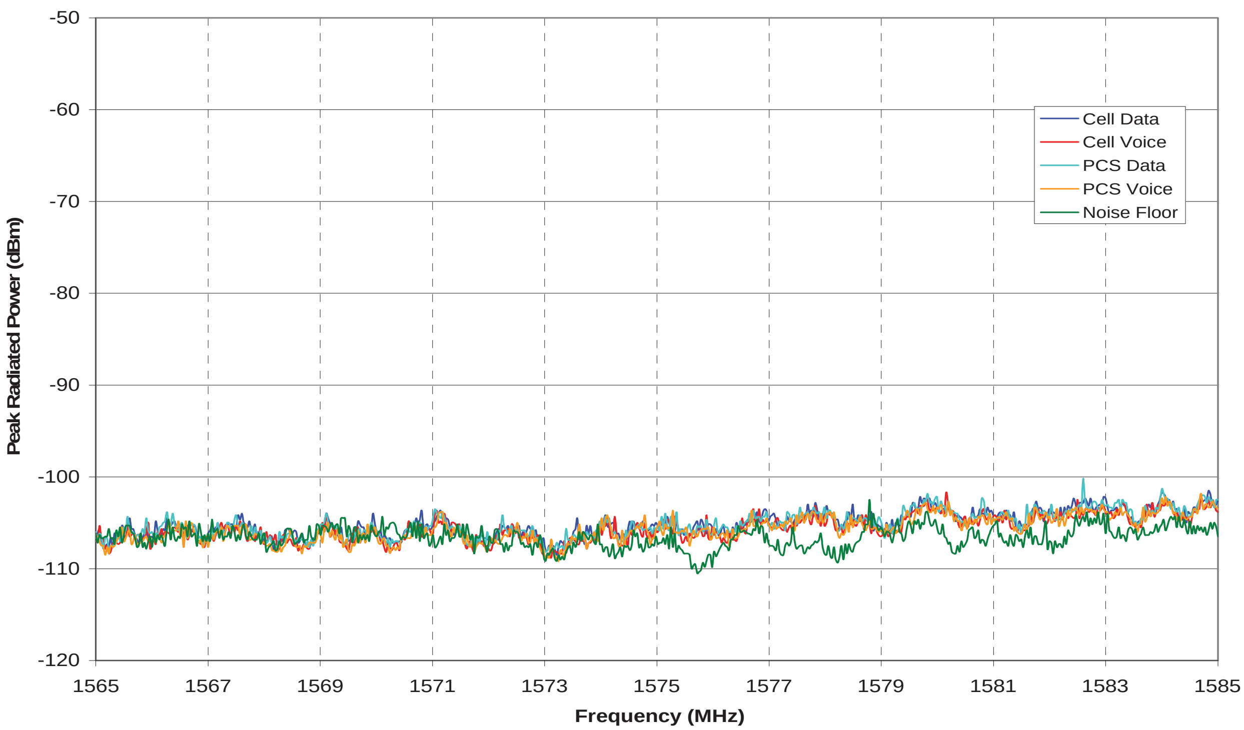


Figure A49: CDM01 four mode envelopes, Band 4.