FIELD INTENSITY and POWER DENSITY

Sometimes it is necessary to know the actual field intensity or power density at a given distance from a transmitter instead of the signal strength received by an antenna. Field intensity or power density calculations are necessary when estimating electromagnetic interference (EMI) effects, when determining potential radiation hazards (personnel safety), or in determining or verifying specifications.

Field intensity (field strength) is a general term that usually means the magnitude of the electric field vector, commonly expressed in volts per meter. At frequencies above 100 MHZ, and particularly above one GHz, power density (P_D) terminology is more often used than field strength.
Power density and field intensity are related by equation [1]:

$$P_D = \frac{E^2}{Z_0} = \frac{E^2}{120\pi} = \frac{E^2}{377} \qquad \textbf{[1]}$$

where P_D is in W/m^2, E is the RMS value of the field in volts/meter and 377 ohms is the characteristic impedance of free space. When the units of P_D are in mW/cm^2, then P_D (mW/cm^2) = $E^2/3770$.

Conversions between field strength and power density when the impedance is 377 ohms, can be obtained from Table 1. It should be noted that to convert dBm/m^2 to dBμV/m add 115.76 dB. Sample calculations for both field intensity and power density in the far field of a transmitting antenna are in Section 4-2 and Section 4-8. Refer to chapter 3 on antennas for the definitions of near field and far field.

Note that the "/" term before m, m^2, and cm^2 in Table 1 mean "per", i.e. dBm per m^2, not to be confused with the division sign which is valid for the Table 1 equation $P=E^2/Z_o$. Remember that in order to obtain dBm from dBm/m^2 given a certain area, you must add the logarithm of the area, not multiply. The values in the table are rounded to the nearest dBW, dBm, etc. per m^2 so the results are less precise than a typical handheld calculator and may be up to ½ dB off.

VOLTAGE MEASUREMENTS

Coaxial cabling typically has input impedances of 50, 75, and 93Ω, (±2) with 50Ω being the most common. Other types of cabling include the following: TV cable is 75Ω (coaxial) or 300Ω (twin-lead), audio public address (PA) is 600Ω, audio speakers are 3.2(4), 8, or 16Ω.

In the 50Ω case, power and voltage are related by:

$$P = \frac{E^2}{Z_0} = \frac{E^2}{50} = 50I^2 \qquad \textbf{[2]}$$

Conversions between measured power, voltage, and current where the typical impedance is 50 ohms can be obtained from Table 2. The dBμA current values are given because frequently a current probe is used during laboratory tests to determine the powerline input current to the system .

MATCHING CABLING IMPEDANCE

In performing measurements, we must take into account an impedance mismatch between measurement devices (typically 50 ohms) and free space (377 ohms).

Table 1. Conversion Table - Field Intensity and Power Density
$P_D = E^2/Z_0$ (Related by free space impedance = 377 ohms)

E (Volts/m)	20 log 10^6 (E) (dBμV/m)	P_D (watts/m^2)	10 Log P_D (dBW/m^2)	Watts/cm^2	dBW/cm^2	mW/cm^2	dBm/cm^2	dBm/m^2
7,000	197	130,000	+51	13	+11	13,000	+41	+81
5,000	194	66,300	+48	6.6	+8	6,630	+38	+78
3,000	190	23,900	+44	2.4	+4	2,390	+34	+74
4,000	186	10,600	+40	1.1	0	1,060	+30	+70
1,000	180	2,650	+34	.27	-6	265	+24	+64
700	177	1,300	+31	.13	-9	130	+21	+61
500	174	663	+28	.066	-12	66	+18	+58
300	170	239	+24	.024	-16	24	+14	+54
200	166	106	+20	.011	-20	11	+10	+50
100	160	27	+14	.0027	-26	2.7	+4	+44
70	157	13	+11	1.3x10^{-3}	-29	1.3	+1	+41
50	154	6.6	+8	6.6x10^{-4}	-32	.66	-2	+38
30	150	2.4	+4	2.4x10^{-4}	-36	.24	-6	+34
20	146	1.1	+0	1.1x10^{-4}	-40	.11	-10	+30
10	140	.27	-6	2.7x10^{-5}	-46	.027	-16	+24
7	137	.13	-9	1.3x10^{-5}	-49	.013	-19	+21
5	134	.066	-12	6.6x10^{-6}	-52	66x10^{-4}	-22	+18
3	130	.024	-16	2.4x10^{-6}	-56	24x10^{-4}	-26	+14
2	126	.011	-20	1.1x10^{-6}	-60	11x10^{-4}	-30	+10
1	120	.0027	-26	2.7x10^{-7}	-66	2.7x10^{-4}	-36	+4
0.7	117	1.3x10^{-3}	-29	1.3x10^{-7}	-69	1.3x10^{-4}	-39	+1
0.5	114	6.6x10^{-4}	-32	6.6x10^{-8}	-72	66x10^{-4}	-42	-2
0.3	110	2.4x10^{-4}	-36	2.4x10^{-8}	-76	24x10^{-4}	-46	-6
0.2	106	1.1x10^{-4}	-40	1.1x10^{-8}	-80	11x10^{-4}	-50	-10
0.1	100	2.7x10^{-5}	-46	2.7x10^{-9}	-86	2.7x10^{-6}	-56	-16
70x10^{-3}	97	1.3x10^{-5}	-49	1.3x10^{-9}	-89	1.3x10^{-6}	-59	-19
50x10^{-3}	94	6.6x10^{-6}	-52	6.6x10^{-10}	-92	66x10^{-8}	-62	-22
30x10^{-3}	90	2.4x10^{-6}	-56	2.4x10^{-10}	-96	24x10^{-8}	-66	-26
20x10^{-3}	86	1.1x10^{-6}	-60	1.1x10^{-10}	-100	11x10^{-8}	-70	-30
10x10^{-3}	80	2.7x10^{-7}	-66	2.7x10^{-11}	-106	2.7x10^{-8}	-76	-36
7x10^{-3}	77	1.3x10^{-7}	-69	1.3x10^{-11}	-109	1.3x10^{-8}	-79	-39
5x10^{-3}	74	6.6x10^{-8}	-72	6.6x10^{-12}	-112	66x10^{-10}	-82	-42
3x10^{-3}	70	2.4x10^{-8}	-76	2.4x10^{-12}	-116	24x10^{-10}	-86	-46
2x10^{-3}	66	1.1x10^{-8}	-80	1.1x10^{-12}	-120	11x10^{-10}	-90	-50
1x10^{-3}	60	2.7x10^{-9}	-86	2.7x10^{-13}	-126	2.7x10^{-10}	-96	-56
7x10^{-4}	57	1.3x10^{-9}	-89	1.3x10^{-13}	-129	1.3x10^{-10}	-99	-59
5x10^{-4}	54	6.6x10^{-10}	-92	6.6x10^{-14}	-132	66x10^{-12}	-102	-62
3x10^{-4}	50	2.4x10^{-10}	-96	2.4x10^{-14}	-136	24x10^{-12}	-106	-66
2x10^{-4}	46	1.1x10^{-10}	-100	1.1x10^{-14}	-140	11x10^{-12}	-110	-70
1x10^{-4}	40	2.7x10^{-11}	-106	2.7x10^{-15}	-146	2.7x10^{-12}	-116	-76
7x10^{-5}	37	1.3x10^{-11}	-109	1.3x10^{-15}	-149	1.3x10^{-12}	-119	-79
5x10^{-5}	34	6.6x10^{-12}	-112	6.6x10^{-16}	-152	66x10^{-14}	-122	-82
3x10^{-5}	30	2.4x10^{-12}	-116	2.4x10^{-16}	-156	24x10^{-14}	-126	-86
2x10^{-5}	26	1.1x10^{-12}	-120	1.1x10^{-16}	-160	11x10^{-14}	-130	-90
1x10^{-5}	20	2.7x10^{-13}	-126	2.7x10^{-17}	-166	2.7x10^{-14}	-136	-96
7x10^{-6}	17	1.3x10^{-13}	-129	1.3x10^{-17}	-169	1.3x10^{-14}	-139	-99
5x10^{-6}	14	6.6x10^{-14}	-132	6.6x10^{-18}	-172	66x10^{-16}	-142	-102
3x10^{-6}	10	2.4x10^{-14}	-136	2.4x10^{-18}	-176	24x10^{-16}	-146	-106
2x10^{-6}	6	1.1x10^{-14}	-140	1.1x10^{-18}	-180	11x10^{-16}	-150	-110
1x10^{-6}	0	2.7x10^{-15}	-146	2.7x10^{-19}	-186	2.7x10^{-16}	-156	-116

NOTE: Numbers in table rounded off

FIELD STRENGTH APPROACH

To account for the impedance difference, the antenna factor (AF) is defined as: AF=E/V, where E is field intensity which can be expressed in terms taking 377 ohms into account and V is measured voltage which can be expressed in terms taking 50 ohms into account. Details are provided in Section 4-12.

POWER DENSITY APPROACH

To account for the impedance difference , the antenna's effective capture area term, A_e relates free space power density P_D with received power, P_r , i.e. $P_r = P_D A_e$. A_e is a function of frequency and antenna gain and is related to AF as shown in Section 4-12.

SAMPLE CALCULATIONS

Section 4-2 provides sample calculations using power density and power terms from Table 1 and Table 2, whereas Section 4-12 uses these terms plus field intensity and voltage terms from Table 1 and Table 2. Refer the examples in Section 4-12 for usage of the conversions while converting free space values of power density to actual measurements with a spectrum analyzer attached by coaxial cable to a receiving antenna.

Conversion Between Field Intensity (Table 1) and Power Received (Table 2).

Power received (watts or milliwatts) can be expressed in terms of field intensity (volts/meter or µv/meter) using equation [3]:

$$\textit{Power received } (P_r) = \frac{E^2}{480\pi^2}\,\frac{c^2}{f^2}\,G \qquad \textbf{[3]}$$

or in log form:

$$10 \log P_r = 20 \log E + 10 \log G - 20 \log f + 10 \log (c^2/480\pi^2) \qquad \textbf{[4]}$$

Then

$$10 \log P_r = 20 \log E_1 + 10 \log G - 20 \log f_1 + K_4 \qquad \textbf{[5]}$$

$$\textit{Where } K_4 = 10 \log \left[\frac{c^2}{480\pi^2} \cdot \left(\begin{array}{l}\textit{conversions}\\ \textit{as required}\end{array} \frac{(\textit{Watts to mW})}{(\textit{volts to } \mu v)^2 (\textit{Hz to MHz or GHz})^2} \right)\right]$$

Values of K_4 (dB)

P_r	E_1	f_1 (Hz)	f_1 (MHz)	f_1 (GHz)
Watts (dBW)	volts/meter	132.8	12.8	-47.2
	µv/meter	12.8	-107.2	-167.2
mW (dBm)	volts/meter	162.8	42.8	-17.2
	µv/meter	42.8	-77.2	-137.7

The derivation of equation [3] follows:

$P_D = E^2/120\pi$ Eq [1], Section 4-1, terms (v^2/Ω)

$A_e = \lambda^2 G/4\pi$ Eq [8], Section 3-1, terms (m^2)

$P_r = P_D A_e$ Eq [2], Section 4-3, terms $(W/m^2)(m^2)$

$\therefore P_r = (E^2/120\pi)(\lambda^2 G/4\pi)$ terms $(v^2/m^2\Omega)(m^2)$

$\lambda = c/f$ Section 2-3, terms (m/sec)(sec)

$\therefore P_r = (E^2/480\pi^2)(c^2 G/f^2)$ which is equation [3]

terms $(v^2/m^2\Omega)(m^2/sec^2)(sec^2)$ or v^2/Ω = watts

Table 2. Conversion Table - Volts to Watts and dBμA
($P_x = V_x^2/Z$ - Related by line impedance of 50 Ω)

Volts	dBV	dBμV	Watts	dBW	dBm	dBμA
700	56.0	176.0	9800	39.9	69.9	142.9
500	53.9	173.9	5000	37.0	67.0	140.0
300	49.5	169.5	1800	32.5	62.5	135.5
200	46.0	166.0	800	29.0	59.0	132.0
100	40.0	160.0	200	23.0	53.0	126.0
70	36.9	156.9	98	19.9	49.9	122.9
50	34.0	154.0	50	17.0	47.0	120.0
30	29.5	149.5	18	12.5	42.5	115.5
20	26.0	146.0	8	9.0	39.0	112.0
10	20.0	140.0	2	3.0	33.0	106.0
7	16.9	136.9	0.8	0	29.9	102.9
5	14.0	134.0	0.5	-3.0	27.0	100.0
3	9.5	129.5	0.18	-7.4	22.5	95.6
2	6.0	126.0	0.08	-11.0	19.0	92.0
1	0	120.0	0.02	-17.0	13.0	86.0
0.7	-3.1	116.9	9.8×10^{-3}	-20.1	9.9	82.9
0.5	-6.0	114.0	5.0×10^{-3}	-23.0	7.0	80.0
0.3	-10.5	109.5	1.8×10^{-3}	-27.4	2.6	75.6
0.2	-14.0	106.0	8.0×10^{-4}	-31.0	-1.0	72.0
0.1	-20.0	100.0	2.0×10^{-4}	-37.0	-7.0	66.0
.07	-23.1	96.9	9.8×10^{-5}	-40.1	-10.1	62.9
.05	-26.0	94.0	5.0×10^{-5}	-43.0	-13.0	60.0
.03	-30.5	89.5	1.8×10^{-5}	-47.4	-17.7	55.6
.02	-34.0	86.0	8.0×10^{-6}	-51.0	-21.0	52.0
.01	-40.0	80.0	2.0×10^{-6}	-57.0	-27.0	46.0
7×10^{-3}	-43.1	76.9	9.8×10^{-7}	-60.1	-30.1	42.9
5×10^{-3}	-46.0	74.0	5.0×10^{-7}	-63.0	-33.0	40.0
3×10^{-3}	-50.5	69.5	1.8×10^{-7}	-67.4	-37.4	35.6
2×10^{-3}	-54.0	66.0	8.0×10^{-8}	-71.0	-41.0	32.0
1×10^{-3}	-60.0	60.0	2.0×10^{-8}	-77.0	-47.0	26.0
7×10^{-4}	-64.1	56.9	9.8×10^{-9}	-80.1	-50.1	22.9
5×10^{-4}	-66.0	54.0	5.0×10^{-9}	-83.0	-53.0	20.0
3×10^{-4}	-70.5	49.5	1.8×10^{-9}	-87.4	-57.4	15.6
2×10^{-4}	-74.0	46.0	8.0×10^{-10}	-91.0	-61.0	12.0
1×10^{-4}	-80.0	40.0	2.0×10^{-10}	-97.0	-67.0	6.0
7×10^{-5}	-84.1	36.9	9.8×10^{-11}	-100.1	-70.1	2.9
5×10^{-5}	-86.0	34.0	5.0×10^{-11}	-103.0	-73.0	0
3×10^{-5}	-90.5	29.5	1.8×10^{-11}	-107.4	-77.4	-4.4
2×10^{-5}	-94.0	26.0	8.0×10^{-12}	-111.0	-81.0	-8.0
1×10^{-5}	-100.0	20.0	2.0×10^{-12}	-117.0	-87.0	-14.0
7×10^{-6}	-104.1	16.9	9.8×10^{-13}	-120.1	-90.1	-17.1
5×10^{-6}	-106.0	14.0	5.0×10^{-13}	-123.0	-93.0	-20.0
3×10^{-6}	-110.5	9.5	1.8×10^{-13}	-127.4	-97.4	-24.4
2×10^{-6}	-114.0	6.0	8.0×10^{-14}	-131.0	-101.0	-28.0
1×10^{-6}	-120.0	0	2.0×10^{-14}	-137.0	-107.0	-34.0
7×10^{-7}	-124.1	-3.1	9.8×10^{-15}	-140.1	-110.1	-37.1
5×10^{-7}	-126.0	-6.0	5.0×10^{-15}	-143.0	-113.0	-40.0
3×10^{-7}	-130.5	-10.5	1.8×10^{-15}	-147.4	-117.4	-44.4
2×10^{-7}	-134.0	-14.0	8.0×10^{-16}	-151.0	-121.0	-48.0
1×10^{-7}	-140.0	-20.0	2.0×10^{-16}	-157.0	-127.0	-54.0