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STANDARDS

Network Operations Subcommittee

SCTE OPERATIONAL PRACTICE

SCTE 221 2020

Field Strength Tutorial & Calculation of LTE User Equipment Field Strength

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1. Introduction

1.1. Executive Summary

Cable operators have been measuring the field strength of over-the-air radio frequency (RF) signals for decades. For instance, most operators are required to measure signal leakage field strength. As well, it can sometimes be helpful to calculate and/or measure the field strength of certain over-the-air signals such as potential interference sources.

In late 2010, a new wireless technology called 4G, or long term evolution (LTE), was introduced in the United States. LTE service operates in several frequency bands, including the 698 MHz to 806 MHz band, which overlaps the frequency spectrum used by many cable operators to deliver services to their customers. As LTE service providers continue to deploy LTE service, the RF signals emanating from LTE towers and user equipment (UE) represent sources of potential interference to services carried on cable systems.

More recently, 5G New Radio (NR) technology is being deployed by service providers. Here, too, some 5G technology operates on over-the-air frequencies that overlap the RF spectrum used in cable networks. One example is the 600 MHz band, with UE-to-tower transmissions in the 663 MHz to 698 MHz range, and tower-to-UE transmissions in the 617 MHz to 698 MHz range.

1.2. Scope

This Operational Practice provides a tutorial on RF field strength, and a method for calculating field strength, such as the field strength of an RF signal emanating from LTE UE. The same principles are applicable to cable network signal leakage field strength.

1.3. Benefits

Understanding the concept of field strength and how to calculate it can help cable operators as they maintain and troubleshoot their networks, and comply with government regulations applicable to signal leakage.

1.4. Intended Audience

The intended audience of this Operational Practice is technical personnel who are interested in understanding the basics of RF field strength, and its application to signal leakage and over-the-air signals that can potentially cause interference to cable networks.

1.5. Areas for Further Investigation or to be Added in Future Versions

No areas for further investigation were identified at the time this Operational Practice was written.

2. Normative References

The following documents contain provisions, which, through reference in this text, constitute provisions of this document. At the time of Subcommittee approval, the editions indicated were valid. All documents are subject to revision; and while parties to any agreement based on this document are encouraged to investigate the possibility of applying the most recent editions of the documents listed below, they are reminded that newer editions of those documents might not be compatible with the referenced version.

2.1. SCTE References

- No normative references are applicable.

2.2. Standards from Other Organizations

- No normative references are applicable.

2.3. Published Materials

- No normative references are applicable.

3. Informative References

The following documents might provide valuable information to the reader but are not required when complying with this document.

3.1. SCTE References

- SCTE 209 2015: Technical Report - UHF Leakage, Ingress, Direct Pickup

3.2. Standards from Other Organizations

- No informative references are applicable.

3.3. Published Materials

- Hranac, R. (2012, July). The Antenna Factor. *Communications Technology*. Retrieved October 14, 2014, from https://scte-cms-resource-storage.s3.amazonaws.com/12-07-01%20the%20antenna%20factor.pdf
- Kraus, J. (1988). *Antennas, Second Edition*. New York: McGraw-Hill
- *The ARRL Antenna Book* (any recent edition); www.arrl.org
- *The ARRL Handbook for Radio Amateurs* (any recent edition); www.arrl.org

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5. Abbreviations and Definitions

5.1. Abbreviations

4G	fourth generation mobile communications technology
5G	fifth generation mobile communications technology
5G NR	5G New Radio
µV/m	microvolt per meter
A_e	effective aperture
A_{em}	maximum effective aperture
dB	decibel
dBi	decibel isotropic
dBm	decibel milliwatt
dBmV	decibel millivolt
dBµV/m	decibel microvolt per meter
e.g.	for example (exempli gratia)
FCC	Federal Communications Commission
ISBE	International Society of Broadband Experts
km	kilometer
LTE	long term evolution
m	meter
MHz	megahertz
mW	milliwatt
NOS	[SCTE] Network Operations Subcommittee
NOS WG1	[SCTE] Network Operations Subcommittee Working Group 1
P_d	power density

P_t	source power
RF	radio frequency
SCTE	Society of Cable Telecommunications Engineers
TR	[SCTE] Technical Report
TV	television
UE	user equipment
UHF	ultra high frequency
VHF	very high frequency
V/m	volt per meter

5.2. Definitions

antenna factor	The ratio of the field strength of an electromagnetic field incident upon an antenna to the voltage produced by that field across a load of impedance Z_0 connected to an antenna's terminals.
decibel (dB)	A logarithmic-based expression of the ratio between two values of a physical quantity, typically power or intensity. The decibel provides an efficient way to express ratios which span one or more powers of the logarithmic base, most commonly 10. Mathematically, the ratio of two power levels P_1 and P_2 in decibels is $dB = 10\log_{10}(P_1/P_2)$ [1]
decibel microvolt (dBµV)	Unit of RF power expressed in terms of voltage, defined as decibels relative to 1 microvolt, where 1 microvolt equals 13.33 femtowatts in a 75 ohm impedance. Mathematically, $dB\mu V = 20\log_{10}(\text{value in } \mu V/1\ \mu V)$.
decibel isotropic (dBi)	the forward gain of an antenna compared with the hypothetical isotropic antenna, which uniformly distributes energy in all directions.
decibel microvolt per meter (dBµV/m)	An RF signal's power density expressed in terms of voltage, defined as decibels relative to 1 microvolt per meter, where 1 microvolt per meter equals 1 microvolt delivered to a receiving antenna's terminals recovered from an imaginary 1 meter x 1 meter square in free-space or air. Mathematically, $dB\mu V/m = 20\log_{10}(\mu V/m)$.
decibel millivolt (dBmV)	Unit of RF power expressed in terms of voltage, defined as decibels relative to 1 millivolt, where 1 millivolt equals 13.33 nanowatts in a 75 ohm impedance. Mathematically, $dBmV = 20\log_{10}(\text{value in mV}/1\ \text{mV})$.
decibel milliwatt (dBm)	Unit of power, defined as decibels relative to 1 milliwatt, where 0 dBm equals 1 milliwatt. Mathematically, $dBm = 10\log_{10}(\text{value in mW}/1\ \text{mW})$.
effective aperture (A_e)	The geometric area over which an antenna receives power from an incident wave and delivers that power to a connected load.

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[1] The decibel, while technically a ratio of two power levels, also can be used to represent the ratio of two voltage levels, assuming the two voltages are across the same impedance. Here is how that relationship is derived: The unit of electrical power, the watt, equals 1 volt multiplied by 1 ampere. Equation-wise $P = EI$, where P is power in watts, E is voltage in volts, and I is current in amperes. Substituting the Ohm's Law equivalent for E and I gives additional formulas for power: $P = E^2/R$ and $P = I^2R$. If the right hand side of the power equation $P = E^2/R$ is substituted for both P_1 and P_2 in the formula $dB = 10\log_{10}(P_1/P_2)$, the equation becomes $dB = 10\log_{10}[(E^2/R)/(E^2/R)]$ which is the same as $dB = 10\log_{10}[(E_1^2)/R_1)/(E_2^2/R_2)]$. In this example, R represents the 75 ohms impedance of a cable network. Since R_1 and R_2 are both equal to 75 ohms, those equation terms cancel, leaving the equation $dB = 10\log_{10}(E_1^2/E_2^2)$. This can be simplified somewhat and written as $dB = 10\log_{10}(E_1/E_2)^2$ which is the same as $dB = 2 * 10\log_{10}(E_1/E_2)$ or $dB = 20\log_{10}(E_1/E_2)$.

	Mathematically, $A_e = \lambda^2 G/4\pi$, where λ is the wavelength of the RF signal, G is the receiving antenna's numerical power gain (e.g., 1.64 for a half-wave dipole), and $\pi = 3.14159265$. If the antenna is considered lossless, effective aperture is called maximum effective aperture (A_{em}). For a half-wave dipole antenna, A_{em} can be approximated by an ellipse whose area is $0.13\lambda^2$.
far-field	The region of an antenna's radiation pattern in which the angular distribution of radiated energy is largely independent of distance from the antenna, and in which the power varies inversely with the square of distance. The approximate distance from the antenna to the beginning of the far-field is generally accepted to be $R = 2D^2/\lambda$, where R is distance from the antenna, D is the largest linear dimension of the antenna aperture, and λ is wavelength. Signal leakage field strength measurements are made in the far-field. See also *near-field.*
field strength	An RF signal's power density within an imaginary 1 meter x 1 meter square (that is, watts per square meter) in free space or in the air. Usually expressed as a voltage; for example, microvolts per meter.
gain	An increase in the power of a signal or signals, usually measured in decibels. Expressed mathematically, $G_{dB} = 10\log_{10}(P_{out}/P_{in})$, where G_{dB} is gain in decibels, P_{out} is output power in watts, P_{in} is input power in watts, and $P_{out} > P_{in}$. When signal power is stated in dBmV, $G_{dB} = P_{out(dBmV)} – P_{in(dBmV)}$.
hertz (Hz)	A unit of frequency equivalent to one cycle per second.
impedance	The combined opposition to current in a component, circuit, device, or transmission line that contains both resistance and reactance. Represented by the symbol Z and expressed in ohms.
loss	A decrease in the power of a signal or signals, usually measured in decibels. Expressed mathematically, $L_{dB} = 10\log_{10}(P_{in}/P_{out})$, where L_{dB} is loss in decibels, P_{in} is input power in watts, P_{out} is output power in watts, and $P_{out} < P_{in}$. When signal power is stated in dBmV, $L_{dB} = P_{in(dBmV)} – P_{out(dBmV)}$.
maximum effective aperture (A_{em})	See *effective aperture*
megahertz (MHz)	One million (10^6) hertz. See also *hertz*.
microvolt (µV)	One millionth (10^{-6}) of a volt.
microvolt per meter (µV/m)	A measure of the field strength of an RF signal, calculated by dividing the received intensity in microvolts by the receiving antenna maximum effective aperture.
millivolt (mV)	One thousandth (10^{-3}) of a volt.
milliwatt (mW)	One thousandth (10^{-3}) of a watt.
near-field	The space around an antenna comprises a reactive region and a radiating region. The radiating region is further subdivided into a near-field region and a far-field region. The radiating near-field is the propagation region where angular contributions from individual antenna elements vary significantly with distance from the antenna. See also *far-field*.

polarization[2]	The orientation of an electromagnetic wave's electric field vector. For terrestrial applications, when the electric field vector is perpendicular to the surface of the Earth, the polarization is vertical. When the electric field vector is parallel to the surface of the Earth, the polarization is horizontal.
radio frequency (RF)	That portion of the electromagnetic spectrum from a few kilohertz to just below the frequency of infrared light.
resonant	A characteristic of an antenna that exists when its impedance is purely resistive with no reactance, and when the voltage and current at the antenna's terminals are in phase.
signal leakage	Unwanted emission of RF signals from a cable TV network into the over-the-air environment, typically caused by degraded shielding effectiveness of coaxial cable, connectors, and other network components, or by poorly shielded subscriber terminal equipment connected to the cable network.

6. What is Field Strength?

The measurement of signal leakage *field strength* – a term used extensively in this document – often is taken for granted. The procedure is fairly straightforward: Using a dedicated leakage detector with a resonant half-wave dipole antenna (or equivalent), orient the antenna to get a maximum reading and see what value the leakage detector reports. The measured field strength is stated in microvolts per meter[3] (µV/m), and hopefully is below the maximum limit defined by a government agency such as the Federal Communications Commission (FCC).

The field strength in µV/m can be converted to a decibel millivolt (dBmV) value at the dipole antenna's terminals using the formula

$$dBmV = 20\log\left[\frac{\left(\frac{E_{\mu V/m}}{0.021 * f}\right)}{1000}\right]$$

where $E_{\mu V/m}$ is the field strength in microvolts per meter, and f is frequency in MHz.

But that still doesn't explain what field strength is. Things get even more confusing when measuring signal leakage at more than one frequency. Assuming the same field strength - say, 20 µV/m – at two frequencies and the use of separate resonant half-wave dipoles for the measurements, the dBmV values at the two dipoles' terminals will be different. For example, a field strength of 20 µV/m at 121.2625 MHz will produce -42.1 dBmV at the terminals of a resonant half-wave dipole for that frequency. A field strength of 20 µV/m at 782 MHz will produce -58.29 dBmV at the terminals of a resonant half-wave dipole for that frequency.

To understand what is happening, consider the following example, based upon the assumptions in Table 1.

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[2] Unless otherwise indicated, discussions about polarization in this Operational Practice refer to linear polarization. There are other types of polarization, such as circular; for more information on the latter, see pp. 70 of *Antennas, Second Edition*, by Kraus, or https://en.wikipedia.org/wiki/Circular_polarization

[3] Outside of the North American cable industry, field strength measurements are more commonly stated in decibel microvolt per meter, or dBµV/m.

Table 1 - Assumptions for example

• Measurement frequencies are 121.2625 MHz and 782 MHz
• Antennas for the two frequencies are lossless resonant half-wave dipoles
• Field strength at the point of measurement is 20 µV/m for both frequencies
• Measurement distance from the leak is 3 meters, which is in the far-field for this exercise
• Each antenna is terminated by a load equal to its radiation resistance (approximately 73 ohms for a half-wave dipole)
• Each dipole is oriented for maximum received signal level
• Each antenna does not re-radiate any of the intercepted signal
• The polarization of the radio frequency (RF) coming from the leak is linear and is the same as the orientation of the dipoles when the field strength measurements are made

Visualize a loose connector radiating RF into the space around it. Now imagine a 6-meter diameter balloon surrounding the loose connector, with the connector at the center of the balloon (See Figure 1). Assume the RF leaking from the loose connector is uniformly "illuminating" the entire surface of the balloon from the inside. Next, imagine a 1 meter x 1 meter square drawn somewhere on the surface of the balloon. The task at hand is to measure the RF power density within the 1 meter x 1 meter square. The power density in that square also can be expressed as a voltage, which is how field strength is expressed: volts per meter. In other words, field strength is the RF power density in a 1 meter x 1 meter square (in free space, in the air, or, as in this example, on the surface of an imaginary 6-meter diameter balloon), expressed as a voltage – hence, the "volts per meter" or "microvolts per meter" designation.

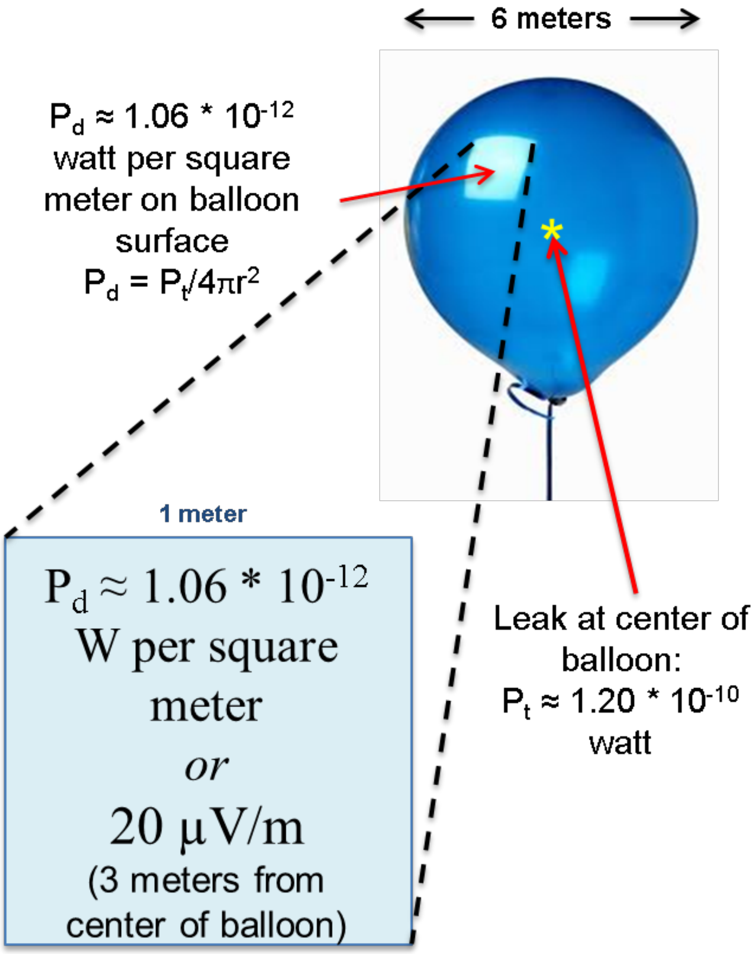

Figure 1 - Field strength example illustrating power density in a 1 meter x 1 meter square on the surface of an imaginary balloon

The RF power transmitted by the loose connector in the center of the balloon is designated P_t, and is called the source power. In order to produce a field strength of 20 µV/m 3 meters away, P_t must equal $\approx 1.2 * 10^{-10}$ watt. Because the RF source power P_t is uniformly illuminating the entire balloon (an analogy is a light bulb at the center of the balloon), the power density P_d on the surface of the balloon in watts per square meter is simply the source power P_t divided by the surface area of the balloon, or

$$P_t/4\pi r^2$$

where r is the radius of the balloon. Since the balloon's diameter is 6 meters, $r = 3$ meters.

Plugging the just-discussed values for P_t and r into the previous formula, the calculated power density on the surface of the balloon is equal to about $1.06 * 10^{-12}$ watt per square meter.[4]

To convert power density in watts per square meter to volts per square meter, use the formula

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[4] A more accurate value is 1.06176749119E-12 watt per square meter.

$$E_{V/m} = \sqrt{P_d Z_0}$$

where $E_{V/m}$ is volts per square meter, P_d is power density in watts per square meter, and Z_0 is the impedance of a vacuum (free space). A common approximation of the impedance of free space is 120π ohms, or ≈377 ohms.[5]

the voltage $E_{V/m}$ on the surface of the balloon in volts per meter is

$$E_{V/m} = \sqrt{([1.06 * 10^{-12}\ watt] * 120\pi\ ohms)}$$

= 0.000020 volt per meter, or 20 µV/m.

So far, so good. A source power P_t of $\approx 1.20 * 10^{-10}$ watt "transmitted" by the loose connector illuminates the surface of the balloon 3 meters away to produce a power density P_d of about $1.06 * 10^{-12}$ watt per square meter, which is equal to a field strength of 20 µV/m. This relationship is true for both frequencies.

Next, the resonant half-wave dipoles are placed one at a time in the square on the balloon, and the field strength within that square measured. The question is how much of the power in the square will be intercepted by each dipole and delivered to the load connected to each antenna's terminals? All of it? Only an amount occupying an area equal to the physical dimensions of each antenna? Or some other amount?

Visualize what happens when a dipole is placed at the surface of the balloon, where RF from the loose connector 3 meters away is passing by at the speed of light. The RF field induces a voltage *V* in the dipole, resulting in a current *I* through the ≈73 ohms impedance at the antenna terminals. What's of interest is the power *P* delivered by the antenna to that impedance, where $P = I^2 R_T$. Here R_T is the sum of the antenna's radiation resistance (≈73 ohms) and loss resistance, the latter assumed to be zero for this example.

Kraus (1988) illustrates a scenario using a horn antenna:

> Let the…power density of the plane wave be *S* watts per square meter and the area of the mouth of the horn be *A* square meters. If the horn extracts all the power from the wave over its entire area *A*, then the total power *P* absorbed from the wave is $P = SA$ (W). Thus, the electromagnetic horn may be regarded as an aperture…

The same is true of a dipole antenna – that is, it can be regarded as an aperture with a specific area that extracts power from a passing wave and delivers it to the load connected to the antenna terminals. Defining aperture isn't quite as simple as one might assume, though. According to Kraus, three types of aperture describe "…ways in which power collected by the antenna may be divided: into power in the terminal resistance (effective aperture); into heat in the antenna (loss aperture); or into reradiated power (scattering aperture)."

A fourth aperture, called collecting aperture, is the sum of the three previous apertures.

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[5] According to the National Institute of Standards and Technology, the characteristic impedance of a vacuum Z_0 is 376.730313668 ohms. For more information about the NIST value, see https://physics.nist.gov/cgi-bin/cuu/Value?z0|search_for=all!

Finally, physical aperture is basically "a measure of the physical size of the antenna." For thin wireline antennas such as dipoles, the length of the antenna is a significant dimension relative to the wavelength involved, but the other dimensions are negligible compared to the wavelength. This makes identifying a physical area elusive since the dipole antenna is essentially one-dimensional. For an ideal (lossless) half-wave dipole, the maximum effective aperture of the antenna, A_{em}, is related to the physical size of the antenna by the formula $A_{em} = 0.52(\text{length})^2$, which gives the same answer as $A_{em} = 0.13\lambda^2$, the latter discussed in the following paragraphs. (Note: Make sure that "length" and λ are in the same units.)

Since the dipoles in this example are assumed to be lossless, effective aperture – more specifically, maximum effective aperture A_{em} – is the criteria that will be used to describe how much of the RF power in the 1 meter x 1 meter square is intercepted and delivered to the load at the antenna terminals. Mathematically

$$A_{em} = (\lambda^2/4\pi)G$$

where λ is wavelength in meters ($299.792458/f_{MHz}$) and G is the antenna's numerical gain (1.64 for a half-wave dipole). A linear half-wave dipole's maximum effective aperture can be represented by an elliptically shaped aperture with an area equal to $0.13\lambda^2$, as shown in Figure 1.

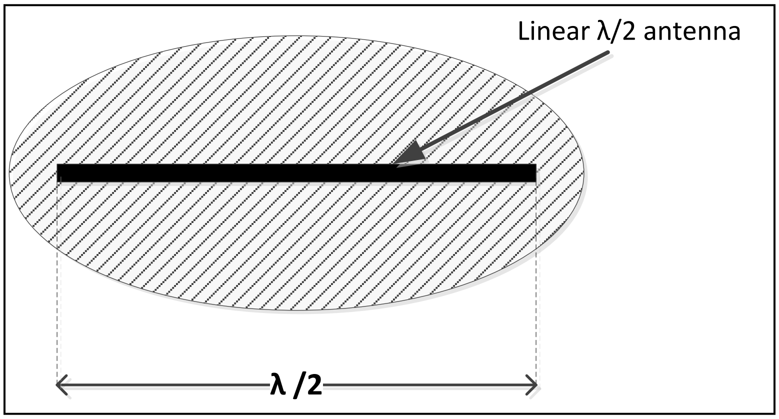

Figure 2 - A linear half-wave dipole's maximum effective aperture *A_{em}* can be represented by an ellipse with an area of 0.13λ². Adapted from *Antennas*, by J. Krauss, New York, NY: McGraw-Hill

The free-space wavelength for 121.2625 MHz is approximately 2.47 meters (2.47226024534) and for 782 MHz is approximately 0.38 meter (0.383366314578). Plugging these numbers into the previous formula gives a maximum effective aperture of 0.797668339532 m^2 for the 121.2625 MHz dipole, and 0.0191805865422 m^2 for the 782 MHz dipole. The A_{em} values denote what percentage of the power within the 1 meter x 1 meter square is intercepted by each dipole and delivered to the load at the antenna terminals. The difference between the two A_{em} values in decibels is

$$10log\left({A_{em}}^{dipole\ 1}/{A_{em}}^{dipole\ 2}\right)$$

or 16.19 dB, which is equal to the antenna factor[6] difference between the two dipoles.

In other words, when measuring a 20 µV/m field strength at 121.2625 MHz and 782 MHz with resonant half-wave dipoles, the lower frequency antenna intercepts and delivers more power to its load ($\approx 8.46 * 10^{-13}$ watt) than the higher frequency antenna does ($\approx 2.04 * 10^{-14}$ watt). Here, too, the decibel difference is

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[6] The antenna factors for the VHF and UHF dipoles in this example are 8.12 dB/m and 24.31 dB/m respectively.

the same as the antenna factor difference. All of this jibes with the two different signal levels at the dipoles' terminals: -42.1 dBmV at 121.2625 MHz and -58.29 dBmV at 782 MHz, for identical 20 µV/m field strengths at the two frequencies.

7. How to Calculate Maximum Field Strength of LTE Equipment

The maximum LTE UE transmit power is +23 dBm (decibel milliwatt) or 200 mW, with a 2 dB tolerance, and the minimum is -40 dBm (0.0001 mW). That's a pretty significant power range that must be supported by LTE UE. Numbers for UE antenna gain ranging from -1 dBi (decibel isotropic) to -3.5 dBi, with -3 dBi being typical. With that information, the following example calculates the predicted field strength (far-field) that might occur 1 meter away from an LTE handset if that handset were transmitting at the maximum +23 dBm power output (the 2 dB tolerance could mean that some UEs transmit as high as +25 dBm at maximum output, but the +23 dBm value in being used in this example). The transmit frequency range for a Verizon LTE handset, for example, is 777-787 MHz, so the center of that range, 782 MHz, is used for the calculation.

Free space path loss is calculated with the formula

$\text{Loss}_{\text{dB}} = 20\log(f_{\text{MHz}}) + 20\log(d_{\text{km}}) + 32.45$

where
f_{MHz} is the frequency in megahertz
d_{km} is the path length in kilometers (1 meter = 0.001 km)

The free space path loss over a 1 meter distance at 782 MHz is

$\text{Loss}_{\text{dB}} = 20\log(782\text{ MHz}) + 20\log(0.001\text{ km}) + 32.45$
$\text{Loss}_{\text{dB}} = [20 * \log(782\text{ MHz})] + [20 * \log(0.001\text{ km})] + 32.45$
$\text{Loss}_{\text{dB}} = [20 * 2.89] + [20 * -3.00] + 32.45$
$\text{Loss}_{\text{dB}} = [57.86] + [-60.00] + 32.45$
$\text{Loss}_{\text{dB}} = 30.31\text{ dB}$

Assume a resonant half-wave dipole antenna located at the point where field strength 1 meter away the LTE UE is being measured. The received signal power at the receive dipole's terminals is:

Transmit power (dBm) – transmit feedline loss (dB) + transmit antenna gain (dBi) – free space path loss (dB) + receive antenna gain (dBi)

For this exercise, assume a UE transmit antenna with -1 dBi gain, and the antenna is connected *directly* to the transmitter's power amplifier stage – no feedline loss, no filter insertion loss. Also assume that there is no additional attenuation to the LTE UE's transmitted signal caused by someone holding the device. Plugging in some numbers gives

23 dBm – 0 dB + (-1 dBi) – 30.31 dB + 2.15 dBi = -6.16 dBm at the dipole's terminals.

Converting the received power in dBm to dBmV is done by adding 48.75 to the dBm value:
-6.16 dBm + 48.75 = +42.59 dBmV. This conversion assumes the receive dipole's impedance is 75 ohms, which is close to a half-wave dipole's approximate free-space impedance value of 73.1 ohms. Next, convert dBmV to field strength in µV/m:

$\mu\text{V/m} = 21 * (782\text{ MHz}) * 10^{(42.59/20)} = 2{,}212{,}718\ \mu\text{V/m}$ or ~2.2 V/m

From this, the calculated field strength 1 meter away that could be produced by an LTE handset operating at maximum transmit power is ~2.2 million microvolts per meter, or ~2.2 V/m. Doubling the distance to 2 meters will still result in a calculated field strength of around 1.1 V/m.

Practically speaking, the UE antenna gain is likely to be closer to -3 dBi, and some additional attenuation will occur as a result of the UE being handheld or sitting by itself on a table or other surface. For example, with 6 dB of total additional attenuation, the 1-meter field strength would be about 1.1 V/m and the 2-meter field strength would be about 0.55 V/m when the UE is transmitting at its maximum power of +23 dBm.