Converting Signal Strength Percentage to dBm Values

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Executive Summary

WildPackets' 802.11 wireless LAN packet analyzers, AiroPeek and AiroPeek NX, provide a measurement of RF signal strength represented by a percentage value. The question sometimes arises as to why a percentage metric is used, and how this relates to the actual RF energy that is present in the environment. This paper discusses RF technology with sufficient detail to provide a basis for understanding the issues related to signal strength measurement.

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Measurement Units for RF Signal Strength

There are four units of measurement that are all used to represent RF signal strength. These are: mW (milliwatts), dBm ("db"-milliwatts), RSSI (Receive Signal Strength Indicator), and a percentage measurement. All of these measurements are related to each other, some more closely than others. It is possible to convert from one unit to another, albeit with varying degrees of accuracy, and not always in the extremes of the measurement range.

The mW and dBm Units of Measure

The first two units to consider are the mW and the dBm (pronounced "dee-bee-em" or spoken as "dee-bee milliwatts"). When energy is measured in milliwatts (mW), the mW signal level is, simply, the amount of energy present. An electrical engineer or physicist could explain "energy" in more detail, but it is sufficient to think about the fact that a typical wireless access point or quality wireless client NIC has a rated output of 100 mW.

Because of the peculiarities of measurement, it turns out that the measuring RF energy in mW units is not always convenient. This is due, in part, to the fact that signal strength does not fade in a linear manner, but inversely as the square of the distance. This means that if you are a particular distance from an access point and you measure the signal level, and then move twice as far away, the signal will decrease by a factor of four. You move by 2x and the signal decreases by 1/4x; hence, the "inverse square law." In any case, the fact that exponential measurements are involved in signal strength measurement is one reason why the use of a logarithmic scale of measurement was developed as an equivalent, but alternative way of representing RF power.

The "dBm" (dB-milliwatt) is a logarithmic measurement of signal strength, and dBm values can be exactly and directly converted to and from mW values. Just like miles and kilometers can be converted directly, so can mW and dBm (of course, the mW-to-dBm conversion is from a linear scale to a logarithmic scale, and miles-to-kilometers would be linear-to-linear).

A mW measurement is first converted to a base-10 logarithm. It turns out that the logarithm values are quite small; convention multiplies this value by 10 with the resulting value called dBm. Here are some examples to help clarify this relationship:

100mw	log 100 = 2 and 10^2=100	20dBm = 100mW
50mw	log 50 = 1.698 and 10^1.698 = 50	15.9dBm = 50 mW
25mw	log 25 = 1.397 and 10^1.397 = 25	13.9dBm = 25mW
13mw	log 13 = 1.113 and 10^1.113 = 13	11.1dBm = 13mW

You can prove these relationships with your scientific calculator. Notice that each time the actual mW power level becomes half as great, the dBm measurement goes down by (roughly) 3 dBm. As a general guideline, it is convenient to remember that a decrease of 3dBm yields roughly half the original value and, conversely, an increase of 3dBm yields roughly twice the original value.

Of course, power is always a positive quantity. You can't have "negative energy" (unless you're studying quantum mechanics and virtual particles!), so the mW measurement will always be something greater than zero. You can, however, have very small values; much less than 1. When representing a fraction less than 1 (but greater than zero), it can be shown that the corresponding logarithmic value is negative. You can prove the following relationships on your calculator if you desire:

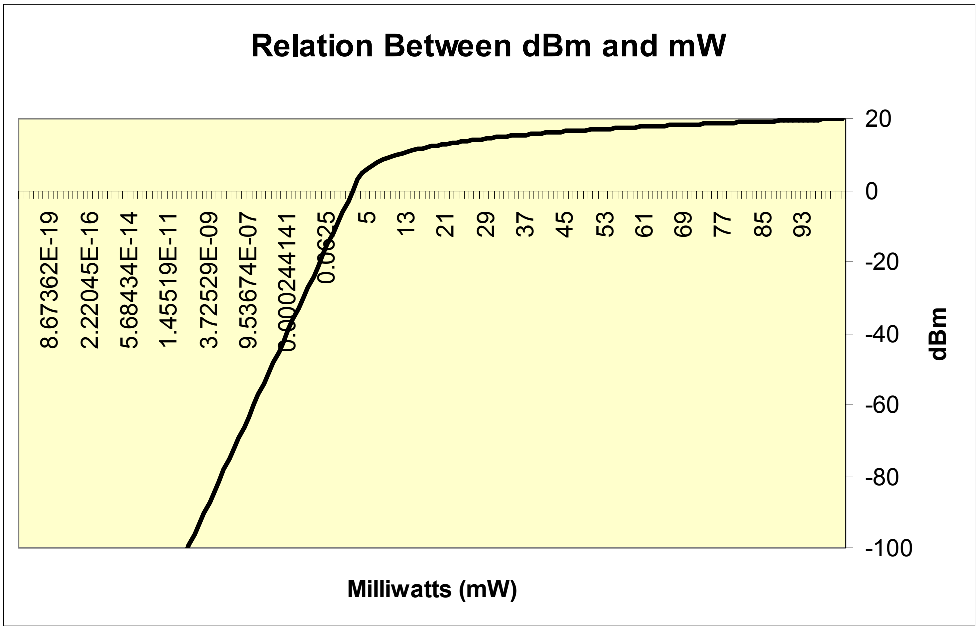
1 mW	log 1 = 0 and 10^0=1	0dBm = 1mW
.5 mW	log .5 = -0.3010 and 10^-0.3010 = .5	-3.01dBm = .5mW
.25mW	log .25 = -0.602 and 10^-0.602=.25	-6.02dBm = .25mW
.13 mW	log .13 = -0.886 and 10^-0.886=.13	-8.86dBm = .13mW

Notice, again, that a decrease of roughly 3dBm yields a change of roughly half in the mW value. It is worth noting, for the discussion that will be presented later in this document, that if you continued building the table until you got down to .0000000002511 mW, you would find that this was equal to –96dBm. It turns out that .0000000002511 mW is about as tiny an RF signal that can be received by most standard 802.11 NICs. This is the "receiver sensitivity" level. As you can see, it is much easier to say, and write, "-96dBm" than to have to figure out where all the zeros are and whether you're talking about "pico-watts" or "fempto-watts" (it is "fempto," by the way; that's why we talk about dBm, which is a much more useful way of measuring signal strength at very low levels).

We can now say, "An 802.11 NIC transmits power at roughly 20dBm and can receive power all the way to –96dBm." You should realize that while it is reasonable to talk about 20dBm as being 100mW, it is cumbersome to talk about –96dBm as being .0000000002511 mW. You should realize that convenience and ease-of-understanding are two fundamental reasons why the dBm metric is used for RF signal strength, rather than mW.

The graph below shows the mathematical relationship between dBm measurements and their corresponding mW values. The actual formula used for the conversion is:

dBm = log (mW) * 10



What you can see in the graph is that there is a relatively linear appearance to the slope as it rises from –100 dBm to the point where the mW value is roughly 5. At that point, the curve turns sharply to the right and flattens out. After the curve a relatively large change in mW value is required to make a significant change in dBm. This is purely a mathematical relationship, however. As will be shown, the fact that dBm measurements don't change much above 5 mW will be significant in how 802.11 NIC manufacturers have chosen to present RF signal strength measurements.

The Receive Signal Strength Indicator (RSSI)

The IEEE 802.11 standard defines a mechanism by which RF energy is to be measured by the circuitry on a wireless NIC. This numeric value is an integer with an allowable range of 0-255 (a 1-byte value) called the Receive Signal Strength Indicator (RSSI). No vendors have chosen to actually measure 256 different signal levels, and so each vendor's 802.11 NIC will have a specific maximum RSSI value ("RSSI_Max"). For example, Cisco chooses to measure 101 separate values for RF energy, and their RSSI_Max is 100. Symbol uses an RSSI_Max value of 31. The Atheros chipset uses an RSSI_Max value of 60. Therefore, it can be seen that the RF energy level reported by a particular vendor's NIC will range between 0 and RSSI_Max. Notice that nothing has been said here about measurement of RF energy in dBm or mW. RSSI is an arbitrary integer value, defined in the 802.11 standard and intended for use, internally, by the microcode on the adapter and by the device driver. For example, when an adapter wants to transmit a packet, it must be able to detect whether or not the channel is clear (i.e., nobody else is transmitting). If the RSSI value is below some very low value, then the chipset knows that the channel is clear. This is the "Clear Channel Threshold" and some particular RSSI value is associated with it. When an 802.11 client is associated to an access point and is roaming, there comes a point when the signal level received from the access point drops to a somewhat low value (because the client is moving away from the access point). This level is called the "Roaming Threshold" and some intermediate (but low) RSSI value is associated with it. Different vendors use different signal levels for the Clear Channel Threshold and the Roaming Threshold and, moreover, the RSSI value that represents these thresholds differs from vendor-to-vendor because different RSSI_Max values are implemented.

RSSI in the 802.11 Standard

Here is what the IEEE 802.11 standard says about the RSSI metric:

14.2.3.2 RXVECTOR RSSI

> The receive signal strength indicator (RSSI) is an optional parameter that has a value of 0 through RSSI Max. This parameter is a measure by the PHY sublayer of the energy observed at the antenna used to receive the current PPDU. RSSI shall be measured between the beginning of the start frame delimiter (SFD) and the end of the PLCP header error check (HEC). RSSI is intended to be used in a relative manner. Absolute accuracy of the RSSI reading is not specified.

Notice that the parameter is specified as optional, although all 802.11 NIC manufacturers appear to implement it. Of greatest significance are the last two sentences: “The RSSI is intended to be used in a relative manner. Absolute accuracy of the RSSI reading is not specified.”

There is no specified accuracy to the RSSI reading. That is, there is nothing in the 802.11 standard that stipulates a relationship between RSSI value and any particular energy level as would be measured in mW or dBm. Individual vendors have chosen to provide their own levels of accuracy, granularity, and range for the actual power (measured as mW or dBm) and their range of RSSI values (from 0 to RSSI_Max).

Granularity in RSSI Measurements

The concept of “granularity” is important to consider here, too. Since the RSSI value is an integer it must increase or decrease in integer steps. For example, Symbol provides 32 separate “steps,” Cisco provides 101 (i.e., from 0 to RSSI_Max for any given manufacturer). Whatever range of actual energy is being measured, it must be divided into the number of integer steps provided by the RSSI range. Therefore, if RSSI changes by 1, it means that the power level changed by some proportion in the measured power range. There are, therefore, two important considerations in understanding RSSI. First, it is necessary to consider what range of energy (the mW or dBm range) that’s actually being measured. Secondly, it must be recognized that all possible energy levels (mW or dBm values) cannot be represented by the integer set of RSSI values.

The Choice of a Suitable Energy Range for Measurement

As was seen in the dBm-to-mW graph above, there is not much change in dBm values above roughly 5 mW. Wireless NIC manufacturers do not measure signal strength in that range. RF energy is almost always measured using dBm values, because the measured range would otherwise have mW values with too many zeros to the right of the decimal point to make for ease of understanding. The graph also shows that the slope of change for dBm below 5mW is very roughly linear, but not exactly. The logarithmic nature of the dBm measurement, coupled with the fact that the RSSI range used for measurement contains dBm “gaps” (due to the integer nature of the RSSI value), has led many vendors to map RSSI to dBm using a table. These mapping tables allow for adjustments to accommodate the logarithmic nature of the curve. The range of energy that is typically measured begins at or below –10dBm (and, compared to the +20dBm of potential output power at a 100mW access point, that’s a relatively weak signal). In addition to the fact that the graph “flattens out” at higher power levels, the –10dBm upper limit on the energy level measurement range is also consistent with the purpose for RSSI measurements in the first place. Remember that RSSI is intended for use in Clear Channel assessment and determination of the Roaming Threshold. It makes sense that the circuitry is designed to provide reasonable accuracy in this range.

The Low Energy End of the Measurement Range

The receiver circuit in an 802.11 NIC must have a minimum level of available RF energy (above the level of the background noise) in order to extract a bit-stream. This minimum level is called the "Receive Sensitivity" and is a NIC spec measured in dBm. For example, a NIC manufacturer may indicate that their particular card has a Receive Sensitivity of –96dBm at 1Mb/sec. If the actual RF energy present at that card were less than –96dBm then the card would no longer be able to differentiate between signal and noise. The dBm value for a NICs Receive Sensitivity is very close to the dBm value associated with an RSSI value of 0. Hence, the Receive Sensitivity of the adapter determines the lower end of the necessary measurement range for signal strength. It should be noted that, typically, if RSSI=0 the dBm signal measurement is below the Receive Sensitivity level.

Using a Percentage Signal Strength Metric

To circumvent the complexities (and potential inaccuracies) of using RSSI as a basis for reporting dBm signal strength, it is common to see signal strength represented as a percentage. The percentage represents the RSSI for a particular packet divided by the RSSI_Max value (multiplied by 100 to derive a percentage). Hence, a 50% signal strength with a Symbol card would convert to an RSSI of 16 (because their RSSI_Max = 31). Atheros, with RSSI_Max=60, would have RSSI=30 at 50% signal strength. Cisco ends up making life easy with an RSSI_Max =100, so 50% is RSSI=50.

It can be seen that use of a percentage for signal strength provides a reasonable metric for use in network analysis and site survey work. If signal strength is 100%, that's great! When signal strength falls to roughly 20%, you're going to reach the Roaming Threshold. Ultimately, when signal strength is down somewhere below 10% (and probably closer to 1%), the channel is going to be assumed to be clear. This conceptualization obviates the need to consider dBm, the RSSI_Max, or the "knee" in the logarithmic curve of mW to dBm conversion. It allows a reasonable comparison between environments even though different vendor's NICs were used to make the measurements. Ultimately, the generalized nature of a percentage measurement allows the integer nature of the RSSI to be overlooked.

The Impossibility of Measuring 0% Signal Strength

In the preceding paragraph, you may have noticed the note in parentheses stating that the clear channel threshold was "probably closer to 1%." There is a very profound reason why this was not "0%." If signal strength falls to 0%, it can be assumed that RSSI=0 and, hence, the signal strength is at, or below, the Receive Sensitivity of the NIC. A NIC can't report that a particular packet has "0% signal strength," because if there were no available signal, there would be no packet to measure!

It is impossible for any tool using a standard wireless NIC to measure signal strength below the NIC's Receive Sensitivity threshold.

Signal Strength and the Inverse Square Law

Earlier, it was stated that the "inverse square law" defined how an RF signal would be reduced in power. A physicist might explain that there are other factors that come into play with signal attenuation, but the inverse square law has the most dramatic impact. In fact, when measurements are taken at a distance greater than approximately one wavelength away from an electromagnetic radiator, the other influences to the energy level of the radiated wave become insignificant and can be ignored. Imagine that a 100mW access point actually had 100mW of measured power 1-inch away from the antenna. Of course, this is a thought experiment only. Antenna loss or gain, and the actual energy of the radiated signal, would influence the real-world measured power and probably not be exactly 100mW. The thought experiment is, nonetheless, interesting. Immediately we're faced with an impossible situation. If the measured power were 100mW at a distance of 1-inch, then the measured power would be 400mW at a distance of ¾-inch (by the inverse-square law). At ¼-inch, the power would have to jump up to 1600mW. Obviously, this is not reality. In fact, theoretical measurements of RF signals are a challenge for students in college physics classes and they involve some complicated formulae. You see, when a transmitter is rated at 100mW, there is an implication that a 100mW signal is present at the last point in the transmitter circuit before the signal enters the antenna! The antenna will introduce some loss or gain, and what comes out will be assumed to be at the power level derived from adjusting the power at the antenna by that gain or loss.

Continuing the thought experiment, however, and recognizing that real-world measurement would probably be smaller than those derived in the thought experiment, adds to an understanding of why RSSI values are associated with dBm signal strengths at levels below -10dBm. If the measured power at 1-inch from an antenna were 100mW, then we could imagine the following measurements, based on the inverse-square law:

1" = 100mW = 20dBm
2" = 25mW = 13.9dBm
4" = 6.25mW = 7.9dBm
8" = 1.56mW = 1.9dBm
16" = 0.39mW = -4.08dBm
32" = .097mW = -10.1dBm
64" = .024mW = -16.1dBm (5.3 feet away)
128" = .006mW = -22.2dBm (10.6 feet away)
256" = .0015mW = -28.2dBm (21.3 feet away)

What you see from the table is that somewhere between roughly 5 feet and 20 feet away from a 100mW radiator, the signal strength falls to below -20dBm. Consequently, measurements represented by RSSI values that refer to energy levels below -10dBm (or lower) are reasonable and practical.

Experimental Confirmation of Theoretical Assumptions

Engineers at WildPackets performed some limited experiments to see how closely these theoretical concepts matched with real-world measurements. An access point rated at 100mW was measured using AiroPeek NX. It was found that within 5 feet of the access point, the indicated signal strength remained at 100%, indicating that the signal was as strong or stronger than the high-end of the dBm range of measurement used by the NIC. Between 5 and 10 feet away from the access point the signal strength occasionally fell to as low as 80%, but essentially hovered at 100%, with only occasional drops to 80%. Measurements were made on the far side of a drywall-on-wooden-stud wall. It was found that there, too, signal strength remained at 100% within 5-feet of the access point. The conclusion drawn from these experiments was that use of AiroPeek for measuring signal strength was reasonable beyond 10 feet from the access point. However, the variations in measured signal level (the "hovering" of the signal strength with a 20% variation) meant that site survey measurements would be generalized, at best. General measurements would be suitable for many practical site survey situations, since a key determination in a site survey involves identifying places where the signal strength is unacceptably low, as opposed to creating an accurate dBm signal strength map of a particular environment. As long as the measured signal strength remains above 30%, there should be sufficient signal for normal 802.11 operations. In practice, one could determine the signal strength percentage at which 802.11 speed dropped from 11Mb/sec to 5.5Mb/sec, and then the level at which the rate dropped to 2Mb/sec or 1Mb/sec, and use those determined signal strength percentages as part of a site survey baseline.

Practical Conversion from Percentage to dBm

The effectiveness or reasonability of using dBm measurements obtained from a standard wireless NIC is questionable when used as part of a real-world network troubleshooting exercise. This is because most NICs only provide RSSI in a range that is below –10dBm, and everything above that is mapped to RSSI_Max (or, 100% signal strength). If it is important to know the difference between –40dBm and –50dBm, then why isn't it equally important to know the difference between +20dBm and +10dBm? Moreover, is it not important to determine the actual output power of an antenna, particularly a directional antenna? The output power would be measured in positive dBm, possibly even greater than +20dBm (for a high-gain antenna). These measurements are outside the RSSI range for most adapters.

Nonetheless, following are conversion tables, based on information obtained from various NIC manufacturers, which will provide a mapping between RSSI and dBm. There is a two-step process when going from a percentage signal strength report in an analyzer to the dBm value in a vendor's table. First, it is necessary to know the RSSI_Max for the vendor and, from that, the RSSI that corresponds to the current percentage value can be obtained (i.e., x% of RSSI_Max = RSSI). Once the RSSI value has been obtained from the percentage, it is only necessary to plug it in to the vendor's table (or formula) and get a dBm value. You should notice, in each description that follows, how the values in the tables don't always increase in a linear manner. Sometimes a table value will go up by 5, other times by 6, and so forth. This is to account for the logarithmic nature of dBm measurements. Embodied in these "gaps" in the table, and exacerbated by the integer nature of the RSSI, are inherent potential inaccuracies that must be recognized.

Conversion for Atheros

Unlike the other vendors described, Atheros uses a formula to derive dBm.

RSSI_Max = 60

Convert % to RSSI

Subtract 95 from RSSI to derive dBm

Notice that this gives a dBm range of –35dBm at 100% and –95dBm at 0%.

Conversion for Symbol

RSSI_Max = 31

Convert % to RSSI and lookup the result in the following table:

RSSI <= 4 is considered to be –100dBm

RSSI <=8 is considered to be –90 dBm

RSSI <=14 is considered to be –80 dBm

RSSI <=20 is considered to be –70 dBm

RSSI <=26 is considered to be –60 dBm

RSSI greater than 26 is considered to be –50dBm

Notice that this gives a dBm range of –50dBm to –100dBm but only in 10dBm steps.

Conversion for Cisco

Cisco has the most granular dBm lookup table.

RSSI_Max = 100

Convert % to RSSI and lookup the result in the following table. The RSSI is on the left, and the corresponding dBm value (a negative number) is on the right.

0	=	-113	34	=	-78	68	=	-41
1	=	-112	35	=	-77	69	=	-40
2	=	-111	36	=	-75	70	=	-39
3	=	-110	37	=	-74	71	=	-38
4	=	-109	38	=	-73	72	=	-37
5	=	-108	39	=	-72	73	=	-35
6	=	-107	40	=	-70	74	=	-34
7	=	-106	41	=	-69	75	=	-33
8	=	-105	42	=	-68	76	=	-32
9	=	-104	43	=	-67	77	=	-30
10	=	-103	44	=	-65	78	=	-29
11	=	-102	45	=	-64	79	=	-28
12	=	-101	46	=	-63	80	=	-27
13	=	-99	47	=	-62	81	=	-25
14	=	-98	48	=	-60	82	=	-24
15	=	-97	49	=	-59	83	=	-23
16	=	-96	50	=	-58	84	=	-22
17	=	-95	51	=	-56	85	=	-20
18	=	-94	52	=	-55	86	=	-19
19	=	-93	53	=	-53	87	=	-18
20	=	-92	54	=	-52	88	=	-17
21	=	-91	55	=	-50	89	=	-16
22	=	-90	56	=	-50	90	=	-15
23	=	-89	57	=	-49	91	=	-14
24	=	-88	58	=	-48	92	=	-13
25	=	-87	59	=	-48	93	=	-12
26	=	-86	60	=	-47	94	=	-10
27	=	-85	61	=	-46	95	=	-10
28	=	-84	62	=	-45	96	=	-10
29	=	-83	63	=	-44	97	=	-10
30	=	-82	64	=	-44	98	=	-10
31	=	-81	65	=	-43	99	=	-10
32	=	-80	66	=	-42	100	=	-10
33	=	-79	67	=	-42			

Notice that this gives a range of –10dBm to –113dBm. Bearing in mind that a Cisco card will have a Receive Sensitivity of –96dBm at its lowest, it is impossible to obtain an RSSI value of less than 16. Note, also, that all RSSI values greater than 93 are assigned –10dBm, and that there are multiple places in the table where two adjacent RSSI values are assigned the same dBm value.

There is another aspect to interpreting the Cisco RSSI. The Cisco device driver code indicates that if the RSSI value converts to less than –90dBm, then it should be converted to a fixed value of –75dBm. This leaves a question as to the exact interpretation of an RSSI value that converts to –76dBm to –89dBm. A measurement of –75dBm would be reported as 36% signal strength. It seems sufficient to leave this quandary unanswered, since whether a signal is at –75dBm or at –92dBm, the entire low-end range is less than what would be desirable for normal 802.11 WLAN operation.

Conclusions

While it is possible to arrive at a dBm value that is somewhat equivalent to a reported Signal Strength percentage, the absolute accuracy of the value is questionable. The range of possible measurements is below –10dBm, which precludes using an off-the-shelf NIC for measurement of high-gain antennae, or anywhere close to an access point (where the signal level is above –10dBm). In general, the use of a percentage value for signal strength allows for a relatively simple, consistent, reproducible metric that can be used as part of a site survey. When, however, accurate dBm measurements must be made as part a site survey, or in the course of network analysis and troubleshooting, the use of an RF Spectrum Analyzer tool should be considered.

In practice, it can be observed that above some particular signal strength (%) traffic moves at 11Mb/sec (in 802.11b) and, as the percentage decreases, there’s a point where the data begins moving at 5.5 Mb/sec. Still later the speed drops, ultimately, to 1 Mb/sec, and finally there are increased numbers of CRC errors with an ultimate loss of reception. Real-world testing can establish the signal levels (as percentages) associated with each of these events, and these can then be used as a baseline for ongoing measurement and analysis.

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