Calculating a link budget

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From numerous discussions among radio hams it is clear that many hams struggle with the concept of link budgets. Bold statements are not unheard of:

- "Antenna X is always better than antenna Y."
- "If A can hear B it doesn't mean that B can hear A, which is proof that propagational paths are not bidirectional."
- "RG-58 coax should never be used for serious DX."
- "If both stations use the same amount of power, their signal reports should be the same."

These and other fallacies could all be heard on the air here in Gauteng during the past few months. Clearly many hams have trouble grasping the fact that a QSO between two stations is a chain with many links.

What is a link budget?

Simply put, a link budget is the sum and total of all gains and losses in the radio connection between two parties from end to end, including antenna's, feed lines and the path between the antenna's, but also the relevant portions of the transmitter and the receiver, as well as miscellaneous gains and losses.

For a line-of-sight radio link, the link budget might look like this:

$$Prx = Ptx + Gtx - Ltx - Lfs - Lm + Grx - Lrx$$

where:

- P_{RX} = received power (dBm)
- P_{TX} = transmitter output power (dBm)
- G_{TX} = transmitter antenna gain (dBi)
- L_{TX} = transmitter losses (coax, connectors...) (dB)
- L_{FS} = free space loss or path loss (dB)
- L_{M} = miscellaneous losses (fading margin, body loss, polarization mismatch, other losses...) (dB)
- G_{RX} = receiver antenna gain (dBi)
- L_{RX} = receiver losses (coax, connectors...) (dB)

To dispense with the mathematical formula, in plain language the above means that:

1. We start with the power of the signal that comes out of the transmitter;
2. To that we add the gain of the transmitter's antenna, also known as *isotropic* antenna gain, or gain relative to an isotropic antenna;
3. From that we subtract the losses between the transmitter and the antenna, which includes all the antenna cables, connectors, baluns and other components;

4. Then we subtract the free space or path loss, which occurs between the two antennas and is a factor of the distance between the antennas (see below);
5. We also subtract whatever miscellaneous losses may occur, e.g. due to polarization mismatch;
6. We then add the receiver's antenna gain;
7. And once again we subtract all losses between the antenna and the receiver - cables, connectors, baluns, etc.

In order to add all these factors, all power levels must be specified in dBm or dBW. For example, if the transmitter puts out 10 Watts (or 10,000 mW) its power is 10,000 times the reference power of 1 mW. Since 10,000 is ten to the fourth power, this gives us a transmitter power of 40dBm. To clarify:

0.01 mW = -20 dBm
0.1 mW = -10 dBm
1 mW = 0 dBm
10 mW = 10 dBm
100 mW = 20 dBm
1000 mW = 30 dBm

and so on. Once we have expressed our power levels in dBm or dBW (where 30 dBm = 0 dBW and 40 dBm = 10 dBW) we can simply add or subtract all gains and losses. For example a power of 40 dBm is transmitted through an antenna with a gain of 6dB, which gives us an Effective Isotropic Radiated Power (EIRP) of 46 dBm, or 10 to the power of 4.6 (in mW) which comes to 39,8 Watts. That means that a 10W transmitter connected to a 6dB gain antenna delivers the same amount of power to the receiver at the other end as a 39,8W transmitter connected to an isotropic radiator.

An example

For short distance line-of-sight communications (e.g. from your hand-held to a nearby 70-cm repeater of which you can see the antenna tower with the naked eye) we can ignore the path loss, as it will be minimal. For example, take a hand-held with a nominal transmitter output power of 100 mW (or 20dBm). The hand-held uses a small "rubber duck" antenna, which is notorious for its bad efficiency. Let's assume this particular rubber duck is a typical one with a gain of, say, -3dB. (In other words it has a "negative gain", otherwise known as "loss". That means that it's less efficient than an isotropic radiator, which is quite common for rubber ducks on hand-helds! The repeater however has a decent antenna with a gain of, say, 6dB, and its receiver input stage has a sensitivity of -130dBm (at 12dB SiNAD, or signal-to-noise-and-distortion, which is generally considered the minimum signal-over-noise ratio for a workable QSO). The cable between the repeater's antenna and the repeater input is 20 meter of Belden RG-213 coax. According to the manufacturer this cable has a loss of 16 dB per 100 meter at 435 MHz, which works out to 3.2 dB for 20 meter. (Obviously this repeater was built on a budget!) If the repeater has a cavity filter at the input with an insertion loss of, say, 1 dB (not too good, but in this example let's assume that that's what it is) and the total loss of all the connectors used is another 0.3dB, our link budget works out as follows:

1. Transmitter power: 100mW = 20 dBm = 20 dBm
2. Transmitter antenna gain: -3 dB = 17 dBm
3. Transmitter loss = zero (no antenna cable!)

4. Path loss = zero (ignored)
5. Receiver antenna gain = 6 dB = 23 dBm
6. Receiver loss (cable, filter, connectors)
   = 3.2 + 1 + 0.3 = 4.5 dB = 18.5 dBm
7. Miscellaneous losses = zero (ignored)

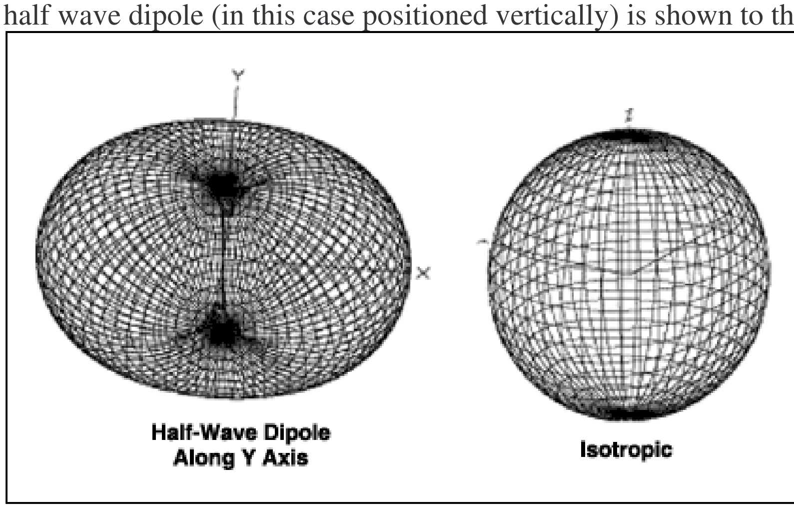
So in this case, the input of the repeater receives 18.5 dBm. Since the minimum for a QSO is considered -130 dBm, we can easily work the repeater. Which is unsurprising, since in this example we're assumed to stand practically next to it! However in the real world we will usually be much farther away, and we have to consider the path loss involved.

Path loss through free space

The path loss occurs on the path traversed by the radio signal between the two antennas. In free space this loss is a factor of the distance between the antennas; through the atmosphere or ionosphere other factors come into play as well.

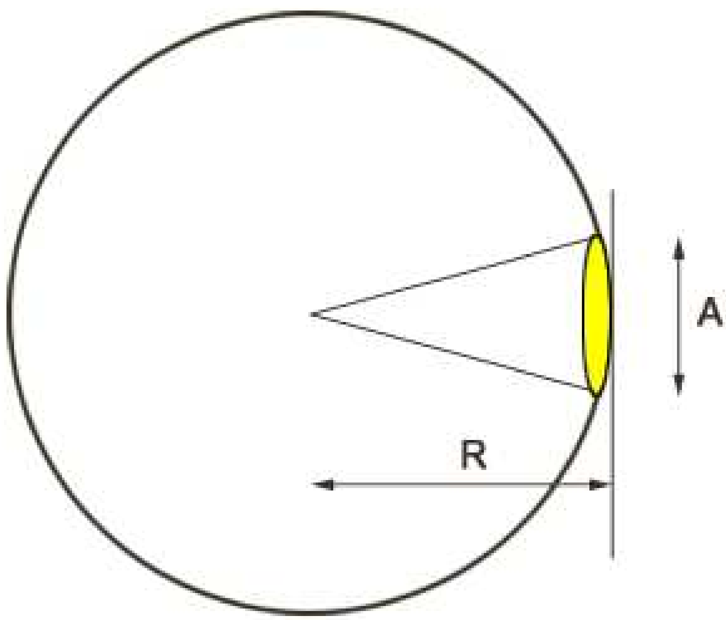
In order to understand path loss, consider an *isotropic radiator*, which is a theoretical point source that radiates in all directions. In order to visualize this, imagine that your antenna is a very small metal ball, which radiates equally in all directions so that the wave front emitted by the antenna is completely spherical. The larger the distance from the source the wave front travels, the larger the spherical wave front gets, and therefore the larger the surface of the spherical wave front that moves outward from the antenna. Therefore the energy radiated from the source will be spread across a larger surface whenever the distance increases, and therefore the strength of the signal at any given point of the spherical wave front will diminish accordingly.

In real life an antenna is not isotropic. A dipole, for example, radiates a toroid-shaped (donut-shaped) pattern when it is suspended in free space, and in a pattern affected by the ground plane, surrounding obstacles and other factors when it is not. In the drawing below, the isotropic radiation pattern is shown on the right hand side, while the radiation pattern of a half wave dipole (in this case positioned vertically) is shown to the left:



The donut-shaped radiation pattern of the dipole is totally different from the isotropic, i.e. in each direction we have a different amount of energy that is being radiated. This makes it very complicated to calculate a line-of-sight link budget. A Yagi antenna, however, is much easier to work with. The Yagi radiates the bulk of its energy in a bundle (ignoring side lobes for the moment). That bundle may be considered a cone-shaped segment of the isotropic sphere, assuming that no other significant environmental factors distort the Yagi's "ideal" radiation pattern too much.

The surface of a Yagi antenna's "cone of radiation" is determined by its aperture, which, in turn, is a measure for how "wide" the surface of the cone is. In the drawing below, the radius of the isotropic sphere (i.e. the distance from the antenna) is shown as 'R', while the aperture is shown as A. The radiant area (the surface of the radiated "cone") is shown in yellow:



The higher the gain of the antenna, the smaller the aperture will be. In physics we get nothing for nothing; the gain of the antenna is in fact nothing but the antenna's ability to "concentrate" the radiated energy on one spot, just like a lens can focus a beam of light: the smaller the spot, the brighter the light.

The surface of a sphere is equal to $4 * \pi * R^2$. Therefore, the amount of power received by surface A is equal to:

$$\frac{A}{4 * \pi * R^2} * Ptx$$

where Ptx is the power emitted by the transmitting antenna.

The isotropic gain (the gain of an antenna over the isotropic sphere) is dependent on the frequency used. An isotropic antenna has an isotropic gain of 1, while a half wave dipole in free space has an isotropic gain of 1.64 (or roughly 2.15dB).

A half wave dipole in, say, the 70-cm band has roughly 1/3rd of the length of a half wave dipole in the 2-metre band. Therefore its effective surface is only 1/9th (the square of its length). In other words, a 70cm antenna will intercept a much smaller portion of the wave front than a 2m antenna.

Because the 'cone of radiation' (see the drawing above) increases with distance, while the portion of the cone's base that is intercepted by the receiving antenna decreases with the frequency, it follows that the path loss is both a factor of distance *and* the inverse of the wavelength used. In other words, path loss increases when the distance increases, but it also increases when the frequency (in kHz, MHz or GHz) goes up.

Without bothering with all the mathematics (deriving the formula is left as an exercise to the reader - HI) the path loss may be calculated as follows:

Free Space Path Loss (dB) = 32.44 + 20*log(F(MHz)) + 20*log(D(km))

An example of path loss

Let's take another look at the above example, in which we try to work a 70-cm repeater with a hand-held at 100mW. Standing next to the repeater we could (of course) work it without problems. Now let's see what happens when we are 10 km away. The path loss over that distance at 435 MHz is:

32.44 + 20*log(435) + 20*log(10) = 105.2 dB

If we add the path loss to our link budget calculation above, we end up with the following:

1.	Transmitter power: 100 mW = 20 dBm	=	20 dBm
2.	Transmitter antenna gain: -3 dB	=	17 dBm
3.	Transmitter loss = zero (no antenna cable!)		
4.	Path loss = -105 dB	=	-88 dB
5.	Receiver antenna gain = 6 dB	=	-82 dBm
6.	Receiver loss (cable, filter, connectors) = 3.2 + 1 + 0.3 = 4.5 dB	=	-86.5 dBm
7.	Miscellaneous losses = zero (ignored)		

Since the minimum power into the repeater's input for a QSO is -130dBm, we can still work the repeater at this distance... but that is because we have a line-of-sight path!

Non-line-of-sight path loss

Standing on a high site with the repeater at another high site and no obstructions in between, we generally *will* be able to work this repeater in practice with fairly low power levels, such as in the above example. However, in practice we have the environment to deal with: buildings, trees, hills and what not. The absorption of a few healthy, well-watered trees at 70cm is easily 6dB or more. Then there's also the absorption of the atmosphere and the humidity therein. Even more important: without a line-of-sight path we are reduced to reflection and/or refraction. All this means that the "miscellaneous loss" factor in our link budget is no longer zero, but quickly jumps up to well over 45 dB, and we can no longer work this repeater from the ground at 100mW. We need to increase the transmitter power, use a better antenna, and/or move to a higher location where we will have a path to the repeater that is closer to line-of-sight in order to make a QSO.

On HF the situation becomes much more complicated. The reflection of the ionosphere is susceptible to significant short-term fluctuations, which causes the received signal to fluctuate in both amplitude and polarization; a phenomenon known as 'fading' or QSB. The radiation patterns of the antennas used are also much more complex. While on VHF and up we could consider the radiated signal to resemble a cone-shaped segment of the isotropic sphere (especially when using a Yagi boom or a dish), on HF we no longer have that luxury. Even a chunky monoband HF dipole on top of a high tower will show a radiation pattern that is sufficiently deformed by the earth's surface, reflective surfaces such as buildings and hillsides, and other "real world" factors, and we will have to substitute expectation for calculation, and experimentation for prediction. Calculating accurate link budgets for non-line-of-sight communication is always difficult and often impossible, since a multitude of environmental and highly variable factors cannot be determined accurately.

Satellites and moon bouncing

In another practical example of line-of-sight communications, we try to receive the OSCAR-51 satellite ("Echo") using a hand-held radio and a hand-held antenna with a gain of 10dB. Let's start with the satellite's FM transponder mode Down Link. Echo will produce a minimum power of 1 Watt (+30dBm) on 70cm. The transmit antenna system has a net gain of 2dB (i.e. cable losses etc. have already been subtracted). The path loss at maximum range (3000 km) is 155 dB. We should allow an extra 3dB loss for polarisation mismatch and another 1dB from travelling through the ionosphere.

A typical 70cm hand-held is rated at -120 dBm for 12dB SiNAD. So we have:

1. Satellite TX power (minimum) = 30 dBm	=	30 dBm
2. Satellite TX antenna gain = 2 dB	=	32 dBm
3. Path Loss = 155 dB	=	-123 dBm
4. Misc. loss (polarisation, ionosphere) = 4 dB	=	-127 dBm
5. Receiver antenna gain = 10 dB	=	-117 dBm

This is just above the minimum for a useable signal.

At minimum range (800 km) the path loss reduces to 143 dB, which will result in a signal of -105dB into the receiver. So Echo in FM mode will be able to be received on a dual band handheld with a handheld Yagi antenna; easily when the satellite is directly overhead, and just barely when the satellite is just over the horizon.

Now let's try a moon bounce QSO at 145MHz. We'll do it the old-fashioned way, using a CW transceiver, key and the human ear rather than a computer with PSK-31. The surface-to-surface distance between earth and moon is assumed to be 370,000 km. For a moon bounce QSO our signal will have to traverse this path twice. Furthermore the moon is not a perfect mirror, which means that much of the signal is being scattered rather than being reflected back to earth. Also, the moon will only intercept a tiny fraction of the beam; most of the signal will travel past the moon and into space. Then there are polarization mismatches and some ionospheric absorption. All in all, the practical path loss for a moon bounce QSO at 144 MHz is around 252dB. (!)

Let's assume a "big gun" at the transmitter end, pouring 1 KW of RF power into a phased array of 16-element Yagi's with a total gain of 20dB. A good quality coaxial cable is being used, but the size of the array and the height of the tower require a lot of cable. Let's assume the total loss of cables and such comes to 3dB. This leaves us with the following:

1. Transmitter power: 1 kW = 60 dBm = 60 dBm
2. Transmitter antenna gain: 20 dB = 80 dBm
3. Transmitter loss = 3dB = 77 dBm
4. Path loss = -252 dB = -175 dBm

Now what do we need at the receiver end to receive the echo's from the moon? We are trying to receive a weak CW signal, so we don't necessarily need 12 dB SiNAD (as we would need for FM). Let's assume that the trained human ear can still fish the dots and dashes out of the noise when we feed a -140 dBm signal into our receiver. That means that in order to receive the echo's, we need to throw 35 dB of gain into the mix, plus enough additional gain to make up for cable losses etc.

Assuming a similar antenna array (4 phased Yagi's with a total gain of 20 dB) at the receiver end, and again 3 dB of loss in cables and the like, the second half of our link budget is:

5. Receiver antenna gain = 20 dB = -155 dBm
6. Receiver loss (cables etc) = 3 dB = -158 dBm
7. Amplification we need to provide = 38 dB = -140 dBm

So we either need a very sensitive receiver (so that we can detect the dots and dashes at less than -140 dBm into the receiver!) or we need an excellent pre-amp! Another option is to use better cable in order to reduce the losses in that link of the chain. Here an important factor is the frequency on which the cable is used, as cable loss increases with frequency. On the lower HF bands there is nothing wrong with using RG-58, for example, since at those frequencies cable losses are relatively insignificant. On VHF and UHF though these losses become much higher, and in this particular moon bounce example a few dB can make the difference between hearing a station and hearing only noise. Another obvious solution would be to increase the gain of the antenna array (more and larger antennas) or to replace Morse code and the human ear with a digital mode that will allow weak signal communications at much lower power levels into the receiver, such as PSK-31.

Link budgets, reciprocity and antenna's

One look at the components of a link budget makes it clear that while some components of the link budget are reciprocal, the entire link budget itself is not. For example, the path loss is a factor of distance and frequency, but not of direction, which proves that the propagational path (be it a line-of-sight path or a non-line-of-sight path) has similar properties in both directions of the link. The path loss of a given propagational path between, say, Africa and Europe will be exactly equal in both directions.

This is not necessarily true for other factors in the link budget, though. Transmitter power may (and often will) be different at both sides of the link, and the same goes for receiver sensitivity. Transmitter low pass filters, receiver band pass filters, antenna tuner circuits or balun cores that may saturate on transmission but not on reception are all examples of factors that apply to the link budget in one direction but not in the other. Also local noise levels are an important factor: if the local QRM level at one side is high, that receiver may very well require 20 dBm or more in order to produce a decent audio signal.

Antenna considerations play a role here, too. It is well known that some antennas are more susceptible to local QRM than others. Closed-loop antennas such as the folded dipole, the quad or the delta loop are known for their 'quiet' reception characteristics, while an open dipole is much "noisier". This is due to the fact that these antennas handle the near field differently. While the antenna itself is reciprocal, i.e. it has the same gain and radiation pattern for transmission as for reception, it is important to keep in mind that an antenna does not exist in a vacuum. Local factors such as QRM add to the mix of signal and noise that the antenna eventually feeds into the receiver. If the local "noise floor" for reception is high, the receiver requires a stronger signal into the receiving antenna in order to produce a decent audio signal. This effectively makes the receiving *station* (as opposed to just the receiver itself!) less sensitive, and as a result the total link budgets in both directions end up being significantly different.

When to calculate a link budget

Making QSO's is generally a matter of "let's try and find out". Is there anything wrong with that? Of course not! However there are cases where a little bit of forethought can save a great deal of trial and error. For example, when setting up a digipeater for packet radio or APRS, it is important to know if the repeater can actually connect to its neighbouring nodes reliably. When trying to work a satellite one has to know whether or not the available transceiver and antenna equipment is sufficient and, perhaps even more importantly, when it is not necessary to invest in expensive elevation rotators and low noise preamplifiers! Microwave enthusiasts may end up working out a link budget more often than not before trying to make a difficult QSO.

In non-amateur applications a properly calculated link budget can save a lot of trouble as well. Wireless computer networking applications such as WiFi or HSDPA (in South Africa known under the brand name iBurst™) use frequencies in the GHz range where the link path is relatively short, and sufficiently close to line-of-sight to make a fairly good prediction on the network's coverage area based upon the minimum signal strength to be delivered to the wireless device.

While radio remains subject to a lot of factors and may always give surprising results, working out a link budget can often save a lot of needless effort and disappointment. A few minutes of thought can save hours or days of work. Try it. You may be surprised.