When considering antennas, the theoretical yardstick is the ideal isotropic antenna. If fed from a transmitter, this antenna radiates power with equal intensity in all directions.

As with any antenna, there will be associated electric and magnetic field lines in space, due to the voltage applied to the antenna elements, and the current flowing in them. In the immediate vicinity of the antenna, these fields are out of phase, and thus represent stored circulating energy: this is called the 'near field' region. This field drops of rapidly with distance, it has almost disappeared at a distance of λ metres, i.e. one wavelength, from the antenna.

But the antenna also generates electric and magnetic fields which are in phase, and these represent a flow of power away from the antenna - the 'far field'. The magnetic field strength corresponds to a magnetising field, measured in amps per metre. This, together with the electric field strength in volts per metre defines the characteristic impedance of free space, which is 120π or 377Ω.

The ideal isotropic antenna looks purely resistive, and this resistance has two components. Resistance R_r is the 'radiation resistance' - a notional non-dissipating resistance representing the 'port' via which power is radiated from the antenna. Loss resistance R_1 is the ohmic component of the antenna's total resistance. Clearly the radiation efficiency η_r is given by:-

$$\eta_r = \frac{R_r}{R_r + R_1} \qquad (1)$$

In some cases, it is possible to make R_1 negligible, but in practice an efficiency well short of 100% must sometimes be tolerated.

An ideal isotropic antenna located in free space, radiating a power P_t will. result in a power density D, in watts per square metre, at a range d, in metres, is given by,

$$D = \frac{P_t}{4\pi d^2} \qquad (2)$$

This assumes that d is much larger than the wavelength concerned, and is of course independent of the frequency. The term $4\pi d^2$ is the surface area of a sphere of radius d, centred on the antenna. The strength of the electric field ε, in volts per metre, in space at any point is given by,

$$\varepsilon = \sqrt{377D} \qquad (3)$$

Warwick Industrial Electronics Ltd
Tel: +44 (0) 1455 233616 Fax: +44 (0) 1455 233179
E-mail: sales@radiotelemetry.co.uk

But if D depends only on P_t and the distance, why does communication over a given distance in free space require a hundred times as much transmitted power at 100MHz as at 10MHz?

Diminishing returns

The answer is all down to the receiving antenna. Consider an ideal isotropic antenna identical to that of the transmitter - i.e. also appropriate to the frequency concerned - immersed in the field given by expression (2). It will pick up an amount of power determined by its effective area, known as its 'effective aperture'. The effective aperture A, in square metres, of an isotropic antenna suitable for operating at a frequency f MHz is given by,

$$A = \frac{\lambda^2}{4\pi} \qquad (4)$$

where $\lambda = 300/f$ metres. Since the aperture of an antenna is inherently proportional to the square of the wavelength, in any given field strength, an antenna of any type operating at half the frequency of another of that type will pick up four times as much energy.

Combining (2) and (4), for isotropic transmit and receive antennas, received power P_r is simply D multiplied by A and is given by,

$$P_r = \frac{P_t}{4\pi d^2} * \frac{\lambda^2}{4\pi} = \frac{P_t \lambda^2}{(4\pi d)^2} \qquad (5)$$

This defines the basic free-space inverse square law for range, i.e. 6dB extra loss for every octave - or doubling - of the range.

It is not possible to construct a simple antenna with an isotropic radiation pattern, so it's time to look at real antennas. There are only as few basic types, but each is capable of various developments and refinements for special purposes.

Half-wave dipole

The simplest practical antenna is the half-wave dipole. Imagine the last quarter wavelength of an open-circuited balanced transmission line opened out at right angles, to form a tee shape.

Normally, at a point one quarter of a wavelength back from an open circuit, a transmission line would look like a short circuit. But because the opened out arms radiate power, they look like a finite resistance, This turns out to be about 73Ω, so if the half-wave dipole were connected to a balanced feeder of this impedance, all of the incident power would be absorbed and radiated into space.

The absence of reflected power means that the voltage-standing-wave ratio, or VSWR, on the line would be 1:1 or unity, a perfect match for the transmitter.

As a receiving antenna, the half-wave dipole may be modelled as a 73Ω source. In accordance with the maximum-power theorem, when connected to a matched load, half the power the antenna picks up from a distant source is delivered to the load; the other half is 'dissipated' internally in the source. But the 73Ω source is the radiation resistance, which unlike a physical resistance, does not turn incident energy into heat. The half of the picked-up power not delivered to the load is re-radiated with the usual radiation pattern of a dipole, described below.

So the field distribution in the immediate vicinity of the dipole is the resultant of the incident and re-radiated fields. Note that if the centre of the dipole had been short circuited, instead of being connected to a matched feeder and load, all of the power picked up would have been re-radiated, locally modifying the field. A Yagi Antenna uses this principle to focus the power..

The current distribution of a half-wave dipole, along its length is a maximum at the centre. The shape of the distribution is a half sine wave, and the shape of voltage distribution a half cosine wave, i.e. zero at the centre and maximum - in antiphase- at each end.

With the feeder connected at a point of current maximum and voltage minimum, the impedance is much lower than the 377Ω characteristic impedance of free space. The radiation pattern, of the dipole is zero along its length. At right angles to the dipole, it is at a maximum everywhere, i.e. in three dimensions it exhibits a toroidal or 'doughnut' shape.

Since the power is concentrated mainly at right angles to the dipole, with zero radiation off the ends, the maximum field is greater than it would be for an isotropic antenna fed with the same power. As a receiving antenna, the same pattern applies - maximum sensitivity to signals from any direction at right angles to the dipole, zero sensitivity to signals arriving end-on.

The half-wave dipole antenna's effective aperture *A* is given by,

$$A = \frac{G\lambda^2}{4\pi} \qquad (5)$$

where *G* is the power gain relative to isotropic; it follows that *G* is a function of the orientation of the antenna relative to the incident field. In the maximum direction, anywhere at right angles to the dipole, *G* is 1.65.

Thus, a half wave dipole exhibits a maximum gain of 10Log(1.65) or +2.15dB relative to isotropic. Any logarithms mentioned from here on are to base 10 by the way.

Note that for a half-wave dipole, the 'figure-of-eight' cross section of the toroid is not like two circles. For an electrically short dipole - length much less than λ/2 - the cross section is circular, but such an antenna is not resonant. Even if brought to resonance by tuning out the reactance, the radiation resistance R_r is very small - often much smaller than the loss resistance R_1.

Quarter-wave whip

Probably the next most important antenna is the quarter-wave monopole or whip. To illustrate its mode of operation, consider first a dipole.

The electric and magnetic fields *E* and *H* in the vicinity of a half wave dipole are everywhere mutually orthogonal, i.e. at right angles to each other.

In time, the fields in the immediate vicinity of the antenna - the near field - are in quadrature, as noted earlier. This means that they represent stored energy as in a tuned circuit; a half-wave dipole antenna is resonant. In the far field, being in phase, they represent a flow of real power away from the antenna.

As mentioned earlier, the impedance of the dipole is 73Ω balanced. Now imagine a flat sheet of copper, of infinite extent inserted between the two halves of the dipole.

The magnetic flux lines do not cut the conducting sheet anywhere: they are completely unaffected by its presence. Likewise, the electric lines are unaffected, because they meet the sheet everywhere at right angles. Thus the antenna behaves as two separate antennas, one radiating half the energy provided into the upper half sphere, the other into the lower, as in the right hand side.

Thus a vertical whip antenna over an ideal ground plane presents an input impedance of 37Ω, and has a radiation pattern which is omni directional in the horizontal plane. the pattern in the vertical plane is a doughnut sliced in half, being simply the upper half of the pattern of the $\lambda/2$ dipole.

Since an ideal suitably matched vertical quarter-wave whip antenna radiates all the energy in the upper half sphere, it provides a maximum directional gain - in the horizontal direction - of 3dB relative to a half-wave dipole, or 5.15dB relative to isotropic.

In practice, the ground-plane is not perfect. Where this is the case, the radiation pattern does not extend down to the horizontal. The direction of maximum radiation is squinted slightly upwards..

In fact, the ground-plane is often very imperfect, being simply the rest of the transceiver, as in the case of a mobile telephone.

There are a number of other antenna that should be considered but the above will provide a good understanding of the way in which RF power is transmitted and received

Warwick Industrial Electronics Ltd
Tel: +44 (0) 1455 233616 Fax: +44 (0) 1455 233179
E-mail: sales@radiotelemetry.co.uk