Stuff You Didn't Want To Know About Antennas

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We don't know how antennas work

Claiming that we don't know how antennas work might seem to be a little strange. Hams have been using them successfully since the very beginnings of the radio art. Most any of us can figure out how to put up a dipole that will let us talk to the world. What I mean is something far more sweeping than that.

We humans, as a species, do not know how or why ham antennas work. Sure, you can point to textbooks full of information on antenna operation. You can also show volumes of equations and calculations showing how to successfully design and build antennas. James Clerk Maxwell created a whole new branch of mathematics relating electricity and magnetism clear back in 1873. A tremendous amount of work has been done in that field since then, mostly based upon his famous equations.

Don't think I am disparaging Maxwell's work. His achievement was monumental. We are still using the results of his work after more than 130 years. His work is in the same category as Sir Isaac Newton's Law of Universal Gravitation. We are still using Newton's equations to send spacecraft to Mars and beyond.

The punch line to all this is "Albert Einstein was born in 1879". Einstein's papers on the photoelectric effect, special relativity, and Brownian motion were not written until 1905. The equation "$e = mc^2$" may have changed most of the world. It didn't effect the mathematics of antennas though. Should that concern us?

If we are perfectly happy using Newton's equations to direct bombs onto terrorist's bases in Afghanistan, why shouldn't we be happy sticking with Maxwell's equations? After everything is considered, they still work don't they? Yep they do. But… We all know that Newton's equations are useful in only a limited range of applications, or at least we should know. Newton equations do not work for things like sub-atomic physics or at velocities near the speed of light. We still use them though. They may not be correct in the most absolute sense but they are simple and easy to use for our average everyday problems.

Maxwell's equations work just fine also. They are also not correct in the most absolute sense. They assume radio transmission occurs as waves in a universal fabric. Photons are simply not figured into the math. Radio signals are not waves. Antennas do not generate or absorb waves. The math still works OK but that does not mean it defines reality.

Antennas send and receive photons

"*The antenna, like the eye, is a transformation device converting electromagnetic photons into circuit currents; but, unlike the eye, the antenna can also convert energy from a circuit into photons radiated into space. In simplest terms an antenna converts photons to currents or vice versa.*" This is from Antennas, Second Edition, 1988, by John D. Kraus. Of course, that is the only reference to photons in that 900 page textbook.

What about those photons?

> *A photon is the quantum unit of electromagnetic energy equal to hf, where h = Planck's constant (6.625 X 10^{-34} Joule second) and f = frequency (Hz).*
>
> *1 Watt = 1 Joule/second*
>
> *1 Watt @ 1 MHz = 1.51 X 10^{27} photons per second*

And how does that relate to our ham operation? When WB0EIL is calling a DX station on 20 meters at 1KW output, he is generating about 1 X 10^{29} photons per second. Since the energy a photon carries is proportional to its frequency, it takes only about one tenth as many to carry the same power on 2 meters (144 MHz) as 20 meters (14 MHz). Even with that difference, when KC0VOB is transmitting on his new handie talkie at 5 watts, he is still generating 5 X 10^{25} photons per second. That is still a VERY big number of photons.

Our radio operation generates so many photons that it is easy to see why most folks prefer to pretend we are transmitting radio waves. The mathematics used by radio engineers treat radio signals as waves. The problem, though, is that people forget that they are only pretending.

Electrons don't move (far)

Even more curious than the photon versus wave question is our concept of current flow in antenna conductors. Discussions of electric current in wires usually present us with a mental image of electrons zooming back and forth. That is probably not an accurate picture of the real world.

First off, lets talk about copper wire. Copper is fairly dense as materials go. There are about 8.46 X 10^{22} atoms in a cubic centimeter of copper. That's a big number. Jumping through a few mathematical hoops involving fermi energy levels and electron charges, it works out that 1 Ampere of current in number 12 wire produces a theoretical average electron movement of about 0.2 millimeters per second.

Of course, our RF current switches back and forth at a rapid rate. A theoretical 0.2 millimeters per second electron drift rate would have to be divided by the RF frequency. At 1 MHz, there would be only 0.5 microsecond for an electron to move before it had to start back in the opposite direction. This, of course, means that electrons in antennas could not move very far at all.

What does actually move when an electric current is flowing? When we close a switch, current sure seems to travel down a wire at nearly the speed of light. As we just saw, electrons are not moving any where near fast enough. What moves, of course is charges. Electrons merely nudge each other to pass the charge along.

Now the real interesting point about electric current flow is that we don't really know how many, if any, electrons actually move in a conductor when a current is flowing. Yep, that's right. Some theories assume electrons move freely from atom to atom. Others assume that the number of electrons available to support electric is much more limited and those that do move could be moving at rates approaching tens of meters per second, which is still very slow compared to charge flow rate. Still other theories claim the electrons do not move at all from atom to atom. Charges could be transmitted along a conductor by photon exchange between electrons.

At first blush, the idea that electrons inside a copper wire are shooting photons at each other sounds absurd. It's not so strange once you get used to the idea. First off, electrons are assumed to be gyrating around the nucleus of an atom at about a third to half the speed of light. Experiments have shown that electrons in an atom tend to prefer specific energy levels. If an outside force raises the energy level of an atom's electron, that electron will give off a burst of energy to drop back down to its preferred energy level. The burst is released as a photon. One common external force applied to electrons is photon absorption. The photon's energy produces additional kinetic energy for the electron. Thus electrons could be passing charges along a wire as a contained stream of photons. Consider the number of photons needed to transmit any significant power along a wire. The number is staggering. I won't even bother to calculate it.

But wait! There's more!

Don't forget that what we are doing with our antennas is generating photons. That copper wire (or any other conductor for that matter) can produce staggeringly large numbers of photons should not be unfamiliar. We can talk around the world with those photons. We often generate a kilowatt or more power worth of them to do it. Production of radio frequency photons may simply be a small leakage caused by a weak, synchronizing effect of our applied RF current.

Photons don't bounce

OK, this is simple. Photons don't bounce. They can be generated. They can be absorbed. Their trajectories can even be bent a little by gravity but they don't bounce. This is probably one of the harder concepts to wrap your brain around. We are familiar with how radio signals "bounce" off mountains, building, and other stuff. This is demonstrable fact. Therefore, photons do bounce, don't they?

The actual mechanism that causes radio signals to reflect is not a bounce in the way that that a tennis ball bounces off a wall. The coherent stream of RF photons from a transmitter striking a reflecting physical object is absorbed. That stream produces an RF current in the object. That RF current in turn generates new photons and sends them on their way. The direction that these new photons are sent depends upon the electrostatic and electromagnetic fields produced in the reflecting object and nicely meets our expectation for "reflection"… some of the time.

When a stream of RF photons encounters dirt, several things happen. First, dirt is not a perfect conductor. The photons penetrate into the soil and are absorbed over a range of depths. Currents induced by photon absorption are partially dissipated in the soil's bulk resistance. Second, the soil typically has a dielectric constant that causes a phase shift in the RF current as compared with what would be found in a perfect conductor. Calculating exact ground reflections can be a complex process.

One of the curious side effects of the way photons interact with dirt is the difference in how vertically and horizontally polarized signals are reflected a low angles to the horizon. Low angle reflection of horizontally polarized signals is very efficient and close to what might be expected from a perfect reflector. Low angle reflection of vertically polarized signals is quite different. The phase shift with low angle vertically polarized signals in dirt is such that it will partially cancel a direct path signal. That means that low angle radiation from vertical antennas is very poor without highly conductive ground screens under them.

Antennas are not reciprocal devices

Another concept that is often glossed over is that antennas are not reciprocal devices. The difference is easily shown when half-wave dipoles are considered. Consider two situations. The first is applying 100 watts of 20 meter RF to a 20-meter half wave dipole. The second is applying 100 watts of 2 meter RF to a 2-meter half wave dipole. Both produce the same amount of RF radiation with the same spatial distribution. Now consider those same antennas for receiving. They definitely do not perform the same.

The difference for receiving is that the two antennas are different sizes. Smaller antennas can't intercept as many RF photons as larger antennas. The 20-meter dipole collects about 10 times as much energy as the 2-meter dipole when exposed to the same energy density. Don't confuse this with antenna gain.

Antenna gain is the same for both transmit and receive. Transmit gain is achieved by concentrating more of its photon radiation in one direction than others. The same number of photons is generated each second but more of them are headed in a favored direction. For receive, the mechanisms that focus photons in one direction over another incidentally improves the ability of that antenna to absorb photons from that favored direction. Sensitivity to photons from other direction is likewise reduced.

For receiving, it all comes down to capture area. How much of the transmitted photon beam is collected determines how much RF current can be fed to a receiver. Smaller antennas have smaller capture areas thus HF antennas collect more HF energy than VHF antennas collect VHF energy given the same transmit power and distance.

The Engineering Approximation Fallacy

Mathematics used by engineers is full of approximations. Exact calculations of physical processes and are often very complex, involving obscure and often difficult to quantify factors. The formula we use for the length of a resonant half wave dipole antenna is:

Length (feet) = 468 / Frequency (MHz)

That formula gets us close enough for practical use. Exact calculations are possible of course they involve complex calculus equations and exact knowledge of things like the conductivity and dielectric constant of the soil under the antenna, the exact diameter and alloy of the antenna conductor, and the dielectric constant and thickness of any insulation. Of course there is the effect of other physical objects within a few wavelengths of the antenna in question. *468/F* is much easier.

The Engineering Approximation Fallacy is attempting to describe a physical process as if our simplified mathematical models are reality. For example, a half wavelength in free space is calculated as approximately *492/F*. A resonant dipole is approximately *468/F* long. Some authors describe the difference between them as "End Effect" shortening. The claim the loop of wire through the end insulator increases antenna capacitance thus lowering the resonant frequency of the antenna. The reality is that the resonant length of the dipole is determined by the velocity of charge propagation along the antenna conductor. That is a function of the metal alloy, the conductor configuration, and the effect of currents induced in surrounding soil and structures. It is always less than the speed of light.

Why do we care about this? Without realizing that our model of radio transmission as waves is merely a convenient approximation, people can come up with some really silly ideas about antenna design. Photons are generated by electrons that are subjected to some form of physical acceleration. In radio this acceleration is the result of radio frequency currents in antenna conductors. **The number of photons produced depends upon the length of the conductor in wavelengths and magnitude of the current.** Short antennas require higher currents to radiate the same RF power.

Another example would be the concept of forward and reflected power in a transmission line. This is a very useful concept that works well in many situations. It is relatively straightforward to build measuring instruments calibrated in forward and reflected power levels. We adjust our antennas or antenna tuners to minimize reflected power and get maximum power transfer to our antennas. The problem created is that some folks don't realize that its all 'make believe.' Forward and reflected power values are simply a convenient engineering approximation.

The Engineering Approximation Fallacy in this case leads people to believe that reflected power is a real quantity that must be dissipated somewhere. They claim that reflect power must be absorbed by a transmitter's output stage thus adding heat that must be dissipated. What is actually reflected back to the transmitter is impedance, not power. Retuning the transmitter to deliver its power to the mismatched transmission line allows all of the transmitters power to be sent to the antenna via the feedline, minus whatever transmission line losses are involved. There is no reflected power to dissipate.

Conclusion

So there you have it. Almost everything you didn't want to know about antennas. Its all true but it probably doesn't matter. Just as for using Newton's laws to send a rocket to Mars, using Maxwell's approximations of reality will probably suffice for antenna designs. Knowing the precise subatomic operation of antennas someday will probably not help us design better antennas. Though, one would hope that it might help us recognize bogus antenna design claims.