How it all started — 1

In this, the first article in a new series, we see that radio and TV transmissions, or to use their proper name "electromagnetic radiation", all consist of travelling associated electric and magnetic fields. We also learn more about this radiation, and the way it behaves.

by BRYAN MAHER

According to legend, the first recorded account of communication by electromagnetic radiation comes from accounts of the Roman Army. It seems that a certain Roman Centurian, Glutius Maximus (not his real name) spent all night leading his scouting platoon deep into enemy territory, to provide his General with instant information on the enemy's movements.

Using his brightly polished bronze shield, from his position on a hilltop he reflected the morning rising sunlight straight back to his General and the main army. By a series of pre-arranged codes of flashes he gave complete information on the enemy's movements, leading to the Roman army conquest of Hispaniola in 133 BC.

And why is this of interest to we radio and electronics bods? Because sunlight and radio waves are but two forms of the same thing — electromagnetic radiation. The only differences between them are their frequencies, wavelengths and energy levels. You don't have to be a technofreak to see the inherent beauty in nature's design!

The complete spectrum of electromagnetic radiation frequencies is like an enormous extended rainbow, extending from sub-audio frequencies around 3Hz (wavelength = 100000km) to the highest frequencies known for Gamma rays, above 10^{22}Hz (10 million million gigahertz), with wavelengths less than a billionth of a metre. All are fundamentally the same electromagnetic radiation.

Many natural and man-made kinds of radiation use various groups of frequencies. Some of the most important are named in the left column of Table 1, our Electromagnetic Spectrum table. For every frequency there corresponds a wavelength and a level of energy of the fundamental "bundle" of radiant energy, the *photon*. (For an explanation of those last few terms, read on . . .)

For your convenience in this table, many frequencies are expressed twice — first in Hertz (written Hz), kHz, MHz or GHz, then secondly in exponent or "scientific" notation. Similarly wavelengths are written first in km, m, mm, microns (i.e. micro-metres) and nm (i.e. nanometres).

The multiples of frequency used are:

kilohertz
(abbreviated kHz) = 1000Hz
Megahertz
(abbreviated MHz) = 1,000,000Hz
Gigahertz
(abbreviated GHz) = 1,000,000,000Hz

For years the radio frequencies were named in hazy groups, but nowadays we use the frequency groupings defined by the Societe Internationale (responsible for the SI units). These are:

Very Low Frequencies (VLF): 3kHz — 30kHz, capable of long range but needing very long wire transmitting antennae. Can penetrate slightly through the surface of the ocean, and down into caves.

Low Frequencies (LF): 30kHz — 300kHz, used where long wire antennae are possible, as on ships.

Medium Frequencies (MF): 300kHz — 3MHz, including the Broadcast Band for local commercial stations. Work well with short antennae over medium distances.

High Frequencies (HF): 3MHz — 30MHz, pioneered by radio amateurs for long distance international communication, even using low power.

Very High Frequencies (VHF): 30MHz — 300MHz, including long range mobile communications, FM broadcasting and our original VHF television system. Propagation characteristics vary greatly over this frequency range. The high frequency end needs high power unless "line-of-sight" path is possible.

Ultra High Frequencies (UHF): 300MHz — 3GHz, including the UHF television stations, early spacecraft and short range mobile communications and radar. Requires "line-of-sight" path. Also includes microwave cooking at 2450MHz, as water molecules will absorb this photon energy level.

Super High Frequencies (SHF): 3GHz — 30GHz, including modern spacecraft communications, radar and some amateur experimental bands.

Extra High Frequencies (EHF): 30GHz — 300GHz, bordering on the low end of infra-red heat rays. This band includes radar, amateur and other experimental transmissions.

Perhaps you wonder about radiation of radio and any other electromagnetic signals — just what is being radiated? Also how does radiation of power into the air from a wire occur?

The first answer is that it is an alternating electric field, together with an associated alternating magnetic field which is being radiated.

Before you ask "how?" you probably ask "Just what are these things called "fields?"

Electric fields

Everyone knows some basic facts about electric fields, even far back in history. Thales of Miletius in 600 BC was experimenting with the electrostatic attraction exhibited by a piece of rubbed amber. Indeed our word "electron" is simply the Greek word for "amber". You have perhaps rubbed a plastic comb and found it then attracts bits of dust and paper. Or you got electric shocks after walking across a dry carpet, or after sliding out of a car.

A precise definition of the electric field is just:

An electric field is any region of space in which a stationary or moving charge or charged object experiences a force, but uncharged objects do not.

So far so good!

Magnetic fields

Now everyone knows the attractive properties of magnets; they are nothing new. Even as far back in history as the era of the captivity of the Israelite nation and their exile by the Rivers of Babylon in 587 BC, at the other end of the Euphrates River in the district of Magnesia in Turkey, the Greeks were conducting magnetic experiments, using pieces of magnetic iron ore from the very much older iron ore quarries. It is from the "Magnesia district" that we get our word "magnet".

Jumping over 2400 years of history to Denmark, Hans Christian Oersted found the magnetic effect of an electric current flowing in a wire, and William Sturgeon in England in 1825 increased the effect by winding the wire into a coil.

William Cook with Charles Wheatstone in England, and Karl Frederich Gauss of Gottingen in Germany separately invented wired telegraph machines, anticipating Samuel Morse. Gauss, always a mathematician, commenced formulating the mathematical theory of magnetism in the early 1800's. Before SI units were in use, magnetic field strength was measured in terms of the unit "gauss", a fitting memorial to that eminent genius. You may still find this (now-outdated) unit used in some loudspeaker data sheets.

These studies and the motor experiments of Michael Faraday in England around 1831 led the Scotsman James Clerk Maxwell in 1864 to devise an exact mathematical representation of the alternating electric and magnetic fields which Faraday had proposed.

In contrast with an electric field, we define a magnetic field as:

A magnetic field is any region of space wherein a moving electric charge or charged body experiences a force, but a stationary charge or uncharged body does not.

COMMON NAME OF RADIATION	FREQUENCY : HZ	WAVELENGTH : METRES	ENERGY OF ONE PHOTON eV
GAMMA RAYS	3.0E+22	0.00001nm 1.0E-14	123960000
	3.0E+21	0.0001nm 1.0E-13	12396000
HARD X RAYS	3.0E+20	0.001nm 1.0E-12	1239600
	3.0E+19	0.01nm 1.0E-11	123960
X RAYS	3.0E+18	0.1nm 1.0E-10	12396
SOFT X RAYS	3.0E+17	1.0nm 1.0E-9	1239.6
	3.0E+16	10 nm 1.0E-8	123.96
ULTRA VIOLET	3.0E+15 7.5E+14	100nm 1.0E-7 400nm 4.0E-7	12.396
VISIBLE LIGHT VIOLET	7.14E+14	420 nm	2.94
BLUE	6.52E+14	460 nm	2.68
GREEN	5.36E+14	560 nm	2.20
YELLOW	5.09E+14	589 nm & 589.6 nm	2.09
ORANGE	4.76E+14	630 nm	1.96
RED	4.13E+14	725 nm	1.70
	3.0E+14	1 micron 1.0E-6	1.2396
INFRA RED	3.0E+13	10 micron 1.0E-5	0.12396
	3000GHz 3.0E+12	100 micron 1.0E-4	0.012396
	300 GHz 3.0E+11	1 mm 1.0E-3	0.0012396
RADAR EHF	30 GHz 3.0E+10	10 mm 1.0E-2	0.000124
SHF	3 GHz 3.0E+9	100 mm 1.0E-1	0.0000124
microwave oven-----	2450 MHz --------	122.4 mm -------	0.00001
UHF TV 520-820 MHz UHF	300 MHz 3.0E+8	1 m 1.0E+0	1.24E-6
VHF TV 45-230 MHz VHF	30 MHz 3.0E+7	10 m 1.0E+1	1.24E-7
OVERSEAS RADIO 3 MHz-30 MHz HF	3 MHz 3.0E+6	100 m 1.0E+2	1.24E-8
BROADCAST RADIO 535 kHz to 1606.5 kHz MF	300 kHz 3.0E+5	1 km 1.0E+3	1.24E-9
NAVAL & MARITIME RADIO LF	30 kHz 3.0E+4	10 km 1.0E+4	1.24E-10
AUDIO FREQUENCIES 20 Hz to 20 kHz VLF	3 kHz 3.0E+3	100 km 1.0E+5	1.24E-11
	300 Hz 3.0E+2	1000 km 1.0E+6	1.24E-12
(power mains----	50Hz -------------	6000 km	
	30Hz 3.0E+1	10 000km 1.0E+7	1.24E-13
SUB AUDIO	3 Hz 3.0E+0	100 000km 1.0E+8	1.24E-14

TABLE 1: An overall look at the electromagnetic spectrum — all the way from sub audio up to gamma rays. Note the use of scientific notation: 3.OE+6 means 3.0 times 10^6, and so on.

Electro magnetic radiation

In one giant step forward for mankind, Maxwell alone used his theory to predict that alternating electric and magnetic fields would act in association, to produce a radiant energy which would propagate through the air or space in the form of waves, travelling at the speed of light.

Maxwell said that the propagation would consist of the electric field and the magnetic field at right angles to each other, and both of them at right angles to the direction of propagation through the air.

Furthermore both fields would be "in-phase" with each other, meaning that their amplitude or strength would rise and fall each cycle, but both would rise at the same time, and both fall at the same time.

Basics of Radio Transmission

Where the electromagnetic radiation originates from a straight conductor (i.e., a transmitting antenna) the alternating electric field is physically aligned in space in the direction of that straight conductor. We call this direction the "direction of polarisation" of the radiation.

If for example the transmitting antenna wire is mounted vertically, we would say the electromagnetic radiation is "vertically polarised". In that case the alternating magnetic field would exist horizontally in space, at right angles to the horizontal direction of propagation.

Furthermore Maxwell proposed that light itself is one form of this radiant energy, so light consists of travelling associated electric and magnetic fields.

Some scientists disputed Maxwell's theories, especially the claim that light and all radiant energy can travel through a vacuum, requires no medium for its propagation and can produce effects at a distance. These arguments raged for many years.

The first radio transmitter

It remained for Heinrich Rudolph Hertz of Germany to experimentally validate Maxwell's theoretical predictions, by constructing in 1887 the very first radio transmitter. Using inductance, capacitance, an electric spark and lots of power, Hertz generated VHF radio waves at a base frequency of around 50MHz. These he transmitted through the air across his laboratory to a very simple "receiver" consisting of a wire loop and spark-gap current indicator.

The age of Radio had begun.

Hertz demonstrated that his waves obeyed the laws of straight line propagation and absorption. Cleverly blocking his transmission by a wall between transmitter and receiver, he showed how a horizontal sheet of metal high overhead above the wall could be used to reflect the signals back down to the receiver. Thus showing that his radio waves did in fact obey all known laws of optics, he convinced the world that radio waves and light are one and the same thing, differing only in frequency and wavelength.

Scientists then believed they had a theoretical explanation for everything, that no new theories would ever be needed, and it only remained to refine their measurements. But how false such complacency proved to be!

An unexplainable observation

The world turned over when later experiments with a simple vacuum tube photo diode upset their applecart completely, showing effects unexplainable by the current theories that light and radio were simple waves.

The vacuum photo diode or "photocell" is just a wire anode and a cold cathode of sensitive material such as zinc, caesium or their compounds, all mounted inside an evacuated glass or quartz envelope. (It was the forerunner of our modern semiconductor photodiodes.)

It was found that with a suitable bias voltage applied, light of a certain colour shining on the cathode caused electrons to be emitted from the cathode, to be collected by the anode. These electrons could then be measured as an electric current flowing in an external circuit.

Light of colour higher up on the frequency scale in the electromagnetic spectrum also caused the same effect, but light below some critical colour would not produce any electron emission at all, even if the light intensity was increased. It became clear that there is a threshold light frequency for this effect. The same idea of a minimum frequency (i.e., colour) of light is a requirement today for semiconductor photo diodes, photo transistors, photo thyristors and solar cells.

No one could explain all these goings-on using the current theories of that day.

It required the genius of Albert Einstein, then an unknown humble clerk in a German patent office, to devise a radical, way-out, brand new theory of radio waves and light.

He theorised that light, and hence all radio waves too, could be viewed as bundles of energy, the energy level of each bundle or *quantum* being proportional to its frequency, and nothing to do with its intensity or strength.

Thus was born the quantum theory of everything.

Energy level

As a result, our table of the electromagnetic spectrum is also a quantum energy table. Calling one "quantum" or "energy bundle" by the name "photon", the right hand column shows the energy level corresponding to each frequency in units of electron-volts (eV).

By definition, one electron volt is the energy possessed by one electron when it has been accelerated through an electric field of one volt.

When you study colour television you will find this quantum idea of light vital to the choice of material for the photocathode of TV camera tubes, and related to the screen material chosen for the TV receiver picture tube.

Also the idea of "quantized colour energy" comes into the colours obtainable from LEDs (light emitting diodes), and rules the colour sensitivity of everything from photo isolator-couplers to photo-multipliers to solar cells. Yet again, amongst the "microwave" or gigahertz radio frequencies, the energy level of each quantum of radio energy decides the wavelength and frequency chosen for your microwave oven.

Quantum energy considerations also predict how dangerous it is for you to stand in front of a radar transmitting dish antenna.

Note that the quantum energy level of a radio or light transmission is just the energy of each photon or "fundamental bundle" of transmitted energy. The quantum energy level for each transmission is decided only by the frequency:

Quantum energy $E = hf$

where E is the energy of each quantum in joules (or eV if converted), f is the frequency of the transmission in Hz and h is a universal constant, called Planck's Constant and equal to 6.625×10^{-34} joule seconds.

The *total energy* of any radio or light transmission is simply the product of the energy of each quantum, multiplied by the total number of quanta.

Wavelength

Now we define this term "wavelength":

The wavelength of any travelling wave is the distance travelled by the wave in the time of one period.

Or in other words,

Wavelength (in metres) = propagation velocity x period

and

Wavelength (in metres) = propagation velocity/frequency

This is why, in our table of the electromagnetic spectrum, you can observe that large frequencies correspond to small wavelengths, and vice-versa.

You are probably bursting with objections by now, gasping something like "Well, is a radio transmission or light a wave or is it not?" or "We have been hearing about 'bundles of energy', which don't sound very wavelike!"

The not-so-simple answer is that it is both! Perhaps this is a bit hard to swallow at first, but that point will become clearer in later episodes. As the man says, "Trust me!"

Propagation velocity

All electromagnetic radiation travels through a vacuum at the speed of light, which is approximately 300 million metres per second. This velocity is a natural constant, known by the symbol "c".

If you want that more precisely, it is

c = 299,792,900 (+/-800) metres per second

in vacuum, only slightly slower in air, and slower still through transparent solids. "Transparent" in the radio sense means any material, such as a brick wall, through which radio transmission will pass.

Radio signal propagation slows down to about 2/3 of the above value if travelling in a coaxial cable, or about 4/5 if travelling in an open wire balanced pair of conductors such as open wire TV down lead cable. The exact value of those fractions depends on the details of each cable construction, tending to be faster for cables having more air and less solid material between the conductors.

That is all very nice but just how and why does energy radiate from a wire?

Later on, we will deal with antenna theory in some detail, but basically this is what happens: When an alternating current generator at low frequency is connected to a wire which is connected to nothing at the far end (i.e., an open circuit end), energy travels out from the generator to the far end of the wire at nearly the speed of light. Call this the forward flow of energy.

On arrival at the open circuited far end of the wire, having nowhere to go from there the energy flow turns around and travels back along the wire, back to the generator. We say the energy is reflected back from the open end. Call this the return flow of energy.

For low frequencies such as the 50Hz power line, that's about all that happens. The generator sees the line as an extremely high impedance capacitive load, consuming no power. (Actually a microscopically small amount of energy does radiate from the wire.)

But possibilities are very different if the generator frequency is higher (and hence the wavelength shorter). Where the length of the wire is of the same order as the wavelength, some energy can radiate from the wire in a direction at right angles to the wire.

This is the electro-magnetic radiation. The art of designing radio transmitting antennae is to have as much energy as possible radiated from the wire, and almost none returned back to the high frequency generator. This means the transmitting antenna looks like a power load driven by the high frequency generator.

Many and varied are the types of transmitting antennae used. Their design is a wide ranging science, a glimpse of which we will see at a later date. The high frequency generator used is called the "Transmitter". It would usually be a transistor circuit of some type, or if either the frequency or the power level (or both) were very high we would expect to see one or more vacuum tubes (valves) included. The design of transmitters is a very complex art, a little of which will again keep us entertained in later episodes.

Next month we will look at those electromagnetic waves again, in some detail.