High Dielectric Antennas

White Paper

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Integrated Antenna and RF Solutions

SUMMARY

In recent years a new type of antenna technology has emerged that is based on research into radiating high dielectric materials that was carried out by two universities; Sheffield in the UK and Griffith in Australia. Dielectrics are insulating materials and they might seem unlikely materials out of which to make antennas, but if they are excited in the right way they can be made to radiate very efficiently.

Antenova has extended the range and types of dielectric antennas and has given the name High Dielectric Antenna (HDA®) to this new technology area. HDAs provide improvements to the performance, and sometimes to the functionality, of modern communications systems.

Antenova's dielectric antennas feature:

- A range of dielectric antenna technologies
- Good isolation between similar antennas
- Resistance to detuning by nearby objects
- Good radiation efficiency
- Flexible bandwidth
- Compact size
- Directionality possible
- Multi-band capability
- Diversity and MIMO systems available
- Surface mount technology

These advantages arise from the use, sometimes in combination, of several different high dielectric antenna technologies.

High Dielectric Antennas have the potential to become important components in the next generation of high-performance communication systems, especially when multiple antennas are needed in an electrically small space.

Current applications include:

- Mobile phone handsets
- PDAs
- Laptops and PCMCIA cards

Many more applications are possible. The Antenova research team has been simulating, building and testing antennas since March l998. Thousands of antennas have been simulated, built and tested by our research and development teams in Cambridge. Many different HDA types and geometries have been explored. As a result of this R&D activity, 35 patents have been filed, 5 have been granted and more patent applications will be filed in the near future.

A BRIEF HISTORY OF DIELECTRIC ANTENNAS

Dielectric antennas have been around a long time. A successful early type was the polyrod, designed at Bell Labs by Dr. George Mueller and his team and first used in anger during WWII, see figure 1. At the same time, in Japan, Dr. Hidetsugu Yagi also worked on a dielectric antenna design, except that his project was to create an antenna that could be raised and lowered with a submarine periscope and did not de-tune with different heights above the salt water. Resistance to de-tuning is a further important aspect of dielectric antenna technology.

Figure 1 Bell Labs X-band "Mark 8" surface fire control radar, using an array of 42 polyrod antennas.
This picture was taken from the www.vectorsite.net website.

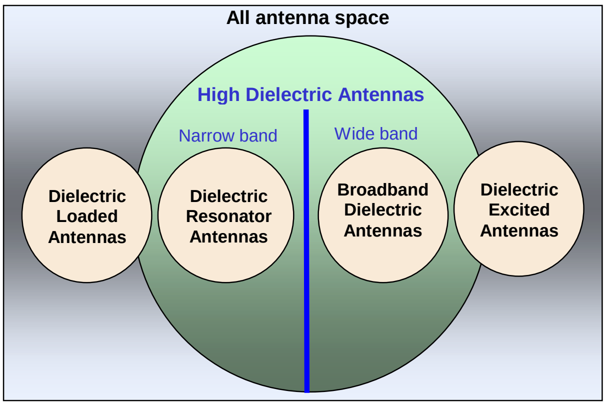

Figure 2. A Venn diagram representation of High Dielectric Antenna technology.

In fact the term ‘dielectric antennas’ encompasses several different types of technology and Antenova has used the term High Dielectric Antenna [HDA®] to describe the whole technology field. Figure 2 shows a Venn diagram representation of HDA technology. Perhaps the best-known type of dielectric antenna is the dielectrically loaded antenna. Here the primary radiating component is a conducting element and the dielectric just modifies the medium, so this antenna type only just intersects the HDA™ circle. The effect of the dielectric is often to reduce the bandwidth. However, dielectric loading of an antenna can impart important performance advantages, particularly a reduction in size and an improved resistance to detuning.

In the 1980’s a new type of dielectric antenna evolved known as the Dielectric Resonator Antenna or DRA[1,2]. In this type of antenna the radiating mechanism is a displacement current circulating in a dielectric medium, usually a ceramic pellet, so this antenna lies inside the Venn diagram of dielectric antenna space. The stored energy inside the dielectric is extremely high and it is difficult for external objects or for other antennas to disturb the resonance and de-tune the device. The use of readily available materials allows the achievement of very low dielectric losses in this type of antenna and so the efficiency is high, the main losses being ohmic and occurring in the feed mechanism and the groundplane currents. Because DRAs tend to have classical and well-matched resonances, they are characterised by excellent return losses, but have quite restricted bandwidths.

DRAs have a well-resolved resonance because of the groundplane beneath them. Antenova has discovered that if this groundplane area is reduced, the bandwidth of the antenna increases significantly, albeit at the expense of a worse return loss and a somewhat greater susceptibility to de-tuning (although still generally better than conducting antennas because the internal stored energy remains high). To distinguish this new type of antenna from DRAs we have called them Broadband Dielectric Antennas (BDAs). Like DRAs, the radiating mechanism of BDAs is primarily displacement current although radiation from the feed structure and even the edge of the groundplane can be present as well. Figure 3 shows how the same ceramic pellet can be configured to be a DRA with a bandwidth of 4.5% or a BDA with a bandwidth of greater than 33%, as measured at the –10 dB return loss level.

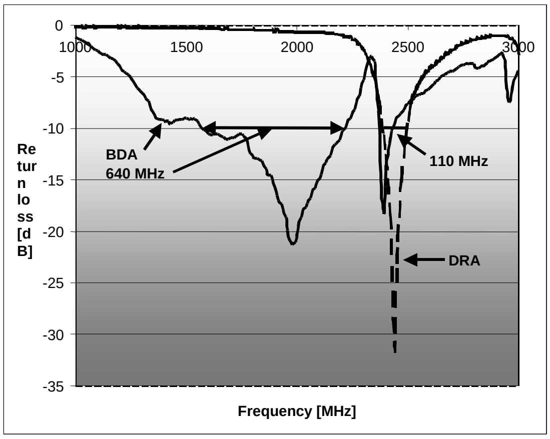

Figure 3. Comparison of a ceramic pellet used as a DRA (dotted line) or a BDA (solid line). The BDA has a bandwidth 7.5 times greater than the DRA.

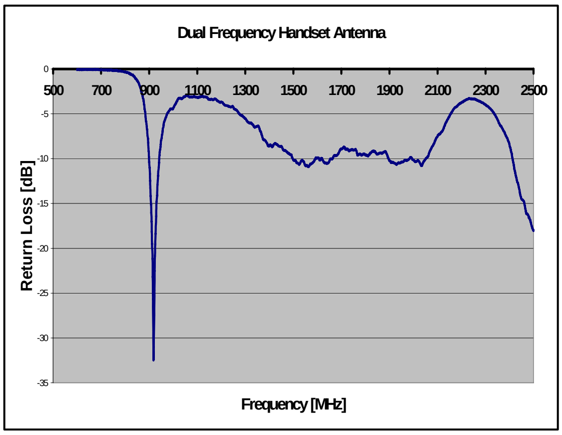

Figure 4 Return loss for a hybrid dielectric and parasitic PILA antenna combination

The last category of dielectric antennas (again discovered by Antenova) involves parasitic antennas with no feeds of their own. It has been known for many years that DRAs can excite other DRAs[3,4] but only recently have various types of dielectric antenna been used to excite parasitic copper antennas or vice versa. We have called this class of antenna the dielectrically excited antenna (DEA). With DEAs, it is often the conductor that forms the major radiating part of the antenna and so they lie on the edge of the Venn diagram shown in figure 2, much as dielectrically loaded antennas do. There are bandwidth advantages in this dielectric-conductor hybrid approach. For example, if a parasitic copper PILA is excited by the BDA used to produce the results shown in figure 3 then the return loss shown in figure 4 is obtained. The lower resonance near 900 MHz comes from the parasitic PILA and the upper wideband resonance comes from the ceramic pellet. This technology formed the basis of early Antenova triband+WCDMA antenna designs.

DIELECTRIC MATERIALS

Conductors are materials whose outer orbit, or valence band, is either only partially filled with electrons or the forbidden band between this and the next conduction band is so small that electrons can be easily liberated. Electrons are then free to migrate through the structure and give rise to conduction. In contrast, dielectrics are materials composed of atoms whose valence band is completely filled with electrons and the energy gap of the forbidden band is so large that free electrons do not normally exist. This means that these materials will not conduct a direct current and they can be regarded as insulators.

Until recently antennas were always made from conducting materials such as copper. It seems almost counter-intuitive to try to design an antenna from an insulating material, but in fact at radio frequencies these materials will support a radiating displacement current. R. D. Richtmyer at Stanford University showed this as early as 1939 in a theoretical paper[5] and it was J. C. Maxwell himself who added the displacement current term to the equations that now bear his name. Obviously a displacement current cannot be a flow of free charge and it is actually caused by a displacement of the electrons about their mean position in the lattice structure. This is similar to the way another dielectric device, the capacitor, will not conduct DC but will pass radio frequencies.

The basic requirement of a dielectric for use in these novel antenna designs is to have a high relative permittivity, but two other important characteristics are required before they can be used. Firstly, they need to be a high-Q material (i.e. low dielectric loss) and secondly the temperature coefficient of the dielectric constant must be low to avoid the antenna de-tuning over wide temperature changes. Fortunately, the dielectric resonator filter industry has been demanding high performance microwave dielectrics for many years and the materials developed are generally suitable for antenna applications. We will now take a short look at these three properties in a little more detail.

Dielectric constant: The most important property of a radio frequency electro-ceramic material is the dielectric constant, which needs to be higher than most conventional materials that surround us. In fact, the absolute values of dielectric constants are very small and it is much easier to compare the dielectric constant of the ceramic with that of a vacuum by using a parameter known as the “relative permittivity ε_r” of the material. Permittivity is the ratio of the electric displacement in a medium to that which would be produced by the same field in free space.

DRAs are volumetric devices, the dimensions of which are smaller than conventional antenna sizes by a factor related to $1/\sqrt{\varepsilon_r}$ because this factor represents how much smaller the radio wavelength is inside the dielectric. In order to reduce the size of a dielectric resonator, it is necessary to increase the permittivity of the material used although this will generally reduce the bandwidth and so a balancing act has to be performed when designing small antennas.

Q and loss: The performance of dielectric materials is usually specified by the quality factor (Q), which is inversely proportional to the loss. The unloaded Q (when the material is not radiating) should be as high as possible, certainly exceeding 1000. Materials with lower Q values do not resonate as well, nor do they make highly efficient antennas. Connected to a radio transmitter, for example, a low Q material will accept power but will radiate only a percentage of it into space, the rest being lost as heat. In many ceramics, high Q is generally associated with a high density of the material; consequently the porosity and fabrication techniques must be closely controlled to achieve good results.

The loaded Q of the dielectric, when it acts as an antenna, is measured in free space and it is determined by losses (loading) due to radiation, conduction and dielectric losses. The efficiency and loaded Q of dielectric antennas can be assessed by a number of techniques including the Wheeler’s cap method[6]. In fact the measurement of the efficiency of small antennas turns out to be a difficult task technically. Often the cables and other parts of the measurement system are significantly larger than the antenna under test. Antenova has put a lot of effort into developing calibrated anechoic chambers and efficiency measuring systems.

Temperature coefficient: A change in dielectric constant and/or physical size with temperature will cause the resonant frequency of a dielectric antenna to drift away from the desired frequency. As some types of dielectric antenna, e.g. DRAs, have bandwidths that are quite narrow, ~5%, this could potentially be a serious problem. Ideally, the temperature coefficient should be zero, but with careful design, values up to nearly a hundred parts per million can be tolerated. Several excellent modern ceramics have temperature coefficients of less than 10 parts per million and are near ideal for use with DRAs and all types of dielectric antennas.
It is now generally accepted that high-quality, low-cost ceramic materials are commercially available for radio applications and Antenova has found these to be suitable for large scale manufacturing of antennas.

THE IMPACT OF DIELECTRICS ON ANTENNA DESIGN

Introducing dielectrics into the design of antennas brings a number of advantages:

- Nearly every type of HDA is a volume device such that any change of volume in the dielectric will result in a change of resonant frequency. Volume antennas offer the designer more degrees of freedom that 2-D patches or 1-D dipole type antennas.
- HDAs can be made to work with a wide range of impedances and feed mechanisms.
- HDAs are usually smaller than conventional antennas because of the $1/\sqrt{\varepsilon_r}$ factor
- The stored energy in a dielectric antenna is proportional to both the **E**-field and ε_r. The **E**-field is generally high because it is concentrated in a smaller antenna and ε_r is chosen to be high. For these reasons, the stored energy is high and the antennas are less susceptible to their surroundings, leading to low detuning and low isolation between closely spaced antennas. This is useful for WLAN diversity and MIMO applications.
- Some degree of diversity can also be obtained from a single antenna by using multiple feeds to either steer a beam or a null in the radiation pattern.

- The high unloaded Q of modern radio frequency ceramic materials means that dielectric losses are low and this reduces the overall losses (the remaining losses being in the feed network and currents flowing in the ground plane).
- Most designs can be manufactured to be surface mountable and ceramic pellets can be simply soldered on in a reflow oven like many other components such as capacitors. This, combined with the toughness of modern ceramics, leads to a very robust technology.

All these advantages give the designer greater freedom to meet customer requirements.

MEETING TODAY'S ANTENNA NEEDS

Whenever a problem can be solved using a simple printed or stamped-metal antenna, then this probably represents the lowest cost and therefore the most desirable solution. However, when there is a need for several antennas to work in an electrically small space, for antennas that do not easily detune, or when high isolation is required between antennas for radio systems that are operating on the same frequency but with different protocols, then dielectric antennas are often the best solution. Some examples are given below. The coupling between closely spaced antennas has components produced by the radiating fields of both antennas (which is inevitable if the antennas are to radiate) and also by local fields, which only represent stored energy. In HDAs this local field is largely contained within the dielectric, so as their spacing is reduced the coupling between these antennas rises less quickly than for conventional antennas.

Antenna diversity is often required in an electrically small space, such as at the end of a PCMCIA card projecting beyond the case of a laptop computer. These antennas might be used for WLAN and Bluetooth^{TM} applications (see figure 5), or for a WCDMA connection (see figure 6).

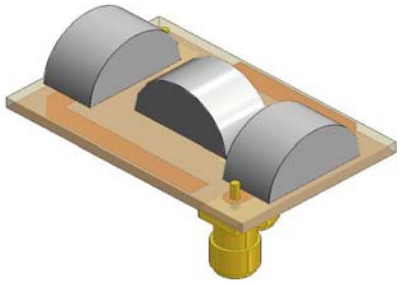

Figure 5. Two orthogonal WLAN antennas for diversity and one Bluetooth^{TM} antenna, all operating on the 2.4 GHz band with 17 dB port isolation between them.

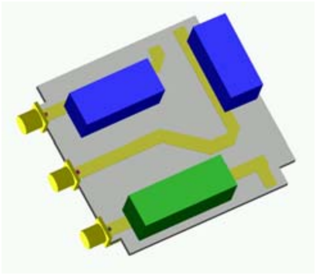

Figure 6. Two orthogonal WCDMA receive antennas for diversity and one WCDMA transmit antenna with 15-20 dB isolation between pellets.

By using DEA hybrid technology, dual-band WLAN antennas can be made to cover the 802.11a&b bands, and provide good isolation and wide bandwidth. Figure 7 shows a pair of WLAN antennas on the end of a PCMCIA card. In the 2.4 GHz band it is the printed copper monopole that is the radiating element, but in the 5-6 GHz band the dielectric is the primary radiator and the monopoles are acting as feeds. This design is inherently self-diplexing and so avoids the need for lossy diplexer circuitry.

Figure 7. Two-dual band WLAN antennas covering the 802.11a&b bands on a PCMCIA card, UK Patent Application Number 0311361.0

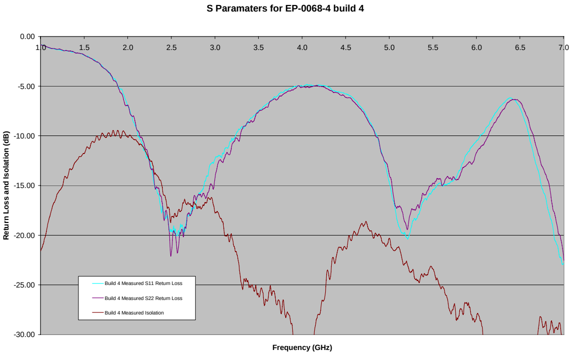

Figure 8. S11 return loss and S21 isolation for the two antenna shown in figure 7Two dual-band WLAN antennas covering the 802.11a&b

The same dual-band, self-diplexing concept can be applied to WLAN and Bluetooth™ laptop antenna combinations. Figure 9 shows a laptop computer with a pair of dual-band WLAN antennas near the top left hand corner of the screen. There is about 15 dB port isolation between these antennas. However there is more than 40 dB isolation between these two antennas and the Bluetooth™ antenna half way up the right hand side of the screen. Reasonably omni-directional patterns can be obtained for these antennas, see figure 10.

Figure 9. Two dual-band WLAN antennas and a Bluetooth™ antenna on a laptop computer, UK Patent Application Number 0318667.3

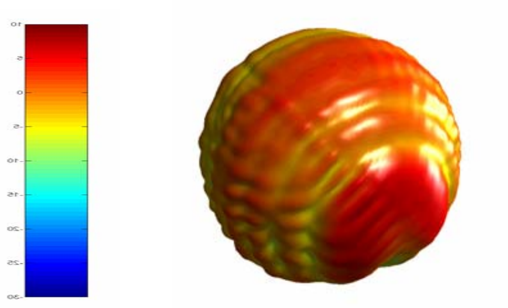

Figure 10. Gain pattern for one of the WLAN antennas measured at 5.5 GHz

Finally the DEA antenna technology discussed in section 2 has been used to make an efficient quadband handset antenna. Figure 11 shows the basic concept of a ceramic high-band antenna exciting a parasitic low-band antenna and the combination of which have the measured return loss shown in figure 12. The antenna covers the bands 824 - 960 MHz and 1710 – 1990 MHz and measured terminal efficiencies are above 50% across these bands. This technology is straightforward to manufacture and Antenova is taking it to market through collaboration with Galtronics.

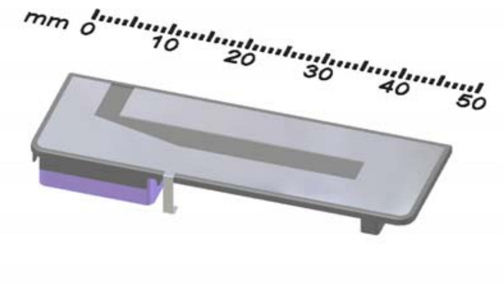

Figure 11. A dielectric quad-band handset antenna with good efficiency, UK Patent Application Number 0313890.6

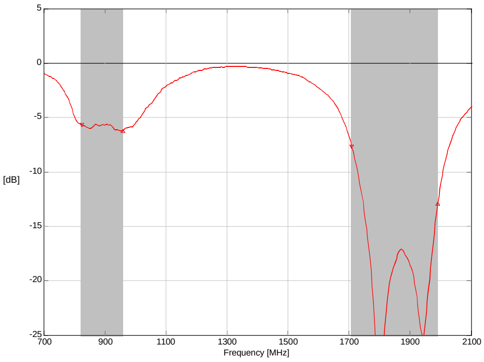

Figure 12. Measured return loss of the quad-band antenna.

In meeting today's antenna needs, the advantages of using dielectric antenna technology can be summarised by the following tables:

Advantages of dielectric-based WLAN antennas are:

- Multiple antennas possible in a small space
- Dual protocols possible on same frequency
- Narrow band sharp filtering possible
- Diplexers may be eliminated
- Wide band/dual band possible

The advantages of dielectric-based handset antennas are:

- Stable performance, reduces design costs
- High terminal and talk position efficiency
- Low detuning for clamshell and flip-phones
- Diversity has been demonstrated

THE FUTURE OF DIELECTRIC ANTENNA TECHNOLOGY

There is a continuous requirement for ever-higher data rates in radio communication systems. A solution already adopted by WLAN to counter the effects of multipath is to use two diversity antennas, even in an electrically small platform such as a PCMCIA card. If more antennas can be provided at the transmitter and receiver sites then Multiple Input Multiple Output (MIMO) techniques can be used to improve the performance of the wireless link. This process does not require increased power or additional bandwidth. In a similar way, the Bell Laboratories BLAST (Bell Labs Layered Space-Time) technique also uses multiple transmit and receive antennas to increase data rates. Combining MIMO techniques with adaptive coding and modulation, interference cancellation and beam-forming technologies, should lead to data rates of around 30 times greater than current 3G systems. The key to this new technology is to be able to build several (4 or more) antennas into an electrically small space.

The properties of dielectric antennas make them well suited to MIMO applications. Figure 13 shows a 50 x 100mm PCB equipped with 4 dielectric antennas, each covering all the upper GSM and WCDMA bands. The measured isolation and cross-correlation figures for these antennas are excellent (cross-correlations are all below 0.3) and the system could form the basis for a future MIMO equipped PDA or even handset. With today's technology, it does not seem likely that MIMO will ever be possible in the AMPS and GSM bands below 1 GHz, but these two bands might be catered for by a single parasitic PILA, as shown in the concept picture in figure 14.

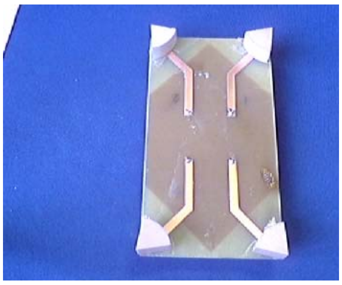

Figure 13. Four dielectric wide band antennas on a small PCB, UK Patent Application Number 0302818.0

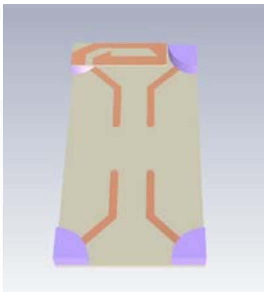

Figure 14. Concept of a PDA or handset equipped with MIMO technology

With the possible future advent of all-dielectric handset antennas and construction techniques using Low-Temperature Co-Fired (LTCC) ceramic technology, it is likely that the concept shown in figure 14 will soon begin to look obsolete as antenna sizes shrink further and approach the Chu-Harrington[7,8] limit, which represents the physical lower-size limit for antenna technology.

In conclusion, dielectric antennas can be used to solve a wide range of radio communication problems; they can be manufactured as simple surface-mount components with wide bandwidths and good efficiencies. Because several dielectric antennas can be packed into an electrically small space for MIMO-type applications, they have the potential to greatly increase the data rate of communication links without a corresponding increase in the radio bandwidth required.

PERFORMANCE AT HIGH FREQUENCIES

The design of HDAs is essentially independent of frequency and the only change needed when the operating frequency is doubled is to halve the size of the device. Given the correct dielectric materials and appropriate ground-plane, a dielectric antenna operating at 40 GHz is expected to have much the same characteristics as one working at 1 GHz (although it will be physically almost 40 times smaller and nearly 64,000 times lighter) and to have close to comparable efficiency. This is not true with conventional antennas, because of the conduction losses in materials such a copper. As shown in Figure 15, the efficiency of a conventional half-wave dipole falls dramatically with frequency in the GHz range.

The efficiency of HDAs is essentially independent of the frequency over a wide frequency range and the antenna can be designed to optimise the efficiency. The losses are connected with both the intrinsic conductivity and the skin depth (how far the radio wave will penetrate a conducting material) which becomes minute at high frequencies. Again, HDAs containing fewer conducting materials do not suffer such high losses. The trend is towards using much higher frequencies in future and this technology should be capable of making chip-chip radio communications, using internal antennas, a reality.

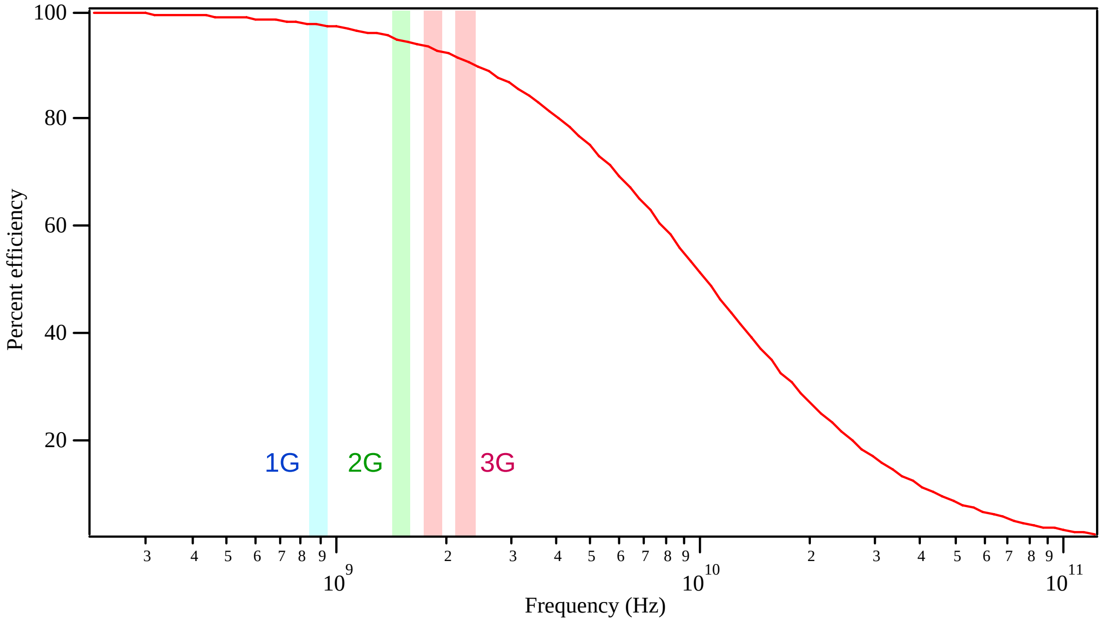

*Figure 15**: efficiency of a conventional half-wave dipole antenna as a function of the resonant frequency. The main mobile phone bands are shown as vertical bands.***

INTELLECTUAL PROPERTY

Antenova maintains a corporate culture of creativity and invention. At the time of writing, the IP portfolio amounts to 35 patent applications filed of which the first 5 to be examined have been granted. The number and rate of inventions continues to grow.

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