Exposure to Electromagnetic Fields from Wi-Fi devices: Effect of signal directivity on EIRP limits

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Introduction

In Wi-Fi devices, such as Wi-Fi enabled laptops and Access Points (AP), it is desirable to have a small antenna while meeting the essential performance requirements. In recent years there has been a significant development in the antenna analysis applications leading to range of antenna designs. The shape and orientation of an antenna in close proximity to other antennas and structures can alter the radiation pattern. Modern Wi-Fi devices use multiple antennas and applications such as switch diversity and other Multiple in Multiple out (MIMO) techniques for enhanced performance. However, this can produce non-uniform radiation pattern around the devices. Laboratory measurements, using in-house built protocol and subject to measurement uncertainty, revealed that some the APs operating at 2.4 GHz, had Equivalent Isotropic Radiated Power (EIRP) above 100 mW (1). This paper examines the radiation pattern and directional characteristics of the most commonly used antennas in Wi-Fi devices.

Materials and methods

There are many numerical modelling methods that can be used to understand the electromagnetic characteristics of radiating antennas. The antenna analysis code Numerical Electromagnetic code (NEC) uses the method of moments (MoM) to numerically solve electric and magnetic field integral equations in order to model the electromagnetic response of conducting structures (2). In NEC, the electric field integral equation (EFIE) is used to solve for structures composed of thin wires and the magnetic field integral equation (MFIE) is used for conducting surfaces divided into patches. A NEC program was used to simulate the wire grid model of monopole, inverted-F and patch antennas to predict the radiation pattern and directivity of the signal. The accuracy of a NEC model depends on the resolutions of the MoM current segmentation limiting the length of the segments used. In the antenna analysis software, NEC-Win Pro, antennas structures were defined with the approximations as summarised in Table 1.

Table 1 NEC modelling approximations

	Guidelines	Approximation	Parameters
Segment length	$\Delta = 0.01\lambda 2$	$\Delta = 0.01\lambda$	$\Delta = 1$ mm
Segment ratio	$\Delta/a > 0.5$	$\Delta/a=10$	a=0.1 mm
Wire diameter	$2\pi a/\lambda << 1$	$2\pi a/\lambda=0.01$	$2\pi a/\lambda=0.005$

A standard grid spacing of 1 mm was used in the wire model which was reduced to 0.5 mm at critical locations, most notably close to the antenna. The grid pitch based on the above approximations is significantly less than the wavelength of Wi-Fi devices to achieve fine resolution in antenna simulations.

Signal directivity of Wi-Fi antennas-theoretical

A radiation pattern is described as the variation of the radiated power away from the antenna. The radiated power from an antenna is generally analysed in the far field region in the horizontal (Azimuth) and the vertical (Elevation) planes. An ideal antenna should transmit equal signal in all the directions and the resulting radiation pattern should be isotropic. However, the antenna with an isotropic radiation pattern does not exist in reality, but it defines the parameters to provide a bench mark for comparison real antennas and antenna simulations.

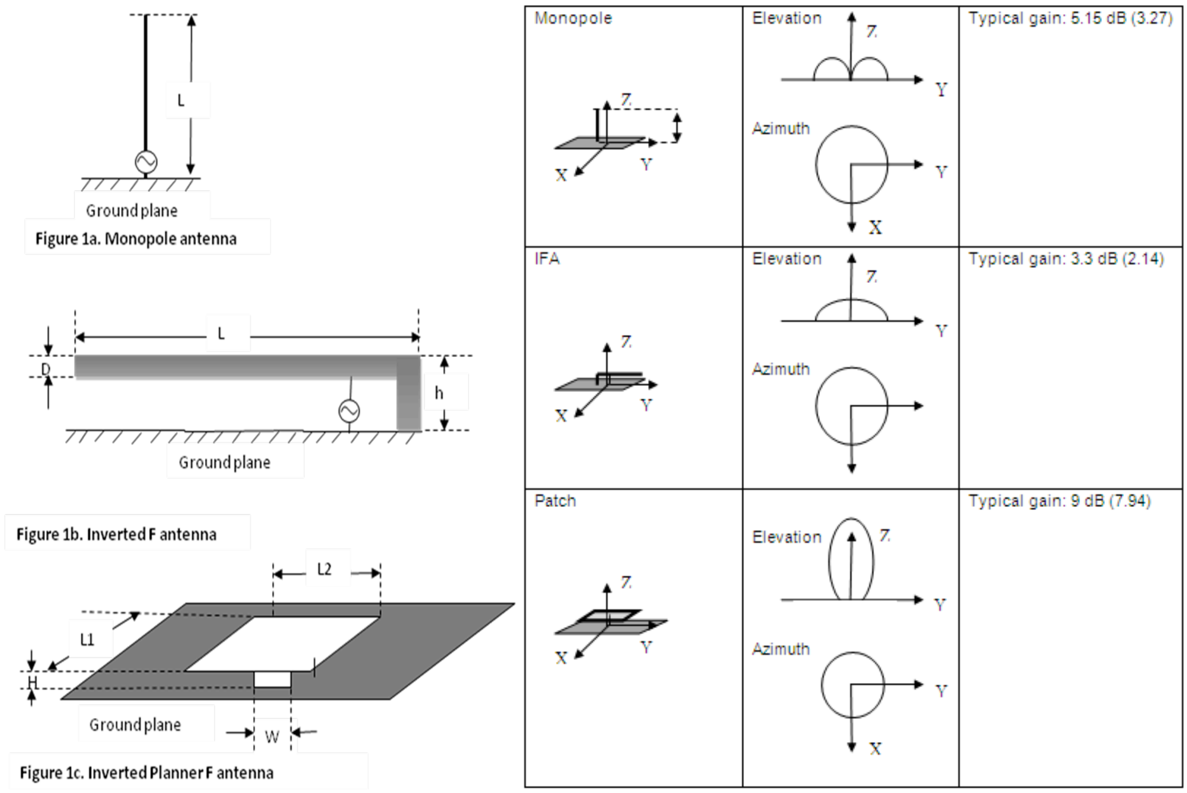

Figure 1 Antenna dimensions of monopole, inverted F and patch antennas used for numerical modelling

The integrated power coming out of the sphere containing the antenna will remain the same irrespective of the antenna gain but the Equivalent Isotropic Radiated Power (EIRP) of the equipment in a given angular position depends on the antenna gain in that direction. Due to the non-isotropic radiation pattern the signal is concentrated in certain directions as shown in Figure 1. Sector antennas direct Radiofrequency (RF) energy in one direction forming a narrow beam. Beam forming techniques can transmit further and receive better incoming signals. Multiple antennas can be used to direct the signal in certain directions. Separation between the antennas and their orientation can be carefully adjusted to focus energy in the required direction. The equipment selected for the study revealed that majority of the Wi-Fi devices used multiple monopole, IFA or patch antennas. The access points with higher EIRPs either employed multiple patch type or monopole antennas beaming the signal in certain directions.

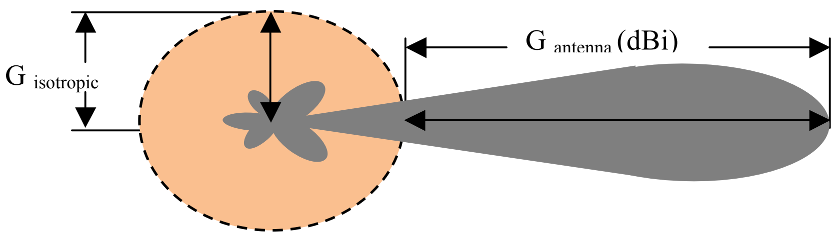

Figure 2 Directivity of the antenna with respect to an isotropic radiator

The technical standard (EN 300 328) allows a maximum value of EIRP no more than 100 mW for the Wi-Fi devices operating in the 2.4 GHz ISM (3). The EIRP and power densities can be calculated with the following expressions.

$$EIRP = P_{out} \times L_{Cable\ loss} \times G_{antenna} \quad (1)$$

$$S = \frac{EIRP}{4\pi d^2} \qquad (\mathrm{Wm}^{-2}) \qquad (2)$$

In order to comply with the regulatory standard, the output power of Wi-Fi device must be reduced if higher gain antenna is to be used.

Signal directivity of Wi-Fi antennas-laboratory measurement

In considering the EIRP values above 100 mW for devices operating at 2.4 GHz, it should be noted that the measurement protocol used did not follow the precise testing schedule required under the emission standards. Also, measurement uncertainty could account for some of the difference. The AP2 had two quarter wave monopole antennas at a wavelength apart which radiated 23.59 dBm. When output of this AP was connected to the power meter by removing the antennas, the output power was 18.4 dBm. The antenna gain of a typical monopole antenna is 5.15 dBm. These investigations revealed that although the output power of the equipment without the antenna was within the 20 dBm EIRP limit but due to the antenna gain (5.15 dBm) the AP exceeded the permitted EIRP limits by 3.59 dBm. Laboratory measurements were made in semi sphere in the horizontal and vertical planes at 15^o steps. Results show that 'hot spots' were formed around the devices at certain angular positions as shown in Table 2.

Table 2 Antenna characteristics and orientation of the Wi-Fi devices with higher EIRP values

	Orientation (Θ, φ)	Antenna (n)	Separation (mm)	EIRP (mW)
AP1	90, -60	¼ mono (n=3)	½ λ	170
AP2	-90, 90	¼ mono (n=2)	λ	229
AP3	30, -90	Patch (n=4)	¾ λ	132
AP7	-90, 90	¼ λ-T (n=2)	¾ λ	146

Note: The laboratory measurement angles 90 (NEC angle 180) to -90 (NEC angle 0.

All the devices reported in Table 1 are APs with multiple antennas. Furthermore, 3 APs (AP1, AP2 and AP3) had multiple monopole antennas and maxima were found at angular positions of ±90^o (corresponding NEC angles of 180^o and 0^o) degrees in the horizontal plane. Whereas the remaining access point (AP7) used multiple patch antennas with a back plate behind the device along the wall. This particular access point had a maxima perpendicular to the ground plane.

Signal directivity of Wi-Fi antennas-NEC

NEC simulation of a typical ¼ wavelength antenna was uniform in the horizontal plane. When another similar antennas was placed close (5 mm) to the radiating antenna the electromagnetic fields was perturbed and the additional antenna acted as director directing the incoming electromagnetic fields towards the radiating element. However, this was reversed as the separation between the antennas was increased.

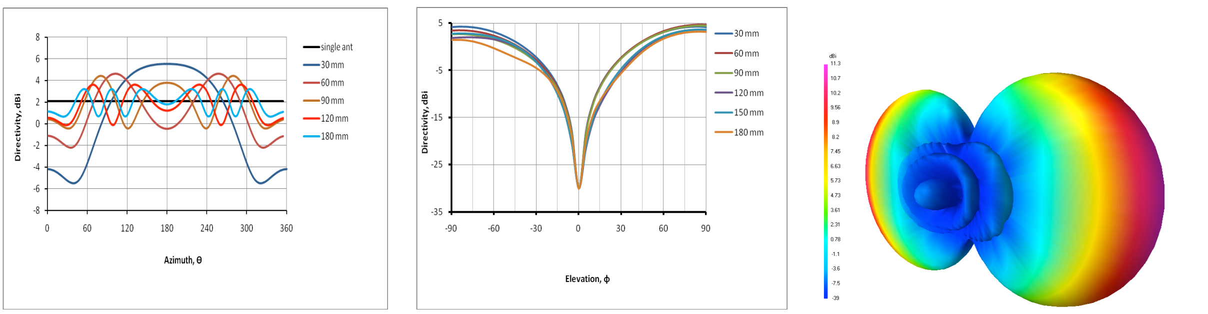

Figure 3 Directivity of monopole antennas (Azimuth: left, Elevation: middle) and modifications (right)

The angular positions of these maxima increased further apart (in the horizontal plane) as the antenna separation was increased until antenna separation reached ½ wavelengths maxima formed at 100 (3.57 dBi) and $\pm 260^0$ (7.74 dBi). The maximum directivity of the signal in the vertical plane was recorded as 9.7 dBi as shown in Figure 3. When antenna separation was increased, number of maxima increased and the directivity of the individual lobes gradually converged around 5 dBi. However, the radiation pattern in the vertical plane remained similar with moderate gain variation (2 to 7 dBi) at -90^0 (crossing 180^0 in the horizontal plane). Results of the 3 antenna simulations were similar to the two antenna system and the radiation pattern had generally higher peaks and deeper troughs as the antenna separation were around ½ and ¾ of a wavelength. Various simulations were carried out to further fine tune the antenna length and separation between the antennas and sharp lobes developed as shown in Figure 3 (right).

NE simulation of Inverted-F antenna (IFA) showed highest directivity (4.5 dBi at 100^0 along the antenna axis) when two antennas were half wavelength (60 mm) apart. Investigations revealed that directivity of the signal was perturbed when another was place close to the radiating antenna (Figure 4, left). Patch antenna, simulations showed that at greater than ½ wavelength separations, the difference in gain between the maximum and minimum directivity was reduced to 1 dB and the radiation pattern showed directivity in multiple directions (Figure 4, right).

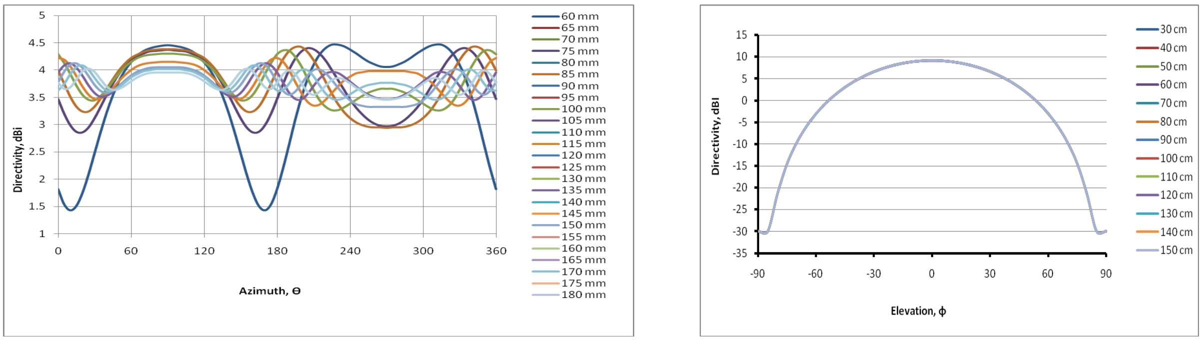

Figure 4 Directivity of IFA (Azimuth:left) and patch antenna (Elevation: right)

NEC simulations confirmed that multiple antennas directed the signal in certain directions providing a possible explanation of the higher values of EIRP found in the laboratory measurements.

Summary

Many Wi-Fi devices used appropriate antennas to minimise radiation where signal was not needed (i.e. towards side walls or towards the ground). Gain of these antennas ranged from 0 to 10.59 dBi in certain directions. Some devices used directional antenna beaming energy in narrow areas. Antenna analysis showed that directivity and radiation pattern is influenced by the dimensions, orientation of the antenna(s). Other antennas in the close proximity can act as reflectors/directors increasing the signal in certain directions. Multiple antennas, body casing and surrounding structures can influence the antenna gain in certain direction. This provides possible explanation why some of the laboratory measurements showed higher EIRP values in certain directions.

References

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