4. FAR FIELD NUMERICAL EVALUATION AND MEASUREMENTS OF HANDHELD ANTENNAS

The problem of antenna radiation normally involves either analytical or numerical solution of Maxwell’s equations. For the analysis of such problems the Green’s functions can be used [2.4]. The complexities of the analytical methods, however, make them impractical for complex problems such as those encountered in antenna analysis. Hence, numerical methods, like the MoM and the FDTD outlined earlier, can be employed to provide an approximate solution to such problems. To verify the accuracy of numerical simulations, appropriate measurements can be performed. However, experimental investigation of antenna parameters suffer from a number of drawbacks too. Some of these, that affect our measurements, according to [2.4] are:

a) Unwanted reflections from the ground and walls of the anechoic chamber to sufficiently small levels, especially at low frequencies.

b) Ancillary equipment used (e.g. the tripod and the turn table) form part of the system under test and they may affect the overall result of the measurements, especially for electrically small radiators. The effect of the support structure is also difficult to compensate via calibration or simulation.

Both experimental and numerical results have been obtained in this study. In the next section, some basic antenna definitions are outlined as a useful background to the antenna measurements and numerical simulations. This will be helpful also in interpretation and assessment of the results.

4.1 Introduction to antennas.

Antenna is a device, which is used to receive and transmit electromagnetic waves efficiently. An antenna also serves as a directional device in addition to a probing device. In most of the cases an antenna is a metallic structure. Many types of antennas are known. Each of these antenna types, including dipoles, monopoles, loop and helix antennas, serves a specific application. Standard definitions and terms for antennas can be found in [2.4-2.6] and these have been agreed by international regulatory bodies such as the IEEE. Standardisation of the antenna glossary terms
helps in providing designers and engineers with a common terminology for antennas. In the following subsections, basic definitions and equations related to antennas, and in particular those designed and used as part of this research, are outlined.

### 4.1.1 Antenna types.

Antennas can be classified as follows.

1. **Wire Antennas**: These are simple antennas consisting of wire, whose shape and length define their radiation characteristics and operational frequency. There are various shapes of wire antennas including dipole, monopole, loop and helix, rectangular and square.

2. **Aperture Antennas**: Aperture antennas are more common at microwave frequencies. These include the pyramidal horn, conical horn, and rectangular waveguide.

3. **Microstrip Antennas**: Microstrip antennas are conductive patches, normally etched on dielectric substrates. The patches have different shapes and a plethora of techniques are used for achieving good radiation characteristics. The microstrip antennas are low profile, conformal to planar and nonplanar surfaces. They are simple and inexpensive to fabricate using modern printed-circuit technology. They can be mechanically robust when mounted on rigid surfaces and versatile in terms of resonance frequency, polarisation, pattern, and impedance.

4. **Array Antennas**: In an array antenna more than one antenna are used in various configurations. The distance between the array antenna elements, the phase, and amplitude of the individual antenna signals define the radiation characteristics of an array antenna.

5. **Reflector Antennas**: Reflector antennas are used for high directivity and gain where this is required. Main use is in the satellite communication and terrestrial point-to-point microwave relay links.

6. **Lens Antennas**: These antennas are used to collimate incident divergent energy to prevent it from spreading in undesired directions.
4.1.2 Antenna definitions and parameters.

This section presents basic antenna definitions, which are used in the following chapters. These definitions are described in more detail in [2.4-2.6].

The *radiation pattern* of an antenna is a mathematical function or a graphical representation of its radiation properties as a function of space coordinates. In most cases, the radiation pattern is determined in the far-field region and represented as a function of the directional coordinates. Radiation properties include power flux density, radiation intensity, field strength or polarisation.

An *isotropic antenna* is a hypothetical lossless antenna having equal radiation in all directions. A *directional antenna* is the antenna having the property of radiating or receiving electromagnetic waves more effectively in some directions than others. This term is usually applied to an antenna whose maximum directivity is significantly greater than that of a half-wave dipole. An *Omnidirectional Antenna* is an antenna having an essentially nondirectional pattern in a given plane and a directional pattern in any other direction. A simple example of an omnidirectional antenna is the half-wave dipole.

The space surrounding an antenna can be divided into three regions. The *reactive near-field region* is that portion of the near-field region immediately surrounding the antenna wherein the reactive field predominates. For most antennas, the outer boundary of this region is commonly taken to lie at a distance \( R \) given by:

\[
R = 0.62 \frac{D^3}{\lambda}
\]  

(4.1)

from the antennas surface, where \( D \) is the largest dimension of the antenna. To be valid, \( D \) must also be larger compared to the wavelength. The *radiation near-field (Fresnel) region* is that region of the field of an antenna between the reactive near-field and the far-field region wherein radiation fields predominate and wherein the angular field distribution is dependent upon the distance from the antenna. Finally, the *far-field (Fraunhofer) region* is defined as that region of the field of an antenna where the angular field distribution is essentially independent of the distance from the antenna. The far-field region is commonly taken to exist at distances greater than...
\[ R = \frac{2D^2}{\lambda} \]  
(4.2)

from the antenna.

**Radiation intensity** is the power radiated from an antenna per unit solid angle. The radiation intensity at a distance \( r \) is a far-field parameter and is given by

\[ U = r^2 S_{rad} \]  
(4.3)

where \( S_{rad} \) is the Poynting vector. The above equation can be also written, in terms of the electric field components, as

\[ U(\theta, \phi) = \frac{r^2}{2\eta} \left[ \left| E(\hat{r}, \theta, \phi) \right|^2 = \frac{r^2}{2\eta} \left| E_0(\hat{r}, \theta, \phi) \right|^2 + \left| E_0(\hat{r}, \theta, \phi) \right|^2 \right] \]  
(4.4)

where \( \eta \) is the intrinsic impedance of the medium. The total power radiated is then

\[ P_{rad} = \int_U d\Omega = \int_0^{2\pi} \int_0^\pi U \sin \theta d\theta d\phi \]  
(4.5)

For an isotropic source, the radiation intensity is simply given by

\[ U_0 = \frac{P_{rad}}{4\pi} \]  
(4.6)

**Directivity** of an antenna is the ratio of the radiation intensity in a given direction to the radiation intensity averaged over all directions. The averaged radiation intensity is equal to the total power radiated by the antenna divided by \( 4\pi \). For a nonisotropic source, the definition is equal to the ratio of its radiation intensity in a given direction over that of an isotropic source.

\[ D = \frac{U}{U_0} = \frac{4\pi U}{P_{rad}} \]  
(4.7)

The total directivity is the sum of the partial directivities for any two orthogonal polarisation.

\[ D = D_0 + D_\phi \]  
(4.8)

where

\[ D_\phi = \frac{4\pi U_\phi}{(P_{rad})_0 + (P_{rad})\phi} \]  
(4.9a)
The directivity of a half-wavelength dipole is \( D = 1.67 \sin^3 \theta \) and for an isotropic source is 1.

The **absolute gain** of an antenna is defined as the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically.

\[
G = 4\pi \frac{\text{radiation\_intensity}}{\text{total\_input(accepted)\_power}} = 4\pi \frac{U(\theta, \phi)}{P_{\text{in}}} \quad (4.10)
\]

On the other hand, the **relative gain** is the ratio of the power gain in a given direction to the power gain of a reference antenna in its referenced direction. The total **radiated power** is related to the input power by

\[
P_{\text{rad}} = e_{cd} P_{\text{in}} \quad (4.11)
\]

where \( e_{cd} \) is the antenna **radiation efficiency**. The gain is related to directivity by

\[
G(\theta, \phi) = e_{cd} D(\theta, \phi) \quad (4.12)
\]

and similarly to partial directivity case the total gain is the sum of the partial gains for any two orthogonal polarisation.

\[
G_0 = G_\theta + G_\phi \quad (4.13)
\]

where

\[
G_\theta = \frac{4\pi U_\theta}{P_{\text{in}}} \quad (4.14a)
\]

and

\[
G_\phi = \frac{4\pi U_\phi}{P_{\text{in}}} \quad (4.14b)
\]

The **antenna efficiency** is the product of the **reflection efficiency** \( e_r \), **conduction efficiency** \( e_c \) and the **dielectric efficiency** \( e_d \)

\[
e_0 = e_r e_c e_d \quad (4.15)
\]

The **bandwidth** of an antenna is defined as the frequency range within which the performance of the antenna, with respect to some characteristics, conforms to a
specified standard. For handheld antennas, described in the following chapters, a bandwidth corresponding to $\text{VSWR} < 2:1$ is used. For this case, the reflection coefficient is $|\rho| = \frac{1}{3}$ which means that $\frac{2}{3}$ of the total power from the transmitter is radiated.

_Polarisation_ of an antenna in a given direction is the polarization of the wave transmitted (radiated) by the antenna. When the direction is not stated, the polarization is taken to be the polarization in the direction of the maximum gain.

_Polarization loss factor_ (PLF) is the loss due to polarization mismatch between the receiving antenna and the electromagnetic wave. If the incoming wave is $\vec{E}_i = \hat{\rho}_w \vec{E}_i$ where $\hat{\rho}_w$ is the unit vector of the wave, and the polarization of the electric field of the receiving antenna is $\vec{E}_a = \hat{\rho}_a \vec{E}_a$ where $\hat{\rho}_a$ is its unit vector the polarization loss factor is

$$PLF = |\hat{\rho}_w + \hat{\rho}_a|^2 = \left|\cos\psi_p\right|^2$$

(4.16)

where $\psi_p$ is the angle between the two unit vectors.

The _input impedance_ of an antenna is defined as the impedance presented by an antenna at its terminals or the ratio of the voltage to current at a pair of terminals or the ratio of the appropriate components of the electric to magnetic fields at a point. Antenna input impedance can be written as

$$Z_A = R_A + jX_A$$

(4.17)

where $R_A$ is the antenna resistance and $X_A$ is the antenna reactance. The resistance consists of two components: the _radiation resistance_ ($R_r$) and the _loss resistance_ ($R_L$).

$$R_A = R_r + R_L$$

(4.18)
4.1.3 Free-space propagation.

In the absence of any reflections or multipath the free propagation equation is

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R}\right)$$  \hspace{1cm} (4.19)

where

- $P_r$ is the received power in watts,
- $P_t$ is the transmitted power in watts,
- $G_t$ is the transmitter antenna gain,
- $G_r$ is the receiver antenna gain,
- $\lambda$ is the wavelength and,
- $R$ is the distance between the receive and transmit antennas.

In logarithmic form eq. (4.19) can be written as

$$P_r (dBW) = P_t (dBW) + G_t (dBi) + G_r (dBi) + 20 \log_{10}\left(\frac{\lambda}{4\pi}\right) - 20 \log_{10}(R)$$  \hspace{1cm} (4.20)

The free space loss (FSL) then can be defined as

$$FSL = 20 \log_{10}\left(\frac{\lambda}{4\pi R}\right)$$  \hspace{1cm} (4.21)

4.2 Antenna measurement facilities and methods.

The anechoic chamber of the Radiowave Propagation and System Design (RPSD) research group has been used for measurements of radiation patterns in the far field. For all far-field radiation pattern measurements, the distance between the antennas is 1 m, which meets the far-field radiation criterion in eq. 4.2. The size and shape of the anechoic chamber are depicted in Fig. 4.1.a. and the coordinates system used in this report is shown in Fig. 4.1.b. The walls of the anechoic chamber are covered by 90mm high pyramid absorbers, which were previously selected for measurements at frequencies greater than 10 GHz. These absorbers are small, compared to those required for measurements in the GSM frequency bands, allowing small amounts of reflections.
4.2.1 Measurement methods for handheld antennas.

Reflection coefficient and radiation measurements have been mainly carried out with the use of the Vector Spectrum Analyser (VNA HP8714c 300MHz-3GHz RF Network Analyser). In particular, some functions of the VNA that were systematically used are:

- **Reflection coefficient measurements**: Using this option, the input impedance and as a consequence VSWR or return-loss \((S_{11})\) of an antenna can be measured directly. The analyser computes the reflection using the following formula:

\[
\text{Reflection coefficient (dB)} = 10 \log \left( \frac{P_{\text{refl}}}{P_{\text{inc}}} \right)
\]

(4.22)

where \(P_{\text{refl}}\) is the power of the signal reflected from the device and \(P_{\text{inc}}\) is the incident power. “One-Port” calibration is needed in advance of the measurements.

- **Transmission coefficient measurements**: This function is used to measure the CW radiation pattern of antennas or to evaluate the absolute gain versus frequency. A “response” calibration is performed for this kind of measurement.

*Measurement calibration* is a process that improves accuracy of VNA measurements by using error correction arrays to compensate for systematic measurement errors.
Measurement errors are classified as random, drift, and systematic errors. Random errors such as noise from connectors that are non-repeatable and as such they can not removed by measurement calibration. Drift errors, such as frequency and temperature drift, are also non-repeatable and so not removable by calibration. To eliminate drift errors, the instrument must operate for at least one hour before measurements. Systematic errors, such as tracking and crosstalk, are the most significant errors in most RF measurements. Fortunately systematic errors are repeatable and for the most part can be corrected. However, small residual errors may remain.

Repeatable systematic errors are due to system frequency response, isolation between the signal paths, and mismatch and leakage in the test setup. Frequency response errors are errors that are a function of frequency. Isolation errors result from energy leakage between signal paths. In transmission measurements, this leakage results into crosstalk. In reflection measurements, it is due to impedance directivity. Finally, mismatch errors results from differences between the Device Under Test (DUT) port impedance and the instrument used port impedance.

For reflection measurements, “one-port” calibration is used. A one-port calibration prompts you to connect three measurement standards: an open circuit, a short circuit and a matched load (50Ω). The analyser measures each standard across the frequency band defined, using the number of points defined. The measurements of these standards are used to remove systematic errors caused by directivity, source match and frequency response. For transmission measurements “response” calibration is used. In a response calibration the VNA prompts the user to connect a through cable as the calibration standard, and then measures it across the frequency band defined and for the number of points defined. This measurement is used to correct systematic frequency response errors. Calibration is performed every time the instrument is used and every time one of the settings changes.

In Fig. 4.2.a block diagrams for reflection and transmission measurements are shown. It can be seen that for reflection measurements only one port of the VNA is used and for this reason the cable between the instrument and the antenna can be short in length. On the other hand, in transmission measurements both ports of the
VNA are used and longer cables are needed mainly due to the distance between the two antennas. In practice, mobile phone antenna reflection measurements can be done outside an anechoic chamber if the antenna is placed at a reasonably long distance from other surrounding objects. The cable used, then, can be short (i.e. 30cm). This is not the case for transmission measurements where the antennas must be in the anechoic chamber and the total cable length exceeds 6m. A photograph of the VNA, the standard loads used for “one-port” calibration and some of the antennas tested are shown in Fig. 4.2.b.

**Fig. 4.2** a) Transmission and reflection measurements geometry. b) The Vector Network Analyser HP8714c 300MHz-3000MHz.
4.3 Antenna reflection and input impedance measurements.

In the investigation carried out on mobile antennas, four different antenna types, three of which are shown in Fig. 4.3, have been built and tested, namely:

a) a half-wavelength dipole (two similar dipoles are used as the reference antenna),
b) a monopole antenna,
c) a small helix antenna, and
d) a Planar Inverted-F Antenna (PIFA).

These antennas have been designed to operate at a centre frequency of 945 MHz. This frequency is repeatedly used for measurements and simulations of antennas designed for the GSM900 system. In Fig. 4.4 the measured VSWRs of the four antennas are shown. It can be seen that the helix and the PIFA antennas have lower VSWR compared to the monopole and the dipole antennas but their bandwidth (VSWR < 2:1) is narrower. Therefore, reflection efficiency is better for these antennas at the operational frequency. No matching elements have been used in order to keep the antennas simple. The Smith chart in Fig. 4.5 shows that the dipole and the PIFA antennas have capacitive impedance. On the other hand, the helix and the monopole antenna are characterised by inductive impedance in their resonance frequency.

Fig. 4.3 The three handheld portable phone antennas.
Fig. 4.4 The VSWR of the four antennas. - - Dipole, ** Monopole, ++ Helix, and oo PIFA

Fig. 4.5 The Smith chart of the four antennas under test. - - Dipole, ** Monopole, ++ Helix, and oo PIFA
4.4 Antenna absolute gain measurements using the 3-antenna method.

A convenient method to measure the absolute gain of the four antennas investigated is due to the U.S. National Bureau of Standards, which utilises a 3-antenna measurement method. An alternative method, with two instead of three antennas, is described in [2.7].

In the three-method model the free space propagation equations can be written as

\[
\frac{P_1}{P_2} = G_1G_2 \left( \frac{\lambda}{4\pi R} \right) \tag{4.23}
\]

\[
\frac{P_1}{P_3} = G_1G_3 \left( \frac{\lambda}{4\pi R} \right) \tag{4.24}
\]

\[
\frac{P_2}{P_3} = G_2G_3 \left( \frac{\lambda}{4\pi R} \right) \tag{4.25}
\]

After measuring the ratio between the transmitted and received signal \( \left( \frac{P_t}{P_t} \right) \) using the VNA and keeping \( R \) constant, the antennas gain can be found by solving the set of equations 4.23-4.25.

In Fig. 4.6, the wide-band boresight antenna gain measured for the dipole, helix and PIFA antennas, using the three-antenna method is plotted. The PIFA performance is superior to that of the other three antennas. This is due to the small directivity of the PIFA towards the boresight and its good efficiency. Relatively low gain has been measured for the dipole and helix antennas. The low gain of the dipole, compared to its theoretical value, as well as the ripple on the wide-band boresight gain plots is due to reflections from the walls and the ground of the anechoic chamber which have been reduced but not sufficiently eliminated by the absorbers.
In the present and following sections far-field radiation pattern data from simulations and measurements are presented and discussed for mobile phone antennas operating in free space. The need for studying the far-field characteristics of an antenna lies in the importance of understanding its radiation characteristics. The far-field gain pattern is one of the most important characteristics in assessing the performance of a radiating device and has significant implications in designing the wireless link. It is also essential to verify the reliability and accuracy of numerical methods against measurements. For antennas used in cellular communications, it is desirable to present omnidirectional radiation characteristics in the horizontal plane and, in particular, for the vertical (E_\theta) electric field component, since commercially used base station antennas are normally vertically polarised. Omnidirectional far-field gain patterns for the antenna allow the mobile phone to exhibit similar performance in all directions. This is because the orientation of the mobile station with respect to the base station antenna is random.