CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Personal communication systems as we see it now is the result of a revolution that started in the 1980s. Though the current market has several contenders, the first viable voice-only cellular system was the NMT (Nordic Mobile Telephone) which was an analogue cellular system deployed in Nordic countries, Eastern Europe and Russia. Other early starters included TACS (Total Access Communications System) in the United Kingdom and AMPS (Advanced Mobile Phone System) in the United States. These systems had handsets that were cumbersome to carry around and the power requirement was also stringent.

For over three decades now there is a widespread interest and market demand for handsets that are not bulky while providing extended capabilities. These handsets were also required to be more robust for operation. This sparked off advancement in technology particularly in the field of miniaturization whereby components of communication system are generally much reduced in size. A huge majority of the current personal communication systems are based around wireless technologies.

An antenna is an integral part of such a wireless transmission system. The function of an antenna is to transform from or into guided energy in the circuitry of the radio into or from an electromagnetic wave. Antennas
have the property that they work best at resonance and their efficiencies are strongly linked to physical size such that they are often made to be at least half a wavelength in at least one of their dimensions. This property of the antenna performing efficiently at a particular size means that they are resistant to miniaturization than other components of personal communication systems. This also means that the antenna is a wireless transceiver would be the most space consuming part. Hence recent trend has aimed at moving the antennas closer to the human body and away from the other circuitry. This would reduce the bulky radios that need to be carried around for communication. Antennas with large apertures can be realized when placed close to the human body to overcome size restrictions in handheld devices. Antennas are slowly being integrated as part of the clothing and these integrated antennas are known as textile antennas or wearable antennas.

Any antenna must be designed keeping in mind that the power consumed must be low while achieving an improvement in the bit error rate. For on-body applications, these antennas should also be resistant to the effects of working close to the human body. These antennas must also bring little harm to our health (Noury et al 2005). Large sized ground planes are usually preferred for wearable antennas since they can increase the stability of the antenna and also serve to isolate the human body from the electromagnetic (EM) radiation. This electromagnetic radiation exposure of the human body is linked to the specific absorption rate (SAR) which is discussed later in this thesis. However, using large sized ground planes increase the size and rigidity of wearable antennas. Many antennas are rigid, which makes them uncomfortable to be embedded into skin or clothing. This has resulted in a demand for new type antennas better suited to operate in close proximity to humans.
Several types of antennas now have wearable implementations. In particular these are microstrip antennas, printed dipoles or loop antennas, printed monopoles or planar inverted F antennas (PIFAs). Such antennas are normally flat and small and can loosely be described as comprising of four elements, namely, a feed, a ground plane, a dielectric substrate and one or more radiating elements all of which have typically been rigid. By replacing the traditional materials used for antenna design with flexible materials, wearable antennas become more comfortable and therefore attractive to users.

1.2 LITERATURE REVIEW ON WEARABLE ANTENNA

Wearable electronic systems can be divided under three categories. First there are systems that are worn directly on the body, secondly there are systems that are integrated into clothing (smart clothing), and thirdly those that are used as accessories on the clothing. Of these smart clothing is most common and popular with the military. Bulky radio equipment may reduce soldiers’ mobility and combat utility, and also the traditional whip or stub antennas make easy targets for the enemies. Hence invisible, lightweight and embedded wearable electronics have become more popular to secure soldiers’ safety and improve their combat utility. Smart clothes are intelligent wearable systems that can find scope for application in sportswear, emergency workers’ outfits, astronauts’ suits, and in medical, military, and entertainment applications. The traditional function of clothes can be extended to comprise new tasks, such as survival assistance in demanding conditions. This goal can be achieved by embedding or integrating additional components into clothing, which will provide new functions, such as calling for assistance or monitoring medical conditions.

When compared with hand held devices, wearable electronics come with the advantage in that, they can help free the user’s hands and enable people to carry more. In addition wearable electronics can provide the user
with some unique experiences. An example of this is the Hug Shirt™ which is a shirt that makes people send hugs over wireless (Anne 2013). The operation is based on a set of wireless controlled actuators integrated into a shirt.

Health care is another segment that benefit greatly due to the emerging trend in wearable electronics. A wrist worn medical monitoring computer was designed to free a high risk patient from the limitations of fixed monitoring device. This system can continuously monitor and log the status of the pulse, blood oxygen saturation and temperature of a patient. Any abnormal trends are then sent via wireless to a hospital (Lukowicz 2002). ‘An Ultrasound Wearable System for the Monitoring and Acceleration of Fracture Healing in Long Bones’ was proposed by the authors Protopappas et al (2005). Noury et al (2004) also describes a device that provides support for health telemetry.

In addition to health care, wearable electronics can realize the functions of many types of communication and entertainment devices. Usage of clothing accessories such as bracelets, rings, glasses or other ornaments as a structure for integrated wearable electronics are also being studied. An mp3 player made in the form of a bangle is conceptualized and shown in the picture in Figure 1.1.

Figure 1.1  iBangle wearable design concept
1.2.1 Features of Wearable Antenna Design

As in most wireless systems, antennas play a very important role in wearable electronics. A good antenna design may extend wireless range and reduce power consumption. Also the wearability of the antenna and robustness under working conditions are factors that need to be addressed. Therefore the design of suitable wearable antenna is important, more so because of the impacts of the human body. In general wearable antennas have been strongly linked to items of clothing. There have been examples of wearable antennas on rings (Asada et al 2003) as shown in Figure 1.2 and as components in prosthesis (Gosalia et al 2004). These reported works on wearable antennas have always tended to appear on cloth parts that are robust. For example antennas in jackets, hats and shoes are far more common than antennas in socks, shirts or undergarments. Challenges arise when affixing antennas in flexible clothing.

![Figure 1.2 Prototype ring sensor with RF transmitter (Asada et al 2003)](image)

Antennas can be attached to the surface of with the fabric of most common items of clothing (Ogawa et al 2000, Massey 2001). Typically the further away from the skin an item of clothing is, it is less likely to be washed
and this fact can make life easier for antenna engineers. However, this is not
the major motive for their placement, as electrical insulation from the body of
a wearer turns out to be a dominant factor in the design

In view of their importance and practicability, the wearable
antennas have been designed to cover a wide application range. Two wearable
antennas that have been designed for military and police applications at
frequency band of 350 MHz are presented in Christ at al (2006) and Ogawa
et al (2000). The first was worn on the lumbar region, and the second was
worn on the shoulder. Similarly wearable antenna designs for GSM 900/1800
can be found in Salonen (1999) and Massey (2001) where the antennas were
incorporated into the sleeve and on the back. Hertleer and his colleagues show
us their wearable antenna designs for 2.45 GHz Industrial, Scientific and
Medical (ISM) frequency band in Hertleer et al (2007) and Hertleer et al
designs for 2.4 / 5 GHz Wireless Local Area Network (WLAN) applications.
More recently wearable Ultra Wideband (UWB) antennas are another focus
point for engineers, and we can find them in Sanz-Izquierdo et al (2007) as
shown in Figure 1.3, Taeyoung et al (2005) and Klemm & Troester (2006), as
shown in Figure 1.4.

Figure 1.3 Textile UWB Antenna (Sanz-Izquierdo et al 2007)
The crucial point derived from all these previously reported work is that, most if not all of these designs do not address the concern that these wearable antennas would be working in proximity to the human body. Hence this dissertation has taken into consideration the working environment of the textile antenna and strives to address any detuning or discrepancy thereof in the working of these antennas.

Figure 1.4 Wearable UWB antenna (Klemm & Troester 2006)

Peter & Yang (2006) in their book on ‘Antennas and Propagation for Body-Centric Wireless Communications’ have presented a guideline on the features that need to be worked during the course of a wearable antenna design. This is presented in the flowchart shown in Figure 1.5. There are seven key areas among others that will form the process of a wearable antenna design.
Wearable Antenna Design

- Textile
- Conductivity
- Performance
- Ground Plane
- Performance Enhancement
- Performance near Human
- SAR

Figure 1.5  Key features related to wearable antenna design (Peter & Yang 2006)
This dissertation has taken into consideration at the least all of these areas during every design and analysis process. While Specific Absorption Rate (SAR), which will be elucidated later in the thesis, is ensured to be minimum and within standard specifications the performance near the human body and the enhancement of the same is also analyzed in this dissertation.

1.2.2 Materials in Wearable Antenna Design

Previously most printed planar antennas have used rigid materials. However for wearable antennas we may desire an antenna that conforms to clothing and is therefore soft, lightweight and comfortable. To retain the nature of clothing, some flexible and comfortable materials have been used to build wearable antennas, such as fleece fabric (Hertleer et al 2006) and denim (Sanz-Izquierdo et al 2007). Different materials may bring significant impacts on the performance of these wearable antennas. Taking microstrip antennas as an example, typically for wearable microstrip antennas the substrate materials chosen have been textiles.

1.2.2.1 Substrate materials

Textile materials that are used as substrates for antennas can be divided into two main categories viz. natural and synthetic fibers. Synthetic fibers are polymers obtained from their molecular structures. The subsets of polymers have the prefix “poly-”. The names of the fibers are generally trademark of companies, and they are classified based on their typical radical. Thus, for example polyesters can have many different molecular formulae. A commonly known polymer is polytetrafluoroethylene (PTFE), which is better known as Teflon.

The effect of using different textile materials as the substrate of a patch antenna was studied in Gupta & Sankaralingam (2010). Four antennas
were designed and fabricated. Different textiles that were used for antenna fabrication are: wash cotton, curtain cotton, polyester and polycot. While cotton was more comfortable for the wearer, the polyester patch antenna yielded the best antenna performance in terms of gain and efficiency (polyester patch antenna yielded measured gain equal to 9.6 dBi compared to 7.2–7.5 dBi with the other antennas). The polyester had the lowest loss tangent compared to the other three textiles that were used for antenna fabrication. Additionally, as shown in Tronquo et al (2006) fleece fabric provides sufficient thickness for an adequate bandwidth. The low permittivity of fleece allows design of textile wearable antennas with large gain and high efficiency which claims fleece fabric as a very good candidate for textile substrate material. However the fleece fabric has its disadvantages as described in the work reported below. An embroidered textile antenna (Sierpinski Carpet Antenna) was designed in Ahmad et al (2012) using the concept of fractals. Two antennas were fabricated. One antenna was embroidered on denim and the other on felt. The firmness of a textile material substrate can affect the performance of the textile antenna. The first one showed the best performance i.e denim fabric has a firm surface compared to felt fabric that has a soft fluffy surface which gives disadvantages to felt. Fluffy surfaces are easily compressed and the variable thickness affects the antenna properties. Hence considering the robustness and durability of the antenna during wear, denim emerged as a better candidate for an antenna substrate.

1.2.2.2  Conductive materials

Peter & Yang (2006) have studied the effect of the conductive layer material on textile antenna performance with six different fabricated prototypes of WLAN antennas. Conductive layers used were copper tape cut and glued, copper tape that was soldered, solid copper tape as well as knitted
copper fabric. The conclusions based on the results analyzed show that the conductive material plays an important role in optimal textile antenna design. Also an important feature studied from the literature on the effect of conductive layer on the performance of the wearable antenna is that the conductive elements can have some discontinuities as long as the discontinuities are parallel to the surface current.

1.2.3 Wearable Antenna Evaluation

1.2.3.1 Free space measurement

Textile antennas designed at a particular frequency work properly or at the desired frequency when evaluated in free space. Measurements of these wearable antennas have close agreement to the simulations, while the flexible nature of the fabrics used for the substrate and/or the conductive layer might introduce a certain amount of discrepancy in the result. However the on-body measurement is required for the evaluation of textile antennas as the antennas are usually placed in the vicinity of the human torso or arm.

1.2.3.2 On-body measurement

In the design of wearable antennas it is important to take an account of the interaction between the antenna and the human body. All the commonly used antenna parameters, such as resonant frequency, bandwidth, radiation pattern, and efficiency are likely to change radically as an antenna moves close to the body and therefore a free space design is only a crude estimate of antenna suitability. To better understand these effects, researchers have created body models or so called phantoms. These models can be grouped into computational and physical types. Most computational models are based on detailed human body parameters which consist of a matrix
mapped to space with each element containing details about conductivity, permeability and permittivity of the body tissues.

Usually detailed body models, those including organs, are complicated and demands more run time while utilizing resource intensively. In literature there are simplified human body models like the lossy cylinder with defined dielectric constant, conductivity and the rectangular body model (Wasife 2011). The rectangular model of the body is chosen for the study as it is found to give excellent agreement with measurements.

1.2.4 Deployment of Wearable Antennas

Distortion of guided electromagnetic waves within the volume of the wearable antenna itself is an additional factor to be considered during the design. Wearable antennas are usually made of soft and flexible materials and are therefore designed to be conformal. Their shape will change with the movement of our joints or the fold of clothing, and the associated EM guided wave paths will also be changed as a result. Hertleer et al (2007) has shown that the electric field may change from having a linearly distributed electric field density in the plane of propagation to that of a logarithmic field distribution in the plane of propagation during flexible movement. Hence while studying the performance of textile antennas the deployment conditions need to be taken into consideration.

1.3 RESEARCH AIMS AND OBJECTIVES

Based on the detailed literature study and following the outline shown in Figure 1.5 the objectives of this dissertation are framed. The textile antennas presented in this thesis are aimed at GSM and ISM frequency bands hence they could cater to healthcare and entertainment applications. Every textile antenna design and its associated study have to address key points
definitively. This would ensure a clear in-depth investigation into optimal wearable antenna concepts.

(i) To critically analyze the wearable antenna’s performance near the human body

This objective includes several sub-objectives such as:

1. To become acquainted with the properties of human body tissues

2. To investigate how to model frequency-dependent tissues by simulations

3. To design planar antennas for studies conforming to standards set by the IEC

4. To examine the impact of the use distance to body on the antenna’s performance in order to achieve the level of operation close to that of free space in terms of matching or efficiency

5. To analyze the antenna behavior in the proximity of a body in detail

(ii) To increase the effectiveness of the aforementioned wearable radiator by making it function at dual resonances.

1. Achieve dual resonance in a planar through slots or slits thereby eliminating the need for vias or shorts that become difficult to integrate with wearable antennas

2. Analyze the performance of the radiator near the human body
3. Analyze the performance of the radiator under deployment conditions where it is subjected to mechanical deformations and wetness

(iii) To address the lack of quantification of the uncertainties surrounding the deployment of wearable antennas

1. To employ statistical tools to quantify the extent of the effect of uncertainties on the response of an wearable antenna

2. To investigate under a structured well defined analytical method, the uncertainties that would contribute significantly in altering the performance of an textile antenna.

(iv) To find out methods to compensate body effects of an wearable radiator

1. To enable immunity from body effects for the wearable antenna by using electromagnetic bandgap structures for dual resonance antennas

2. To make the antenna robust to deformations occurring due to wear

(v) To improve the wearability of the textile radiator and offer complete integration of the component

1. To address the challenge of taking a conventional rigid construction and reproducing it successfully using a soft substrate whilst retaining the natural characteristics of a textile
2. To take a section of the mobile communications infrastructure, the antenna, and produce it using conductive yarn and integrating it into a fabric at the point of production.

3. To explore the possibility of producing good quality conductors in a range of fabric and to construct reliable and useful antennas in fabric using these conductors.

4. To fabricate a completely integrated textile antenna which has the possibility of introducing an automation in its production.

5. To study the performance that can be expected from wearable antennas fabricated from such fabrics.

1.4 RESEARCH CONTRIBUTIONS

Problems solved within the framework of this dissertation are depicted in Figure 1.6. Each layer of the oval represents the increasing importance in the design of wearable antennas as addressed in this thesis.

The primary task in every antenna design is to design and model antennas at a specified resonant frequency in accordance with the application.

(a) This dissertation works with design of wearable antennas at the GSM and ISM frequency bands.

(b) Crucial observation is made during the performance evaluation of the antenna when operating near the body. Best location to place the antenna is brought out through a detailed analysis.

(c) Investigations and substantial reasoning is done to prove patch antennas are best suited to operate as wearable antennas.
(d) Dual band textile antenna using slot and slits to create additional current paths are designed and their performance under deployment conditions is also studied.

(e) Also these antennas are analyzed when they were working in proximity to the body tissues

Research contributions (a) to (e) are in line with, and aimed at achieving research objectives (i) and (ii) in section 1.3

(f) Statistical tool is employed to quantitatively prove that shear effect in fabric is an important parameter to address during the design of wearable antennas in addition to commonly studied effects of bending and stretch.

The above contribution (f) is aimed at addressing research objective (iii).

(g) Fractals are used to achieve dual frequency operation in wearable antennas.

(h) To avoid detuning of the wearable antennas when operating under certain deformed conditions as well close to the body tissues, Electro Band Gap structures are used. This makes the antenna immune to changes during deployment.

Research contributions (g) and (h) are solutions worked towards achieving objective (iv). Contributions towards the research of textile antennas as discussed above address the design and satisfactory working of the antenna.

The following research contributions (i) and (j) address the research objective (v)
(i) Work is then extended to ensure increased wearability and durability of the wearable antennas. To this end, various materials for the fabrication of the textile antennas are studied.

(j) Finally if textile antennas are to become a revolution in modern technology, automation should be introduced in its production. A novel method is introduced in this dissertation that provides scope for automation in wearable antenna production. This is achieved by eliminating the tasks of positioning and fastening of components of the antenna as would have been the case otherwise.

Figure 1.6 Research contribution in this dissertation
1.5  THESIS ORGANIZATION

The thesis comprises 5 Chapters as depicted in Figure 1.7

Chapter 1 gives an introduction to wearable antennas. Materials used for wearable antennas are discussed in this chapter. Literature review of the advent and growth of research in wearable antennas are presented here. It describes the objective of the thesis and the summary of the other chapters of the thesis.

Chapter 2 provides an analysis on the performance of conformal wearable antennas. Usage of approximations of human body phantoms for the on-body analysis is discussed in detail. Conclusions drawn on the selection and placement of antennas on the human body are derived in this chapter. A novel design of a dual frequency wearable antenna is presented in the later part of this chapter. The designed antenna’s performance is investigated under real time deployment scenario by subjecting it bending, crumpling, wrinkling and moisture. Also effects of the human body on the antenna’s performance are studied.

Chapter 3 describes a statistical method for the evaluation of the performance of textile antennas under deployment scenario. The conditions that are studied are bending, crumpling/stretching and shear. The work is extended to bring out an empirical relation between deployment conditions and the response of the antenna. These studies are performed by conducting experiments on a novel dual frequency textile antenna.

The next section of this chapter focuses on the performance enhancement of textile antennas through the design and analysis of a novel dual frequency textile antenna backed by dual frequency electromagnetic bandgap structure (EBG). Evident improvement in the performance of the textile antenna under real time deployment scenario is noticed and the results are presented.
Chapter 4 deals with the various fabrication techniques and materials for textile antenna design. The main objective of this chapter is not investigating the various designs of wearable antennas but to increase the wearability of the same. Here substrate materials and their application are
thoroughly investigated. Various methods for manufacture of the conductive material are also done and important conclusions are drawn.

Chapter 4 finally presents a unique first of its kind fabrication technique for the fabrication of textile antennas. The major advantage of this fabrication method is the possibility of automation of the production of wearable antennas. The technique employs multi-layer weaving for the production of a wearable antenna on a cotton substrate.

Chapter 5 discusses the overall summary, the salient features of the thesis and also presents the future scope of this work.