CHAPTER I

INTRODUCTION TO THE RESEARCH PROBLEM

1.1 WEARABLE ANTENNA- AN INTRODUCTION

The beginning of the century witnessed an exponential proliferation in wearable devices and technology due to the surge in generation and communication of information. A wearable device with its electronic and computational capabilities are "subsumed into the personal space of a user and utilizes the advantage of operational and interactional constancy, i.e., always accessible" [1, 2]. In the recent years, wireless wearable devices have demonstrated enormous potential to provide unprecedented opportunities for monitoring real-time healthcare, fitness, sports, defence strategic sectors, Internet-of-Things (IoT) and specially for people who are on move or staying in remote areas [3].

Wearable devices have the capability to communicate with external devices through their embedded wireless modules comprising of battery, sensors, antenna, and related electronics. Antennas are one of the most vital components of this communication system, also known as Body Centric Wireless Communication (BCWC) [4]. BCWC entails wearable antennas which are required to be conformable enough to tolerate the degrading effects whilst being placed on non-planar surfaces and due to human body-movements. The need to develop flexible and wearable antenna designs with desired characteristics are demanded in this body-centric wireless network domain also more commonly known as Wireless Body Area Network (WBAN) [5].

Patch antenna, in general, comprises of conductive materials for radiating patch element and ground plane and non-conductive materials for substrate. Wearable antenna specifically demands that the mechanical properties of these materials be capable enough to adjust under conditions such as bending, crumpling, and stretching [6]. Apart from the mechanical properties, the electrical properties of the substrate such as permittivity, loss tangent, and conductivity in case of patch and the ground plane must be suitable in the desired frequency range as they have a considerable impact in the antenna characteristics such as gain and efficiency [7, 8]. Researchers in the domain of wearable antennas have employed textile based [9], polymer based [10] and paper-based materials [11] as substrates.

Nonconductive textile material that are usually used in the design of wearable antennas are felt [12], silk [13], nylon [14], leather [15], wash cotton [16], denim [17] and fleece [18]. Textile antennas made of fabric materials are prone to moisture absorption and conductive E-textiles possess low conductivity [6]. Paper based substrates have also been demonstrated in literature [19], however their practical applications are limited owing to their low mechanical strength [20]. The polymer-based substrates due to their robustness, flexibility, wettability, and stretchability have been able to cater the requirements of the wearable antennas [21]. Polydimethylsiloxane (PDMS) [22], silicone rubber [21], Ethyl Vinyl Acetate (EVA) [23], Linear Low-Density Poly-Ethylene (LLDPE) [24], Polyethylene terephthalate (PET; polymer used as textile material) [25], Polyethylene Naphthalate (PEN) [26] and Kapton [27] are some of the commonly used polymer substrates. The polymer class of materials have low surface energies, and adhering conducting layers to it is generally difficult [28].

The conducting layers vide the patch and ground plane are inevitable components of a microstrip antenna. Moreover, flexibility in antennas require proper adhesion of these conducting layers to the flexible substrate such that it can withstand repeated bending cycles throughout its lifetime and hence decides its suitability for BCWC. This poses a major challenge in fabricating wearable antennas. Flexible conductive materials can be classified into categories, as non-metallic, metallic, and liquid metals. Non-metallic conducting materials such as electro-textiles or conductive fabrics [29], conductive polymer composites [30] and polymers loaded with conducting nano-composites (CNT, Ag nano-particles, graphene fibres) [31] are being used in the flexible antennas. However, their intrinsically low conductivity values limit the antenna's efficiency [32]. Liquid metals do have higher conductivity [33] and have been utilized as conducting elements in antennas [34], although the cost and difficulty in fabrication of such antennas adds to its challenges. Metallic layers have been the most common choice in traditional antennas. Nevertheless, integrating metal layers to the flexible substrate, mostly polymers, is a major hindrance in fabricating such antennas. Although some literatures have dealt in improving the adhesion between metal and polymers, there has been a disadvantage of low efficiency and gain exhibited by the antennas [35]. There are several reports focused on different fabrication techniques like screen printing [36], inkjet printing [37] and embroidery [38]. Thus, selection of the suitable material and their overall integration is the first challenge towards developing a wearable antenna.

The performance of the antenna degrades when subjected to bending [39]. Most importantly, the resonant frequency shifts depending on the plane of bending [40]. The shift may sometimes be as high as to interfere with the nearby communication bands leading to operational issues. Similarly, bending also effects the radiation pattern, polarization and the gain of antenna to quite an extent [6]. Minimizing the susceptibility in terms of shift in frequency has been attained by ensuring a wideband operation [41], and by using Artificial Magnetic Conductor (AMC) [42] and Electromagnetic Band Gap (EBG) [43] structures. Alternatively, reconfigurations techniques using PIN diodes [44] and by injecting liquids [45] have been reported to mitigate the shift in frequency. The techniques are mostly externally aided, i.e., auxiliary components need to be integrated with the antenna, making it either bulky or less flexible or at times affecting its performance or combination of all the three. As in an article by Long et. al. reported a substrate-integrated compensation mechanism, wherein capillary is integrated in the substrate. Post-bending a colloidal solution was injected into the capillary to undo the shift in the frequency [46]. The technique was demonstrated for a fixed angle and required an external injection system. Origami based reconfiguration has also been explored in many literatures, which are based on paper substrates that limits the mechanical strength of the antenna developed on it [47]. Mitigating the detuning effects of bending while sustaining the conformability and compactness of the wearable antenna thus holds a precinct of interest for researchers.

WBAN devices are often used in proximity to human body [40]. Human body being a conducting dielectric lossy medium [48] ensues some interaction when any WBAN system is placed in vicinity to it. Body part is made up of different type of tissues which will influence the extent of interactions. Thus, evaluation of the performance parameters of the antenna as a function of the human body variables are of prime importance in wearable antenna characterization. To comprehend the performance variation and suitability of wearable antennas, testing over free space is not sufficient, and therefore researchers have resorted to replicating human electromagnetic models commonly known as phantoms, which can be further classified as numerical phantoms [49] and physical body phantoms [50]. Testing the designed antenna over these phantoms have led to understanding of the interactions of the human body and the antenna although not much consideration has been shed on the variation of the antenna performance with variation in body dimension.

Reciprocally, back radiations emanating from a WBAN antenna and directed towards the human body has detrimental effects on the body. A measure of the radiations absorbed by the human body is quantified by Specific Absorption Rate (SAR). SAR compliance specified by organizations such as International Commission on Non-Ionizing Radiation Protection (ICNIRP) assures safety limit to avoid damage to human tissues. SAR limit for head tissue is 2 W/kg and for limbs it must be below 4 W/kg averaged over 10 gm of the tissue [51]. Most of the reported techniques for reducing back radiations may be classified broadly into three categories - first technique is by creating an additional field that compensates the radiations directed towards the human body by structural modification of the radiating element or ground plane [52, 53, 54]. Second technique used is through surface wave degradation by use of artificial materials like Electromagnetic Band Gap (EBG) material, Artificial Magnetic Conductor (AMC) or resistive surfaces [55, 56, 57]. The third category is through absorption of waves by use of shielding materials which exploits the dielectric, magnetic, conducting losses and/or negative refractive index property of the shields [58]. The primary challenge in incorporating any of the techniques is its integration with the WBAN antenna system whilst retaining the compactness, conformability, and comfortability of the device. The other challenge is the effect of the implemented technique on the antenna performance mainly -10 dB impedance bandwidth, gain and directivity.

1.2 OBJECTIVES OF THE RESEARCH WORK

The design considerations and subjects highlighted in the review of literature, fetches certain generic requisites that may be emphasized upon for WBAN applications. As such, a wearable antenna is entreated to be -

- compact and flexible enough with good adhesion strength between the layers
- less prone to performance variation with bending
- consistent in terms of its impedance bandwidth, gain and directivity when in proximity to a human body
- electromagnetically well isolated from the human body exhibiting low back radiation penetration and SAR.

In view of these challenges and the current state of the art, the following objective have been formulated –

A. Development of a flexible, robust antenna system for wearable purposes.
B. Mitigating the detuning effects of bending.
C. Study of the effects of the human body on the developed wearable antenna.
D. Back radiation reduction and evaluation of SAR of the developed antenna for compliance as per international standards.

1.3 THESIS STRUCTURE AND OUTLINE

Modern day wearable technology is not just limited to entertainment and fashion industry, but also has penetrated the healthcare sector, military communications for warfare and combat, including for rescue and security purposes [6]. X-band (8.2 GHz to 12.4 GHz) is primarily used for maritime, aeronautical and defence communications [59]. Commercial X-band Point-to-Point communication channel has in the recent time also been considered as an alternative to nearby bands due to its higher spectral efficiency, less susceptibility to rain fading and less interference in terms of satellite separation [60]. Therefore, considering the enormity in applications, the current study is carried out at X-band, however, the study is not limited to the band and can be re-designed at any desired frequency range.

As per the formulated objectives, the thesis has been organized into six chapters. In the current chapter an introduction to wearable antenna, its design challenges, along with a review of literature and state of the art is presented to devise the desired requirements of wearable antenna technology and thus formulating the research objectives.

Chapter II carries out the selection of the flexible substrate based on its physical and microwave properties. A technique to improve the adhesion between the conducting layer and the substrate layer is developed and tested. Antenna is, thereafter, fabricated on the developed flexible substrate and tested for its performance with bending.

In **Chapter III**, a technique of self-compensating nature to mitigate the detuning effects of bending is developed and implemented. The technique is further optimized, tested, and analysed through field distribution for two orthogonal bending planes.

Development of a physical EM phantom and a numerical phantom is carried out and validated in **Chapter IV**. The effect of human body on the performance of developed antenna using different phantom dimension is carried out.

Chapter V demonstrates a technique to reduce back radiations of the developed antenna prototype through simulation and experimental studies. Evaluation of SAR (simulated) is also carried out.

Chapter VI summarizes the suitability of the developed antenna for WBAN application in X-band.

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