Radiation Pattern Analysis of Single and Multi-Antenna Wearable Systems

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***Abstract*—This paper presents 3D radiation pattern analyses for omnidirectional (dipole) and directional (patch) antennas for various body locations encompassing wrist orientations and chest positions when mounted on a body phantom. In addition to analysing the directivities and relative efficiencies at 2.44GHz for different body positions, the study considers Sector and Slice analysis of the radiation patterns. In Sector analysis, the directivity is averaged for 12 azimuth-elevation sectors, while in Slice analysis, it is averaged for 28 azimuth sectors over the full elevation. It is shown that the antenna efficiency due to body blockage can be as low as 23% relative to the chest position efficiency, and directivities ranges from 5.4 to 10.5dBi for the antennas at different orientations. The Sector analysis identifies highest average signal levels, which are between table and door height for the dipole and above door height for the patch. The Slice analysis, which doesn't account for access point or user heights, shows average directivities that peak at 5.1 and 4.4dBi for the dipole and patch antenna, respectively. Using these antennas as part of a switch diversity system would improve the average directivity by approximately 7dBi in regions of low signal levels, and hence are potentially useful for wristbands and smart clothing.**

Keywords—3D Radiation Pattern; Directivity; Polarization; Phantom; Sector Analysis; Slice Analysis; Multi-antenna system

I. INTRODUCTION

Wearable systems for remote health monitoring and fitness applications are increasingly becoming an integral part of our lives. Industry giants like Apple, Samsung and Nike, are driving the market of wrist-mounted wearables catering to communication, multi-media and health applications. In addition to corporates, governments over the world are also investing in remote health monitoring systems (RHM) and have designed national and regional policies to develop e-health as a viable alternative to in-person hospital care. The development of such RHM options requires an efficient system design and detailed analysis of the antennas used at both sides of the link. It therefore becomes imperative to study the effect of body movements, postures and orientations on the radiation patterns. In wearable systems, the key challenges to an efficient wireless link are: (a) Signal drop due to body shadowing [1], (b) Polarization misalignments [2] due to body movements and postures and (c) Antenna detuning due to body proximity [3-5]. In recent times, a number of publications [6,7] have focused on off-body channel measurements, modeling and comparison of antennas along with a detailed investigation into the off-body links for wrist mounted antennas. Efficiency and radiation patterns determine the performance of an antenna in a wireless system. As highlighted in [8], 3D radiation patterns are often overlooked, in favour of 2D patterns. An analysis of 3D radiation patterns is important because of the fact that an incoming wave can be any direction in a multi-path environment and not necessarily in the principle planes. The current study focuses on developing an analysis method (sector [9] and slice) for 3D radiation patterns, to determine average directivity and the variations in relative efficiency for different body positions [10] and postures, resulting in polarization misalignments and body shadowing. The reasons for choosing these three antenna characteristics namely average directivity, relative efficiency [11,12] and polarizations [13] as performance metrics are detailed in the next sections.

The remaining paper is organized in four sections. Section II titled Measurement Procedure discusses the methodology used for the measurements and the analysis. Section III is Radiation Patterns and Analysis, which discusses the radiation pattern and provides a detailed analysis of power distribution and directivity through sector and slice analysis. Section IV titled Multi antenna system discusses possible antenna configurations to improve average antenna directivity, particularly in the regions on concerm. Section V provides the final conclusion of the study and Section VI describes the future work that will be carried out.

II. MEASUREMENT PROCEDURE

The on-body antenna is influenced not only by the electro-magnetic properties of the human tissues but also by local factors such as body shadowing, reflections, diffractions and scattering, which are mainly attributed to the body shape and orientation. It therefore becomes imperative to model the human body for an in-depth analysis of the performance of wearable antennas. Ideally, the designed phantom needs to be an exact copy of the human body, with similar dielectric properties. However as the focus of the current study is analyze antenna characteristics as a function of body proximity, orientation and shadowing, the designed phantom is sufficient for all possible measurements.

A. *Human-Body Phantom*

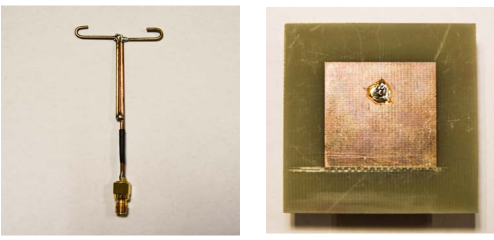
The advantages of a phantom over an actual human subject are: (1) Ease of generating 3D radiation patterns in the available experimental setup, (2) Repeatability of measurements and (3) Statistically significant results. The various types of human body phantoms along with their manufacturing procedure is discussed in [14]. Liquid and semisolid (gel) phantoms are unsuitable for 3D pattern measurements because the electrical properties will change as they are rotated. The designed phantom differs from the conventional solid (dry) designs as it is made up of two parts, with individual specifications: (1) Wrist and (2) The torso and arms. The tissue emulating wrist (2/3rd muscle equivalent phantom) is made from a mixture of polythene powder, TX151, and water to have dielectric properties similar to skin, fat and muscles. Its dielectric properties at 2.44GHz are given in Table I. The torso and the arm are made of plastic cylinder with an outer lining of thin radiation absorbing material (RAM) and a tube respectively, as shown in Fig. 2b. The diameter and the height of the phantom is 32 and 47 cm respectively.

Table I: Dielectric Properties at 2.44GHz

Relative Permittivity (ε_r)	1.5
Conductivity (σ) (s/m)	41.6
Attenuation (dB/cm)	3.7

B. *Measurement Process*

The radiation patterns are measured in an anechoic chamber, by placing the Antenna Under Test on the wrist and chest of the phantom, which is then mounted on a turntable and rotated with 1° steps in elevation plane and 10° steps in azimuthal plane. This is done to integrate the effect of local environment on all antenna measurements. The received power is measured from a transmitting horn antenna in each polarization. The on-body antenna is the receiver and is either an Omni-directional (half wavelength dipole) or a Directional (Patch on FR-4 substrate) antenna, as shown in Fig. 1. Both the antennas are matched with a return loss lower than -20dB at 2.44GHz.

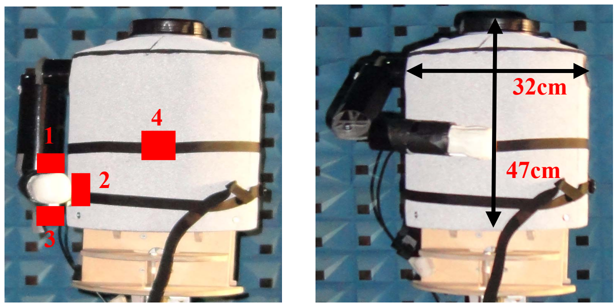


(a) (b)

Fig. 1: (a) Half-Wavelength Dipole Antenna & (b) Patch on FR-4 substrate

C. *Types of Measurements*

The effect of the local environment (torso and arms) on a wearable antenna is studied for different body positions and orientations as shown in Fig. 2. The different wrist positions are: hand *forward* (or handshake position) and hand in *front* of chest / torso. Further, for each of these positions, different orientations are studied, which are: Antenna on (1) Top, (2) Side and (3) Bottom of wrist. In addition to wrist, the antenna is also placed on the chest (4). Table II lists body positions and corresponding maximum directivity in Vertical Polarization (D_V), Horizontal Polarization (D_H), Total Directivity (D_T) and Percentage Power contained in Vertical Polarization (P_V). Antenna efficiency for different wrist positions is determined relative to that of the chest location, which indicates how it changes as the wrist moves in space.



(a) (b)

Fig. 2: (a) Handshake: **Forward** and (b): Hand in front of chest: **Front**. The four red blocks correspond to different antenna positions: **Top (1), Side (2) & Bottom (3) of Wrist and Chest (4)**.

Table II: Antenna Characteristics for Dipole and Patch Antenna for Different Wrist Positions

Wrist Orientation	Dipole Antenna				Relative Efficiency (%)
	DV (dBi)	DH (dBi)	DT (dBi)	PV (%)	
Forward- Top	6.0	7.6	8.0	38	73
Forward-Side	8.8	-1.7	8.8	91	60
Forward-Bottom	6.8	7.8	7.9	29	69
Front- Top	4.5	5.4	5.4	36	70
Front -Side	8.0	2.1	8.0	75	38
Front -Bottom	6.9	5.9	7.6	34	51
Chest	-1.3	8.1	8.2	11	100 (Ref)
Wrist Orientation	**Patch Antenna**				**Relative Efficiency (%)**
	DV (dBi)	**DH (dBi)**	**DT (dBi)**	**PV (%)**	
Forward- Top	8.6	9.2	9.4	49	100
Forward-Side	1.7	7.7	7.7	19	78
Forward-Bottom	8.8	8.4	8.9	47	100
Front- Top	6.7	10.1	10.2	42	85
Front -Side	0.8	7.3	7.3	15	23
Front -Bottom	7.6	10.1	10.5	47	88
Chest	7.8	-0.5	7.8	90	100 (Ref)

The variation in total directivity, power content in the polarizations and relative efficiency is observed in Table II. The total directivity of the dipole antenna and patch antenna varies from 5.4 to 8.8dBi and from 7.3 to 10.5dBi respectively, as the arm moves and rotates. The standard deviation for total directivity is found to be higher for Patch antennas. It is also observed that the relative antenna efficiency has a higher standard deviation for Patch (28.8) as compared to Dipole Antenna (13.5). Therefore, it can be safely assumed that wrist mounted Omni-directional antennas show less variation in relative antenna efficiencies for different orientations and movements. However, despite the higher standard deviation, the relative antenna efficiency of the patch is higher than that of the dipole for majority of the cases. The relative gain patterns for total power for a dipole antenna for different body locations and wrist orientations are provided in Fig. 3. The patterns are colour coded to reflect the two orthogonal polarizations.

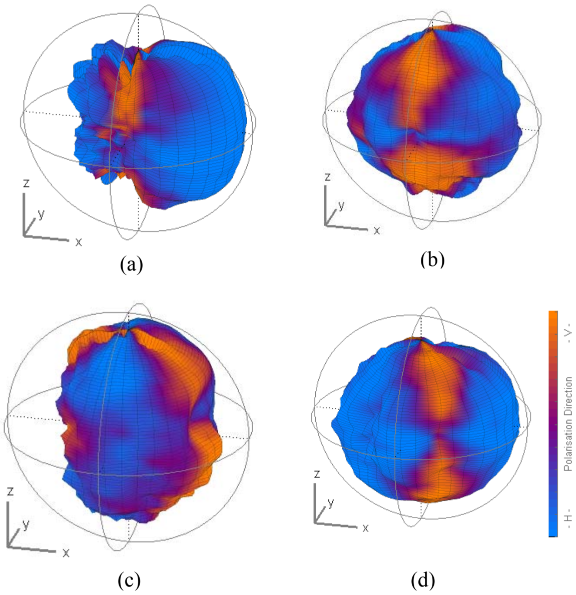


Fig. 3: Dipole Antenna on: (a) Chest, Top of wrist: (b) Hand forward, (c) Hand in front of chest, and (d) Side Arm-top.

As shown in Fig. 3, the radiation pattern changes as the location on the body is changed. The extent of this change is determined by correlating the wrist pattern with that of the chest position. The correlation coefficient for dipole antenna varies from 0.3 (hand in front of chest with bottom wrist orientation) to as high as 0.9 (side-arm, antenna on top position). On the other hand, the patch antenna shows less variation in radiation patterns and varies from 0.5 to 0.9, for the same positions. It is worth mentioning that due to body proximity, any on-body antenna essentially behaves likes a directional antenna. However, the effect of directionality is more profound when the antenna is placed on the chest.

Total Directivity or maximum directivity can be because of spike in power at one particular point in the space around the antenna. Further, the direction of maximum directivity may or may not be in the direction of access point. The study therefore proposes the use of average directivity as a performance metric instead of maximum directivity. The method of determining average directivity over sectors and slices of the 3D radiation patterns are detailed in the next section.

III. Radiation Patterns and Analysis

In a highly dynamic environment, coupled with different body movements [15], the concept of maximum directivity loses its significance. A wireless wearable system with a highly directive antenna can still have signal outage. This is because an on-body antenna having higher directivity, might still loose connection when it radiates most of its power in a angle away from the AP due to body postures, rotation and shadowing, despite having high directivity. In this section, sector and slice method for determining average directivities is presented

A. *Sector Analysis*

In the sector analysis, 3D radiation pattern is divided into 12 sectors, in such a way that the azimuthal plane is divided into 4 sectors (with the human body at the centre) and the elevation plane into 3 sectors (in accordance to access point height), as shown in Fig. 4. Average directivity is then determined for each of these sectors, with the preferred access point in the sector having maximum average value. Table III lists polarizations, highest sector average directivities and corresponding sectors for different wrist orientations and chest position.

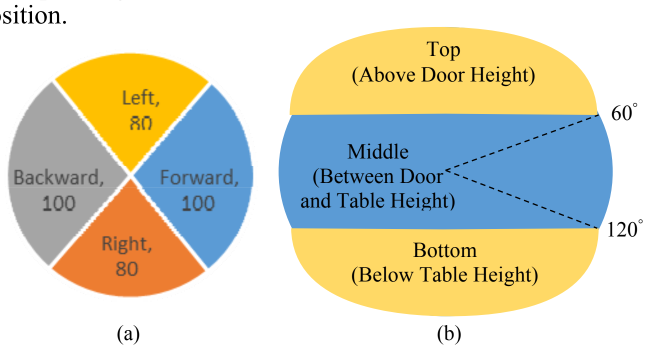


Fig 4: (a) Azimuthal Plane and (b) Elevation Plane

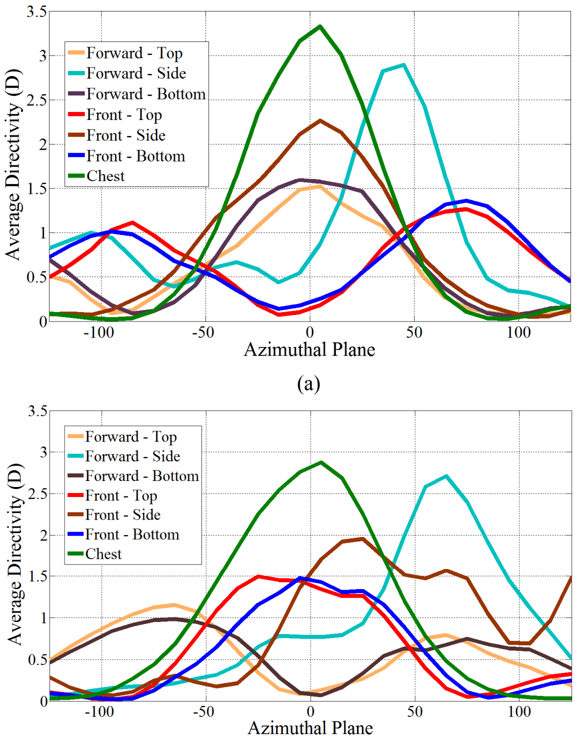
Table III: Preferable Access Point Locations for Antenna Positions

Dipole Antenna			
Antenna / Wrist Location	**Polarization**	**Average Directivity**	
		dBi	**Sector**
Forward-Top	Horizontal	3.6	Top-Forward
Forward-Side	Vertical	3.4	Middle-Forward
Forward-Bottom	Horizontal	3.4	Bottom- Forward
Front-Top	Horizontal	3.4	Top-Right
Front-Side	Vertical	4.4	Middle-Forward
Front-Bottom	Horizontal	3.1	Bottom-Left
Chest	Horizontal	5.1	Middle-Forward
Patch Antenna			
Antenna / Wrist Location	**Polarization**	**Average Sector Directivity**	
		dBi	**Sector**
Forward-Top	Horizontal	5.1	Top-Forward
Forward-Side	Horizontal	4.3	Middle-Right
Forward-Bottom	Horizontal	4.5	Bottom- Forward
Front-Top	Horizontal	6.8	Top-Forward
Front-Side	Horizontal	1.7	Middle-Right
Front-Bottom	Horizontal	5.9	Bottom-Forward
Chest	Vertical	5.5	Middle-Forward

It is observed from Table III that for an Omni-directional (dipole) and Directional (patch) antenna, the average of the sector average directivity is 4.4 and 6dBi, respectively, which corresponds to an Access Point located Between Door and Table Height and Above Door Height respectively for the two antennas. It can be safely assumed that sector analysis method gives a better indication of the achievable directivities as compared to using total directivity for Omni-directional (Mean: 7.8dBi) and Directional antenna (Mean: 9dBi). Further, changing the location of an access point, results in a lower standard deviation for Omni-Directional antenna as compared to Directional antenna. The benefit of 'Sector analysis' is that it helps in determining useful pattern sectors with higher power concentration, however, it is still an average over larger angular spreads, and is incapable to reflect on the details associated with smaller angles, wherein the directivity or the received power might fall below a particular threshold resulting in signal outage. Therefore, 'Slice Analysis' is developed for a detailed understanding of such issues

B. Slice Analysis

In the slice analysis, radiation pattern in the azimuthal plane comprising of left, forward and right sections (Fig 4a) is combined and divided into slices of 10° width. The directivity is determined by averaging over the entire elevation plane of these slices. This is done to take into account different height variations that an on-body antenna might go through. The variation of average directivity with azimuthal angle is shown in Fig. 5. The best average directivity is obtained when the antenna is placed on the chest, and is found to peak at 3.25 (5.1dBi) and 2.75 (4.4dBi) for Omni- and Directional antenna, respectively.



(a)

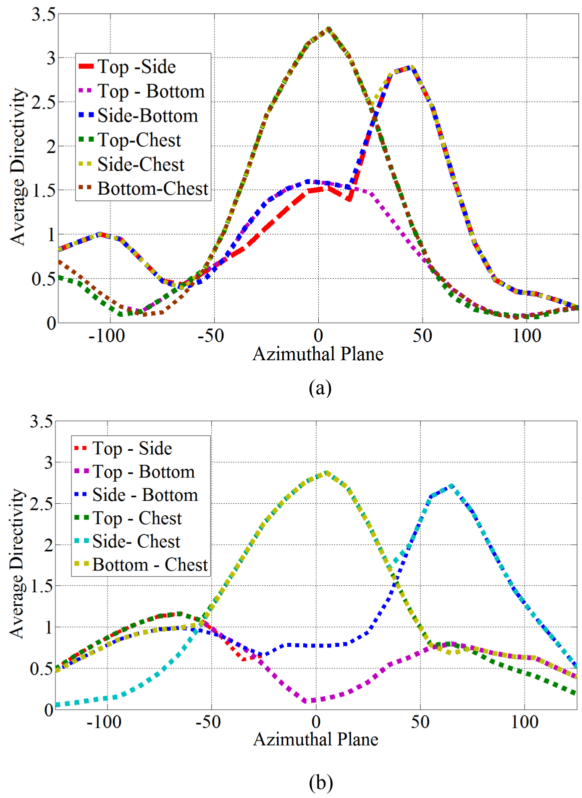
(b)

Fig 5: Average Directivity vs Azimuthal Angles for: (a) Dipole Antenna and (b) Patch Antenna

The slice average directivity is a more robust performance metric as it doesn't take into account Access Point and user height. This analysis shows the variation in directivity as a hand/wrist moves in space. In Fig. 5, it is observed that the forward region in the azimuthal plane, extending from -50° to +50°, usually has higher values of average directivity, irrespective of the Access Point Location. The study concentrates on those regions, which are essentially outside the aforementioned azimuthal angles. Using the slice analysis method, thresholds limits are determined for average directivity values, which is 0.02 (-17dBi) for both Omni-Directional (dipole) and Directional (patch) antenna. Such a characteristic is usually missing from antenna specification sheets, but is important for an on-body antenna operating in a dynamic indoor environment. Further, the slice analysis method also demonstrates that the overall average directivity can be significantly improved by employing antenna diversity.

IV. Multi Antenna Wearable Systems

A multi-antenna wearable system can have antennas arranged in various combinations: Wrist Top & Side, Wrist Top & Bottom, Wrist Side & Bottom, Wrist Top & Chest, Wrist Bottom & Chest and Wrist Side & Chest (as shown in Fig. 2). Such a system would be driven by either synchronized transmission or selection combining. In former, data will be transmitted through two orthogonal antennas, with a safe assumption that at least one of them is connected to the access point. On the other hand, selection combining tracks the maximum value of directivity, allowing the system to switch from one antenna to the other. Figure 6 shows the final directivity of a system with different antenna configurations.



(a)

(b)

Fig 6: Average Directivity for Multi-Antenna System vs Azimuthal Angles for (a): Dipole Antenna and (b) Patch Antenna

It is observed in Fig. 6 that in regions of concern (below -50° and above +50°), the average directivity improved by at least 7dBi for both the Omni- and Directional antennas. Such antenna configurations can be applied to wrist-mounted wearable systems where the antennas are embedded in the band around the wrist. In addition, if the system wants to employ space diversity as well, then Wrist Side & Chest configuration is preferable, which can be employed in smart clothing.

V. Conclusion

The theme of the paper is to analyze 3D radiation pattern of Omni- and Directional wrist or chest mounted wearable antennas, which are studied for different wrist orientations associated with hand movements. A human-body phantom is designed and used to assimilate the effect of body proximity in repeatable measurements. The percent power distribution in the horizontal polarization over different wrist orientations and body positions is 55% for Omni- and 56% for Directional Antenna. In addition to polarization and power content, the total directivity varies from 5.4 to 8.8dBi and 7.3 to 10.5dBi for the two antennas, respectively. The antenna efficiencies relative to the chest location vary with a standard deviation of 14 and 29, respectively. It is also observed that due to body blockage, the relative antenna efficiency can be as low as 23%.

Sector analysis method determines average directivity over certain sectors of the radiation pattern and thereby identifies those, useful for Access Point locations. With this method, the average directivity is found to be 4.4 and 6dBi for Omni- and Directional antenna, corresponding to an Access Point located Between Door & Table Height and Above Door Height, respectively. Further, changing the location of an access point, results in a lower standard deviation for Omni- as compared to for Directional antenna.

Slice analysis method is a further improvement over sector method, as the latter is still based on a large angular spread. This method determines average directivity over the entire elevation plane and presents its variation over the azimuthal plane. The best average directivity is obtained when the antenna is placed on the chest, and is found to peak at 3.25 (5.1dBi) and 2.75 (4.4dBi) for Omni- and Directional antenna, respectively. This ensures a performance metric, which is more robust to body movements and access point heights. The study identifies regions of concern, and establishes thresholds of average directivity (-17dB for both the antennas), which should be used for more efficient link designs.

Finally, the study endeavours to use multi-antenna systems for improving overall average directivity. Selection combining and synchronized transmission is able to improve the average directivity by at least 7dBi. Such antenna configurations can be used in wrist bands and smart clothing.

VI. Future Work

This is a passive study of radiation pattern analysis at 2.44 GHz. However, a system analysis for on-body sensors with these antennas would be conducted for Bluetooth and ZigBee.

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