Performance of a Radiation Pattern Steering On-body Gateway Antenna For On-body and Off-body Propagation

Sema Dumanlı

TRL Toshiba Research Europe, Bristol, BS1 4ND, UK

***Abstract*— Antennas in Body Area Networks (BAN) should be designed according to the link they are expected to form. In most of the systems, an on-body gateway collects data frames from other on-body sensors and relays them to an off-body gateway, realizing two different modes of operation, on-body and off-body. For such a device, the on-body link and the off-body link have different radiation pattern requirements. Moreover the antenna should be designed taking the effects of human body being in the nearfield of the antenna on the performance into account.**

A planar antenna operating in the 2.4 GHz ISM band which can satisfy all requirements by radiation pattern steering with frequency is analysed here in terms of its on-body and off-body propagation performance. Analysis were performed through simulations featuring two layered numerical chest phantoms, one being cylindrical and one being flat. The effects of the antenna - body spacing are investigated through the flat phantom while the on-body and off-body propagation are investigated through the cylindrical phantom.

The antenna is shown to be performing well upto 5 mm spacing. It has been proved that the antenna provides 9 dB advantage in average for the on-body link compared to the case where its off-body radiation mode is used to connect to the on-body sensor and vice versa.

***Index Terms*— Antennas, directional antennas, omnidirectional antennas, patch antennas, body sensor networks.**

I. Introduction

BANs form three types of communication links: in-body, on-body and off body [1]. In-body links are the links formed inside the human body. On-body links are the links formed between on-body devices positioned on the Person Under Monitor (PUM)'s body which can be used to collect continuous data or provide real-time feedback [2]. Finally, off-body links are formed to connect an on-body device to an off-body gateway. Each BAN antenna should be designed to have a radiation pattern optimum for its dedicated link.

On-body gateways form both on-body and off-body links. The antenna for the on-body link should have a monopole-like radiation pattern with vertical polarization with respect to the body surface as discussed in [3] whereas the antenna for the off-body link should have a patch-like radiation away from the body. A single antenna satisfying both requirements is favoured since the size of a small on-body sensor is not sufficient to house two different antennas. The size of the antenna discussed here is 4.5 cm x 1.4 cm x 0.48 cm.

This paper analyses the on-body performance of a novel on-body gateway antenna of which radiation pattern can be changed by switching the channels of the operating band. The antenna model is briefly described in Section II. On-body performance of the antenna is analysed in Section III. An on-body communication scenario is discussed in Section IV. The paper concludes with Section V.

II. Antenna Design

A single layer low profile radiation pattern steering antenna was designed and simulated to be used at the 2.4 GHz ISM band [4]. It is a rectangular patch antenna shorted with 4 pins and excited with a coaxial feed as seen in Fig. 1. It is well isolated from the lossy body tissue by having a ground plane. The overall dimensions of the antenna is 45 x 14 x 4.8 mm. It generates two resonances at two different frequencies with different radiation patterns which are merged very close to each other within the band as seen in Fig. 2.

This antenna is adopted to be used as an on-body gateway

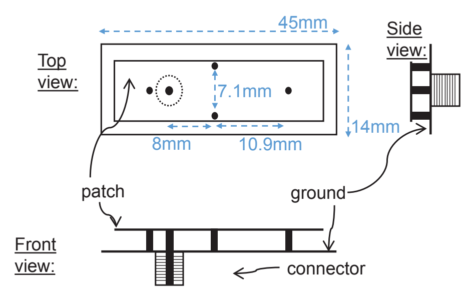


Fig. 1: Antenna model

antenna. 2D radiation patterns at two selected frequency points are given in Fig. 3a and Fig. 3b. For the first selected frequency 2.4 GHz, 2.6 dB maximum gain is observed. There is minimal radiation in the vertical direction with respect to the body surface. That stops energy being wasted in the body or transmitted away from the body. It directs the energy towards the other on-body antennas along the body. Moreover, it has vertical polarization which is favoured over horizontal polarization for on-body

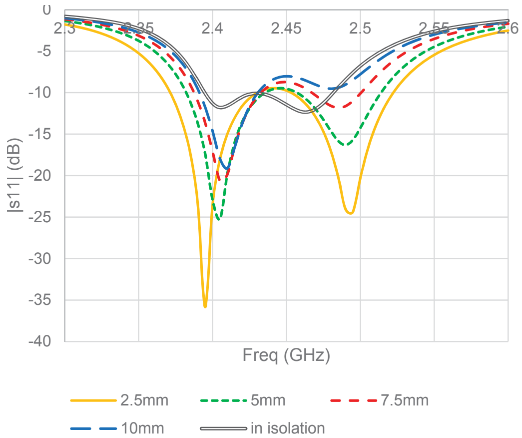


Fig. 2: $|s11|$ vs. frequency for antenna-body separations of 2.5, 5 mm, 7.5 mm, 10 mm and ∞. 82 MHz 10 dB bandwidth from 2.408 GHz to 2.49 GHz, centre frequency of the on-body mode and the off-body mode at 2.42GHz and 2.47GHz

communications due to the excitation of the surface waves. On the other hand, at the second selected frequency 2.48 GHz, the radiation pattern is optimized for connecting to an off-body gateway with 5.8 dB maximum gain. Note that the on-body mode can be chosen over the off-body mode to connect to off-body gateways which are located laterally to the PUM.

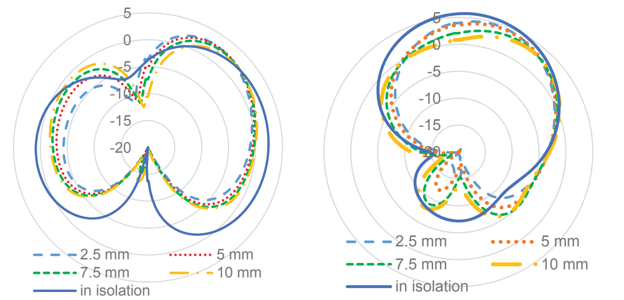
III. ON-BODY PERFORMANCE

The antenna's frequency and radiation characteristics are tested using a layered planar chest phantom, designed in HFSS with 3 mm thick skin and fat and 20 mm thick muscle layers [2]. The antenna body separation is changed with 2.5 mm steps from 2.5 mm to 10 mm and the frequency characteristics demonstrating the two different modes and their frequency coverage for these antenna body separations can be seen in Fig. 2. As the antenna body separation is decreased, the modes are shifted away from each other. The efficiency of the antenna degrades as the separation between the ground plane and the phantom decreases as seen in Table I. This is expected due to the lossy nature of the tissues introduced in the phantom. However, in all cases the efficiency is greater than 50%. We can see that the degradation in efficiency once the antenna is located on the phantom is greater for the off-body mode. This is due to the off-body mode having higher electric field and lower magnetic field in the near-field of the antenna. Note that magnetic near fields are less susceptible to dissipation on human body since human tissues have no magnetic losses $(\mu_r'' = 0)$ [6].

From these analysis, it can be seen that the dual antenna is suitable to be used in an on-body gateway device. An optimum separation of 5 mm is chosen and the analysis are

TABLE I: Radiation Efficiency

	2.5 mm	5 mm	7.5 mm	10 mm	in isol.
2.4 GHz	59	65	70	73	84
2.48 GHz	54	55	59	61	92



(a) (b)

Fig. 3: 2D Gain patterns in dBs at $\phi = 0$ for different antenna-body separations (a): On-body mode of the antenna at 2.4GHz, (b): Off-body mode of the antenna at 2.48GHz

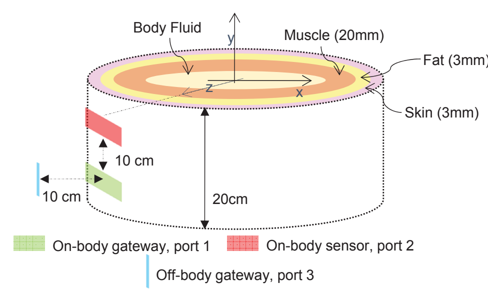


Fig. 4: Diagram of the Propagation Scenario where on-body gateway is transmitting and off-body gateway and the on-body sensor are receiving

extended to a realistic scenario with a cylindrical multi-layered chest phantom, an on-body sensor, an on-body gateway and an off-body gateway in Section IV.

IV. ON-BODY AND OFF-BODY PROPAGATION

The performance of the proposed antenna is tested on a cylindrical multi-layered chest phantom. Different numerical phantoms have been reported in the literature from simple flat uniform models to MRI based voxel models [7].Considering that the physical properties of individuals vary drastically, an average model is selected to be appropriate for this case. The height of the modelled chest phantom is taken to be 20 cm with major and minor diameters of 35 cm and 17.5 cm. The rest of the phantom is filled with body fluid. The dielectric properties are calculated at 2.4 GHz [5]. The off-body gateway, the on-body gateway and the on-body sensor are located on the sagittal plane of the PUM. The on-body sensor is located 10 cm inferior to the on-body gateway as seen in Fig. 4.

The off-body gateway is located at the same transverse plane as the on-body gateway with 10 cm separation in z direction. The separation is kept small to keep the simulation run time low; however, the results are scalable for Line of Sight (LOS) scenarios. In the simulation set-up, a half wavelength dipole antenna with almost flat frequency response over the ISM band is used for the off-body gateway. The proposed beam steering antenna is used both for the on-body gateway and the on-body sensor.

As expected, the existence of these modes result in big variations in the transmission coefficients across the band. The on-body link |s21| reaches its maximum at the lower end of the ISM band and decreases quickly as the frequency increases. Similarly, the off-body link |s31| peaks at the higher end of the ISM band and decreases as the frequency decreases. The transmission coefficients across the ISM band are plotted in Fig. 5. |s21| is approximately -21 dB 2.4 GHz, and the variation is approx. 3 dB up to 2.425 GHz. For higher frequencies, the transmission coefficient decreases drastically. At 2.465 GHz, the received power level of the on-body sensor is 12.8 dB less than that of 2.405 GHz. That is due to the radiation pattern contribution from port 1 at ϕ_1=0^0 θ_1=90^0 and from port 2 at ϕ_2=0^0 θ_2=-90^0. The gain could be even higher if the antennas were located in such a way that their beams at their maximum radiation direction (θ_1=90^0, θ_2=90^0) directed towards each other. However, an average performance is investigated here since the best case scenario as such cannot be maintained for each on-body link if there are multiple on-body sensors. The $|s31|$ values peak at the higher end of the frequency band where the maximum radiation direction of the on-body gateway θ_1=0^0 is towards the off-body gateway. As mentioned in Section II the antenna switches to the off-body mode starting from 2.425 GHz up to 2.48 GHz. As seen in Fig. 5, the variation in the received power levels is less than 3 dB across these channels. However it decreases quickly once the frequency is below 2.425 GHz. At 2.395 GHz, the received power level of the off-body gateway is 8 dB less than that of 2.485 GHz.

If the on-body gateway was only optimized for the on-body mode, the off-body link performance in the whole frequency band would be similar to the poor performance at the lower end of the frequency band. Likewise, the poor $|s21|$ values observed at the higher end of the frequency band would be the typical quality of the on-body link, if the beam was only optimized for the off-body mode.

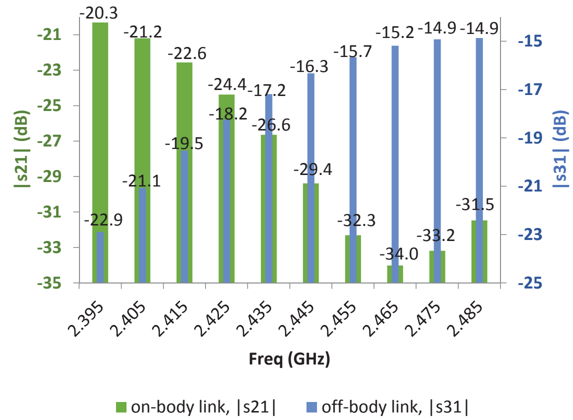


Fig. 5: $|s21|$ and $|s31|$ vs. frequency, the received power levels of the on-body sensor and the off-body gateway

V. Conclusion

A low profile radiation pattern steering antenna which has the ability to accommodate both an on-body mode and an off-body mode has been analysed in this paper. At the lower end of the frequency band up to 2.425 GHz, the antenna generates nulls away from the antenna's main axis which is suitable for on-body communications. On the other hand, for the rest of the band, a directional radiation pattern away from the antenna's main axis is formed which is optimum for off-body communications. For BAN performance analysis, a realistic scenario where an on-body gateway transmits energy to an on-body sensor and an off-body gateway on a cylindrical body phantom is simulated. It has been shown that the antenna provides more than 10 dB advantage for the on-body link compared to the case where its off-body radiation mode is used to connect to the on-body sensor. More than 8 dB advantage is achieved for the off-body link compared to the case where its on-body radiation mode is used to connect to the off-body gateway. This diversity can also be used for interference rejection in multiple off-body gateway scenarios.

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