Design of a Cardiopulmonary Antenna for Vital Signs Monitoring Robust to Different Subjects

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***Abstract*—With the advancement of wireless diagnosis and treatment technologies, antennas deployed close to the human body are now widely used. The use of on-body antennas, along with other technologies, presents itself as an innovative method for detecting and monitoring vital signs. These antennas can be attached directly on the body or on clothes, making it comfortable to use and less invasive when compared to conventional methods, allowing at-home monitoring of elderly patients or high risk workers with a single antenna. In this paper, a robust high bandwidth patch antenna was developed to operate in the dedicated Industrial, Scientific and Medical frequency band, namely at 2.45 GHz, capable of monitoring vital signs in any subject. This work presents the design and results of a robust cardiopulmonary antenna, to be further used to monitor the respiratory rate of five different subjects, each one with different physiognomy.**

***Index Terms*—On-body antenna, patch antenna, high bandwidth, vital signs.**

I. INTRODUCTION

Respiratory diseases have a major effect on society, as over 3 million deaths are associated with chronic respiratory diseases [1]. As a primary approach, there is a need for monitoring non-critical patients at their homes and thus preventing the hospitals congestion. That way, by creating a reliable home healthcare device it is possible to reduce unnecessary hospitalizations. Noninvasive vital signs monitoring is becoming a popular theme of various research. Furthermore, the recent advances in integrated electronics and wireless technology, together with the reduced hardware costs, make off-the-shelf devices available directly for the not-specialized final user. Thus, home systems are becoming popular for monitoring known syndromes where intrusive and uncomfortable traditionally prescribed chest-strap monitors could be replaced by methods that are more adequate for the subjects [2], [3].

The use of on-body antennas is introduced in [2], [3], where the possibility of measuring vital signs by analyzing the phase variation of the S_{11} parameter is demonstrated and where several antennas types were tested. To be able to capture vital signs, it is necessary to ensure that the antenna is prepared to work in contact with the human body, making its matching an additional challenge. For the vital signs acquisition, and given the results presented in [2], the microstrip patch antenna type was selected to be developed in this work, since it presented a higher accuracy in obtaining the vital signs. The human body have a high impact on the antenna matching [4]. Together with the different physiognomies of each person, creating a standard antenna model is a challenging task. In order to ensure the antenna's matching, increasing its bandwidth presents can be a possible solution. Therefore, this paper presents a model of a high bandwidth microstrip patch antenna capable of monitoring vital signs in any person. For this the method proposed in [5] was implemented and it consists of a main element tuned to the desired center frequency and four parasitic elements that cause adjacent resonances, thus increasing the bandwidth.

This paper is divided as follows: first, the antenna design is presented in Section II. In Section III the influence of the human body on the antenna is presented, as well as the parametric study of the variation of the biological model. The ability of the antenna to monitor vital signs is also verified in simulation. In Section IV, the experimental results obtained on the 5 subjects are presented. Finally, Section V presents the conclusions.

II. CARDIOPULMONARY ANTENNA DESIGN

After choosing the type of antenna to be used, the first tests of the antenna were performed. Likewise, an operation frequency belonging to the ISM (Industrial, Scientific and Medical) band was selected, where the 2.45 GHz frequency presented the best results in capturing vital signs [2]. Initially, a conventional free-space microstrip retangular patch antenna was sized, using the ROGERS RO4725JXR substrate, with $\epsilon_r = 2.55$, thickness equal to $h = 1.54$ mm and loss tangent of $\tan\delta = 0.0026$. The antenna was then placed in contact with the human body. In this stage of the work, it was used a simple 3 layer model consisting of a layer of skin, fat, and muscle. It was verified that the antenna was fully mismatch when it is in contact with the body. Fig. 1 shows the simulated S_{11} parameter, for the free-space and on-body cases.

In order to match the antenna, layers of superstrate, namely ROGERS RO4725JXR and ROGERS RO4360G2, were used to decrease the impact caused by the transition on the propagation medium. After resizing the antenna with the superstrates it was found that the antenna could maintain its matching level while being in contact with the human body model. Thereafter, several tests were conducted to verify the robustness of the

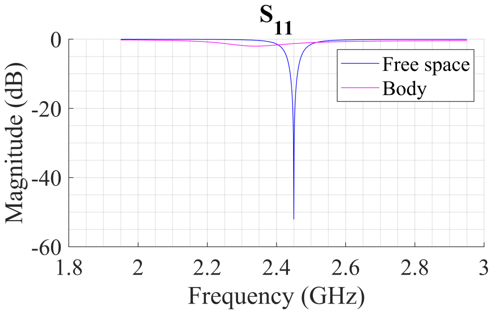


Fig. 1. S_{11} parameter, for the free-space and on-body cases.

antenna S_{11} for different subject physiognomies. For this purpose, the thickness of the human body layers were varied and it was found that the resonance frequency shifted accordingly.

In order to address this varying mismatch, the bandwidth of the antenna was increased. To do this, and as presented in [5], parasitic patches were used to increase the bandwidth of the antenna. Four patches were placed on a ROGERS RO4725JXR substrate, with the same characteristics as the main patch. The presence of the parasitic patches created a second resonance close to the main one, thus increasing the bandwidth of the antenna. To help the increase of the antenna's bandwidth the substrate thickness was also increased to 2.32 mm.

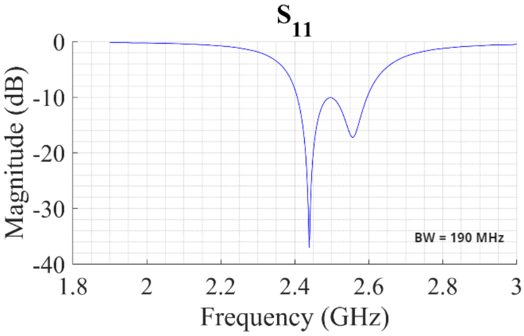


Fig. 2. S_{11} parameter with 4 parasitic patchs.

The bandwidth increase with the use of parasitic patches has been achieved, reaching a value of approximately 190 MHz. As depicted in Fig. 2, the second resonance created a "valley" between resonances, resulting in a point with a S_{11} magnitude not inferior to -10 dB. With the variation of the layers of the human body it was found that in this region the antenna would be mismatched.

In order to compensate this effect, two symmetric slots were added in the ground plane as shown in Fig. 5. Their addition allowed the two resonances to join together, creating a single resonance. Although the bandwidth of the antenna has slightly decreased (down to 170 MHz) as shown in Fig. 3, these values show a considerable increase considering the average values of a microstrip patch antenna of approximately 100 MHz [6].

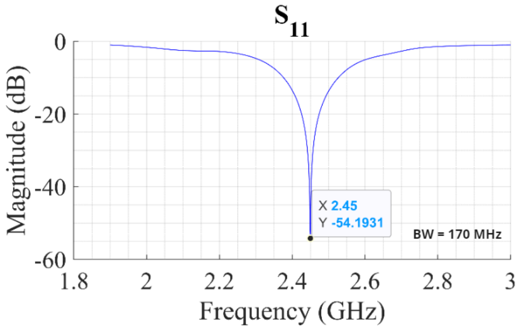


Fig. 3. S_{11} parameter with 4 parasitic patchs and ground plane slots.

For this case, the use of superstrates is also fundamental for the matching of an antenna in contact with the body. A gradient of superstrates was used, trying to minimize as much as possible the transition between propagation medium. For the outermost substrate, which will be in contact with the body, a ROGERS RO4360G2 superstrate block with $h = 5.67$ mm was used, the second block used was ROGERS RO725JXR and was placed between the parasitic patches and the ROGERS RO4360G2 superstrate with $h = 6.24$ mm. Fig. 4 presents the substrate and superstrate configuration of the antenna.

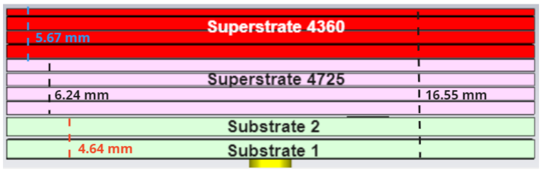


Fig. 4. Substrate and superstrate configuration.

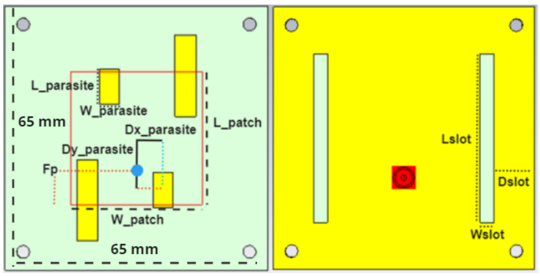


Fig. 5. Parasitic patch and ground slots parameters.

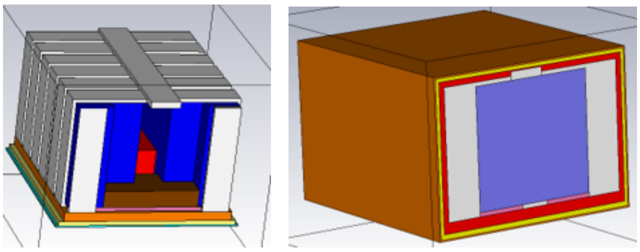
The final parameters of the antenna design are presented in Table I.

In order to reproduce the human chest to be included in the antenna simulation, a cubic model was created. The model consists of initial layers of skin, fat and muscle, where the ribs and their cartilage have been placed. The lungs and heart are also included in the model. Layers of skin, fat and muscle were also placed on the sides and top of the model. Finally, the model was filled with visceral fat in order to best simulate

TABLE I
PATCH SLOT ANTENNA FINAL PARAMETERS.

Parameter	Wpatch	Lpatch	FP	Lparasite1	Wparasite1	Lparasite2	Wparasite2	Dxparasite1	Dxparasite2	Dyparasite1	Dyparasite2	Dslot	Lslot	Wslot
Value (mm)	32.48	32.77	6.6	20.05	5.16	8.66	4.94	19.11	8.34	16.78	10.64	19	41.8	3.5

the human model. The final model is shown in Fig. 6, with the dielectric characteristics of its constituent elements shown in [7]–[10].



(a) Side view; (b) Full view;

Fig. 6. Human chest model considered in the antenna simulations.

III. PARAMETRIC STUDY OF THE ANTENNA IN THE PRESENCE OF THE HUMAN BODY

A. *Influence of biological layers on the antenna matching*

The physiognomy of the human body is different from person to person. This is mainly due to the layers of skin, fat, and muscle. The thicknesses of these layers vary from person to person, as well as their dielectric properties, which vary depending on the age and gender of the subject [11]. In this way, a parametric study of the variation in the thickness of these layers was performed in order to verify their influence on the S_{11} parameter of the antenna. Following the thickness variations presented in [7]–[9], the layers of skin, muscle fat were varied using the model built in CST. It was observed that the layer with the most influence was the skin, as it is the first layer that is in contact with the skin. The variation of the fat and muscle layers have also influence in the adaptation of the antenna S_{11}. Despite the observed variations, the antenna always maintained its adaptation, with the parameter S_{11} always below -15 dB as shown in Fig. 7.

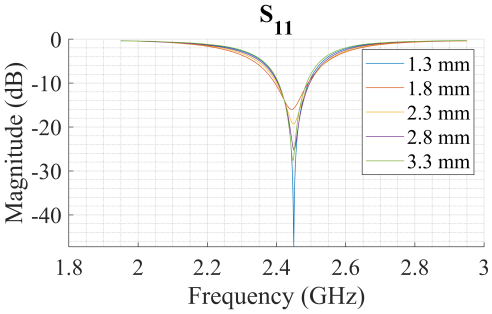


Fig. 7. S_{11} parameter according the variation of the skin thickness.

B. *Cardiopulmonary movement*

The respiratory and cardiac movements cause variations in the size of the lungs and heart, respectively. The breathing motion also cause the dielectric properties of the lungs to vary [10]. A test was performed in a simulation environment in order to verify, to what extent the cardiopulmonary motion affects the phase of the S_{11} parameter. The test consisted in the variation of the lung volume, as presented in [10], which causes the movement of all the constituent layers of the chest and consequently the variation of the dielectric properties, according to [12]. With this test it was possible to verify that the antenna is able to detect variations in the phase of the parameter S_{11}. For instance, the respiratory movement resulted in a phase variation equal to 1.1°. Thus, it was possible to conclude that it is possible to measure the respiratory activity using the developed antenna.

IV. EXPERIMENTAL RESULTS

The cardiopulmonary antenna was manufactured and then tested using the PNA-X (Performance Network Analyzer) N5242A from Keysight. During the evaluation process of the antenna in contact with the human body, the possibility of respiratory rhythm detection was verified. The position of the antenna as well as the force applied against the body proved crucial to capture signals with less noise.

A. S_{11} *parameter results*

In a first stage, the antenna was placed on five subjects with different physiognomies in order to verify its operation by analyzing the S_{11} parameter. In Table II the physical characteristics of the subjects are presented.

TABLE II
PHYSICAL CHARACTERISTICS OF TEST SUBJECTS.

	Rib cage perimeter [cm]	BMI [kg/m^2]	Gender
Subject 1	94	22.4	M
Subject 2	95	23	M
Subject 3	78	18.7	F
Subject 4	89	22.5	F
Subject 5	110	30	M

Fig. 8 shows the obtained results for the different subjects. During testing it was found that the position of the antenna would affect its matching. In order to try to replicate the simulated case, the antenna was placed on the left side of the chest, slightly to the left of the sternum, and the same position was preserved for all subjects. By analyzing the results, it is possible to conclude that the antenna maintained its matching for all the tested subjects, presenting only slight deviations of the central frequency between subjects. Due to those deviations and despite the antenna being initially designed to operate at 2.45 GHz, during the experimental tests it was found that there was a common deviation in the resonance frequency to 2.55 GHz for all subjects, therefore it was the frequency used for the subsequent tests to verify the ability to measure the respiratory signal.

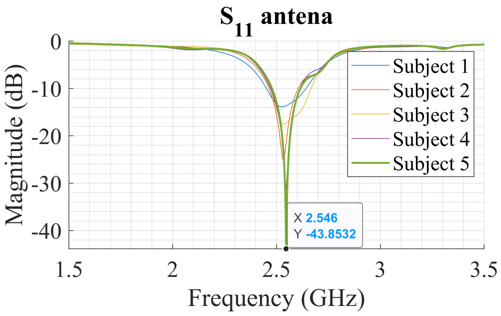


Fig. 8. S_{11} parameter for the five subjects.

B. Acquisition of the respiratory signal

After verifying the antenna operation in contact with the body, the phase variation of the S_{11} parameter was evaluated. For that, and using the PNA-X, a continuous sweep in time domain was performed for 60 seconds and for the frequency of 2.55 GHz. A sampling frequency of 16.67 Hz and an transmitted power of -20 dBm were used.

In order to validate the obtained results a certified measuring equipment was used, namely the BIOPAC MP36. This system is composed of a respiratory band placed around the subject's chest wall. The full measurement system setup is shown in Fig. 9.

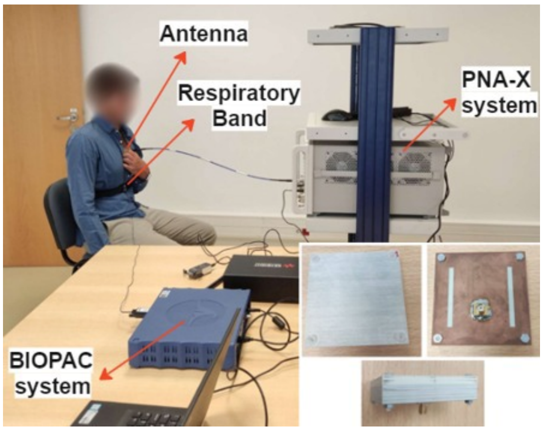


Fig. 9. Experimental setup.

The subject was asked to keep the antenna in the same position and breathing calmly until the end of a sampling cycle. At the beginning of the experiment the subject took a deep breath and held his breath for 5 seconds, thus allowing a synchronization of the VNA and BIOPAC signals during post-processing.

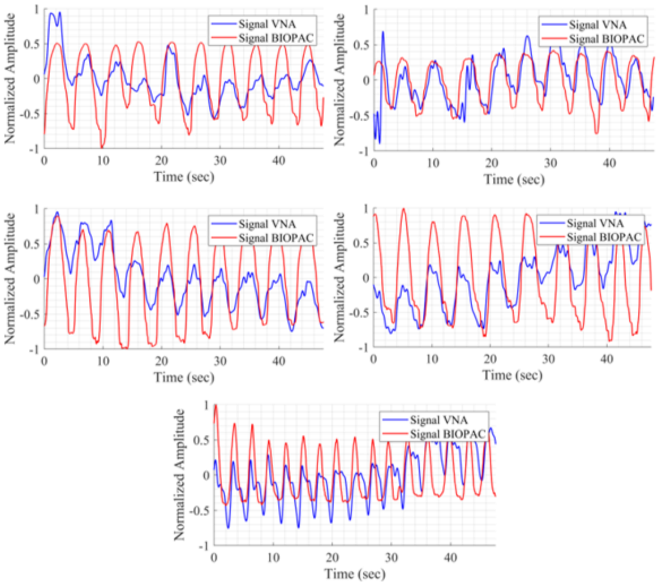


Fig. 10. Respiratory rhythm for all five subjects (1 to 5).

The extracted signals for the different subjects can be seen in Fig. 10. The signals from the PNA-X were post-processed using MATLAB software. A low-pass FIR filter of order 56 and cutoff frequency of 1 Hz was used. Interference caused by gripping the antenna may also cause interference in the captured signals. Not having an optimal point for signal detection can also be a source of noise.

A healthy individual in normal conditions (without physical or psychological exertion) has a respiratory rate between 12 and 20 breaths per minute [13]. On the other hand, it, can reach values of 25 breaths per minute in cases of physical exertion or high levels of stress [13]. For each subject, the respiratory rate was then calculated and the results are presented in Table III.

TABLE III
RESPIRATORY RHYTHM FOR ALL SUBJECTS.

	Respiratory rhythm PNA-X (BPM)	Respiratory rhythm BIOPAC (BPM)
Subject 1	16.34	16.84
Subject 2	11.35	11.13
Subject 3	14.03	14.08
Subject 4	11.6	11.61
Subject 5	20.99	21.04

The values obtained by the antenna are similar with the ones obtained by the BIOPAC system. Table III presents the respiratory rhythm to each subject, consolidating the measurements performed by the antenna, since the respiratory rhythms obtained by the antenna and by the BIOPAC are practically identical, as proved by the MAE (Mean Absolute error) that was obtained, with a value of 0.166 breaths per minute (BPM).

It is possible to verify that subjects 2 and 4 have the lowest respiratory rhythms, being slightly below the average. On the other hand, subject 5 has the fastest respiratory rate, being slightly above the average.

The values obtained during the experimental process are similar with those obtained through the simulations. The differences obtained can be justified by the fact that in the simulation process there are some aspects that cannot be taken into account, namely the influence of external factors, such as the difficulty of keeping the antenna always in the same position throughout the measurements. The presence of the blood vessels or other body components not included in the biological model, may also be a reason for the noise present in the results obtained by the antenna. Although the phase variations observed in the experimental and simulated measures are small (0.86º and 1.1º, respectively), it was still possible to obtain the respiratory rhythm for all subjects.

With these tests it was possible to conclude that the designed antenna fulfilled its objective of detecting the respiratory rhythm, regardless of the person who used it.

V. CONCLUSION

In this work, a robust cardiopulmonary antenna was developed in order to be able to capture respiratory activity in different subjects, each with a different physiognomy. The human body has proven to be an obstacle to the use of a simple patch antenna in monitoring vital signs. Therefore, the bandwidth of the antenna was increased to ensure that it could be adapted to any body physiognomy. For this purpose parasitic patches were used combined with supertrates. The designed antenna was manufactured and tested on five different subjects, measuring the parameter S_{11} and respiratory rate for each. It was possible to prove the operation of the antenna for respiratory rate monitoring, since the results obtained were compared with those obtained by the BIOPAC system. For future tests the immobilization of the antenna, with the subject leaning against the antenna to perform the measurements, will be a possibility to explore. Increasing the number of test subjects will also be a proposal to consider in future work. The use of flexible substrates and the reduction of the antenna size, thus allowing a better placement and comfort of use of the antenna next to the body may be improvements to be made in the future.

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