Embroidered Wearable Antenna-based Sensor for Real-Time Breath Monitoring

Mariam El Gharbi, Raúl Fernández-García, Ignacio Gil

Department of Electronic Engineering, Universitat Politècnica de Catalunya, 08222 Terrassa, Spain
mariam.el.gharbi2@upc.edu (M.E.G.); raul.fernandez-garcia@upc.edu (R.F.-G.); ignasi.gil@upc.edu (I.G)

Abstract

In this paper we present the design and the validation of a novel fully embroidered meander dipole antenna-based sensor integrated into a commercially available T-shirt for real-time breathing monitoring using the technique based on chest well movement analysis. The embroidered antenna-based sensor is made of a silver-coated nylon thread. The proposed antenna-sensor is integrated into a cotton T-shirt and placed on the middle of the human chest. The breathing antenna-based sensor was designed to operate at 2.4 GHz. The sensing mechanism of the system is based on the resonant frequency shift of the meander dipole antenna-sensor induced by the chest expansion and the displacement of the air volume in the lungs during breathing. The resonant frequency shift was continuously measured using a Vector Network Analyzer (VNA) to a remote PC via LAN interface in real-time. A program was developed via Matlab to collect respiration data information using a PC host via LAN interface to be able to transfer data with instrumentation over TCP/IP. The measurements were carried out to monitor the breathing of a female volunteer for various positions (standing and sitting) with different breathing patterns: eupnea (normal respiration), apnea (absence of breathing), hypopnea (shallow breathing) and hyperventilation (deep breathing). The measured resonance frequency shift to 2.98 GHz, 3.2 GHz and 2 GHz for standing position and 2.84 GHz, 2.95 GHz and 2.15 GHz for sitting position, for eupnea, hyperventilation and hypopnea, respectively. The area of the textile sensor is 45 x 4.87 mm², reducing the surface consumption significatively with regard to other reported breath wearable sensors for health monitoring.

Keywords: Antenna sensor, Breath monitoring, Embroidered textile, Real-time.

1. Introduction

Health care expenditures are constantly increasing and take up a large part of the states national budget [1]. One of the current challenges in the state of the art is to investigate new strategies for the implementation of sensors fully integrated into fabrics (clothing, sheets, etc.) that allow monitoring and control in real time the state of health of people with maximum comfort. The benefits of this type of devices would generate an overall improvement of the healthcare system in terms of assistance efficiency and overall cost. During medical care, a vital sign such as breathing is an essential factor that must be continuously monitored [2]. Breathing is a principal physiological task in living organisms and is considered as an indicator of pathological instability such as sleep apnea, asthma, lung disease and cardiopulmonary arrest. Breathing monitoring may be used during the surveillance of patients or for treatment, it also plays an important role in the monitoring of newborns, some of whom are born in sensitive conditions, and this monitoring may avoid any injury due to sleep apnea in infants [3]. Hence, continuous monitoring of respiration is critical to evaluate the subject's health status.

Continuous monitoring of patients using wearable technologies is an important diagnostic technology as it opens a new era for medical assistance in advancing healthcare outside the hospital [4]. Various techniques were proposed in the literature to perform breathing monitoring [5]. To measure breathing parameters a sensor could be an alternative diagnostic device to monitor an important physiological sign for the human being in real-time. There are large differences among techniques determined by sensors and breathing parameters, sensing techniques, sensor locations, processing sensor data, software of analysis, and performance evaluation. In the literature, several non-invasive methods were proposed to monitor breathing [6] such as passive radars, camera-based system [7], optics infrared thermography, Ultra-Wide-Band (UWB) radar, and thermal imaging [8]. The main disadvantage of these techniques is that they require a complex measurement equipment and data analysis and they suffer from the implementation complexity for patients daily use. The most popular contact-based techniques for respiration monitoring are summarized as follows [9]:

- Technique based on air humidity: possible sensors are fiber optic sensors, resistive or capacitive sensors, impedance sensors, nanoparticles and nanocrystal sensors.
- Technique based on respiratory airflow that uses photoelectric sensors, hot wire anemometers, turbine flowmeters and differential flowmeters.
- Technique based on the modulation of cardiac activity: can use radar sensors, PPG (photoplethysmography) and ECG (electrocardiography) sensors.
- Technique based on chest well movement analysis, this technique contains three different measurement approaches: Firstly, the impedance analysis used transthoracic impedance sensors and secondly strain measurement that uses triboelectric nanogenerator, pyroelectric and piezoelectric sensors, fiber optic sensors, resistive and inductive sensors. Thirdly, the movement measurement is based on ultrasonic proximity sensors, magnetometers and gyroscopes sensors, Kinect sensors, accelerometers and frequency shift sensors.

Recent technological advances in wireless communications and microelectronics ushered textiles into a novel era of smart wearable systems. The use of clothing is a major part of people's daily life, and is the most natural form of integrating electronic devices. These garments are often called smart textiles [10]. The latter can be defined as textiles that are able to sense and respond to changes in their environment. Smart textiles present a challenge in various areas such as military [11],
Fashion [12], sport [13] and medicine [14]. Thanks to new developments in textile research, smart textile clothing can now perform continuous monitoring of respiration. The sensing area is either incorporated into textile such as microbend multimode fiber technology [15], sensors based on fiber Bragg grating (FBG) [16,17], piezoelectric sensor [18], or integrated into fibers and threads composing the textiles such as conductive polymers [19] and conductive yarn [20].

For respiration monitoring, wearable devices such as smart T-shirt provides more comfort and user-friendly approaches using embedded sensors. Smart textile sensors have received a lot of research interest for the breath monitoring. A twelve Fibre Bragg Grating (FBG) sensors glued on the elastic T-shirt was validated to monitor breath and heart rates in two different positions standing and sitting [21]. This detection-based technology is complicated and expensive to manufacture the sensors as well as the use of FBG into the T-shirt causes a discomfort to the user when used for a long time. In [22], a spiral antenna-based sensor using multi-material metal-glass-polymer fibers was integrated into standard t-shirt to monitor the respiration rate of an adult. The breathing antenna-based sensor was incorporated into a T-Shirt using cyanacrylate glue. For breathing monitoring using a T-shirt, most researchers have embedded the sensor into the T-shirt with a specific glue.

Nowadays, we are seeing an increasing demand for smart textiles as they can be applied directly to the body for sensing/communicating such as antenna sensors. Wearable antenna sensors have demonstrated a significant impact on the future of healthcare applications [23]. Despite their development, these devices face several challenges related to lack of reliability, rigid form, user convenience and challenges in data analysis that have limited their wide application. In order to address these problems, it is necessary to develop a new reliable and user-friendly approach that allows incorporating antenna-sensors into garments without restricting movement or compromising the comfort of the user. In this work, we have developed a new embroidered meander dipole antenna-based sensor for real-time breath detection of an adult using the technique based on chest well movement analysis. The proposed antenna-based sensor is placed on the middle of the human chest and takes into account the user’s comfort with no movement constraints. The sensing method relies on the resonant frequency shift of the antenna-based sensor induced by the chest movement and the displacement of the air volume in the lungs during breathing. The respiration data information was continuously measured using a Vector Network Analyzer (VNA) to a remote PC via LAN interface in real-time using Matlab. The measurements were carried out to monitor the breathing of a female volunteer for various scenarios (standing and sitting) with different breathing patterns: eupnea (normal respiration), apnea (absence of breathing), hyperpnea (deep breathing) and hypopnea (shallow breathing). The paper is organized as follows: Section 2 describes the mechanism of breathing detection, the design of the proposed antenna-sensor and data collection and treatment. Section 3 shows the results obtained from the controlled experiments and analysis, Section 4 provides the discussion and finally the conclusions are drawn in Section 5.

2. Textile Antenna-Sensor for Real Time Breath Monitoring

2.1. Mechanism of breathing detection

A simplified illustration of the lungs during inspiration and expiration is shown in Fig.1(a). During breathing, the volume of the respiratory system changes due to the movement of the abdomen and chest wall caused by contractions of the intercostal muscles and the diaphragm. The contraction of the diaphragm causes the abdominal organs to be pushed down, causing a decrease in intrathoracic pressure. The diaphragm contracts during inhalation (inspiration) and relaxes during exhalation (expiration). During inhalation, the external intercostal muscles and the diaphragm contract and this causes the rib cage to expand and move outward as well as the expansion of the lung volume and thoracic cavity. For the expiration, the intercostal muscles and diaphragm relax, the abdomen and chest take back relax position and lung volumes decrease as shown in the lower portrait of Fig.1(a). A technique based on the analysis of chest wall movement was used to monitor breathing using a meander dipole embroidered antenna-sensor integrated into a cotton T-Shirt. The antenna-based sensor is located on the middle of the human chest whereas the breath sensing depends on the resonant frequency shift of the embroidered antenna-sensor induced by the abdominal and thoracic movement during respiration. The respiratory signal was continuously measured using a N9916A FieldFox microwave analyzer operating as Vector Network Analyzer (VNA) to a remote PC via LAN interface in real-time.

2.2. Antenna-Sensor Design

Similar to conventional antennas, a wearable textile meander dipole antenna-sensor contain two elements: conductive and non-conductive parts. The material used for the conductive part is a commercial Shieldex 117/17 dtex 2-ply. This commercial conductive yarn is made of 99% pure silver-plated nylon yarn 140/17 dtex which furnishes a good conductivity. The non conductive part is a cotton substrate of a commercially available T-Shirt. The dielectric properties of the T-shirt have been accurately characterized using a Split Post-Dielectric Resonator (SPDR). The cotton relative dielectric constant and loss tangent are $\varepsilon_r = 1.3$ and $\tan\delta = 0.0058$, respectively.

![Fig.1. (a) Simplified illustration of the lungs during inspiration and expiration, (b) Fabrication process of the embroidered antenna-sensor integrated into a cotton T-Shirt.](image)

![Fig.2. Meander dipole antenna-based sensor. Dimensions are: W=45mm, L= 4.8mm, d = 7.6 mm, g = 2 mm.](image)

$\varepsilon_r$ and $\tan\delta$ were measured for the following T-shirts: A commercial Shieldex 117/17 dtex 2-ply. A commercial Shieldex 117/17 dtex 2-ply.
On the other hand, an Electronic Outside Micrometer was used to measure its thickness (0.464 mm). A meander dipole antenna-sensor was integrated into a commercially available T-shirt at the pectoral region of the chest. The dimensions of the proposed antenna sensor are depicted in Fig.2. The breathing antenna-sensor was designed to operate at 2.4 GHz. The manufacturing embroidery process of the proposed antenna-sensor is represented in Fig.1(b) and can be summarized in three steps:

- **Step 1 (Antenna Design):** The design of the proposed antenna-sensor is simulated using the commercial CST Studio Suite 3D full electromagnetic simulator 2019. The design was developed to specify pre-set performance criteria (operating frequency and size).

- **Step 2 (Digitization):** The conductive part is converted to a stitch pattern using a Digitizer Ex Software. This software is used to produce a digital stitch format file to be readable by embroidery machine Singer Futura XL550.

- **Step 3 (Embroidered Prototype):** The design was modified by the functions of the embroidery machine by means of the desired embroidery pattern, desired stitch density and thread tension.

2.3. **Data Collection and Treatment**

The meander dipole antenna-sensor is integrated into the cotton T-Shirt to monitor respiration data of a healthy woman volunteer in a laboratory environment. The main figure of merit of the proposed antenna-sensor is the shift of the resonant frequency that appears due to the change in lung volume under the movement of the chest. To test this concept, a Vector Network Analyzer (VNA) was connected to PC host for data processing via a LAN interface. Data was analyzed in Matlab environment. The measurement setup configuration for the respiration detection in real time of the meander dipole antenna-sensor integrated into a T-Shirt is presented in Fig.3. The volunteer was asked to perform two positions (standing and sitting) with different breathing patterns eupnea, apnea, hypopnea (deep breathing) and hypopnea (shallow breathing). The data process model is presented in Fig.4. We developed a program via Matlab to collect respiration data information from VNA. The most important step is to configure the VNA with the same IP address used in the PC host via LAN interface to be able to transfer data with instrumentation over TCP/IP. The program was able to detect repetitive respiration and measure the resonant frequency shift continuously. Table 1 outlines common breathing patterns with a description and possible causes. Therefore, continuous monitoring of respiration is critical to evaluate the subject's health status, as it helps in the diagnosis and management of a variety of pathological conditions.

The aim of this work was to provide a technique to detect human breathing status using a wearable meander dipole antenna-sensor embroidered into a cotton T-shirt. The human respiratory status was compared with the standard respiration signal for different breathing patterns presented in the figure 5. The respiratory signals come in various forms depending on the breathing patterns, and are generally defined in four types of breathing, as presented in Fig.5. For the eupnea, is a normal respiration of an individual under resting conditions. Apnea present a stop breathing. For the hypopnea describe a low signal amplitude due to the shallow breathing. The hyperpnea is a deep breathing, the amplitude of the signal breathing is higher than the eupnea.
3. Results and Analysis

3.1. S-parameter

The main parameters characterizing the antenna resonant frequency are the parameters S, more specifically \( S_{11} \). The prototype of the proposed antenna-sensor was characterized in terms of \( S_{11} \) and the Specific Absorption Rate (SAR) to evaluate its performance for the wireless communications. In order to verify the accuracy of the embroidery technique, the meander dipole antenna-sensor was tested by measuring \( S_{11} \) using the Vector Network Analyzer. The simulated and measured \( S_{11} \) for the proposed antenna-sensor is presented in Fig. 6. From this figure, we can observe that the experimental measurement of the \( S_{11} \) has a good agreement with the numerical 3D electromagnetic simulation. The operating frequency of the experimental and simulation results is 2.4 GHz. Due to manufacturing errors, a small deviation in the \( S_{11} \) amplitude is observed. It is noted that this proposed antenna-sensor has achieved a realized gain of 1.86 dB.

Fig. 6. Simulated and measured \( S_{11} \) of the textile meander dipole antenna-based sensor.

3.2. Antenna under stretching

When textile antenna-based sensor is worn by a human body, its geometry is subject to significant deformations caused by the body shape. The antenna-sensor deformation causes alterations to the radio frequency (RF) signal. Therefore, the impact of mechanical deformations needs to be quantified for the proposed antenna-sensor. The main feature of the proposed textile antenna is the resonance frequency shift caused by the change in lung volume and the stretching of the textile under the movement of the chest. The proposed antenna-based sensor is located on the middle of the human chest, allowing the chest expansion to slightly stretch the antenna-sensor as presented in Fig. 7. The resonance frequency shift as a function of stretching deformation have been performed for the proposed antenna-sensor. In order to evaluate the performance of the meander dipole antenna-sensor under stretching, the proposed antenna was simulated by different width (w) ranging from 47 mm to 53 mm to mimic the stretching of the antenna (Fig. 8). It is important to note that the stretching does not cause any deformation to the antenna, only the width changes. Note that the antenna at rest had \( w=45 \) mm (Fig. 2). The simulated and measured results of the resonance frequency of the textile antenna-sensor as a function of the induced stretch are shown in the figure 6. From this figure, a linear function is used to fit the data and the coefficient of determination \( (R^2) \) shows the curves fitting well. From the obtained results, the feasibility of the textile antenna-sensor under stretching is confirmed and the proposed antenna-sensor can work to measure the resonant frequency with different values of \( w \) in a linear way at a determined frequency.

Fig. 7. Configuration of the proposed antenna-sensor under the stretching caused by the chest expansion during the breathing.

Fig. 8. \( S_{11} \) Simulation results of the antenna-sensor under stretching.

Fig. 9. Simulated and measured results of the resonant frequency of the textile antenna-sensor as a function of the induced stretch.
3.3. Specific Absorption Rate (SAR) Analysis

Since the proposed antenna-sensor operates close to the human body, it is important to consider the rate of absorption of radio frequency (RF) energy in the involved tissues. Specific Absorption Rate (SAR) is defined as the power absorbed by the biological tissue when exposed to a RF electromagnetic field. Specifically, it is defined as:

\[ SAR = \sigma |E|^2/(\rho) \]

Where, \( E \): Electric field (V/m).
\( \sigma \): Electrical conductivity (S/m).
\( \rho \): Tissue density (kg/m³).

SAR is a very important parameter used to help ensure safety aspects of exposure to RF energy. Institute of Electrical and Electronics Engineers (IEEE) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) have provided recommended SAR limits in order to protect users from the hazards of exposure to electromagnetic fields. According to the both organizations, the limit of SAR was set as: 1.6 W/Kg and 2 W/Kg averaged over 1g and 10g tissue, respectively [24,25]. Since the proposed respiration antenna-sensor can be used by people of different ages and gender such as monitoring the breathing status of a newborn infant, a voxel model was used for simulation. This voxel family is a group of seven realistic human model data sets created from seven persons of different stature, age and gender including their corresponding tissues. The complete SAR analysis is done by importing the proposed antenna into CST Studio Suite 3D full electromagnetic simulator 2019. The SAR simulations are carried out using different voxel models under two standard as presented in Table 2, which shows that the proposed antenna-sensor offers an acceptable SARs at different voxel model for both standards. The power used for the simulations is 50 mW. The SAR simulations were carried out considering the IEEE/IEC 62704-1 standard, according to the regulators. All models take into account up to 80 human tissues and organs. As an example, the proposed antenna-sensor is placed on the chest of a realistic Emma voxel human model with a SAR distribution at 2.4 GHz for two standard (1g and 10g) as shown in Fig.10.

For SAR simulation, the proposed antenna-based sensor is placed at distance d=10 mm from the voxel model to imitate realistic worn placements. In order to address a complete SAR analysis, the simulations over different voxel models with different age, size and weight have been performed. The absolute SAR value as well as the percentage of safety (%) with regard to the standard SAR limits are reported in Table 2.

Table 2. Specific absorption rate values at different voxel model and standards.

| Voxel model | Age (Year) | Size (cm) | Mass (kg) | Sex | Resolution/mm | SAR (1g) W/kg | SAR (10g) W/kg |
|-------------|------------|-----------|-----------|-----|---------------|--------------|---------------|
| Baby        | 8-9 weeks  | 57        | 4.2       | F   | 0.85 x 0.85 x 4 | 1.53 (4%)  | 0.86 (57%)    |
| Child       | 7          | 115       | 21.7      | F   | 1.54 x 1.54 x 8 | 1.54 (4%)  | 1.54 (4%)  |
| Donna       | 40         | 176       | 79        | F   | 1.875 x 1.875 x 10 | 0.295 (81%) | 0.141 (92%) |
| Emma        | 26         | 170       | 81        | F   | 0.98 x 0.98 x 10 | 0.878 (45%) | 0.414 (79%) |
| Gustavo     | 38         | 176       | 69        | M   | 2.08 x 2.08 x 8 | 1.57 (2%)  | 0.786 (60%) |
| Laura       | 43         | 163       | 51        | F   | 1.875 x 1.875 x 5 | 0.489 (69%) | 0.247 (87%) |
| Katja       | 43         | 163       | 62        | F-P | 1.775 x 1.775 x 4.84 | 0.456 (71%) | 0.226 (88%) |

3.4. On-body measurements

The main concept of this work is to validate the embroidered meander dipole antenna-sensor integrated into a commercially available T-Shirt for the breathing monitoring in real time. The breathing tests were attended with the help of a female volunteer (28 years, 1.67cm, 70kg) having approximately the same characteristics with human Emma voxel model. Various respiratory patterns were professionally role played in real time based on the description of the breathing patterns reported in Table 1. Fig.11 shows a photograph of the volunteer wearing the T-shirt under laboratory testing for sitting and standing positions. To investigate the feasibility and consistency of the proposed antenna-based sensor, various experimental tests were performed to study different breathing patterns (eupnea, apnea, hypopnea and hyperpnea).

When the antenna-based sensor is placed on the human chest, the participant was asked to:
1- Normal breath.
2- Deep breaths (hyperpnea) followed by shallow breaths (hypopnea).
3- Deep breaths (hyperpnea) followed by apnea (absence breathing).

The normal respiration (eupnea), the female volunteer was asked to breath normally and at ease for different positions (standing and sitting on a chair). During the apnea test, there is no air exchange either through the mouth or the nose means that no diaphragmatic and intercostal muscle activity. The measured S11 for eupnea, hyperpnea and hypopnea patterns are presented in Fig.12. The obtained results are taking during inhalation of the female volunteer for sitting position. This change in resonance frequency is caused by the change in lung volume and the stretching of the textile under the movement of the chest. It can be clearly seen a consistent frequency shift of the main resonance frequency of the embroidered antenna-sensor.

Fig.10. Antenna-sensor on human Emma voxel model, SAR at 2.4GHz (a) 1g, (b) 10.
Fig. 11. Photograph of the embroidered antenna-based sensor into a cotton T-shirt under laboratory testing for different scenarios, (a) sitting, (b) standing.

Fig. 12. Measured $S_{11}$ for different breathing patterns in sitting position.

Fig. 13. Measured respiratory patterns of an adult female volunteer in standing position, (a) Eupnea, (b) hypopnea and hyperpneoa, and (c) Apnea.
The resonant frequency shift was continuously measured using a N9916A FieldFox microwave analyzer operating as Vector Network Analyzer (VNA) to a remote PC via LAN interface in real-time. Matlab environment was used to test our methodology for different breathing signals (Fig.4). The acquisition rate was adjusted to provide the measurement per second. Real-world breathing tests were attended with help of a female volunteer. The different breathing patterns of the female volunteer for standing position were presented in Fig.13. From this figure, a noticeable resonant frequency shift can be seen that allowed the correct detection of different breathing patterns (eupnea, apnea, hypopnea and hyperpnea) of the volunteer. For the eupnea, a stable rhythm breathing was observed with a large shift frequency up to 2.98 GHz (Fig.13(a)). The participant was asked to take a deep breathing (hyperpnea) following by a shallow breathing (hypopnea), the resonant frequency shifted to 3.2 GHz and 2 GHz, respectively (Fig.13(b)), the hypopnea has a low breathing signal according to a low respiratory taking by the volunteer. For the apnea, the volunteer take a deep breathing followed by a stop breathing for several seconds (no air exchange either through the mouth or the nose). We can observe that the signal is saturated for different breathing patterns, because the female volunteer keeps her breathing cycle constant during inhalation to show the accuracy for the proposed system for different breathing patterns. The curve peak saturation for apnea is due to the absence of breathing, and this corresponds to the standard breathing signal. They are presented to demonstrate that our antenna is able to monitor different breathing patterns. The measurements was repeated in sitting position for different breathing patterns as presented in Fig.14. For the eupnea, a resonant frequency shifted to 2.84 GHz (Fig.14(a)). The measured resonant frequency shift for hypopnea and hyperpnea are 2.15 GHz and 2.95 GHz, respectively (Fig.14(b)). All the results have the same behavior as the standard respiration signal presented in Fig.5, this fact confirms that the obtained results from these measurements seem to be very promising for an embroidered antenna-based sensor to monitor human breathing, as the proposed approach is able to detect different breathing patterns for several positions and this could be useful to evaluate the subject's health status.

4. Discussion

The objective of this study is to verify the proposed breathing antenna-sensor embroidered into a commercial cotton T-shirt for real time monitoring of a human being breath. The breathing antenna-sensor was designed to operate at 2.4 GHz. The proposed antenna sensor is placed on the middle of the human chest and takes into account the user’s comfort with no movement constraints. The breathing sensing mechanism is based on the resonant frequency shifts of the embroidered antenna-sensor due to textile stretching induced by chest wall movements. The obtained results could make our embroidered antenna-sensor as a potential system for medical application such as: breathing troubles in neonates, children and adults, evaluating sleep apnea and monitor people suffering from asthma. The principal advantage of the proposed process consists of high user comfort associated with conventional clothing, as it does not require a connection of electrodes of any form. Table 3 presents a comparison of different techniques, sensor type, location, measuring parameter and size for previously reported works of the wearable category for respiration monitoring.
Table 3. Comparison of the respiratory monitoring systems.

| Ref | Technique | Sensor Type | Location | Measuring parameter | Size (mm²) | BP (s) | Textile |
|-----|-----------|-------------|----------|---------------------|------------|-------|---------|
| [26] | Abdomen movements/ Chest wall | Multimodal Patch | Abdomen Chest | Signal Amplitude | 65.53 x 26.67 | 1.91 ± 0.12 | x |
| [27] | Respiratory air flow | Fiber optic | Cervical spine | FBG¹ signal | 90 x 24 | 4.52 ± 0.35 | x |
| [28] | Chest wall movements | Piezoelectric | Mat | Raw signal | 70 x 60 | 2.78 ± 0.27 | x |
| [29] | Air humidity | Nanoparticles | Mouth mask | Respiratory rate | - | 4.50 ± 0.35 | x |
| [30] | Chest wall movements | Resistive | Chest (T-Shirt) | RIP² signal | 310 x 40 | 5.34 ± 0.84 | ✓ |
| [31] | Air temperature | Camera | - | Raw signal | 72 x 26 | - | x |
| [22] | Chest wall movements | Spiral Antenna | Chest (T-Shirt) | Frequency shift | 200 x 100 | 9.50 ± 0.74 | ✓ |
| [32] | Modulation of Cardiac | Radar | Distance from subject (200cm away) | Amplitude and phase shift | 150 x 100 | 5.20 ± 0.14 | x |
| [33] | Chest wall movements | Capacitive | Chest | Amplitude and phase shift | 478 x 478 | 5.10 ± 0.15 | x |
| [34] | Chest wall movements | Photoplethysmographic | Shirt pocket | Cardiac signal | 100 x 80 | 7.76 ± 0.21 | x |
| [35] | Respiratory sounds | Microphone | Ear | Digital audio signal | - | - | x |
| This work | Chest wall movements | Meander dipole antenna | Chest (T-Shirt) | Frequency shift | 45 x 4.87 | 5.22 ± 0.33 | ✓ |

¹FBG: Fiber Bragg Grating.
²RIP: Respiratory Inductive Plethysmograph.

A breathing parameter (BP) was calculated from breath to-breath interval. BP is the time that elapses between two consecutive peaks of the respiratory signal during normal breathing. This parameter shows the accuracy of the system during the breathing cycle. Most of the reported works were fabricated using conventional printed circuit board substrates. There are two sensors made from textile substrates, one is a piezoresistive sensor stitched into a T-shirt and the other one is a spiral antenna based on multi-material fibers integrated into a T-shirt. As shown in the table 3, both T-shirts have a large sensor size. The main novelties of our research are to consider a new approach to monitor breathing using a a fully textile wearable meander dipole antenna-sensor embroidered into a cotton T-shirt with a compact size presenting a high comfort for the user. Moreover, the overall size of the breathing antenna-based sensor is reduced by up to 90% compared to the reported works.

5. Conclusion

In this work, a new embroidered meander dipole antenna-based sensor integrated into a commercially available T-Shirt for real-time breathing monitoring using the technique based on chest well movement analysis is presented. The breathing antenna-sensor was designed to operate at 2.4 GHz. The working principle is based mainly on the resonant frequency shift of the meander dipole antenna-sensor induced by the chest expansion and the displacement of the air volume in the lungs during breathing. We have demonstrated the feasibility and consistency of the proposed antenna-based sensor in various breathing patterns (eupnea, apnea, hypopnea and hyperpnea) for two different postions (standing and sitting). The ability and accuracy of the embroidered antenna-based sensor to detect in real time the breathing patterns of a female volunteer has been demonstrated. Our system may be used for healthcare applications, such as in situ diagnosis of breathing diseases and monitor people suffering from Pulmonary Edema, Asthma and so on. The proposed antenna-based sensor has the advantages of combining wearability, compact size, consistent performance and no fabrication complexities.
Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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