Design and Implementation of a 2.45 GHz RF Sensor for Non-contacting Monitoring Vital Signs

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Abstract

The design and implementation of a non-contact RF (radio frequency) sensor that can monitor vital signs-respiration rate and heat rate is proposed. The designed low-cost system operates at 2.45 GHz by using one single Yagi antenna system to transmit and receive RF signals, realizes a miniaturized design of PCB that integrates both microwave transceivers and receivers. The gain of the sensor is 8.96 dB. The return loss is -22.87 dB at 2.45 GHz and the directionality of the antenna is satisfactory for monitoring vital signs. In comparison with pulse sensor and respiration sensor, it has been validated that the sensor could detect the respiration and heartbeat with mean error for the respiration rate within 0.5 beat/min and the heart rate within 1.9 beat/min.

1. Introduction

Along with the improvement of people's health consciousness, the cost in healthcare is increasing rapidly every year. It is estimated that one hundred million Americans suffer from chronic diseases including heart disease, lung disorders, which cost three-fourths of total US healthcare costs [l]. Respiration rate and heartbeat rate are the fundamental vital signs that are monitored by healthcare and prevent some disease at the early stage [2-5]. A non-contact radio frequency (RF) sensor with low cost, comfortable, portable, low power consumption is very attractive for the healthcare in comparison with most wearable sensors. Non-contact monitoring of human vital signs using a Doppler radar has been proposed for many decades, Since the 1970s, microwave Doppler radar has drawn attention for new applications on human healthcare [6,7], with initial applications in apnea and respiration monitoring [8], later, wireless heart monitoring [9]. Besides, A large number of clinical experiments show that microwave Doppler radar can accurately monitor cardiopulmonary activity [10], which can replace the conventional cardiopulmonary monitoring products [11,12].

This paper designed a non-contact RF sensor working at 2.45 GHz for non-contact monitoring vital signs [13,14]. And the non-contact RF sensor's performance evaluation with pulse sensor and respiration sensor will be presented in this paper.

2. Design and implementation

According to the principle of Doppler effects, if a target changes position with respect to time but has no net velocity, the phase of the reflected signal is proportional to the time-varying position of the target [2]. In comparison with the speed of electromagnetic wave, the speed of human body's periodic respiration is almost close to zero in quiet state. Therefore, microwave radar will receive the phase modulation signal that is similar to transmitting signal. This signal contains information of respiration, heartbeat and body movements.

2.1. Yagi antenna design

The Yagi patch antenna has a high directivity, low profile and it has attracted more interest in recent years. Considering the simple structure and high directivity, Yagi patch antenna is selected for detecting physiological parameters such as the heartbeat, respiration in daily life. The Yagi antenna, as depicted in Fig 1, consists of two dipole elements, a reflector and five director patch elements. The antenna operates at 2.45 GHz, which works at the industrial scientific medical (ISM) band.

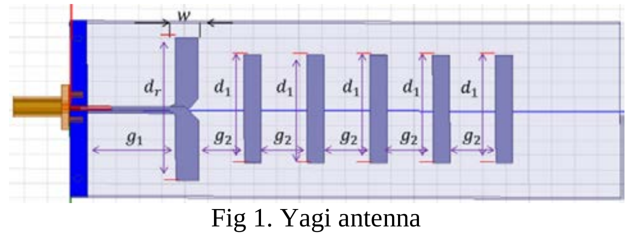

Fig 1. Yagi antenna

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In this article, the original antenna patches are based on the FR4 substrate whose permittivity ε_r =4.4. Using electromagnetism simulation software-HFSS (Version 14.0), this paper designed a Yagi patch antenna based on the FR4 substrate with the thickness of 0.8 *mm*, and size of 120*80 mm^2. Table 1. shows the values of designed antenna.

Table 1. The parameters of antenna

Parameters	d_r	d_1	g_1	g_2	w
Value(mm)	41.5	37.0	18.0	10.0	3.7

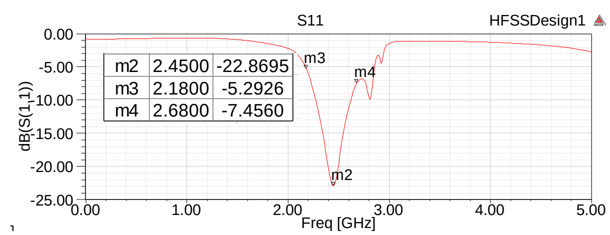


Fig 2. The S11 parameters of designed antenna.

The HFSS solver is employed to simulate and process the data. Fig 2 shows the S11 parameters at different frequencies with a single Yagi antenna. As shown in Fig 2, the value of S11 is -22.87 dB at 2.45 GHz, which indicates that most of the electromagnetic wave is transmitted by designed antenna and only few are returned back. The results demonstrate that the Yagi antenna's impedance matching is 50 Ω.

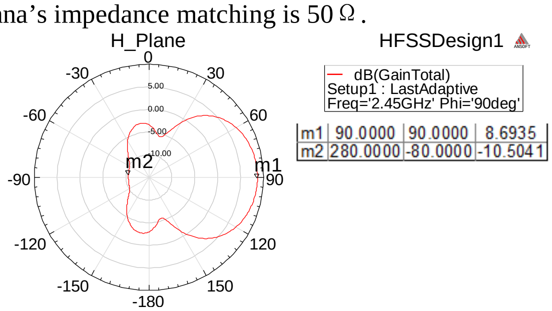


Fig 3. H Plane of the Yagi antenna

Radiation pattern is used as another indicator to depict the performance of an antenna. Fig 3 shows H plane of the simulated result for radiation pattern. We can find that there is a maximum forward gain of 8.69 dB and backward gain of -10.50 dB, therefore, the directionality is satisfactory for non-contact RF sensor to detect the vital signs.

2.2. Circuit design

The design of non-contact RF sensor consists of a Yagi PCB antenna as a microwave transceiver, a circulator, analog signal processing and data acquiring circuits as shown in Fig 4.

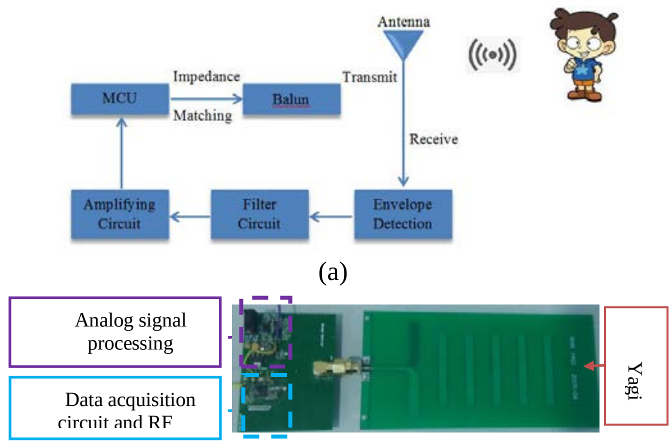


Fig 4. (a) Block diagram of non-contact biosensor system; (b) Non-contact biosensor system PCB.

A RF chip produces the RF signals and acquires data as shown in Fig 5. The RF chip was set to transmit a pulse-square wave whose period is 10 ms at the carrier frequency of 2.45 GHz. According to previously description, the echo signal has some information about body movements. The design of the circuit can remove high frequency components and demodulate the human dynamic information of low frequency component, and filter and amplify the signals. Use of the chip with digital converter (ADC) converts signals into 8 hex decimal numbers, coded and encoded into a pulse by Gauss frequency Shift Keying (GFSK). Finally, the signals are sent under the carrier frequency of 2.45 GHz.

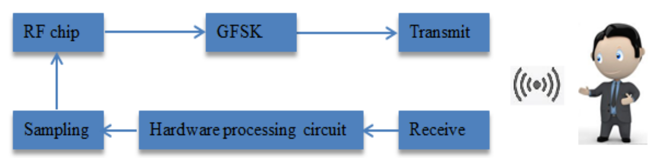
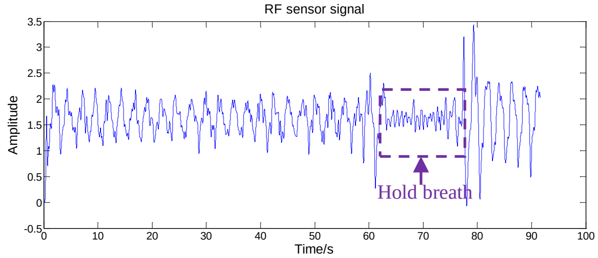


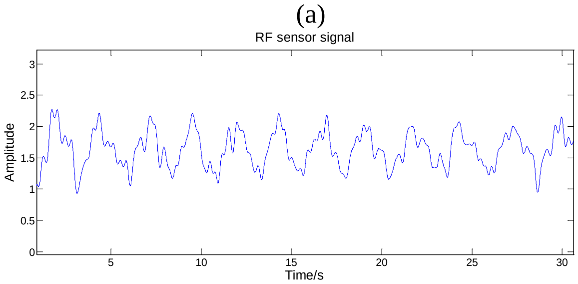
Fig 5. Block diagram of software design

3. Measurements and results

The accuracy of detection of heart and respiration with designed non-contact RF sensor, pulse sensor, and respiration sensor are verified with different human subjects. The signals were collected at the distance of 20 *cm* from Yagi antenna with subjects facing towards the Yagi antenna and wearing the pulse sensor and respiration sensor at the same time. The duration of the data collection was 60 seconds for each dataset. Fig 6(a) shows the original signal collected by designed non-contact biosensor system. According to the Doppler principle, echo signal consists of heart and respiration information as shown in the Fig 6(b).

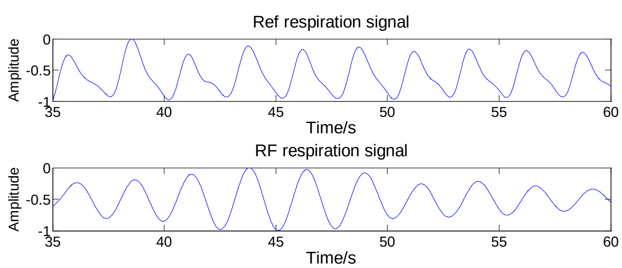


(a)



(b)

Fig 6. (a) Echo signal from RF sensor; (b) Local amplification of original signals;



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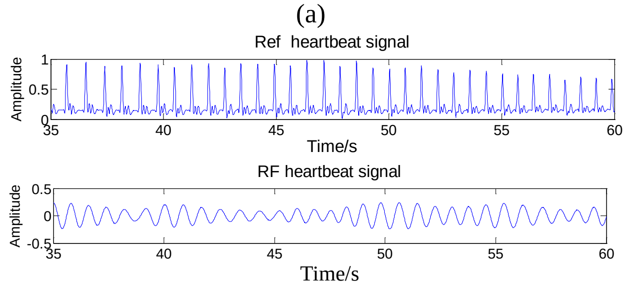
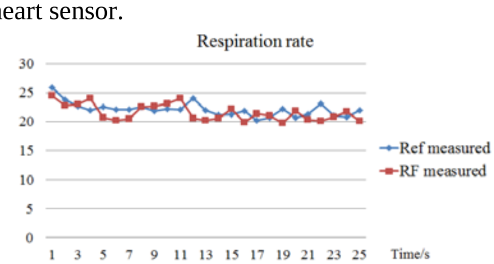


(b)

Fig 7. (a) Respiration from RF sensor; (b) breathing sensor.

Fig 7 shows the respiration signal and heart signal separated from the RF signal, which are very similar to the reference signal collected by the respiration sensor and heart sensor.



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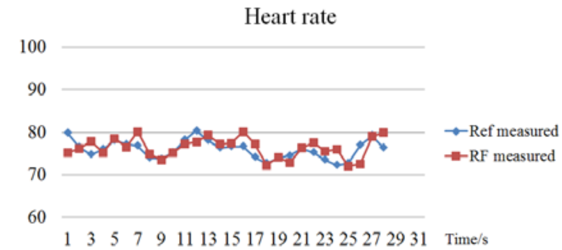
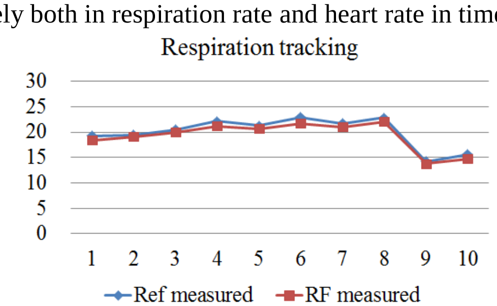


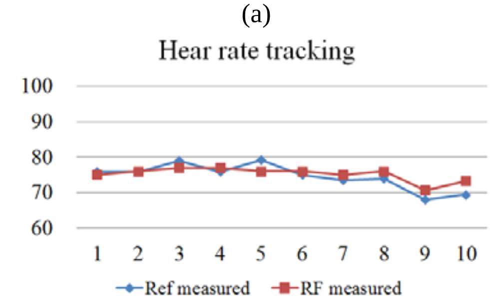
(b)

Fig 8. (a) Instantaneous respiration rate; (b) Heart rate.

To verify the accuracy of measurements of designed non-contact RF sensor, we randomly selected a subject from 10 subjects and calculated the instantaneous respiration rate $\frac{60}{T_{RR}}$, where T_{RR} is the time of adjacent peaks of respiration signal. The instantaneous heart rate of the time t_1 is calculated by $\frac{60(n-1)}{T_n - T_1}$, where n is the numbers of peaks from t_1-2.5 s to t_1+2.5 s, T_n is the time of last peak, T_1 is the time of first peak. The trend of instantaneous respiration rate and heart rate is compared with that of pulse and respiration signals collected by the pulse and respiration sensor, respectively, as shown in Fig 8. It is easy to see that our designed non-contact RF sensor tracks the pulse sensor and respiration sensor very closely both in respiration rate and heart rate in time.



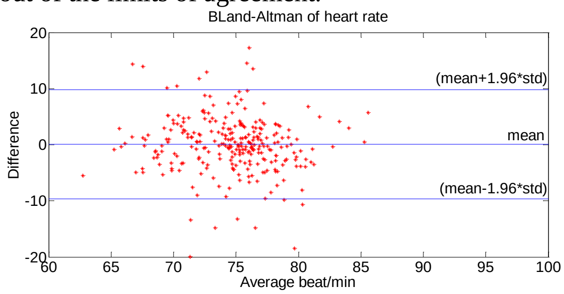
(a)



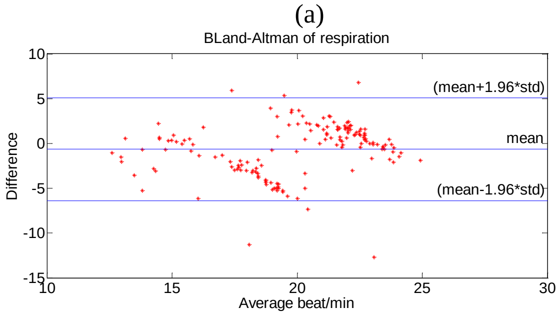
(b)

Fig 9. Respiration rate (a) and Heart rate (b) tracking with the Ref system for all subjects.

This paper also calculated the average respiration rate and heart rate of each subject. Fig 9 shows our deigned RF sensor tracks the reference signal closely for both respiration rate and heart rate for almost all the 10 collected subjects. This designed RF sensor can reach very accurate results with mean error less than 0.5 beat/min for respiration rate and 1.9 beat/min for heart rate.Fig 10(a) shows the Bland-Altman of instantaneous heart rate, it is clear to see that most of points between 95 limits of agreement. 6.07% (17/280) points are not in the limits of agreement. Fig 10(b) shows the results of instantaneous respiration rate, 3.51% (6/171) points are out of the limits of agreement.



(a)



(b)

Fig 10. Bland-Altman of respiration and heart rate.

4. Conclusion and discussion

A non-contact RF sensor was designed for contactless monitoring the vital signs on the PCB and separated the respiration and heartbeat information effectively from biological radar echo signal. The maximum gain of our designed sensor in the front is 8.96 dB. The RF chip produces RF signals and acquires data by writing program in the chip. Compared with pulse sensor and respiration sensor, non-contact RF sensor can reach very accurate results with mean error less than 0.5 beat/min for respiration rate and 1.9 beat/min for heart rate.

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