# Design and Evaluation of Typical Antennas for Monitoring Vital Signs

**Ramadhani Selemani Mpanda [1], Lin Qi [1*], Qiancheng Liang [1], Lisheng Xu [1], Jingjing Shi [1], and Lei Zhao [2]**

[1] Sino-Dutch Biomedical and Information Engineering School
Northeastern University Shenyang, Liaoning Province, 110819, China
mpandamgimba@yahoo.com, *qilin@bmie.neu.edu.cn

[2] Center for Computational Science and Engineering
School of Mathematics and Statistics, Jiangsu Normal University, Xuzhou, China
leizhao@jsnu.edu.cn

***Abstract*** — Non-contact method to monitor vital signs using radar-based sensor system is a more convenient way in comparison with the contact monitoring devices. Portable with a low profile and low-cost non-contact vital signs sensors system that are capable to monitor heart and respiration rates are presented and evaluated their performances. A printed 2x1 patch array antenna, Yagi-Uda antenna and dipole array antenna are designed and integrated with sensor system Tx/Rx module for their performances analysis. The gain of the designed antennas are 6.38 dBi, 7.7 dBi, and 10.5 dBi, VSWR are 1.1, 1.15, and 1.0, and return loss are -26.26 dB, -22.7 dB and -21.6 dB respectively at 2.4 GHz. The evaluations performances of these antennas were compared with a standard respiratory-rate measurement using a pulse sensor and respiratory sensor. The measurement results using the proposed non-contact sensor systems and the standard contact systems showed excellent performance with the printed dipole array antenna compared with other two antennas, the error between the average heart rate extracted by the non-contact systems and the reference systems are ±1.1 beat/min for dipole array antenna, ±1.5 beat/min for printed 2x1 patch array antenna and ±1.9 beat/min for Yagi-Uda antenna.

***Index Terms*** — Heartbeat rate, printed dipole array arrays, printed patch array antenna, printed Yagi-Uda antenna, respiration rate, vital signs.

## I. INTRODUCTION

Due to the increase of healthcare costs, aging population and difficulties in getting access to healthcare, especially in physiological monitoring systems, telemedicine and continuous remote patient monitoring applications are urgently needed [1]. The conventional respiration measurement techniques that mostly based on contact methods, such as, ECG monitoring [2], and other wearable systems are still cost-fully [3]. The contact nature of these devices makes the subject aware of being monitored, as the result it affects the spontaneous breathing patterns and may lead to inaccurate assessment of physical states. Wired connections for data acquisition of these conventional devices hinder patient mobility and normally measure only one specific vital sign, also they are not capable for long term continuous monitoring of vital signs especially when monitoring patients with disease that need long term treatment such as stroke [4].

A non-contact radio frequency (RF) radar sensor with low cost, comfortable, portable and low power consumption is very attractive for the healthcare applications. Using microwaves radar system to detect small physiological movements such as respiration and heartbeat dates back to the 1970s [5]. It is realized by detecting the phase information in the received radar signals, which is caused by Doppler shift due to the moving chest wall.

Radar physiological system play crucial role in our daily life application. It has wide applications, such as searching for human subjects under earthquake rubble or behind a barrier, security monitoring based on motion detection, and monitoring breathing conditions and identifying potential abnormality of sleeping people [6]. The radar sensor has also been used for indoor detection of human falls which allows timely and accurate reporting of fall incidents to avoid severe injuries. Recently, radar technology has been extended for accurate respiration measurement in motion adaptive cancer radiotherapy [7].

In detection process with radar system, there are basically two types of radars: continuous wave (CW) radar and ultrawideband (UWB) radar. The CW radar falls into three subcategories: single-tone, stepped frequency (SFCW), and frequency-modulated CW (FMCW). Each category of radars has its specific advantages. The single tone CW radar has a simple system architecture that allows high level chip integration. It also has high

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accuracy in relative displacement measurement [8]. With the advantages of CW radar system our designed radar based-sensors will be based on CW architecture.

With simple structure, low profile and easy integrated with other systems of the printed antennas to detect and monitor vital signs, this paper focus on implementing three kind of antennas and make comparative analysis on their performances. Printed 2x1 patch array antenna, printed dipole array antenna and printed Yagi-Uda antenna are designed and evaluated their performances on vital signs detection. The antennas analysis and evaluation were based on radiation properties such as directivity, gain, S11 and VSWR of the antennas. Then various measurements were performed on heartbeat and respiration rate to compare their performances. The designs of these printed antennas are based on the ISM frequency band.

This paper starts with design process and simulation result of antennas in Section II. Section III describes result and discussion of the designed antennas. Evaluation of the antenna performances are described in Section IV. Conclusion of the paper is offered in Section V.

## II. DESIGN PROCESS AND SIMULAION RESULTS OF ANTENNAS

Printed 2x1 patch array, printed dipole array, and Yagi-Uda antenna are described in this section. The proposed antennas are designed and simulated using HFSS software. FR4 substrate with relativity of $\varepsilon_r$ = 4 used as the dielectric constant of substrate in the designing of the antennas. The antennas are designed to work at resonating frequency of 2.4 GHz.

### A. Printed 2x1 patch array antenna design

A micro-strip printed patch antenna consists of a radiating patch with an electrically large ground plane separated by a dielectric material as shown in Fig. 1 (a). The design of a 2x1 patch array antenna is done by first design a single micro-strip patch antenna. The design of a single patch antenna is designed according to the formula given bellow:

$$W = \frac{C}{2f}\left(\frac{\varepsilon+1}{2}\right)^{-\frac{1}{2}}, \quad (1)$$

$$\varepsilon_r = \frac{\varepsilon+1}{2} + \frac{\varepsilon-1}{2}\left(1+12\frac{h}{w}\right)^{\frac{1}{2}}, \quad (2)$$

$$\Delta l = 0.412\frac{(\varepsilon_r+0.3)\left(\frac{W}{h}+0.064\right)}{(\varepsilon_r-0.258)\left(\frac{W}{h}+0.8\right)}, \quad (3)$$

$$L = \frac{C}{2f}\frac{1}{\sqrt{\varepsilon_r}} - 2\Delta l, \quad (4)$$

where W is the width of the rectangular radiating patch, L is the length of the radiation patch and $h$ is the height of the substrate and FR4 substrate with relativity of $\varepsilon_r$ = 4.3 used as the dielectric constant of substrate. To increase the gain of the patch antenna, the cascade patch is arranged in array as shown in Fig. 1 (b). Table 1 show the the optimized parameter of 2x1 patch array antenna.

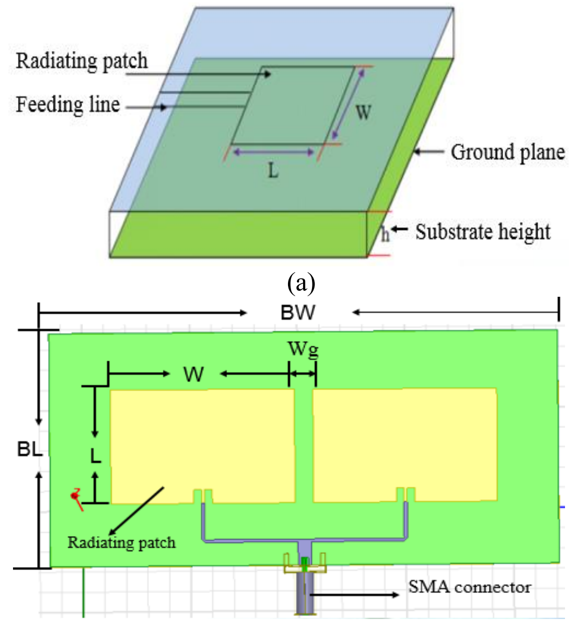



Fig. 1. (a) The structure of micro-strip patch antenna; (b) the structure of rectangular 2x1 patch array antenna.

Table 1: The optimized parameter of 2x1 patch array

| Variable | BW | BL | W | L | Wg |
|---|---|---|---|---|---|
| Values (mm) | 137.4 | 82.7 | 48.5 | 38 | 12 |

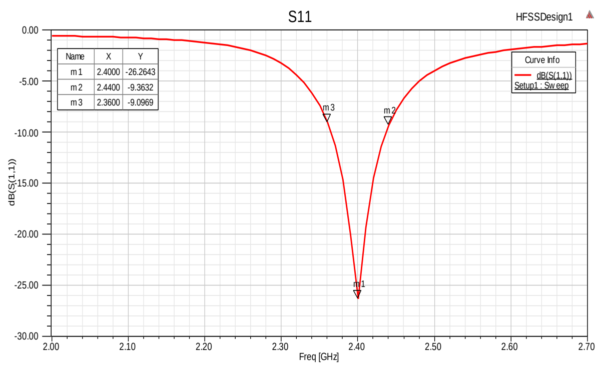
Figures 2 (a) and (c) show the simulation results of reflection coefficient and radiation pattern of proposed 2x1 patch array antenna. The simulation results indicate that the S11 of the designed patch array is -26.26 at resonating frequency of 2.4 GHz. In this working band, its radiation also satisfies directional radiation with gain of 6.38 dBi as indicated in Fig. 2 (b).

### B. Printed dipole array antenna design

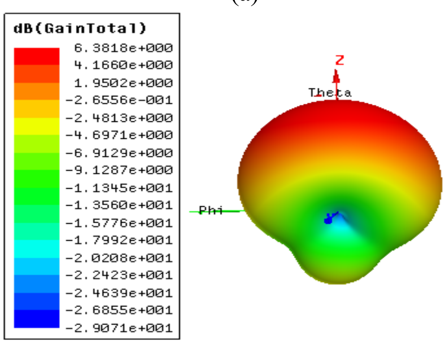
Printed dipole array antenna has a simple and novel structure with symmetrical array elements for attaining high antenna gain and a reflector to focus the radiation beam at a specific direction as shown in Figs. 3 (a) and (b). Each dipole array element has two arms in the same side of the substrate, and the length of each arm equals to $\lambda/4$, where $\lambda$ indicates the wavelength at 2.4 GHz. The FR4 substrate with relativity of $\varepsilon_r$ = 4 and thickness of $h$ = 4 mm was used in this antenna which can shorten the wavelength compared to free space. Therefore, the corresponding theoretical value of radiation element $l_1$ can be described as:

$$l_1 = \frac{1}{4}\lambda = \frac{c}{4f\sqrt{\varepsilon_r}}, \quad (5)$$

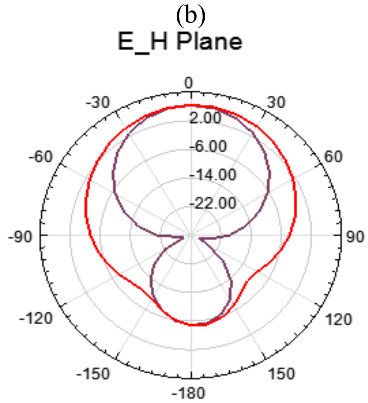
where, $c$ is the velocity of light, $f$ is the resonance frequency. A metal plate worked as antenna reflector is added to the back side of dipole array elements, with a distance of $h = \lambda/4$ from the FR4 substrate [9]. The calculated optimized parameters of the dipole array antenna shown in Table 2.




(a)




(b)




(c)

Fig. 2. (a) The S11 parameter of 2x1 patch array antenna; (b) the 3D radiation pattern of the designed 2x1 patch array antenna; (c) the radiation performance of EH plane of 2x1 patch array antenna.

Table 2: The optimize parameter of dipole array antenna

| Variable | $l_1$ | d | $d_1$ | $d_2$ | h | w | l |
|---|---|---|---|---|---|---|---|
| Values (mm) | 35 | 51 | 17 | 12 | 12 | 120 | 78 |

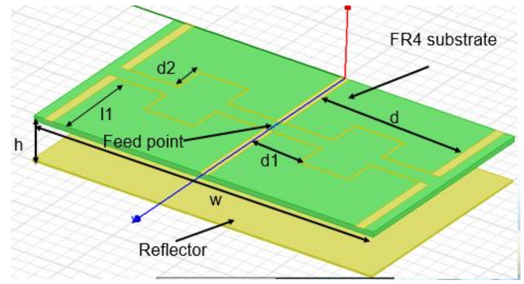


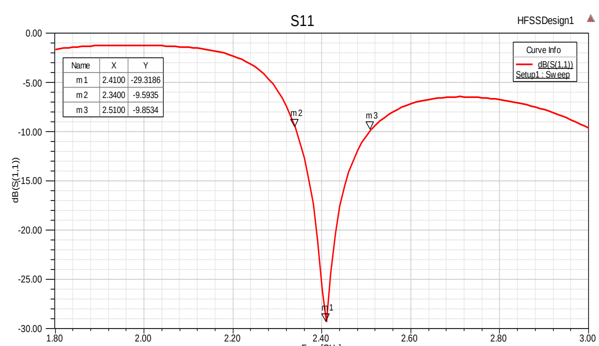

Fig. 3. Geometrical structure of the dipole array antenna.

The simulation result of the designed dipole array antenna is described below, Fig. 4 (a) show that the reflection coefficient of the design is -29.31 dBi at 2.4 GHz, with a gain of 10.5 dB and a directional lobe as shown in Figs. 4 (b) and (c), respectively.

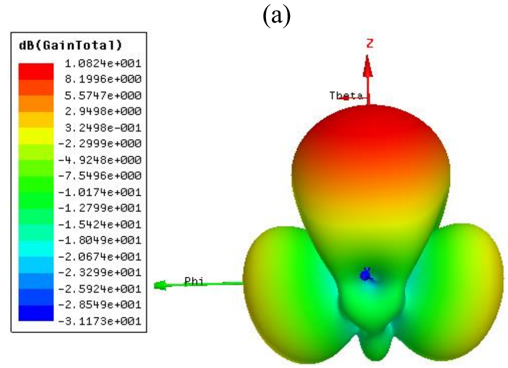
## C. Yagi-Uda antenna design

The Yagi-Uda antenna has a high directivity, low profile and simple structure. With this properties of the directivity of the Yagi-Uda antenna it can be deployed in detecting physiological parameters such as heartbeat and respiration rate.

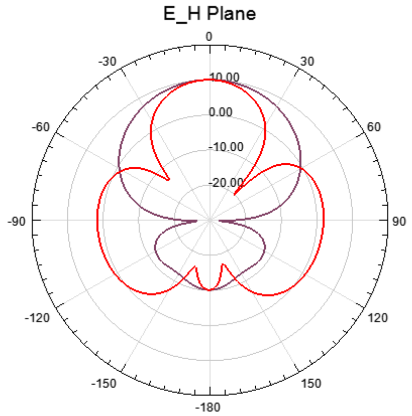
The design of the printed Yag-Uda antenna consist of two dipole elements, a reflector and five director patch elements, shown in Fig. 5 (a) and the optimized calculated parameters of the antenna is shown in Table 3. The length of two dipole elements is equal to the half of the wavelength. For the sake of size and universal feasibility, the antenna designed to work at 2.4 GHz, which belongs to industrial scientific medical (ISM) band [10].




(a)




(b)



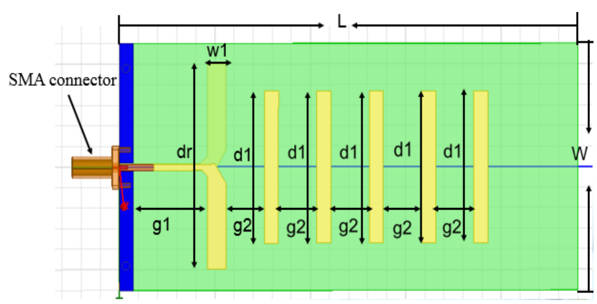

(c)

Fig. 4. (a) The S11 parameter of dipole array antenna at 2.4 GHz; (b) the 3D radiation pattern for the dipole array antenna; (c) the radiation performance of EH plane of dipole array antenna.

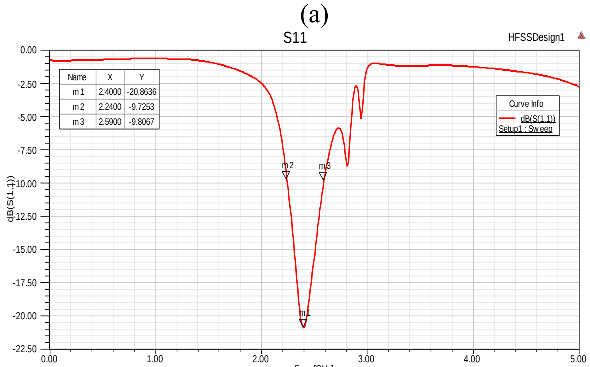
Table 3: The optimized parameter of Yagi-Uda antenna

| Variable | $d_r$ | $d_1$ | $g_1$ | $g_2$ | $W_1$ |
|---|---|---|---|---|---|
| Values (mm) | 42.5 | 37.0 | 18.0 | 10.0 | 3.7 |

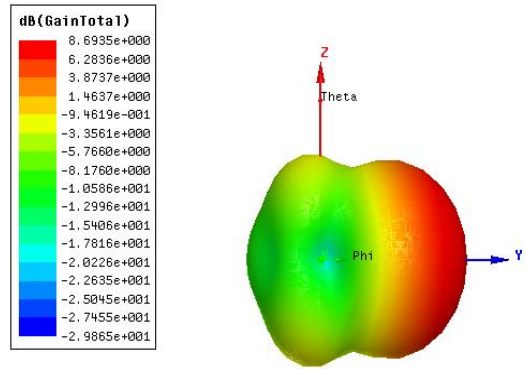
Figures 5 (b) and (d) show the simulation results of reflection coefficient and radiation pattern of proposed Yag-Uda antenna. The simulation results indicate that the S11 of the designed Yag-Uda is -20.86 at resonating frequency of 2.4 GHz. In this working band, its radiation also satisfies directional radiation with gain of 8.69 dBi as indicated in Fig. 5 (c).



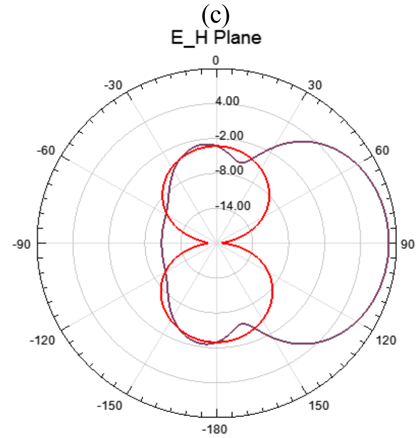

(a)




(b)




(c)




(d)

Fig. 5. (a) The configuration designed Yagi-Uda antenna; (b) the S11 parameter of Yag-Uda antenna at 2.4 GHz; (c) the 3D radiation pattern for the Yagi-Uda antenna; (d) the radiation performance of EH plane of Yag-Uda antenna.

## III. RESULT AND DISCUSSION OF THE DESIGNED ANTENNAS

Figure 6 shows the fabricated antennas, the measurement of each antenna were carryout to compare the measurement and simulation result, different parameters such as reflection coefficient S11, antenna gain and VSWR of the antennas were compared. Table 4 lists the simulation and experimental measurement of each antenna.

Table 4: The simulation and experimental results of S11, gain and VSWR of the designed antennas

| Antenna | | S11 dB | Gain dBi | VSWR |
|---|---|---|---|---|
| Patch array | Sim | -26.26 | 6.38 | 1.1 |
| | Exp | -26.8 | 6.42 | 1.0 |
| Yag-Uda | Sim | -20.86 | 7.7 | 1.15 |
| | Exp | -21.8 | 7.62 | 1.2 |
| Dipole array | Sim | -29.31 | 10.82 | 1.3 |
| | Exp | -22.7 | 10.5 | 1.5 |

***Sim=Simulation results**
***Exp=Experimental results**

Table 4 lists the simulations and experimental measurement results of the designed antennas; the result shows that the simulation and the experimental measurement of the designed antennas have only slightly difference.

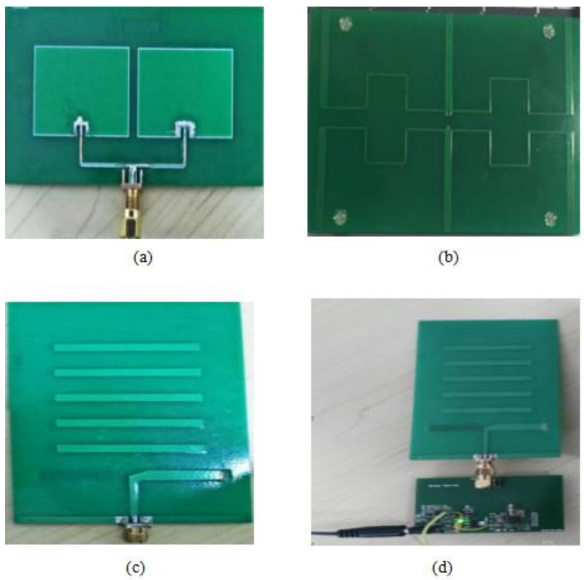



Fig. 6. (a) 2x1 fabricated patch array antenna; (b) fabricated dipole array antenna; (c) fabricated Yagi-Uda antenna; (d) fabricated Yagi-Uda together with the Tx/Rx module.

## IV. EVALUATION OF THE ANTENNAS PERFORMANCES

In order to verify the feasibility of the antennas performances, the corresponding experimental scheme was conducted. The experimental devices includes a set of contact physiological signal acquisition devices, pulse sensor, respiratory sensor and the non-contact detection system was setup to evaluate our designed performances.

As shown in Fig. 7, during the experiment, the contact device and the non-contact detection device are used to collect the physiological signals of the human body. The pulse sensor is attached to the fingertip of the subject's finger, and the respiratory sensor is attached to the abdomen of the subject. The non-contact detection systems were placed 35 cm away from the human thoracic cavity and the experimental data was collected for 60s.

In order to increase accuracy of data collected by the non-contact sensors, it is necessary to avoid interference activities of other people around when collecting experimental data. Our designed antennas are directional, in order to obtain good signal detection, the antenna is placed to focus the human chest as shown in Fig. 7.

According to the experimental measurements described above, the physiological signals of 10 groups of subjects were collected by the non-contact detection system based on our design, 2x1 patch array antenna, dipole array antenna and Yagi-Uda antenna, respectively. The contact reference system is also used for synchronous acquisition of signals.

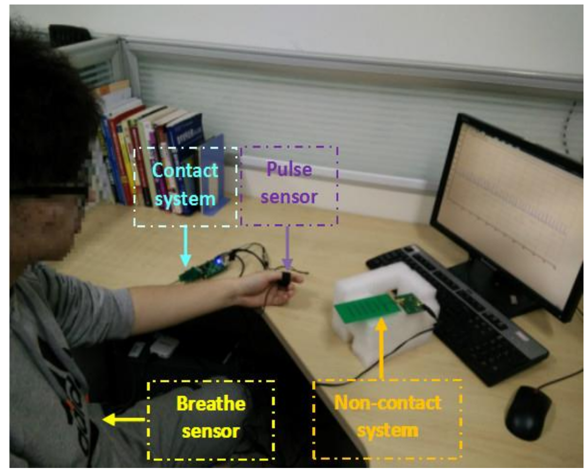



Fig. 7. The experimental setup to detect vital signs.

Table 5, Table 6 and Table 7 shows the average heart rate (AHR) calculation results of the 10 sets of samples data extracted by the printed 2x1 patch array antenna, dipole array antenna and Yagi-Uda antenna-based non-contact monitoring system respectively and the error with the reference system. AHR can be calculated by equation 6, where n is the length of time for each set of data samples and $\mathrm{IHR}(\mathrm{i})$ is the heart rate:

$$AHR = \frac{\sum_{i=1}^{n} IHR(i)}{n}. \tag{6}$$

It can be seen from the tables that there are a certain error between the average heart rate extracted by the rectangular array antenna, dipole array antenna and Yagi-Uda antenna, based non-contact monitoring system and the average heart rate extracted based on the reference systems acquisition signal. The error between the average heart rate extracted by the non-contact systems and the reference systems are $\pm$ 1.1 beat/min for dipole array antenna, $\pm$ 1.5 beat/min for printed 2x1 patch array antenna and $\pm$1.9 beat/min for Yagi-Uda antenna.

In addition in order to compare the signals collected by the designed non-contact sensors with reference respiration sensors, the extraction of respiration signals collected by non-contact sensor are achieved by digital filter and wavelet transform to remove noise. Figure 8, Fig. 9 and Fig. 10 shows the respiration signals that collected by respiration sensor and that collected by the designed non-contact sensors.

Table 5: Averaged heart rate of non-contact monitoring system based on 2x1 patch array antenna

| Experimental sample | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Non-contact system based on 2x1 patch array | 80 | 78 | 74 | 79 | 82 | 86 | 67 | 71 | 78 | 70 |
| Reference system | 82 | 76 | 74 | 77 | 84 | 88 | 67 | 70 | 80 | 72 |
| Error (beat/min) | -2 | 2 | 0 | 2 | -2 | -2 | 0 | 1 | -2 | -2 |

Table 6: Averaged heart rate of non-contact monitoring system based on dipole array antenna

| Experimental sample | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Non-contact system based on dipole array | 72 | 70 | 75 | 73 | 80 | 71 | 73 | 73 | 68 | 68 |
| Reference system | 73 | 71 | 75 | 71 | 78 | 71 | 75 | 75 | 68 | 69 |
| Error (beat/min) | -1 | 1 | 0 | 2 | 2 | 0 | -2 | -2 | 0 | -1 |

Table 7: Averaged heart rate of non-contact monitoring system based on Yagi-Uda antenna

| Experimental sample | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Non-contact system based on Yagi-Uda | 76 | 68 | 79 | 76 | 78 | 75 | 74 | 80 | 71 | 69 |
| Reference system | 75 | 71 | 77 | 79 | 77 | 76 | 72 | 82 | 70 | 72 |
| Error (beat/min) | 1 | -3 | 2 | -3 | 1 | -1 | 2 | -2 | 1 | -3 |

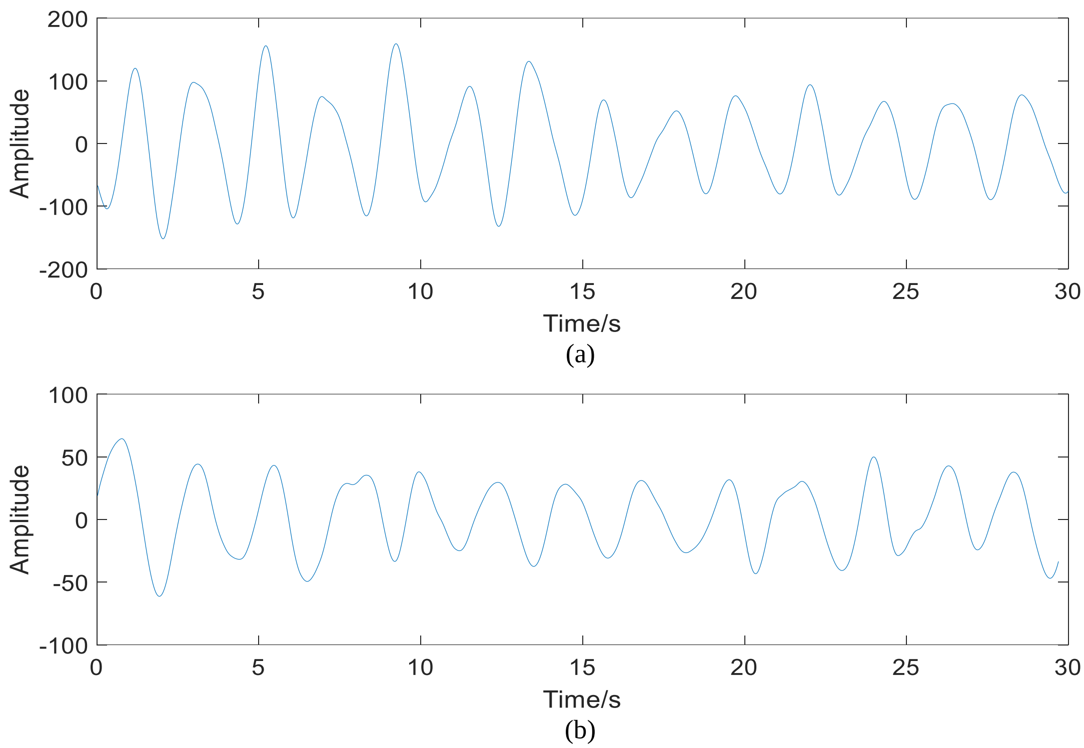



Fig. 8. Respiration signal: (a) signal from reference sensor (respiration belt sensor), and (b) signal from printed 2x1 patch array antenna.

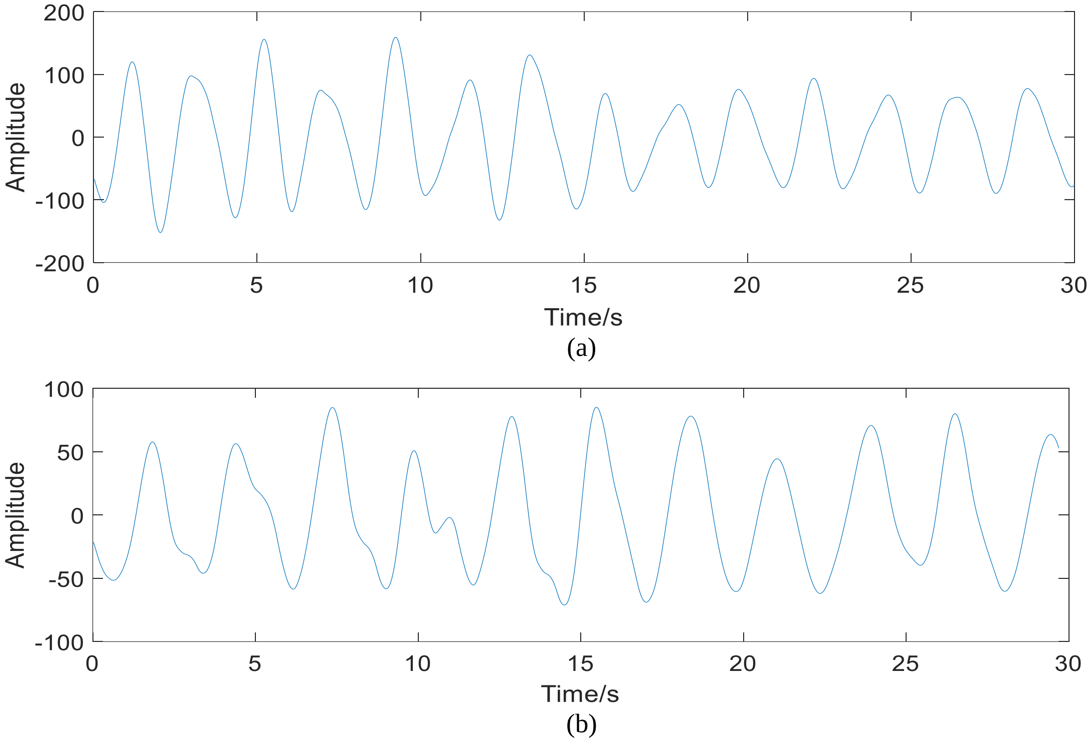



Fig. 9. Respiration signal: (a) signal from reference sensor (respiration belt sensor), and (b) signal from dipole array antenna.

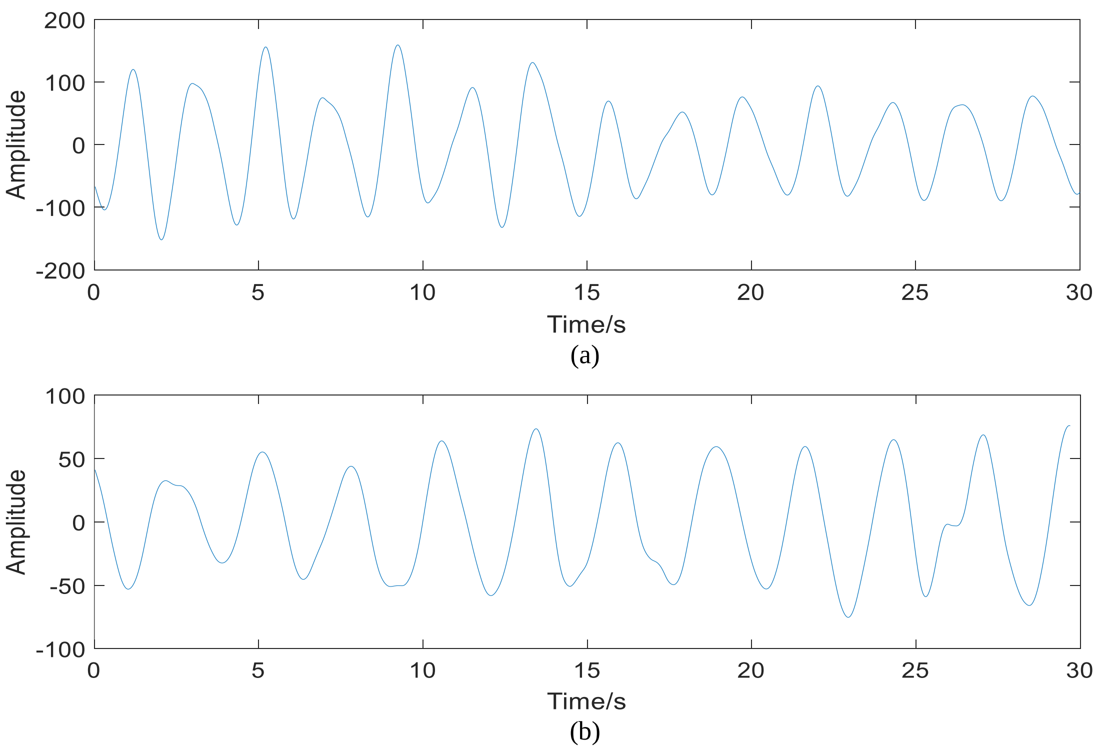



Fig. 10. Respiration signal: (a) signal from reference sensor (respiration belt sensor), and (b) signal from printed Yagi-Uda antenna.

It observed that the signal accuracy of the non-contact monitoring system based on the experimental data collected on the tables above and wave form signals of the non-contact sensors together with the reference monitoring systems, shows that the dipole array antenna has higher accuracy than that of the 2x1 patch array antenna and Yagi-Uda antenna non-contact monitoring system.

## V. CONCLUSION

Portable with low profile and low cost Doppler-based non-contact vital signs monitoring system operating at 2.4 GHz were presented. With the advantages of CW radar system our designed radar system was based on CW architecture, the systems were assessed with other contact monitoring devices to analyze their performances. Focusing on the heart rate and respiration signal, a large amount of experimental data indicates that a dipole array antenna can significantly perform well as compared with 2x1 patch array antenna and Yagi-Uda antennas. Therefore dipole array antenna can be the best candidate antenna to be integrated with other medical device for vital signs detection due to its excellent features, such as low weight, profile, and cost, while maintaining good performances on detecting vital signs.

## ACKNOWLEDGMENTS

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**R. S. Mpanda** received the B.S. degree in Electronics Science and Communication from University of Dar es Salaam, Dar es Salaam, Tanzania, 2012, He is currently working toward the M.S. degree in Biomedical Engineering at the Northeastern University, Shenyang, China. His research interests include antenna structures design to monitor physiological signs, wearable sensor design, digital signal processing and electronic circuits design.

**Lin Qi** (M'08) received the Ph.D. degree in the Department of Electronic Engineering, the Chinese University of Hong Kong in 2013. He got the B.S. and M.S. degrees in Biomedical Engineering, School of Medicine, and Tsinghua University. He is now the Associate Professor in Sino-Dutch Biomedical and Information Engineering School, Northeastern University, China. His research interests include medical robotics and biomedical signal processing.

**Lisheng Xu** (SM'15) received the B.S. degree in Electrical Power System Automation, the M.S. degree in Mechanical Electronics, and the Ph.D. degree in Computer Science and Technology from Harbin Institute of Technology, Harbin, China, in 1998, 2000, and 2006, respectively. He is currently a Full Professor in the Sino-Dutch Biomedical and Information Engineering School, Northeastern University, China. He has authored or coauthored more than 100 international research papers, and holds fifteen patents and four pending patents. His current research interests include nonlinear medical signal processing, computational electromagnetic simulation, medical imaging, and pattern recognition.

Xu is the Director of Theory and Education Professional Committee of China Medical Informatics Association. He is Senior Member of IEEE and Chinese Society of Biomedical Engineering. He is the Member of the editor board for many international journals such as Physiological Measurement, Biomedical Engineering Online, Computers in Biology and Medicine and so on.