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SYSTEMS-LEVEL QUALITY IMPROVEMENT

Cognitive bio-radar: The natural evolution of bio-signals measurement

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Abstract In this article we discuss a novel approach to Bio-Radar, contactless measurement of bio-signals, called Cognitive Bio-Radar. This new approach implements the Bio-Radar in a Software Defined Radio (SDR) platform in order to obtain awareness of the environment where it operates. Due to this, the Cognitive Bio-Radar can adapt to its surroundings in order to have an intelligent usage of the radio frequency spectrum to improve its performance. In order to study the feasibility of such implementation, a SDR based Bio-Radar testbench was developed and evaluated. The prototype is shown to be able to acquire the heartbeat activity and the respiratory effort. The acquired data is compared with the acquisitions from a Biopac research data acquisition system, showing coherent results for both heartbeat and breathing rate.

Keywords Bio-radar · Noncontact monitoring · Vital signals sensing · CW radar

Introduction

A radar is a device that transmits electromagnetic energy and detects the echo reflected by a radiated object. The transmitted wave is reflected by the object of interest and rebounds in the original signal direction. The characteristics of the returning echo signal are different from the original transmitted wave and can be used to retrieve physical information of the target. Bio-Radar technology aims the combination of radar and biomedical measurements to achieve the detection of vital signals, such as respiration and heartbeat without using electrodes or sensors [1]. Non-contact methods for measuring bio-signals, in particular cardiac and respiratory signals are a very active area of research. Wireless measuring of human physiological parameters, like heart rate variability and breathing pattern are of great interest not only in the medical field as in monitoring hospitalized patients, home health care, rehabilitation and nursing of elderly but also commercially oriented applications, such as automotive industry for driver monitoring or for applications in psychology as for example measurement of stress response [2]. One of the most promising techniques for wireless measurement of bio-signals is commonly called Bio-Radar and is based on Doppler radar. In particular, Continuous-Wave (CW) Doppler radar that is being widely used in current research [3, 4].

Doppler radar for bio-signals

Doppler radar concept

A Doppler radar is a system that, by directing a microwave signal to an object and listening to its reflection can infer it movement characteristics by analyzing how the frequency of the signal sent is altered by the object's motion [5]. This frequency variation is due to the Doppler effect and can also be analyzed as a phase rotation between

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the generated signal from the radar and the received reflection. Therefore, if an object is at a d_o distance, then the phase difference φ between the generated and the received signal is given by,

$$\varphi = \frac{2d_o 2\pi}{\lambda} \quad (1)$$

where λ is the wavelength of the transmitted signal. If an object changes its position, the distance change results in a phase variation that can be used to determine the object's movement.

Doppler detection in a CW bio-radar

In a CW Bio-Radar the system is constantly transmitting a sine wave in the direction of the target. This signal is then reflected by the person under test and any small movements on the chest area will change the received signal phase according with the distance that it traveled. This distance will be smaller if the chest is inflated or larger if the chest is deflated. The received wave is then demodulated using the same transmitted sine wave in order to obtain the phase difference between the two. A detailed analysis of the Bio-Radar operation is presented in Fig. 1.

A CW Bio-Radar operates by transmitting a sine wave, but this generated signal is not perfect and is corrupted with phase noise. The transmitted signal will then be given by, $T(t) = \cos[2\pi f t + \varphi(t)]$ with f being the frequency of operation and φ the phase noise [6]. This signal is then transmitted to a subject at a distance d_o from the device and reflected back after being modulated by the physiological movement, as heartbeat and respiration, $x(t)$. If we neglect amplitude variations, we will have the following equation for the received signal in the Bio-Radar [7],

$$R(t) \approx cos\left[2\pi\text{ft} - \frac{4\pi d_o}{\lambda} - \frac{4\pi x(t)}{\lambda} + \varphi\left(t - \frac{2d_o}{c}\right)\right] \quad (2)$$

where c will be the electromagnetic wave's speed and λ it's wavelength. Therefore, the received signal is then a time delayed version of the transmitted signal with a phase modulation created by periodic motions of the target [6]. At the receiver the signal is demodulated back to the baseband,

$$B(t) = cos\left[\theta + \frac{4\pi x(t)}{\lambda} + \Delta\,\varphi\,(t)\right] \quad (3)$$

where $\theta = 4\pi d_o/\lambda + \theta_o$ is given by the subject distance and the θ_o is the phase shift in the reflection surface. The $\Delta\varphi\ (t) = \varphi(t) - \varphi\ (\ t - 2\ d_o/c\ )$ is then the residual oscillator phase noise. By then analyzing the angle, every parameter will be constant except the varying physiological movement and the phase noise. As we only want to acquire the bio-signals we can then filter the angle according with the signal that we want to obtain.

Usually the typical healthy adult resting values for this kind of signals are for the respiration around 15 bpm and for the Heart Rate 70 bpm [8]. In terms of the signals amplitude it's expected that the movements caused by the heart contraction are of about 5 % than those caused by the respiration [9].

State of the art

Frequency selection

The Bio-Radar should use a Radio Frequency (RF) signal with a wavelength of the same order of magnitude as the small distances of the chest movement. In [10] a comparative study was done between an operating frequency of 2.4GHz and 10GHz for usage in a Bio-Radar. The results show that the 10GHz implementation allows for smaller antennas to be used and thus a more compact and directional transceiver can be used. As expected the 10GHz system, has a lower range and is also more affected by phase noise but will detect better the Doppler phase changes. The authors conclude that the behavior of the two frequencies is very similar for commercial off-the-shelf components. There are also usage of even higher frequencies for Bio-Radar, as for example 94GHz [11] that require quasi-optical directional antennas that while showing good performance are limited by the use of Gunn diode oscillators. For through-wall measurements, the attenuation of common obstacles (e.g. as concrete and brick-wall), increases with frequency [12]. Due to this reason, bio-radar measurements of visually obscured targets should use lower frequencies [13].

Antennas usage

For the antenna selection, for millimeter-wave Bio-Radars, a Gaussian quasi-optical antenna with focus lens is needed [11]. For lower microwave frequencies simpler antennas can be used, as circuit printed F antennas [14]. For better signal to noise ratio, highly directional horn antennas can be used with the added inconvenience of occupying more space [15]. For more compact and portable solutions while maintaining a good directional gain, multi patch antennas are the optimal solution [16, 17].

Software defined radio

The Software-Defined Radio (SDR) was first introduced by Joseph Mitola as a concept for the future of the radio [18]. A SDR needs to be able to modulate and demodulate any signal entirely in software, regardless of the standard, operating frequency or bandwidth of the signal. The transmitter has, in this vision, the ability to create any waveform, and translate it to any frequency to be later converted to the analog domain by a Digital-to-Analog Converter (DAC) to then be amplified and transmitted into the medium. On the other hand the receiver should be able to collect a certain bandwidth of the spectrum, amplify it and convert it into digital domain with an Analog-to-Digital Converter (ADC). After the conversion, the process of demodulation of the signal would be carried by software.

There has been a large and fast development in the area of SDR and versatile and portable hardware platforms are now accessible and can be easily acquired. This massification allows for new applications based on this architecture to be implemented and produced.

Cognitive bio-radar proposal

The novel idea is then to create a Bio-Radar based on a SDR. This will allow the creation of a Cognitive Bio-Radar that is able to do spectrum sensing, have an opportunistic spectrum allocation, an adaptive dynamic range and others. This cognitive features allows the creation of more capable and robust non-contact monitoring systems that are able to acquire the respiratory rate and heartbeat while avoiding possible noise sources.

The cognitive Bio-Radar is then an improvement of the common Bio-Radar, allowing to sense the environment and intelligently choose the programmable RF parameters to better acquire the signal without affecting other local wireless systems. This optimizations will allow for Bio-Radars to be more spectrum efficient, less prone to jamming and even allowing to reach better signal to noise ratios not possible in a conventional Bio-Radar.

By taking off-the-shelf SDR equipment and design them in order to create a Bio-Radar system, we can have access to a flexible RF front-end and FPGA resources that enable us to have a full working and flexible cognitive Bio-Radar. The data acquired from this Bio-Radar system can then be compared and calibrated using state-of-the-art systems for measuring breathing and heartbeat but that need contact with the patient.

By implementing the Bio-Radar in a SDR we turn possible cognitive features that can highly increase the performance of the device. These possible features are listed and explained next.

Multiple bio-radars usage, cooperation or self-awareness

Usually in a Bio-Radar there is no concern for the use of multiple devices in the same location, this could be the case in application on a hospital. If a high amount of devices were to be used in the same area, inter-device interference is to be expected. In a situation where a multiple number of devices are working at the same time, a cooperative network can be created between devices in order to share the spectrum resources between them and avoid interference with each other. Another way to avoid this interference is for each Bio-Radar, individually, sense the spectrum and decide what type of operation it needs to have in order to bypass any interference. Using either one of the methods, the Bio-Radar will then decide the emitting power, central frequency and bandwidth to better manage the current spectrum usage.

Cognitive multiple CW operation

With a flexible RF front-end it is possible to obtain a detailed knowledge of the medium, which allows an opportunistic usage of the spectrum of the Bio-Radar device. The simplest example is the usage of these free bands for a multiple CW radar operation. The Bio-Radar can then occupy those bands with pilots, this allows the analysis of the Doppler effects from multiple carriers and combine them to reduce the noise from the received reflected signal. This allows to obtain the subject's bio-signals with higher SNR as we are combining the Doppler effect from multiple pilots.

Opportunistic spectrum allocation

Usually in a Bio-Radar device fixed conditions are used as a fixed waveform, central frequency and bandwidth. By building it based on a SDR it is possible to alter these parameters in real time. This allows for the device to use multiple frequency bands thanks to this flexible RF front-end, increasing the capability for acquisition of bio-signals. The device knows the available spectrum resources and will use this information in order to avoid collision with other transmitting RF devices. For this type of operation the system needs to constantly sense the spectrum, so if a new signal is detected in the same frequency, the Bio-Radar will then stop the transmission in that band in order to avoid interference. This cognitive feature also jamming avoidance as demonstrated in Fig. 2.

In red the noise floor is visible, after the device senses the spectrum it decides what frequency bands are going to be

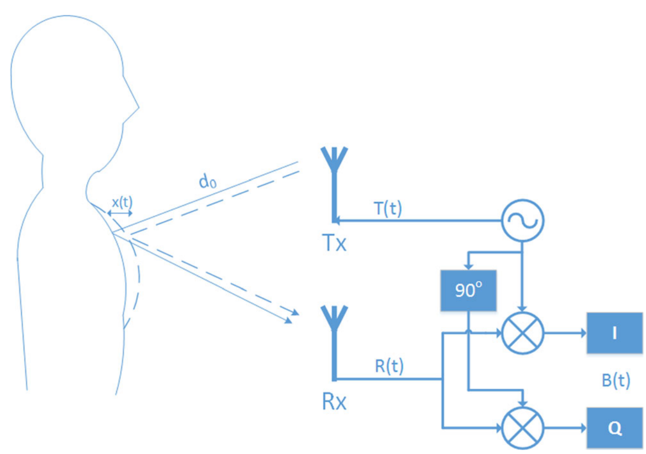


Fig. 1 Bio-radar using doppler effect to detect chest movement

used, shown in green. The system will constantly sense the spectrum and if a new signal is detected, as it shows in orange, the system will stop the transmission in that band as soon as possible to avoid interference with other RF devices.

Spectrum testing

Spectrum testing is a technique that allows to obtain the best RF operation parameters. It works in the following way, after a period of sensing, the ambient spectrum, without bio-radar transmission is sensed. After these measurements and by taking advantage of a flexible full duplex SDR, the DAC can be used to test a slice of the spectrum. For this purpose the DAC convert to analog domain a signal with flat frequency response (e.g. Zadoff–Chu sequence) in order to obtain a constant power spectrum in a large frequency band. This test signal needs to be low power in order to minimize interference with other nearby devices, but needs to be high enough to be distinguishable from the ambient noise.

While the digital test signal is generated with constant power spectrum, the conversion to analog domain and subsequent amplification and transmission uses non-ideal devices. The used components as the DAC, amplifiers and antennas do not exhibit a flat frequency response. Due to this, the transmitted test signal will perform better and have higher power at certain frequency intervals. This information can be interpreted from the reflected test signal that is acquired by the receiver ADC. After evaluating both the ambient spectrum and the test signal behavior, the frequency band with greater signal to noise ratio is then chosen (Fig. 3).

Adaptive dynamic range controlled by the amplifiers gain

In order to obtain the best signal to noise radio in a Bio-Radar system, the highest amount of power should be transmitted, under the necessary health norms, in order to get the best signal to noise radio in the reflected wave. However if the received signal is higher than the dynamic range of the receiver amplifiers, as the LNA, then the signal will saturate the amplifier and distort the signal. This is even more critical if there is a high crossover between the transmitter and receiver path as it make easier for the receiver amplifier to saturate.

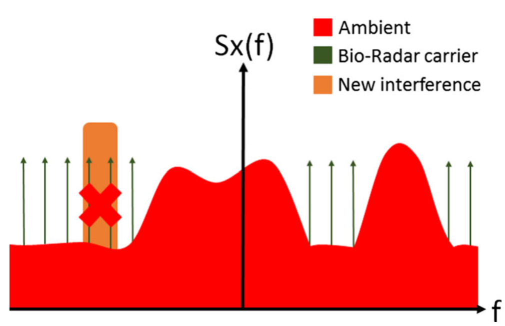


Fig. 2 Opportunistic use of the spectrum

In order to avoid this problem a periodic analysis of the received signal should be evaluated and the amplifiers gain should be enough to be near the dynamic range but leaving the necessary space for a possible increase on the received signal power.

MIMO for multiple patients detection

A Bio-Radar with a single transmitter and received individual antennas (or a single antenna with a circulator) is only able to analyze the cardiorespiratory signals of a single person. In order to obtain that data from multiple persons then multiple antennas are needed. By using, for example, two receiving antennas it is possible to correlate the received signals reflected by two persons and then separate them and analyze each one individually.

MIMO for precise chest pointing

Taking advantage of a MIMO implementation, we can use the multiple transmitting antennas in order to do beamforming as illustrated in Fig. 4.

With a multiple antenna system it is possible to use beamforming in order to precisely point to the best point in the chest in order to gather breathing and heartbeat signals. The system will start with a narrow beam pointing to an initial location. Then the phase feed to each individual antenna will vary in order to change the directionality of the radiation pattern, allowing to test various points in space.

This allows us to search for the best location for data acquisition, usually where we get the closest reflection to the Bio-Radar system. After an initial calibration, we may want a more precise extraction point and an even narrower beamwidth can be used to search for the location with higher respiration and heartbeat signal amplitude.

As we expect the patient to move, this method can be used as a tracking system, where this calibration is run periodically in order to keep an updated chest location information.

MIMO for cancellation of movement artifacts

With a complex MIMO system it is possible to constantly analyze the received reflections in order to obtain an image

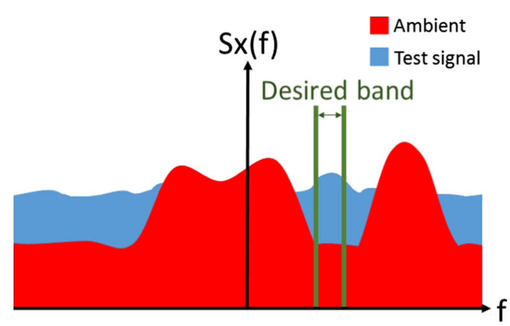


Fig. 3 Choosing of the desired spectrum

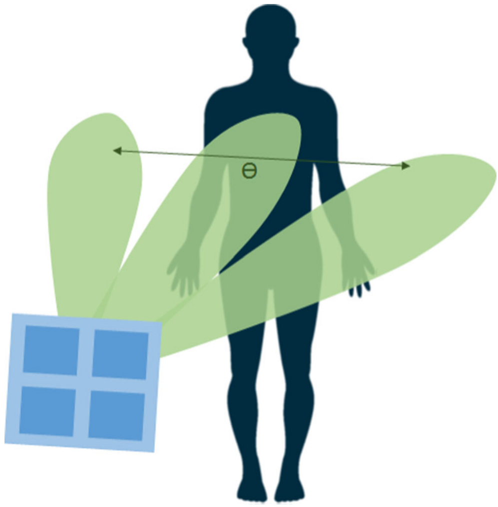


Fig. 4 Beamforming to precise Bio-Radar directivity

of the environment. This image will also include the patient that is being tracked. At the same time that the bio-signals are being evaluated, periodically using beamforming, an array of points in space can be evaluated. The knowledge of the distance of these points in space enables a periodic analysis of the person's movement. These artifacts caused by movement can then canceled in the extracted bio-signals.

Developed software defined radio bio-radar testbed

To validate the possibility of having cognitive features in a Bio-Radar in order to increase the performance of the device, it was implemented a SDR Bio-Radar solution to work as testbed.

The chosen front-end was an ETTUS USRP B200 that provides a, single board SDR platform with continuous frequency coverage from 70 MHz–6 GHz. The board uses an Analog Devices AD9364 allowing full duplex operation, ideal for a CW Bio-Radar.

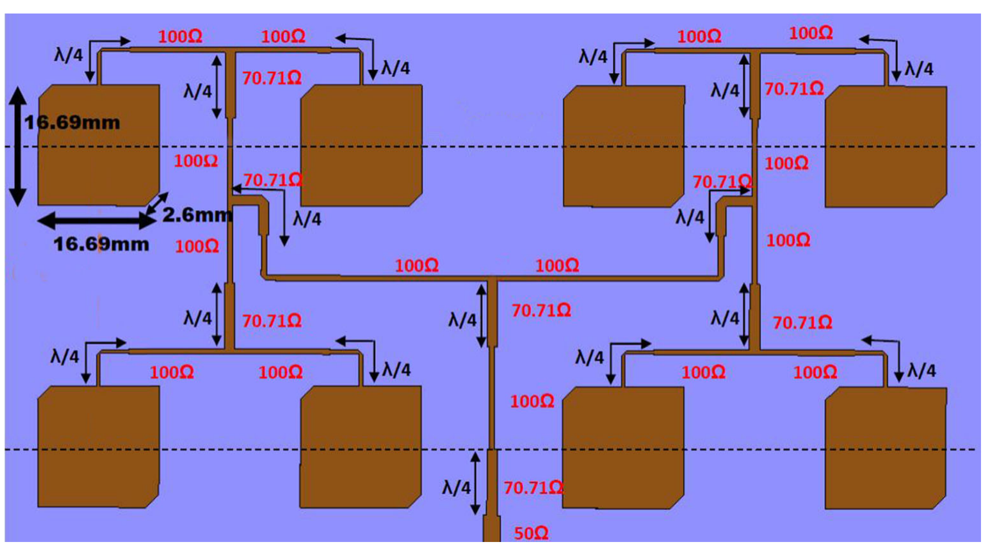
The developed SDR Bio-Radar uses two identical eight patch array antennas. The utilization of this microstrip antennas allows for a very directional radiation pattern while maintaining a low footprint, compared for example to horn antennas. The directional behavior is beneficial to both transmission and reception allowing a better signal to noise ratio of the bio-signals. A diagram of the used patch array antennas in presented in Fig. 5.

The used antennas are optimized for frequency operation in 5.77GHz. In terms of antenna's directivity, the patch array is designed to have 16dBi of directional gain. The distance from both antennas to the person under test is of approximately 0.5 m and the subject is seated facing them. The antennas are connected with SMA-female to SMA-female cables to the B200, whitch is connected to a personal computer using USB2 as seen in Fig. 6.

The Bio-Radar is operating as a Continuous-Wave (CW) radar where both receiver and transmitter mixers are driven by the same 5.77GHz local oscillator. The transmitted sinewave is generated at the DAC with a frequency of $\Delta = 10$kHz before upconversion. The transmitted signal will then be a CW at 5.77+ Δ GHz. This signal is reflected and sampled by the receiver path of the Bio-Radar. Due to the use of a Δ frequency offset, the noise from the local oscillator leakage, centered at DC, is avoided. After downconversion the received data is sampled at 100ksps. In order to analyze the Doppler effect of the reflected wave, thes Δ offset is removed digitally with a digital down-converter and the baseband signal angle is obtained. The signal is then filtered with a band pass of 0.05 Hz to 50 Hz. The signal is then resampled to 1 kHz. In this test the USRP amplifiers were configured for a RX gain of 60 dB and TX gain of 45 dB.

In terms of electromagnetic field exposure safety, for the defined RF settings, the SDR has an output power of -33dBm.

Fig. 5 Diagram of the used patch antennas



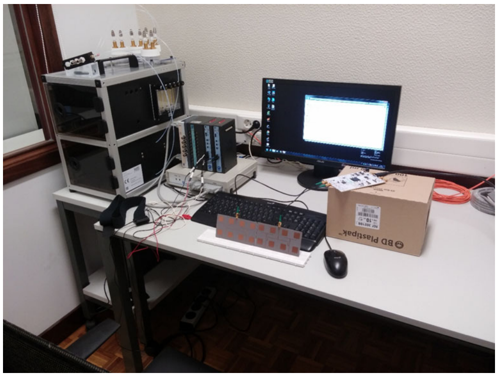


Fig. 6 Experiment setup

The antenna used has a gain of 16dBi and a main lobe of 70° aperture. Assuming, for simplicity, a spherical sector as the radiation pattern the area segment at a distance of 0.5 m is of 0.1m2. This give us a theoretical value of 0.2 mW/m2 for the transmitted wave power density. This value is in orders of magnitude bellow the recommended value of 10 W/m2, for general public exposure to time-varying electric and magnetic fields from the International Commission on Non-Ionizing Radiation Protection [19].

To evaluate the data acquired by the Bio-Radar and validate those measurements with a certified research equipment, a Biopac MP100 was used [20]. The focus is in the evaluation of the Bio-Radar acquired data of both breathing and heartbeat and comparing it to the sampled signals from the two used modules of Biopac. For breathing, the Biopac RSP100C was used and for the ECG the ECG100C was utilized.

The Biopac MP100 system is connected to two acquisition boards. The ECG100c, an Electrocardiogram Amplifier, is used to record the ECG data. The ECG uses three electrodes, two on the wrist and one for ground reference in the leg. The second board is an RSP100c used as a direct physical measurement of respiratory effort, which acquires this data with a TSD201 respiration transducer chestband. The transducer strap wraps around the thorax and measures the instantaneous thoracic circumference in order to obtain an estimation of the respiratory rate. Both acquisition boards are sampling at 1ksps.

The overall system used in the experiment is shown in Fig. 6 and a functional diagram is in Fig. 7.

Methodology

Before starting the acquisition, the person under test is seated at 0.5 m away from the Bio-Radar, with the three electrodes and chestband in place. With the setup in place both the Biopac and the Bio-Radar start the acquisition at the same time. The procedure is illustrated in Fig. 8 and starts when the person takes three heavy breathings to then stay in apnea as long as possible. These heavy breathings will generate a relevant displacement in the distance acquired by the Bio-Radar and a respiratory effort obtained by the chestband. This expected displacement will later be used for synchronization of the two devices. After a period of apnea, the person under test is asked to proceed with rapid breathing.

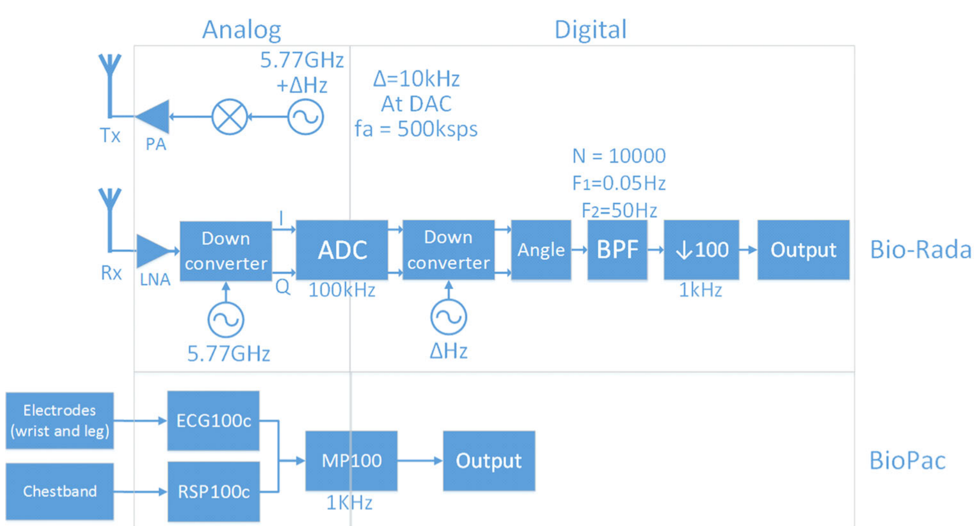
After a period of rapid breathing the experience is given as completed, the devices stop the acquisition and the data is stored for evaluation.

Results

Full test

For a good comparison of results, the data from both equipment is first normalized. For this normalization, the DC of both signals is removed and the amplitude is divided by the maximum absolute value of each signal. After normalization both signals are synchronized, with a shift in the Y-axis, using

Fig. 7 Diagram of the system used



as reference the transition from the three heavy breathings to the apnea.

The physical measurement of respiratory effort, acquired from the Biopac system, is compared with the one obtained in the Bio-Radar. In Fig. 9, we can see a comparison of the full test for both the Bio-Radar and the signal obtained with the chestband.

While the data seems coherent trough both devices there are some details that deserve attention. While near the end of the test, during fast breathing, both acquired signals are very similar, in the first three heavy breathings there is a wrap effect of the signal acquired by the Bio-Radar [21].

The origin of this problem can be explained by the continuous wave used in this test. As the system is using a sine wave with a 5.77GHz, the signal wavelength is of 5.2 cm. Due to the use of a CW the interval of detected displacement is then limited by half of this wavelength. If at a given instant the movement by the person under test is bigger than 2.6 cm, instead of causing a higher amplitude at the Bio-Radar receiver data the amplitude will actually decrease.

Fast breathing

While the deep breathing showed wrap problems due to the wavelength of the transmitted signal, the fast breathing part of the experience show good coherence. As the fast breathing is associated with lower chest movements, then the determined Bio-Radar distance variance is below the wavelength of the constant waveform.

As shown in Fig. 10 the Bio-Radar acquired data is consistent with the breathing pattern acquired from the Biopac system.

Apnea heartbeat

During apnea, there is no movement of the muscles used inhalation and the volume of the lungs remains unchanged, making it the perfect situation to test the Bio-Radar heartbeat detection. The comparison between the Bio-Radar data and the ECG acquired by the Biopac is showed in Fig. 11.

Along with the data acquired by both equipment it is also shown a peak analysis of the Bio-Radar acquired signal, for an expected peak period of between 50 and 150 beats per minute. The detected peaks were able to follow the ECG signal while

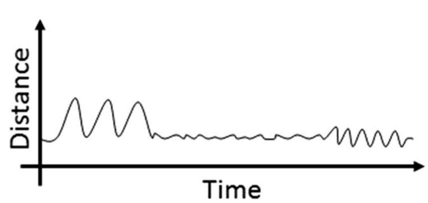


Fig. 8 Expected variation of the distance measured by the Bio-Radar

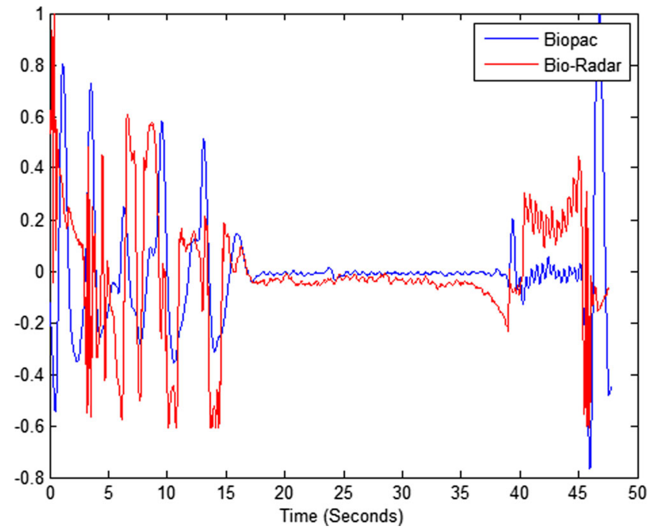


Fig. 9 Full test results

missing three heartbeats of the thirteen acquired during apnea. A zoom of the comparison of the ECG and Bio-Radar data is shown in Fig. 12.

While the data is not enough to determine the validity of the statement, there is the possibility that the peaks values acquired from the Bio-Radar do follow the T wave on the ECG.

Conclusions and future work

In order to improve Bio-Radar systems and allow them to enter in mass consumer market cognitive functions should be embedded. To achieve this, the optimum solution is to create a Bio-Radar built in a SDR, allowing for a flexible spectrum interface to be implement and a truly robust cognitive Bio-Radar to be built. This architecture will allow in the

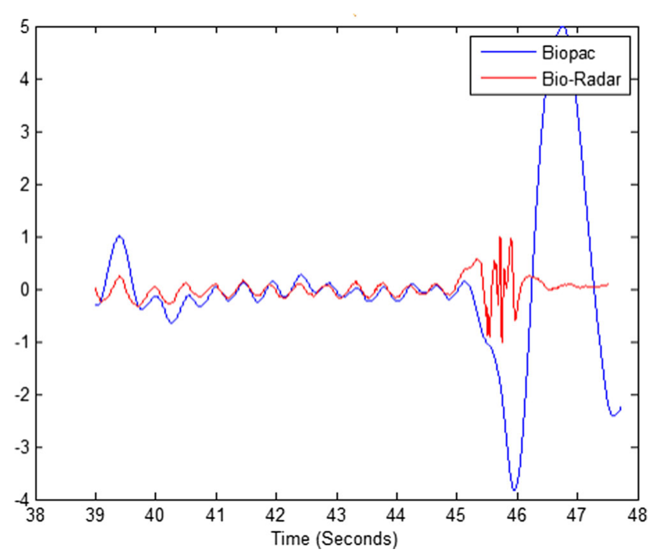


Fig. 10 Fast breathing using the angle of the complex values

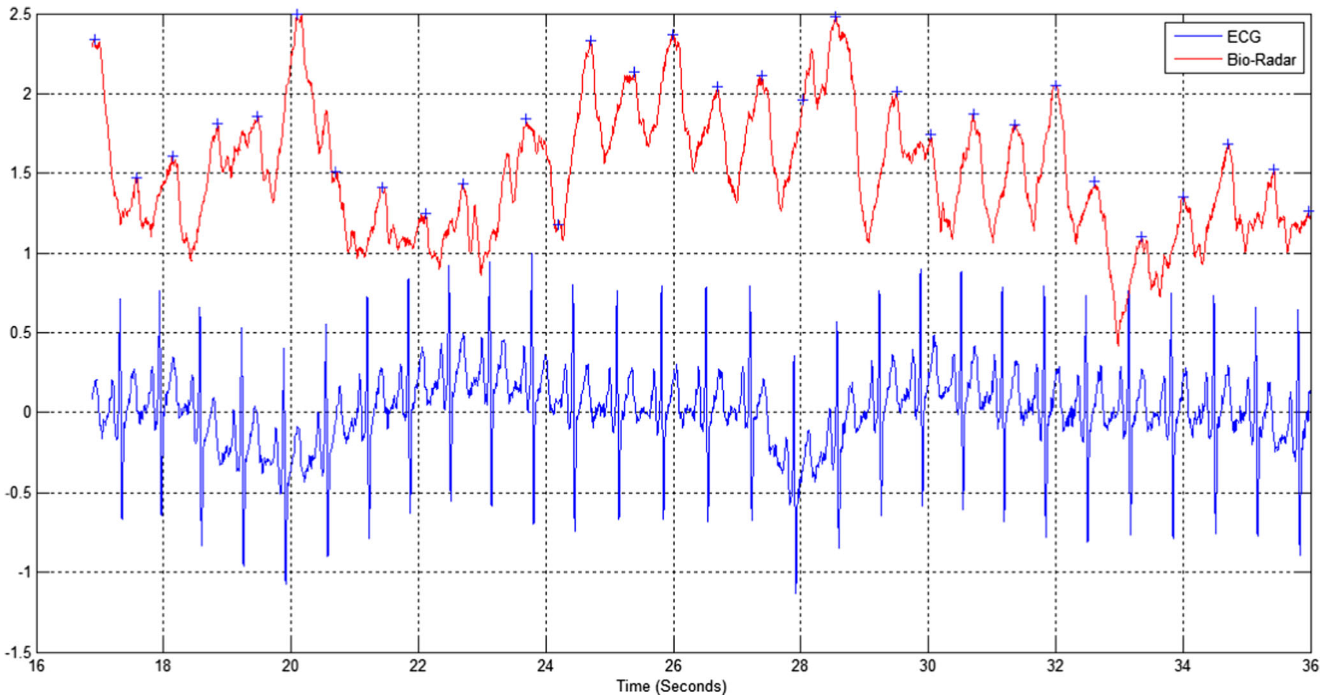


Fig. 11 Heartbeat comparison between the ECG and bio-radar

future a symbiosis of remote monitoring sensors with everyday life objects, allowing new assisted living applications to be created.

The developed testbed show that a SDR based Bio-Radar is indeed capable of detecting breathing pattern and is coherent with the data acquired by validated research equipment. In addition, it has demonstrated that the heartbeat frequency is also present on the developed Bio-Radar acquisition data and can be extracted when no other movement of the patient is present. There is the possibility of the heartrate information acquired from the Bio-Radar to be compared to the T signal obtained from the ECG and future relationship between the data extracted by the Bio-Radar and other waves present on the ECG seems plausible. Future work should focus on

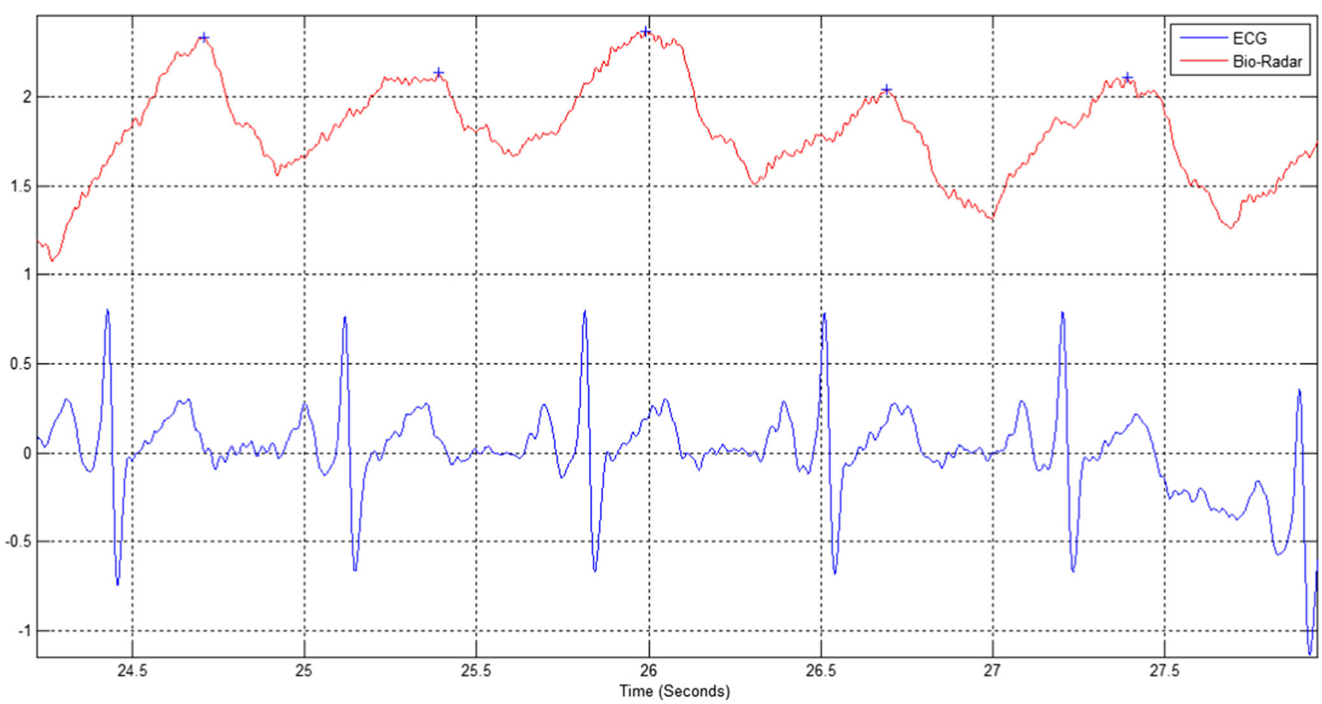


Fig. 12 Zoom of the heartbeat comparison between the ECG and bio-radar

implementation of the cognitive features that are made available by using SDR based Bio-Radar system.

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