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Multi-Target Vital Signs Monitoring using SIMO CW RADAR

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Abstract:
Electrocardiography is a reliable method for acquisition and recording of the heart activity. However, it can be relatively uncomfortable for the patient, due to the large number of wires needed to be attached to patient's body. Additionally, the patient's mobility is significantly reduced, especially if the monitoring has to be performed for an extended period of time. A possible solution to this problem is to use contactless monitoring of the heart functions. In recent years, RADAR has gradually gained prominence in the medical field because of its ability to capture heartbeat-induced torso vibrations. In this paper, we present an algorithm for monitoring multiple user heart activity simultaneously using Single-Input Multiple-Output (SIMO) continuous-wave (CW) RADAR. In the presented approach, digital beam steering acts as a spatial filter to filter out signals coming from irrelevant directions and then the heart activity signal of the person of interest is extracted. Simulation results show that the heart activity signals of multiple users can be effectively separated and extracted using the proposed method.

Keywords: Vital sign detection, Heart rate, SIMO, CW RADAR, Digital beam steering.

Introduction

Heart rate is an important parameter for initial evaluation of a patient's health. Conventional electrocardiogram instruments require several electrodes to be attached to the body, which can cause inconvenience. This can be extremely inconvenient for newborns or patients with severely damaged skin [1]. This is the main motivation for investigating other approaches for heart activity monitoring.

In the recent years, non-contact heart activity monitoring has become a popular topic for the scientific community. Sensors like camera or RADAR are considered as best candidates. Between them, RADAR has the advantage that it is stable and is not affected by lighting conditions. RADAR also does not infringe user's privacy compared to camera-based heartbeat monitoring systems.

In this work, CW RADAR-based heart monitoring approach is being investigated. Single-channel CW RADAR used to observe patient's heart activity was extensively investigated in [2] and [3]. Although promising results were achieved, they were not suitable for the multi-patient scenario, i.e. are not able to monitor multiple patients with a single RADAR sensor. CW RADAR with an uniform linear antenna array is used to monitor the heart activity of two or more patients simultaneously in this work. Heart activity signals from different patients are mixed together and is challenging to separate them. Using beam steering it is possible to effectively filter out other irrelevant signals and enhance signals coming from the corresponding directions of interest.

Beam forming and beam steering is performed by combining signals from multiple antennas in analog or digital domain. In analog domain, beam forming/steering is performed by introducing delays in the signals from every antenna. This can be also achieved by using phase shifters. This is usually called analog and digital beamforming. These signals are further summed and digitized.

However, once the hardware has been fabricated, it is very difficult to introduce changes to it. Therefore, in this work, we will investigate beam forming/steering in the digital domain, which can be implemented in software.

The rest of the paper is organized as follows: in Section II and III, the CW RADAR system and the proposed beam steering based approach are described, and then the simulation results are

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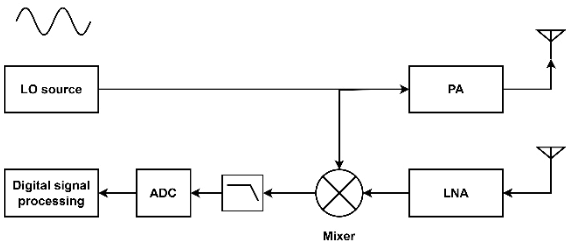

Fig. 1. A block diagram of a CW RADAR system.

presented in Section IV. The conclusion is drawn in Section V.

CW RADAR system

The system block diagram of a CW RADAR is shown in Figure 1. It comprises a local oscillator (LO) source, power amplifier (PA), transmitter antenna, receiver antenna, low noise amplifier (LNA), mixer, low-pass filter, analogue-to-digital converter, and digital signal processor (DSP). In the following paragraphs, the function of each module will be described specifically.

A CW tone with constant frequency f_c and amplitude is generated from an LO source, amplified by PA and emitted into space via antenna. The transmit signal can be written as:

$$T(t) = e^{j(2\pi f_c t + \phi(t))}, \quad (1)$$

where $\varphi(t)$ is the phase.

When the transmitted waveform encounters a target in space and is reflected back to the receiver, the received signal for the antenna channel n can be written as:

$$R(n,t) = A_n e^{j\left(2\pi f_c t - \frac{4\pi d_0}{\lambda} - \frac{4\pi x_h(t)}{\lambda} + \phi\left(t - \frac{2d_0}{c}\right)\right)}, \quad (2)$$

where d_0 is the distance between the torso and RADAR. λ is the wavelength. The light speed is represented by c. A_n is the amplitude of the received signal at the n-th antenna. The rhythm of the heartbeat is periodic and can be approximated to a sinusoidal signal if only heart rate is to be monitored. It can be expressed as follow:

$$x_h(t) = A_h \sin(2\pi f_h t), \quad (3)$$

A_h is the amplitude of the heart sound and f_h is the heart-beat frequency of the patient.

The received signal is down-converted with the help of the mixer and then low-pass filtered to obtain the low inter-mediate (low-IF) signal.

For a single patient scenario, the low-IF signal at the n-th antenna can be written as:

$$B(n,t) = \mu e^{j\left(-\frac{4\pi}{\lambda}\sin(2\pi f_h t) + 2\pi(n-1)\frac{\Delta d}{\lambda}\sin(\theta)\right)}, \quad (4)$$

where n is the index of the antenna and the value of n in the range between *1* and N. Δd is the distance between the receiving antennas and is typically $\lambda/2$. θ is the angle between the antenna and the target. μ is the received amplitude. For multiple targets, the signal will be a summation of the reflected signals from different targets:

$$B_{sum} = B_1 + B_2 + \cdots, \quad (5)$$

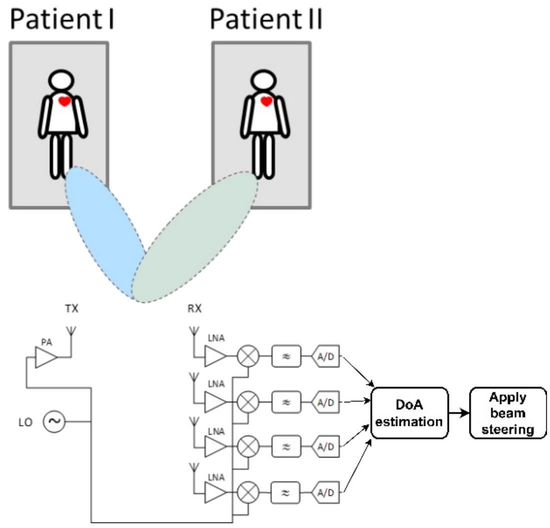

Fig. 2. Digital beam steering by adding phase shift.

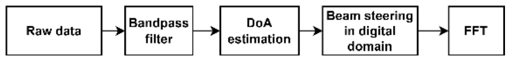

Fig. 3. Signal processing chain.

Processing of the received signal

In this section, an approach with the aid of beam steering is investigated to suppress irrelevant signals and improve the signal-to-noise ratio of the signal in the direction in which the target is located to enable simultaneous observation of the heart rate from multiple patients.

As shown in Figure 2, the RADAR is mounted on the ceiling and observes the heartbeats of two targets simultaneously. The raw RADAR signal is first fed into a bandpass filter that preserves only the frequency components from 0.1 to 80 Hz. This is because the heartbeats and their harmonics are contained in this part of the signal spectrum. The direction-of-arrival (DoA) in which the patients are located can be calculated using super-resolution DoA methods, such as MUSIC [4], root-MUSIC or ESPRIT as illustrated in Figure 3. The beams are steered in the estimated angular directions by adjusting the phase shifter angles.

By assuming that the angle of the target position is Θ, then the IF signal after the beam is steered towards that target can be expressed as:

$$B_{shift}(n,t,\Theta) = e^{j2\pi(n-1)\frac{\Delta d}{\lambda}\sin(\Theta)} B^{*}_{sum}(n,t), \quad (6)$$

The patient's heart rate can then be obtained by transforming the coherently combined signal into frequency domain using FFT.

Simulation and results

The carrier frequency of the simulated RADAR is set to 61 GHz. The simulated RADAR has one transmitting antenna and eight receiving antennas. The distance between the receiving antennas is half a wavelength.

Two patients are considered. Patient I is viewed at an angle of -18 degrees and has a heart rate of 90 beats per minute. Patient II is viewed at an angle of 30 degrees and has a heart rate of 78 beats per minute.

The spatial directions of the two patients are calculated using signal samples from all the antennas without beam steering by the MUSIC algorithm. The angular directions at which two patients are located can also be found by sweeping the beam. For example, the beam steering module scans from -90 degrees to 90 degrees with a scanning resolution of one degree. After the integrity of the phase shift for each scan, the energy of the signal at each scanning angle reveals the target's angular position, as shown in Figure 4.

Based on the information provided by the DoA estimation, the beam is steered to the angle of the patient's location by adding phase shifts to the IF signal.

Three sets of signals in the frequency domain are illustrated in Figure 5. The solid red line shows the result when the beam is steered to -18 degrees. The blue solid line shows the result when the beam is steered to 30 degrees. The results based on the original raw data that has not been integrated with the phase shift are shown by the black solid line.

It can be noticed that the heartbeat frequencies of the two patients are effectively separated using two different beams. When the beam is

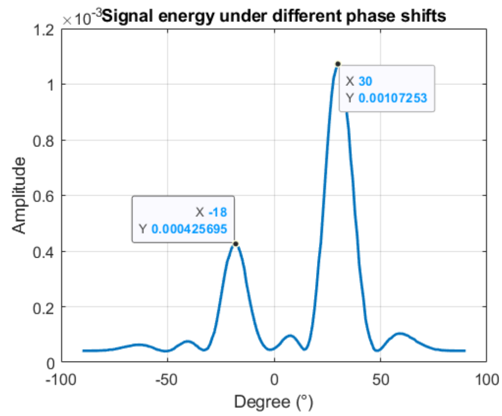

Fig. 4. Direction-of-arrival estimation via digital beam steering.

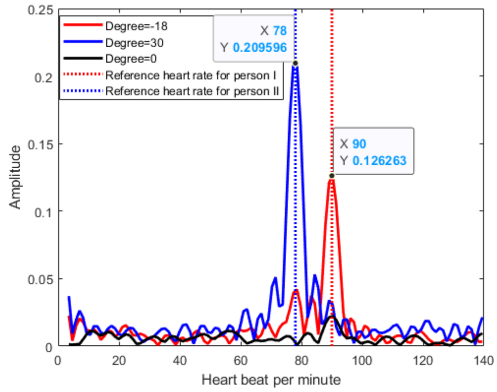

Fig. 5. Results of simulations.

steered to the angle at which the patient is located, its heartbeat rate is obtained and signals from the other directions are suppressed. Using parallel computing concepts or multi-core systems, it is feasible to estimate the heartbeats of several patients simultaneously.

When there is no beam steering, the heartbeat information of the two patients is fused together and cannot be easily extracted.

When parallel computing capabilities or multi-core systems are not available, in order to achieve simultaneous estimation, the two beams can be directly superimposed, and two dominant peaks will appear on the spectrum for two patients. For the continuous monitoring of the heart rate of two patients, the processing flow of the algorithm is shown in Figure 6. It is assumed that the patient's heart rate does not change much over an extremely short period of time. The RADAR data is divided into data chunks and the overlap step is 128.

In the first two frames, the patient's heart rate is extracted separately, without superimposing the two beams, according to the procedure proposed above. For the subsequent data, the patient's heart rate is searched in a specific spectral

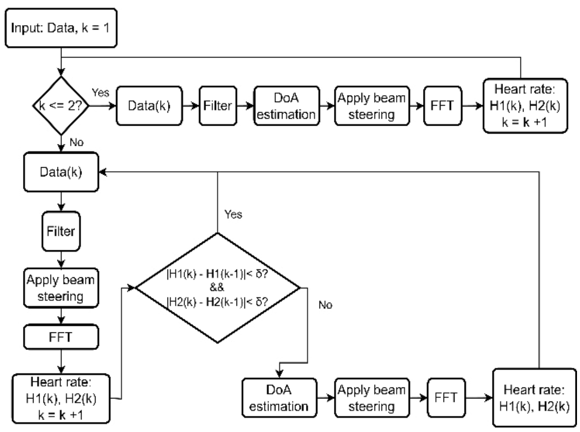

Fig. 6. Processing flow for multiple patients' heart rate monitoring.

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range, only if the patient's heart rate changes significantly, at which point it is necessary to re-estimate the angles of the two patients, recalculate the phase shift factors, estimate heart rate from the single-beam steered data and compute a new search range.

Tab.1: Patients heart rate and angular position summary. Bpm is short for beats per minute.

	P1(Bpm)	P2(Bpm)	P1(°)	P2(°)
Section 1	90	78	-18	30
Section 2	84	72	-19	29
Section 3	66	78	-18	30
Section 4	78	66	-17	30
Section 5	96	60	-20	27

In this experiment, the patients' heart rate and angular position changes at certain intervals. All the parameters are listed in Table 1.

The results of the estimated heart rate for patient I and patient II are presented in Figures 7 and 8, respectively. The gap between the estimated heart rate and the reference value is small. For patient I, the average mean error is less than 0.55 bpm. For patient II, the average mean error is less than 1.54 bpm.

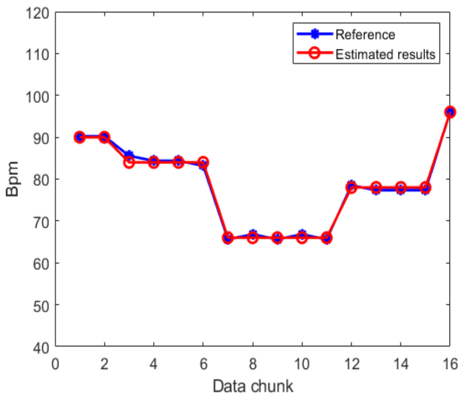

Fig. 7. Estimation for Patient I.

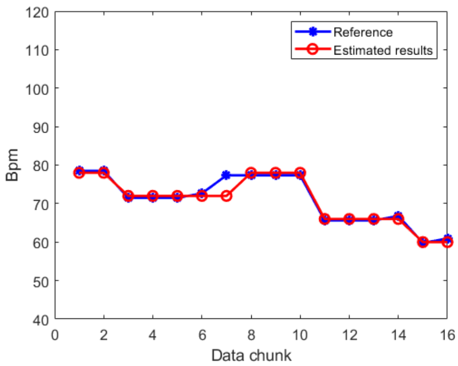

Fig. 8. Estimation for Patient II.

Conclusion and outlook

In this paper, we investigated an approach to separate and monitor multiple patient heartbeat signals simultaneously using beam steering in the digital domain. Using digital beam forming/steering, the beam can be pointed at the patient and effectively suppress signals in directions not related to it. Simulation results show that digital beam forming/steering can be used not only to estimate the angle at which the target is located, but also to help separate the heartbeat frequencies of multiple patients.

In future work, we will validate presented approach with a real single-input-multi-output CW RADAR, and novel beam-tracking algorithms will be investigated and implemented for multi-user heart sound monitoring.

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