DETECTION OF MULTIPLE HEARTBEATS USING DOPPLER RADAR†

Qin Zhou, Jianhan Liu, Anders Høst-Madsen, Olga Boric-Lubecke, Victor Lubecke
Department of Electrical Engineering, University of Hawaii

ABSTRACT

Doppler radar life sensing has shown promise in medical and security applications. The current paper considers the problem of determining the number of persons in a given area (e.g., a room) using the Doppler shift due to heartbeat. The signal is weak and time-varying, and therefore poses a complicated signal processing problem. We develop a generalized likelihood ratio test (GLRT) based on a model of the heartbeat, and show that this can be used to distinguish between the presence of 2, 1, or 0 subjects, even with a single antenna. We further extend this to N antennas. The results show that one can expect to detect up to $2N$-1 subjects using this technique.

1. INTRODUCTION

Doppler radar remote detection of heart and respiration is a promising technique for unobtrusive health monitoring and life sensing, with proof of concept demonstrated for various applications [1-3]. However, so far this approach has been limited to sensing and detection of a single subject. When there are two or more subjects present in the environment, it is more challenging to isolate signals from individual subjects. We are exploring separation of signals from multiple subjects in single and multiple antenna systems. In a single antenna system, based on expected different spectral signatures of individual cardiovascular related motion, it is possible to separate individual signals in the frequency domain. In a multiple antenna system (SIMO or MIMO), even if individual cardiovascular signatures are very similar, it is possible to distinguish different subjects based on angle of arrival. In this paper we will discuss theoretical background for both of these approaches, experimental results for a single antenna system, and simulation results for the SIMO system.

The use of Doppler radar to sense vital signs is a relatively recent innovation [1-3]. The clear advantage of such a method is that individuals can be monitored at a distance, with no contact required. Due to the Doppler effect, an RF wave reflected at a moving surface undergoes a frequency shift proportional to the surface velocity. If the surface is moving periodically, such as the chest of person breathing, this can be characterized as a phase shift proportional to the surface displacement. If the movement is small compared to the wavelength, a circuit that couples both the transmitted and reflected waves to a mixer can produce an output signal with a low-frequency component that is directly proportional to the movement. This is the case when measuring chest surface motion related to respiration and heart activity. Figure 1 illustrates this concept. Internal body reflections are greatly attenuated (more severely with increasing frequency) and will not be considered here.

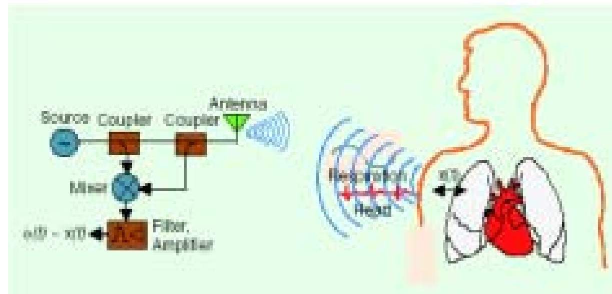

Fig. 1 A single antenna system with single subject. A homodyne radio is used to detect the phase shift proportional to chest displacement due to cardiopulmonary activity.

The current paper focuses on the problem of detecting the number of subjects within range of the device, and possibly location, through direction of arrival (DOA). This has a number of important applications, for example to find survivors in disaster situations like earthquakes, and for military recognizance.

2. SIGNAL MODEL

We assume a continuous wave (CW) radar system transmiting a single tone signal at frequency ω.. This signal is reflected from a target at a nominal distance d, with a time-varying displacement given by $x(t)$. Suppose at first that the signal from a given subject arrives from a single path. The sampled, passband received signal at the n-th antenna in a SIMO system with quadrature receivers can be written as [12]

$$r_n(t) = A\exp(j\omega(t + x(t - n\tau) - n\tau)) + w_n(t), \quad n = 0..M-1$$

$$\tau = \frac{d}{c}\sin(v)$$

† This research was sponsored by NSF under contract ECS0428975 and the U.S. army under contract W15P7T-05-C-B202

Here τ is of the order $1/(3\cdot 10^8)$, so that $x(t-n\tau)\approx x(t)$. After mixing with the carrier wave, the baseband received signal can be written as

$$r_n(t) = A\exp(j(\omega x(t) - n\phi - \theta)) + w_n(t), \quad n = 0..M-1$$
$$\tau = \frac{2\pi d}{\lambda}\sin(v)$$

for a linear array, with angle of incidence v and noise $w_n(t)$. If we collect the signal received at the M antennas into a vector, this can be written as

$$\begin{aligned} \mathbf{r}(t) &= A\exp(j\omega x(t))\mathbf{s}(\phi) + \mathbf{w}(t) \\ \mathbf{s}(\phi) &= [1, \exp(j\phi), \ldots, \exp(j(M-1)\phi)]^T \end{aligned} \tag{1}$$

As $\omega x(t)$ is very small

$$\exp(j(\omega x(t)) \approx (1 + j\omega x(t)) \tag{2}$$

is a good approximation, so that

$$\mathbf{r}(t) \approx A(1 + j\omega x(t))\mathbf{s} + \mathbf{w}(t)$$

Thus, the signal is characterized by a characteristic vector $\mathbf{s}$. If there are now S subjects at different positions, they will likely have different DOA vectors $\mathbf{s}$, and we can write the total received signal as

$$\begin{aligned} \mathbf{r}(t) &= \sum_{s=1}^{S} A_s \exp(j(\omega x_s(t))\mathbf{s}_s + \mathbf{b} + \mathbf{w}(t) \\ &\approx \sum_{s=1}^{S} j\omega A_s x_s(t)\mathbf{s}_s + \sum_{s=1}^{S} A_s \mathbf{s}_s + \mathbf{b} + \mathbf{w}(t) \end{aligned}$$

where $\mathbf{b}$ is a DC component due to reflection from other objects (e.g., walls, furniture) than humans. This shows that the DC component of the signal does not contain any information, and this can therefore be filtered out.

2.1. Heartbeat signal model

The signal $x_i(t)$ generated by each subject consists of respiration and heartbeat. The respiration is usually in the range 0-0.8 Hz and the heartbeat in the range 0.8-2 Hz. While the respiration is a stronger signal than the heartbeat, it is also more difficult to characterize and therefore to detect. In the current method we therefore remove most of the respiration by high pass filtering. The heartbeat signal itself is a rather complicated signal. It is nearly periodic, but the period can vary from one beat to the next; this is called heart rate variability (HRV). HRV can be modeled as a random process [5] with strong periodicity. To simplify the modeling, we filter the received signal with a bandpass filter with a pass band of 0.8-2 Hz so that only the fundamental frequency of the heartbeat is received. The resulting signal is modeled as

$$\begin{aligned} x_i(t) &= (A_i + \alpha_i(t))\cos(\omega_i t + \varphi_i(t) + \theta) \\ &= A_i \cos(\omega_i t + \theta) + n(t) \\ n(t) &= A_i(\cos(\varphi_i(t)) - 1)\cos(\omega_i t + \theta) \\ &\quad + \alpha_i(t)\cos(\omega_i t + \varphi_i(t) + \theta) \\ &\quad + (A_i + \alpha_i(t))\sin(\omega_i t + \theta)\sin(\varphi_i(t)) \end{aligned}$$

The amplitude variations $\alpha_i(t)$ and $\varphi_i(t)$ are zero mean random processes modeling the HRV. We assume that these have zero mean not only at DC but also at all frequencies, i.e.,

$$\lim_{T\to\infty}\frac{1}{T}\int_{-T}^{T}\alpha_i(t)e^{-i\omega t}dt = \lim_{T\to\infty}\frac{1}{T}\int_{-T}^{T}\varphi_i(t)e^{-i\omega t}dt = 0$$

From this we can conclude that

$$\lim_{T\to\infty}\frac{1}{T}\int_{-T}^{T}n(t)e^{-i\omega t}dt = 0$$

and therefore that

$$\lim_{T\to\infty}\frac{1}{T}\int_{-T}^{T}x_i(t)e^{-i\omega t}dt = \begin{cases} 1 & \omega = \omega_i \\ 0 & \omega \neq \omega_i \end{cases}$$

Thus, if we calculate the Fourier transform (and not the power spectral density) of the received signal, we can expect to see peaks at the heartbeat frequencies ω_i. The HRV is included in the term $n(t)$ which can be seen as an additional noise term.

3. GLRT FOR DETECTION OF HEARBEAT

There exist a number of methods for determining model order, e.g., AIC and MDL [9]. However, since our *primary* objective is to determine the number of subjects, we prefer to state the problem as a traditional Neymann-Pearson hypothesis test [9].

Consider at first the case of a single receiver antenna with only the I-component available with at most 2 subjects in range. As argued in the previous section, we model the data received in an interval as a mixture of two periodic signals,

$$\begin{aligned} y[k] &= A_1\cos(\omega_1 kT) + B_1\sin(\omega_1 kT) \\ &\quad + A_2\cos(\omega_2 kT) + B_2\sin(\omega_2 kT) + n[k] \end{aligned} \tag{1}$$

where $n[k]$ is white Gaussian noise (WGN) with power σ^2, and A_1, A_2, B_1, B_2, ω_1, ω_2, and σ^2 are unknown. Since $n[k]$ includes terms due to HRV, the assumption that it's WGN is indeed a rough approximation. However, in absence of detailed information about HRV terms, one can argue from maximum entropy principles that a WGN model is the most robust. The problem of determining if there are two or more or less than two persons present can then be stated as the following hypothesis test problem

$$\begin{aligned} H_1 &: (A_1, B_1) \neq (0,0), (A_2, B_2) \neq (0,0) \\ H_0 &: (A_2, B_2) = (0,0) \end{aligned}$$

This is a composite hypothesis test problem with many unknown parameters, and the best detector for this kind of problem is commonly accepted to be the generalized likelihood ratio test (GLRT) [12-13]. In the GLRT the following test statistic is defined

$$t(\mathbf{y}) = \frac{\max_{A_1,B_1,A_2,B_2,\omega_1,\omega_2,\sigma^2} f(\mathbf{y})}{\max_{A_1,B_1,A_2=0,B_2=0,\omega_1,\omega_2,\sigma^2} f(\mathbf{y})}$$

where $f(\mathbf{y})$ is the likelihood function (probability density function) for the received data $\mathbf{y}=[y[1],\ldots,y[N]]$. If $t(\mathbf{y})>\tau$, where τ is some threshold, the GLRT decides H_1 (two or more persons), otherwise H_0 (less than two persons). The threshold τ is determined so that a desired false alarm probability is guaranteed. If H_0 is decided, another GLRT can then be used to decide between 0 and 1 subject.

In the Gaussian case, the GLRT test statistic can be simplified to

$$t(\mathbf{y}) = \frac{\min\limits_{A_1,B_1,\omega_1} \sum_{k=1}^{N} \left(y[k] - A_1\cos(\omega_1 t) - B_1\sin(\omega_1 t)\right)^2}{\min\limits_{A_1,B_1,A_2,B_2,\omega_1,\omega_2} \sum_{k=1}^{N} \left(y[k] - \sum_{i=1}^{2} A_i\cos(\omega_i t) + B_i\sin(\omega_i t)\right)^2}$$

The minimization over A_1, A_2, B_1, B_2 is a linear problem, but the minimization over ω_1, ω_2 is a non-linear problem. As well known, approaches like Prony's method and MUSIC can effectively find the frequencies of multiple sinusoid signals. However, these methods do not work well at low SNR, which is the case of wireless heartbeat signal. As this paper's main focus is not how to find these frequencies or on efficient implementation we currently solve this problem by using a simple grid search, so as to make sure it's optimal as a maximum likelihood estimator.

3.1. Extension to multiple sensors

Assume that there are multiple receiver antennas with both I and Q-components, and that multipath is negligible. The received signal can then be modeled by

$$\mathbf{y}[k] = \left(A_1\cos(\omega_1 kT) + B_1\sin(\omega_1 kT)\right)\mathbf{s}(\phi_1) + \left(A_2\cos(\omega_2 kT) + B_2\sin(\omega_2 kT)\right)\mathbf{s}(\phi_2) + \mathbf{n}[k]$$

where $\mathbf{s}(\phi)$ is given by (1). The GLRT test statistic is now

$$t(\mathbf{y}) = \frac{\min \sum_{k=1}^{N} \left\|\mathbf{y}[k] - \left(A_1\cos(\omega_1 t) - B_1\sin(\omega_1 t)\right)\mathbf{s}(\phi_1)\right\|^2}{\min \sum_{k=1}^{N} \left\|\mathbf{y}[k] - \sum_{i=1}^{2}\left(A_i\cos(\omega_i t) - B_i\sin(\omega_i t)\right)\mathbf{s}(\phi_i)\right\|^2}$$

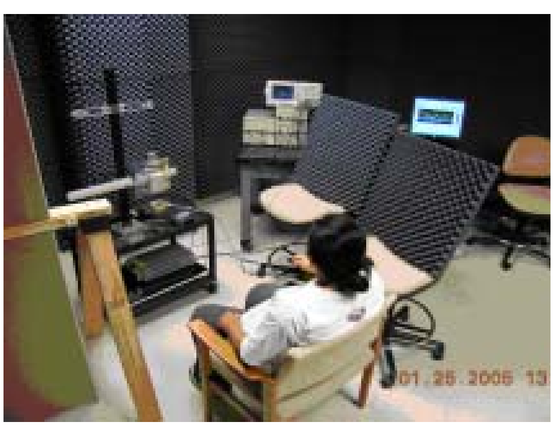

Fig. 2. Photograph of an Experimental Doppler radar set-up

Now the minimization ω_1, ω_2, ϕ_1, ϕ_2 is a non-linear problem also solved by using a simple grid search.

Notice that the minimization with respect to ϕ_1, ϕ_2 give DOA as a by-product, so the methods can also be used for localizing subjects.

4. EXPERIMENTAL SETUP

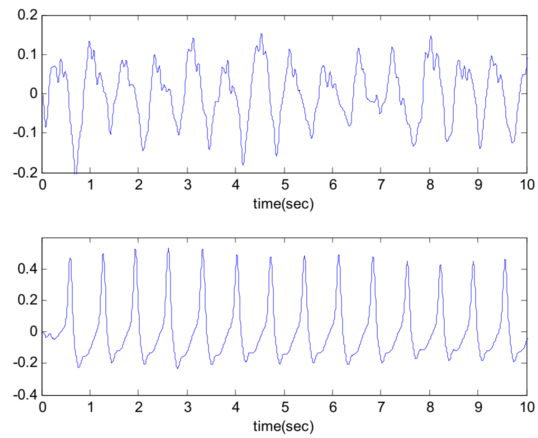

Fig.3. Top: wireless signal; Bottom: reference signal.

A single antenna system, with one subject in the antenna field of view, is illustrated in Fig. 2. The return signal is mixed with a sample of the transmitted signal to produce an output voltage with its magnitude proportional to the phase shift between them, which in turn is proportional to chest displacement due to cardiopulmonary activity. All radar measurements were conducted with the CW signal source at 2.4 GHz with 0 dBm output power.

Fig. 3 shows a typical heart beat signal, compared with a reference signal measuring the pulse from a finger sensor. The signal has been filtered with a lowpass filter with cutoff 10Hz. It can be seen that the signal, compared with the reference signal, is very noisy, and the heartbeat cannot be found simply from peak detection.

5. RESULTS

Fig. 4 shows the test statistic (2) applied to a group of three different measurements with a single antenna. The measurements are at first filtered with a bandpass filter with a passband 0.8-2Hz to remove respiration and higher order harmonics, and are then divided into (overlapping) intervals of length about 15s. This interval ensures that the model (1) is reasonably accurate, and has been verified through tests with different reference signals. The test statistic is now evaluated in each interval. It shows that it is objectively possible to determine the number of persons, e.g., by using threshold of 1.25. Notice once it has been determined that less than two persons are present with the above test, another GLRT can then be used to distinguish 0 and 1 persons.

Results do not always turn out as well as in Fig. 4. Subjects with strong HRV are sometimes not detected. To remedy this either the SNR has to be improved, or multiple antennas applied.

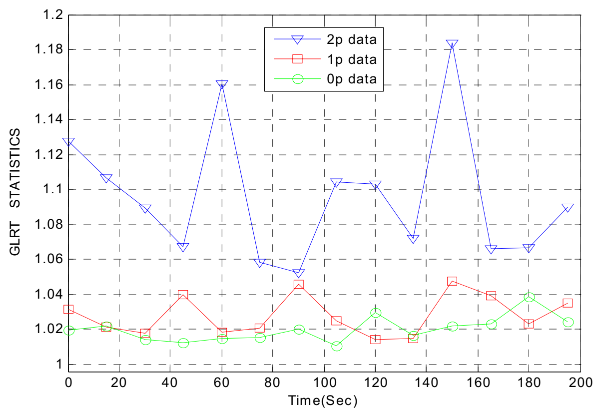

Fig.4. GLRT test for 2/1/0 person with 1antenna

We do not yet have a working experimental setup with multiple antennas. Multiple antenna data is therefore obtained from partial simulation. Reference signals are measured for different persons. They are then multiplied with DOA vectors, and independent noise is added at each antenna. Fig. 5 shows some results. In this case we used test subject with strong HRV. With single antenna it is therefore difficult to detect reliably if there are 1 or 2 subjects. With more antennas, the test statistics tend to fluctuate less. Therefore, it is clearly possible to distinguish these situations by set reasonable thresholds. Although we didn't do nested hypothesis test for 4 antennas, we can see it has the potential to detect up to 2N-1 subjects with N antennas, while MUSIC and other SVD-based approaches can only detect N-1 subjects.

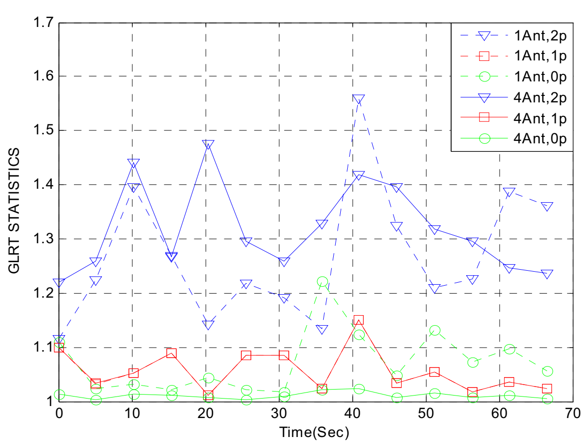

Fig.5. 1 antenna versus 4 antennas GLRT test

6. CONCLUSION AND FUTURE WORK

We have shown that it is possible to determine the number of subjects within range using hypothesis testing, although we are dealing with very weak and complicated signals. The method has potential of detecting up to $2N$ subjects with N antennas. The performance is acceptable, but could possibly be improved by taking into account more characteristics of the signals. We currently do not have enough experiments to determine false alarm and detection probabilities. On the other hand, already the current method is very computationally complex. It can be simplified by using an approximate minimization, for example by using 2D FFT and peak search.

If there is heavy multipath the current method cannot be used. Essentially, the method used is a spatio-temporal DOA. With heavy multipath blind source separation methods must be used, for example methods inspired by space-time MUSIC [6-8].

Finally, we are also working on extracting heart rate and HRV from the data, but this is beyond the scope of the current paper.

REFERENCES

[1] J. C. Lin, "Microwave sensing of physiological movement and volume change: a review," Bioelectromagnetics, vol. 13, pp. 557-565, 1992.

[2] K. M. Chen, D. Mirsa, H. Wang, H. R. Chuang, E. Postow, "An X-band microwave life detection system," IEEE Transactions of Biomedical Eng., vol. 33, pp. 697-70, 1986.

[3] V.M. Lubecke, O. Boric-Lubecke, G. Awater, P.-W. Ong, P. Gammel, R.-H. Yan, J.C. Lin, "Remote sensing of vital signs with telecommunications signals," World Congress on Medical Physics and Biomedical Engineering (WC2000), Chicago IL, July 2000.

[4] D. Samardzija, O. Boric-Lubecke, A. Host-Madsen, V. M. Lubecke, T. Sizer, A. D. Droitcour and G. T. A. Kovacs, "Applications of MIMO Techniques to Sensing of Cardiopulmonary Activity", IEEE/ACES International Conference on Wireless Communications and Applied Computational Electromagnetics, 2005.

[5] McSharry PE, Clifford GD, Tarassenko L, Smith L. "A dynamical model for generating synthetic electrocardiogram signals". IEEE Trans. Biomed. Eng., vol 50(3), pp: 289-294, Mar. 2003.

[6] A. Belouchrani, K. A. Meraim, J.-F. Cardoso, and E. Moulines, "A blind source separation technique using second order statistics," IEEE Trans. Signal Processing, vol. 45, pp. 434–444, Feb. 1997.

[7] A. Belouchrani and M. G. Amin, "Time-frequency MUSIC," IEEE Signal Processing Lett., vol. 6, pp. 109–110, May 1999.

[8] Bousbia-Salah, A.; Belouchrani, A.; Cichocki, A.;"Application of time-frequency distributions to the independent component analysis of ECG signals". Signal Processing and its Applications, Sixth International, Symposium on. 2001. vol.1, pp.238 – 241, Aug. 2001.

[9] S.M. Kay: "Fundamentals of statistical signal processing," Vol. 2, Prentice Hall, 1998.