Advanced Signal Processing Techniques for Microwave Cardiopulmonary Signals Separation

D. Obeid, S. Samad, S. Sadek, G. Zaharia, and G. El Zein

Abstract—This paper presents different signal processing techniques used in separating cardiopulmonary signals measured using a microwave Doppler radar. For different sides from the person under test, the microwave system is tested for several operational frequencies simultaneously with a PC-based electrocardiograph. Wavelet transforms are used in order to separate heartbeat signal from the cardiopulmonary signals. High accuracy is obtained in terms of heartbeat rate for the whole measurements.

***Keywords*—**Wavelet transforms, electrocardiograph, microwave system, cardiopulmonary signals.

I. Introduction

The demand for wireless monitoring has increased recently for many applications including life sign detection for people under rubble or snow, newly born infant or burn victims, where electrocardiograph (ECG) with affixed electrodes can be perturbing. Thus, the utility of the microwave Doppler radar has increased as used for touch-less monitoring.

According to the Doppler theory, a subject with a quasi-periodic movement will reflect the transmitted continuous wave signal with its modulated by the subject displacement [1]. When transmitted to a person's chest, the signal will be reflected with the phase modulated according to the chest displacement. This latter is due to both, respiration and heart beating. As the heartbeat and the respiration signals are laid together, signal processing techniques are required to separate the heartbeat signal from the cardiopulmonary signal in order to extract the heartbeat rate (HR).

As the chest displacement due to respiration (4 – 12 mm) is much higher than that due to heartbeat (0.2 – 0.5 mm), the respiration rate can be determined without filtering while determining the heartbeat rate needs a processing technique [2]–[4]. This can be established due to the fact that the heartbeat rate varies between 50 and 90 beats per minute (0.83 to 1.5 Hz) while the respiration rate varies between 9 and 24 breaths per minute (0.15 to 0.4 Hz) [5]. This allows the extraction of an average heartbeat rate over a specific window of time. On the other hand, tracking the variations of the heartbeat rate over time requires signals separation and a peak-finding technique.

Previous works tend to detect the heartbeat rate either by measuring separately the heartbeat and respiration signal, or by using classical filters, then by applying Fourier transform to the filtered signal and considering the peak to correspond to the HR [6]–[8]. Other studies show the possibility of estimating the HR based on the periodicity of the auto-correlation function [9] or upon applying FFT to the auto-correlated signal to obtain the heartbeat rate [10], [11]. Recently, another processing techniques are used for cardio-respiratory separation: field-programmable gate arrays (FPGAs) is used to process either time- or frequency-domain signals in human sensing radar applications applied for CW and UWB radars [12] as well as the use of compact quadrature Doppler radar sensor where Continuous-wavelet filter and ensemble empirical mode decomposition (EEMD) based algorithms are applied for cardiorespiratory signal to separate the cardiac and respiratory signals [13].

These works show the possibility of detecting the HR for person when holding the breath as well as when breathing normally. However, they lack providing information about the heart rate variation in time as only an average value of the HR is extracted.

The aim of this work is to show the possibility of detecting the cardiopulmonary signals of a person from four different sides: front, back, left, and right. The proposed system is tested at different operational frequencies: 2.4, 5.8, and 10 GHz. Simultaneously to the microwave system, PC-based ECG is used as a reference signal in order to validated the HR extraction. Obtained signals are processed using several wavelet transforms in order to extract the heartbeat signal along the time-axis.

The rest of this paper is organized as follows: section II presents the proposed system and the measurement setup. Section III discusses the signal processing techniques used. Section IV shows and discusses the obtained results. Section V concludes the work.

II. Proposed System and Measurement Setup

A. Proposed System

The contact-less detection of the cardiopulmonary activity is based on the reflected signal off the person's chest. The RF signal penetrates clothes with minimal reflection, and has a much higher reflection at the air/skin interface. This depends on the frequency of the transmitted signal. The signal reflection at the air/skin interface decreases as the frequency decreases, and has more significant reflections from clothing or bedding, and vice-versa. The amount of the phase variation is indirectly proportional to the wavelength of the carrier frequency. Thus, the signal-to-noise ratio is directly proportional as well to the operational frequency ($f = C/\lambda$). Higher frequency results in a shorter the wavelength, and then in a greater phase variation. Another feature related to the operational frequency is the size of the antenna. As the frequency increases, the same antenna gain can be achieved with a smaller antenna.

The proposed microwave system is based on using a Vector Network Analyzer (VNA), and two horn antennas. In addition to the installation simplicity, the VNA provide the ability of tuning both frequency and power of the transmitted signal. Moreover, it measures many parameters and especially the time variation of the phase and module of the S parameters of the system under test. The phase of the S_{21} parameter corresponds to the difference between the phase of the received signal and the phase of the transmitted signal. Simultaneously with microwave system, a PC-based ECG is used in order to extract the electrocardiogram signal. This signal is used as a reference signal to which the processed microwave signal is compared. More details about the system setup can be found in [14], [15].

B. Measurement Setup

Measurements are performed on healthy subject of 54 years old, sitting at a distance of 1 meter from the antennas. As the life sign detection for patients and people under rubble requires heart activity detection regardless their positions with respect to the system, measurements are performed at the four different sides from the person under test: front, back, left, and right. As the reflection at the air/skin interface changes when the operational frequency changes, a comparative study is provided in terms of operational frequency where several frequencies are tested using the proposed system. The operational frequencies should cover as much radar band designations as possible, as well as ISM bands. Thus, the operational frequencies tested in this work are: 2.4 GHz (ISM S-band), 5.8 GHz (ISM C-band), and 10 GHz (X-band). From each side of the person under test, the system is tested at several operational frequencies: 2.4, 5.8, and 10 GHz. The total output power of the transmitted signal is 0 dBm. Each measurement lasts 30 seconds during which the subject breathes normally. Both the microwave and the ECG measurements start simultaneously. The phase variation due to the chest displacement is stored in the VNA and sent to the personal computer for processing. The processed signals are compared to the ECG signal. The ECG provides the electrical activity of the heart, however, only the RR interval is used as reference information for the comparison with the VNA filtered signal.

III. Signal Processing Techniques

As the phase variations of S_{21} due to breathing are higher than those caused by the heart beating, processing techniques are necessary to extract the heartbeat signal from the obtained cardiopulmonary signal. Previous work tends to apply the Fourier transform to the obtained cardiopulmonary signal in order to extract the heartbeat rate. This provides a mean value of the HR over a specific window of time; thus, it lacks providing the more important information about the variation of the HR in time, and cannot be established in real-time as it requires a window of long-duration. In order sto overcome these problems, the Discrete Wavelet Transform (DWT) is applied for the extraction the heartbeat signal.

The DWT $\left(W_j, k\right)$ of a signal *f(t)* is given by the scalar product of *f(t)* with the scaling function (i.e. the wavelet basis function $\phi\left(t\right)$ which is scaled and shifted:

$$\left(W_j, k\right) \quad (1)$$

where the basis function is given by:

$$\phi_j, k\left(t\right) = 2^{\frac{-j}{2}} \phi\left(2^{-j} t - k\right) \quad (2)$$

where j is the j^{th} decomposition level or step and k is the k^{th} wavelet coefficient at the j^{th} level [16]. DWT is computed by successive low- and high-pass filtering of the discrete time-domain signal. The main advantage of the DWT determination is that the examination of the signal at different frequency bands with different resolutions by decomposing the signal into Approximation coefficients *(A)* and Detailed information *(D)*. Hence, this algorithm gives precise analysis of frequency domain at low frequency and time domain at high frequency.

The "detail" D_n contains frequencies between $fs/2^n$ and $fs/2^{n+1}$. At rest, the HR varies between 60 and 120 beats per minute and the corresponding frequency is located between 1 and 2 Hz. The actual sampling frequency used in the VNA is 666.7 Hz, thus, there is no decomposition that provides the signal with frequency components between 1 and 2 Hz. A re-sampling is required in order to convert the sampling frequency from 666.7 Hz to 512 Hz which allows the extraction of the desired signal. This lets the 1-2 Hz components to be included in the 8^{th} decomposition of the wavelet. Once the wavelet decomposition is extracted, the signal is reconstructed in time-domain. A peak-detection method is applied to the time-domain reconstructed signal in order to detect the peaks that correspond to the beats and to extract the heartbeat rate.

Several wavelet families are tested in Matlab for the measurement performed at different sides from the person under test and for all the operational frequencies. The wavelet families include Bio2.4, Rbio2.3, Sym5, Db5, Coif3, and Dmey.

As not all the wavelet families fulfill the properties of the desired signal, the wavelet family has to be chosen as close as possible to the analyzed signal to give a better reconstruction with fewer decomposition levels [17], [18]. The choice of a suitable wavelet is based on the perfect reconstruction of the power system signal. The error between the original signal and the reconstructed signal should be the smallest for perfect reconstruction. The Mean Square Error (MSE) is calculated and used as indicator to measure the error between the original signal and the reconstructed signal. The MSE is computer with the following relation [17], [18]:

$$MSE = \|S - S_{reconstructed}\| = \sqrt{\sum_{n=0}^{N-1} \left|x\left(n\right) - \hat{x}\left(n\right)\right|^2} \quad (3)$$

In order to compare the ECG signal to the reconstructed filtered cardiopulmonary signal, the peak detection method is applied to both signals. This allows comparing the beat-to-beat interval. The mean error is calculated for each measurement and for the different wavelet decompositions. The mean of the MSE of all available signals is calculated for each wavelet type according to the following equation:

$$MSEmean_{wavelettype} = \frac{\sum_{p=1}^{4} \sum_{q=1}^{3} MSE_{wavelettype}\left(p\right)\left(q\right)}{p \times q} \quad (4)$$

where *p* indicates the positions and *q* corresponds to the emitted frequency. Four positions are considered: p=1 for the front side position, p=2 for the back side position, p=3 for the right side position, and p=4 for the left side position. Three emitted frequencies are considered during measurements: q=1 for 2.4 GHz, q=2 for 5.8 GHz, and q=3 for 10 GHz.

IV. Results and Discussion

This section presents the results obtained upon measuring the cardiopulmonary signals using a microwave touch-less technique and for different sides from the person under test. Fig. 1 shows the cardiopulmonary signal detected from the four sides of the subject when using the 5.8 GHz operational frequency: a) the S_{21} variation due to breathing is shown when measured from the front side a), from the back side b), from the left side c), and from the right side d).

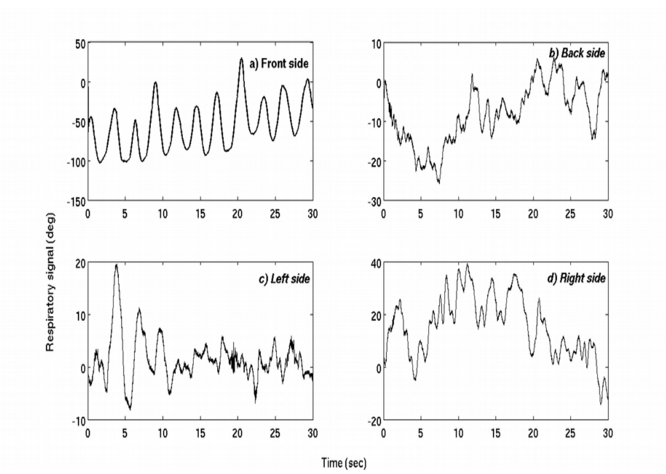

Fig. 1 Cardiopulmonary signals detected at 5.8 GHz and from different sides of the subject: (a) front side, (b) back side, (c) left side, and (d) right side

The measurement duration is 30 seconds during which the subject is requested to breathe normally. As seen in the figure, the time-domain respiration signal is clear when measured from the front side.

The signal separation is achieved upon applying several wavelet transforms families. Fig. 2 shows the D8 level extracted from the cardiopulmonary signal measured at 5.8 GHz from the front side upon using Coiflet wavelet (Coif3) compared to the corresponding ECG signal.

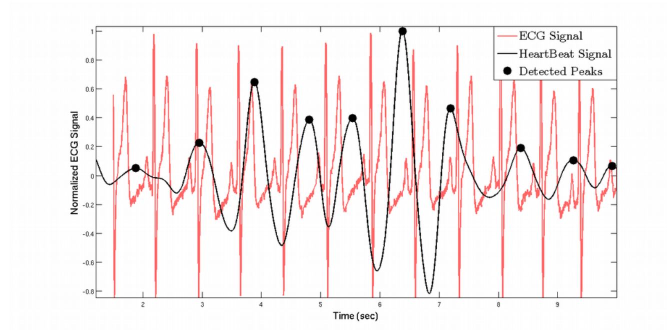

Fig. 2: Front side measurement: wavelet decomposition signal at level 8 (d8) using Coif3 Vs the corresponding ECG signal

Fig. 3 shows the heartbeat signal extracted from the cardiopulmonary signal measured from the back side.

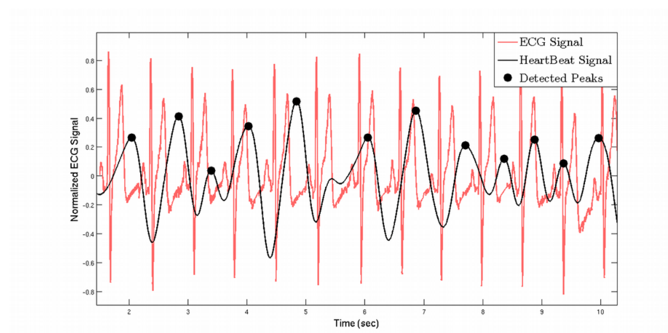

Fig. 3: Back side measurement: wavelet decomposition signal at level 8 (d8) using Coif3 Vs the corresponding ECG signal

The heartbeat signal extracted from the left side of the subject is shown in the Fig. 4.

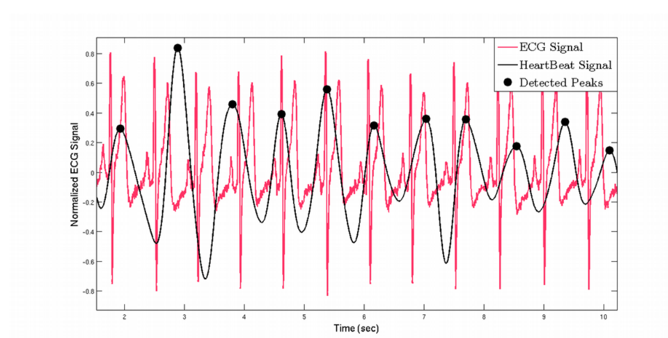

Fig. 4: Left side measurement: wavelet decomposition signal at level 8 (d8) using Coif3 Vs the corresponding ECG signal

The heartbeat signal extracted from the right side of the subject is shown in Fig. 5.

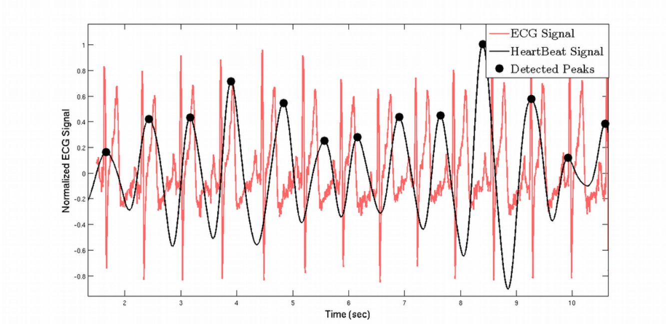

Fig. 5: Right side measurement: wavelet decomposition signal at level 8 (d8) using Coif3 Vs the corresponding ECG signal

The heartbeat rates extracted from the ECG signal and VNA microwave signal are calculated as follows:

$$HR = \frac{60\,N}{d1 + d2 + \ldots + dN} \qquad (5)$$

where N is the number of peaks and d_k is the duration between two consecutive peaks. The peaks that correspond to beats are detected using a peak-detection algorithm.

The absolute value of the relative error of the HR is calculated as:

$$Error = \frac{100 * \left(HR_{ECG} - HR_{VNA}\right)}{HR_{ECG}} \qquad (6)$$

The following table shows the relative error calculated for the different wavelet transforms to each of the performed measurement.

Table 1. HR absolute relative error using different wavelet families and for cardiopulmonary signals measured from the different sides of the subject

Side	Frequency (GHz)	Wavelet Family					
		Bior 2.4	Rbior 1.3	Sym5	Db5	Coif3	Dmey
Front	2.4	12	14	3	3	6	2
	5.8	9	2	7	5	15	18
	10	8	4	7	4	3	17
Back	2.4	2	11	11	11	8	15
	5.8	6	10	23	10	6	14
	10	13	12	8	17	15	17
Left	2.4	5	1	1	4	3	6
	5.8	2	3	3	5	3	6
	10	8	2	2	3	9	6
Right	2.4	6	1	9	1	11	13
	5.8	10	13	15	18	10	13
	10	15	17	15	15	13	9

As shown in the table, most of the wavelet transforms show the ability to extract the heartbeat signal from the cardiopulmonary signal when using different operation frequencies and from all sides of the person under test. The lowest error obtained is when using the wavelet type Bior2.4. Concerning the positions, it can be noticed that the right position results in the highest relative error (>10%). This is due to the fact the far side from the heart position is less affected by heart beating. All tested operational frequencies, 2.4, 5.8, and 10 GHz, show the possibility to track the cardiopulmonary signals from all sides.

V. Conclusion

This paper presents the results of detecting cardiopulmonary signals from different sides of a person while breathing normally. Several wavelet transform families are used for signal separation and heartbeat rate extraction. Bior2.4 shows the highest accurate HR when compared to the ECG reference signal. Measurements are performed for several operational frequencies, 2.4, 5.8, and 10 GHz, for a distance of 1 meter from the subject, simultaneously with an electrocardiograph.

Future work will focus on tracking the heart activity for persons in motion.

References

[1] J.C. Lin, Microwave sensing of physiological movement and volume change: A review, Bioelectromagnetics 13 (1992), 557–565.

[2] Ramachandran and M. Singh, "Three-dimensional reconstruction of cardiac displacement patterns on the chest wall during the p, qrs, and t-segments of the ECG by laser speckle interferometry", Medical and Biological Engineering and Computing, Sept. 1989, vol. 27, No. 5, pp. 525–530.

[3] A. DeGroote, M. Wantier, G. Cheron, M. Estenne, and M. Pavia, "Chest wall motion during tidal breathing", Journal of Applied Physiology, 1 November 1997, Vol. 83, Issue. 5.

[4] T. Kondo, T. Uhlig, P. Pemberton, and P. D. Sly, "Laser monitoring of chest wall displacement", European Respiratory Journal 1997, Vol 10, Issue. 8.

[5] D. L. Gorgas, "Vital Signs and Patient Monitoring Techniques", 2004, Clinical Procedures in Emergency Medicine 4th ed (JR Roberts and JR Hedges, Eds) Sauders, Philadelphia, USA.

[6] K. M. Chen, Y. Huang, J. Zhang, and A. Norman, "Microwave life-detection systems for searching human subjects under earthquake rubble or behind barrier", IEEE Transactions on Biomedical Engineering, Jan. 2000, Vol. 47, Issue 1.

[7] A. D. Droitcour, O. B. Lubecke, V. M. Lubecke, and J. Lin, "0.25μm cmos and bicmos single chip direct conversion Doppler radars for remote sensing of vital signs", Solid-State Circuits Conference, 2002. Digest of Technical Papers. ISSCC. 2002 IEEE International.

[8] B. Lohman, O. B. Lubecke, V. Lubecke, P. Ong, and M. Sondhi, "A digital signal processor for Doppler radar sensing of vital signs", IEEE Engineering in Medicine and Biology Magazine, Vol. 21, Issue. 5, Sept.-Oct. 2002.

[9] O. B. Lubecke, G. Awater, and V. M. Lubecke, "Wireless LAN PC card sensing of vital signs", Wireless Communication Technology, Oct. 2003.

[10] C. Li, Y. Xiao, and J. Lin, "Experiment and spectral analysis of a low-power ka-band heartbeat detector measuring from four sides of a human body", IEEE Transactions on Microwave Theory and Techniques, Vol. 54, Issue. 12, Dec. 2006 .

[11] C. Li, J. Lin, and Y. Xiao, "Robust overnight monitoring of human vital signs by a noncontact respiration and heartbeat detector", 28thannual international conference of IEEE in engineering in medicine and biology society (EMBS). Sept. 2006.

[12] Y. Wang; Q. Liu; A. E. Fathy, "CW and Pulse–Doppler Radar Processing Based on FPGA for Human Sensing Applications", IEEE Transactions on Geoscience and Remote Sensing, Vol. 51, Issue. 5, May 2013, pp. 3097-3107.

[13] W.Hu; Z. Zhao; Y. Wang; H. Zhang; F. Lin, "Noncontact Accurate Measurement of Cardiopulmonary Activity Using a Compact Quadrature Doppler Radar Sensor", IEEE Transactions on Biomedical Engineering, Vol. 61, Issue. 3, Mar. 2014, pp. 725 – 735.

[14] Dany Obeid, Sarah Samad, Sawsan Sadek, Gheorghe Zaharia and Ghaïs El Zein (2016). Position-Free Vital Sign Monitoring: Measurements and Processing, Advanced Biosignal Processing and Diagnostic Methods, Dr. Christoph Hintermüller (Ed.), InTech, DOI: 10.5772/63915. Available from: http://www.intechopen.com/books/advanced-biosignal-processing-and-diagnostic-methods/position-free-vital-sign-monitoring-measurements-and-processing
[15] Dany Obeid, Gheorghe Zaharia, Sawsan Sadek , Ghaïs El Zein, Microwave Doppler radar for heartbeat detection vs electrocardiogram, 2012
[16] G. A. Blackburn, J. Garke Ferwerda, “Retrieval of chlorophyll concentration from leaf reflectance spectra using wavelet analysis”, Remote Sensing of Environment, Vol. 112, Issue. 4, April 2008, pp. 1614-1632.
[17] S. Z. Mohd Tumari, R. Sudirman, A. H. Ahmad “Selection of a Suitable Wavelet for Cognitive Memory Using Electroencephalograph Signal”, Scientific reaserch, doi:10.4236/eng.2013.55B004 Published Online May 2013.
[18] A.I. Megahed, A. Monem Moussa, H. B. Elrefaie, Y.M. Marghany “Selection of a Suitable Mother Wavelet for Analyzing Power System Fault Transients”, Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE , Pittsburgh, PA, 20-24 July, 2008, pp.1 – 7.