Noncontact Measurement of Human Vital Signs during Sleep Using Low-power Millimeter-wave Ultrawideband MIMO Array Radar

Takuya Sakamoto[1,2,3]

[1]Graduate School of Informatics, Kyoto University, Kyoto, Kyoto 606-8501, Japan

[2]Japan Science and Technology Agency, PRESTO, Kawaguchi, Saitama 332-0012, Japan

[3]Graduate School of Engineering, University of Hyogo, Himeji, Hyogo 671-2280, Japan

***Abstract*—Radar-based noncontact measurements of human bodies have increasingly been attracting attention in healthcare applications because such measurements allow for the unobtrusive sensing of vital signs without sensors being attached to the body. In particular, measurement of the heart rate is considered to be important because it provides various types of information on the physical and mental health of the person under test. In such applications, it is preferable to use low-gain omni-directional antennas so that the person under test does not have to be located at a specific spot. In addition, the use of high-power microwaves is not allowed in many countries owing to public health regulations. Because of such factors, the signal-to-noise ratio is relatively low in these applications although the target person might be within a few meters of the antennas. To overcome this difficulty, we adopt the maximum ratio combining technique with a multiple-input multiple-output antenna array for improving the signal-to-noise ratio and accuracy in measuring the instantaneous heart rate.**

***Index Terms*—MIMO, radar, vital signs, ultrawideband.**

I. Introduction

As represented by Apple Watch (Apple Inc., Cupertino, CA, United States), heart rate measurement has been of increasing interest in various healthcare applications [1]-[9]. For such measurement, Doppler radar systems are considered a promising technology because they can measure human vital signs without contact and unobtrusively.

The skin displacement caused by the heartbeat is as small as a few tens of micrometers. To detect such a tiny displacement, a high signal-to-noise (S/N) ratio is necessary in addition to a low timing jitter of the local oscillator. Li et al. [3] and Vinci et al. [4] therefore used a directional horn antenna with a relatively high gain (>20 dBi) for improving the S/N ratio. This means that the person under test must remain at the specific spot where the antenna gain is at a maximum during the measurement.

However, this condition limits the applicability of the system especially when the system is used for monitoring people in a daily setting. In such an application, it is necessary to have a wide antenna beam in which the users remain. Low antenna gains of 5.8 dBi [5], 8 dBi [6], 10 dBi [7], and 4.5 dB [9] have been used for a wide beam. However, a low antenna gain lowers the S/N ratio and degrades the accuracy in heartbeat measurements.

To overcome this difficulty, the present paper introduces a multiple-input multiple-output (MIMO) array to adaptively form an optimal antenna pattern for tracking a person under test during measurement. We specifically use the maximum ratio combining (MRC) technique to improve the S/N ratio and demonstrate an accurate heartbeat measurement using an ultrawideband (UWB) MIMO array millimeter-wave (MMW) radar and proposed signal processing approach.

II. System model and measurement setup

The present study used a UWB MMW radar (central frequency of 60.5 GHz and bandwidth of 1.25 GHz), with a range resolution of 12.0 cm that is sufficiently high to separate echoes from body parts, such as the torso, head, and limbs. Because the transmitting signals are orthogonal functions of time, the total transmission power using M transmitting elements is MP_0, where P_0 is a transmission power from each element. The EIRP must be kept within the compliance limit taking the number of transmitting elements into account. In our system, the total transmission power MP_0 was less than 13 dBm, and the array elements were a vertically polarized open-ended rectangular waveguide having an aperture of $3.5\mathrm{mm} \times 1.7\mathrm{mm}$ with a single mode TE_{10} at 60.5 GHz. The antenna element gain was 3.9 dB and the element beam width was $\pm 48^\circ$ (1.7 rad), which covers an area of 3.4 m at a distance of 2.0 m from the antennas, which is wide enough to cover the entire bed.

Two transmitting and four receiving elements constituted a MIMO radar system as shown in Fig. 1. The transmitting and receiving elements were respectively aligned vertically and horizontally. Although we see four elements in the vertical array (Fig. 1), only the two lower elements were used for the measurement. All element spacings were 4.5 mm. The transmitting elements were sequentially switched, while signals were simultaneously received by the four receiving elements. This allowed us to record using eight channels, which are adaptively combined to improve the S/N ratio in later sections. The signals were sampled every 0.458 ms and digitized and stored in computer memory. The target person remained asleep on a bed during the measurement. The side edge of the bed was 0.6 m from the radar antennas. We cannot show the inside structure of the system due to a non-disclosure agreement with our partners.

Figure 2 shows the actual measurement setup with a participant on a bed. An infrared video camera and radar system were both installed in a cabinet. In addition, an electrocardiogram (ECG) device was attached to the participant during the measurement and used as a reference for the heart rate.

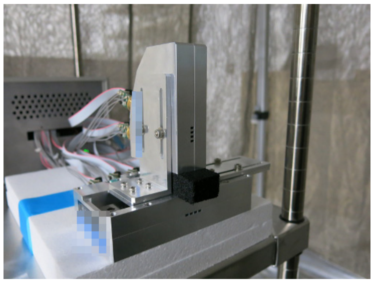

Fig. 1. UWB MMW MIMO array radar used in the study. There were four vertical and four horizontal arrays, of which six elements (two transmitting and four receiving elements) were used in this study.

Fig. 2. Measurement setup and a participant on a bed. An infrared camera and ultrawideband MIMO array radar were installed in a cabinet. The participant had an ECG device attached to his chest.

III. MIMO RADAR SIGNAL PROCESSING

Even during sleep, human bodies move unconsciously, resulting in a body position varying over time and meaning that the radar beam must track the target person accurately. We adopted adaptive array signal processing with the MIMO array for tracking the moving target and improving the S/N ratio and accuracy in measuring the heart rate.

The performance of a MIMO array can be inferred using an equivalent virtual array. The virtual array of the MIMO array used in this study has a 2×4 horizontally long rectangular topology with higher resolution in the horizontal direction and lower resolution in the vertical direction. The horizontal and vertical resolutions were optimized for our measurement because a person sleeping on a bed hardly changes his/her vertical position.

As an adaptive signal processing technique, we used the MRC technique, which is widely used in MIMO wireless communications to improve the S/N ratios of signals. Although the performance of the MRC technique degrades if there is more than one arriving signal, the technique does not require any calibration of the array elements, which is an important advantage over other techniques.

The received eight-channel signals are denoted as a signal vector $\boldsymbol{s}(t) = [s_{1,1}, s_{1,2}, \cdots, s_{2,4}]^{\mathrm{T}}$, where superscript T is a transpose operator and $s_{i,j}$ is the signal for the i-th transmitting and j-th receiving elements. The correlation matrix is expressed as

$$R_{ss} \simeq \int \boldsymbol{s}(t)\boldsymbol{s}^{\mathrm{H}}(t)\mathrm{d}t, \tag{1}$$

where superscript H is a complex-conjugate transpose operator. By applying the eigenvalue decomposition of R_{ss}, we obtain

$$R_{ss} = [\boldsymbol{v}_1\boldsymbol{v}_2\cdots\boldsymbol{v}_N]\mathrm{diag}\{\sigma_1, \sigma_2, \cdots, \sigma_N\}[\boldsymbol{v}_1^*\boldsymbol{v}_2^*\cdots\boldsymbol{v}_N^*]^{\mathrm{T}}, \tag{2}$$

where $\sigma_1, \sigma_2, \cdots$, and σ_N are eigenvalues sorted in descending order, and eigenvector $\boldsymbol{v}_i$ $(i = 1, \cdots, N)$ corresponds to the i-th eigenvalue σ_i. The dimension of the vectors is denoted $N = 8$. The MRC technique uses the first eigenvector $\boldsymbol{v}_1$ as a weight vector $\boldsymbol{w} = \boldsymbol{v}_1$ and obtain the ouput signal $s(t)$ as $s(t) = \boldsymbol{w}^H\boldsymbol{s}(t) = \boldsymbol{v}_1^H\boldsymbol{s}(t)$, where the eigenvectors and weight vector are normalized i.e., $|\boldsymbol{v}_i|^2 = 1$ for $i = 1, 2, \cdots, N$ and $|\boldsymbol{w}|^2 = 1$.

IV. PERFORMANCE EVALUATION OF THE MRC TECHNIQUE

The performance of the proposed approach including the MRC technique and our MIMO array radar system was evaluated through measurements involving a human participant. The measurement time was 150 s. First, the static clutter components in the received signals were suppressed using a clutter rejection method [10].

The upper graph of Fig. 3 shows the normalized signal power as a function of slow time t. Blue and red lines respectively show the power of a single channel whose power was maximum among eight, and average power of eight channels, whereas the black line shows the power of the proposed combined multi-channel signal $s(t)$ obtained using the MRC technique. Note that the signal power increased while the noise level was unchanged because the norm of the weight vector remained at unity $|\boldsymbol{w}|^2 = 1$. The figure shows that the MRC improves the S/N ratio by 8 dB relative to the average channel and by 6 dB relative to the best channel. This result suggests that the MRC is effective in the improving S/N ratio, which is necessary for the noncontact measurement of the heartbeat.

Figure 4 shows the phase sequences of the single channel whose power was maximum among eight (blue) and a combined signal using the MRC technique (black). The phase sequences contain both respiration and heartbeat components. The dominant components in Fig. 4 are caused by the respiration with a period of approximately 5.8 s. The respiration component is suppressed using a filter so that the heart rate can be accurately estimated in the next step.

Next, signals were processed using a topology method [11] and the instantaneous heart rate was obtained. Figure 5 shows

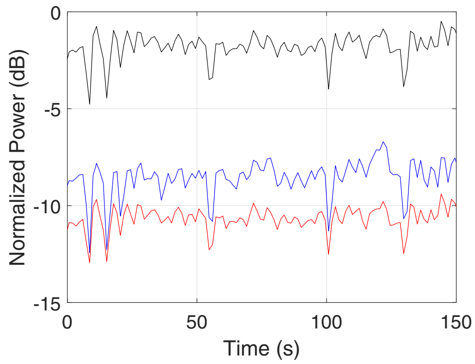

Fig. 3. Normalized signal powers for the MRC-combined signal (black), the maximum single channel (blue), and the average of eight single channels (red).

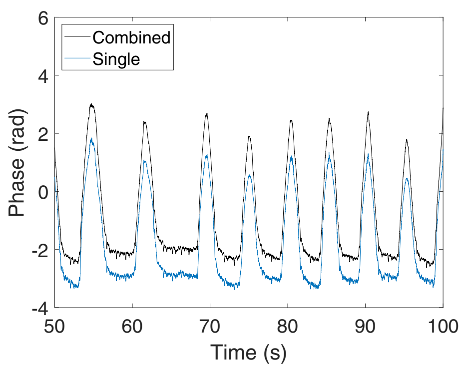

Fig. 4. Signal phase sequence for the MRC-combined signal (black), and the single channel with the maximum average power (blue).

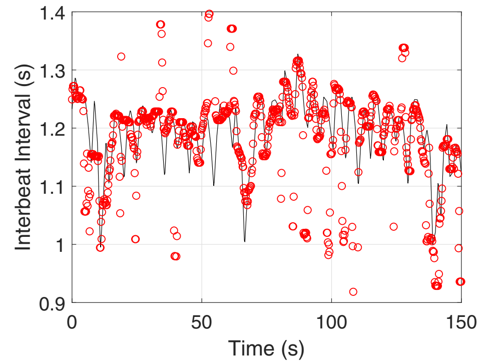

Fig. 5. Heartbeat IBI measured using the ECG (black) and the maximum-power single channel (red circles).

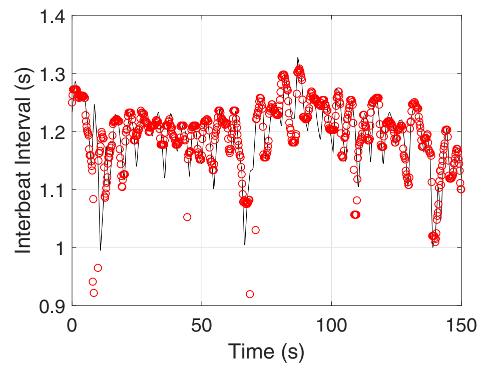

Fig. 6. Heartbeat IBI measured using the ECG (black) and the MRC combined multiple channels (red circles).

the interbeat interval (IBI), which is the reciprocal of the heart rate measured using the ECG (black line) and a single radar channel with the maximum power (red circles). Figure 6 shows a similar graph with the IBI estimated using the MRC technique of combined multiple channels (red circles) superposed with the reference IBI (black line) measured using the ECG. The root-mean-square error in the IBI was respectively 182 and 148 ms when using the maximum-power single channel and the MRC signal combining eight channels, resulting in an 18% improvement in the heart rate accuracy. This result suggests the effectiveness of using a MIMO array and adaptive MIMO array processing (i.e., MRC) in improving the heart rate measurement accuracy.

V. Conclusion

This paper proposed the use of an adaptive array processing MRC technique for measuring the heart rate using an MMW UWB MIMO array radar. The proposed technique was applied to real radar data recorded for a sleeping participant. The proposed MIMO array system and signal processing technique were demonstrated to be effective in improving the S/N ratio of the echo signals and enhancing the accuracy when measuring the instantaneous heart rate. The MRC technique improved the S/N ratio by 8 dB relative to the maximum-power signal channel and the accuracy in measuring the heart rate by 18%.

Acknowledgment

This study was supported in part by Kyoto University SPIRITS Project, the Kyoto University Center of Innovation (COI) Program, JSPS KAKENHI Grant Numbers 15K18077 and 15KK0243, and Japan Science and Technology Agency PRESTO Grant Number JPMJPR1873, Japan. We thank Mr. Hiroyuki Sakai, Mr. Kenji Mizutani, Mr. Takeshi Fukuda, and Mr. Kenichi Inoue of Panasonic Corporation for developing the UWB MIMO array radar system. We also thank Prof. Toru Sato and Dr. Shigeaki Okumura of the Graduate School of Informatics, Kyoto University for their help in performing the measurements. We thank Mr. Kyo Watanabe of Denso Ten Technology Ltd. and Mr. Kosuke Yamashita of Graduate School of Engineering, University of Hyogo for their help with data processing. We thank Glenn Pennycook, MSc, from Edanz Group (www.edanzediting.com/ac) for editing a draft of this manuscript.

References

[1] J. C. Lin, "Noninvasive microwave measurement of respiration", *Proceedings of the IEEE*, p. 1530, 1975.

[2] B. Lohman, O. Boric-Lubecke, V. M. Lubecke, P. W. Ong, and M. M. Sondhi, "A digital signal processor for Doppler radar sensing of vital signs", *IEEE Engineering in Medicine and Biology*, pp. 161–164, 2002.

[3] 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 Trans. Microwave Theory and Techniques*, vol. 54, no. 12, pp. 4464–4471, 2006.

[4] G. Vinci, S. Lindner, F. Barbon, S. Mann, M. Hofmann, A. Duda, R. Weigel, and A. Koelpin, "Six-port radar sensor for remote respiration rate and heartbeat vital-sign monitoring", *IEEE Trans. Microwave Theory and Techniques*, vol. 61, no. 5, 2013.

[5] M. Nosrati and N. Tavassolian, "High-accuracy heart rate variability monitoring using Doppler radar based on Gaussian pulse train modeling and FTPR algorithm", *IEEE Trans. Microwave Theory and Techniques*, vol. 66, no. 1, pp. 556–567, 2018.

[6] A. D. Droitcour, O. Boric-Lubecke, and G. T. A. Kovacs, "Signal-to-noise ratio in Doppler radar system for heart and respiratory rate measurements", *IEEE Trans. Microwave Theory and Techniques*, vol. 57, no. 10, pp. 2498–2507, 2009.

[7] S. Suzuki, T. Matsui, M. Kagawa, T. Asao, and K. Kotani, "An approach to a non-contact vital sign monitoring using dual-frequency microwave radars for elderly care", *J. Biomedical Science and Engineering*, vol. 6, pp. 704–711, 2013.

[8] J. Kranjec, S. Begus, J. Drnovsek, and G. Gersak, "Novel methods for noncontact heart rate measurement: a feasibility study", *IEEE Trans. Instrumentation and Measurement*, vol. 63, no. 4, 2014.

[9] C. Lee, C. Yoon, H.-J. Kong, H. C. Kim, and Y. Kim, "Heart rate tracking using a Doppler radar with the reassigned joint time-frequency transform", *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 1096–1099, 2011.

[10] S. Okumura, T. Sakamoto, T. Sato, M. Yoshioka, K. Inoue, T. Fukuda, and H. Sakai, "Comparison of clutter rejection techniques for measurement of small displacements of body surface using radar", *Electronics Letters*, vol. 52, Issue 19, pp. 1635–1637, Sep. 2016.

[11] T. Sakamoto, R. Imasaka, H. Taki, T. Sato, M. Yoshioka, K. Inoue, T. Fukuda, and H. Sakai, "Feature-based correlation and topological similarity for interbeat interval estimation using ultrawideband radar," *IEEE Trans. Bio-med. Eng*, vol. 63, no. 4, pp. 747–757, Apr. 2016.