Indoor Human Tracking with Millimeter-Wave Minimum Redundancy MIMO Radar

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***Abstract-* Array radar needs enough array length to realize high angular resolution. However, it takes cost to increase elements physically. Recently, Minimum Redundancy Multiple-Input Multiple-Output (MR-MIMO) was proposed to increase the number of virtual elements efficiently. Further improvements by using Khatri-Rao (KR) transformation in the case of incoherent waves were also proposed. In this paper, we show experimental results on indoor human tracking with millimeter-wave MR-MIMO radar to verify the improvements of resolution and tracking performance in comparison with the results by a conventional MIMO radar.**

I. INTRODUCTION

Recent years, radar sensor has been attracting attentions because of various applications (e.g. traffic monitor, automotive radar, gesture identification, and so forth). To realize high angular resolution, large array aperture is required. However, it takes high cost to increase array elements physically. Multiple-Input Multiple-Output (MIMO) is a well-known technique to increase array length virtually. We have proposed a more effective virtual array technique which combines a minimum redundancy array [1] and the MIMO to increase virtual array length. We call it a Minimum Redundancy MIMO (MR-MIMO) in this paper. Furthermore, the virtual array length can expand by applying Khatri-Rao (KR) transformation when incoming wave is incoherent [2]. There are several reports on these techniques to show the validity. However, the report with millimeter-wave radar is fairly few.

In this paper, we show experimental results on human tracking in indoor multipath environment with millimeter-wave MR-MIMO radar. We confirm the validity of the MR-MIMO by comparing the conventional Uniform-Linear-Array MIMO (ULA-MIMO) with/without the KR transform.

II. DATA MODEL & KR TRANSFORMATION

Let us assume that the transmitter and receiver are linear arrays and the radar system is monostatic. When incoherent K waves are incoming, the receiving data model $\boldsymbol{x}(t)$ at time t is given by

$$\boldsymbol{x}(t) = \boldsymbol{A}\boldsymbol{s}(t) + \boldsymbol{n}(t), \qquad (1)$$

$$\boldsymbol{A} = [\boldsymbol{a}(\theta_1), \boldsymbol{a}(\theta_2), \cdots, \boldsymbol{a}(\theta_K)], \qquad (2)$$

$$\boldsymbol{a}(\theta_k) = \boldsymbol{a_t}(\theta_k) \otimes \boldsymbol{a_r}(\theta_k), \qquad k = 1, 2, \cdots, K, \qquad (3)$$

$$\boldsymbol{s}(t) = [s_1(t), s_2(t), \cdots, s_K(t)]^T, \qquad (4)$$

where $\boldsymbol{A}$ is a mode matrix, $\boldsymbol{a}_t(\theta_k)$ and $\boldsymbol{a}_r(\theta_k)$ are the mode vector of transmitter and receiver, $\boldsymbol{s}_k(t)$ and θ_k is complex amplitude and direction of arrival (DOA) of the *k*th wave, $\boldsymbol{n}(t)$ is a noise vector, and $\otimes$ denotes the Kronecker product operator. Correlation matrix $\boldsymbol{R}_{xx}$ can be given by

$$\boldsymbol{R}_{xx} = E[\boldsymbol{x}(t)\boldsymbol{x}(t)^H] = \boldsymbol{A}\boldsymbol{S}\boldsymbol{A}^H + \boldsymbol{R}_N, \qquad (5)$$

where $E[\cdot]$ and $[\cdot]^H$ denote the ensemble averaging, complex conjugate transpose, respectively. $\boldsymbol{S}$ and $\boldsymbol{R}_N$ are the source correlation matrix and noise correlation matrix, respectively. By applying KR transformation to the data model $\boldsymbol{x}(t)$, the expanded data model $\boldsymbol{z}$ can be given by

$$\boldsymbol{z} = \mathbf{vec}[\boldsymbol{R}_{xx}] = \boldsymbol{A}'\bar{\boldsymbol{s}} + \mathbf{vec}[\boldsymbol{R}_N], \qquad (6)$$

$$\boldsymbol{A}' = \boldsymbol{A}^* \odot \boldsymbol{A}$$
$$= [\boldsymbol{a}(\theta_1)^* \otimes \boldsymbol{a}(\theta_1), \boldsymbol{a}(\theta_2)^* \otimes \boldsymbol{a}(\theta_2), \cdots \boldsymbol{a}(\theta_K)^* \otimes \boldsymbol{a}(\theta_K)\,], \qquad (7)$$

where vec$[\cdot]$ is the function to vectorize a matrix, $[\cdot]^*$ is complex conjugate, $\odot$ is the KR product operator. $\bar{\boldsymbol{s}}$ denotes a vector whose element shows average power of each signal within the observation time (note that the KR transformation drops phase information of the signals, hence it transforms complex amplitude $\boldsymbol{s}(t)$ into average power $\bar{\boldsymbol{s}}$).

Here, we define $\boldsymbol{z}'$ by extracting non-overlapping elements in $\boldsymbol{z}$, and employ the square root of the correlation matrix $\boldsymbol{R}_{z'z'}$ for DOA estimation as follows:

$$\boldsymbol{R}_{z'z'} = (\boldsymbol{z}'\boldsymbol{z}'^H)^{\frac{1}{2}}. \qquad (8)$$

The number of non-overlapping elements in $\boldsymbol{R}_{xx}$ becomes virtual elements by the KR transformation. Minimum Redundancy Array (MRA) has the most effective arrangement having non-overlapping elements, so it is optimum in KR transformation.

Furthermore, we can expand virtual elements by combining MRA and MIMO (MR-MIMO) [2]. The ULA and MRA arrangement in MIMO radar having 2-transmitter and 4-receiver ((2, 4)-MIMO) is shown in Fig.1, where Δd_r denotes a half wave length. 15 virtual elements can be generated by the (2, 4)-MIMO with ULA by applying KR transformation and that increases to 39 virtual elements with MRA. Needless to say, (2, 4)-ULA-MIMO without KR transformation has 8 virtual elements, so it is effective to adopt MRA arrangement and/or apply KR transformation.

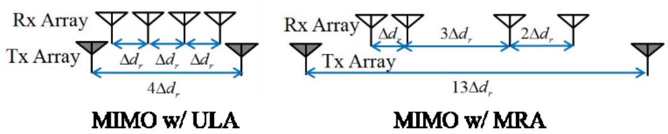

Figure 1. Array arrangement of (2, 4)-MIMO with ULA and that of MRA.

Note that the virtual array by KR transformation do not work properly for coherent incoming signals. It often occurs in the stationary environment. However, in the case of moving targets having diverse Doppler frequencies, coherence among incoming waves becomes low. Therefore, KR transformation will be applicable in such a dynamic environment [3].

III. Indoor Human Detection & Tracking

We adopt Moving Target Indicator (MTI) to suppress unwanted responses (e.g. wall, ground, direct coupling, and so forth). By using MTI, the number of targets effectively decreases and then, detection of human in indoor multipath environment becomes much easier. After applying MTI to receiving data and carry out position estimation, we also apply tracking filter to update position of each target. Kalman filter is adopted as the tracking filter in this study.

IV. Experimental Results

We have conducted experiments on human tracking in indoor multipath environment and evaluated the validity of millimeter-wave MRA-MIMO radar with KR transformation. The experimental parameters are listed in Table I. Also, Fig. 2 shows the experimental setup. We show 3 persons scenario in this report. They walk from about 2 m to 6 m from the radar identically.

Fig. 3 shows the results of human tracking by ULA-MIMO without KR transformation and Fig. 4 shows the results by ULA-MIMO with KR transformation, respectively. From Fig. 3, we see that the targets are tracked until about 3.8 m from the radar. However, they cannot be properly tracked beyond 3.8 m because of the lack of angular resolution. Higher angular resolution is needed to detect targets correctly as they are away from the radar. From Fig. 4, the targets are tracked well until about 5 m from the radar, hence it is clear that the tracking performance can be improved by KR transformation. However, the left target turned to the right side at the end. In addition, each track of the targets in Fig. 4 is not linear as shown in Fig.2. The track of middle target exceeds 6m. It is because the tracking filter misdetected the unremoved wall response as the target response.

Finally, the tracking results by MR-MIMO with KR transformation is shown in Fig. 5. The tracking performance was further improved compared with that of ULA-MIMO shown in Fig. 4. The tracking results of each target are almost linear and correctly tracked from 2 m to 6 m from the radar.

From these results, we can conclude that the improvement of tracking performance by the millimeter-wave MR-MIMO radar can be verified experimentally.

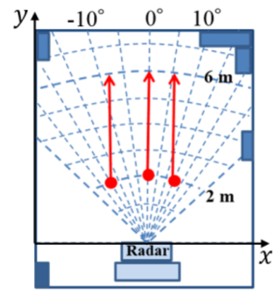

Figure 2. Experimental setup.

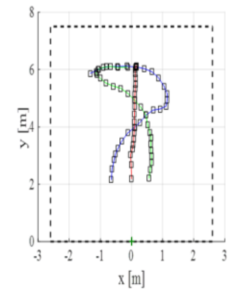

Figure 3. Tracking by ULA w/o KR.

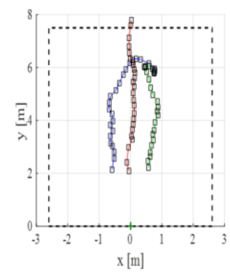

Figure 4. Tracking by ULA w/ KR.

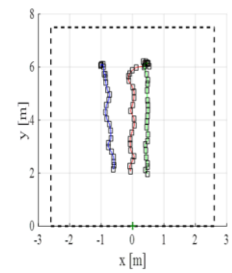

Figure 5. Tracking by MRA w/ KR.

TABLE I
EXPERIMENTAL PARAMETERS

Radar system	FMCW
The number of element (Tx, Rx)	(2, 4)
Array arrangement	ULA-MIMO, MRA-MIMO
Center frequency	76.5 GHz
Bandwidth	500 MHz
Sweep time	100 μsec.
Pulse Repetition Interval as MIMO	220 μsec.
Cut off velocity in MTI	-0.05 ~ 0.05 m/sec.
Range estimation	FFT
DOA estimation	Beamformer

V. Conclusion

In this paper, we have shown experimental results of indoor human tracking by millimeter-wave MR-MIMO radar with KR transformation. Resolution of the proposed radar is verified by comparing the results with the conventional ULA-MIMO. Experimental scenario in this report is a simple one. Results of more complicated scenarios will be presented in the presentation.

Acknowledgment

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References

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