A Low-Complexity Subarray-Based UCCA for Robust LoS MIMO Communications

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***Abstract*—In line-of-sight (LoS) communication environments, geometrical placement and adjustment of antennas are crucial to improving achievable rates while ensuring robust communication performances for varying transmission distances between transmitter and receiver. In this paper, hence, we propose a novel low-complexity *subarray*-based uniform circular concentric array (UCCA) selection technique for robust line-of-sight (LoS) MIMO communication systems. In particular, we dynamically control the allocated power to each antenna of UCCA at the transmitter while the conventional schemes only consider the radius and the relative rotation angle of UCCA. Through extensive computer simulations, we show that the proposed subarray-based UCCA selection technique significantly outperforms the conventional scheme in terms of achievable rate and robustness for varying transmission distances in practical LoS MIMO communication environments.**

***Index Terms*—6G communications, line-of-sight MIMO channel, terahertz band, uniform circular array (UCA), subarray.**

I. Introduction

High-frequency bands such as millimeter wave (mmWave) and terahertz (THz) have attracted much attention for the next-generation wireless system called 6G [1]. In such high-frequency bands, the wireless channel becomes sparse in terms of multiple paths and it is assumed to be a line-of-sight (LoS) communication channel in general. From perspective of the classical multiple-input multiple-output (MIMO) communications, the spatial multiplexing in LoS environments has been considered practically impossible because the MIMO channel matrix tends to be rank-deficient. On the other hand, several studies on antenna design and placement to improve spatial multiplexing gain in LoS environments have been investigated with uniform linear array (ULA) [2] and uniform circular array (UCA) [3], [4]. However, the existing antenna placement methods considered only distance among antennas or radius/rotational angle of antenna arrays as optimization parameters even though an allocated power to each antenna significantly affects performance.

Also, we adopt as another strategy to select the UCCAs for achieving the channel capacity. Finally, through computer simulations, we verify our proposed subarray-based UCCA selection can achieve the channel capacity and outperform the existing array antenna placement to all transmission distances.

II. Proposed Subarray-based UCCA Selection

We consider a point-to-point LoS MIMO communication systems including a transmitter equipped with several UCCAs

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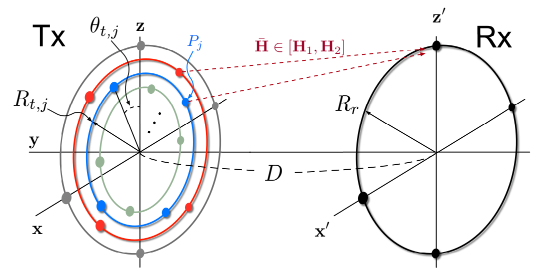

Fig. 1. System model of LoS MIMO communication system including a transmitter equipped with several UCCAs and receiver with UCA.

for different radii and rotational angles and a receiver with a UCA, as shown in Fig. 1. Specifically, the receiver has a M elements-UCA with the radius of R_r, and the transmit array is composed of a total of N antennas with the radius of R_t in which J UCCAs are embedded. Here, N is assumed to be a multiple of J, i.e., each UCCA consists of $\widetilde{N} = N/J$ antennas. In addition, $j \in \{1, \cdots, J\}$-th UCCA has the radius of $R_{t,j}$ and the rotational angle $\theta_{t,j}$ relative to the receive UCA where $R_{t,j}$ and $\theta_{t,j}$ are predetermined by the j-th UCCA structure, respectively. The transmission distance is denoted as D, and it is assumed that both a transmitter and receiver are perfectly aligned and there are $K = \min(N, M)$ RF chains for practical LoS MIMO communication systems.

A. LoS MIMO Channel Model with Subarray-based UCCA

As we parameterized the power allocation in the array antenna placement problem to achieve channel capacity, more than one UCCA can be exploited in the transmission. Hence, the number of transmit antennas $\bar{N}$ used for actual transmission is the number of antennas of the selected $\nu^*(\leq J)$ UCCAs, i.e., $\bar{N} = \nu^* \widetilde{N}$. Let P_i be the allocated power of $i \in \{1, \cdots, \nu^*\}$-th selected UCCA. Then, the LoS MIMO channels for actual transmission $\bar{\mathbf{H}} \in \mathbb{C}^{M \times \bar{N}}$ can be expressed as $[\mathbf{H}_1 \mathbf{H}_2 \cdots \mathbf{H}_\nu]$ where $\mathbf{H}_i \in \mathbb{C}^{M \times \widetilde{N}}$ denotes the channel matrix between i-th selected UCCA and a receive UCA. Here, the element in $m \in \{1, \cdots M\}$-th row and $n \in \{1, \cdots, \widetilde{N}\}$ column of $\mathbf{H}_i$ is defined as

$$h^i_{m,n} = \frac{\lambda \sqrt{G_t G_r P_i}}{4\pi D} e^{-j \frac{2\pi}{\lambda} \sqrt{D^2 + R^2_{t,i} + R^2_r - 2R_{t,i} R_r \cos(\phi^i_{m,n})}}, \quad (1)$$

$$\phi^i_{m,n} = \theta_{t,i} + (m-1)\frac{2\pi}{M} - (n-1)\frac{2\pi}{\widetilde{N}}, \quad (2)$$

where λ denotes the wavelength, and G_t and G_r mean transmit and receive antenna gain, respectively. Therefore, the channel capacity according to actual transmission between the selected transmit UCCAs and the receive UCA can be represented as

$$C^* = \log_2 \left[\det \left(\mathbf{I}_M + \frac{1}{K\sigma^2_n} \bar{\mathbf{H}} \bar{\mathbf{H}}^H \right) \right], \quad (3)$$

Algorithm 1 Optimal transmit UCCAs selection

1: **Input:** TX/RX antenna parameters, D, $\mathcal{P}_t$.
2: **Output:** ν^*, $\mathcal{S}^*$, $\mathcal{P}^*$.
3: **Initialization:** $\mathcal{S}^* = \varnothing$, $\mathcal{P}^* = \varnothing$
4: **for** $\nu = 1, \cdots, J$ **do**
5: Generate tuples S_ν and P_ν:
6: $\mathsf{S}_\nu = \{\mathcal{S} \mid |\mathcal{S}| = \nu,\ \mathcal{S} \subseteq \{1, \cdots, \nu\}\}$.
7: $\mathsf{P}_\nu = \{\mathcal{P} \mid |\mathcal{P}| = \nu,\ \mathcal{P} \cup \mathcal{P}_t \subseteq \mathcal{P}_t,\ \sum_{P \in \mathcal{P}} P = P_t\}$.
8: $[\mathcal{S}_\nu, \mathcal{P}_\nu] = \arg\max_{\mathcal{S} \in \mathsf{S}_\nu, \mathcal{P} \in \mathsf{P}_\nu} C(\mathcal{S}, \mathcal{P})$
9: $C_\nu = C(\mathcal{S}_\nu, \mathcal{P}_\nu)$
10: **end for**
11: $\nu^* = \arg\max_\nu C_\nu$
12: $\mathcal{S}^* \leftarrow \mathcal{S}_{\nu^*}$ and $\mathcal{P}^* \leftarrow \mathcal{P}_{\nu^*}$

where σ_n^2 denote the noise variance.

B. Transmit UCCAs Selection and Performance Measurement

Given the transmission distance, the selection of the best number of transmit UCCAs, the set of indices to selected UCCAs, and the set of power to be allocated are jointly performed according to Algorithm 1. The transmit/receive antenna parameters as illustrated in Fig. 1, transmission distance D, and $\mathcal{P}_t$ are given as inputs, in which $\mathcal{P}_t$ stands for the candidate power set including the discrete power levels. And then, as the number of UCCAs of ν is increased, the selectable UCCA indices combination sets and allocable power combination sets are generated as elements of the S_ν and P_ν, respectively. Herein, each element set of the tuple S_ν is mutually exclusive, and the constraints on power allocation is that the allocated power level of each UCCA should be chosen within $\mathcal{P}_t$ and the total used power is limited to P_t. Afterward, when the number of UCCAs is ν, the sets $\mathcal{S}$ and $\mathcal{P}$ that can maximize the channel capacity as in (3) are substituted into $\mathcal{S}_\nu$ and $\mathcal{P}_\nu$, respectively, while the corresponding channel capacity is stored in C_ν. Finally, the best number of transmit UCCAs can be determined by the one with the largest channel capacity, mapping the indices set and the power be allocated of the corresponding selected UCCAs.

In this paper, to evaluate the spatial multiplexing capability of the proposed subarray-based UCCA selection technique, the normalized capacity gain was exploited as performance measurement for the robustness of LoS MIMO communication systems have given the transmission distance as follows

$$\eta = \frac{C^*}{K \cdot \log_2 \left[1 + G_t G_r \left(\frac{\lambda}{4\pi D}\right)^2 \frac{P_t}{\sigma_n^2}\right]}, \tag{4}$$

where the denominator is the one for K parallel sub-Gaussian channels, so that the maximum value of η is normalized to one. We also provided a quantitative performance evaluation by calculating the geometric mean describing the distribution of the singular values of the wireless channels [4].

III. Simulation Results

In this section, we verify our proposed subarray-based UCCA selection can achieve channel capacity and improve the robustness over transmission distances for LoS communication systems. We assume that the carrier frequency f_c is 62GHz, the average signal to noise ratio (SNR) is 30dB, and the transmit/receive array gains are one. Then, the transmission distance is considered in [1, 200]m. The radius of receive UCA is R_r = 2m and the number of receive antennas M is four. We set the total number of UCCAs J is four where each radius of UCCAs is $\{0.5, 1, 1.5, 2\}$m and each relative rotational angle is $\{0, 5, 10, 15\}^\circ$. Also, the power candidate of each UCCA $\mathcal{P}_t$ is set to $\{0, 0.25P_t, 0.5P_t, 0.75P_t, P_t\}$.

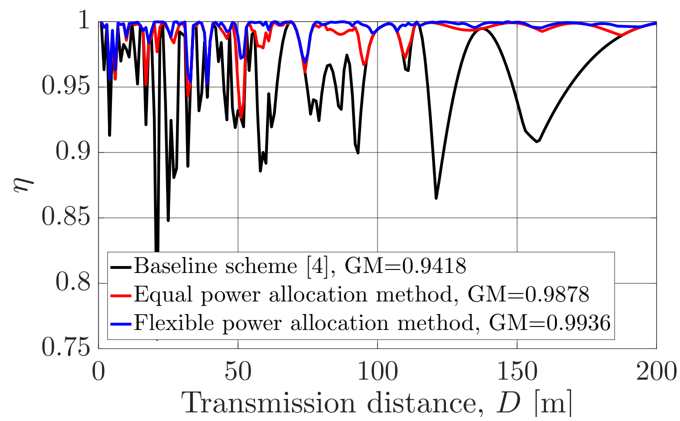

Fig. 2. Normalized capacity gain and geometric mean [4] performance of the proposed subarray-based UCCA selection.

Fig. 2 shows the normalized capacity gain and geometric mean performance of the proposed technique by varying the transmission distance. As a performance comparison method, The baseline scheme is that only one UCCA can be selected without power allocation. In other words, it only considered the radius and rotational angle of UCA for achieving channel capacity as in [4]. The proposed method with equal power allocation is that once the number of transmit UCCAs ν^* is fixed, the same power is allocated to each UCCA, i.e., $P_i = P_t/\nu^*, \forall i \in \{1, \cdots, \nu^*\}$. On the other hand, the proposed method with general power allocation supports more flexible subarray operation by selecting the number of UCCAs and the power levels included in $\mathcal{P}_t$. In Fig. 2, it can be verified that the proposed technique provides more robust spatial multiplexing capability than the existing single UCA selection to all transmission distances.

IV. Conclusion

In this paper, we proposed a low-complexity subarray-based UCCA selection method to improve both the achievable rate and the robustness of LoS MIMO communication systems. It was shown that the proposed technique significantly outperforms the existing scheme via computer simulations. It is worth noting that the proposed technique adopts a subarray architecture to reduce complexity at the transmitter.

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