Complexity Reduced Direction Finding Massive MIMO System Using EM Lens

Sarmad Ahmed Shaikh
Institute of Networked and Embedded Systems
Alpen-Adria-Universität Klagenfurt
9020, Austria
sashaikh@edu.aau.at

Andrea M. Tonello
Institute of Networked and Embedded Systems
Alpen-Adria-Universität Klagenfurt
9020, Austria
andrea.tonello@aau.at

***Abstract*—In this paper, we propose a low complexity based direction finding approach in an electromagnetic (EM) lens assisted massive antenna system. The EM lens provide the advantage of focusing the received signal energy on a small area/subset of the antennas array at the base station (BS). Thus, by taking the advantage of this focusing ability, we propose a complexity reduced sum $\left(\sum\right)$ and difference (Δ) pattern technique to find the direction of arrival (DoA) of the received radio frequency (RF) signals. The proposed technique is simple and implemented in RF.**

***Index terms*—** Massive antenna array, EM lens, DoA estimation, 5G networks.

I. INTRODUCTION

Massive multiple-input-multiple-output (MIMO) systems are considered as an important option for next generation networks such as 5G. Typically, a massive MIMO system deploys a very large number of antenna elements in the network design to attain advantages in spectral efficiency and reliability. However, the massive antenna array system has brought some challenging issues to be tackled for instance, a large amount of hardware (RF-chains) implementations and signal processing computation costs [1], [2]. In the relevant literature, many solutions have been proposed to tackle these challenges such as those mentioned in [2], [3] and the references therein. However, these methods can be further investigated to address few other important applications of the massive MIMO system, for instance the DoA estimation of the impinging waves.

The DoA or angle-of-arrival (AOA) estimation having applications in radar, sonar, military, acoustic, communications and medical imaging, is frequent task in array signal processing [4]. Although the existing related works about the direction finding in the massive MIMO systems can provide the desired results, they involve a significant amount of hardware and computational complexity which must be tackled for any practical deployment.

The purpose of this paper is to address the direction finding application in a massive antenna array system with reduced hardware and computational complexity using the EM lens antennas. In this regard, by extending our basic idea presented in [5], in this paper, we propose a simple direction finding approach that we refer to as sum-difference $\left(\sum - \Delta\right)$ pattern detection scheme. Since the EM lens focuses the received signal energy on a small subset of the antennas array deployed at the BS, the $\sum - \Delta$ pattern detection scheme can be applied on the RF signals of these few excited antennas to find the DoA. As a result, this simple scheme avoids to process the signals in the base band (BB) and helps to reduce further the signal processing computation complexity for direction finding.

II. SYSTEM MODEL DESCRIPTION

The proposed approach for direction finding in the massive antenna system is based on the estimation of the AoA of the received signal. We propose to combine the EM lens with the uniform linear array (ULA) of antenna elements at the base station (BS). The EM lens has the ability to focus/excite the received signal power on a small subset/area of the antenna array as a function of the incident angle (θ) as shown in Fig. 1. This property of the EM lens provides the advantage in reducing the number of antennas to be processed and the signal processing computational complexity [3], [5]. Fig. 1 shows that as the incident angle θ of the received signal changes, the focused signal power distribution on the subset (peak power location) sweeps accordingly. However, the average total captured signal energy on the subset remains the same as without the EM lens. This is due to the fact that the EM lens only changes the received signal's power distribution on the ULA. The number of J excited antennas in a subset is given by the lens geometric design parameter x (function of the radius and extension length) as $J = 2x + 1 \ll M$, where M is total number of antenna elements in the ULA [5].

In this way, by using this distinctive focusing property of the EM lens enabled massive MIMO system, the direction of the received signals can be estimated efficiently. This can be obtained by applying an appropriate antenna selection strategy followed by the AoA estimation technique i.e., $\sum - \Delta$ pattern detection scheme, to the excited subset's RF signals. Although, we can also apply the conventional subspace-based DoA algorithm such as the multiple signal classification (MUSIC), it involves high computational complexity because that is digitally implemented in BB which requires the use of down converters, ADCs, and the computation of the eigen value decomposition of the covariance matrix.

Here, we discuss the direction finding method and omit the

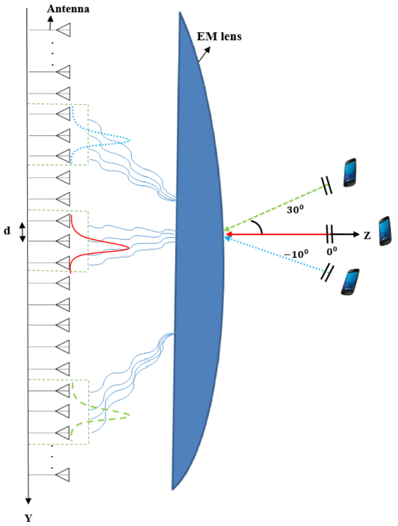

Fig. 1: Design overview of the EM lens assisted massive antenna array.

antenna selection procedure in order to be consistent with the scope of the paper and space limitations. With this essential information, now we describe the channel model with the EM lens.

A. *EM Lens Based Channel Model*

Let us consider that K users with one omnidirectional antenna transmit the narrowband signals towards a BS consisting of a large ULA. The transmitted signals impinge as a plane wave on the ULA via N_P paths with the AoA of θ_{kp}, where $k = 1, 2, \ldots, K$ and $p = 1, 2, \ldots, N_P$. In this way, the channel coefficient h_{km} between the k^{th} user terminal and the m^{th} antenna element can be defined as

$$h_{km} = \sum_{p=1}^{N_P} \sqrt{a_m(\theta_{kp})}\sqrt{\alpha_{kp}} \times \exp\left(j\psi_{kp} + j\frac{2\pi md}{\lambda}\sin\theta_{kp}\right), \tag{1}$$

where α_{kp} represents the channel gain of the user k via the p^{th} path which is determined by the distance-dependent signal attenuation and shadowing. ψ_{kp} is the arrival k^{th} signal phase of p^{th} component and can be modeled as a random variable with the uniform distribution over [0, 2π]. Moreover, λ and d denote the free space wavelength and the inter-antenna elements spacing, respectively. Furthermore, the AoA θ_{kp} can be expressed as $\theta_{kp} = \theta_k + \eta_p$, where $\theta_k \in [-\phi, \phi]$ is the nominal AoA with $\phi \in (0, \pi]$ represents the range of angular coverage of the antenna array. While, η_p denotes the offset of the path p relative to θ_k, that is distributed by a certain power azimuth spectrum with zero mean and angular spread σ_η.

So far, the expression in (1) looks like the traditional channel model except the additional lens factor $a_m(\theta_{kp})$. This additional lens factor $a(\theta)$ is the actual power distributor that brings all the energy of an incoming signal on the subset of J antenna elements focused by the EM lens as a function of the AoA. Where $a_m(\theta_{kp})/M$ reflecting the power fraction obtained by the m^{th} antenna element. The lens factor $a_m(\theta_{kp})$ depending on the lens design parameter *x*, can be modeled by a power density function $f(i;\theta)$ with mean $\bar{i}(\theta)$ and variance σ^2, as [3]

$$a_m(\theta) = \begin{cases} c\int_{i_m-d/2}^{i_m+d/2} f(i;\theta)di, & \mid m - m^*(\theta) \mid\leq x, \\ 0, & otherwise, \end{cases} \tag{2}$$

where i_m denotes the m^{th} antenna location (in terms of the wavelength), *c* is a constant such that $\sum_{m=1}^{M} a_m(\theta) = M$ and $m^*(\theta)$ represents the AoA-based peak power location. The power denisty function $f(i;\theta)$ can be modeled by using the Gaussian power distribution function with mean and variance as indicated earlier. Moreover, for simplicity, in the remainder of the paper we assume N_P=1 and σ_η=0 $\forall K$ which we consider as the line-of-sight (LoS) path. In this manner, we can express the channel vector of the k^{th} user with the EM lens as $\mathbf{h}_k = [h_{k,1}, ..., h_{k,M}]^T$. Furthermore, we can define the received unmodulated carrier signal at the frequency f_0 for the user k at the m^{th} antenna element as

$$r_{km}(t) = \sqrt{\rho_t}h_{km}e^{j2\pi f_0 t} + n(t), \tag{3}$$

where ρ_t is the transmitted power of the signal and *n*(t) represents the additive white Gaussian noise. Moreover, $\mathbf{r}_k(t) = \left[r_{k,1}(t), ..., r_{k,J}(t)\right]^T$ is the received signal vector of the k^{th} user obtained at the focused subset's *J* antenna elements as a function of θ_k. In this way, we can now apply the direction finding scheme on the excited subset's antennas signals in the following manner.

B. *Direction Finding Procedure*

Once the EM lens-focusing antenna system is designed properly with a particular design parameter *x*, the process of estimation of the AoA can be followed. Many algorithms exist to find the AoA from the received signals such as the MUSIC, ESPRIT, root MUSIC and Capon's method which are mainly operated in the BB. Here, we present a simple direction finding scheme that can be operated on the RF signals and is based on taking the sum $\left(\sum\right)$ and difference $\left(\Delta\right)$ of any two excited antennas' RF signals. Then, by taking the ratio Δ to $\sum$ we can obtain the AoA of the received signal. Hence, unlike the subspace-based methods i.e., MUSIC, we do not need to process the received signals in the BB which requires the use of down conversion chains.

Let us suppose that the k^{th} user signal is excited on a subset of *J*=3 antennas (at *x*=1) out of *M* total antennas and we mark those antennas as m^*-1, m^* and m^*+1. In this regard, by considering only m^* and m^*+1 antennas' RF signals and $a_{m^*}(\theta_k) \approx a_{m^*+1}(\theta_k)$, we can take the sum and difference using (3) as

$$\sum = r_{km^*}(t) + r_{k(m^*+1)}(t) \tag{4}$$

$$\Delta = r_{km^*}(t) - r_{k(m^*+1)}(t) \tag{5}$$

In this way, to find the direction of the received k^{th} user signal, we can process the $\sum - \Delta$ patterns which practically can be obtained by using the 180° hybrid couplers such as the rat race ring and magic-T couplers [5]. Thus, by using the patterns equations in (4) and (5), the AoA can be derived by taking the ratio Δ to $\sum$ as

$$\frac{\Delta}{\sum} = \frac{1 - e^{j\beta d \sin\theta_k}}{1 + e^{j\beta d \sin\theta_k}} \tag{6}$$

where $\beta = 2\pi/\lambda$. Finally, corresponding $\hat{\theta}_k$ can be estimated as

$$\hat{\theta}_k = \sin^{-1}\left(\frac{\lambda}{\pi d}\tan^{-1}\left(\frac{\Delta}{\sum}\right)\right) \tag{7}$$

III. SIMULATION RESULTS

In this Section, we report the obtained simulation results of the AoA estimation with an EM lens assisted massive MIMO system using the $\sum - \Delta$ pattern detection scheme. For comparison, the MUSIC algorithm has been investigated as well in both cases (with lens and without lens) in BB where we follow the algorithm steps from [4]. We also investigate the performance of these techniques in terms of the root-mean-square error (RMSE) in degrees which is defined as $RMSE = \sqrt{\mathbb{E}\left[|\theta_0 - \bar{\theta}|^2\right]}$, where θ_0 is the actual angle and $\bar{\theta}$ denotes the estimated AoA.

In this manner, let us consider a BS that comprises a ULA with M=100 antenna elements with antenna spacing d=λ/2 and the angle coverage of the ULA is $\phi = \pi/3$. Further, we consider that K=3 users signals arrive at the BS in the LoS. In this way, we generate the corresponding random transmission angles and form the channel model as discussed in Section II. In the EM lens case, subset size x=1 has been assumed. Moreover, for the without EM lens case, we set a(θ)=1 in (1) to get the traditional channel model.

As an example, by following the proposed methodology, in Fig. 2, we show the estimated directions (AoAs) in degrees at *SNR*=15dB, for K=3 randomly generated transmission angles (Tx AoAs), with lens versus without (w/o) lens using the $\sum - \Delta$ pattern and the MUSIC algorithms. Furthermore, Fig. (3) shows the observed *RMSE* performance as a function of the *SNR* by averaging the estimated results over 10,000 realizations of randomly generated signals, i.e., with random AoA for K=3 users. It can be realized from the results plots that the estimated results with the lens case are in good agreement to the without lens case, despite reduced hardware resources and signal processing computation complexity. Moreover, in the lens case, the $\sum - \Delta$ pattern detection technique provides the identical results with dramatically reduced computational complexity as compared to the conventional MUSIC algorithm. This is because the $\sum - \Delta$ pattern detection scheme performs the AoA estimation directly on the RF signals and avoids to form the covariance and EVD matrices.

IV. CONCLUSION

We presented an approach to find the direction of the received signals in an EM lens assisted massive MIMO system using the $\sum - \Delta$ pattern detection scheme. The proposed methodology showed that direction finding can be addressed with reduced hardware and computational complexity, and it can be implemented in the RF-domain. Because the EM lens focuses/separates each signal on a different subset of the antennas as a function of the AoA, the proposed method can discriminate the multipath components arriving from different directions. Then, the first arriving path (assumed to be the LOS component) can be isolated and its DoA estimated.

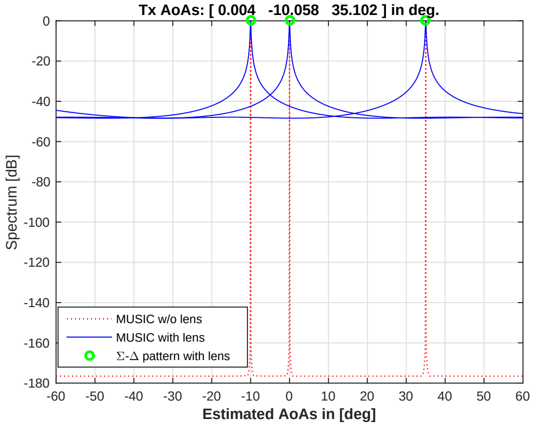

Fig. 2: Estimated directions (AoAs) using the $\sum - \Delta$ pattern and the MUSIC techniques.

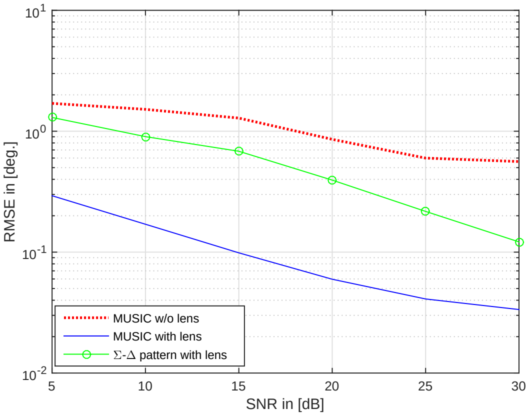

Fig. 3: RMSE performance as a function of the *SNR* in dB.

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