A Comparative Study of Channel Hardening Between Fixed-Position and Movable Antennas

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***Abstract*—Movable antenna (MA) systems represent a novel technology capable of dynamically reconfiguring antenna positions in space. This flexibility introduces capabilities that are inherently unavailable in conventional fixed-position antenna (FPA) systems. In FPA setups, adverse channel conditions such as deep fading are often unavoidable, leading to sporadic performance degradation. Although multiple-input multiple-output (MIMO) technology alleviates these effects to some extent using multiple antennas distributed over the space, it still falls short of fully exploiting the spatial diversity available in a continuous domain. In contrast, MA systems can actively avoid unfavorable channel conditions by repositioning antennas to locations with improved channel conditions. From a channel estimation standpoint, the ability to observe diverse channels across different positions enhances the reliability of the estimation process. Consequently, MA systems exhibit stronger channel hardening effects compared to their FPA counterparts. Numerical results confirm that MA architectures significantly improve channel hardening performance.**

***Index Terms*—Movable antenna (MA), channel hardening, channel estimation.**

I. Introduction

Multiple-input multiple-output (MIMO) technology has become a cornerstone of 5G communications due to its various advantages, including significant path loss mitigation, enhanced spectral efficiency, and improved energy efficiency [1]–[4]. The superiority of MIMO over single-input single-output (SISO) stems from the additional spatial degrees of freedom (DoF) enabled by spatially distributed antennas, allowing for more reliable communication through enhanced channel hardening.

However, conventional MIMO systems are inherently composed of fixed-position antennas (FPA), which cannot adapt to spatial variations. As a result, the full spatial potential available in continuous space remains unexploited, making it difficult to avoid unfavorable channel conditions such as deep fading, and leading to degraded communication performance.

Movable antenna (MA) technology has recently emerged to overcome these limitations [5]–[7]. Unlike FPAs, antennas in MA systems can be mechanically repositioned across continuous spatial domains, thereby unlocking the full spatial DoF and enabling intentional channel reconfiguration under favorable conditions. Recent studies have demonstrated performance gains of MA systems over FPA counterparts across various communication objectives [5]–[7].

In this paper, we focus on the comparative analysis of the channel hardening capabilities between FPA and MA systems in the context of channel estimation. MA-MIMO, by leveraging mobility within the block fading interval, observes the channel from a broader set of spatial locations, thereby enhancing estimation reliability. Numerical results confirm that MA-MIMO achieves superior channel hardening compared to both FPA-MIMO and FPA-SISO systems, validating its potential for more robust channel estimation.

II. System Model

We consider an MA-aided system, where the base station (BS) equipped with MA-enabled multiple M antennas communicates with a single-antenna user. Let $x_m(t)$ denote m-th antenna of the BS at the t-th time slot. The antennas are adjustable along the linear lined with a range of $[-A, A]$. Accordingly, antennas can move to any position on the specified region, which means $-A < x_m(t) < A$.

The user transmits pilot to the BS over the T time slots. The transmitted pilot at the p-th time slot is denoted by $s(t)$. This pilot passes the channel and the BS receives it. This received pilot at the t-th time slot, denoted as $\mathbf{y}(t)$, can be expressed as

$$\mathbf{y}(t) = \mathbf{h}(t)s(t) + \mathbf{n}(t), \tag{1}$$

where $\mathbf{h}(t)$ indicates channel and $\mathbf{n}(t) \sim \mathcal{CN}(\mathbf{0}, \sigma^2\mathbf{I})$ represents additive white Gaussian noise (AWGN) at the t-th time slot. The corresponding channel can be characterized as

$$\mathbf{h}(t) = \sum_{l=1}^{L} \mathbf{a}_t(\theta_l) g_l, \tag{2}$$

where L is the number of channel paths, $\mathbf{a}_t(\theta_l)$ denotes array response vector at the t-th time slot, and $\theta_l \in [-1, 1]$ and g_l represent spatial angle and complex path gain of the l-th path. The array response vector is given by

$$\mathbf{a}_t(\theta_l) = \left[e^{j\frac{2\pi}{\lambda}x_1(t)\theta_l}, e^{j\frac{2\pi}{\lambda}x_2(t)\theta_l}, \dots, e^{j\frac{2\pi}{\lambda}x_M(t)\theta_l}\right]^T. \tag{3}$$

This array response changes as the position of MA changes at each time.

In FPA systems, $x_m(t)$ remains constant across all time slots. Specifically, for FPA-SISO, we can treat all $x_m(t)$ are the same regardless of m and t. In FPA-MIMO, $x_m(t)$ are different for all m, but stays the same regardless of t.

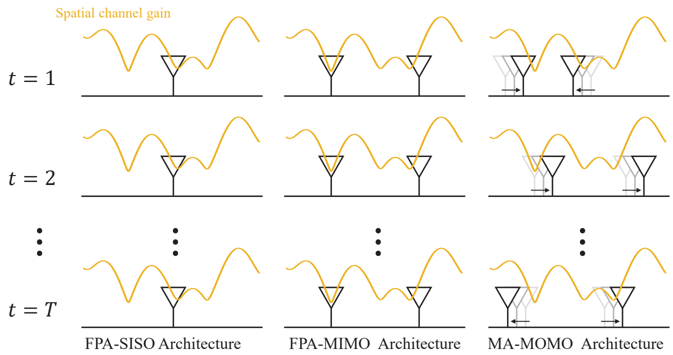

Fig. 1. Comparison of system architectures.

III. Measurement Methodology for Channel Hardening

Channel hardening can be measured by averaging the all signals received by the BS over the total T time slots. Specifically, channel hardening level V can be measured by

$$V = \mathbb{E}(|\mathbf{y}(t)|). \tag{4}$$

We assume that MAs are continuously re-positioned at the random location on the specified region across the time slots.

IV. Numerical Results

The simulation environment is constructed to evaluate the channel hardening performance of different antenna configurations. Each channel realization consists of $L = 5$ multipath components. For channel observation, $T = 256$ time slots are allocated. We compare three antenna system types: FPA-SISO, FPA-MIMO, and MA-MIMO. In the FPA-SISO case, a single antenna observes the channel from a fixed position across all time slots. For the MIMO configurations, $M = 3$ antennas are employed. In FPA-MIMO, antennas are spaced by half-wavelength intervals to provide spatial diversity. In contrast, MA-MIMO continuously adjusts the antenna position at each time slot, thereby utilizing the full spatial domain. To compare the degree of channel hardening, we generate 10,000 samples using Monte Carlo simulations and plot the corresponding cumulative distribution functions (CDFs).

Fig. 2 compare the channel hardening effect of different systems. It can be observed that FPA-SISO exhibits the weakest channel hardening effect, owing to the limited spatial diversity from observing the channel at a single, fixed location. FPA-MIMO provides moderate improvement due to its spatially distributed antennas, which increase the diversity across different positions. MA-MIMO achieves the best performance, benefiting from its ability to dynamically explore the spatial domain and maximize spatial diversity over time. These observations confirm that MA-MIMO significantly enhances channel hardening, thereby offering more reliable communication performance compared to conventional FPA-based systems.

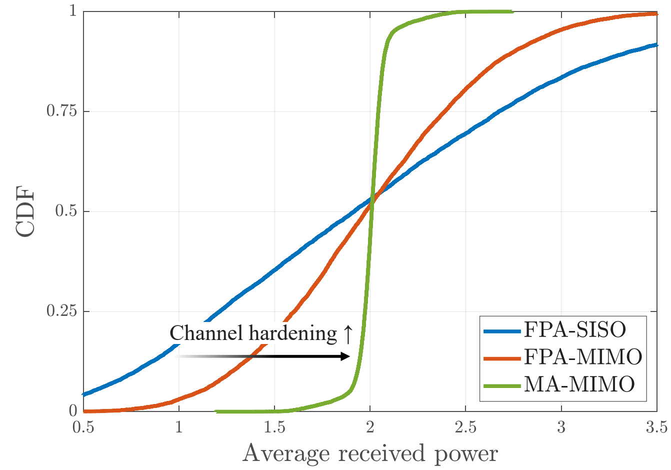

Fig. 2. Comparison of channel hardening effects.

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