A Novel Analytical Framework with Matrix Approximation for 6G Fluid Antenna Systems

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Abstract— Advanced multiple-input multiple-output (MIMO) technology is expected to be an emerging solution for 6G wireless communication systems [1]. MIMO technology significantly improves the data rate, reliability, and even communications security by employing multiple antennas at the transmitter and receiver. However, deploying MIMO systems involves substantial hardware costs, especially since each antenna requires a radio frequency (RF) chain, which grows proportionally with the number of antennas. In addition, there are physical limitations when attempting to install many antenna arrays in a tiny space. Thus, various types of antennas have recently been developed to lower the size and weight of the MIMO systems.

Liquid metal antennas utilizing gallium and tin alloys have emerged as new antennas. The authors of [2] introduced a novel antenna technology called a fluid antenna system (FAS), also known as a movable antenna system (MAS). This type of antenna can alter its shape, size, and position using a software-controlled fluid. For conventional MIMO systems, it was known that antennas must be spaced at least half a wavelength apart ($\boldsymbol{\lambda/2}$) to achieve diversity gain, according to Jake's model. However, according to [2], it was discovered that as small as $\boldsymbol{\lambda/10}$ in space could distinguish between a deep fade and a great reception. Inspired by this, the concept of FAS was introduced, and many application techniques were investigated. Fluid antennas exploit the intrinsic properties of the wireless channel to effectively control the correlation between antenna ports, thereby allowing for the appropriate adjustment of antenna correlation to improve quality. Furthermore, the antenna pattern can be optimized according to the dynamic environment or the user's location to maximize communication efficiency.

Many academic studies are being conducted to analyze the performance of the FAS. The authors of [2] derived a lower bound on the ergodic capacity with a closed-form representation of the FAS. They demonstrated that a single-antenna FAS can achieve the capacity of a multi-antenna maximum ratio combining (MRC) system. In [3], the authors proposed a closed-form approximation of the average channel correlation coefficient parameter, which can be helpful in performance analysis. In [4], the authors approximated the cumulative distribution function (CDF) of the FAS with a simple gamma distribution via an asymptotic matching method, improving the computational complexity. However, [2], [3], [4] only considered the correlation between an arbitrary antenna and the first port. So, in [5], a general correlated channel model was proposed and approximated in two steps to derive the CDF in the form of a single integral. The authors of [6] derived an approximate probability density function (PDF) and CDF for the channel amplitude. They used the Taylor series approximation to obtain a closed-form expression for the outage probability at a high signal-to-noise ratio (SNR).

However, no studies have considered the exact channel correlation among all antenna ports, and the distribution of the correlated channel is not a closed form. Therefore, we mathematically derived the closed-formed expression of CDF of FAS with matrix approximation methods, i.e., Green's matrix and geometric matrix approximation. Through computer simulation, we verify that our mathematical analysis results are matched well with computer simulation results.

Keywords—6G, MIMO, Fluid antenna systems, Matrix approximation, Outage probability, Movable antenna systems

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