

Simulation-Based Performance Analysis of Uplink Cell-Free Massive MIMO Networks for 6G

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Abstract - With advancement, research is going on for various aspect of 6th generation wireless communication system. One of the aspects is Cell-Free Massive MIMO (CF-mMIMO), which is a paradigm shift from traditional cellular networks, where a large number of distributed Access Points (APs) serve a smaller number of users simultaneously, without cell boundaries. This architecture promises uniform high-rate coverage, improved spectral and energy efficiency, and enhanced reliability, making it a strong candidate for 6G networks. In this paper, Simulation of uplink Cell-Free Massive Multiple-Input Multiple-Output (CF-mMIMO) system is reported. A large number of distributed Access Points (APs) are used. They serve a smaller number of users simultaneously and coherently. The performance is evaluated in terms of Bit Error Rate (BER) and achievable uplink spectral efficiency (SE) under varying user transmits power levels. The results for different configuration of Aps and users are discussed in this paper.

Keywords : 6G Wireless Communication System, MIMO, Cell Free Massive MIMO, Terahertz Communication etc.

1 INTRODUCTION :-

In wireless communication system, 5G technology is the giving the ultimate performance for satisfying the user demands and improving the speed of communication. However, various foundations are begin towards the 6G wireless communication systems for handling the increasing demands of data communication [1]. The 6G era involves the fusion of the physical, digital, and human worlds to provide seamless connectivity between machines, humans, and the virtual service field. The key motivating and expected trends in 6G include very high data rates of 1Tbps, extremely low latency (1/10 of 5G), 50x faster than 5G, 2x more energy efficiency, 2x more spectrum efficiency [2]. International Telecommunication Union-Radio Communication Sector (ITU-R) recommended the start of 6G work by 2030 for more than 5ZB per month mobile data traffic [3].

Various technologies are required for any new generation of wireless communication system. For 6G wireless communication system need technologies like reconfigurable intelligent surfaces, photonic and visible light communication technology, distributed intelligent computing network, mobile and cell-free user-centric networking, Terahertz sensing and communication etc. The key technologies of the 6G WCN are depicted in Fig. 1 [4].

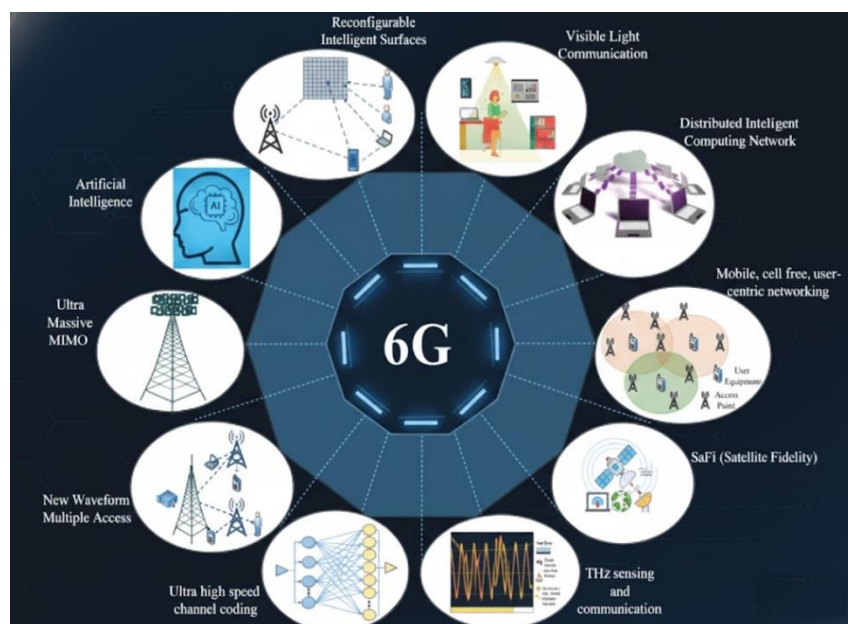


Figure 1:- A conceptual framework of 6G wireless communication technologies, categorized into intelligent infrastructure, physical layer innovations, spectrum expansion, and ubiquitous network coverage [4].

The figure depicts the multi-dimensional ecosystem of 6G, highlighting the shift toward Intelligent, Sensing, and Ubiquitous connectivity. By combining non-terrestrial networks (SaFi) with advanced spectrum usage (THz/VLC) and AI-driven infrastructure, 6G aims to create a fully integrated digital-physical world [4]. Among the technologies for 6G, cell-free massive MIMO, is a promising solution to enhance the wireless transmission efficiency and provide better coverage. Cell free massive MIMO (CF-mMIMO) combines the advantages of distributed systems and massive MIMO [5-6].

In CF-mMIMO, all APs are connected to a Central Processing Unit (CPU) via fronthaul links. Each user is served by all APs coherently, eliminating inter-cell interference and providing macro-diversity gains [7]. This distributed nature offers significant advantages over co-located Massive MIMO, especially in terms of coverage and user experience at the cell edges [8]. Evaluating CF-mMIMO performance involves assessing its capabilities across several dimensions Spectral Efficiency (SE), Energy Efficiency (EE), Coverage Uniformity, Latency, Reliability, Fronthaul Load, Complexity etc. Despite its promises, CF-mMIMO faces several challenges that limit its full potential like Pilot Contamination, Channel Estimation Accuracy, Resource Allocation (Power Control & User Scheduling, Fronthaul Capacity, Interference Management etc. Artificial Intelligence (AI), particularly Machine Learning (ML) and Deep Learning (DL), offers powerful tools to address the aforementioned challenges and significantly enhance CF-mMIMO performance for 6G [9-10].

In this paper, Simulation of uplink Cell-Free Massive Multiple-Input Multiple-Output (CF-mMIMO) system has been carried out to evaluate the Bit Error Rate (BER) and achievable uplink spectral efficiency (SE) under varying user transmits power levels.

2. METHODOLOGY :-

System Configuration

The proposed study considers an uplink Cell-Free Massive Multiple-Input Multiple-Output (CF-mMIMO) architecture in which multiple geographically distributed access points (APs) jointly serve a set of active user equipments (UEs). Unlike a conventional cellular arrangement, the coverage region is not divided into individual cells. The APs are distributed over a 200×200 m area and are assumed to cooperate through a central processing unit. The simulated network consists of 20 APs, with four antennas at each AP, and five active users. This configuration provides a distributed multi-antenna environment for evaluating the effect of user transmit power on uplink performance.

Channel and Propagation Model

For each coherence block, the distance between every AP and user is used to determine the large-scale channel attenuation. The small-scale channel component is generated using independent and identically distributed Rayleigh fading coefficients for the antennas of each AP. The resulting channel therefore contains both distance-dependent large-scale fading and random small-scale fading. In compact form, the channel between AP m and user k can be represented as $h_{mk} = \sqrt{\beta_{mk}} g_{mk}$, where β_{mk} denotes the large-scale fading coefficient and g_{mk} represents the small-scale fading vector. A new channel realization is generated for each coherence block to account for channel variation and to obtain statistically averaged results.

Pilot Transmission and Channel Estimation

Orthogonal pilot sequences are assigned to the five active users. During the training phase, the users transmit their pilot sequences simultaneously and each AP receives the superimposed pilot observations in the presence of additive white Gaussian noise (AWGN). Each AP correlates the received pilot signal with the corresponding known pilot sequence to obtain a channel estimate for every user. The present simulation employs Least Squares (LS) channel estimation, and the estimated channel coefficients are stored for subsequent uplink signal processing. The use of orthogonal pilots in the simulated configuration prevents pilot overlap among the active users during pilot correlation.

Uplink Data Transmission

Following channel estimation, the users transmit QPSK-modulated data symbols over the uplink. The received signal at every AP contains the contributions of all active users together with receiver noise. The distributed AP observations are jointly considered for the evaluation of the CF-mMIMO uplink. For each operating point, the transmission process is repeated over multiple coherence blocks and data symbols so that the measured performance reflects different channel realizations rather than a single channel condition.

Noise and Simulation Parameters

The receiver noise is modeled as AWGN with a fixed noise figure of 5 dB. The system bandwidth is set to 20 MHz and the operating temperature is 290 K. The simulation uses 100 coherence blocks and 1000 data symbols per user. User transmit power is swept from -10 dBm to 20 dBm in 2 dB increments. These parameters are kept consistent for all power levels so that the resulting performance variation can be attributed primarily to the change in user transmit power.

Performance Evaluation

The main performance measure presented in this manuscript is average uplink spectral efficiency (SE), expressed in bits/s/Hz. For every transmit-power value, the performance is evaluated over the simulated coherence blocks and the resulting SE values are

averaged. The study also identifies Bit Error Rate (BER) as an uplink performance metric; however, the results currently presented in the manuscript focus on the relationship between user transmit power and achievable spectral efficiency. The averaged SE values are subsequently plotted against transmit power to illustrate the performance trend of the CF-mMIMO system.

Simulation Workflow

The simulation follows a sequential procedure. First, the network dimensions and physical-layer parameters are initialized. Second, 20 APs and 5 users are deployed within the 200×200 m region. Third, the distance-dependent large-scale fading and Rayleigh small-scale fading components are generated for each coherence block. Fourth, orthogonal pilot sequences are transmitted and the received pilot signals are used for LS channel estimation. Fifth, QPSK data symbols are generated and transmitted by the users. Sixth, the received uplink signals are evaluated in the presence of AWGN using the estimated channel information. Finally, the process is repeated over all coherence blocks and transmit-power levels, and the resulting performance values are averaged. This workflow provides a consistent simulation framework for studying the influence of user transmit power on the uplink performance of the distributed CF-mMIMO network.

3. SIMULATION:-

The simulation platform for achieving first objective has been developed successfully. In this simulation, physical layer and data transmission was analysed for CF-mMIMO system for uplink scenario. The following key components and parameters are used in the simulation.

	Deployment Area	200×200 meters
	Access Points (APs):	20 distributed APs (equipped with 4 antennas.)
	User Equipments (UEs):	5 active users within the same area.
	Modulation	QPSK
	Channel Noise	AWGN with a fixed noise figure of 5 dB, a system bandwidth of 20 MHz, and a temperature of 290 Kelvin
	Channel Model:	Large-Scale Fading
	Pilot Sequences	Orthogonal pilot sequences
	No. of simulations	100 coherence blocks with 1000 data symbols per user

The simulation proceeds in an outer loop iterating through a range of user transmit power levels (from -10 dBm to 20 dBm in 2 dB steps), and an inner loop for coherence blocks. Within each coherence block, the following steps are performed:

For each coherence block, new channel realizations are generated. This involves:

- Calculating the distance-dependent path loss between each AP and each user.
- Generating i.i.d. Rayleigh fading coefficients for each antenna of each AP to each user.
- Combining the large-scale and small-scale fading to form the true channel matrix H_{true} .
- **Pilot Transmission:** Each user transmits its unique orthogonal pilot sequence simultaneously.
- **Received Pilots at APs:** Each AP receives the superimposed pilot signals from all users, corrupted by AWGN.
- **Channel Estimation:** Each AP performs Least Squares (LS) channel estimation. This involves correlating the received pilot signal with the known pilot sequences to estimate the channel from each user to its antennas. The estimated channels are stored in H_{est} .

4. Result :-The simulation environment is shown in the figure 1.

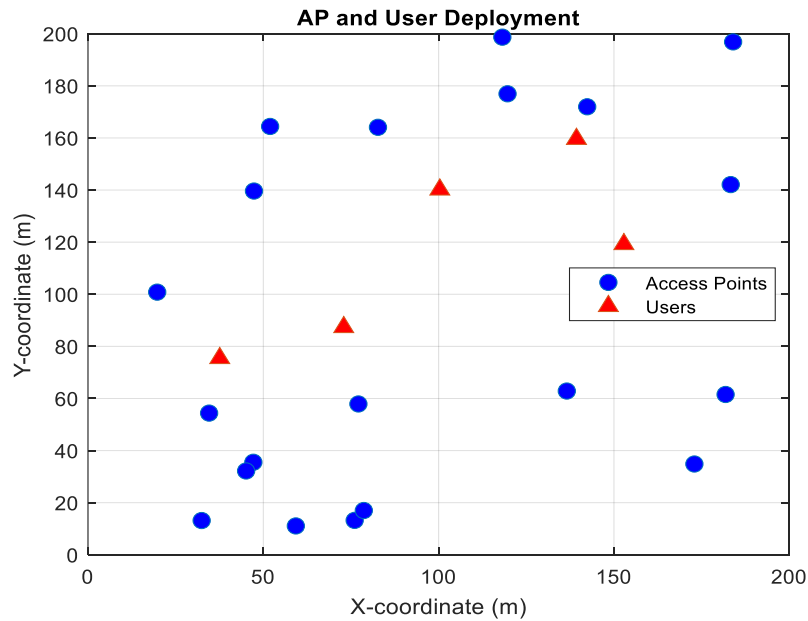


Figure 1: Spatial Distribution of AP and users for simulation

The simulation provides a foundational understanding of CF-mMIMO performance. The transmitted power is increased linearly and the effect on achievable spectral efficiency has been identified. The typical graph between transmitted power and spectral efficiency is shown in the figure 2.

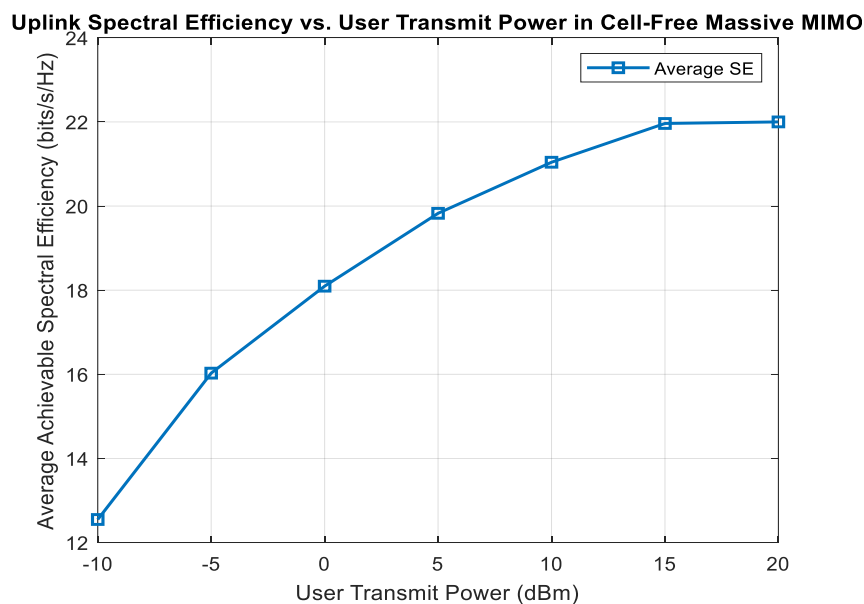


Figure 2: Spectral efficiency for different SNR level

The results demonstrate the basic operational principles and how system parameters like transmit power influence fundamental communication metrics.

CONCLUSION:-

AI technology is not merely an add-on but a fundamental enabler for unlocking the full potential of Cell-Free Massive MIMO in 6G. By intelligently managing complex interactions, optimizing resource allocation, and enhancing signal processing, AI can push the boundaries of spectral efficiency, energy efficiency, coverage uniformity, and reliability, paving the way for truly ubiquitous and high-performance wireless communication.

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