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Performance Evaluation and Enhancement of Free Cell Massive MIMO for 6G using AI Technology under Various Channel Conditions and System Parameters

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Abstract **- With advancement, research is going on for various aspect of 6th generation wireless communication system. One of the aspect 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, a simulation results and analysis of an 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 primary objective of this simulation is to evaluate the system's performance 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 - MIMO,CELL FREE MMIMO

INTRODUCTION

The one of the objective is “Analyse the performance of cell-free massive MIMO under various channel conditions and system parameters”. This includes key performance metrics like achievable rate, bit error ratio, and spectral efficiency. To achieve this objective, initially a simplified MATLAB simulation of an uplink Cell-Free Massive Multiple-Input Multiple-Output (CF-mMIMO) system has been carried out and reported here. In this simulation, a large number of distributed Access Points (APs) are used. They serve a smaller number of users simultaneously and coherently. The primary objective of this simulation is to evaluate the system's performance in terms of Bit Error Rate (BER) and achievable uplink spectral efficiency (SE) under varying user transmits power levels. The results are discussed in this paper .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. This distributed nature offers significant advantages over co-located Massive MIMO, especially in terms of coverage and user experience at the cell edges.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:

- **Pilot Contamination:** If non-orthogonal pilots are reused across users in different coherence blocks, their channels become indistinguishable, leading to interference during channel estimation.
- **Channel Estimation Accuracy:** Accurate Channel State Information (CSI) is crucial for coherent processing. Estimating channels for a large number of AP-user links can be challenging due to noise and interference.
- **Resource Allocation (Power Control & User Scheduling):** Optimally allocating power to users and scheduling them across time/frequency resources in a distributed system is complex.
- **Fronthaul Capacity**: The aggregation of signals from many APs to the CPU can demand very high fronthaul capacities, which can be expensive and difficult to implement.
- **Interference Management:** While inter-cell interference is eliminated, intra-user interference (if multiple users are served simultaneously) and pilot contamination remain.
- **Computational Complexity:** Centralized processing at the CPU can be computationally intensive, especially with a massive number of APs and antennas.
- **Mobility Management:** Handover-like procedures are simplified, but maintaining optimal performance for highly mobile users requires dynamic channel tracking and resource adaptation.

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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.

- **AI for Channel Estimation and Prediction:**
  - **Deep Learning (DL):** Convolutional Neural Networks (CNNs) or Recurrent Neural Networks (RNNs) can learn complex channel dynamics from historical data, improving estimation accuracy, especially in rapidly changing environments. They can also predict future channel states, enabling proactive resource allocation.
  - **Federated Learning:** Can be used to train channel estimation models across distributed APs without sharing raw channel data, addressing privacy concerns and reducing fronthaul load.
- **AI for Resource Allocation (Power Control & User Scheduling):**
  - **Reinforcement Learning (RL):** An agent (e.g., at the CPU) can learn optimal power allocation strategies and user scheduling policies by interacting with the network environment and receiving rewards based on SE, EE, or fairness. This can adapt to dynamic network conditions.
  - **Deep Reinforcement Learning (DRL**): Combines DL with RL to handle high-dimensional state and action spaces, making it suitable for complex CF-mMIMO scenarios.
- **AI for Beamforming Optimization:**
  - **DL-based Beamforming:** Neural networks can learn non-linear mappings from estimated CSI to optimal precoding/combining vectors, potentially outperforming traditional optimization methods, especially with imperfect CSI.
  - **Graph Neural Networks (GNNs):** Can model the relationships between APs and users in the distributed network to optimize cooperative beamforming.
- **AI for Interference Management:**
  - **DL-based Interference Cancellation:** Neural networks can be trained to identify and mitigate various forms of interference (e.g., pilot contamination, residual interference) more effectively than traditional signal processing techniques.
- **AI for Fronthaul Optimization:**
  - **Data Compression:** ML models can learn efficient compression schemes for the data transmitted over fronthaul links, reducing bandwidth requirements.
  - **Intelligent Quantization:** AI can optimize the quantization of channel state information (CSI) or received signals at the APs before sending them to the CPU, balancing performance and fronthaul load.
- **AI for Network Management and Orchestration:**
  - **Predictive Maintenance:** AI can predict network failures or performance degradation, enabling proactive maintenance.
  - **Self-Organizing Networks (SON):** AI can automate network configuration, optimization, and healing, reducing operational costs and improving efficiency.
- **AI for Energy Efficiency Optimization:**
  - **Sleep Mode Management:** RL can learn optimal AP sleep/wake-up schedules based on traffic patterns to save energy without compromising performance.
  - **Dynamic Power Scaling:** AI can adapt transmit power levels dynamically based on user demand and channel conditions.
- **AI for Mobility Management:**
  - **Predictive Handover:** ML models can predict user movement patterns to facilitate seamless transitions and reduce ping-pong effects.
  - **Channel Tracking:** AI can improve the tracking of rapidly changing channels for mobile users.

SIMULATION

- It is primary method for evaluating AI-enhanced CF-mMIMO. This involves developing detailed system models, integrating AI algorithms, and running extensive simulations under various traffic and channel conditions. 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	5 active users with in the

	(UEs):	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

A. *Simulation Methodology:-*

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 Htrue.
- 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 Hest.

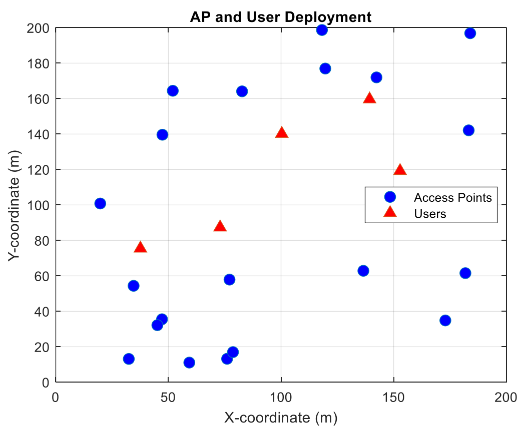

Figure 1: Spatial Distribution of AP and users for simulation

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.

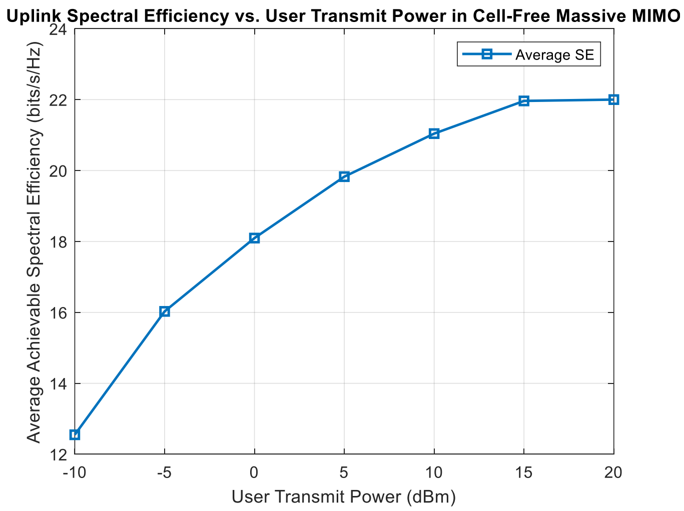

Figure 2: Spectral efficiency for different SNR level

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

This simplified MATLAB simulation successfully demonstrates the core functionalities of an uplink Cell-Free Massive MIMO system, including channel modeling, pilot-based channel estimation, MRC combining, and the evaluation of BER and achievable spectral efficiency. The results align with theoretical expectations, showing improved performance with increased transmit power.

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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