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Towards Robust Space- and Frequency-Domain Cooperative Distributed-Large MIMO Systems

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Abstract

Multiple-input multiple-output (MIMO) is a technique that has been extensively studied and successfully implemented in various communication systems over the past few decades. It has been a key technology in both 4G and 5G mobile communication systems and will be a key enabler in 6G to support the extreme requirements of data rate, energy efficiency (EE), etc. However, meeting these requirements necessitates evolution in the architecture of massive MIMO systems, and distributed MIMO (D-MIMO) has garnered significant attention as a potential solution. This article articulates one of the key findings on adaptive large MIMO systems from the Hexa-X-II European 6G Flagship project and provides a vision of what large MIMO systems may entail in 6G. To achieve this, we examine an adaptive deployment strategy in a joint co-located and distributed MIMO setup, including the utilization of different carrier frequencies and coordinated transmission under an ideal channel state information assumption. We evaluate EE and data rate across various user densities. Additionally, we provide a framework to select the MIMO architecture based on user density and spatial distribution. The key challenges and future research directions on robust large MIMO systems towards realistic 6G networks are also discussed.

I. Introduction

Multiple-input multiple-output (MIMO) is a technique extensively studied in the literature and implemented in real communication systems. It basically consists of the use of base stations (BSs) equipped with multiple antennas and able to transmit/receive multiple data streams to/from multiple active user equipment (UE) simultaneously. MIMO is one of the crucial physical layer technologies utilized in 4G and 5G networks [1], [2]. In 4G-advanced and 5G networks, it evolved into massive MIMO (mMIMO), which consists of the adoption of BSs equipped with a very large number of antenna elements. Recently, the industry has started working on the evolution of mMIMO towards 6G networks: distributed MIMO (D-MIMO), also known as cell-free mMIMO in the literature. During the development of 4G and 5G standards, several techniques were explored to overcome inter-cell interference, and coordinated multi-point (CoMP) is one of them [3], [4]. Moving towards 6G, CoMP techniques are gaining importance with the growth of D-MIMO research.

Indeed, it is challenging to ensure satisfactory communication performance with co-located mMIMO (C-MIMO), particularly for 6G-and-beyond communications. D-MIMO has the potential to enhance communication performance and expand the coverage area demonstrated in a considerable number of research works. Additionally, it is compatible with upcoming technologies like integrated sensing and communication (ISAC) and the Internet of things (IoT) 4.0. Network operators around the world have recently made investments in 5G infrastructure. Thus, they might not be willing to make significant extra investments or modifications to their current infrastructure within a few years. Aiming at future 6G deployments, operators wish to reuse as much 5G radio access network (RAN) hardware as possible [5]. For this reason, the transition from the C-MIMO approach deployed in 5G to the future D-MIMO paradigm is expected to be smooth. In other words, new features of access points (APs) will be gradually introduced into the mobile system and will need to be compatible with the existing cellular system.

The transition from C-MIMO networks to D-MIMO networks raises concerns about the potential increase in implementation costs and network complexity. Both fully co-located and distributed deployments present challenges in achieving optimal performance across diverse network conditions. In addition, the density and spatial distributions of active users impact the network performance. Indeed, within real-world communication networks, these factors only persist for a limited period of time, and in essence, the space features, i.e., the density and spatial distribution, evolve as time and events occur. As a result, an unchangeable MIMO

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deployment may be unable to cover the constantly changing circumstances or may spend excessive energy over a long period of time in an effort to cover all potential scenarios. Furthermore, it is important to mention that both sub-6 GHz and mmWave have unique pros and cons. Sub-6 GHz is recognized for its reliable communication coverage and mature technologies but mmWave provides a broader bandwidth and more directive beams.

This article introduces a robust and cooperative hierarchical hybrid massive MIMO (H-MIMO) deployment that enables the smooth transition from C-MIMO to H-MIMO. The main contribution is summarized as follows. Firstly, in contrast to existing D-MIMO and H-MIMO deployments [6], [7], our proposed H-MIMO deployment allows all transceivers to alternate between sleep and active modes to satisfy varying requirements. Secondly, the collaboration among BS, MBSs, and APs enables multi-frequency band transceivers to serve UEs with different space features, including those in non-uniform and extremely crowded scenarios. Finally, an aggregated user-level aware network is utilized for simulations, focusing on service coverage probability (SCP) generated by data rate and energy efficiency (EE) as performance metrics, to compare various deployments under both fair and practical simulation settings.

Notions: Various terminologies have been employed for the network nodes. In this context, in the following, we provide a comprehensive overview of the various function nodes in the open radio access network (O-RAN) and 3rd generation partnership project (3GPP), in order to enhance the clarity of their definitions. A network element transmitting and receiving radio signals to/from UE via a set of geographically co-located antennas, or radio units, is called the transmission-reception point (TRP). In the O-RAN architecture [8], logical nodes are further defined based on a lower layer functional split, i.e., O-RAN radio unit (O-RU) hosting Low-PHY layer and radio frequency (RF) processing, and O-RAN distributed unit (O-DU) hosting MAC/High-PHY layers, and O-RAN central unit (O-CU) hosting protocols. One can also commonly see AP and CU instead of O-RU and O-DU, respectively, which will be used in the following sections of the paper.

The rest of this article is organized as follows. In Section II we detail our considered large MIMO deployments. In Section III we provide an illustration of the aggregated user-level aware network, along with the application of various MIMO deployments. Subsequently, we present and discuss our simulation results. In Section IV, we present our research findings on robust large MIMO system, key challenges, and future directions, and in Section V we conclude the article.

II. Massive Deployments and MIMO Processing

This section provides an overview of the various massive antenna deployments and multi-antenna processing, which include hierarchical H-MIMO, C-MIMO, and D-MIMO. It aims to provide a concise explanation of the fundamental definitions of various massive deployments and corresponding MIMO networks, along with their pros and cons. Additionally, we present the robust and cooperative H-MIMO network. Moreover, to ensure a fair evaluation of the performance of various MIMO approaches, we present our simulation of the rate performances at the end of this section.

A. Centralized Deployment

In traditional cellular networks, a coverage area is split into several cells, and each one is served by a single BS located at its center. Adopting the mMIMO technology, each BS is equipped with a massive number of antenna elements, and serves multiple UEs located in its cell simultaneously [1]. Several works have proven tremendous performance improvements in terms of spectral efficiency (SE) and EE in C-MIMO.

Owing to the scarcity of available frequency resources in sub-6 GHz bands, academia and industry have become increasingly interested in high-frequency bands, e.g., mmWave and sub-THz, for 6G-and-beyond networks. The operation in such bands can increase the data rate significantly owing to the plenty of bandwidth available, and improve the SE due to its directive beams. Moreover, considering that the wavelength shrinks as we increase the operating frequency, it becomes possible to pack a larger number of antenna elements at the BS. As a consequence, the beams utilized to transmit/receive data to/from multiple UEs simultaneously become more narrow, which significantly reduces the inter-user interference. However, C-MIMO systems operating in mmWave bands suffer from blockages, human shadowing, and low outdoor-to-indoor penetration, which are impairments that significantly affect the achievable data rates and coverage capabilities.

B. Distributed Deployment

According to the initially envisioned D-MIMO paradigm, there may no longer be fixed cell boundaries [9]. The coverage area will be served by multiple APs, each equipped with either a small number or a single antenna element. Then, all the APs can jointly cooperate to serve all the active UEs. In the case of centralized processing, several APs will be connected to the same CU through fronthaul connections. The CU is responsible for the signal processing and coordination tasks of the system.

D-MIMO not only achieves the same benefits of C-MIMO, such as increased SE, improved EE, and a higher number of connected users, but it also ensures a more uniform coverage area. Moreover, as a result of the spatial distribution of APs, D-MIMO is a potential solution to the blockage problem faced in mmWave systems because it is very likely that the UEs will be very close to one or a subset of APs. Authors in [6] conducted a comparison of the performance of C-MIMO and D-MIMO systems using minimum mean square error (MMSE) with 4 different coordination levels. The results show that the performance of the centralized system is inferior to that of distributed installations in the sub-6 GHz frequency region. Moreover, the distributed infrastructure of D-MIMO aims to support 5G and 6G use cases such as IoT and can enhance the performance of other enablers such as ISAC. Each AP may be used to provide connectivity to several IoT devices located in a small area. Finally, multiple APs can provide multi-angle observations required for localization and sensing tasks.

Even though D-MIMO is considered as one of the main physical layer novelties in both 5G-advanced and 6G networks, D-MIMO faces some concerns in communication networks. Firstly, the very large number of equipment being deployed over the coverage

		BS (2.6 GHz, 100MHz)		MBS (28 GHz, 1GHz)		AP (28 GHz, 1GHz)	
	Deployments	Number of antenna	Power	Number of antenna	Power	Number of antenna	Power
Fair Comparison	C-MIMO	256 (16 × 8)	100 W	✗		✗	
	D: 4MBSs	✗		64 (8 × 4)	25 W	✗	
	D: 32APs	✗		✗		8 (2 × 2)	12.5 W
	H: BS+4MBSs	128 (8 × 8)	60 W	32 (4 × 4)	10 W	✗	
	H: BS+16APs	128 (8 × 8)	60 W	✗		8 (2 × 2)	2.5 W
	H: 4MBSs+32APs	✗		32 (4 × 4)	15 W	4 (1 × 2)	1.25 W
	H: BS+4MBSs+16APs	128 (8 × 8)	64 W	16 (4 × 2)	5 W	4 (2 × 1)	1 W
Practical Scenario	H: BS+4MBSs+32APs	128 (8 × 8)	100 W	32 (4 × 4)	10 W	8 (2 × 2)	1 W

TABLE I. Simulation settings for fair and practical comparison, where H and D determine H-MIMO and D-MIMO, respectively. Power in this table determines the power per equipment.

area; Secondly, the network requires very large number of fronthaul connections necessary to connect the APs to the CU; Finally, the higher computational complexity of the system are critical problems.

C. Heterogeneous Deployment

In the H-MIMO deployment, generally, a central BS equipped with an antenna array is placed at the center of the coverage area, while distributed APs span the periphery. Certain research works propose such a combination of co-located and distributed deployments, e.g., [7].

In this article, the proposed robust and cooperative H-MIMO deployment offers a more flexible, sustainable, robust, and feasible approach. In general, H-MIMO refers to a multi-layer hierarchical deployment that involves BS, Micro Base Stations (MBSs), and APs. The BS is located in the central node and is equipped with a significant number of antennas operating at sub-6 GHz. The MBSs are equipped with a modest number of antennas, and APs are equipped with a small number of antennas operating at 28 GHz. There exists a logical node that has the potential to include a CU in order to provide a superior level of computing capacity. Such a CU can synchronize the processing of both MBSs and APs. Due to the presence of BS, MBSs, and APs operating in two frequency bands, the proposed H-MIMO facilitates cooperation among different frequency bands. The sub-6 GHz frequency offers stable and broad service coverage, while the 28 GHz frequency enhances user performance. In an H-MIMO deployment, the issues of blockage and channel degradation related to high-frequency bands, as well as the poor communication performance of sub-6 GHz, are addressed.

A simulation was conducted in this regard. The simulation follows the user-centric selection rule, in which each user chooses an optimal MBS and one/multiple APs. For the results in all the simulation figures, we present four different numbers of selected APs for coordinated data transmission: 1, 2, 10, and 16 coordinated APs. In the absence of a specified number of coordinated APs, the curve determines the best APs chosen by a user for data transmission. As a result, certain APs and MBSs are inactive due to being far away from the UEs. The particular method of transmission may vary depending on several factors, such as UE density, spatial distribution, weather conditions, surroundings, and unique requirements.

To streamline the simulation process and demonstrate the impacts of interference, we assume the use of perfect channel state information (CSI) at the CU, applying a global zero-forcing precoder. This is because the

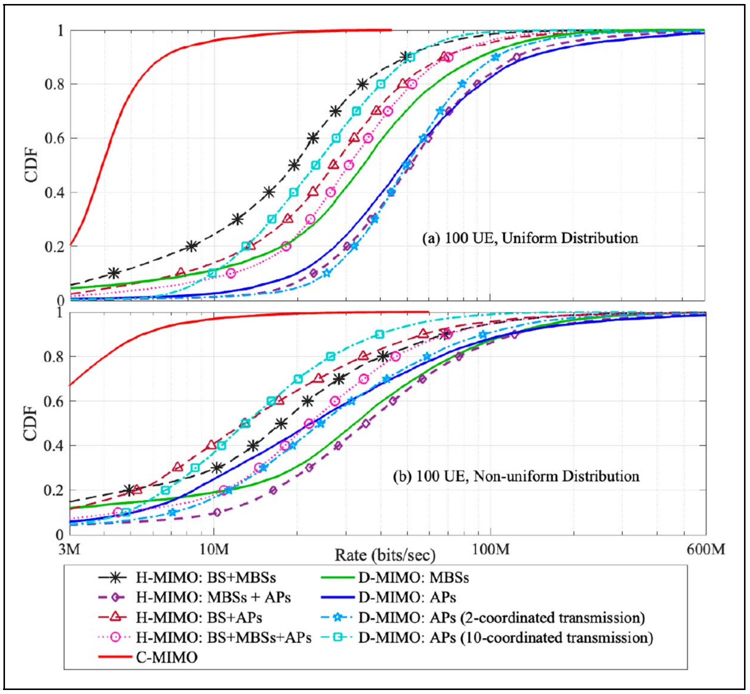

FIG. 1. CDF of Rate under a fair comparison setting for uniform and non-uniform user distribution.

article investigates the impact of interference on performance rates. In multi-user systems, particularly with extra high user density, the low accuracy of estimated channels results in indistinguishable performance during the downlink data transmission phase. To clarify and demonstrate performance across different frequency bands and bandwidths, we utilize rate and EE metrics to evaluate performance under the assumption of perfect CSI. Then, the channel estimation problem is discussed in Section IV.

On the one hand, the proposed robust and cooperative H-MIMO deployment provides enhanced flexibility and adaptability. This is particularly beneficial for scenarios that change over time and in response to the users' density and spatial distribution. It can possibly also leverage the existing 5G radio hardware in the 6G network. On the other hand, such a system encounters a highly complex algorithm in order to optimize performance in complicated scenarios. In order to provide a fair evaluation of different deployments, we analyze their performance from three distinct perspectives while following a predetermined budget for antennas and power serving 100 UEs. The settings for the seven deployments considered in this section,

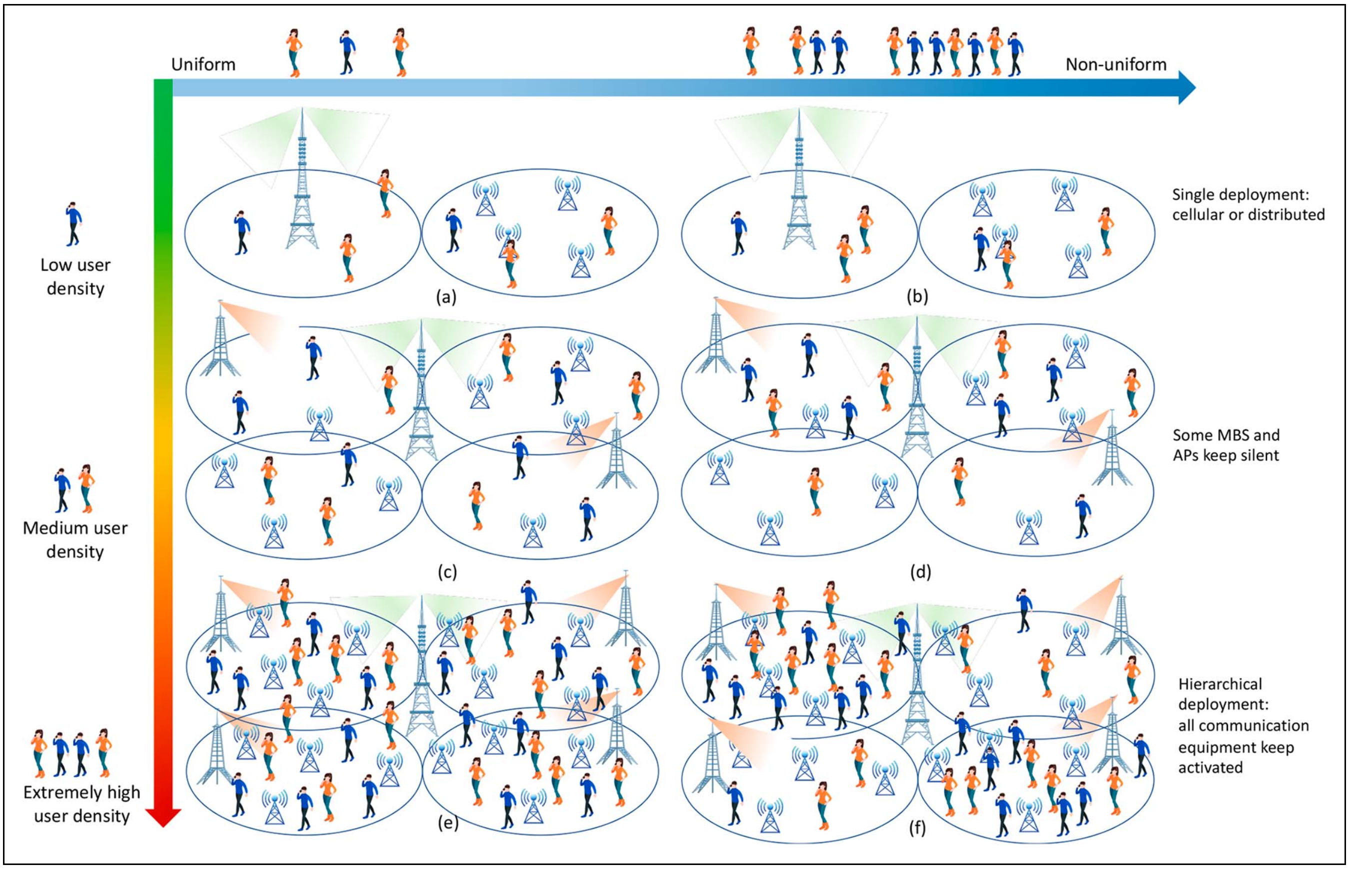

FIG. 2. Aggregated user-level aware scenarios.

which include C-MIMO, D-MIMO: APs, D-MIMO: MBSs, and H-MIMO, are outlined in Table I, and the numerical results are shown in Fig. 1.

As observed in Fig. 1, D-MIMO with centralized coordination has the best performance when the user density is uniformly distributed throughout the area. This is due to the utilization of the high-frequency band, e.g., 28 GHz, which has a wider bandwidth, and the fact that the distributed deployments are closer to the served user in comparison to C-MIMO. MBSs have the capability to improve performances in practical scenarios, where user distribution becomes non-uniform. Finally, when the APs reach ideal synchronization and central coordination at the CU, D-MIMO systems can deliver optimal performance.

The following sections provide an extensive discussion of the components involved in proposing robust and cooperative H-MIMO, along with its advantages and disadvantages.

III. Aggregated User-Level Aware Network

This section demonstrates an aggregated user-level aware network with the system concept illustrated in Fig. 2. We investigate three different levels of user densities in a given area: low, medium, and extremely high user density, each with uniform and non-uniform user distribution. It should be noted that the model identifies several alternative system models in an area that are influenced by changes in time and events, e.g., concerts and sports. In this section, we discuss the three types of user density with uniform and non-uniform distribution as depicted in Fig. 2. At the end of this section, we summarize the performance of the proposed H-MIMO deployment within the context of an aggregated user-level aware network.

A. Simulation Settings

Before evaluating the performance of the aggregated user-level aware network, we first introduce the deployments and parameters. To evaluate the performance in a practical scenario, in this article, we utilize the Quadriga channel model to construct the communication scenario [10]. Without specific determination, we consider an outdoor setting consisting of a circular area with a radius of 500 m. In this area, a cellular BS is positioned at the center, with a height of 20 m. There are four fixed MBSs located in the center of four sections of the circular area, and all transmitters are equipped with dual-polarized uniform planar array (DP-UPA) antenna array. The bandwidths of 2 GHz and 28 GHz are 100 MHz and 1 GHz, respectively. By implementing two frequency bands, interference between D-MIMO and C-MIMO is eliminated. The details are shown in Table I. In addition, the height of MBS is defined as 5 m while the height of AP is specified as 2.5 m.

It is essential to note that in this area, the BS, APs, and MBSs can be either activated or quiet for data transmission. This indicates that the MIMO deployment in this area follows a robust and cooperative H-MIMO. As mentioned in Section II-C, in the aggregated user-level aware network, the same user-centric selection rule is implemented. This means that each user selects the optimal MBS and one/multiple APs. If certain MBSs and APs are not selected, they will be switched to deactivation mode. Ensuring coordination within the same layer is an essential problem in real-world situations. This article assumes the use of perfectly known CSI, synchronization, and coordinated zero-forcing in order to simplify the simulation for D-MIMO. In this article, both the fair comparison in Section II and this part focus on the coordination in the CU. This implies that all data and CSI are transferred to the CU through an error-free link. Then, the zero-forcing precoder for the MBSs is determined by using all CSI from the MBSs, while the APs remain the same approach. Therefore, the coordination discussed in this article is limited to the same type. To evaluate the appropriate MIMO deployment and accommodate different user densities, Figs. 3 and 4 present the SCP, i.e., the probability of the user's minimum rate satisfies the requirement, versus the user rate, and the cumulative distribution function (CDF) plots of EE, respectively.

In this article, we focus only on the impact of RF chain power in order to understand the topology structure. Other factors, such as the power of using CU, fronthaul processing, and hardware power are disregarded. Hence, the EE mentioned in this article refers to the rate per unit of RF energy. Similarly, this article focuses on the power usage and power consumption of the RF chain. Indeed, considering a practical power model in the simulation results for varied deployment strategy selection can have a significant impact. This is due to the varying transmitters and levels of information transmission, which play a crucial role in power consumption. Our future work will involve assessing the power consumption and impact of different deployment methods. Thus, in this article, we focus primarily on evaluating the practicality and topological aspects of the considered MIMO deployments.

To demonstrate the three levels of user density, we use 30 UEs, 80 UEs, and 300 UEs to represent low, medium, and extremely high user densities, respectively. To determine the most suitable method and assess the effectiveness of flexible MIMO deployments, we define a threshold at which the SCP is over 80% when the user rate is 10 Mbits/s, see the big black nodes in Fig. 3. The following subsections aim to evaluate the method based on three essential factors: usage of power, EE, and practicality. In order to demonstrate the impact of coordination on the system, we evaluate the practicality of the strategy as one of the evaluation criteria. The practicality of a strategy is evaluated based on three specific viewpoints: the level of complexity in coordinating actions, the difficulty in synchronizing actions, and the frequency of changes in information. Typically, a deployment is deemed to have low practicality if it requires considerable coordination, precise synchronization, and frequent updating of CSI and transmission data between APs and CU to achieve coordination among all APs. Thus, based on the prior determination, the practicality rating, from lowest to highest, is as follows: D-MIMO, MBSs-based small cell mMIMO, and C-MIMO. Table II(a) is an overview of the recommended strategy. Table II(b) summarizes the performance, advantages, and disadvantages of all evaluated MIMO deployments.

B. Low User Density

For the low user density, as shown in Fig. 2(a) and (b), a single communication deployment, such as C-MIMO or D-MIMO, is sufficient to serve the users. This results in a significant reduction in power consumption for the region. Based on the aforementioned threshold, all strategies with low user density meet the criterion. However, D-MIMO offers the highest EE and the lowest power usage among all options. In addition, the interference has been eliminated according to the rate-performance, see Fig. 3. On the other hand, the strategies give different results in the case of a non-uniform user distribution. In such a case, the level of interference between users in a confined space is significantly increased, requiring the transmitter in that area to provide larger power utilization in order to serve the users. Therefore, as suggested by the results shown in Fig. 3, the MBSs could assist in reducing interference and increasing SNR. Due to the non-uniform distribution of users, the best strategy from all three viewpoints is the implementation of MBS-assisted H-MIMO.

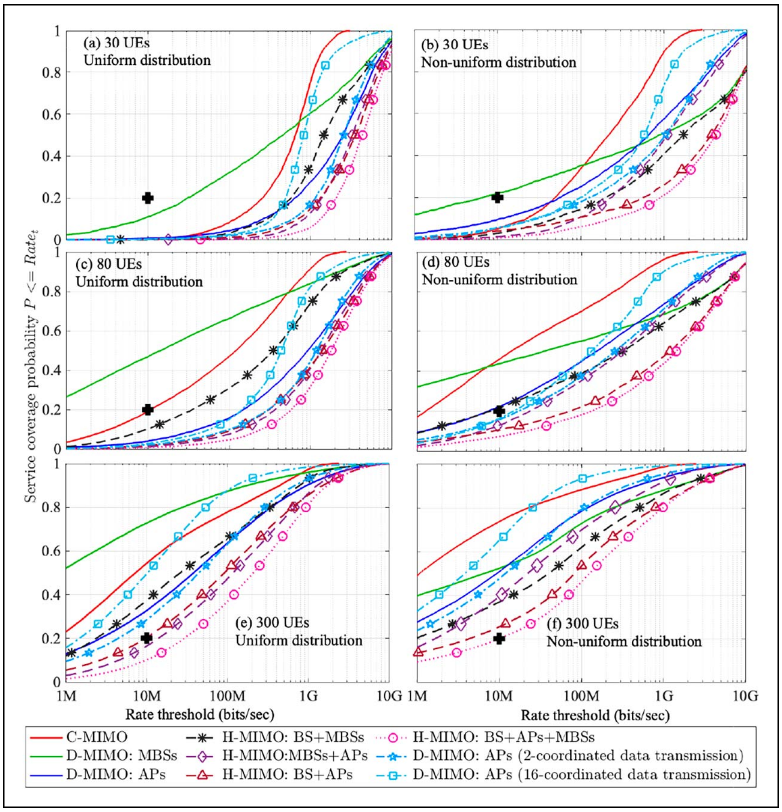

FIG. 3. SCP for low, medium, and high density under both uniform and non-uniform distribution. The specified rate requirement is determined by the black point.

C. Medium User Density

A medium user density in the region under consideration might be regarded as a more common scenario, as seen in Fig. 2(c) and (d). From observation in Fig. 4, the D-MIMO: MBSs fails to achieve the required criterion when the UEs are spread evenly. In contrast, D-MIMO provides the highest EE. Although C-MIMO may reach our data rate SCP criterion above, its EE is considerably worse compared to D-MIMO and MBS-assisted D-MIMO, (H-MIMO: MBSs+APs). However, if the user distribution becomes non-uniform, C-MIMO is unable to satisfy the data rate SCP criteria. When faced with such a case, the most advantageous approach is to utilize H-MIMO: BS+MBSs+APs, which provides superior rate performance and EE. This is because the MBS can provide users with a greater degree of freedom (DoF) within a limited area. In addition, due to the

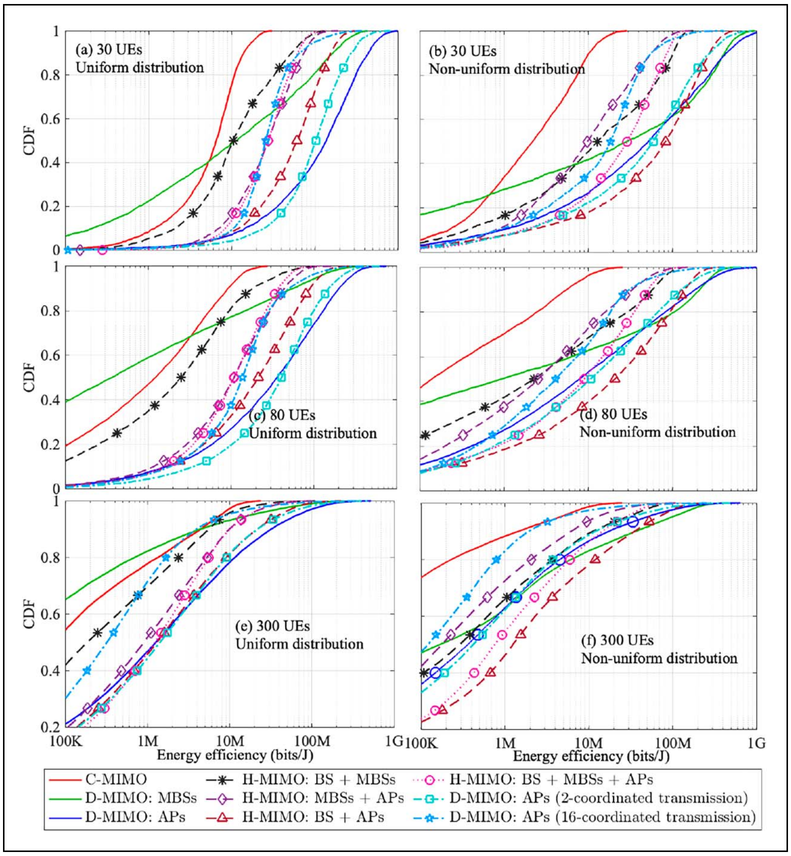

FIG. 4. The CDF plot of EE under both uniform and non-uniform distributed low, medium, and high density UEs.

selection criteria, certain APs and MBSs stay inactive when they are located far away from users.

D. Extremely High User Density

In some scenarios, the network needs to serve a high user density, but still be able to maintain sufficient service levels. In such scenarios, the user distribution often tends to be concentrated in certain parts of the coverage area. To this end, both uniform and non-uniform user distributions should be taken into account as illustrated in Fig. 2(e) and (f). Particularly during concerts, sporting events, and similar events, user density is significantly increased and distributed in a non-uniform manner, the demands of a large number of connectivities and high data rates are critical. As shown in Figs. 3 and 4, the uniform user distribution is satisfied by the H-MIMO deployments: BS+APs, MBSs+APs, and BS+MBSs+APs, all of which have comparable EE. In the presence of non-uniform user distribution, the H-MIMO: BS+MBSs+APs exhibits superior EE and rate performance. When compared to a uniform distribution, the efficacy of D-MIMO is inferior when compared to MBSs+APs. Furthermore, in contrast to other user densities, interference appears as a significant concern, particularly in cases of non-uniform distribution. Therefore, interference management and an appropriate scheduling algorithm are critical research directions.

Consequently, the analysis of our considered three different user densities and two spatial distributions reveals that the H-MIMO: BS+MBSs+APs exhibits superior robustness performance. In scenarios with an extremely high user density and non-uniform distribution, the proposed H-MIMO effectively delivers high-quality performance. This is because the proposed H-MIMO deployment can adjust system resources based on space features. The following section delves further into the challenges and important research direction towards the implementation of flexible cooperative H-MIMO systems.

IV. Key Challenges and Future Directions

In this section, we discuss potential challenges and future research directions on robust large H-MIMO systems with a wide range of topics, including algorithm design, hardware implementation, techniques that are practical for beyond 5G and 6G networks, and critical challenges associated with distributed MIMO. In particular, it comprises hardware impairments, interference management, regulatory electromagnetic fields (EMF) compliance aspects, RIS-assisted MIMO, and AI for future robust large MIMO systems.

A. Algorithm Design

The proposed H-MIMO deployment demonstrates improved performance across varying user density and spatial distribution, exhibiting notable robustness and scalability. In this deployment, the CU must adjust the APs and MBSs to activate or deactivate based on varying user density and distribution. Additionally, whether employing centralized or decentralized channel estimation or precoder design, the CU is required to communicate with all APs and MBSs. Consequently, this deployment presents several challenges related to algorithm design, including channel estimation algorithms, beamformer and precoder design, issues arising from high-velocity dynamic systems, and low-complexity algorithms.

The topological structure could be used as a viable approach for aiding algorithm design. The concept has been applied to address the dynamic pilot assignment problem in D-MIMO. The objective is to convert the H-MIMO deployment and its communication performance into a graph structure along with the associated optimization goal. This transformation can be applied by utilizing the channel statistics, path loss, distance, and blockage information to establish connections among all transmitters and users, thereby representing the system as a graph. Graph theory and topology theory can provide theoretical support for optimization and the design of low-complexity algorithms.

B. Interference Management

Interference management in D-MIMO systems has been broadly studied in the literature [9]. In this context, beamforming techniques can generally be divided into non-cooperative and cooperative approaches. In the absence of cooperation, each AP individually optimizes its beamformers based solely on local CSI. In this setting, the interference cancellation capability of D-MIMO systems is limited by the number of antennas at each AP. If the APs cooperate, cluster- or network-wide beamforming can be achieved at the cost of increased signaling overhead (e.g., CSI exchange among APs or with a CU). In this setting, the APs in the cluster or network act as a larger (distributed) antenna array, with great potential for enhanced interference management. D-MIMO makes local beamforming (based on, e.g., maximum ratio transmission/combining) attractive thanks to the very large number of antennas across the network. However, allowing (limited) cooperation among the base stations to enable cooperative beamforming

User-Density	Uniform Distribution			Non-Uniform distribution		
Low	Potential deployments	Power usage	D: APs	Potential deployments	Power usage	H: MBSs+APs
	All deployments	Energy efficiency	D: APs	All deployments	Energy efficiency	H: MBSs+APs
		High practicality	C-MIMO	except for D: MBSs	High practicality	C-MIMO
Medium	All deployments	Power usage	D: APs	H: MBSs +APs	Power usage	H: MBSs+APs
		Energy efficiency	D: APs	H: BS+APs, D: APs	Energy efficiency	H: MBSs+APs
	except for D: MBSs	High practicality	H: BS+MBSs	H: BS+MBSs+APs	High practicality	H: BS+MBSs
High	H: BS+APs,	Power usage	H: MBSs+APs	H: BS+MBSs+APs	Power usage	H: BS+MBSs+APs
	H: MBSs+APs,	Energy efficiency	H: BS+MBSs+APs		Energy efficiency	H: BS+MBSs+APs
	H: BS+MBSs+APs	High practicality	H: BS+APs		High practicality	H: BS+MBSs+APs

(a) The recommended MIMO deployments for low, medium, and high user density respectively. In this table, the characters D and H, denote D-MIMO, H-MIMO, and co-located mMIMO is denoted by C-MIMO.

MIMO Deployments	Performance				Pros & Cons	
	Fair		Practical		Pros	Cons
	Uniform	Non uniform	Uniform	Non uniform		
C-MIMO	Low user rate	Low user rate	Low user rate; Low EE	Low user rate; Low EE	High practicality; Muture technique; Low complexity; No cooperation	Low performance
D-MIMO: MBSs	Medium user rate	Good user rate	Low user rate; Low EE	Low user rate; Low EE	High practicality; Higher user rate; Low complexity; No/Low cooperation; Good for non-uniform scenario	Sensitive for blockage (High frequency band); Not good for crowded scenarios
D-MIMO: APs	Good user rate	Medium user rate	Medium user rate; High EE	Low user rate; Medium EE	High user rate; Good EE performance; Low power usage	Medium cooperation; Medium complexity; Not good for non-uniform scenario; Sensitive for blockage (High frequency band); Synchronization problem
H-MIMO: BS+MBSs	Low user rate	Medium user rate	Medium user rate; Low EE	Medium user rate; Medium EE	High practicality; Robust performance; Good for non-uniform scenario; Low cooperation; Low complexity	Hardware design (cooperative in frequency domain); Not good for EE performance
H-MIMO: BS+APs	Medium user rate	Low user rate	Good user rate; High EE	Good user rate; High EE	Good for non-uniform scenario; Good for crowded scenario	Low EE performance; High cooperation; High complexity; Sensitive for blockage; Synchronization problem; Hardware design
H-MIMO: MBSs+APs	Good user rate	Good user rate	Good user rate; Medium EE	Medium user rate; Low EE	Good for non-uniform scenario; Good for crowded scenario	Low EE performance; High cooperation; Sensitive for blockage; Synchronization problem; Hardware design
H-MIMO: BS+MBSs+APs	Medium user rate	Medium user rate	Good user rate; High EE	Good user rate; High EE	Good for non-uniform scenario; Good for crowded scenario; Acceptable performance for all scenarios	High cooperation; High complexity; Synchronization problem; Hardware design; Need proper designed algorithms

(b) A summary of the performance, complexity, cooperation requirements, pros, and cons related to various MIMO deployments.

TABLE II. Simulation results summarization.

can still provide significant gains [6], especially with imperfect CSI. In this regard, there is a plethora of centralized and distributed beamforming designs, which usually require extensive CSI exchange via backhaul links. In addition, iterative bi-directional training between base stations and users enables distributed schemes without any backhaul signaling for the CSI exchange.

C. Hardware and Synchronization Impairments

The performance of MIMO transmission schemes can be degraded by RF hardware impairments such as power amplifier (PA) non-linearity, oscillator phase noise, quantization noise from digital-to-analog converter (DAC) and analog-to-digital converter (ADC). These RF hardware impairments cause inband and out of band distortions, and the impact of the impairments on MIMO transmission schemes is expected to become even more severe in 6G radio systems. For example, the need for enhanced EE drives the PAs to operate in more nonlinear regime, transmission at higher frequency bands (e.g. sub-THz) lead to higher phase noise, and the need to lower the complexity for low latency would require low resolution converters that cause extra quantization noise. These would be pronounced in D-MIMO transmissions that rely on RF hardware components that are cost efficient with relatively low complexity.

Therefore, MIMO transmission schemes including beamforming methods that take into account RF hardware and are robust to the distortions are essential. It is also envisioned that hardware impairment compensation methods such as digital pre-distortion (DPD) at the transmitter side or digital post distortion compensation (DPoD) [11] to be critical for the operation of 6G MIMO transmission schemes.

Other impairments that affect the performance of D-MIMO networks are the imperfect time and frequency synchronization. In D-MIMO networks, multiple APs send/receive signals to/from multiple UEs simultaneously. Considering that the APs are installed at different locations, it is unlikely that the transmitted signals will reach the intended receivers at the same time instant. As showed in [12], the asynchronous reception due to the timing offsets causes significant reduction on the desired signal power.

Moreover, the APs in D-MIMO systems are each equipped with their own local oscillator (LO). Owing to the imperfection of the LO hardware in practical systems, carrier frequency offsets (CFOs) and phase noise are inevitable. While phase noise is a random fluctuation of the phase of the output signals of the LOs, CFOs correspond to the mismatch in the carrier frequencies generated by the LOs at different APs and UEs. CFO leads to degradation of the achievable rates, while phase noise reduces the power of the desired signals.

D. EMF Compliance and Power Coordination

Regardless of which MIMO architecture is chosen, exposure to RF EMF from the radio equipment must comply with applicable standards and regulations. The recent simulation studies suggest that the environmental EMF exposure levels from D-MIMO and mMIMO deployments are similar and far below the EMF exposure limits, which are typically expressed as power density levels averaged over 6 or 30 minutes, as specified in the international EMF exposure guidelines.

Before putting BSs into the operation, operators need to verify that the compliance boundary, outside of which the EMF exposure is below the limits, does not extend into areas accessible by the general public. When more BSs, power, or spectra are to be deployed on an existing site for 6G, there might be challenges due to the available size of the compliance boundary. One way to address such challenges is to use time-averaged transmitted power or effective isotropic radiated power (EIRP) levels rather than the maximum transmitted power or EIRP in EMF compliance assessments, as specified in the IEC 62232 Ed3 standard. Software features may be required by regulators to monitor or control the time-averaged power or EIRP. Algorithms for such power/EIRP monitoring and control for a single BS have been developed, e.g., [13]. However, network performance can be degraded if such an algorithm triggers power control. As EMF compliance of a site should consider the cumulative contributions from all co-located BSs, a good strategy could be coordination of such algorithms in the MIMO transmission and the MBS/AP selection process to avoid performance degradation.

E. RIS-Assisted MIMO

Reconfigurable intelligent surfaces (RISs) have been recognized as a key enabler for future 6G systems in order to cater to the demanding connectivity and sustainability requirements [14]. The term commonly refers to inexpensive, quasi-passive planar structures comprising tunable unit cells that can alter the properties of impinging electromagnetic waves. By suitably configuring the phases and amplitudes of said cells, one can reshape the radio propagation environment. Owing to their versatility, RISs have been suggested for a broad class of applications, including communications, localization and sensing, physical-layer security, etc. In conjunction with D-MIMO, several uses can be envisaged. RISs can enable connectivity or enhance reliability, especially for millimeter-wave and THz communications. At these frequencies, blockage and high signal attenuation often lead to the formation of radio shadowed regions. By deploying RISs at selected locations, such limitations may be overcome, thereby extending the coverage of the proposed hybrid adaptive MIMO paradigm while enhancing the EE of the system. More generally, RISs may reduce the activation frequency of the APs (thus improving EE) or even replace one or more of them (thus reducing costs and deployment time). However, before RISs can be deployed in 3GPP networks, the technology must be integrated into the standard, and some challenges addressed. One such challenge is the lack of frequency and spatial selectivity of RISs, which manifests as out-of-band emission and the reflection of unintended impinging-outgoing direction pairs. Recent progress in [14] suggests that such challenges may be overcome with special RIS architectures.

F. AI for MIMO

The ongoing evolution of both mMIMO and D-MIMO systems is characterized by the scalability of antenna elements within densely populated user environments. This trend presents a plethora of challenges, e.g., user association, channel estimation and prediction in high-mobility environments, and the development of efficient precoding and beamforming algorithms. Some of the optimal algorithms addressing these challenges are NP-complete, which motivates using machine learning (ML) in mMIMO or D-MIMO for 6G. For mobile D-MIMO systems, reinforcement learning-based algorithms can be employed for autonomous optimal association between user and AP, which can further reduce fronthaul load in the network [15]. The distributed architecture of D-MIMO also paves the way for ML techniques like federated learning to be employed, and it can be used for precoder design and optimal resource allocation. However, the integration of ML models with D-MIMO encounters two primary obstacles: compromising EE and ensuring reliability in dynamic network conditions.

V. Conclusion

In this paper, we presented a robust H-MIMO system that cooperatively operates in the space, time, and frequency domains. The system is designed to meet the communication requirements and can smoothly switch between various MIMO deployments by activating and deactivating nodes. In order to investigate the performance of alternative MIMO strategies in various scenarios, we evaluated the EE and rate performance for three different user densities, considering both uniform and non-uniform spatial distributions, respectively, and we then proposed suitable strategies. Finally, we summarized challenges and future research directions toward robust large MIMO systems for 6G.

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