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Massive MIMO and NOMA for 6G Wireless Networks: Key Technologies, Challenges, and Prospects

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Abstract. Wireless access technology is a key area of research since 6G wireless networks are anticipated to enable immersive communication, enormous IoT, intelligent sensing, and ubiquitous coverage. Utilizing the method of literature review, this paper examines Massive Multiple-Input Multiple-Output (Massive MIMO) and Non-Orthogonal Multiple Access (NOMA) as two complementary access technologies for 6G wireless networks and compares their roles in the spatial and power domains. The review finds that Massive MIMO improves spectrum efficiency, system capacity, and link reliability through large antenna arrays, beamforming, and spatial multiplexing, while NOMA increases access density and edge-user fairness through power-domain multiplexing and successive interference cancellation. Their convergence can better support high-capacity 6G access, but it also introduces asynchronous interference, channel state information overhead, and high-frequency coherence challenges. By connecting these challenges with Radio Access Network digital twins, AI-assisted scheduling, and integrated sensing and communication, the paper clarifies a practical research path for Massive MIMO-NOMA convergence in future 6G networks.

Keywords: 6G wireless networks, Massive MIMO, NOMA, Giga-MIMO, integrated sensing and communication

1. Introduction

Wireless communication is moving from 5G connectivity toward 6G networks that must support immersive interaction, massive IoT, intelligent sensing, and ubiquitous coverage. Existing studies and industry roadmaps describe 6G as an integrated system combining communication, computation, sensing, and intelligence, rather than a simple upgrade in peak rate [1-3]. In this context, wireless access technology becomes decisive because it determines how efficiently limited spectrum, power, and spatial resources are shared among dense users and devices. Massive Multiple-Input Multiple-Output (Massive MIMO) and Non-Orthogonal Multiple Access (NOMA) are two important candidates for this role. Massive MIMO extends the spatial dimension through large antenna arrays and beamforming, while NOMA uses power-domain multiplexing and successive interference cancellation to serve multiple users on the same time-frequency resource. However, existing research still needs clearer comparison of their complementary mechanisms and their integration risks in high-frequency, non-cellular 6G scenarios.

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Utilizing the method of literature review, this paper explores the principles and advantages of Massive MIMO and NOMA, analyzes the main challenges of their convergence in 6G wireless networks. It also discusses possible solutions based on digital twins, artificial intelligence, and integrated sensing and communication, thereby providing a theoretical reference for designing high-efficiency, intelligent, and scalable multiple access schemes under heterogeneous service constraints and dynamic spectrum conditions.

2. Overview of Massive MIMO technology and NOMA systems

2.1. Massive MIMO technology

First, Massive MIMO refers to the use of dozens, hundreds, or even more antenna elements at the base station to communicate with multiple user equipments on shared time-frequency resources. Compared with conventional MIMO, the larger array gives the network stronger spatial resolution, higher array gain, and better support for dense multi-user transmission [4, 5]. In the 6G context, this concept is often extended toward Giga-MIMO, where very large antenna surfaces and distributed transmit-receive points provide the spatial foundation for cell-free and wide-area access.

Figure 1 shows the fundamental working principle of Massive MIMO, allowing the same spectrum be reused in the spatial domain with reduced mutual interference.

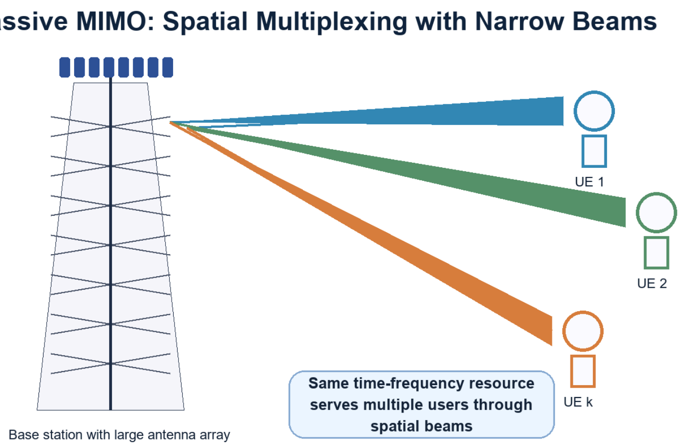

Figure 1. Massive MIMO beamforming and spatial multiplexing

Second, the working process of Massive MIMO includes channel estimation, beamforming, and spatial multiplexing. Users first transmit pilot signals, and the base station estimates channel state information from these reference signals. Beamforming then adjusts the phase and amplitude of each antenna element to focus energy toward target users. Finally, spatial multiplexing enables parallel data transmission to multiple users on the same resource block, which converts antenna scale into system throughput [6].

Another important feature of Massive MIMO is channel hardening. The effective channel becomes more stable as the number of antennas rises because the random fluctuation of each individual propagation path is averaged across the array. This stability helps simplify link adaptation and scheduling because the base station can make more reliable decisions from estimated channel information. In dense 6G access, channel hardening is useful for supporting many low-mobility terminals, sensors, and industrial devices that require stable service rather than only peak data rate.

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Nevertheless, the benefit is not automatic. Particularly when the array scale shifts from traditional Massive MIMO to ultra-large or scattered antenna surfaces, it depends on antenna spacing, propagation environment, pilot design, and hardware calibration.

Third, Massive MIMO improves spectral efficiency, system capacity, coverage, and reliability. Spatial multiplexing allows scarce spectrum to carry more independent user streams, while beamforming compensates for path loss and improves edge-user signal quality. Fourth, several 6G optimization technologies can strengthen this advantage. Probabilistic shaping can move the signal distribution closer to the Shannon limit, subband full-duplex can reduce uplink-downlink waiting time, and AI-based channel prediction can reduce the cost of channel acquisition.

2.2. NOMA systems

First, NOMA is a multiple access method that allows several users to share the same time-frequency resource by separating their signals in the power domain. Unlike orthogonal multiple access, which assigns exclusive resources to each user, NOMA superposes user signals with different power levels and therefore improves access capacity when spectrum resources are limited [7].

As illustrated in Figure 2, the base station allocates more power to users with weak channel conditions and less power to users with strong channel conditions. The receiver then applies successive interference cancellation (SIC) to decode and subtract stronger signals before recovering weaker ones.

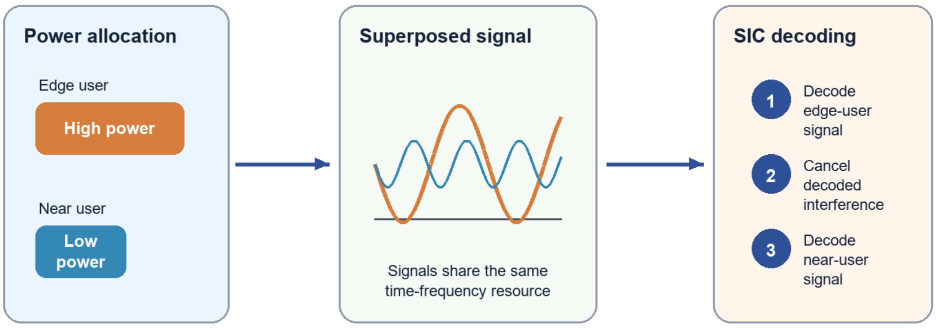

Figure 2. NOMA power-domain multiplexing and SIC decoding

Second, the main NOMA procedure consists of power allocation, signal superposition, and SIC decoding. These steps allow near and edge users to be served simultaneously, but they also require accurate channel information and careful user pairing. Third, NOMA improves connection density, spectral utilization, and edge-user fairness. Its power-domain multiplexing is naturally complementary to Massive MIMO spatial multiplexing, and recent studies on NOMA-aided cell-free Massive MIMO show that the two techniques can jointly improve throughput and user access in dense 6G scenarios [8].

In practical deployment, NOMA must also manage the trade-off between spectral gain and receiver complexity. If the power difference between paired users is too small, SIC becomes unreliable and error propagation may reduce the expected capacity gain. If the power difference is too large, near users may experience unnecessary rate loss and the system may become unfair. Therefore, user pairing, power allocation, and decoding order should be jointly designed with channel conditions and service requirements. Table 1 compares Massive MIMO and NOMA from

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the perspective of 6G wireless access and shows why their integration is attractive but technically demanding.

Table 1. Comparison of Massive MIMO and NOMA in 6G wireless access

Aspect	Massive MIMO	NOMA	Convergence implication
Resource domain	Uses the spatial domain through large antenna arrays and directional beams.	Uses the power domain by superposing user signals on the same resource block.	Spatial and power resources can be jointly reused for higher access capacity.
Main mechanism	Channel estimation, beamforming, and spatial multiplexing.	Power allocation, signal superposition, and SIC decoding.	Beam design and power control must be coordinated rather than optimized separately.
Primary advantage	Improves spectral efficiency, coverage, and multi-user throughput.	Improves connection density and edge-user service fairness.	The combined system can support dense users with stronger edge performance.
Critical requirement	Accurate channel state information and calibrated antenna arrays.	Reliable user pairing and sufficient received-power difference.	Integrated scheduling must consider CSI, mobility, traffic type, and interference.
Main risk	Pilot overhead, hardware impairment, and beam misalignment.	SIC error propagation and unfair power allocation.	The convergence gain may disappear without intelligent resource management.

3. Current challenges and solutions for 6G convergence technologies

The convergence of Massive MIMO and NOMA can combine spatial-domain and power-domain gains, but it is not a simple stacking of two technologies. In wide-area 6G networks, distributed access points, high-frequency deployment, and large user density create new coordination problems that must be addressed before the integrated system can be commercially reliable.

3.1. Core technical challenges

First, asynchronous interference and cross-link interference become serious in cell-free or non-cellular networks. When signals from different transmit-receive points reach a user with different propagation delays, the delay may exceed the cyclic prefix and create inter-carrier interference. At the same time, dense cooperation among many distributed nodes produces complicated cross-links between access points and users, making traditional interference suppression insufficient [4, 8].

Second, the system must balance channel information overhead with calibration accuracy. Massive MIMO beamforming and NOMA power allocation both rely on accurate CSI, but dense users and distributed access points require many pilot exchanges. Reducing pilots lowers overhead but also weakens calibration accuracy, user pairing, and SIC performance. This trade-off is especially difficult in ultra-large-scale or near-field MIMO channels, where spatial non-stationarity becomes more visible [9, 10].

Third, high-frequency deployment makes coherence maintenance more difficult. Millimetre-wave and terahertz links can provide high data rates, but they are sensitive to blockage, phase noise, hardware impairment, and beam misalignment. These issues affect Massive MIMO beamforming and NOMA signal separation at the same time, so 6G systems above 6 GHz need stronger channel modelling, synchronization, and link adaptation support [11].

These three challenges are closely coupled. Interference affects the accuracy of channel estimation, inaccurate channel estimation weakens beamforming and power allocation, and weak

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beamforming further increases interference for SIC decoding. Furthermore, it is anticipated that 6G services would be diverse. Holographic communication may require stable high-throughput links, industrial control may require extremely low latency and reliability, and massive IoT may require low-cost access for many devices. A single optimization target is therefore insufficient. Capacity, fairness, latency, energy efficiency, and robustness should all be assessed simultaneously for the converged system.

3.2. Key solutions and supporting cutting-edge technologies

Figure 3 summarises the relationship between the main convergence challenges and the supporting technologies that can help solve them. The solution path should combine virtual network modelling, intelligent resource control, and environment-aware link optimization.

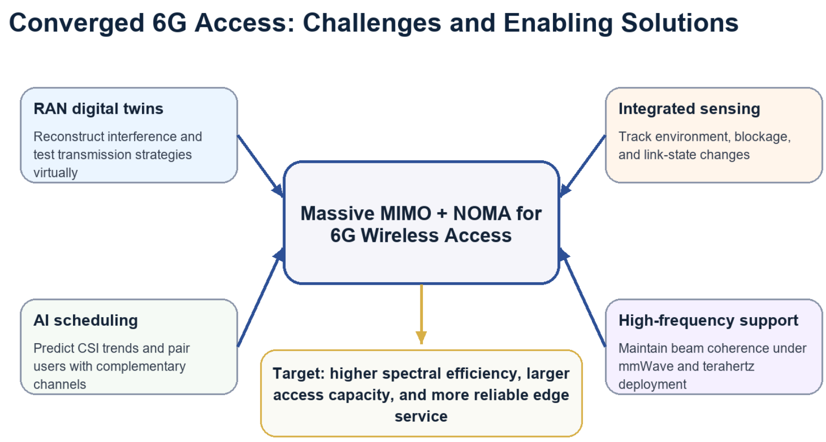

Figure 3. Enabling technologies for Massive MIMO-NOMA convergence in 6G

First, RAN digital twins can reconstruct interference and optimize transmission strategies before applying them to the physical network. By combining ray tracing, statistical channel modelling, and measurement data, a digital twin can map access-point locations, user distribution, and interference paths. This enables safer testing of Massive MIMO beam directions and NOMA power allocation strategies. The value of the digital twin is not only visualization; it also creates a low-risk environment for comparing scheduling decisions under different traffic loads, mobility patterns, and blockage conditions.

Second, AI-assisted distributed scheduling can reduce CSI overhead and improve user pairing. Machine learning models can learn channel variation from historical data, predict CSI trends, and reduce unnecessary pilot transmission. They can also match users with complementary channel conditions, improving NOMA SIC performance and Massive MIMO spatial multiplexing efficiency.

Third, integrated sensing and communication can support high-frequency links by giving the network real-time environmental awareness. Sensing information about blockage, mobility, and link quality can guide beam tracking, phase calibration, backup link preparation, and dynamic power allocation. Joint beamforming and resource allocation for integrated sensing, communication, and computation is therefore an important direction for 6G access convergence [12].

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4. Conclusion

Massive MIMO and NOMA are two complementary technologies for 6G wireless access. Massive MIMO expands the spatial dimension through large antenna arrays, beamforming, and spatial multiplexing, which improves spectrum efficiency, capacity, coverage, and reliability. NOMA expands the power dimension through signal superposition and SIC decoding, which improves access density and edge-user service. When they are combined, a 6G network can use both spatial and power resources more efficiently, making the integration valuable for dense, high-capacity, and intelligent wireless scenarios. This paper finds that the convergence of the two technologies is promising but still constrained by three main problems: asynchronous and cross-link interference in wide-area non-cellular networks, the conflict between CSI acquisition overhead and calibration accuracy, and the difficulty of maintaining coherent transmission in high-frequency bands. The proposed directions, including RAN digital twins, AI-assisted scheduling, and integrated sensing and communication, can reduce these constraints by improving interference reconstruction, resource allocation, channel prediction, beam tracking, and link adaptation.

However, this paper does not provide simulation results, hardware testing, or quantitative comparison across different network scenarios. Future work should build system-level simulation models, evaluate Massive MIMO-NOMA performance under realistic mobility and channel conditions, and compare AI-based algorithms with conventional optimization methods. More recent literature and experimental data should also be included as 6G prototypes mature. Future studies may further examine energy consumption, security, hardware cost, and interoperability with satellite, aerial, and terrestrial access networks. These improvements would make the analysis more measurable and provide stronger support for practical 6G wireless network design.

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