



Performance Evaluation of MIMO Techniques for Next-Generation Wireless Communication Systems

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Abstract

Multiple-input multiple-output (MIMO) transmission is a central mechanism for increasing the reliability, spectral efficiency, and peak data rate of modern wireless networks. This methodology paper evaluates how antenna scaling changes the achievable performance of wireless links and connects classical MIMO principles with the requirements of next-generation 5G/6G systems. A simulation-based framework is developed for SISO, 2×2 , 4×4 , and 8×8 configurations over independent Rayleigh flat-fading channels. Equal power allocation and perfect receiver channel-state information are assumed, while ergodic capacity, lower-tail capacity, and outage probability are used as the principal performance measures. Twenty thousand independent channel realizations are generated at SNR values from 0 to 20 dB. The results show a strong and nearly proportional capacity increase with the number of spatial dimensions under ideal uncorrelated fading: at 10 dB, mean capacity increases from about 2.91-bit/s/Hz for SISO to 5.54-, 10.93-, and 21.81-bit/s/Hz for 2×2 , 4×4 , and 8×8 MIMO, respectively. The analysis also shows that additional antennas reduce outage risk by hardening the distribution of achievable rates. These findings support the use of spatial multiplexing, large arrays, and adaptive beamforming in next-generation networks while emphasizing that practical gains depend on channel correlation, channel estimation, radio-frequency complexity, and interference management.

Introduction

The rapid growth of mobile traffic has made the spatial dimension of the radio channel as important as bandwidth and transmit power. In a conventional single-input single-output (SISO) link, only one transmitted signal and one received observation are available in each time-frequency resource. MIMO instead uses multiple antennas to create parallel spatial channels, provide diversity against fading, or form directional beams. The fundamental capacity studies of Foschini and Gans (1998) and Telatar (1999) established that, under rich scattering and suitable signal processing, capacity can increase approximately with the minimum number of

transmit and receive antennas rather than only logarithmically with power. This property became one of the key theoretical reasons for the adoption of MIMO in broadband wireless standards.

MIMO techniques can pursue different objectives. Space-time diversity methods improve reliability by transmitting structured replicas across antennas and time; the two-branch scheme proposed by Alamouti (1998) is the best-known example. Spatial multiplexing increases throughput by sending independent data streams simultaneously, whereas precoding and beamforming shape the transmitted signal toward desired users or propagation paths. As

wireless systems moved toward 5G, the number of antennas became much larger, motivating massive MIMO, multiuser precoding, and millimeter-wave beamforming. Andrews et al. (2014) identified large antenna arrays and high carrier frequencies as core 5G ingredients, while later 6G visions continued to treat multi-antenna transmission as an enabling physical-layer technology (You et al., 2021).

Performance evaluation is therefore needed at two levels. First, a controlled channel model is useful for quantifying the ideal scaling law of MIMO capacity and outage. Second, the results must be interpreted in the context of implementation constraints, because additional antennas also require channel estimation, RF chains, calibration, signal processing, and interference control. The objective of this paper is not to claim a particular hardware prototype performance; instead, it develops a transparent Monte Carlo methodology that can be reproduced and extended for different antenna sizes, propagation assumptions, precoders, and channel-estimation errors. The selected methodology makes the capacity gain from spatial dimensions directly observable and provides a baseline against which more realistic next-generation wireless designs can be evaluated.

The study addresses three questions: (i) how rapidly does ergodic capacity grow when symmetric MIMO arrays are scaled from 1×1 to 8×8 , (ii) how does antenna scaling affect the lower tail of the capacity distribution and outage probability, and (iii) what practical factors prevent ideal capacity scaling from being obtained in deployed systems? These questions

are relevant to conventional point-to-point MIMO, multiuser massive MIMO, and high-frequency systems where beamforming is necessary to overcome propagation loss.

Literature Review

Early MIMO literature established both diversity and multiplexing benefits. Alamouti (1998) demonstrated a simple orthogonal transmit-diversity technique that provides diversity without transmitter feedback or bandwidth expansion. Foschini and Gans (1998) showed that multi-element arrays can produce large capacity gains in fading channels, and Telatar (1999) derived capacity expressions for multi-antenna Gaussian channels. These studies form the analytical basis for the determinant-based capacity model used in the present methodology. The research direction later shifted toward very large arrays and multiuser transmission. Marzetta (2010) showed that base stations with very large antenna counts can suppress uncorrelated noise and fast fading asymptotically, although pilot contamination becomes an important limitation. Rusek et al. (2013) summarized the opportunities and challenges of very large arrays, including channel estimation, signal processing, and hardware architecture. Ngo, Larsson, and Marzetta (2013) quantified major energy- and spectral-efficiency improvements for large multiuser MIMO systems using linear receivers. Larsson et al. (2014) subsequently positioned massive MIMO as a practical next-generation wireless technology with favorable power scaling and simple linear processing under suitable operating conditions.

Table 1. Selected literature supporting the evaluation framework

Study	Technique / focus	Key contribution	Use in this paper
Alamouti (1998)	Transmit diversity	Orthogonal two-antenna diversity	Reliability context
Foschini & Gans (1998)	Spatial MIMO	Capacity limits with multiple antennas	Capacity motivation
Telatar (1999)	Information-theoretic MIMO	Multi-antenna Gaussian channel capacity	Capacity equation
Marzetta (2010)	Massive MIMO	Very large base-station arrays	Scaling interpretation
Ngo et al. (2013)	Multiuser massive MIMO	Energy/spectral-efficiency trade-offs	Next-gen context
El Ayach et al. (2014)	Hybrid mmWave MIMO	Sparse RF/baseband precoding	Hardware context
You et al. (2021)	6G vision	Multi-antenna technology for 6G	Future relevance

At millimeter-wave frequencies, MIMO design is strongly connected to beamforming because propagation loss is high and fully digital RF chains may be costly. Rappaport et al. (2013)

demonstrated the feasibility of directional millimeter-wave cellular links, and El Ayach et al. (2014) proposed spatially sparse hybrid precoding that approximates fully digital

processing with fewer RF chains. These results are important because the theoretical capacity of an 8×8 or larger array does not automatically translate into practical throughput when hardware constraints restrict the number of simultaneously processed streams.

The broader 5G literature emphasizes that MIMO must be considered together with densification, spectrum, and interference. Andrews et al. (2014) described unprecedented antenna counts as part of the 5G paradigm shift. Björnson, Larsson, and Marzetta (2016) addressed common misconceptions about massive MIMO and stressed that array size, processing complexity, propagation, and deployment assumptions must be treated carefully. Björnson, Hoydis, and Sanguinetti (2018) further showed that massive-MIMO capacity need not be fundamentally bounded by pilot contamination when spatial correlation and improved multicell processing are exploited. For 6G, You et al. (2021) identified multi-antenna technologies, cell-free architectures, and new air-interface mechanisms among major enabling directions. Collectively, these studies justify a methodology that first establishes ideal spatial scaling and then discusses the gap between ideal and deployable performance.

Methodology

1. Research Design

A quantitative simulation design is adopted. Each wireless link is modeled as a narrowband, flat-fading MIMO channel with independent complex Gaussian coefficients. Four symmetric antenna configurations are evaluated: 1×1 SISO, 2×2

MIMO, 4×4 MIMO, and 8×8 MIMO. The symmetric cases isolate the effect of increasing the number of spatial degrees of freedom and provide a clear progression from a conventional single-antenna link to a moderately large array. The results are intended as a reference baseline, not as a complete 5G or 6G system-level simulation.

2. Channel and Signal Model

For a system with N_t transmit and N_r receive antennas, the received complex baseband vector is represented as $y = Hx + n$, where H is the $N_r \times N_t$ channel matrix, x is the transmitted vector, and n is circularly symmetric complex Gaussian noise. Every entry of H is generated independently as $CN(0,1)$, representing rich-scattering Rayleigh fading. The transmitter has no instantaneous channel-state information and distributes power equally among transmit antennas; the receiver is assumed to know H perfectly. These assumptions correspond to a commonly used capacity benchmark and directly align with the classical multi-antenna capacity analysis of Telatar (1999).

$$C = \log_2 \det [I_{N_r} + (\rho/N_t) H H^H] \text{ bit/s/Hz}$$

Here ρ is the average received SNR in linear scale, I is the identity matrix, and H^H is the Hermitian transpose. The instantaneous capacity is evaluated for each random channel realization. Ergodic capacity is then estimated by averaging over all realizations. Because no water-filling or transmitter-side adaptation is used, the comparison reflects gains obtainable from the spatial channel itself under equal power allocation.

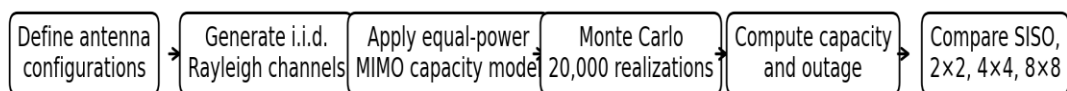


Figure 1. Simulation-based methodology for MIMO performance evaluation.

3. Compared MIMO Techniques and Interpretation

The numerical experiment compares antenna configurations rather than a specific commercial detector. The 1×1 case provides the baseline. The 2×2 and 4×4 cases represent conventional spatial multiplexing dimensions common in broadband links, while the 8×8 case represents a larger-array transition toward next-generation operation. Diversity-oriented STBC is discussed as an alternative when reliability is more important than multiplexing rate, whereas massive MIMO extends the array concept to many base-station antennas and many users. Hybrid beamforming is treated as a practical implementation option for millimeter-wave

systems, following the sparse-precoding principle of El Ayach et al. (2014).

4. Simulation Procedure

The procedure is executed with a fixed random seed to make the numerical results reproducible. For each antenna configuration, 20,000 statistically independent channel matrices are generated. Capacity is evaluated at SNR values of 0, 5, 10, 15, and 20 dB. For every SNR, the sample mean provides the ergodic-capacity estimate. The 10th-percentile capacity is reported as a lower-tail robustness measure. Outage probability is defined as the fraction of channel realizations whose instantaneous capacity falls below a selected target rate. Two illustrative

targets, 4- and 8-bit/s/Hz, are used in the analysis. This process is repeated independently for every antenna size.

5. Performance Metrics and Analysis Logic

Three complementary metrics are used. Ergodic capacity measures long-term average spectral efficiency and is the principal indicator of multiplexing gain. The 10th-percentile capacity characterizes performance under unfavorable

fading without focusing only on the absolute worst case. Outage probability measures the likelihood that a fixed target service rate cannot be supported. The results are interpreted in terms of spatial degrees of freedom, channel hardening, and practical implementation cost. A favorable result therefore means not only a larger average capacity but also a narrower lower tail and a reduced probability of failing a target rate.

Table 2. Simulation parameters

Parameter	Value / assumption
Antenna configurations	1×1, 2×2, 4×4, 8×8
Channel model	Flat i.i.d. Rayleigh fading, $H_{ij} \sim \text{CN}(0,1)$
Receiver CSI	Perfect
Transmitter CSI	Not used; equal power allocation
SNR range	0, 5, 10, 15, 20 dB
Monte Carlo samples	20,000 independent channel realizations
Primary metric	Ergodic capacity, bit/s/Hz
Robustness metrics	10th-percentile capacity; outage probability
Outage targets	4- and 8-bit/s/Hz

Results

The Monte Carlo results show a strong capacity increase as the number of antennas rises. At 10 dB, the mean capacities are 2.91-, 5.54-, 10.93-, and 21.81-bit/s/Hz for 1×1, 2×2, 4×4, and 8×8, respectively. Relative to SISO, the 2×2 system provides approximately 1.91 times the mean capacity, the 4×4 system about 3.76 times, and the 8×8 system about 7.50 times under the assumed independent channel model. At 20 dB the same scaling trend remains, with mean capacities of 5.88-, 11.28-, 22.11-, and 43.97-bit/s/Hz. The near-proportional increase illustrates the multiplexing benefit predicted by foundational MIMO capacity theory (Foschini & Gans, 1998; Telatar, 1999).

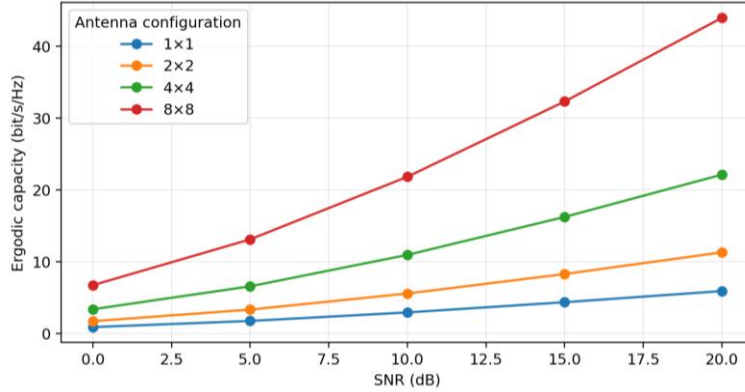


Figure 2. Ergodic capacity versus SNR for the evaluated antenna configurations.

Table 3. Simulated ergodic capacity (bit/s/Hz)

Config.	0 dB	5 dB	10 dB	15 dB	20 dB
1×1	0.86	1.72	2.91	4.33	5.88
2×2	1.68	3.30	5.54	8.26	11.28
4×4	3.35	6.54	10.93	16.21	22.11
8×8	6.70	13.08	21.81	32.30	43.96

The lower-tail results improve even more clearly with antenna scaling. At 10 dB, the 10th-percentile capacity is approximately 1.03-bit/s/Hz for SISO, 3.89 for 2×2, 9.30 for 4×4, and

20.18 for 8×8. For a 4-bit/s/Hz target at 10 dB, the estimated outage probability is roughly 77.7% for SISO but only about 11.9% for 2×2; in the 4×4 and 8×8 cases it is effectively zero within

the 20,000-sample experiment. This behavior reflects both additional spatial degrees of freedom and increasing concentration of aggregate channel gain. In practical massive-MIMO terminology, the latter trend is related to channel hardening, although real propagation correlation and imperfect CSI can weaken the effect (Larsson et al., 2014; Björnson et al., 2016).

Discussion

The numerical results confirm that multiple antennas can transform the capacity and reliability of a fading wireless link. Under independent Rayleigh fading and equal power allocation, the average capacity increases almost in proportion to the number of balanced transmit-receive dimensions. The 8×8 case delivers roughly seven and a half times the SISO capacity at 10 dB while simultaneously moving the lower tail of the capacity distribution far upward. Thus, spatial multiplexing is not only an average-throughput mechanism; when several independent propagation dimensions are combined, it also makes high-rate operation less sensitive to individual deep fades.

These ideal results should not be interpreted as guaranteed field performance. Correlated antennas, limited scattering, line-of-sight dominance, mutual coupling, RF impairments, quantized converters, and imperfect channel estimates can reduce the rank and usable singular values of H . In multiuser networks, pilot overhead and interference also grow in importance. Marzetta (2010) identified pilot contamination as a central issue in early massive-MIMO analysis, while later work showed that improved spatial modeling and multicell processing can remove some apparently fundamental limits (Björnson et al., 2018). Therefore, next-generation MIMO performance depends as much on accurate channel acquisition and interference management as on the physical antenna count.

The comparison also illustrates why different MIMO techniques coexist. If a link is power-limited or must achieve extremely low error rates, diversity transmission such as the Alamouti method can be preferred because it spends spatial resources on reliability rather than independent streams (Alamouti, 1998). If the channel supports multiple well-conditioned spatial modes and traffic demand is high, spatial multiplexing provides much greater spectral efficiency. At a base station serving many terminals, massive MIMO uses a large excess of antennas to create array gain and user separation, with studies showing favorable energy and spectral efficiency using linear processing (Ngo et al., 2013). At millimeter-wave

frequencies, directional beamforming is indispensable and hybrid precoding offers a way to obtain array gain without dedicating a complete high-cost RF chain to every antenna (Rappaport et al., 2013; El Ayach et al., 2014).

From a 5G/6G perspective, the methodology provides a useful baseline for more detailed experiments. Andrews et al. (2014) linked 5G evolution to unprecedented antenna counts and high-frequency operation, and You et al. (2021) placed multi-antenna transmission within a broader 6G architecture that includes intelligent, cell-free, and heterogeneous networks. Future extensions of this study should therefore add antenna correlation, Rician fading, mobility, imperfect CSI, multiuser precoding, hybrid beamforming constraints, and energy consumption per RF chain. A second useful extension would compare linear detectors such as MRC, ZF, and MMSE and directly evaluate BER alongside spectral efficiency.

Conclusion

In conclusion, the study demonstrates through a reproducible Monte Carlo framework that MIMO antenna scaling provides large gains in ergodic capacity and substantial reductions in outage under rich-scattering conditions. At 10 dB, moving from 1×1 to 8×8 increases mean capacity from about 2.91 to 21.81-bit/s/Hz, while the lower-tail capacity improves even more sharply. These results are consistent with the theoretical foundations of MIMO and explain why spatial multiplexing, massive arrays, and beamforming are central to next-generation wireless systems. The most important engineering implication is that antenna count alone is not a sufficient design criterion: practical systems must balance multiplexing gain, diversity, CSI quality, processing complexity, RF hardware cost, and propagation characteristics. The proposed methodology can serve as a compact benchmark for subsequent studies that introduce these real-world constraints.

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