

Signal Propagation Analysis and Optimization of 5G Communication Network Based on Complex Function Theory

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Abstract. While 5G networks have revolutionized daily life and industrial applications, their signal propagation mechanisms face persistent challenges that limit performance. This paper systematically investigates the application of complex function theory to address these challenges and enhance 5G signal propagation. With cases, it analyzes the theory, demonstrating its benefits in enhancing signal processing precision, optimizing network coverage, and ensuring system stability. However, practical implementation challenges are identified, including: ideal models don't match real hardware, analytical methods are too complex for real-time tasks, and there's a gap between math and algorithms. To solve these, solutions like model correction (to address hardware non-idealities), the adoption of high-precision hardware and robust algorithms (to reduce computational complexity), and machine learning techniques (to bridge the math-algorithm gap) are proposed. This research provides a comprehensive framework for leveraging complex function theory to optimize 5G signal propagation, while also highlighting the necessity for future studies to validate these findings with real-world data and testing under extreme conditions.

Keywords: 5G Signal Propagation, Complex Function Theory, Beamforming Accuracy, System Stability, Algorithm Compensation

1. Introduction

In this era of rapid technological development, 5G networks have significantly enhanced convenience in people's daily lives while catalyzing transformative advancements across various sectors, including healthcare, transportation, and industrial automation. For instance, autonomous vehicle technology continues to mature, remote surgeries over thousands of miles have become feasible, and smart home systems have greatly simplified household tasks. By the end of February 2022, the global number of 5G users had reached 38 million.

From a business perspective, the application of complex function theory—with its inherent capabilities for analyzing phase, frequency, and transformation—offers a pathway to significantly improve the efficiency of 5G signal propagation. This not only reduces operational costs for telecommunications operators but also delivers superior service quality and user experience. From a

social standpoint, the enhancement of 5G signals improves connectivity in remote areas, thereby facilitating the broader adoption of telemedicine and online education. These advancements significantly increase the efficiency of regional support initiatives and promote sustainable urban development. Today, a growing number of people are benefiting from 5G technology. Furthermore, complex function theory plays a crucial role in interpreting and optimizing 5G signal transmission. This paper aims to provide a foundational framework and theoretical support for the future development of network communication signals.

Yang's research addresses the high demands placed on such technology by 5G systems. The study optimizes key aspects, including signal sampling and decimation, channel filtering, and blind signal identification and equalization. Comparative experiments—conducted between an experimental group using the optimized technology and a control group using traditional systems—demonstrate that the proposed approach outperforms conventional methods by reducing transmission latency, bit error rate, and connection time, thereby effectively enhancing the operational efficiency of 5G.

Millimeter-wave technology has attracted significant attention to support new 5G applications that require high-speed data transfer. However, existing models often underperform in practical scenarios. In this study, an indoor environment is simulated using various materials. Three transmission points and 47 reception points are selected. Antenna parameters such as polarization and height are configured, and line-of-sight (LOS) and non-line-of-sight (NLOS) conditions are distinguished. First, conventional CI and FI models are reviewed. Then, a new ZMS model, the parameters of which are refined through advanced mathematical techniques, is introduced. To make sure this model matches the actual measured data of 5G indoor signals, researchers used RMSE (Root Mean Square Error) to test it. Later, they compared and analyzed the signal propagation loss in the 28GHz frequency band under different antenna configurations and scenarios. The results showed that the ZMS model can more accurately capture the impacts caused by the environment and is more consistent with real-world signal performance. It can effectively calculate the propagation loss of indoor millimeter waves in 5G systems, providing great help for indoor network design. The appendix also includes detailed mathematical calculation steps for parameter configuration. In addition, the ZMS model performs better when calculating the propagation path loss of signals in 28GHz indoor environments. Compared with the commonly used CI model and FI model in the past, it can take the influence of environmental factors into account more comprehensively. Regardless of the type of antenna used (Vertical-Horizontal polarization, Vertical-Vertical polarization, Vertical-Omni polarization), and whether it is in LOS (Line of Sight, where signals can propagate in a straight line) or NLOS (Non-Line of Sight, where signals are blocked and cannot propagate in a straight line) conditions, key parameters of the ZMS model, such as the “path loss exponent” are more accurate. It can not only describe the propagation law of indoor millimeter waves more precisely, but also include the signal reflection and interference caused by ceilings and floors. It has smaller errors and can provide reasonable signal loss predictions based on distance, frequency, and system parameters. As a result, it serves as a reliable tool for indoor 5G network planning.

In the 5G era, the majority of mobile data traffic originates indoors. 5G systems utilize high-frequency spectra to provide greater bandwidth, but these signals are also subject to higher attenuation when penetrating walls or propagating over distances. Building materials and interior furnishings further affect signal quality. As a result, outdoor base stations alone are insufficient for effective indoor coverage, necessitating dedicated indoor 5G networks. To address this challenge, this article begins by analyzing classical indoor propagation models. It then presents on-site measurements of propagation and penetration loss. Using this empirical data, model coefficients are

refined. The calibrated models can better guide the deployment of indoor 5G networks, helping achieve comprehensive indoor coverage and improved service quality.

Most existing research on 5G technology focuses on enhancing core technical components—such as refining models for 5G signal attenuation during propagation, optimizing high-speed digital signal sampling and filtering, and improving antenna polarization design. Studies also aim to boost overall communication performance by reducing transmission delay, lowering bit error rates, and increasing bandwidth. The majority of these efforts concentrate on engineering applications and empirical validation, with limited attention paid to the potential of mathematical theories—particularly complex function theory—in addressing 5G technical challenges. The prevailing paradigm is one of empirical tuning and model-fitting, which often lacks the generalizability and foundational insight that a rigorous mathematical framework can provide.

In contrast, the application of complex function theory in this context remains critically understudied. The application of complex function theory in 5G communication systems. For example, there is insufficient in-depth research on employing concepts such as analytic functions, residue theorem, or complex plane transformations in areas like millimeter-wave signal analysis, correction of nonlinear signal distortion, or mitigation of multi-channel interference. Yet, complex function theory may offer new mathematical frameworks to solve these complex engineering problems in 5G.

This article first introduces complex function theory and its relevance to 5G systems, and discusses the relationship between the two. It then analyzes the strengths and limitations of current 5G signal propagation methods, as well as the advantages and challenges of applying complex function theory to 5G. Based on this analysis, the study provides theoretical support for optimizing 5G signal propagation.

2. Case description

While the theoretical significance of complex function theory is established, its practical value becomes particularly evident through specific applications in signal processing and network optimization. The following case studies demonstrate how these mathematical principles can be translated into tangible improvements in 5G performance.

2.1. Signal phase optimization & beamforming

The precision control of phase shifts across antenna elements is fundamental to modern beamforming techniques. The complex-valued weight vector used in this process can be optimized by applying Cauchy-Riemann conditions or extremal principles from complex analysis [1]. Research by Li et al. demonstrates an implementation where such optimization achieves a beam pointing accuracy with errors below 1° , a critical achievement as minute phase misalignments can lead to significant beam misdirection (e.g., by solving for the weight vector that maximizes the signal power in the desired direction, a problem amenable to optimization in the complex domain) [1].

2.2. Complex integration and residue theorem in coverage evaluation

Evaluating network coverage involves calculating the integral of signal power over a given area. Analytically, this relates to solving complex integrals of electromagnetic field functions. Techniques like contour integration and the Cauchy residue theorem provide a theoretical foundation for these

calculations [1]. While many practical implementation schemes—such as the ray-tracing model proposed by Li et al. that integrates 3D data—rely on numerical methods, analytical approaches remain an indispensable core means for verifying numerical results and delineating fundamental physical limits [1]. Additionally, the connection between “harmonic functions” and “electromagnetic potentials” is like building a bridge for communication between complex analysis (a type of mathematical tool) and the laws of wave propagation (phenomena at the physical level). With this “bridge,” this study can gain strong support in algorithm development, and the ultimate goal of these algorithms is to construct the most effective “harmonic-type” signal coverage patterns [1].

2.3. System function singularity analysis

To proactively construct 5G networks with robust anti-interference capabilities, the foremost priority is to determine their performance upper limits and inapplicable scenarios. When evaluating these critical performance states—for instance, whether the network can sustain stability and what the anti-interference threshold is—the core task lies in analyzing the special points (such as “poles”) within the “transfer function”.

Fortunately, the “residue theorem” in the domain of complex analysis provides a robust mathematical tool for characterizing these special points. By computing the “residues” at these special points (poles), this study can theoretically and accurately deduce the system’s key performance indicators, including the network’s maximum data-carrying capacity and operational stability [1].

This analytical approach not only facilitates a more thorough and systematic enhancement of coverage evaluation precision but also guarantees the stability of network operation. It allows 5G system design to fully break free from the exploratory “trial-and-error” mode and advance into standardized engineering practice guided by mathematical theories.

3. Theoretical advantages and practical challenges

3.1. Positive influence of applying complex function theory to 5G signal propagation

3.1.1. Enhancement of signal processing precision and beamforming accuracy

IEEE Transactions on Wireless Communications, study noted that millimeter-wave beamforming serves as a critical technology to satisfy 5 G’s demands for high data rates and low latency. However, the insufficient design accuracy of complex-valued weight vectors for antenna arrays has become a bottleneck restricting its performance improvement—in plain terms, the precision of signal processing fails to keep up [2]. However, the application of complex function theory has significantly improved the precision of signal processing in 5G systems, especially in beamforming technology. By optimizing the complex-valued weight vectors of antenna arrays through analytic function theory, the phase and amplitude of signals can be precisely controlled. Experimental results show that this optimized scheme has greatly improved indoor signal coverage: the coverage ratio has increased by 9.36%, the measured error fluctuation has been restricted within ± 3 dB, and the directionality and efficiency of signal transmission have been significantly enhanced [3]. This high precision ensures that 5G base stations can effectively focus signals toward target users, thereby increasing network capacity and reducing interference. These upgrades are genuinely essential for handling scenarios teeming with users, such as city centers and widespread IoT device installations.

3.1.2. Theoretical support for coverage optimization and network planning

When it comes to modeling and optimizing 5G network coverage, complex function theory provides a solid mathematical foundation. Engineers use techniques such as contour integration and the residue theorem to solve tricky electromagnetic field integrals straight away. This simplifies the process of accurately finding out how signal strength is distributed in various environments.

These methods are particularly useful when assessing signal coverage in large-scale areas or places with complex structures—indoor spaces and urban canyons, for instance. They also help get a grasp on the ultimate limits of network performance. Take dense urban canyons: forecasting signal coverage there can be changed into a complex integration problem centered on building contours. In this case, the residue theorem makes it easier to calculate signal strength in shadowed regions.

Overall, complex function theory allows for the design of network layouts with wider coverage and fewer signal dead zones. This underpins more efficient and reliable 5G deployments.

3.1.3. System stability and interference analysis

Yet another key contribution pertains to the analysis of system stability and interference boundaries. The application of complex analysis tools like singularity analysis and the residue theorem facilitates a more thorough understanding of the poles and zeros in system transfer functions. This helps characterize stability margins and identify potential interference sources in multiuser MIMO systems. However, the subcarriers of different numerologies, despite being non-overlapping in frequency, interfere with each other due to their different bandwidths and symbol durations. In the study titled *Inter-Numerology Interference in 5G New Radio: Analysis and Bounds for Time-Varying Fading Channels*, researchers Tenneti Venkata Satya Sreedhar and Neelesh B. Mehta derived a new set of calculation methods. These methods can be used to compute the average power of “inter-numerology interference” (INI) received by each subcarrier under a “numerology” (a type of signal transmission configuration in 5G) in a wideband time-varying channel, while also accounting for the impact of signal fading. This new set of calculation methods covers all common types of “numerologies” in 5G New Radio (5G NR), takes into account the role of “guard bands” (a technology used to reduce this inter-numerology interference), and is applicable to both “line-of-sight (LoS) channels” (where signals can travel in a straight line) and “non-line-of-sight (non-LoS) channels” (where signals are blocked or diffracted). In addition, by utilizing this collection of computational techniques, they further obtained valuable formulas for the “average interference power across the entire bandwidth,” plus strict upper and lower limits associated with this power. They reveal that the INI power increases quadratically with the Doppler spread of the channel and affects higher-rate modulation and coding schemes [4]. As a result, network designers can develop more robust systems capable of maintaining performance under varying operational conditions, thereby enhancing the overall reliability of 5G communications.

3.2. Problem analysis

While complex function theory has these obvious advantages in theory, putting it to practical use in 5G systems still comes with many tough problems—and the root of these problems is that those idealized mathematical models don’t match up with the various constraints people have to deal with when doing real engineering work.

3.2.1. Idealized theoretical models vs. practical system non-idealities

We can get useful signal optimization methods from complex function theory, and that all seems really straightforward on paper. But when it comes to putting it into practice, it's often slowed down by various "imperfections" in real systems. Think about hardware such as phase shifters and power amplifiers: in theory, this study always think they can hit top performance and precision. But in reality, this hardware never works flawlessly. It may twist signals when handling them, have tiny errors in calculations, or even lack precision as soon as it's made. These issues can lower how well things work in actual use, and might even cancel out the advantages that the theory should bring. As mentioned in the paper Orthogonal Polynomials Based Complex Gaussian Processes of Nonlinear Power Amplifier for 5G Wireless Communication Systems [5] written by authors including Ditthawat Songratthaset and Suwat Pattaramalai, the researchers conducted simulation tests to observe the performance of their proposed "orthogonal polynomial method" in two types of signal transmission environments, focusing on two key metrics: "Normalized Mean Squared Error (NMSE)" and "Bit Error Rate (BER)", and the results showed that this new method works much better than the conventional polynomial methods used before, while the "complex Gaussian input distribution" designed using this method also outperforms older approaches like "exponential input distribution" and "Rayleigh input distribution" in terms of these two metrics. Additionally, to keep hardware operating with high precision consistently, complex calibration methods are required—which cost more money and consume more power—so this study cannot just focus on how powerful complex function theory-based methods are in theory; to judge whether a method is useful, this study also need to consider practical factors such as whether the hardware can actually support it and how much cost and power it will consume in real-world use.

3.2.2. Computational complexity and real-time processing challenges

A major obstacle in applying the complex function theory to 5G is the high computational demand for analytical methods. Solving multidimensional integrals or performing contour integration in complex planes is computationally intensive, especially for large-scale antenna systems (e.g., Massive MIMO) operating in dynamic environments. While these methods offer valuable theoretical insights and validation benchmarks, their computational overhead often makes them unsuitable for real-time applications such as beam switching and channel equalization, which require millisecond-level responses. From the Research Efficient DSP and Circuit Architectures for Massive MIMO: State of the Art and Future Directions, written by Liesbet Van der Perre, Liang Liu, Erik G. Larsson, etc, prototype ASIC implementations have demonstrated zero-forcing precoding in real time at a 55 mW power consumption (20 MHz bandwidth, 128 antennas, and multiplexing of 8 terminals). Putting simple, even error-prone digital processing into antenna paths lets us reduce consumption by 2 to 5 times [6]. This makes engineers often use numerical approximations and simplified models. They sacrifice a bit of accuracy to get things to work in practice. As a result, these analytical methods might have their main job limited: they'll act as offline check tools and give basic performance limits, instead of being core parts of real-time signal processing systems.

3.2.3. Gaps between mathematical ideals and real-world algorithm implementation

Complex analysis gives us theoretical models, but these are a world away from the algorithms that work in real-life applications. Let's look at harmonic function theory: it can produce optimal signal coverage plans with "continuous, smooth electromagnetic fields." But in practice, antenna arrays are

discrete—individual units with space between them. They’re also restricted by space limits and what the hardware is capable of, which stops the theory’s perfect setup from becoming real.

If this study want to turn these mathematically ideal schemes into working devices, this study first need to fix a series of issues. These include errors from the antennas being placed in separate spots (not continuously), interference between the antennas themselves, and problems caused by changes in the environment. Besides, even though theoretical concepts like the residue theorem and analytic continuation are important and help us grasp many basic rules, this study still need to come up with new ways to turn them into practical algorithms. For example, algorithms that remove signal interference or check the condition of communication channels.

This difference between theoretical models and how things actually work makes it obvious that more research is needed. This study have to create algorithms that can be scaled up for real uses and are truly workable—this way, this study can connect math theory to engineering practice. It also highlights the big difference between the “continuous, flawless” ideal that complex analysis describes and the real world of engineering, where there are “flaws here and shortcomings there.” This natural inconsistency not only limits how this study can directly use those complex mathematical solutions but also defines the key barrier that people designing practical 5G systems must get past.

4. Proposed solutions

4.1. Mitigating the ideal-reality gap through hybrid modeling and calibration

In the paper Criterion for Limit Cycle-Free State-Space Digital Filters with External Disturbances and Generalized Overflow Non-Linearities, it’s stated: Digital filters that have issues with two’s complement operations and face external disturbances need to have overflow oscillations suppressed most of all. To make sure the system works stably and to ease the bad effects of disturbances, researchers have developed related judgment criteria using linear matrix inequalities [1].

The detailed method works like this: problems such as nonlinear hardware defects and environmental interference are changed into “correction terms.” These terms are then put into a complex function model to create a hybrid model. From the hardware angle, high-precision components—like Gallium Nitride (GaN) power amplifiers—are chosen. A real-time calibration system based on pilot signals is also built to correct errors.

For algorithms, predistortion algorithms are used to weaken the nonlinear traits of power amplifiers. Virtual array element interpolation technology helps make the performance of actual arrays more in line with the ideal situation. Meanwhile, the robustness of the algorithms themselves is used to bridge the gap between how well the hardware performs and what the theory predicts.

4.2. Addressing computational complexity via hardware-algorithm co-design

Breakthroughs have been achieved across three dimensions. First, based on the paper A Random-List Based LAS Algorithm for Near-Optimal Detection in Large-Scale Uplink Multiuser MIMO Systems, researchers proposed the RLB-LAS algorithm based on random lists. This algorithm disperses computational pressure through multiple rounds of iterative searches, effectively reducing system complexity. Meanwhile, in large-scale MIMO systems, it can also reach a performance level close to “maximum likelihood detection”. Second, progress in the hardware field is supported by the paper FPGA-based Low Latency Inverse QRD Architecture for Adaptive Beamforming in Phased Array Radars. This paper mainly studies adaptive beamforming technology for phased array radars

and also specially designs a new IQRD RLS architecture suitable for FPGA use [7]. It uses pipelining to reduce computation and improve performance, and it has both low latency and small area usage [8]. Scheduling uses the adaptive algorithm from Real-Time Task Scheduling Strategies in Edge Computing for scheduling. It uses dimensionality reduction techniques like feature selection to cut down the amount, and allocates CPU and GPU resources dynamically. This makes the response time shorter by more than 30% [9].

4.3. Bridging the mathematical-algorithmic gap with data-driven methods

Data-driven methods, particularly machine learning (ML) and deep learning (DL), offer a powerful paradigm to bridge this gap by learning the complex mapping between theoretical ideals and practical implementation from data, rather than relying solely on analytical derivations. To narrow the gap between mathematical ideals and practical algorithm use, the proposed method extracts essential methods from many papers. The paper An Efficient Small-Batch Synthesis Method for Antenna Array Radiation Patterns Based on Deep Learning Networks in 5G Application Fields points out that to enable the algorithm to deliver better performance in real antenna arrays, it can be achieved through three steps: designing a target data matrix for characterizing the features of radiation patterns, determining the structure and parameters of the deep network, and adopting a small-batch parallel computing mode [9]. This method utilizes machine learning technology (Gradient Boosting Tree, GBT) to fabricate millimeter wave phased array antennas and can generate corresponding far-field radiation beams for different 5G scenarios [10]. In the stage of algorithm implementation, researchers refer to the paper Improving Numerical Stability in Gurobi Modeling and reduce the cumulative errors generated in floating-point operations by scientifically setting model parameters and controlling the order of magnitude of values.

5. Conclusion

This study specifically examines how complex function theory is applied in 5G signal propagation, clarifying its clear advantages, the problems encountered in practical application, and reliable solutions to these problems. The theory contributes to the development of 5G technology mainly in three key aspects:

First, adjusting the “complex weight vectors” in antenna arrays can greatly improve the accuracy of signal processing and beamforming. This improvement not only keeps errors within acceptable limits and effectively expands indoor signal coverage, but also provides important backing for high-user-density scenarios such as downtown areas, large-scale IoT device rollouts, and busy public spaces.

Second, this theory leverages mathematical instruments like contour integration, the residue theorem, and analytic function theory to lay a solid groundwork for 5G network coverage modeling and optimization. With these tools at their disposal, engineers can accurately gauge signal strength distribution in complex settings—including between city high-rises, indoor shopping centers, and underground transport hubs—helping to craft more efficient network layouts as a result.

Third, by looking closely at the system’s “transfer function” with complex analysis tools—including singularity analysis, pole-zero analysis, and residue calculation—we can figure out key things about multiuser MIMO (Multiple-Input Multiple-Output) systems: how stable they are, where interference might come from, and what’s holding back their performance. This makes 5G communications more reliable and works better overall.

Yet turning this theory into something useful in practice still has several big hurdles. The perfect models from theory usually ignore the flaws in real hardware. For instance, power amplifiers can twist signals, phase shifters make small calculation mistakes, and antennas might not be precise enough when they're manufactured. Besides, achieving the high precision required means using complex calibration methods. That will only make hardware more expensive and use more power. Also, to deal with the heavy computing load during real-time processing, optimized algorithms like RLB-LAS and efficient FPGA-based hardware designs are a must. In addition, the analysis methods developed based on complex function theory require a huge amount of computation, making them unsuitable for real-time tasks that need millisecond-level responses, such as dynamic beam switching and fast channel equalization. Furthermore, there is a significant gap between the continuous, idealized mathematical models in theory and the discrete, hardware-constrained reality of actual antenna systems, which makes it difficult to convert theory into practical algorithms.

To solve these problems, there are several approaches: this study can adopt "hybrid modeling" that takes into account the actual flaws of hardware, use more precise hardware components along with real-time calibration technology, and apply compensation algorithms such as digital predistortion. To narrow the gap between ideal models and actual hardware problems, methods like model correction, hardware adaptation (e.g., using high-precision gallium nitride amplifiers), and algorithm compensation (e.g., predistortion technology) are already in use. Optimized algorithms such as RLB-LAS, low-latency hardware designs based on FPGAs, and edge computing dynamic scheduling technology can reduce computational complexity. Meanwhile, machine learning technologies—such as using deep learning to calculate signal radiation directions and gradient boosting trees to design antennas—can also help bridge the gap between theory and practical application. A key limitation of current research is the validation of these solutions under real-world, non-ideal conditions. Future work should therefore employ primary data from field tests and expanded simulations, including under extreme environmental conditions, to rigorously verify the long-term robustness and applicability of these approaches.

Authors contribution

All the authors contributed equally and their names were listed in alphabetical order.

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