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Joint Analysis of Antenna Mutual Coupling and RF Hardware Impairments in Millimeter-Wave Systems

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ABSTRACT

Millimeter-wave communication systems use antenna arrays to get high data rates and send signals in a specific direction. When the antennas are close together, they can affect each other a lot. Also, real radio-frequency parts have problems like phase noise, differences in signal strength, errors in direction, and problems with the amplifiers. These issues can make the quality of the signal worse. Make the communication not work as well, especially when there are a lot of antennas. This paper looks at both the antenna effects and the radio-frequency problems in millimeter-wave systems. A simulation setup is created to show how the antenna effects and the radio-frequency problems work together and how they affect the performance. The setup takes into account distances between antennas, how much they affect each other, and the different types of radio-frequency issues. The performance is checked using Bit Error Rate, Error Vector Magnitude, Signal-to-Interference-Plus-Noise Ratio, and how much data can be sent. A normal model that assumes ideal radio-frequency parts is compared with a model that includes real problems to see how much the performance drops because of real-life issues. The study shows how important it is to look at both the antennas and the radio-frequency parts when designing millimeter-wave communication systems. It can also help create ways to fix problems with the antennas and the radio-frequency parts.

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1. INTRODUCTION

Millimeter-wave or mmWave communication looks very promising for the generation of wireless networks. It gives us bandwidth and lets us send data at very high rates. Because mmWave signals lose a lot of power over distance, people usually use antenna arrays and directional beamforming to keep the link alive. When antenna elements sit close to each other, they can interfere with one another. This mutual coupling changes how each antenna radiates and hurts the quality of beamforming. Research shows that mutual coupling can really hurt the performance of an antenna array [1]. Designers need techniques to cut down on the unwanted interaction between neighboring radiators [2].

Besides antenna problems, real mmWave systems also suffer from radio-frequency (RF) hardware impairments. When a power amplifier is not perfectly linear. When transceivers have small errors left over, the signal gets distorted. This makes beamforming less accurate. Lowers the reliability of the link. Maletic and Grass [3] studied how power amplifier flaws affect mmWave phased-array systems. Their work reminds us that designers must account for hardware limits. Similarly, other studies have looked at how leftover transceiver imperfections impact RF beamforming [4]. All of these studies point to one fact: we must think about realistic hardware characteristics when judging how mmWave systems perform. Though antenna mutual coupling and RF hardware impairments have each been studied, we still need to know how they work together and affect overall performance. Examining them one at a time does not capture what actually happens in a system, where antenna interactions and hardware faults happen at the same time. That is why this paper looks at both antenna coupling and RF hardware impairments together in mmWave systems. The simulation model we built looks at spacing, how strong the coupling is, phase noise, errors in amplitude and phase, and the nonlinearity of the power amplifier. We measure how the system performs by looking at bit error rate, error vector magnitude, signal-to-interference-plus-noise ratio, and the data rate that can actually be achieved. In this study, we compare an ideal system with versions that include antenna mutual coupling, RF hardware impairments, and both together [5].

The goal of this comparison is to see how each kind of imperfection and the combination of them changes the performance of the link. The results give clues for designing better antenna arrays, fixing RF problems, and building mmWave systems that are both reliable and high-performing.

2. LITERATURE SURVEY

Hunukumbure et al. [6] presented performance and impairment modelling for hardware components in millimeter-wave transceivers. Their work focused on modelling practical hardware imperfections and analysing their impact on mmWave communication performance. The study provides a foundation for incorporating realistic RF hardware characteristics into communication system simulations. However, the combined effect of antenna mutual coupling and RF hardware impairments requires further investigation.

Wu et al. [7] investigated hardware impairments in millimeter-wave communication systems using Orthogonal Frequency-Division Multiplexing (OFDM) and Single-Carrier Frequency-Domain Equalization (SC-FDE). Their study considered the influence of practical hardware limitations on transmission performance. The research highlights the importance of evaluating hardware imperfections in mmWave communication systems. However, a unified analysis incorporating antenna mutual coupling alongside RF hardware impairments is needed for more comprehensive performance evaluation.

Prisiceanu et al. [8] studied the effects of mutual coupling on lattice reduction-aided hybrid beamforming in millimeter-wave communication systems. Their work examined how electromagnetic interactions between antenna elements influence beamforming performance. The study highlights the importance of considering mutual coupling when designing efficient mmWave antenna arrays. However, combining antenna coupling models with practical RF hardware impairment models remains a relevant direction for further system-level investigation.

3. PROPOSED METHODOLOGY

The suggested approach offers a simulation-based system for looking at antenna coupling and RF hardware issues in millimeter-wave communication systems. The main goal is to see how antennas affect each other and how real-world hardware problems impact the quality of communication. The system includes an antenna array, a mmWave transmitter and receiver, a channel, and various RF impairment models. The performance of this system is checked against a system to find out how much performance drops because of real-life situations.

3.1 System Model

A mmWave communication system that has many antenna elements at the transmitter is studied. The signal that is sent goes through an antenna array where the elements are close together. Because of this, there is a mutual coupling effect between the elements. This coupling effect is shown using a mutual coupling matrix [8]. The matrix represents how the antennas interact with each other. The signal that comes out is changed by the channel and by problems in the radio frequency hardware. These problems include phase noise, differences in amplitude and phase, and issues from power amplifiers not working. The signal that is received is processed to figure out what data was sent. Various amounts of space between the antennas and different levels of coupling are looked at to see how they affect the quality of the received signal.

3.2 RF Hardware Impairment Modelling

The RF hardware impairment model includes real-world problems that can happen in mmWave transceivers. Phase noise causes changes in the phase of the signal. Amplitude and phase mismatches create differences between what's supposed to be sent and what is actually sent. Power amplifier nonlinearity causes the signal to become distorted, especially when the input power is high. These problems are added to the simulation model one by one, together with antenna mutual coupling. A perfect system that has no antenna coupling and no RF hardware problems is used as a reference to compare performance. This method helps find out how each problem and the combination of problems affect the system performance.

3.3 Performance Evaluation

The proposed framework checks how well a system works by looking at four numbers: Bit Error Rate (BER), Error Vector Magnitude (EVM), Signal-to-Interference-plus-Noise Ratio (SINR), and the maximum data rate that can be reached. BER counts how many bits are wrong in the message. EVM shows how far the received signal points are from where they should be. SINR tells how strong the wanted signal is compared to signals and noise. The data rate shows how fast information can travel under the test conditions. The tests are run for different antenna distances, different levels of coupling, and different strengths of radio-frequency problems. The results are compared for four setups: a system, a system that only has mutual coupling, a system that only has hardware impairments, and a system that has both problems. By looking at the comparison, we can see how the combination of impairments changes the reliability of communication and the speed of data transmission.

Figure 1 shows the proposed architecture, for analyzing antenna mutual coupling and RF hardware impairments in millimeter-wave communication systems. The transmitted signal passes through the antenna array the channel and the receiver while experiencing antenna coupling and practical RF hardware imperfections. The proposed framework evaluates system performance using bit-error-rate, error-vector-magnitude signal-to-interference-plus-noise ratio and the achievable data rate. Finally the results are compared across the scenario, the coupling-only scenario, the

RF-impairment-only scenario and the combined-impairment scenario to understand how each scenario and their combination affect communication performance.

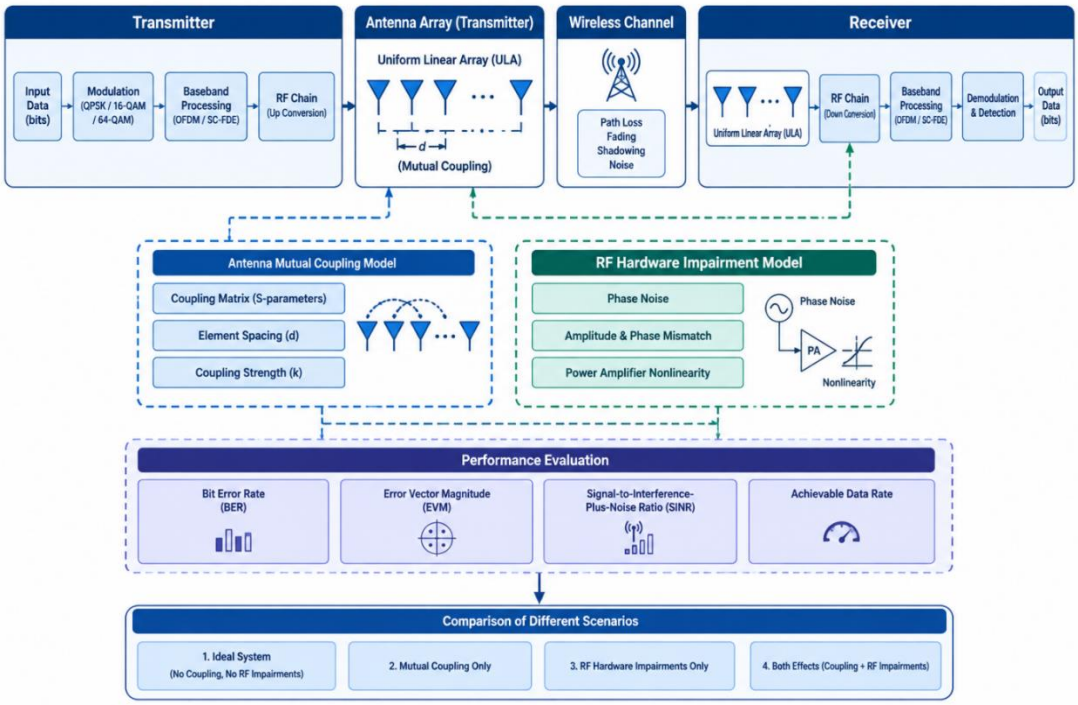


Figure 1. Architecture of the Proposed Joint Analysis of Antenna Mutual Coupling and RF Hardware Impairments in mmWave Systems

4. RESULTS AND DISCUSSION

We evaluate the proposed framework to examine how antenna mutual coupling and RF hardware impairments influence millimeter-wave communication systems. The simulation examines four configurations: a system with no impairments, a system affected only by antenna mutual coupling, a system affected only by RF hardware impairments, and a system affected by both impairments at the same time. We analyze performance using four metrics: Bit Error Rate (BER), Error Vector Magnitude (EVM), Signal-to-Interference-plus-Noise Ratio (SINR), and achievable data rate. These metrics give us a view of signal quality, communication reliability and transmission efficiency across different operating conditions.

4.1 Performance Evaluation

The ideal system acts as a reference model to measure the performance degradation caused by antenna and RF hardware limitations. In this configuration, antenna mutual coupling and hardware imperfections are ignored, leading to better signal quality and stronger communication performance. When we introduce antenna coupling, electromagnetic interactions between adjacent antenna elements alter the array response and reduce beamforming accuracy. Likewise, RF hardware impairments introduce phase variations, amplitude and phase mismatches, and nonlinear distortion, which lower the accuracy of transmission and reception. The performance of the four configurations is compared in Table 1.

Table 1. Performance Comparison Under Different Impairment Conditions

System Configuration	BER	EVM (%)	SINR (dB)	Data Rate (Gbps)
Ideal System	0.001	2.5	25.0	8.5
Mutual Coupling Only	0.008	6.2	20.5	7.4
RF Hardware Impairments Only	0.012	8.1	18.7	6.9
Combined Impairments	0.025	12.4	14.2	5.8

4.2 Bit Error Rate (BER) Analysis

Bit Error Rate measures the number of received bits compared to the total number of transmitted bits. It is a metric for evaluating the reliability of digital communication systems. As shown in Table 1, the ideal system achieves a BER of 0.001, indicating reliable data transmission under impairment-free conditions. When antenna mutual coupling is considered, the BER increases to 0.008 because interactions between antenna elements can change the transmitted signal characteristics and reduce beamforming accuracy.

The system with RF hardware impairments has a BER of 0.012 due to phase noise, amplitude and phase mismatches, and power amplifier nonlinearity. These imperfections add signal distortion and increase the chance of incorrect symbol detection at the receiver. When both mutual coupling and RF hardware impairments are considered together the BER goes up to 0.025. This result shows that the combined effects can greatly reduce communication reliability compared to the system.

4.3 Error Vector Magnitude (EVM) Analysis

Error Vector Magnitude measures the difference between the transmitted symbols and the received or measured symbols. A lower EVM means better modulation quality, while a higher EVM means more signal distortion. The ideal system has an EVM of 2.5%, showing symbol transmission and reception.

When mutual coupling is added, the EVM goes up to 6.2% because electromagnetic interactions between antenna elements affect the array response and signal characteristics. The presence of RF hardware impairments makes the EVM go up to 8.1% because of phase noise gain changes and amplifier nonlinearities. Under impairment conditions, the EVM reaches 12.4%, showing the most signal distortion among the four setups. Therefore, good antenna isolation, RF calibration and impairment compensation are important for keeping quality in real-world mmWave systems.

4.4 Signal-to-Interference-plus-Noise Ratio (SINR) Analysis

SINR is the ratio of the desired received signal power to the interference and noise power. A higher SINR usually supports reliable signal detection and better communication performance. The ideal system has a SINR of 25.0 dB because the model leaves out antenna coupling and RF hardware issues.

The SINR drops to 20.5 dB when only mutual coupling is considered. This happens because coupling can change the antenna response and interfere with the beamforming pattern. When RF hardware impairments are added, the SINR falls to 18.7 dB because of signal distortion and leftover interference. The combined-impairment setup has the SINR of 14.2 dB. This shows

that looking at both effects together is important for understanding real-world mmWave system performance.

4.5 Achievable Data Rate Analysis

The achievable data rate tells how much information is successfully sent per unit time under the system conditions. In general, data rate depends on things like bandwidth, SINR, modulation, coding, and implementation limits. The ideal system gets a data rate of 8.5 Gbps, which's the highest performance among the tested setups. When antenna mutual coupling is added, the data rate drops to 7.4 Gbps because changes in the antenna array response can lower beamforming gain. The system with RF hardware impairments has 6.9 Gbps, showing the effect of distortion on reliable transmission. Under impairment conditions, the data rate falls to 5.8 Gbps. This drop shows how important it is to think about both antenna issues and RF hardware limits when designing a high-speed mmWave Communication System.

The comparison in Figure 2 shows that antenna mutual coupling and RF hardware problems can affect parts of mmWave communication. Mutual coupling mainly changes how the antenna array works and how beams are formed. RF hardware problems add signal issues because of things like phase noise, gain and phase errors, and nonlinearity in amplifiers. When both are present they can cause higher bit error rates and error vector magnitude lower signal to interference plus noise ratio and slower data speeds.

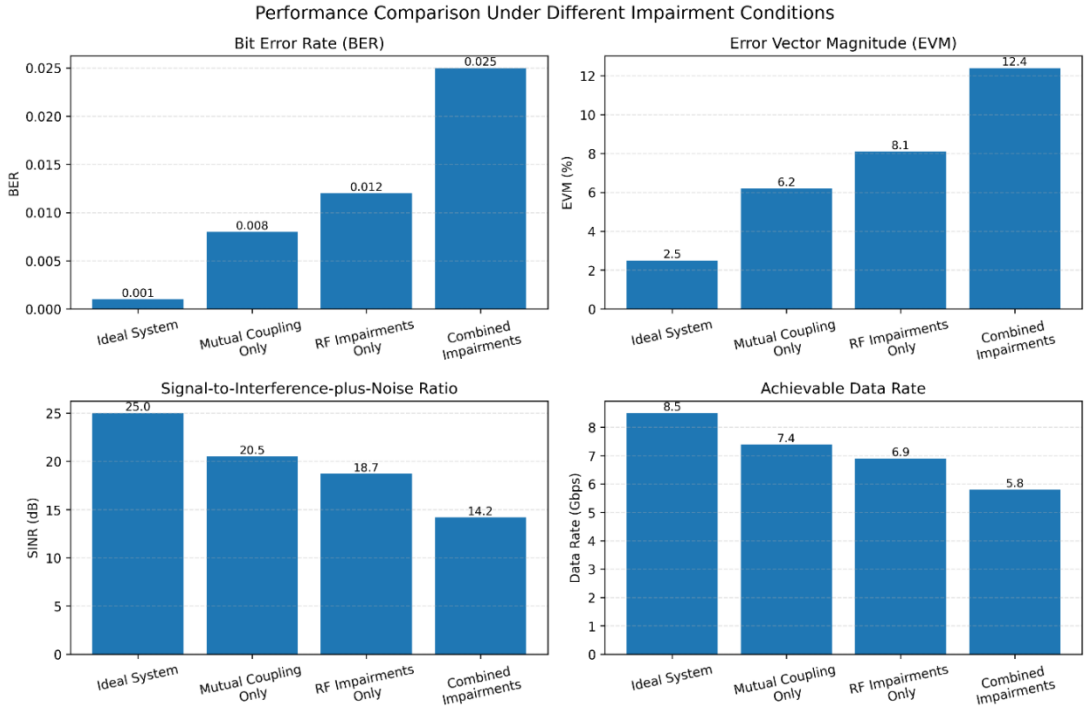


Figure 2. Performance comparison graph

The results also show that the perfect system works best while the one with both problems has the worst performance, among the options looked at. These findings prove that looking at both issues together is important, rather than checking antenna coupling and hardware problems on their own. The framework suggested can be used to study antenna distance, coupling amounts, problem levels, and signal-to-noise situations. These studies can help find antenna setups and ways to fix problems for making next-generation mmWave systems more reliable and efficient.

5. CONCLUSION

This paper talked about looking at how antennas affect each other and how real-life radio frequency hardware isn't perfect in millimeter-wave communication systems. The research looked at how the way antennas interact with each other and how the actual radio frequency hardware isn't perfect can change how well the communication works. A way to test setups was used. The setups included one that was perfect, one that only had antenna effects, one that only had hardware issues, and one that had both. The performance was checked using Bit Error Rate, Error Vector Magnitude, Signal-to-Interference-plus-Noise Ratio, and how fast data can be sent.

The results showed that when antennas are close together, it changes how the antenna array works and how well the beams are aimed. When the radio frequency hardware has problems like phase noise, changes in amplitude and phase, or power amplifier problems, it adds distortion to the signal. When both of these things happen together, the system doesn't work as well as when it's perfect. The results showed that when both are present, the Bit Error Rate and Error Vector Magnitude go up, and the Signal-to-Interference-plus-Noise Ratio and how fast data can be sent go down. These results show that it's important to look at both antenna issues and hardware issues instead of looking at them separately.

The method that was suggested gives a way to understand how real-life millimeter-wave systems work and where improvements can be made. Future work could try beamforming methods, ways to keep antennas from affecting each other, ways to fix hardware problems, and using machine learning to make things better. Testing at different antenna distances, how much they affect each other, different ways to send signals, different levels of noise, and different places to use the system could help understand how the system works better. In the end, looking at both antenna issues and hardware problems together can help make more efficient and better millimeter-wave communication systems for the next generation of wireless networks.

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