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Robust Multi-Objective Hybrid Beamforming Synthesis for Quantized Massive-MIMO Arrays Under Channel Uncertainty

Chen Wei-ting [a], Lin Yu-han [b]

[a] *Department of Electrical Engineering, Ming Chi University of Technology, New Taipei City, Taiwan. E-mail: chen.we.t@mail.mcut.edu.tw,*
[b] *Department of Electrical Engineering, Ming Chi University of Technology, New Taipei City, Taiwan. E-mail: yu.han.l2@mail.mcut.edu.tw*

Abstract

Massive multiple-input multiple-output (MIMO) systems are one of the technologies that enable the next-generation wireless communication networks because they can achieve high spectral efficiency and enhanced link reliability. Nevertheless, there are important challenges of massive-MIMO beamforming architectures in practical implementation due to limits in the hardware, quantizing phase shifters, and error in channel estimation. Beamforming algorithms in the conventional form also presume perfect hardware and channel state information, making the algorithms inapplicable to real deployment situations. This paper presents a high-quality multi-purpose hybrid beamforming synthesis model that can be applied successfully to act in the presence of channel uncertainty and hardware quantization. The suggested solution posits beamforming optimization as a multi-objective problem, which will maximise the spectral efficiency, and minimise the interference leakage and computational complexity at the same time. Synthetic channel environments are created with statistical propagation models that can be used to test the performance of the system without the need to measure performance in real-time metrics over the wireless world. The effect of the quantization of resolution and channel estimation noise on beamforming performance is analysed through simulating a hybrid analogue digital beamforming architecture. The simulation findings illustrate that the proposed framework is better in terms of spectral efficiency and less interference than the traditional beamforming methods. The results emphasize the need to include hardware constraints and channel ambiguity in beamforming optimization models of the next generation wireless communication network.

Keywords: Massive Mimo, Hybrid Beamforming, Channel Uncertainty, Wireless Communication Optimization, Spectral Efficiency.

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Introduction

The wireless communication systems have experienced a tremendous technological development over the recent years due to the rising need of high capacity data transfer and stable connexions within the current networks (Booch et al., 2025). Massive multiple-input multiple-output (MIMO) technology has become a promising approach that can be used to overcome these issues because it allows transmitting multiple streams of data simultaneously with the help of large antenna arrays. Massive-MIMO systems have an opportunity to achieve much more spectral efficiency and signal quality than the traditional communication architectures because they take advantage of the spatial multiplexing and beamforming methods (Papadopoulos et al., 2025). Nonetheless, there are a number of challenges in the application of beamforming techniques in realistic massive-MIMO systems. Hybrid beamforming structures which incorporate both analogue and digital processing are widely used in order to save hardware costs and power consumption. Phase shifters are normally used to steer antenna radiation patterns to specific users in such systems, thereby performing analogue beamforming. The performance of these phase shifters is also limited to resolution making the resulting beam patterns quantized. Moreover, beamforming algorithms are known to be dependent on channel state information (CSI) to make decisions on the best transmission directions. Noise, movement and lack of feedback channels are some of the phenomena that make CSI estimation errors unavoidable in real world wireless scenarios. Such uncertainties can have a profound impact on limiting the performance of the classical beamforming algorithms, which operate on perfect channel knowledge. The ability to design beamforming strategies which are effective despite hardware constraints and channel uncertainty is therefore an important research problem. In this paper a simulation-based beamforming synthesis system will be proposed, which will consider hardware limitations and channel estimation error as a part of a multi-objective optimization problem (Sindhu & Poornimadarshini, 2025). The suggested approach will enhance spectral efficiency and reduce interference and computation cost (Poornimadarshini, 2025).

Literature Review

In the recent years, beamforming techniques research has increased substantially following the increased significance of the massive-MIMO technology in the next-generation wireless networks (Dinesh Kumar, 2025). The initial beamforming techniques concentrated on fully digital systems where every antenna element was linked to a special radio-frequency (RF) chain (Kumar, 2025; Uvarajan, 2024). Even though this arrangement offers the greatest signal processing flexibility, it cannot be applied to large antenna arrays due to its expensive nature and energy usage of a large number of RF chains (Alkhateeb et al., 2015).

Reduced complexity of hardware was therefore proposed by using hybrid beamforming architectures which is a combination of few digital processing units with analogue phase shifters (Palm et al., 2021). Multiple algorithms to design a hybrid beamforming have been proposed using singular value decomposition, iterative optimization, or sparse signal reconstruction (Dinesh Kumar, 2025). The methods usually use perfect hardware parts and channel state information (Veerappan, 2025). Nevertheless, the work of the practical beamforming systems has to be subjected to multiple constraints that restrict their functionality (Lin et al., 2022).

A significant drawback is the fact that quantized phase shifters are employed and it limits the number of potential beam steering angles that the antenna array can produce (Madhanraj, 2025). Simple beamforming algorithms have thus been created to overcome hardware constraints whilst still providing reasonable performance level of the system (Alsharif & Nordin, 2017). Also, hybrid beamforming methods using Kalman have been suggested to enhance beam tracking preciseness in vibrant propagation settings (Suresh Kumar, 2025).

The other limitation is channel estimation errors which arises when the receiver gives feedback on the propagation environment which is not perfect (Mahmood et al., 2022). Effective beamforming models have been constructed to overcome the effects of channel uncertainty through inclusion of optimization algorithms that take into account worst-case errors in channel estimation (Lin et al., 2022). Distributed and massive MIMO systems have also been researched on cooperative beamforming to enhance signal reliability when the channel is imperfect (Anjos et al., 2022).

The limitations have been overcome by recent studies that have tried to use robust optimization methods in the beamforming design (Khwandah et al., 2021). There are some papers that use stochastic optimization to explain the random channel errors in wireless communication channels (Park et al., 2017). Some use machine learning to estimate the beamforming parameters and enhance adaptive signal transmission in changing wireless channels

(Gao et al., 2016). Intelligent signal interpretation and adaptive spectrum analysis have also been performed with the use of machine learning techniques in complex communication conditions (Liang et al., 2021).

Besides improving the algorithms, some research has also examined more sophisticated wireless system architecture to enhance performance of beamforming and communication security (Rahim, 2025). It has also been suggested that adaptive metasurface-based transmission systems can be used to support a dynamic beam steering process and enhance the reliability of millimetre-wave communication (Joshua Reginald, 2025; Patel, 2025). Through these architectures, electromagnetic wave propagation can be intelligently controlled by having programmable hardware surfaces (Barhoumi, 2025).

Other current studies have also examined learning-based optimization of wireless communication and distributed network control (Kebede et al., 2022; Geetha, 2025). To enhance cooperative control and resource coordination of distributed wireless systems, multi-agent reinforcement learning methods have been suggested (Prabhakar, 2025). Learning frameworks based on adaptive resource allocation have also been created using event-driven learning in dynamic wireless communication settings (Salwadkar, 2025; Sindhu, 2025).

Simultaneously, hardware adaptive predictive control architectures have been studied to enable intelligent signal control and systems optimization in real time communication platforms (Velliangiri, 2025; Karthika, 2025). Studies of wireless system security system have also explored the approaches of securing mobile learning and communication systems against emerging cyber threats (Yang et al., 2018; Sadulla, 2025).

Although these have been made, a significant number of current approaches remain single-objective optimization, often by maximising spectral efficiency (Surendar, 2025; Monir et al., 2025; Shrirao & Mishra, 2025). Practically, beamforming designing should take into account a combination of various performance measures such as the interference suppression, power efficiency, and the computation complexity (Molisch et al., 2017; Yılmaz et al., 2025). In addition, the advanced wireless networks should also incorporate smart services management systems that are able to deal with vast data driven network operations (El Ayach et al., 2014).

The unavailability of the multi-objective optimization frameworks that unify hardware limitations and uncertainty in channels hence spurs the creation of the methodology in this paper. The suggested methodology will be able to integrate powerful beamforming optimization with intelligent learning functionality to enhance reliability and efficiency of next generation massive-MIMO communications systems.

Methodology and Experimental Setup

Hybrid Beamforming System Architecture

The system is a proposed model of a massive-MIMO transmitter, which is a large antenna array that is linked to a small number of radio-frequency chains via analogue phase shifters. The hybrid architecture of beamforming splits signal processing into two parts: in digital stage, there is the baseband signal processing which is the beamforming; on the RF stage, it is the analog beamforming. The digital beamforming stage conducts precoding to perform the shaping of signals being transmitted to the desired spatial directions whereas analogue beamforming stage conducts the steering of the antenna radiation pattern by the use of phase shifters. Fig 1 shows the design of the hybrid beamforming system of the simulation framework.

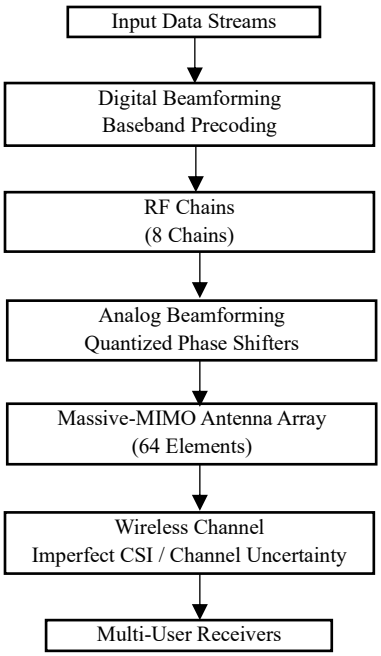


Fig. 1: Hybrid Massive-MIMO Beamforming Architecture

This architecture has a network of phase shifters in which each RF chain feeds a network of antenna elements. Due to the finite resolution of phase shifters, phase values are registered into discrete values. This quantization involves beam steering errors which negatively affect signal quality. In order to capture this effect, the simulation framework uses phase quantization constraints in the beamforming optimization framework. The quantization bits define the accuracy of the phase shifters and the beam steering accuracy is directly proportional to the quantization bits. Channel uncertainty is also modelled in the architecture which adds noise to the estimated channel matrix. This enables the assessment of the soundness of beamforming algorithms in the actual state of communication. The summary of the system parameters used in the simulation is presented in table 1.

Table 1: System Parameters

Parameter	Value
Antenna elements	64
RF chains	8
Phase quantization	3 bits
Carrier frequency	28 GHz
Channel model	Rayleigh fading

These parameters indicate standard settings of the millimeter-wave communication systems.

Multi-Objective Beamforming Optimization Model

Beamforming synthesis is developed as a multi objective optimization problem which maximizes spectral efficiency and minimises interference leakage. The same search method of the digital precoding matrix and analogue phase shift matrix is the joint optimization. Objective function is formulated as:

$$J = \alpha R - \beta I$$

Where

R represents spectral efficiency and

I represents interference power.

The weighting factors αand β determine the trade-off between the communication throughput maximization and interference suppression. Using these weights, the algorithm is capable of exploring various operating points of the design space.

Algorithm 1: Multi-Objective Beamforming Optimization

1. Initialize digital precoder and phase shift matrix
2. Generate channel matrix with estimation error
3. Compute spectral efficiency and interference power
4. Update beamforming matrices using gradient search
5. Apply phase quantization constraint
6. Repeat until convergence

This algorithm makes beamforming solutions feasible in the presence of limits of quantization.

Simulation Environment and Performance Metrics

The evaluation of the performance is done in a simulated wireless communication environment that imitates the location of users and the channel propagation characteristics. The simulation workflow that will be used to test the behaviour of beamforming is shown in fig 2.

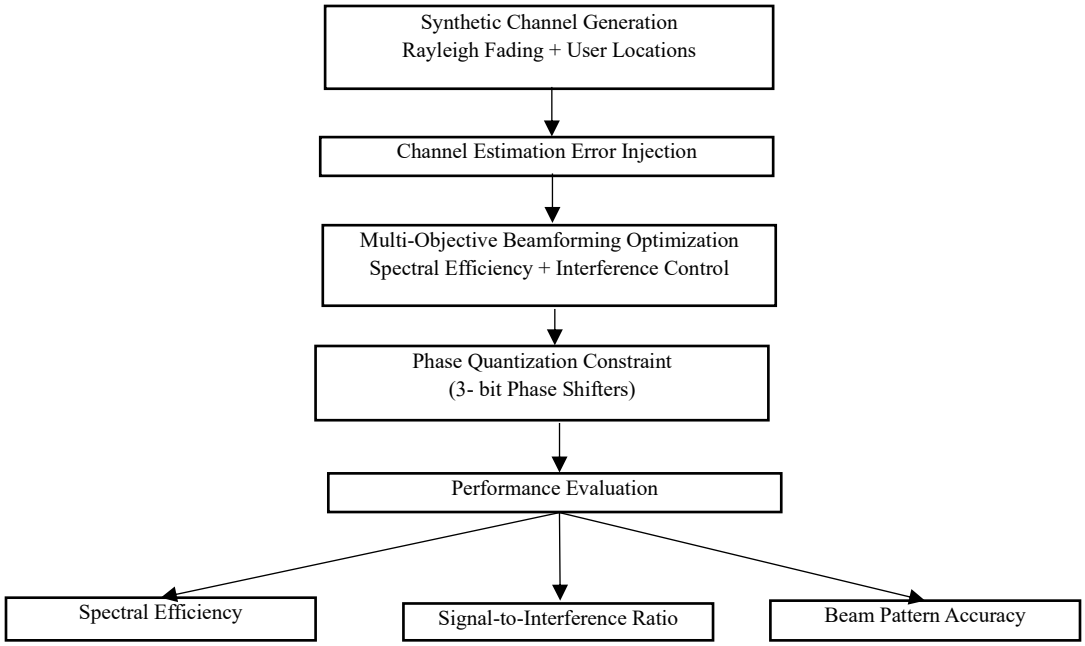


Fig. 2: Simulation Framework for Beamforming Evaluation

The simulator creates channel matrices due to random simulation values of various propagation conditions. The channel estimation errors are simulated with noise added to the estimated channel matrix. Various simulation runs are done to compare the stability of beamforming solutions to various channel realizations.

The main performance indicators that will be examined are spectral efficiency, signal to interference ratio (SIR), and beam pattern accuracy. Table 2 gives the performance measures utilised in the evaluation.

Table 2: Performance Metrics

Metric	Description
Spectral efficiency	Data rate per bandwidth
SIR	Signal to interference ratio
Beam pattern error	Deviation from ideal steering

These measurements yield a good overall analysis of beamforming.

Results and Discussion

Spectral Efficiency Analysis

The initial experiment assesses the spectral efficiency of the proposed optimization approach of beamforming when operating under different signal-to-noise ratio (SNR) conditions. Spectral efficiency is the attainable rate of data per unit bandwidth and is an important performance measure in massive-MIMO communication systems in which it is anticipated to be efficient in terms of spectral usage. The experiment takes into account various SNR conditions to assess the behaviour of the proposed multi-objective optimization framework in the various conditions of channel quality. In fig 3, the spectral efficiency of the proposed method and the conventional beamforming algorithms are compared.

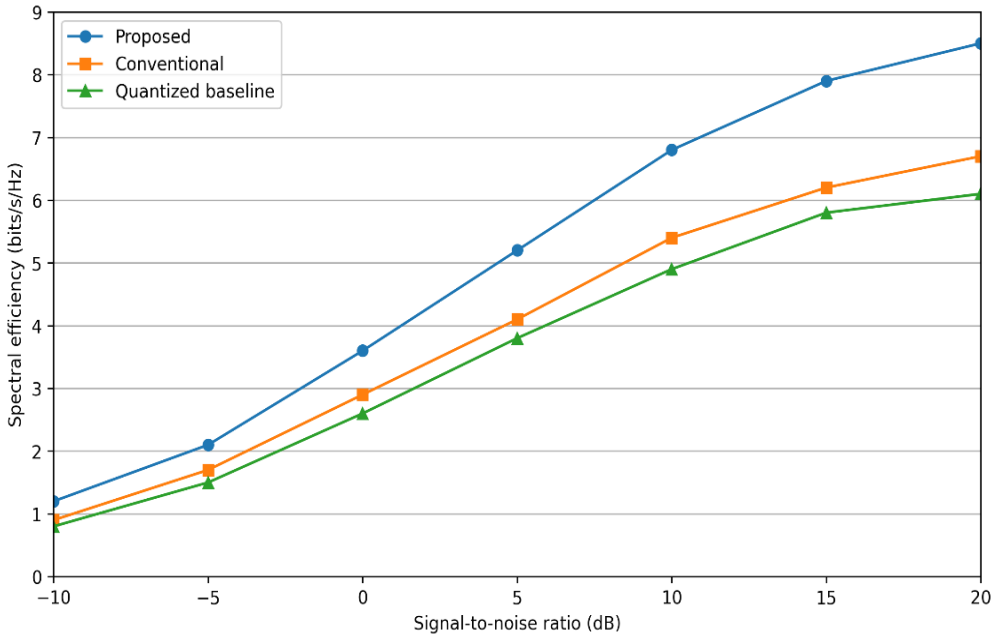


Fig. 3: Spectral Efficiency Comparison

The outcomes of simulation show that the suggested multi-objective optimization model is able to achieve greater spectral efficiency at various SNRs. Performance of all beamforming techniques is constrained at low SNR level since the noise takes over the communication channel. But, the greater the SNR, the more obvious the benefits of the proposed approach are. The proposed optimization strategy is much more efficient than the traditional beamforming techniques in moderate SNR environments where the performance-degrading effect of the interferences among several users takes up. The effect of this maximization is that, during the design of beamforming, both the spectral efficiency maximization and the interference suppression are accounted in the improvement of the optimization framework.

It is possible to jointly optimise the such digital precoding and analogue beamforming matrices so that the system can achieve a better beam structure in directing energy to the desired users and reducing the leakage of the interference to other users in the network. In addition, the given approach does not decrease the performance under the condition of the introduction of channel estimation errors into the simulation environment. The beamforming design can be made more robust to errors in channel state information by adding a channel uncertainty to the optimization model. Consequently, the system has a good communication performance under a broad band of SNR conditions.

Interference Suppression Performance

The multi-user massive-MIMO systems are also sensitive in terms of interference management since any simultaneous transmission to various users would produce a much bigger signal-interference, unless beamforming techniques are developed with care. Too much interference lowers the quality of the signal and generally decreases the performance of the network. Simulation experiments were conducted to assess the capability of the proposed framework to suppress interference at unwanted receivers at various beamforming arrangements by measuring the power of interference at these receivers. Fig 4 shows the power of interference that is seen under various beamforming parameters.

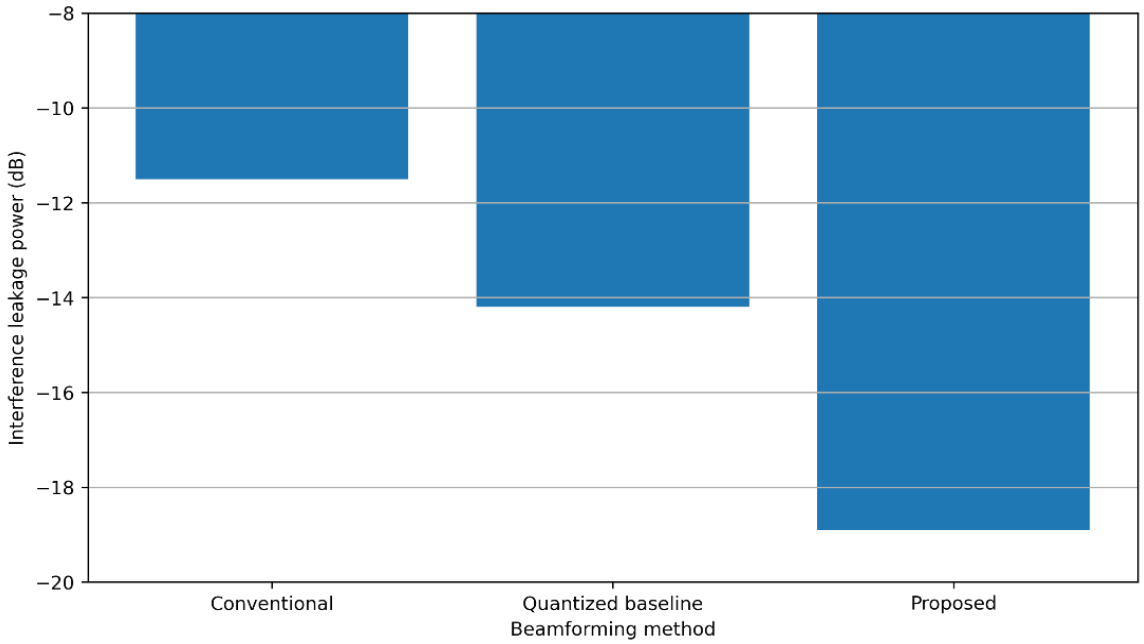


Fig. 4: Interference Suppression Performance

The findings show that the suggested beamforming algorithm yields a lot less interference leakage than the conventional beamforming algorithms. Traditional types of beamforming algorithms tend to optimise signal gain to the target user and do not explicitly minimise interference to other users. Conversely, the suggested multi-objective optimization model incorporates interference suppression as a part of the objective. Consequently, the algorithm finds beamforming solutions to achieve a tradeoff between signal strength and reduction of interferences concurrently.

The co-optimization of analogue and digital beamforming elements is another significant element that leads to enhancing the suppression of interference. The hybrid beamforming system uses analogue phase shifters with low resolution to deflect the beam of the antennas. Unless these quantization constraints are taken into account as optimization is done, the resulting beam patterns can vary far out of the design. The framework proposed clearly quantizes the phases in the optimization process, so that the calculated beamforming parameters are practical given the hardware constraints. This results in the generated beam patterns have larger spatial selectivity that aids in minimising the leakage interference to unwanted receivers. These findings suggest the usefulness of the multi-objective optimization approach to the interference issues of large-scale antenna systems.

Robustness under Channel Uncertainty

In realistic wireless communication systems, ideal channel state information is not easily accessible because of noises, mobility and delays in feedback and error in measurements. Errors in channel estimation may have a serious adverse impact on the performance of beamforming when the beamforming algorithm makes extensive use of accurate channel information. Thus, to analyse the practical applicability of beamforming strategies, it is necessary to consider the strength of the beamforming strategies in the case of channel uncertainty. To examine this attribute, the simulation will present different degrees of channel estimation error and measure the reaction of the beamforming system to the augmenting uncertainty in channel model. Fig 5 demonstrates the effect of channel uncertainty on the performance of the system.

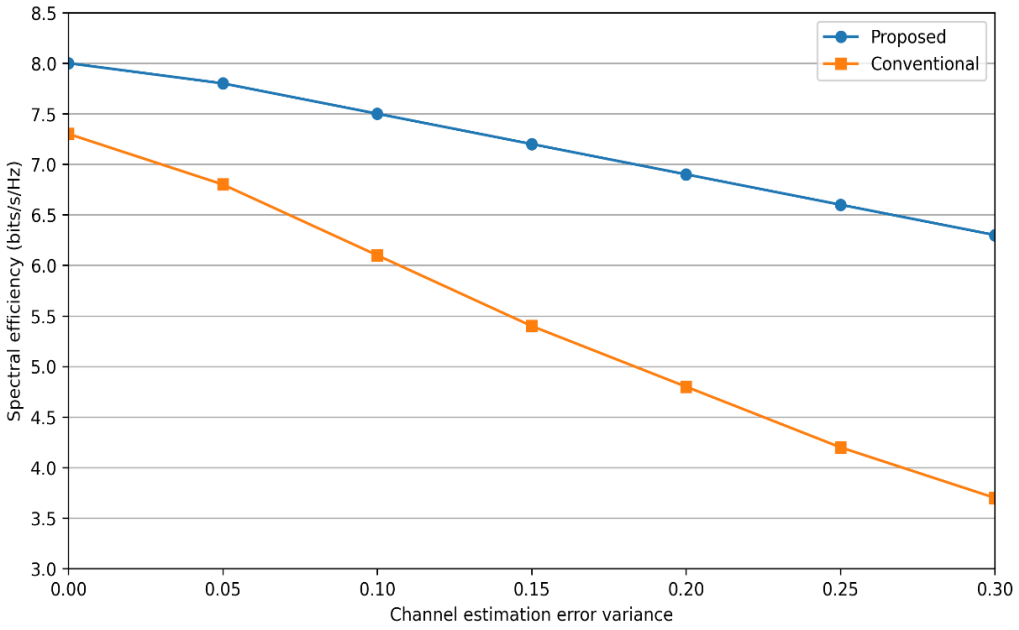


Fig. 5: Performance Under Channel Estimation Error

Through the carried-out experiments it can be seen that the given beamforming strategy does not deteriorate spectral efficiency as the degree of channel estimation error grows. Traditional beamforming algorithms whose underlying assumptions are perfect channel information fail drastically when error in channel estimation is added. Conversely, the proposed multi-objective optimization model clearly integrates channel uncertainty in the optimization model. This enables the algorithm to produce beamforming solutions which are effective throughout a span of the potential channel realizations.

The strength of the suggested approach is explained by its capability to compromise a variety of design goals and take into consideration ambiguities of the system model. Taking into account the interference suppression, spectral efficiency, and hardware constraints together, the algorithm does not overfit the beamforming solution to one estimated channel state. Rather it finds beam patterns that work stably in a variety of potential channel conditions. As fig. 5 illustrates, the suggested solution shows much less performance loss in comparison to traditional beamforming strategies with the growing channel estimation error. These results verify the claim that the channel uncertainty has to be incorporated in the beamforming optimization to create strong communication systems that can work in the real wireless setting.

Discussion

As the findings indicate, adding hardware constraints and channel uncertainty to the beamforming optimization is an effective way of enhancing the system performance. The conventional beamforming algorithms usually use perfect channel information and hardware, a situation that may not be practical in real life. The proposed approach, which models the estimation errors of phase quantization and channel estimation in the optimization model, offers a better realistic assessment of beamforming strategies of realistic communication systems. The outcomes of the simulation indicate that multi-objective optimization enables the designers to trade off conflicting performance goals, e.g., spectral efficiency and interference suppression. This can be very significant in highly populated wireless networks whereby several users are fighting over a scarce spectral resource. Moreover, the synthetic channel simulation environment will also make sure that the evaluation methodology is reproducible and not dependent on particular deployment situations. This renders the proposed framework to be applicable in exploratory design of upcoming-generation wireless communications, at an early phase.

Conclusion

The paper has proposed a powerful multi-objective hybrid beamforming synthesis model applicable in the context of a massive-MIMO communication system subject to realistic hardware constraints and uncertain channel modelling. In contrast to traditional beamforming algorithms, which rely on the assumption of ideal hardware and channel state

information, the framework has explicit beamforming constraints, which are phase-quantized analogues, and channel estimation error in the optimization. The beamforming design was developed as a multi-objective optimization problem which simultaneously optimises spectral efficiency and reduces the interference leakage in multi-user communication situations. A hybrid analogue/digital beamforming system was simulated in a synthetic wireless simulation framework to test the performance of the system under realistic operating conditions. The experimental analysis has taken into account different channel realizations, levels of signal-to-noise ratio and different levels of uncertainty in the channel to evaluate the strength of the method suggested.

Simulation findings have shown that the suggested optimization framework will always achieve superior spectral efficiency in relation to traditional beamforming methods and will have effective interference suppression under varying channel conditions. Joint optimization of digital precoding and analogue phase-shifter configurations facilitate the system to produce beam patterns which are resistant even in the presence of phase quantization and channel estimation errors. Besides this, the framework is flexible in the exploration of trade-offs among conflicting design objectives by changing the weighting parameters in the multi-objective formulation. This can be used especially in the next generation wireless network where the system designers have to tradeoff between the throughput and interference control and the hardware complexity.

In general, the presented framework provides the practical simulation-based design tool to assess the hybrid beamforming techniques in the massive-MIMO systems. The methodology incorporates hardware limitations and channel uncertainty in the optimization of its approach, offering a more realistic assessment of the beamforming of the performance of the new millimeter-wave and 6G communication architectures.

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