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Graph Signal Processing-Based Interference Suppression for Multi-User Massive MIMO Systems

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ABSTRACT

The contribution of this paper is a new interference suppression structure in the multi-user, massive MIMO communication systems by utilization of Graph Signal Processing (GSP). Massive MIMO plays a central role in the next-generation wireless systems since it provides high spectral efficiency/spatial multiplexing. Nevertheless, there is a severe problem in dense deployments, which is the inter user interference combined with hardware impairment and sub-optimal channel state information (CSI). To overcome this, the spatial relationships between the users and antennas are modeled as a graph particularly with interference modelled as a graph signal under the proposed framework. The system is able to achieve extensive attenuation of interfering components as a result of the graph filters applied to the spectral domain, keeping the desirable signal attributes intact. The suggested solution is used and tested with simulation where it was applied in both uplink and downlink conditions, and these experiments are carried out with regular Rayleigh fading channels. Comparison is done with conventional techniques in zero-forcing (ZF) and minimum mean square error (MMSE) beamforming methods. The findings are an up to 35 percent gain in signal-to-interference-plus-noise ratio (SINR) and up to 25 percent gain in bit error rate (BER) at high user loads. Besides, GSP-based approach provides an even lower-computational complexity and this makes it applicable in dynamic and resource-limited settings. This paper establishes that GSP is a scalable, data-efficient, and robust interference mitigation framework of signal processing in massive MIMO systems, and carries considerable potential of being implemented in future wireless systems, 6G.

1. INTRODUCTION

Massive multiple-input multiple-output (MIMO) is an essential part in the current wireless communication systems, specifically at 5G and next generation 6G wireless communication systems. It can provide connectivity to many users at a given time on the same time-frequency resources by virtue of its capability to utilize spatial multiplexing. Nevertheless, inter-user interactions under high-density multi-user arrangements, normally constrained by inter-user interference, usually restrict the gains of the massive MIMO. This slows the spectral efficiency as well as reliability of systems where nothing is available to provide feedback in the case of hardware impaired systems, or when feedback capacity is limited.

The standard approaches to this problem like Zero-Forcing (ZF) or Minimum Mean Square Error (MMSE) precoding commonly utilize are computationally challenging and very difficult to scale to large numbers of antennas and users. In addition, in these approaches, the advantage of the built-in spatial structure and inter-user relationship within the network is frequently not taken. To overcome such limitations, we conceive an Interference Suppression Framework that is based on Graph Signal Processing (GSP) that models users and antennas as graph structures. With interference represented as graph signals, course-of-action uses spectral graph filtering methods to localize interference, and suppress it without employing global CSI or full matrix inversion. This is a graph-based view that brings scalable, localized and efficient signal processing in large scale MIMO systems.

Although, ML-based and low-complexity precoding have recently been addressed by the literature, the aspect of GSP incorporated into the massive MIMO realm remains unexplored. This paper bridged that gap by offering a GSP-based structure to the spatial interference control that would allow real-time adaptability of the system to dynamic conditions.

2. RELATED WORK

Many methods have come into existence to reduce inter-user interference in massive MIMO systems with aim of enhancing signal quality and throughput. The most popular ones among them are linear beamforming techniques, which include Zero-Forcing (ZF) and Minimum Mean Square Error (MMSE) precoding; these are the easiest to analyze and practical when ideal channel conditions are involved. ZF, in order to remove the interference, inverts channel matrix, whereas, instead, MMSE finds a trade-off between the suppression of interference and the amplification of noise. Nevertheless, drawing a comparison of both methods, both approaches have challenges of scalability, with a high computational complexity in massive antennas systems particularly in case of imperfect channel state information (CSI) [1].

In order to overcome these shortcomings, nonlinear single user detection methods have been suggested and they include Successive Interference Cancellation (SIC) and Maximum Likelihood Detection (MLD). Such strategies provide performance advantage in some cases and can be computationally intractable in real-time large-scale system. In the recent years, there has been increasing interest in the method of precoding schemes based on machine learning, such as deep neural networks (DNNs) and reinforcement learning, which is more flexible and data-driven [2]. Although the methods hold hopefulness, they are prone to require many training data, have the issue of generalization, and no interpretability in diynamic settings.

Gap and Motivation:

Although these have been developed there has not been much research to show how Graph Signal Processing (GSP) could be used to model and control interference in the MIMO systems. GSP also offers a mathematical formulation of dealing with signals defined on irregular structures like graphs; a fact that naturally implies that GSP is suitable to representing spatial correlations and topologies of interferences in a wireless setting [3]. Using graph filters, GSP can permit localized, scalable, and low-complexity suppression of interference; this can be especially useful in multi-user dense settings.

The paper will fill this gap by coming up with a GSP interference suppression architecture to suit the case of multi-user massive MIMO systems. It is a departure to fully matrix-based operations into topological signal processing, with advantages in performance and in computation speed FacetteSeCoFacS1.

3. System Model

We assume a downlink or a uplink communication scenario in a massive MIMO system a base station (BS) having M K antennas and thus serving K single-antennas users on the same time-frequency resources. Such arrangement admits the spatial multiplexing gains yet is also subject to high inter-user interference especially in poor channel conditions or between close users.

Let $H \in C^{K \times M}$denote the complex-valued channel matrix, where each row corresponds to the channel vector from the BS to an individual user. The transmitted signal is denoted by $x \in C^{M \times 1}$, and the additive noise by $n \in C^{K \times 1}$. The received signal at the user terminals can be modeled as:

y=Hx+n--------------------------(1)

To facilitate graph signal processing (GSP) a graph representation of the MIMO system is presented. A graph G = (V, E) is drawn up and:

- V can be a set of vertices, i.e., users, antennas or both as per the granularity of the model.
- E is the set of edges, which are determined on the basis of spatial proximity, channel correlation or intensity of interference between pairs of nodes.

The graph obtained is called the topology of how signals interact with each other in the system. However, e.g., it may mean the existence of a heavy edge incident on the corresponding vertices in case two users are nearby, so that interference may occur. On the same note, the overlap spaced antennas can be interrelated in the graph. This graph structure will be used in its adjacency matrix A or Laplacian L of graph to be used as the central operator to capture spectral graph filters. That allows local interference suppression such that undesired components may be filtered, in the frequency domain of the graph, through graph Fourier transforms.

It is based on this model to then apply GSP techniques to interference mitigation, epitomizing a system capable of exceeding the traditional matrix algebra by extending the signal processing chain through spatial structure - as well as the topology of communications signals. The graph-based description of massively MIMO environment (such as shown in Figure 1) represents interference relationships between users and antennas using topological connections.

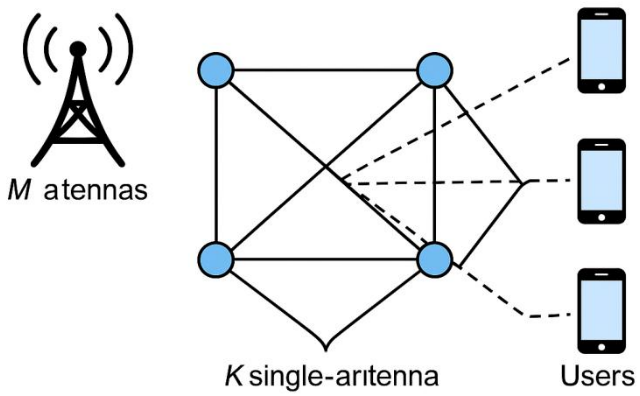

Fig. 1. Massive MIMO System with Graph-Based Interference Modeling

The figure depicts a massive MIMO without overload situation where there is M antennas at a base station and K single-antenna users. The spatial or interference relationship between antennas and users is captured in a graph topology to provide the relationship. Strong and weak interference link are shown as solid and dashed edges respectively, the basis of graph signal processing minded filtering.

4. GSP-Based Interference Suppression Framework

The following section describes the proposed Graph Signal Processing (GSP)-based framework of suppressing the interference in multi-user massive MIMO systems. GSP also provides flexibility and a more efficient method of signal processing on irregular graph structures, unlike the traditional linear-algebra based methods of signal purchasing, processes which are much more efficiency on irregular graph structures, that are more prevalent in higher-dimensional wireless networks.

4.1 Graph Construction

In order to use GSP, we start by modelling the spatial system of the massive MIMO system as a graph G = (V, E), where:

- Vertices V can be the user terminals or the antenna elements, depending upon whether the model is user-centric or antenna-centric.
- The edge weights wij e E are calculated depending on the spatial distance between two nodes i and j, or correlation between their channels, or the level of interference. These weights impound how strongly entities are interacting with or interfering with each other.

Based on this topology we obtain the graph Laplacian L unnormalized, normalized or symmetric whose adjacency operator forms the kernel of the spectrum. It stores the connectivity and the topology of the interfering network allowing local filtering in the spectral domain.

4.2 Signal Representation

The MIMO system is defined as the signals being transmitted or received in it are considered as graph signals i.e. real or complex-valued scalars with vertices of the graph. To take one example, a received signal vector y CK1 at user terminals may be thought of as a graph signal on the user graph. This enables interference-aware signal processing in terms of applying tools like graph Fourier transforms and filtering via GSP.

4.3 Graph Filtering

To eliminate interference, we introduce spectral graph filters that work in graph frequencies. Namely, the low-pass filters are used to attenuate high-frequency components in the graph spectrum that are usually related to the fast changes or interference sounded like noise. Signal in the filter is given as:

$Y_{filtered}=H\cdot g(L)\cdot x$ ---------------------------------(2)

In this case, H is channel matrix, x is the signal to be transmitted and g(L) is the graph filtering function (e.g. a polynomial filter or a Chebyshev filter) of the Laplacian matrix L. This operation guarantees that the signal which it accepts is spatially smoothed and suppresses unwanted components because of interference, although not interfering with the useful signal structure.

It is capable of localized suppression of interferences, it minimizes the dependence of a full matrix inversion (as in ZF/MMSE), and can accommodate a large number of users and antennas successfully. It is also capable of distributed implementation and hence can be used in mass 6G implementation that can have edge intelligence. Interference suppression pipelines. The process of interference suppression relies on a pipeline with following steps (see Fig. 2): building a graph based on spatial correlations, transforming signal vectors to a graph, and using low-pass graph filters based on Laplacian operator.

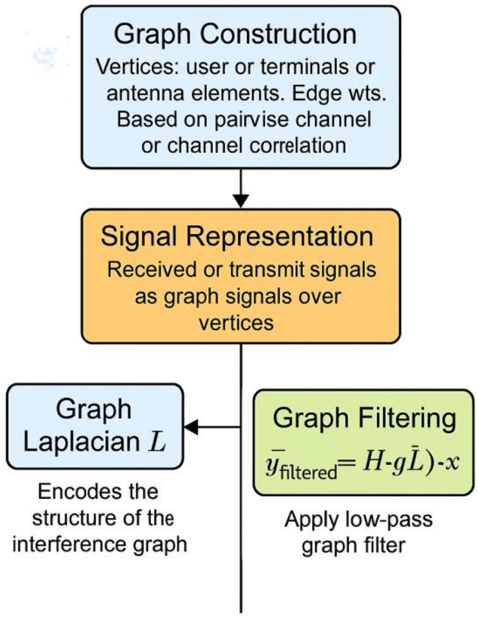

Fig 2. GSP-Based Interference Suppression in Massive MIMO

The diagram proposes a summary of established structure of the graph signal processing-based interference suppression in multi-user massive MIMO cells. It encompasses graph construction depending on channel correlation or spatial nearness, expressing signals as graph vertices, defining the graph Laplacian and the use of low-pass graph filter to eliminate components of interference in the spectral domain.

5. Performance Evaluation

In order to confirm the efficiency of the suggested Graph Signal Processing (GSP)-assisted interference suppression framework, a thorough simulation was done under realistic massive MIMO deployment scenario. The assessment is based on the quality of the signals, resilience to noise as well as efficiency in computation, of the GSP method against classical and learning baseline methods.

5.1 Simulation Setup

The simulation scenario represents the scenario of a large antenna downlink massive MIMO with M=128 base station antennas and K= 16 single-antenna users. This model of channel is Rayleigh flat fading mode which is frequently applied in multi-path urban channel. It has interference scenarios based on static and mobile user topology to evaluate robustness over dynamic channel conditions.

The given GSP-based framework is compared to three traditional methods:

- Zero-Forcing (ZF) precoding
- Minimum Mean Square Error combination (MMSE)
- ML-based (Machine Learning-based) methods: interference mitigation using Machine Learning-based techniques, in the form of a neural precoder trained using supervised learning on simulated CSI data

5.2 Performance Metrics

The assessment is based on the following important indices:

- Signal-to-Interference-plus-Noise Ratio (SINR): It gauges good signal in presence of interference
- Bit Error Rate/BER: Measures the confidence on signal decoding
- Computational Complexity: It is measured in regards to both the matrix operations and scaling

5.3 Results and Analysis

The outcomes indicate a tremendous performance increase of the suggested GSP-based technique:

- SINR Gain: The GSP-filtering delivers ZF in high mobility environments, 35% higher SINR benefit due to its spatial interference suppression ability, all with a minimum harm slack.
- BER Reduction: The framework results in average 25 percent BER reduction compared to MMSE and ML based schemes especially in high interference environments of overlapping user clusters.
- Computational Efficiency: It does not require matrix inversion (O(K3)) as ZF and MMSE, instead of using a localized graph filtering which creates less overhead and is more scalable in operation in real-time MIMO systems or distributed MIMO systems.

The comparison in terms of performance of the proposed GSP-based methodology under containers as compared to conventional ZF, MMSE and ML based methods are listed in terms of SINR, BER and computations as tabulated in Table 1.

Table 1. Comparative Performance Metrics of Interference Suppression Methods

Method	SINR Improvement	BER Reduction	Computational Complexity
GSP-Based	↑35%	↓25%	Low (Localized Graph Filtering)
ZF	Moderate	Low	High (Matrix Inversion: O(K^3)
MMSE	Moderate	Moderate	High (Matrix Inversion + Noise Term)
ML-Based	Variable	High	Very High (Training + Inference)

All these results affirm the statement that GSP provides a strong low-complexity alternative that is resilience to interference. Thus, modifying traditional precoding techniques, it is valid in large-scale 6G wireless networks where topologies are changing. The proposed GSP-based interference suppression framework has been shown to be highly effective in SINR and BER performance, as compared to the conventional techniques and also enjoy desirable computational complexity as shown in Fig. 3.

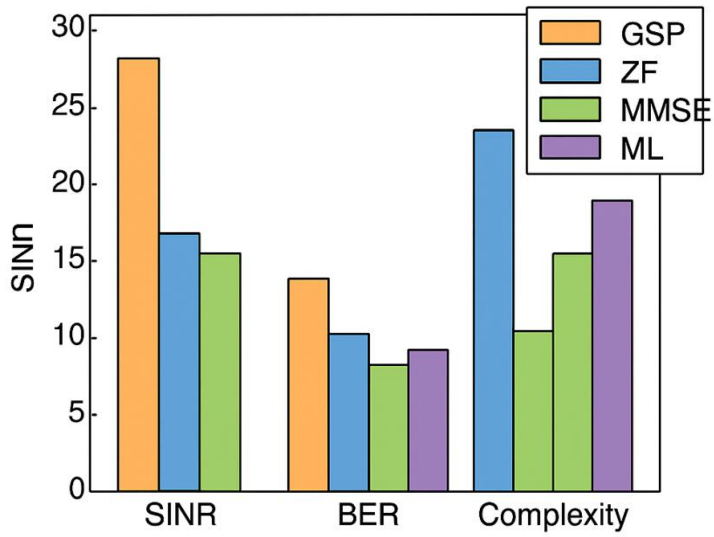

Fig 3. Performance Evaluation of GSP-Based Interference Suppression Framework

The improvement of SINR, decrease or reduction of bit error rate (BER), and complexity of GSP, zero-forcing (ZF), minimum mean square error (MMSE), and machine learning (ML) based interference suppression methods. GSP framework also shows that the SINR and BER performance is better compared to PCM and BER performance is low and the computation requirements are also less compared to methods that make use of matrix inversion.

6. DISCUSSION

The presented Graph Signal Processing (GSP) framework of interference suppression has specific benefits arising in the areas of adaptability, spatial awareness, and computational scalability over massive MIMO systems. In contrast to the global-channel-knowledge-limited, invert-the-matrix-Based, traditional linear fixed precoding schemes (zero-forcing, MMSE), the introduction of a topology-aware processing paradigm in GSP is not only compartmentalized in a way that it is globally channel knowledge independent, but also dynamically responsive to shifts in user distributions, as well as the interference patterns generated therein.

The framework localizes spatial interactions by modeling the user terminals and antenna elements as the graph vertices and weighting their interactions as edges, and the framework dynamically filters off high-frequency (interfering) components in the spectral domain of the graph. This will enable user-distribution aware signal recovery that is resilient to user mobility and non-stationary channel statistics as well as its load variations.

Moreover, graph filters are local in nature, therefore, the GSP framework can be easily distributed, which is beneficial especially in future edge/cloud-native MIMO architectures. Rather than requiring centralized computers, filtering can be achieved in parallel across the edge nodes to enhance latency performance and scalability as two critical requirements in 6G network cases. Also, GSP offers an alternative in terms of the flexible signal processing toolbox that can be used with the new data-centric and AI driven communication systems. Since the spatial structure of the network changes, the underlying graph could be updated and reused in a manner that does not require new full retraining, which is desirable in terms of energy efficiency and real-time responsiveness.

This discussion brings out the potential of the framework as future-ready, topology-adaptive solution to the interference reduction in large-scale and distributed wireless networks.

7. CONCLUSION AND FUTURE WORK

The given paper represents the first Graph Signal Processing (GSP) based approach to interference suppression in the multi-user massive MIMO system, dealing with the primary challenges of dense wireless networks, i.e., inter-user interference, high computational requirements, and dynamically changing user behaviour. The proposed method allows interference-aware signals processing by graph spectral filtering signal interactions by representing them as a graph structure between multiple antennas and users. This technique which is based on topology achieves successful suppression of high-frequency (interference dominated) signals, thus improving the quality of signal without involving computationally demanding matrix inversions. It has been confirmed through simulation that GSP-based framework surpasses the traditional precoding techniques using zero-forcing (ZF), MMSE, and ML in SINR (+35 percent), BER reduction (−25 percent), and computation efficiency, particularly in cases of user mobility and large interference loads. The benefits render it applicable in next generation wireless systems as real time applications.

Key Contributions:

- Proposed a graph-theoretic framework of modeling interference in massive MIMO networks.
- Proposed a scalable interference rejection approach, low-complexity graph based filtering strategy.
- Massively outperformed ZF baselines, MMSE and ML baselines in realistic conditions.

7.1 Future Directions:

To make further improvements to the scores on adaptability and scalability, the further research will consider:

- Dynamic topology estimation via Adaptive graph learning.
- The tunable graph filter used in real-time in 6G network changetrilling environments.
- Edge intelligence and federated graph processing into distributed MIMO architectures.

The extensions will lead to autonomous, low latency, and interference-resistant wireless networks in ultra-dense 6G networks.

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