Interference Alignment in Wireless Mesh Networks

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Motivation

Future mobile wireless networks are faced with an increasing demand for higher data rates. The mobile data volume will increase 18 times in next five years thus doubling every year (Cisco ‘12). Due to the high costs of frequency spectrum these systems need to be extremely efficient in terms of the spectrum usage. Promising approaches to achieve this are:

- Novel ways of interference management,
- Smaller cells (micro, femto, pico),
- Reusing and mesh networks.

Dimensions of Interference Management

Interference is one of the principal challenges faced by Wireless Networks [1]. At present four ways to manage interference are known:

- (i) interference rejection,
- (ii) interference avoidance,
- (iii) interference co-allocation, and
- (iv) interference exploitation.

The first two consider interference as a problem and try to eliminate it. For the latter two interference is a source of information. Here the Base Stations (BS) cooperate with each other in order to coordinate exploit interference.

Exploitation:

- Cooperation between BSs
- Requires sharing of Channel State Information (CSI) + user data
- E.g. Network MIMO (multi-cell MIMO cooperation)

Coordination:

- Cooperation between BSs
- Requires sharing of CSI
- Using multiple antennas (e.g., interference Alignment)

Evaluation Methodology

The proposed solution is evaluated by means of simulations. The following 4 important simulation steps can be identified:

1. Geometry and node placement/mobility
2. Channel with realistic correlation in time, frequency, and space
3. System level simulation
   - Considering external interference, delayed imperfect CSI, ...
4. Evaluation metrics
   - Service throughput
   - Flow fairness
   - Protocol overhead
   - Impact of delayed/imperfect CSI, mobility
   - Comparison with P2P MIMO, MU-MIMO

Results

As an example the impact of delayed channel state information is evaluated. The following scenario was used:

- IA scenario: (2x2)3 - 3 active links
- 2 antennas at each node
- Node velocity: 0.5, 2, 16 m/s
- Node mobility: 1D random walk
- Evaluation metric: sum rate (bits/s/Hz)

Conclusion & Future Work

Interference Alignment (IA) is a novel way to manage interference in wireless networks. The performance of IA was evaluated in cellular and infrastructure networks showing a dramatic improvement in network performance. However, there do not exist works analyzing the gain of IA in Ad-hoc Wireless Mesh Networks (WMN). A significant difference between WMNs and infrastructure or cellular networks is the missing wired backbone, which is used for interference coordination. Further, the resource scheduling in WMNs is more challenging. In my current research I am interested to find out whether there is a gain from applying IA in WMNs. Therefore a MAC/Routing layer protocol supporting IA is developed and evaluated.


Spatial domain IA is achieved if we are able to design a set of precoding vectors \( \mathbf{a} \) and interference-suppression vectors \( \mathbf{s} \) such that, for \( i = 1 \ldots 3 \):

\[
\mathbf{u}_i^T H_i \mathbf{v}_j = 0, \quad \forall j \neq i
\]

\[
\mathbf{u}_i^T H_i \mathbf{v}_i \neq 0
\]

Analytical procedure to obtain pre-decoders:

1. Precode \( v_i \) for user \( i \) if \( i \) is an eigenvector of:
   
   \[
   (H_{ii} - H_{ij}) H_{ij} H_{ji} + n_i
   \]

2. Precode \( v_j \) for user \( j \) and \( \mathbf{S} = \mathbf{H}_i \mathbf{H}_{ji} / \mathbf{H}_{ij} \mathbf{H}_{ij} \mathbf{H}_{ji} \mathbf{H}_{ij}

When precoders and decoders are applied at both sides of the link, the \( i \) th user received signal is:

\[
r_i = \mathbf{u}_i^T H_i \mathbf{v}_i s_i + \sum_j \mathbf{u}_i^T H_{ij} \mathbf{v}_j s_j + \mathbf{u}_i^T n_i
\]

\( \mathbf{a} \) is the 1-dimensional signal vector of the \( i \) th TX node.

Problem Statement

It is unknown how to apply Interference Alignment (IA) in Ad-hoc Wireless Mesh Networks (WMN). Moreover, it is unclear whether there is a performance gain from applying IA in such networks.

The challenges are:

- No wired backbone (coordination over the air),
- Random medium access (CSMA),
- How to obtain Channel State Information (CSI),
- Do we need full or only partial CSI,
- Impact from delayed and imperfect (e.g. quantization and reciprocity error) CSI,
- Synchronization mismatch (time & frequency),
- Wideband channel (frequency selectivity),
- Asynchronous co-channel interference from outside

Interference coordination within IA cluster (green), strong asynchronous co-channel interference from outside the IA cluster (red), weak interference from far-away nodes (white).