Interference Alignment in Wireless Mesh Networks

Anatolij Zubow

Humboldt-Universität zu Berlin
{zubow}@informatik.hu-berlin.de

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),
- Relaying and mesh networks.

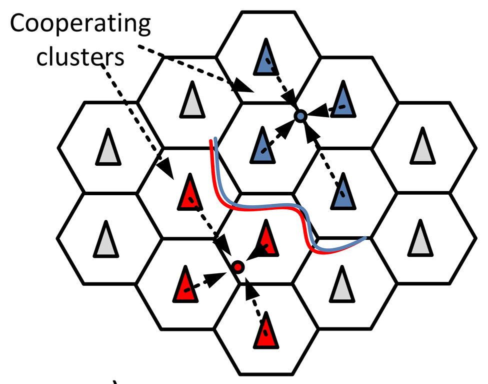
New mobile applications

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 coordination 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 or exploit interference.

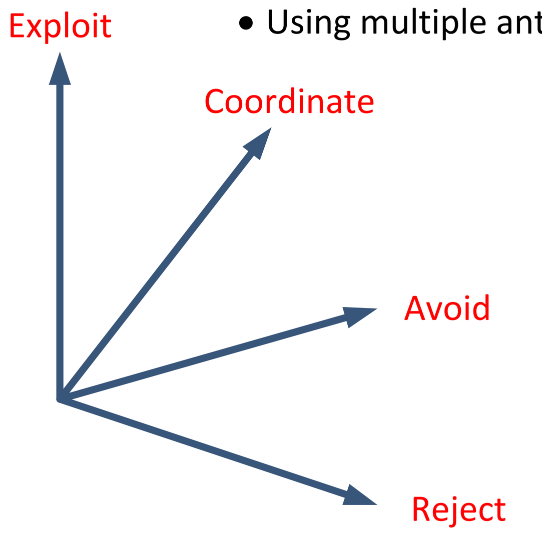
Exploitation:

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

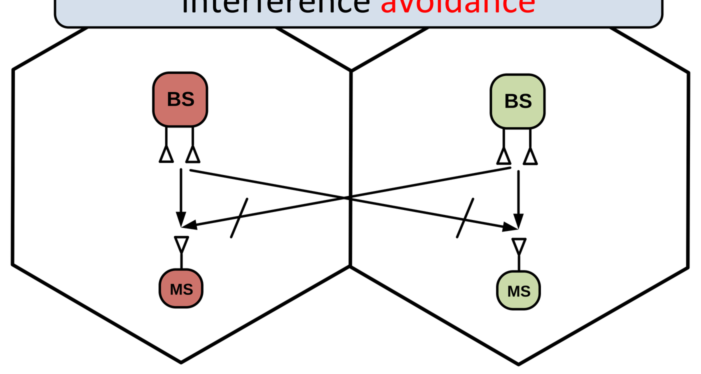


Coordination:

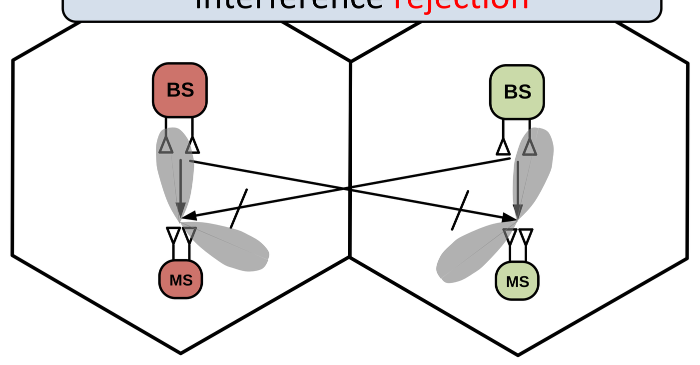
- Cooperation between BSs
- Requires sharing of CSI
- Using multiple antennas (e.g. Interference Alignment)



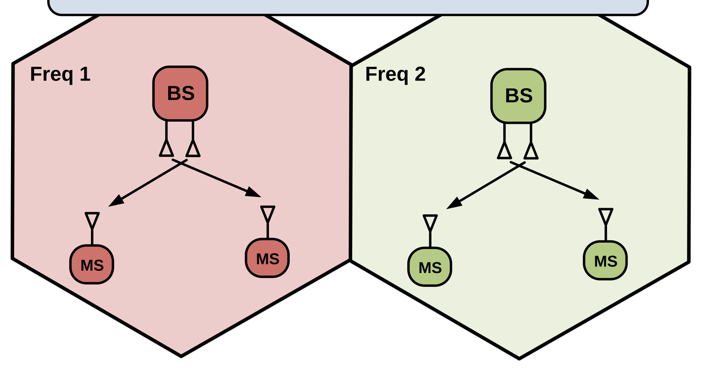
Transmit beamforming-based interference avoidance



Receiver beamforming-based interference rejection

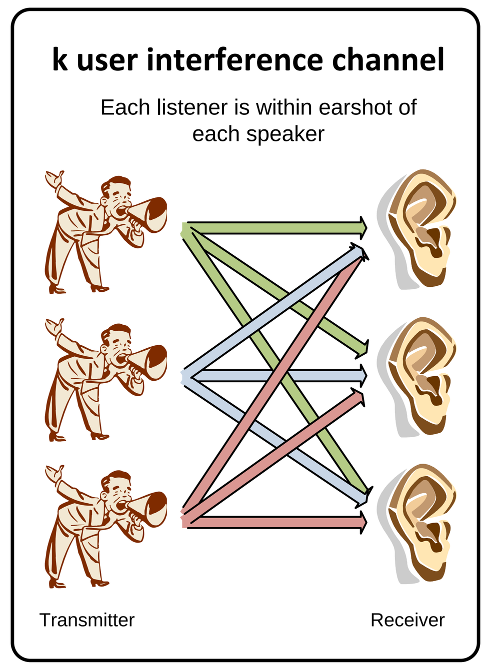


Reuse-based interference avoidance



Coordinating Interference - Interference Alignment

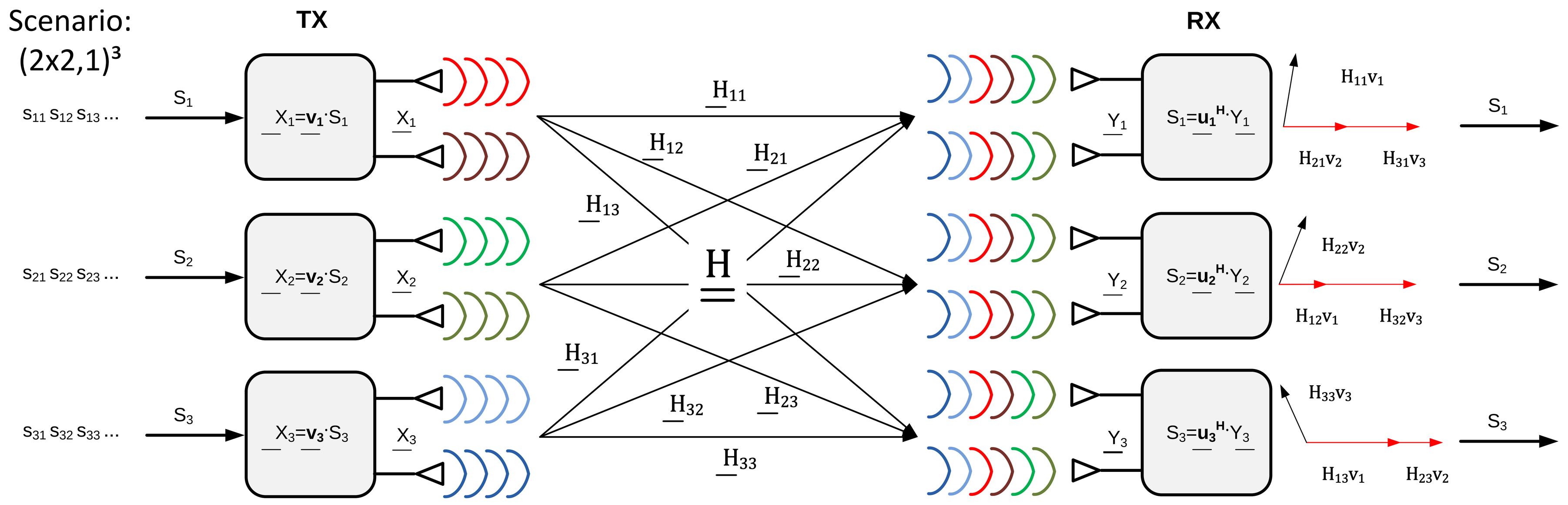
- Cadambe et al. [2] showed that with perfect channel knowledge (H) the k user interference channel is not interference limited:
- Interference alignment (IA) is a transmission strategy that results in sum capacities that scale linearly, at high signal-to-noise ratio (SNR), with the number of users in the system.
- Note: linear scaling of sum capacities with users is achieved without cooperation in the form of message sharing!
- Consequence: We grossly underestimated the capacity of WNs: e.g., true capacity is higher by 50%, 900%, and 4900% than anything previously shown to be achievable for networks with 3, 20, and 100 interfering users, respectively.



Interference Alignment in Spatial Dimension

Interference Alignment (IA) cooperatively aligns interfering signals over the time, frequency, or space dimensions. My focus is on MIMO interference channels. IA aligns signals in the spatial dimension by choosing transmit precoders such that interference at each receiver spans only a subspace of the receive space.

Scenario: (2x2,1)[3]



System model:

$$y_i = H_{ii} x_i + \sum_{j \neq i} H_{ij} x_j + n_i$$

wanted signal, interference, noise

- $x_i \in C^{2\times1}$ is the signal transmitted by i-th user
- $H_{ij} \in C^{2\times2}$ is the 2x2 MIMO channel from transmitter i to receiver j
- $v_i \in C^{2\times1}$ is the precoding vector of the i-th user
- $u_i \in C^{2\times1}$ is the interference-suppression vector of the i-th user
- $y_i \in C^{2\times1}$ is the signal received by i-th user

H is a matrix of complex numbers – amplitude & phase

Spatial domain IA is achieved if we are able to design a set of precoding vectors $\{v_i\}$ and interference-suppression vectors $\{u_i\}$ such that, for i = 1..3

$$u_i^H H_{ij} v_j = 0, \quad \forall j \neq i$$ — remove interference

$$u_i^H H_{ii} v_i \neq 0$$ — preserve wanted signal

Analytical procedure to obtain pre-/decoders:

(1) precoder v1 for user 1 is any eigenvector of:

$(H_{31})^{-1}H_{32}(H_{12})^{-1}H_{13}(H_{23})^{-1}H_{21}$

(2) precoder for user 2 and 3 (v_2,v_3):

$v_2=(H_{32})^{-1}H_{31}v_1$

$v_3=(H_{23})^{-1}H_{21}v_1$

When precoders and decoders are applied at both sides of the link, the i-th user received signal is

$$r_i = u_i^H H_{ii} v_i s_i + \sum_{j \neq i} u_i^H H_{ij} v_j s_j + u_i^H n_i$$

$$= u_i^H H_{ii} v_i s_i + u_i^H n_i$$

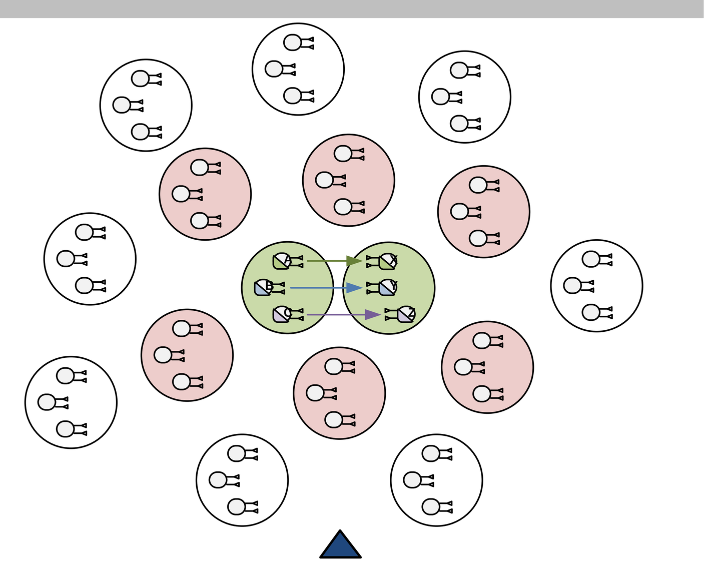
s_i is the 1-dimensional signal vector of the i-th TX node.

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),
- MAC protocol overhead is significant,
- 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

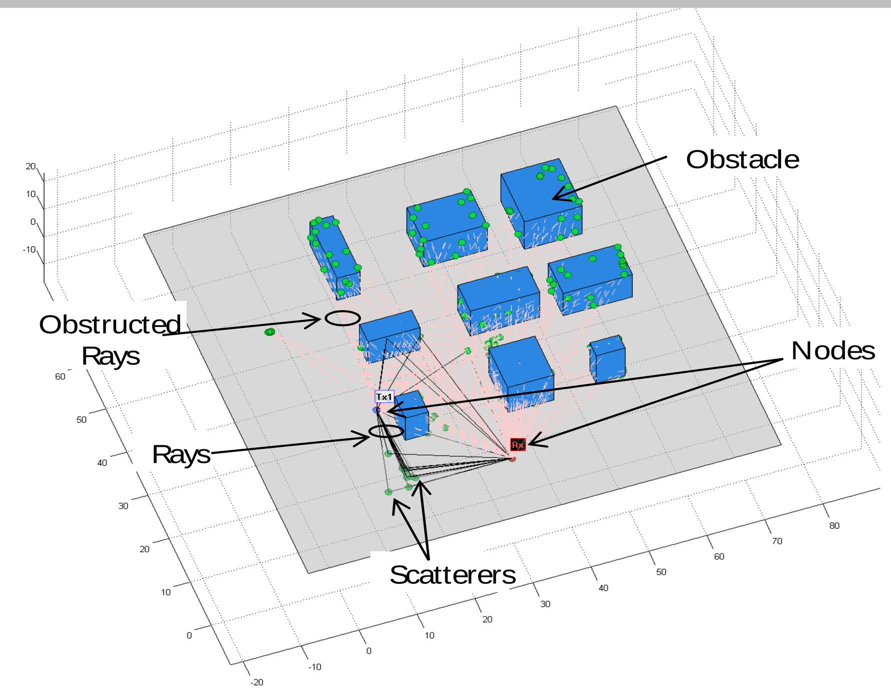


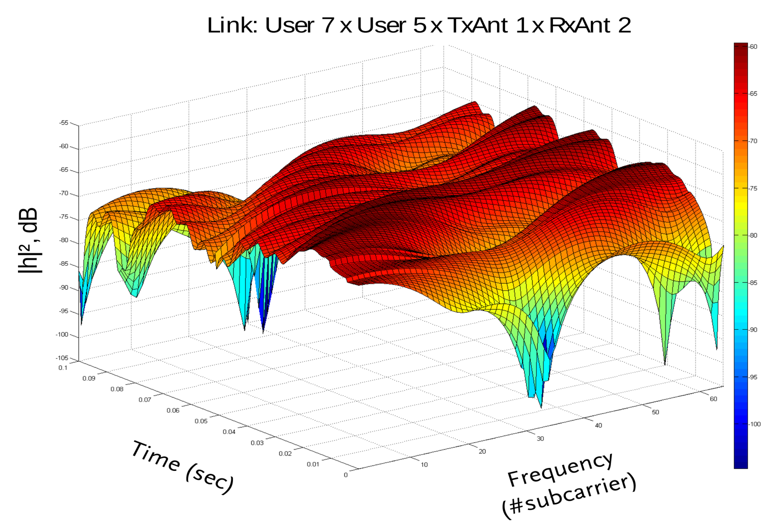
Interference coordination within IA cluster (green), strong asynchronous co-channel interference from outside the IA cluster (red), weak interference from far-away nodes (white)

Evaluation Methodology

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

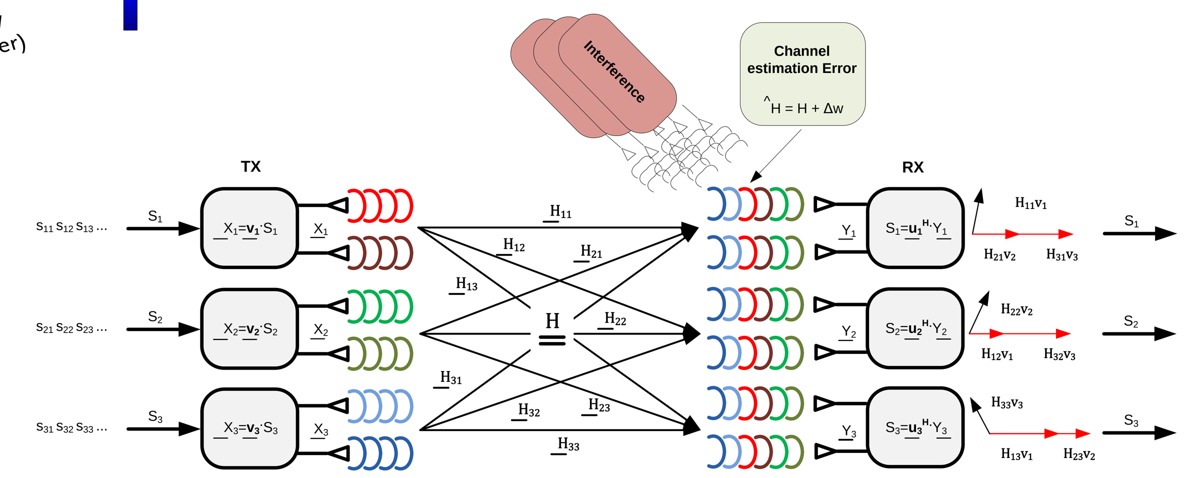
(1) Geometry and node placement/mobility
> Channel with realistic correlation in time, frequency, and space





(2) MIMO channel
> Generation of the P2P channel transfer functions (H)

(3) System-level simulation
> Considering external interference, delayed+imperfect CSI, ...



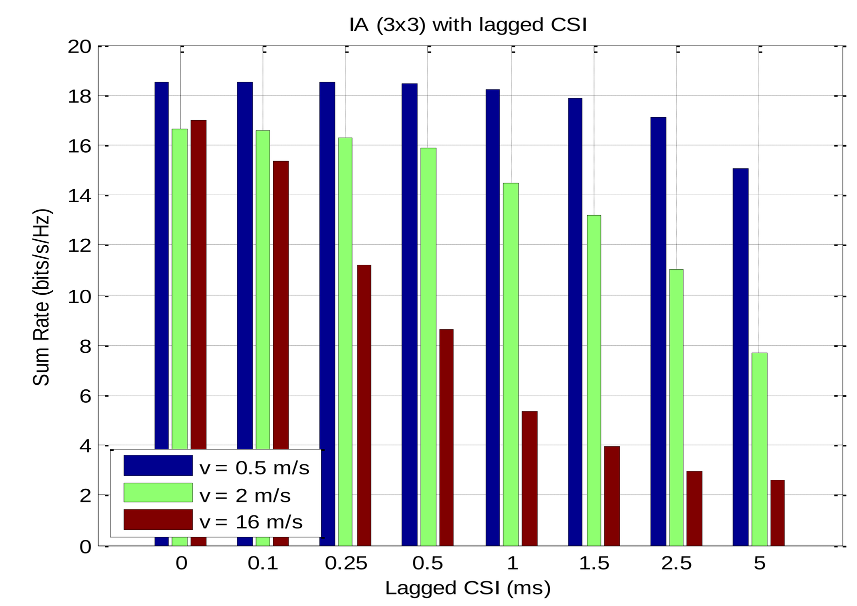
(4) Evaluation metrics

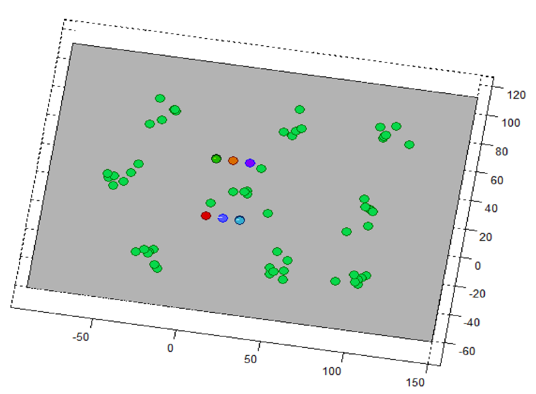
- Service throughput
- Flow fairness
- Protocol overhead
- Impact of delayed/imperfect CSI, mobility
- Comparison with P2P MIMO, MU-MIMO

Results

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

- IA scenario: (2x2,1)[3] - 3 active links
- 2 antennas at each node
- Node velocity: 0.5, 2, 16.6 m/s
- Node mobility: 1D random walk
- Evaluation metric: sum rate (bits/s/Hz)





Placement of node (middle) and scatterers (green).

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 cross layer protocol supporting IA is developed and evaluated.

[1] Tse, D. and Vishwanath, P.: Fundamentals of Wireless Communications, Cambridge Press, 2005.
[2] Cadambe, V.R., Jafar, S.A.: Interference Alignment and Spatial Degrees of Freedom for the K User Interference Channel, ICC, 2008.