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),
- Relaying and mesh networks.

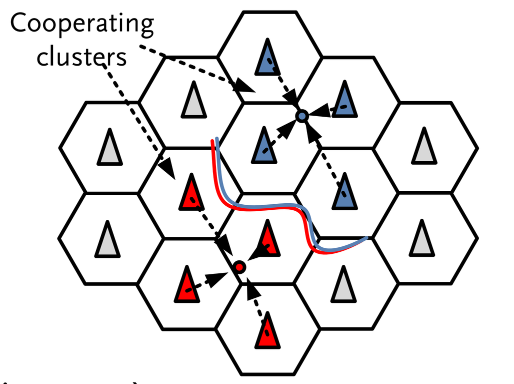
New mobile devices

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.

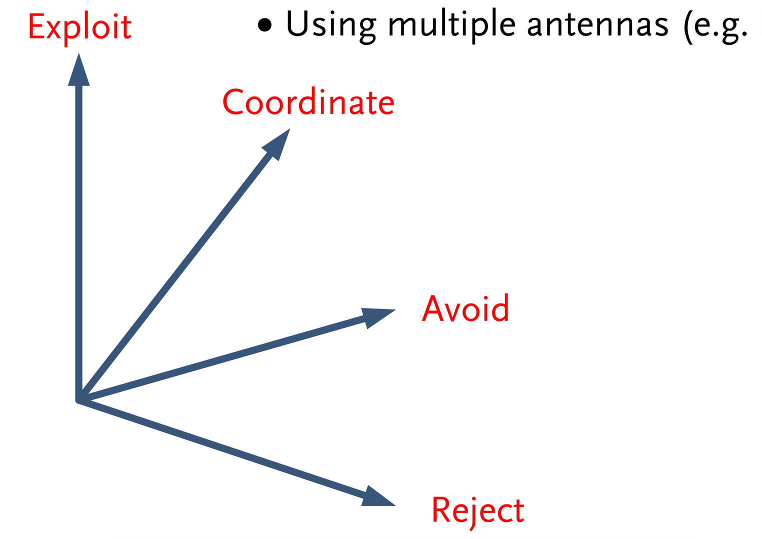
Exploitation:

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

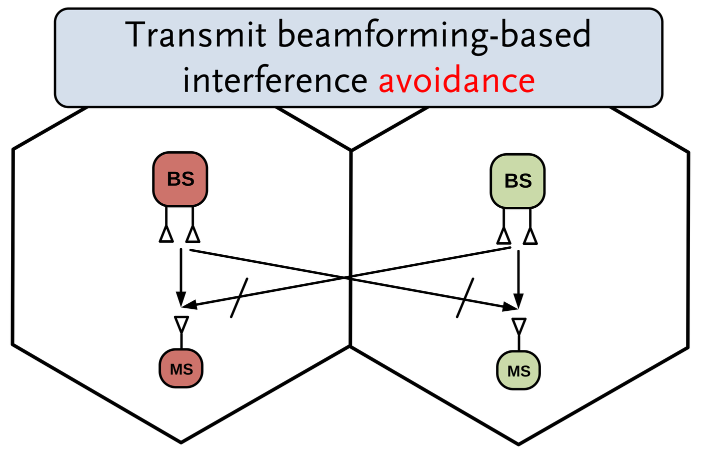


Coordination:

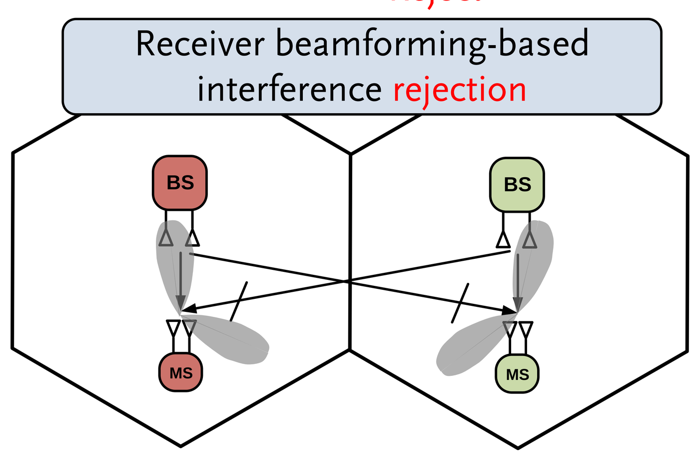
- Cooperation between BSs
- Requires sharing of CSI
- Using multiple antennas (e.g. Interference Alignment)



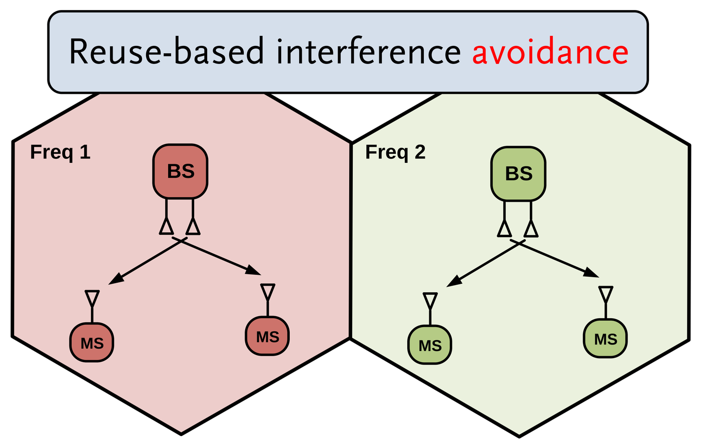
Transmit beamforming-based interference avoidance



Receiver beamforming-based interference rejection



Reuse-based interference avoidance

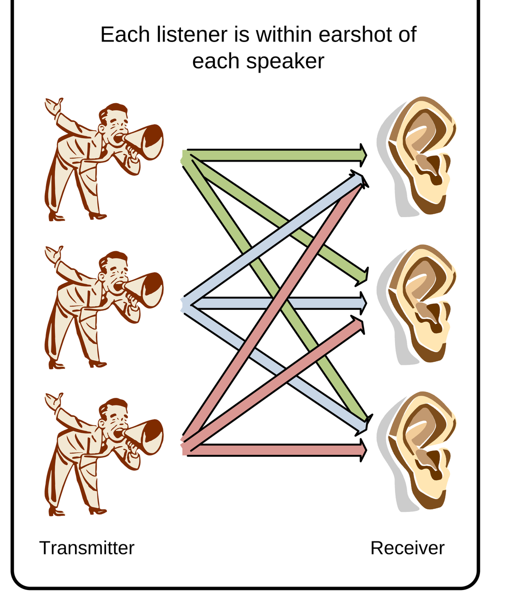


Coordinating Interference - Interference Alignment

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, that linear scaling of sum capacities with users is achieved without cooperation in the form of message sharing! These results indicate that we grossly underestimated the capacity of wireless networks:

- 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.

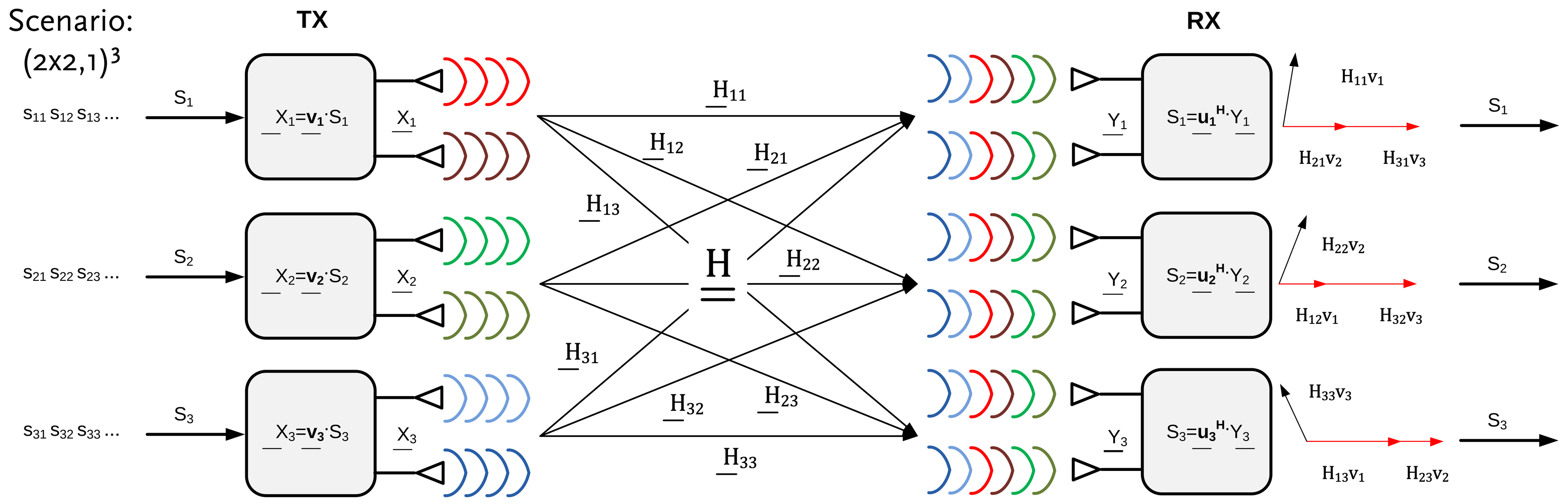
k user interference channel



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. Here 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:

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

noise
wanted signal
interference

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

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

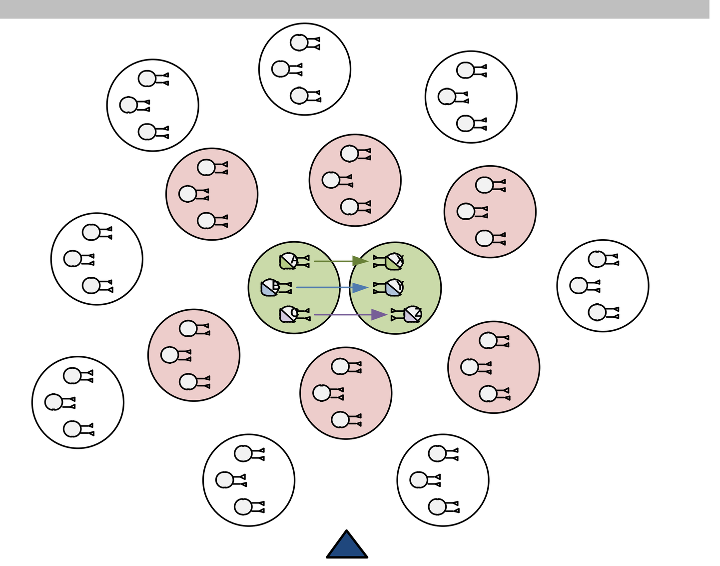
s_i is the 1-dimensional signal vector of the i-th TX node.

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 main challenges can be summarized as follows:

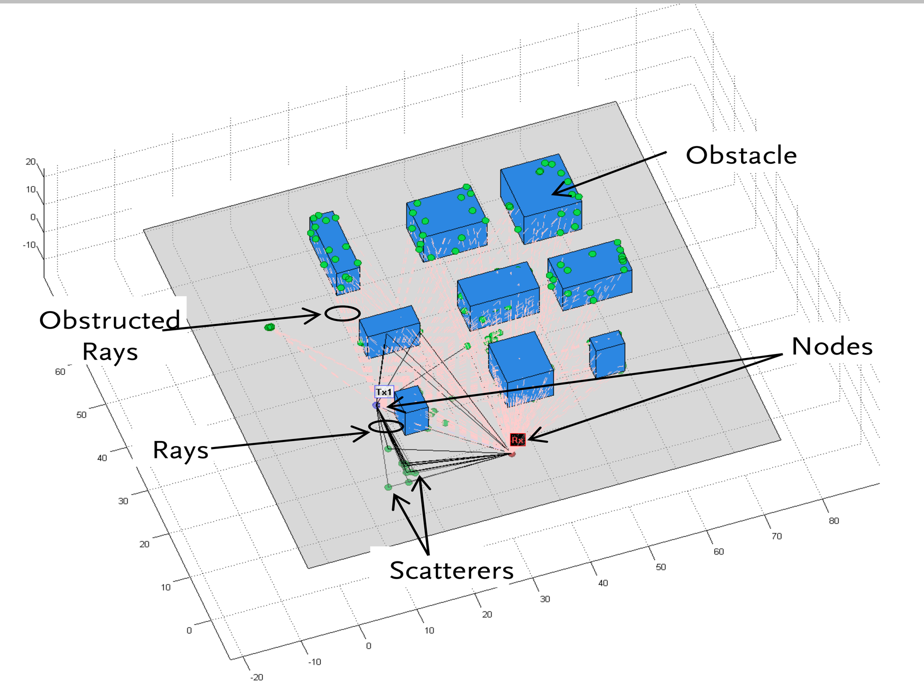
- Lack of a wired backbone (coordination over the air),
- High MAC layer protocol overhead,
- Random medium access (CSMA),
- Distributing Channel State Information (CSI) is expensive (full vs. partial CSI),
- Impact from delayed and imperfect (e.g. quantization and reciprocity error) CSI
- Synchronization mismatch (time & frequency),
- Wideband channel (frequency selectivity),
- Asynchronous co-channel interference from outside



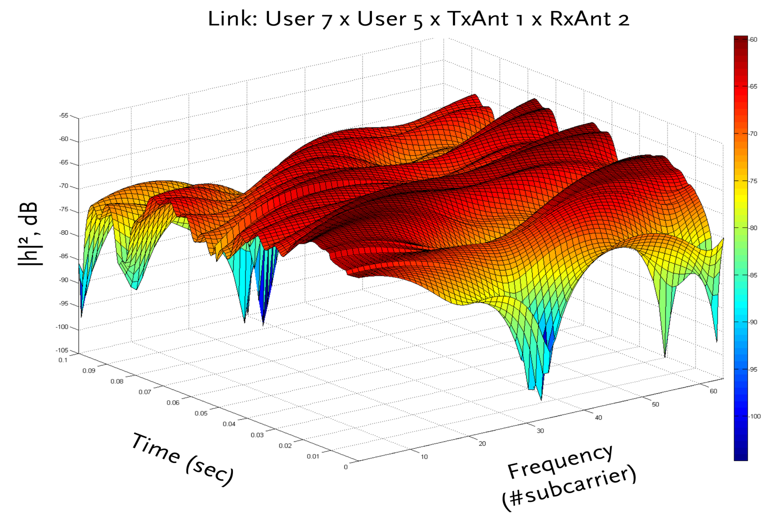
Interference coordination within IA cluster (green), strong asynchronous co-channel interference from outside the IA cluster (red), weak interference from far-away nodes (white)

Evaluation Methodology

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

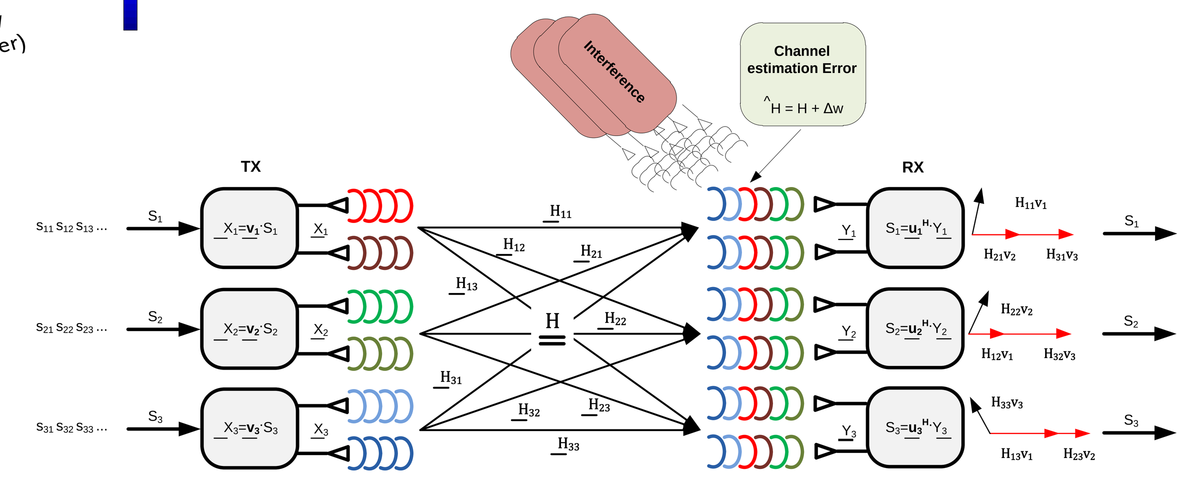


(1) Geometry and node placement/mobility
> Channel with realistic correlation in time, frequency, and space



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

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



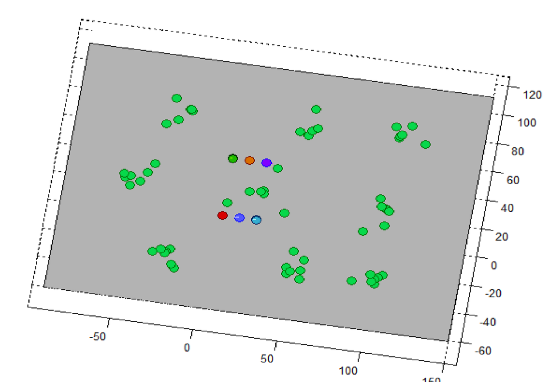
(4) Evaluation metrics

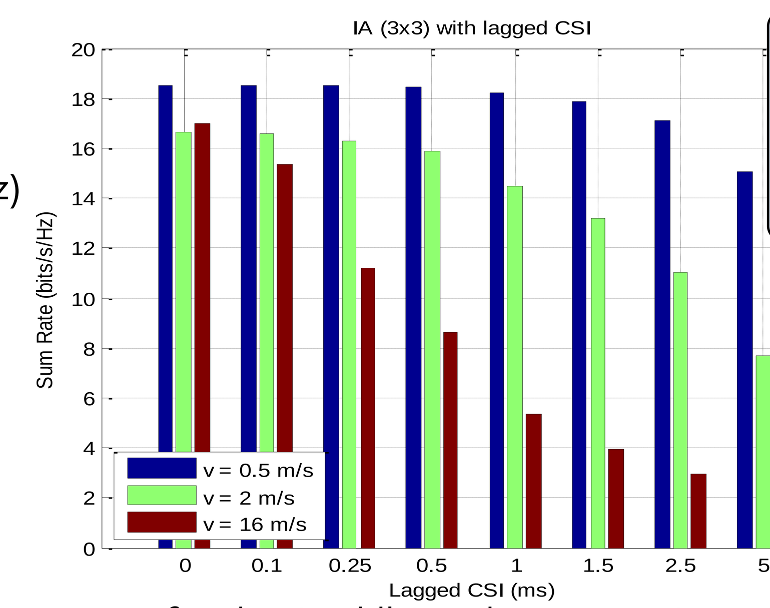
- Service throughput
- Flow fairness
- Protocol overhead
- Impact of delayed/imperfect CSI, mobility
- Comparison with P2P MIMO, MU-MIMO

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)





The performance degradation is much higher at high node mobility.

Placement of nodes (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.