Dynamic Spectrum Allocation in Uncoordinated Cognitive Radio Networks Based on Adaptive Antenna Array Interference Mitigation Diversity

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Background

Area of interest

- Decentralized dynamic spectrum allocation (DSA) in unsynchronized adaptive antenna array networks
- Possible application: Vertical (primary and secondary users) and horizontal cognitive radio (CR) systems in license-exempt spectrum

State of the art

- Game theory is a customary tool to investigate spectrum sharing problem.
- Normally, the main objectives are finding system configurations, algorithms and conditions to guarantee local or global convergence to Nash equilibrium.
- In the general case, decentralized selfish (greedy) maximization of data rates cannot guarantee convergence. Particularly, this is the case for joint iterative selfish decentralized DSA and beamforming in MIMO ad hoc networks.
- Normal practice is to treat this kind of solutions as "useless from practical perspective".
- Explicit cooperation between nodes (data exchange, possibly at MAC layer) can be used to guarantee convergence to NE.

Approach

Question

- **Can we make it practical without explicit data exchange between nodes?**

Observation

- **In fact, convergence with probability one to a certain stationary point is not necessary for a particular algorithms if we are able to demonstrate:**
  - an overwhelming majority of stationary points with sufficiently high steady-state performance over few inappropriate ones;
  - sufficiently high probability of the reasonably fast convergence compared with a tiny probability of non-convergence or slow convergence.

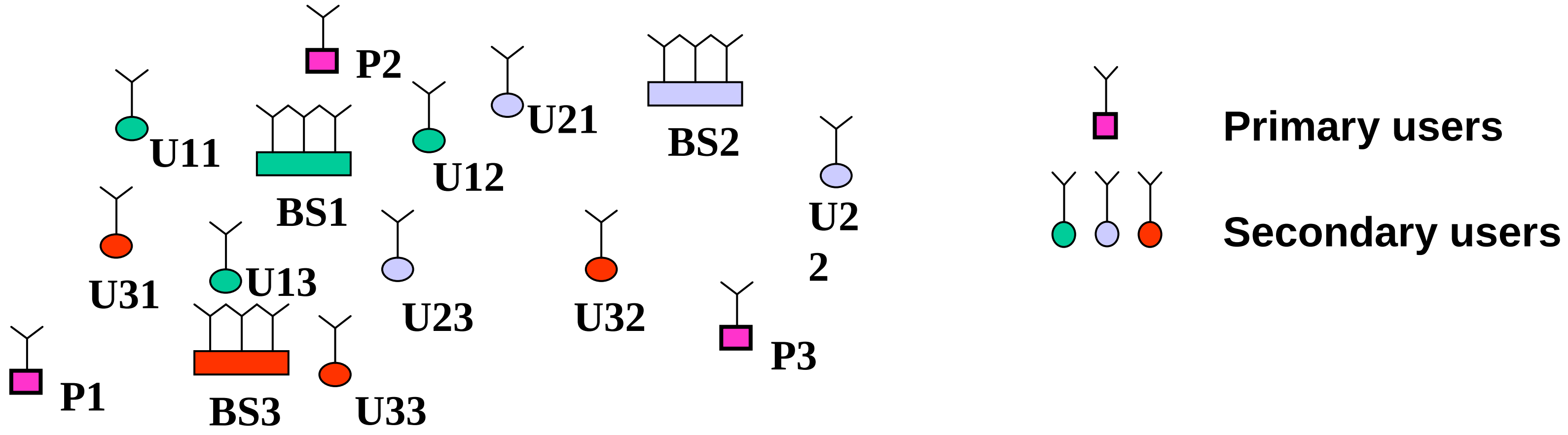
Approach

- **Introduce and study new "good neighbor" strategies that can be viewed as rule-regulated cooperation between spectrum sharing nodes without explicit data exchange between them.**
- **Use Markov chains to find convergence/non-convergence probabilities, and convergence rate**

Outline

- Data model and problem formulation
- "Selfish" and "Good Neighbor" solutions
- Summary of Markov chain analysis
- Summary of D8.1 results on IM-based DSA
- Conclusions
- Appendix: PHY requirements for unsynchronized CR networks

Decentralized DSA in unsynchronized CR networks



Assumptions

- A number of frequency bands formed by means of spectrally efficient FBMC PHY is available in some geographical area.
- Primary users dynamically occupy some of them.
- Secondary network consists of a number of independent subsystems that are allowed to use bands, which are not currently occupied by the primary users.
- Each base station is sensing spectrum in all the available bands to detect presence of the active primary users.
- Secondary subsystems include base stations equipped with multiple antennas and single-antenna users transmitting data to their base stations.
- Secondary subsystems are not coordinated and synchronized.
- Secondary base stations have full information and control on their own users.

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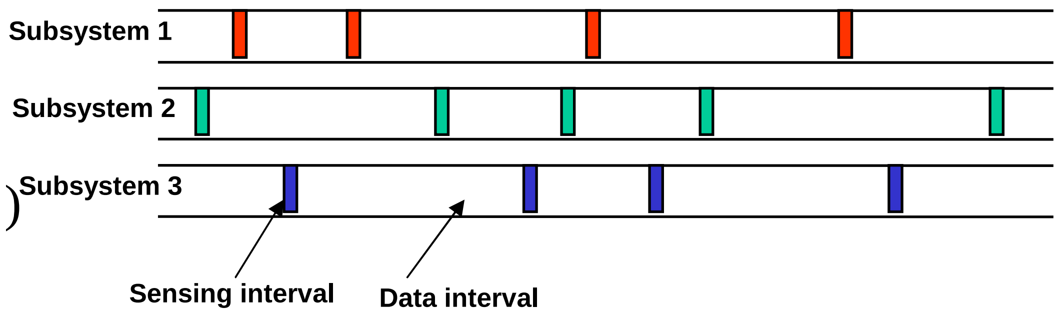
Decentralized DSA in unsynchronized CR networks

Spatial filter: $\mathbf{w}_{nl_m} = \alpha_{nl_m} \mathbf{R}_{nl_m}^{-1} \mathbf{h}_{nl_m}$

SINR: $\mathrm{SINR}_{nl_m} = \mathbf{h}_{nl_m}^{*} \mathbf{R}_{nl_m}^{-1} \mathbf{h}_{nl_m}$

Rate: $\gamma_{nl_m} = \log_2(1+\mathrm{SINR}_{nl_m})$

Criterion: $\rho = \min_{n,m} \gamma_{nl_m}$



Interference mitigation diversity

- **IM-based DSA algorithm at each subsystem should allocate bands to its users, such that the propagation channels from the users to their BSs are as orthogonal as possible to the active interference propagation channels.**
- **We refer to such a variety of IM options as adaptive array interference mitigation diversity**

Difficulty

- **Any decision made by a given BS regarding frequency allocation of its users may have an arbitrary and unknown at the given BS impact on interference scenarios for other BSs, due to the non-reciprocal nature of propagation channels from the users of a given subsystem to other BSs**

“Selfish” IM-based DSA

Algorithm: Sensing interval

Step 1 **(*space-time sensing*): Estimate the interference covariance matrix with no transmissions from the users in the n-th subsystem**

$$\mathbf{R}_{fn},\ f=1,\ldots,F$$

***Step 2*: Find bands for all the local users using exhaustive or simplified MaxMin local search**

$$\mathbf{d}_n = \arg\max \min_{[f_1,\ldots,f_M],\ f_i \neq f_j} \mathbf{h}^*_{f_m mnn} \mathbf{R}^{-1}_{f_m n} \mathbf{h}_{f_m mnn}$$

***Step 3*: Calculate the optimal MSE weight vectors**

$$\mathbf{w}_{nm} = \frac{\mathbf{R}^{-1}_{d_{nm} n} \mathbf{h}_{d_{nm} mnn}}{\mathbf{h}^*_{d_{nm} mnn} \mathbf{R}^{-1}_{d_{nm} n} \mathbf{h}_{d_{nm} mnn}},\ m=1,\ldots,M$$

Algorithm: Data interval

$\mathrm{U}_{nm},\ m=1,\ldots,M$ **transmit data in the bands assigned in** $\mathbf{d}_n$

BS_n **receives data with the optimal weights** $\mathbf{w}_{nm},\ m=1,\ldots,M$

Disadvantage

- **In pursuing the best results for its own subsystem, the interference environment of other BSs keeps changing, leading to poor convergence properties for the whole network.**

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"Good Neighbour" IM-based DSA

Idea

- **Controllable local performance should be achieved with minimum changes in band allocation to reduce non-stationary interference to other subsystems**

Solution

- **Threshold regulated local search that minimizes the number of band changes subject to the minimum SINR above the threshold**

Algorithm: Sensing interval

***Step 1a*: For the current $\mathbf{d}_n$ calculate**

$$\gamma_n = \min_{m=1,\ldots,M} \mathbf{h}^*_{d_{nm}mnn} \mathbf{R}^{-1}_{d_{nm}n} \mathbf{h}_{d_{nm}mnn}$$

***Step 1b*: If $\gamma_n \geq \gamma_0$, then go to Step 3 without any updates in band allocation, otherwise, go to Step 2.**

Step 2: Find bands for all the local users using exhaustive or simplified MinSwitch local search

$$\mathbf{d}_n = \arg\min_{f} \sum_{m=1}^{M} |\operatorname{sign}(f_m^j - d_{nm}^{j-1})|$$

$$\text{subject to } \mathbf{h}^*_{f_m^j mnn} \mathbf{R}^{-1}_{f_m^j n} \mathbf{h}_{f_m^j mnn} \geq \gamma_0$$

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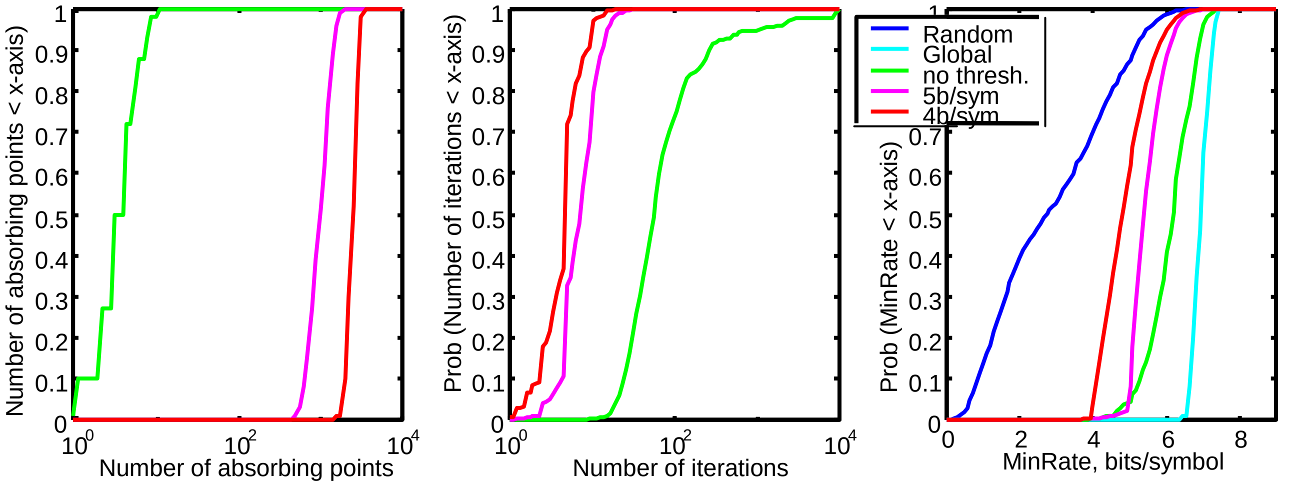
Markov chain analysis for IM-based DSA [2]

Approach

- **Calculate the transition probability matrix**
- **Classify all the states into 3 groups: absorbing, transient and ergodic**
- **Form absorbing Markov chain by means of replacing the ergoding suchains with the corresponding absorbing states**
- **Calculate probabilities of absorption by the absorbing states (desirable behaviour) and ergodic subchains (undesirable non-convergent behaviour) and average convergence rate**
- **Calculate the global performance for the absorbing states if they exist**

Probability of undesirable non-convergent behavior in 200 channel realizations for 5 BS, 2 users per BS, 3 bands, 4 BS antennas, SNR=20dB

Performance	"Selfish"	"Good neighbor" - MinSwitch	
		5 bits/symbol	4 bits/symbol
Probability to find networks with no absorbing points	2.5%	0%	0%
Probability of absorption by ergodic subchain	4.1%	0.15%	0.002%



[2] A.M.Kuzminskiy, Y.I.Abramovich, "Decentralized dynamic spectrum allocation based on antenna array interference mitigation diversity: Algorithms and Markov chain analysis," in Proc. ICASSP, Apr. 2009.

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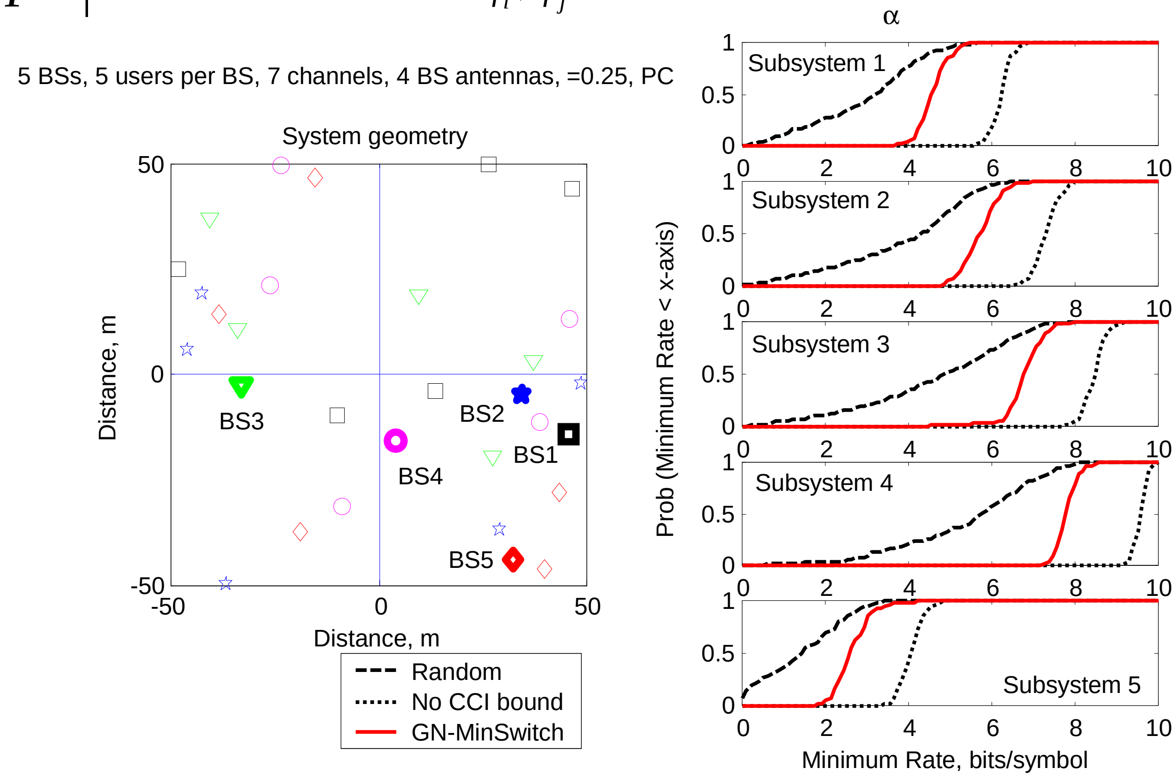
Higher-dimension IM-based DSA networks

Main results [3]:

- **Global bounds for IM-based DSA potential performance assessment for Rayleigh channels**
- **Simplified algorithms for high number of users and bands**
- **Power control for throughput maximization, power saving or guaranteed QoS for selected users**
- **On-line threshold selection in propagation scenarios with pathloss and shadowing**

for $K \geq \left\lceil \frac{NM}{F} \right\rceil$ **:** $$\gamma_{0n} = \alpha \max \min_{f_i \neq f_j \in \Phi} \sigma^{-2} \| \mathbf{h}_{f_m mnn} \|^2$$



[3] Application of the physical layer in a cognitive radio scenario, PHYDYAS D8.1, July 2009.

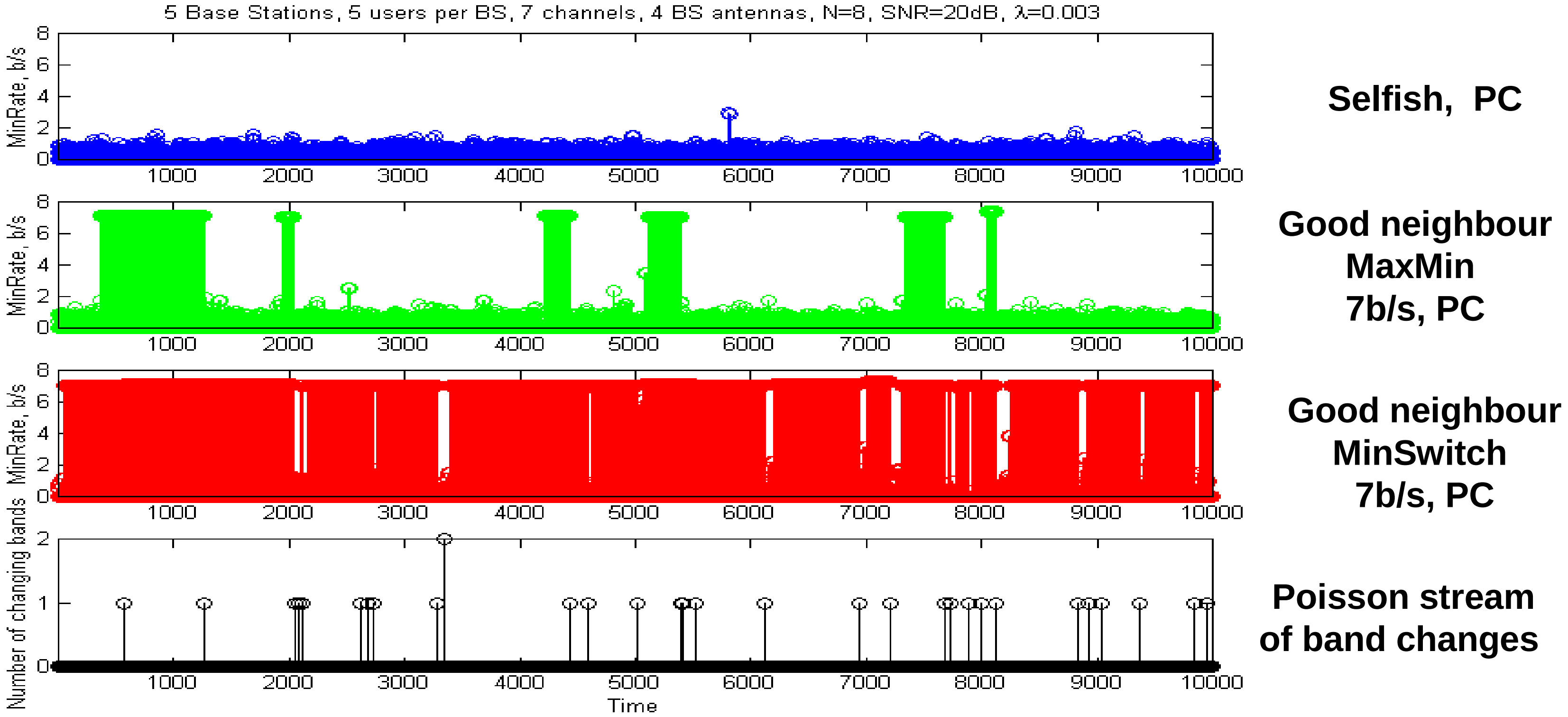
Decentralized IM-based DSA in non-stationary CR scenario

Assumptions

- **Propagation channels in randomly selected bands are randomly changing in time according to the Poisson law**
- **The same bands are available for all secondary subsystems**
- **The number of bands is constant in time**

Interpretation

- **Primary users change their bands at random moments**
- **Secondary subsystems (perfectly) sense the spectrum, detect changes and react (leave one bands and occupy others)**



Conclusions

- Decentralized DSA based on interference mitigation diversity has been addressed in a non-reciprocal environment, where any changes in frequency allocation of a certain subsystem introduce a non-stationary interference scenario for other subsystems in the network.

- A threshold regulated “good neighbour” decentralized DSA has been proposed that is based on minimization of the number of local band changes subject to the QoS constraints.

- Analysis based on the theory of Absorbing Markov Chains and simulation results show that the proposed threshold-regulated IM-based DSA significantly outperforms the conventional decentralized DSA schemes.

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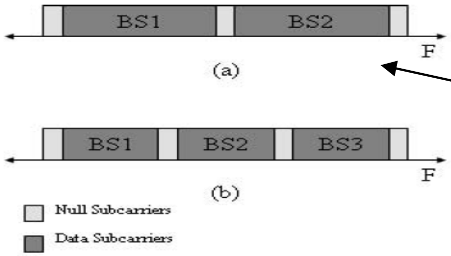
Appendix

PHY requirements for unsynchronized CR networks

PHY requirements for unsynchronized CR networks

OFDM PHY needs guard bands for unsynchronized channels

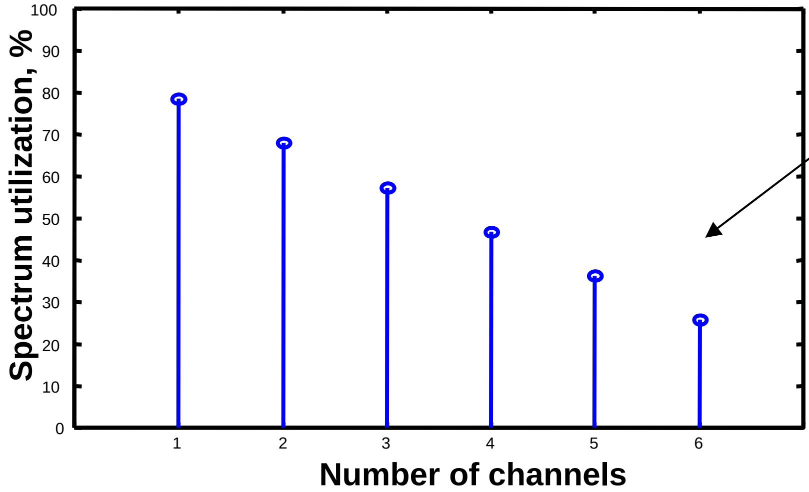
Example [1]: Distributed interference management for unsynchronized 802.16-2004 networks in license-exempt spectrum



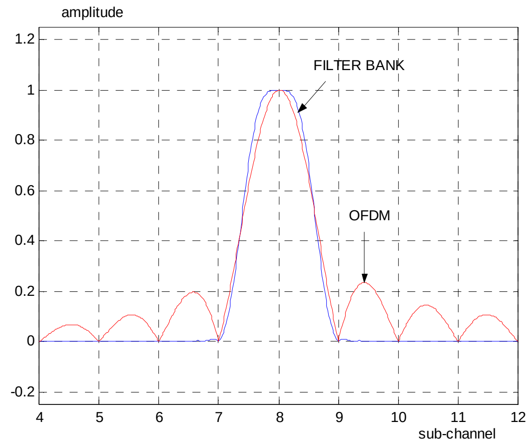
$$\text{Spectrum utilization} = 1 - \frac{(1+\text{Number of channels})\,\text{Number of guard subcarriers}}{\text{Total number of subcarriers}}$$

75% of spectrum wasted for guard bands in 6-channel case

256 sub-carriers, minimum 10 sub-carriers in a channel, 27 guard sub-carriers



PHYDYAS solution: Filter Bank Multi Carrier (FBMC) PHY



[1] O. Ashagi, S. Murphy, L. Murphy, “A distributed approach to interference mitigation between OFDM-based 802.16 systems operating in license-exempt spectrum," in Proc. ICC, June 2007.

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