Decentralized "Good Neighbor" DSA Based on Adaptive Antenna Array Interference Mitigation Diversity: Finite Amount of Data Effects

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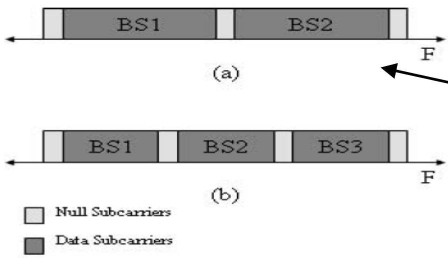
Outline

- PHY requirements for unsynchronized CR networks
- Rule-regulated approach to decentralized DSA
- Summary of the "Good Neighbor" algorithm and its Markov chain analysis
- Finite amount of data effects
- Conclusions

PHY requirements for unsynchronized CR networks

OFDM PHY needs guard bands for unsynchronized channels

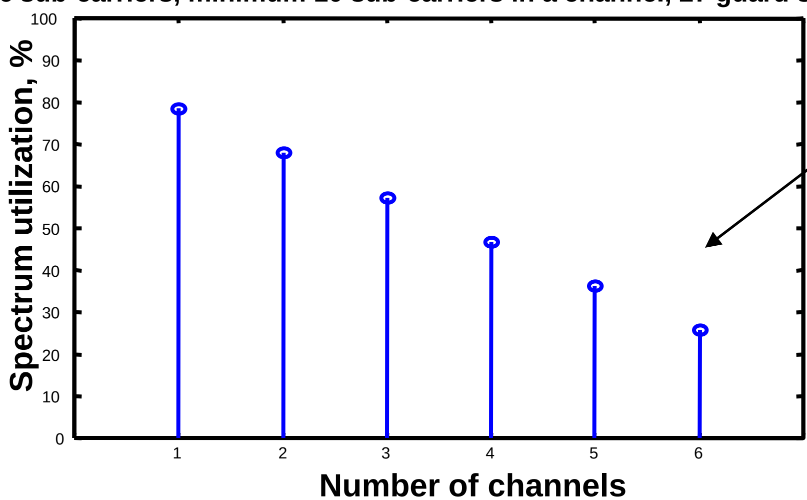
Example [1]: Distributed interference management for unsynchronized 802.16-2004 networks in license-exempt spectrum



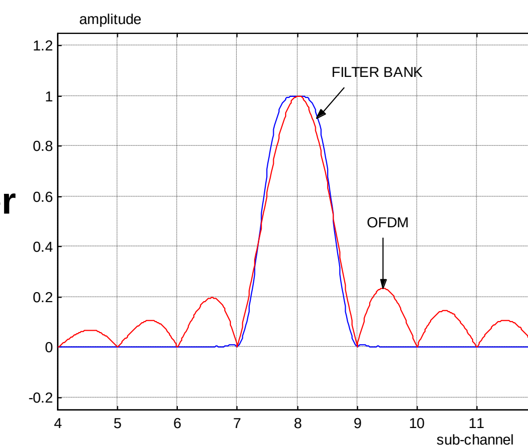
$$\text{Spectrum utilization} = 1 - \frac{(1+\text{Number of channels})\ \text{Number of guard subcarriers}}{\text{Total number of subcarriers}}$$

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 approach: 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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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 with data exchange (possibly at MAC layer) can be used to guarantee convergence.

“Good Neighbor” Rule-Regulated Approach

Question

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

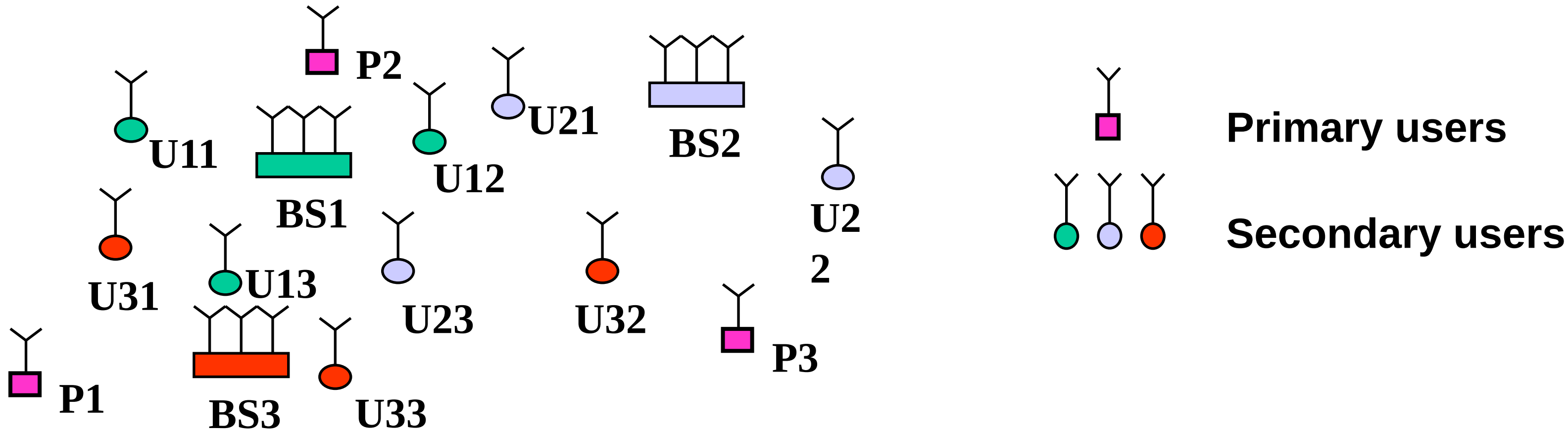
Observation

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

Approach

- Introduce and study new “good neighbor“ (GN) strategies that can be viewed as rule-regulated cooperation between spectrum sharing nodes without explicit data exchange between them.
- Use semi-analytical (analytical for the given channel realizations) Markov chain analysis of convergence/non-convergence probabilities and convergence rates for low-dimension networks to establish the main trends.
- Verify them by simulations and comparison with the performance bounds for higher-dimension networks.

Decentralized DSA in unsynchronized CR networks



Assumptions

- A number of frequency bands are 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.
- Secondary subsystems include base stations equipped with K antennas and single-antenna users transmitting data to their base stations.
- Secondary subsystems are not coordinated and synchronized.
- Secondary base stations have full control on their own users.

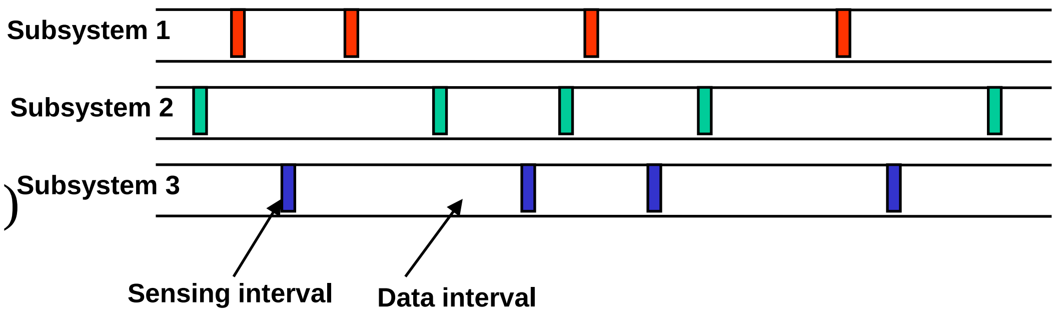
Decentralized DSA in unsynchronized CR networks

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**

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"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” (GN) 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 (modifications to the “selfish” one): Sensing interval

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

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

***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 over subset of band allocations that includes users with SINR below threshold

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

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

Main results

- **GN formulation, performance bounds and Markov chain analysis – IEEE Trans. SP, Apr. 2010.**
- **Simplified DSA algorithms with power control for higher-dimension systems – ICC, June 2009.**
- **Randomized GN-based DSA for reduced non-convergence probability – ICASSP, Mar. 2010.**
- **Rule-breaks effect in rule regulated spectrum sharing networks ("crime and punishment" for cognitive radio) – DySpan, Apr. 2010.**
- **Summary and details – PHYUDYAS Deliverables D8.1 and D8.2, www.ict-phydys.org.**

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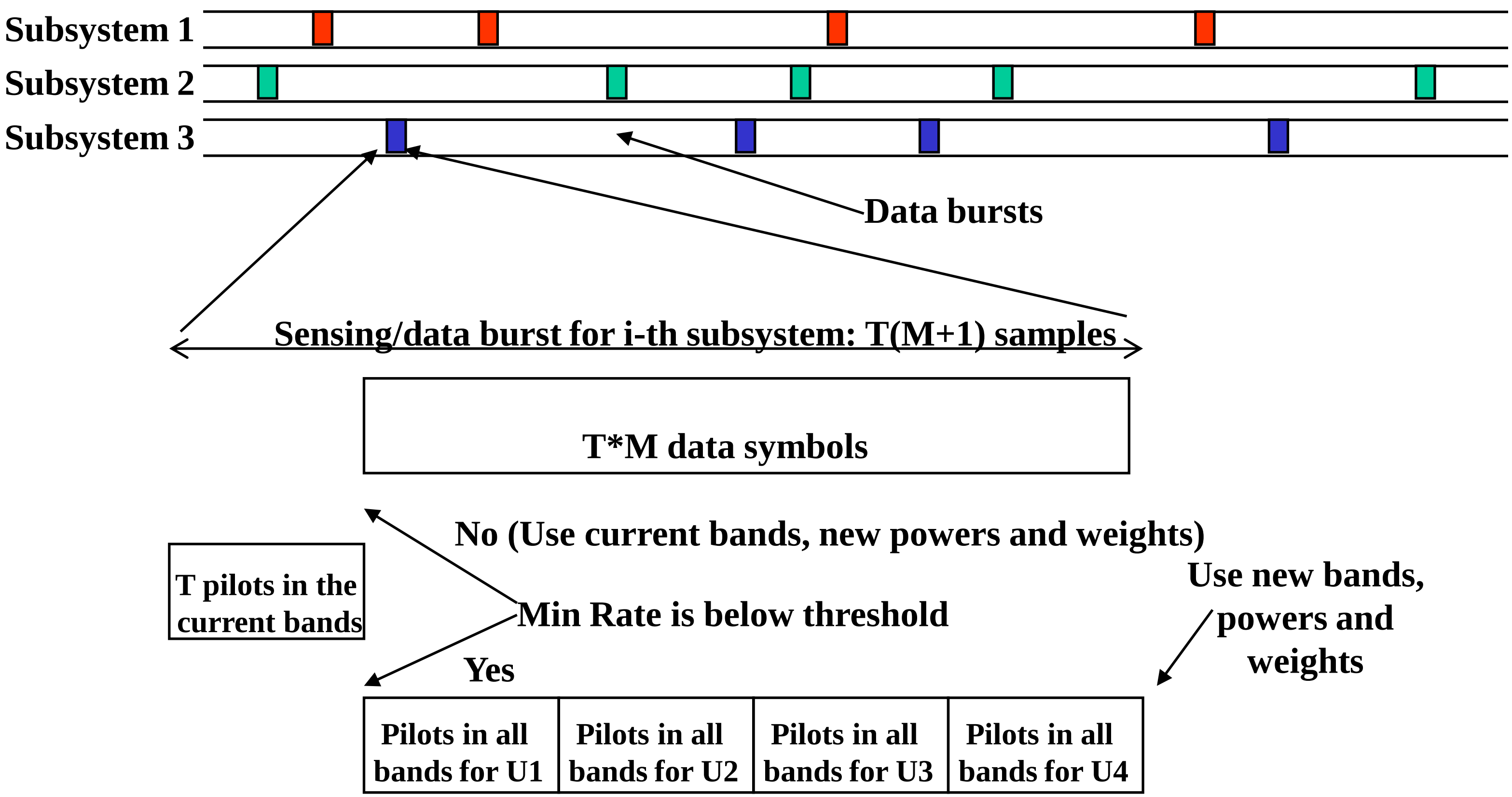
Space-time spectrum sensing protocol

Requirement

- Pilot transmission in all available bands must be avoided after convergence

Simplification

- Users can transmit pilots simultaneously in all available bands



Note: T is the number of pilot symbols
M is the number of users in the i-th subsystem

Markov Chain Analysis of Spectrum Sharing Networks

Locally known second-order statistics

- Calculate the transition probability matrix for the given channel realization and algorithm
- Classify all the states into 3 groups: absorbing, transient and ergodic
- Form absorbing Markov chain by means of replacing the ergodic sub-chains with the corresponding absorbing states
- Calculate probabilities of absorption by the absorbing states (desirable behavior) and ergodic sub-chains (undesirable non-convergent behaviour) and average convergence rates
- Calculate the global performance for the absorbing states

Locally estimated second-order statistics

- Derive distribution of SINR estimated over T pilot symbols
- Calculate the transition probability matrix of the non-absorbing Markov chain
- Introduce a simplified Markov chain model, where the states with $p_{ii} = 1 - \alpha_0$ for the given $\alpha_0 << 1$ are replaced with the absorbing points with $p_{ii} = 1$
- Calculate the corresponding fundamental matrix, locate the ergodic sub-chains (if they exists), and find average absorbing times for all initial states.
- The average absorbing time can be interpreted in this case as the average number of sensing intervals before reaching the sates with probability to leave them less than $\alpha_0 << 1$

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Finite amount of data effects

SINR

$$\nu_{nm} = \mathrm{SINR}_{nm} = \left(1-\hat{\mathbf{g}}^{*}_{d_{nm}n}\hat{\mathbf{R}}^{-1}_{d_{nm}n}\hat{\mathbf{g}}_{d_{nm}n}\right)^{-1}$$

Locally estimated statistics

$$\hat{\mathbf{R}}_{fn} = T^{-1}\sum_{t=1}^{T}\mathbf{x}_{fn}(t)\mathbf{x}^{*}_{fn}(t),\ \ \hat{\mathbf{g}}_{fn} = \sum_{t=1}^{T}\mathbf{x}_{fn}(t)s^{*}_{\mathrm{p}}(t)$$

p.d.f.

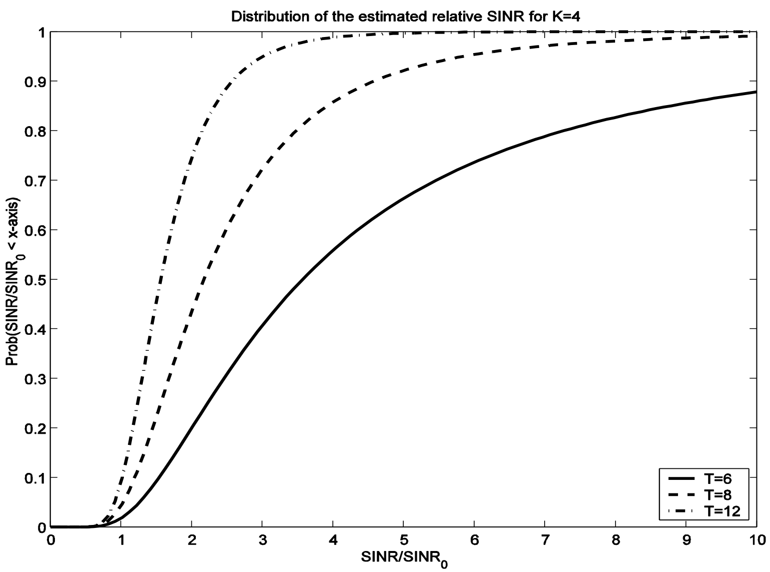
$$\hat{\eta} = \frac{T}{d_{11}},\ \ w(d_{11}) = \frac{1}{\Gamma(T-K)}d_{11}^{T-K-1}e^{-d_{11}}$$

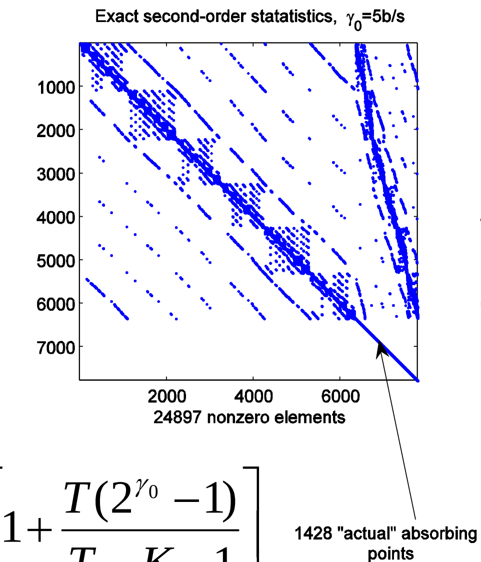
Moments

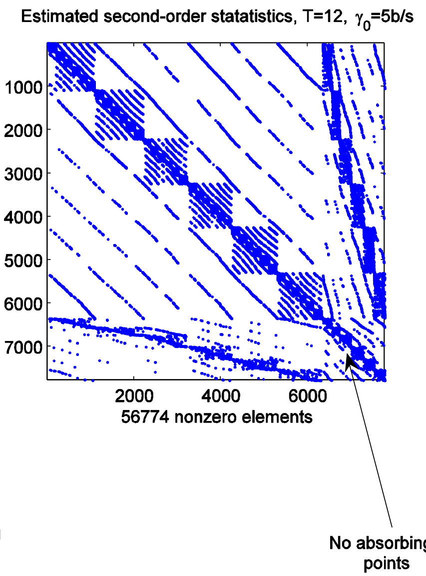
$$\mathrm{E}(\hat{\eta}^{l}) = \frac{T^{l}(T-K-1-l)!}{(T-K-1)!}$$

c.d.f.

$$\mathrm{Prob}(\hat{\eta} < \delta) = e^{-\frac{T}{\delta}}\sum_{t=0}^{T-K-1}\frac{1}{t!}\left(\frac{T}{\delta}\right)^{l}$$



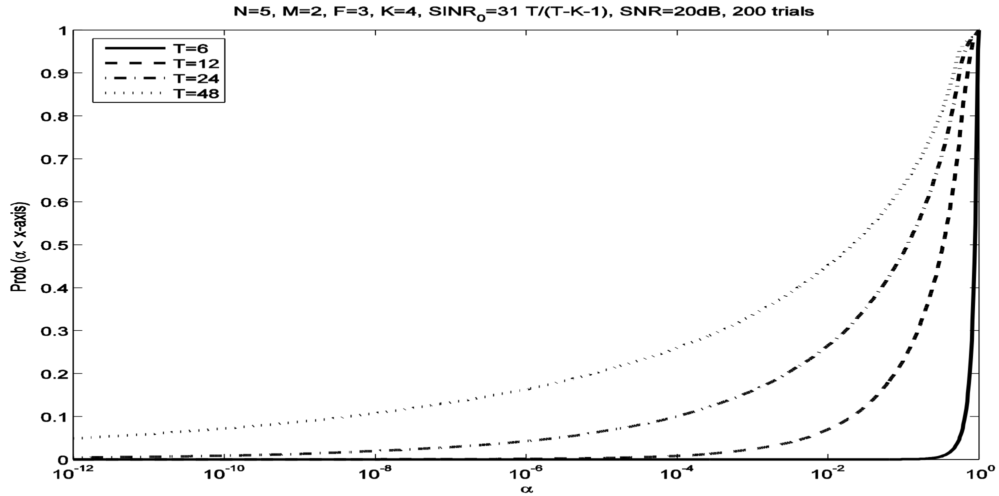


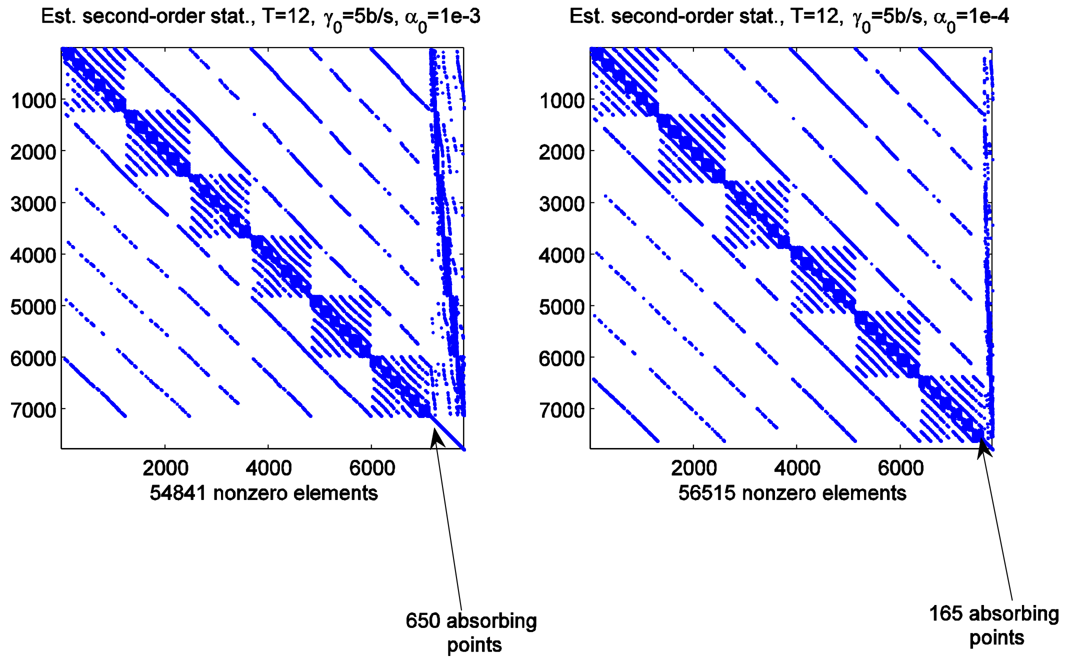


Threshold

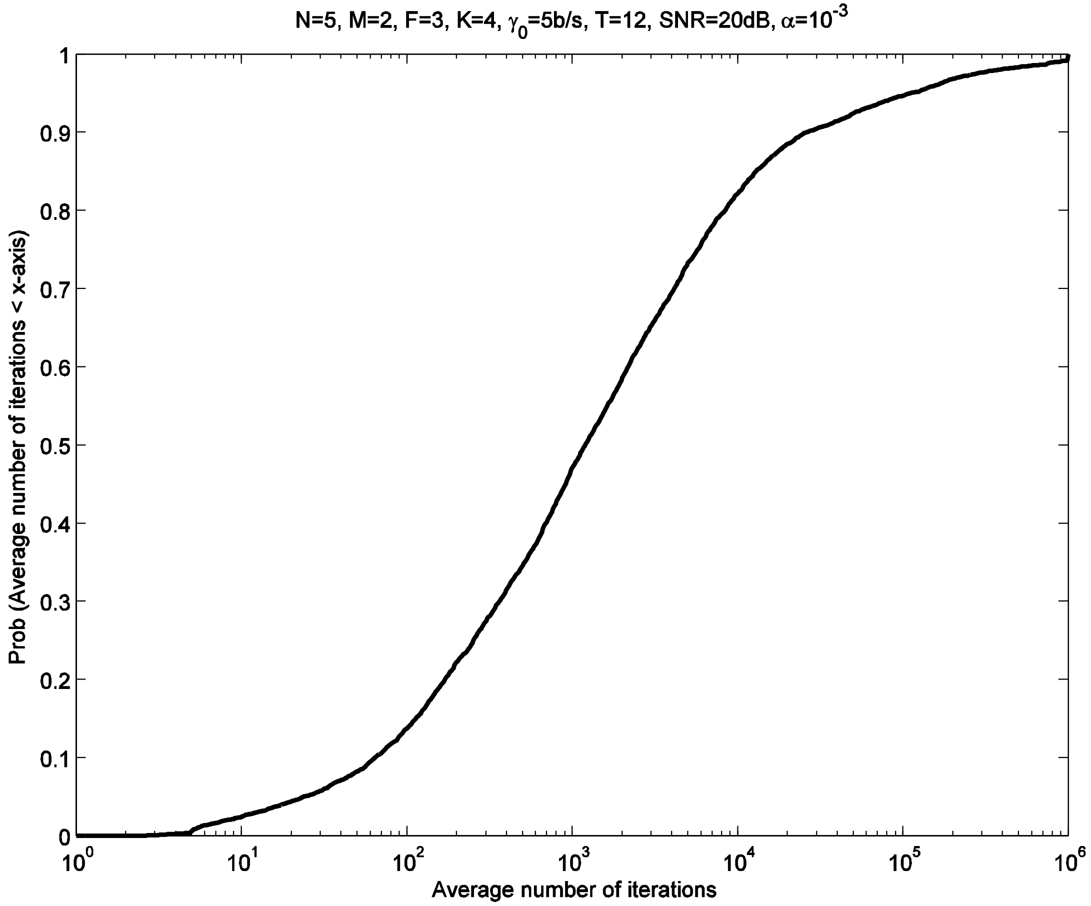
$$\hat{\gamma}_0 = \log_2\left[1+\frac{T(2^{\gamma_0}-1)}{T-K-1}\right]$$

Probability to leave the states corresponding to the "actual" absorbing points and simplified Markov models

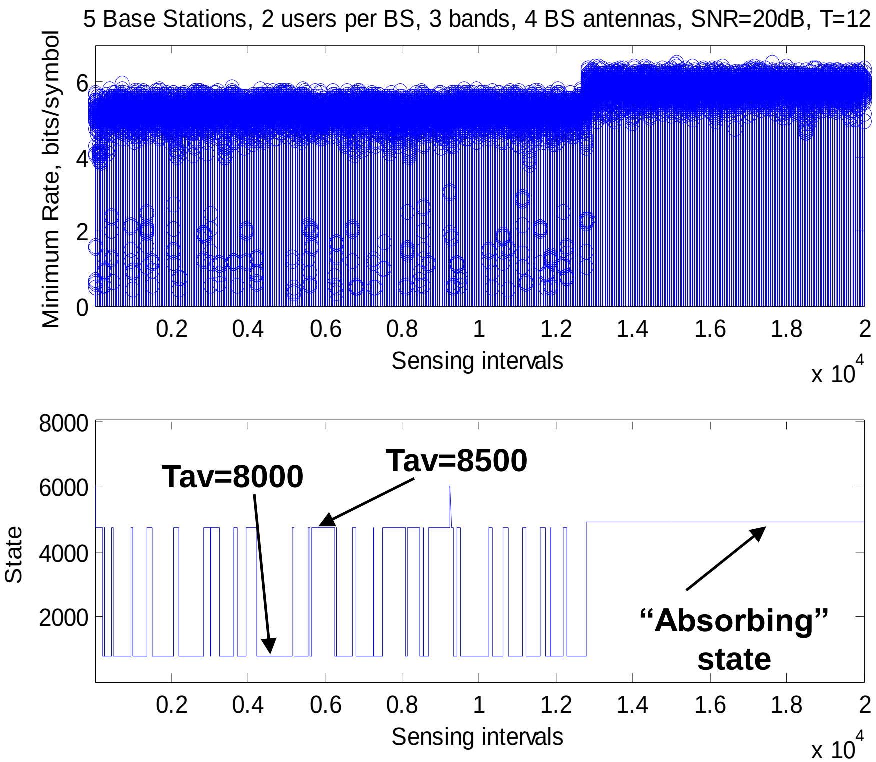


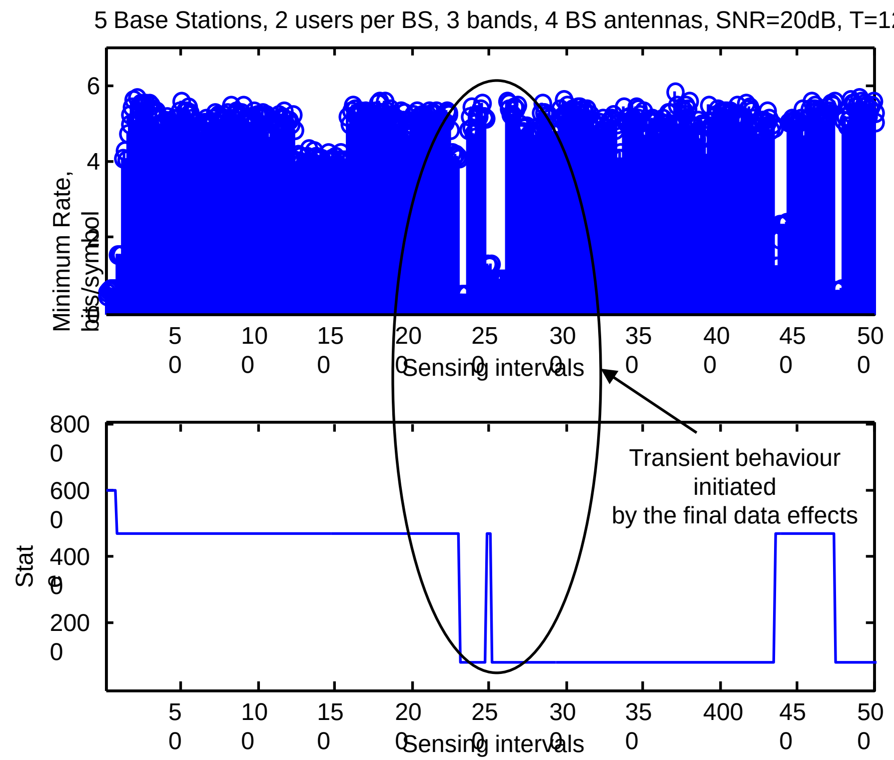


C.d.f. of the average number of sensing intervals before reaching the states with probability to leave them less than 0.001

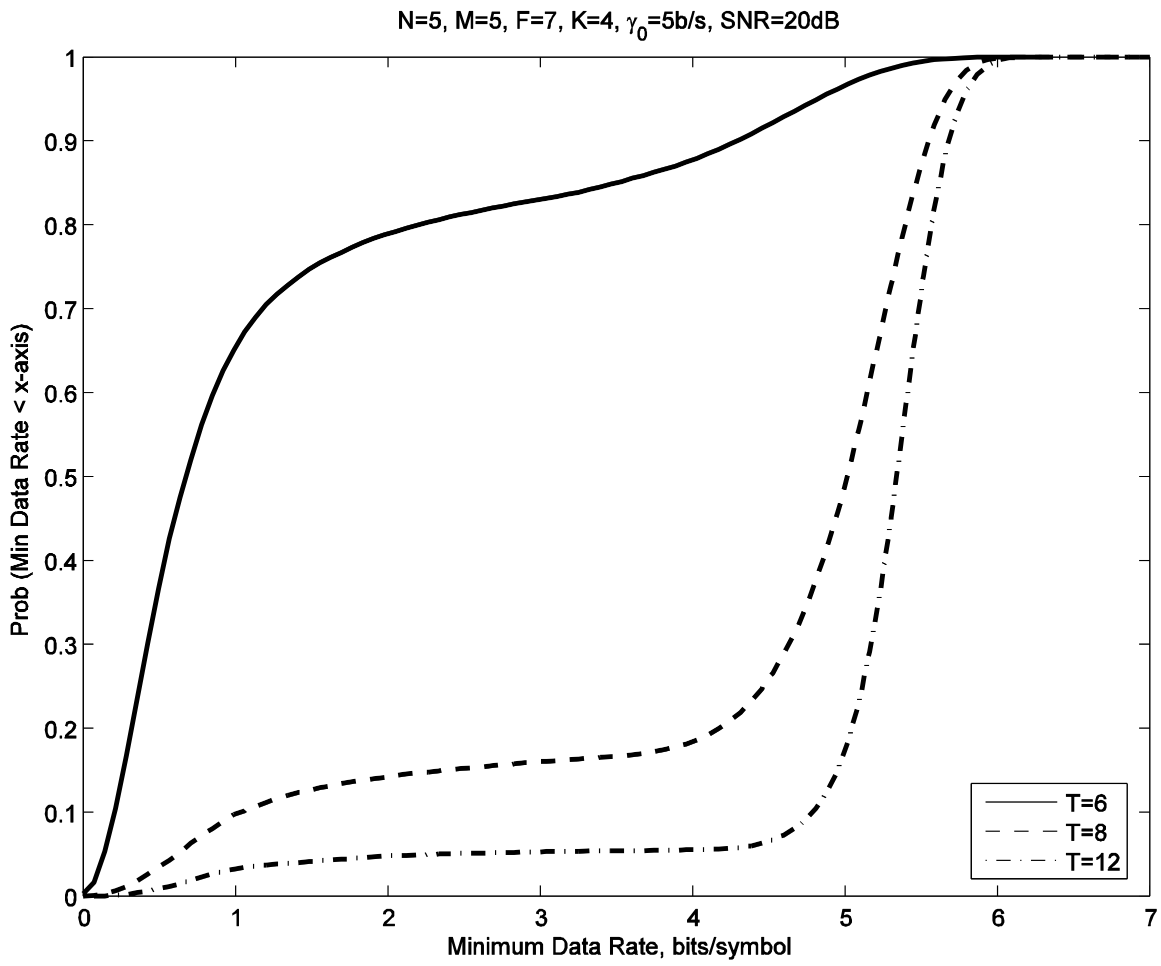


Typical example of long-term behavior





Simulation results for higher-dimension network of 5 sub-systems with 5 users each sharing 7 bands for 4 Rx



Conclusions

- **Space-time spectrum sensing protocol has been proposed for estimation of second-order statistics locally at spectrum sharing sub-systems.**

- **Markov chain analysis and statistical simulations have been applied to investigate finite amount of data spectrum sensing effects in decentralized “good neighbor" DSA in spectrum sharing wireless networks based on FBMC PHY developed at the PHYDYAS project.**

- **Further results on the finite amount of data effects such as adaptive temporal averaging for reduced training support can be found in D8.2, www.ict-phydyas.org.**

Acknowledgement

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On-line threshold selection in scenarios with pathloss and shadowing

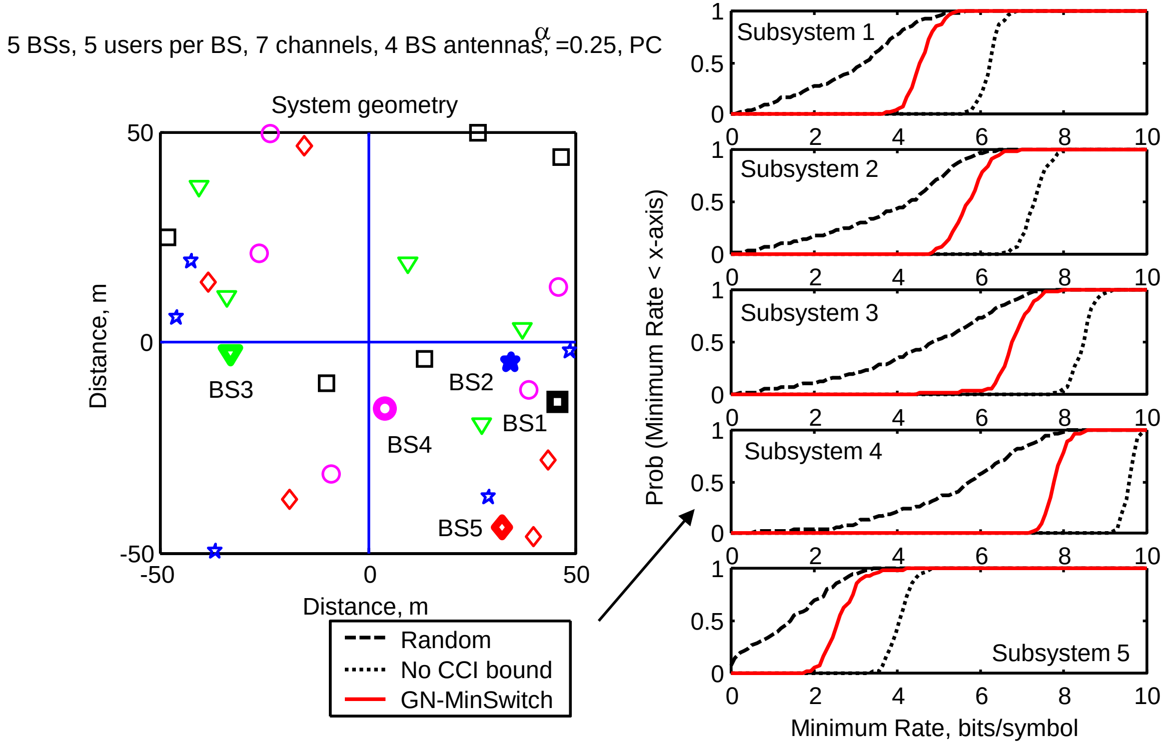
Idea:

• **If interference mitigation is efficient, than the steady-state SINR should be mainly defined by SNR, which can be estimated locally**

Solution:

• **For sufficiently high number of antennas the threshold can be estimated locally:**

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



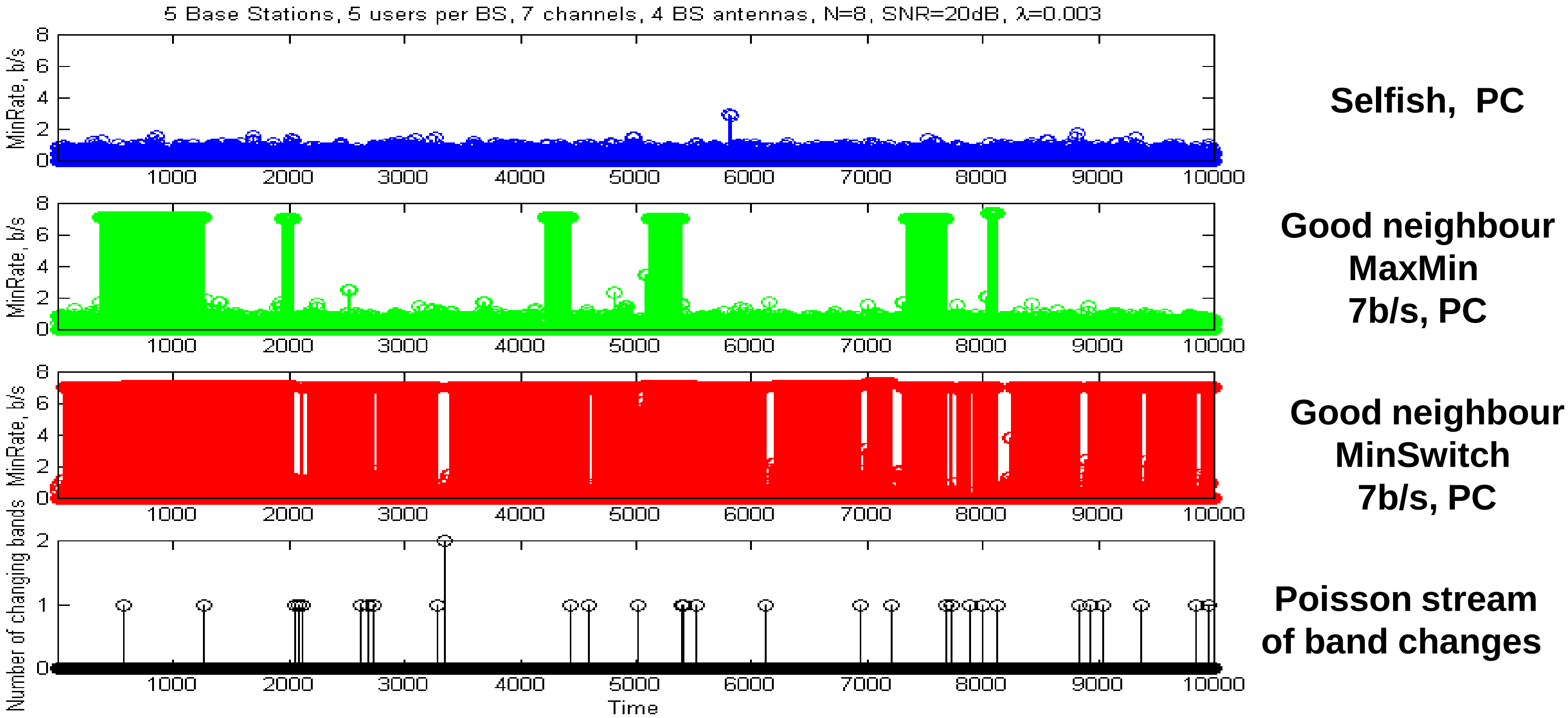
Decentralized IM-based DSA in non-stationary CR scenario

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)



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