Hopping Strategies for Adaptive FH-CDMA Ad Hoc Networks under External Interference

Jens P. Elsner, Ralph Tanbourgi, Jörg Schmid, Friedrich K. Jondral

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Communications Engineering Lab
Prof. Dr.rer.nat. Friedrich K. Jondral

Overview

Hopping strategies for Adaptive FH-CDMA Ad Hoc Networks under External Interference

- **Motivation**
- **System model and hopping strategies**
- **Results**
- **Summary / Q&A**

FH-CDMA in ad hoc networks: Motivation

Every nodes has limited RF bandwidth: multi-channel networks are necessary for a high number of nodes in the network.

Requirements

- Ad hoc network: Infrastructureless communication between arbitrary nodes
- Robustness against external interference
- High number of nodes

- Tactical communication networks
- Overlay (minimum interference) spectrum access
- Robust industrial sensor networks

Applications

Target platform

- Flexible (possibly Software Defined) Radio Platform
- Limited RF bandwidth but high tuning bandwidth

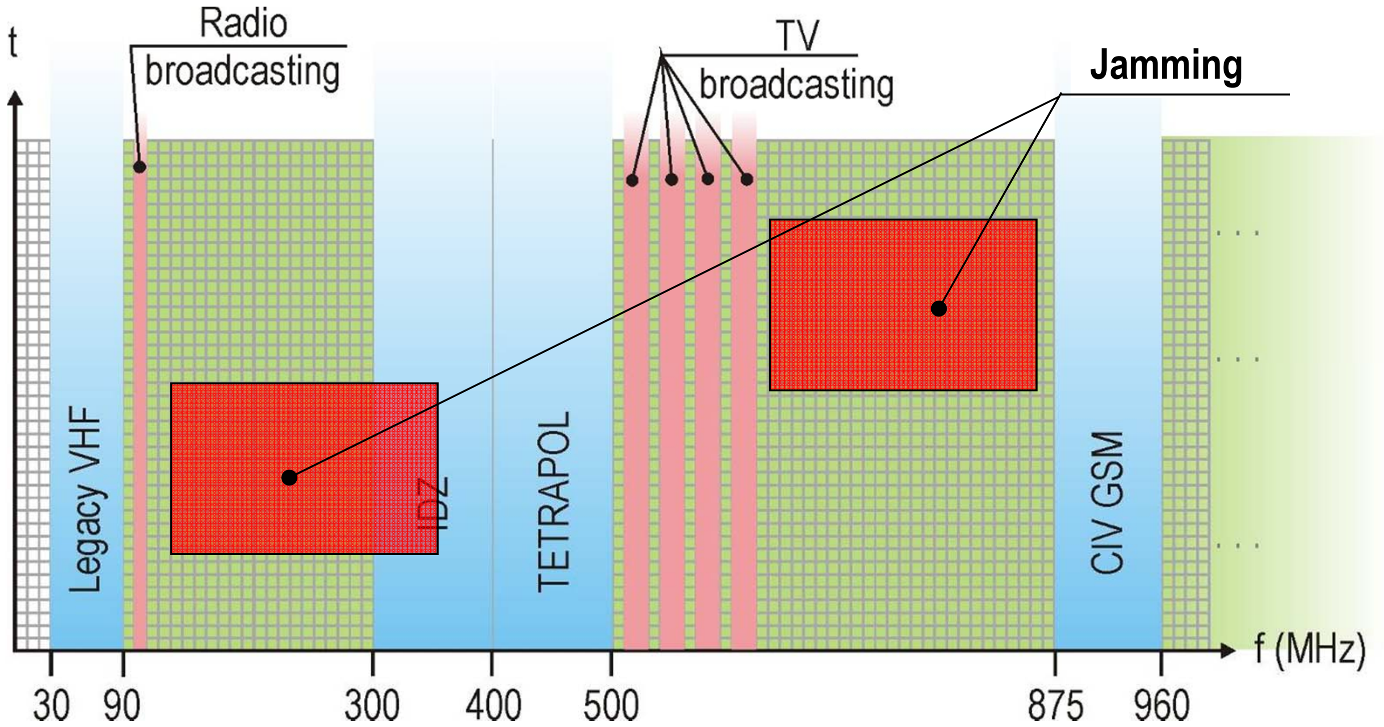
E.g. USRP2

- **Requirements call for multi-channel ad hoc networks with a flexible FDMA component, FH-CDMA**

USRP2 picture source: Ettus Research LLC, http://www.ettus.com

FH-CDMA in ad hoc networks: Motivation

Application example: Overlay spectrum access for highly robust communication; Frequency hopping networks need to minimize MAI and jamming influence.



1. Reduction of internal interference (MAI) through dynamic frequency planning.
2. Reduction of external interference (jamming) by adaptive hopping.

→ Modeling of networks with *stochastic geometry*, analytical and simulative description of average network performance

System model

Stochastic geometry offers a possibility to describe the performance of wireless ad hoc networks analytically, averaged over all possible spatial configurations.

System model

- Node positions of interfering transmitters are described by a homogeneous PPP.
- M orthogonal channels are available for communication. Channel access is synchronized between nodes (slotted ALOHA).
- The PPP model offers analytical tractability and creates a homogeneous interference field: Reference connection can describe the whole network.
- Metric is Shannon outage capacity; Receiver is assumed to work above an SINR threshold; Interference is AWGN with random variance

Possible statements

- Influence of parameters such as bandwidth, path loss exponent, node density, transmission range …
- Comparison of protocol strategies
- Model averages node positions, if a PPP is a realistic assumption has to be decided on case to case basis

See, e.g., S. Weber, J. Andrews, N. Jindal, *An overview of the transmission capacity of wireless networks,* IEEE Transactions on Communications, vol 58, no. 12, December 2010

System model

Core assumptions: Homogeneous Poisson point process, independent choice of channel, reference transmission over distance *r*.

System model

- Node positions X_i of interfering transmitters are described by a homogeneous, marked PPP Φ of density λ.
- Marks m_i denote channels; total of M channels.
- Receiver works above an SINR threshold β; outage probability in channel m is q_m
- Reference transmission takes place over distance r with path loss exponent α subject to fading with coefficient G_0
- External interference level and interference fading in each channel given by $G_N\, N_m$

$$\Phi \triangleq \{(X_i, m_i)\}_{i=1}^{\infty}$$

$$q_m(\lambda_m) \triangleq \mathbb{P}^{!x}\left[\mathrm{SINR}_m < \beta\right] \stackrel{(a)}{=} \mathbb{P}\left[\mathrm{SINR}_m < \beta\right],$$

$$\mathrm{SINR}_m \triangleq \frac{\rho\, G_0 r^{-\alpha}}{G_N\, N_m + \sum_{\Phi_m \setminus \{x\}} \rho\, G_i \|X_i\|^{-\alpha}} = \frac{G_0}{G_N\, \mathrm{NSR}_m + r^{\alpha} \sum_{\Phi_m \setminus \{x\}} G_i \|X_i\|^{-\alpha}}$$

CEL

Optimal hopping strategies

We consider two optimal strategies: 1) Maximization of transmission capacity and 2) maximization of transmission capacity under a constant QoS constraint.

Channel access hopping probabilities given by vector *p*:

Goal is to optimize over this vector to lower outage.

Def.: Average outage probability *q* and transmission capacity *c*

$$q(\lambda, \mathbf{p}) \triangleq \sum_{m=1}^{M} p_m q_m(p_m \lambda) \qquad c(\lambda, \mathbf{p}) \triangleq \lambda(1 - q(\lambda, \mathbf{p}))$$

Optimization problem 1 ("opt"):
Maximizes TC, non-convex

1

$$\mathbf{p}_{\text{opt}} = \arg\min_{\mathbf{p}} \sum_{m=1}^{M} p_m q_m(p_m \lambda) \text{ s.t. } \|\mathbf{p}\|_1 = 1,\ p_m \geq 0$$

Optimization problem 2 ("min-max"):
Maximizes TC with constant QoS

2

$$\mathbf{p}_{\text{opt}} = \arg\min_{\mathbf{p}} \max_{m} p_m q_m(p_m \lambda) \text{ s.t. } \|\mathbf{p}\|_1 = 1,\ p_m \geq 0$$

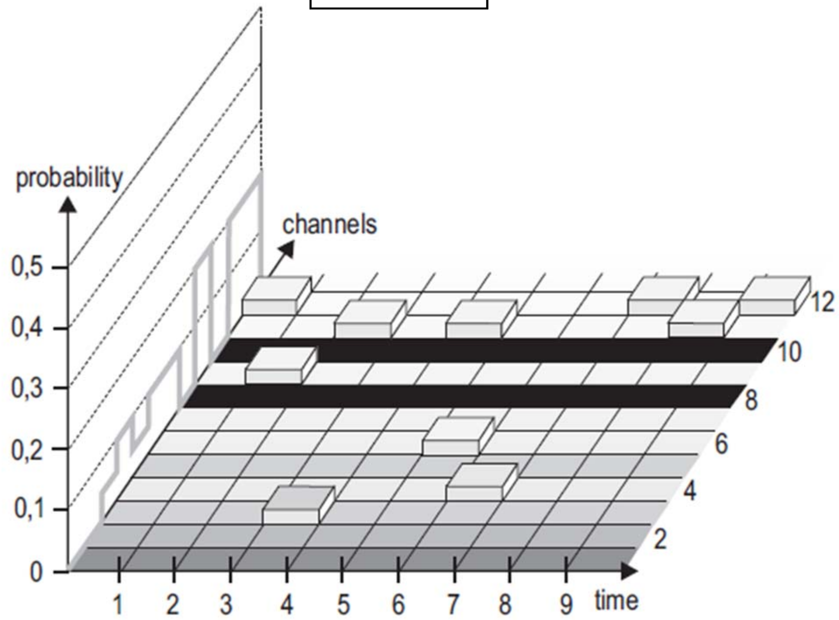
Optimal hopping strategies

Optimal hopping strategies balance internal and external interference in all channels.

Modeling

- **Opt: Maximize TC**
  - Closed form solution in convex region (small l) derived in paper
- **Min-Max: Maximize TC with constant QoS**
  - Closed form solution derived in paper

Illustration



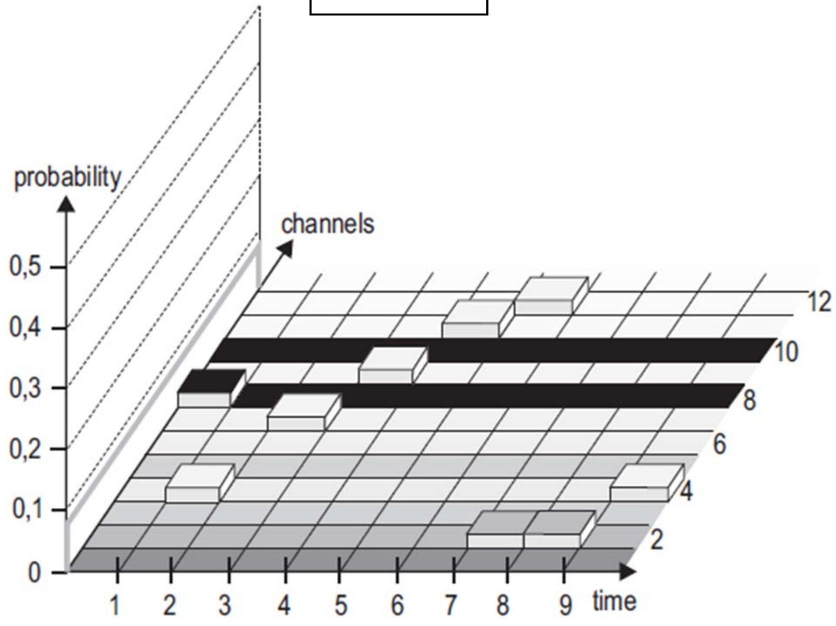
Suboptimal hopping strategies 1/3

Naïve hopping and “best channel only” are used for comparison with adaptive solutions.

Naïve FH-CDMA, best channel

- **Naïve FH-CDMA**: Channel access probabilities are independent of channel qualities
- **“Best channel only”** strategy: All nodes choose the best channel with probability 1

Illustration



Suboptimal hopping strategies 2/3

Threshold-based hopping assures that bad channels are not used and that at least *K* channels are used at all times.

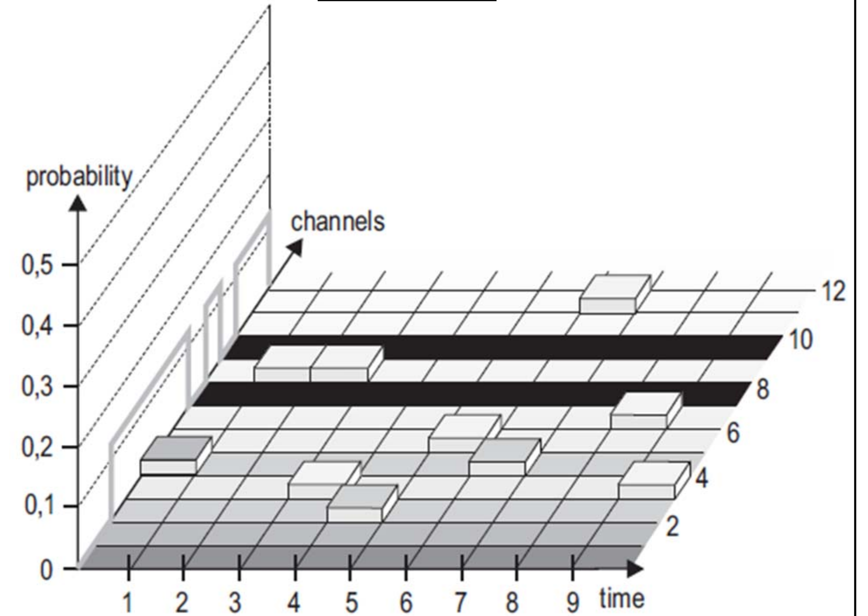
Hard-adaptive thresholding

$$\mathcal{K} \triangleq \{m \in \mathbb{M} : \text{NSR}_m \leq \kappa \vee \text{NSR}_m \text{ among the } K \text{ smallest}\}$$

$$\lambda_m = \begin{cases} \frac{\lambda}{|\mathcal{K}|} & , m \in \mathcal{K} \\ 0 & , \text{otherwise.} \end{cases}$$

- **Hard-adaptive Thresholding**: Hopping with equal probability over at least the k best channels

Illustration



Suboptimal hopping strategies 3/3

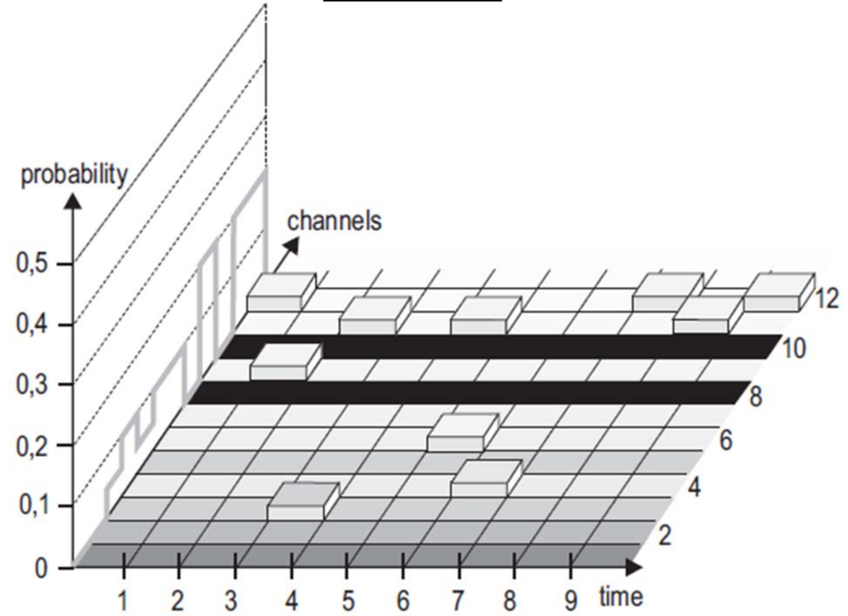
Threshold-based hopping assures that bad channels are not used and that at least *K* channels are used at all times.

Soft-adaptive thresholding

- **Soft-adaptive Thresholding**: Hopping with weighted probabilities over at least the k best channels:

$$\min_{\mathbf{p}} \max_{m} p_m q_m(p_m \lambda)$$
$$\text{s.t. } p_m \geq 0 \text{ if } m \in \mathcal{K},$$
$$p_m = 0 \text{ if } m \in \mathcal{K}^c,$$
$$\|\mathbf{p}\|_1 = 1.$$

Illustration



In summary, we consider

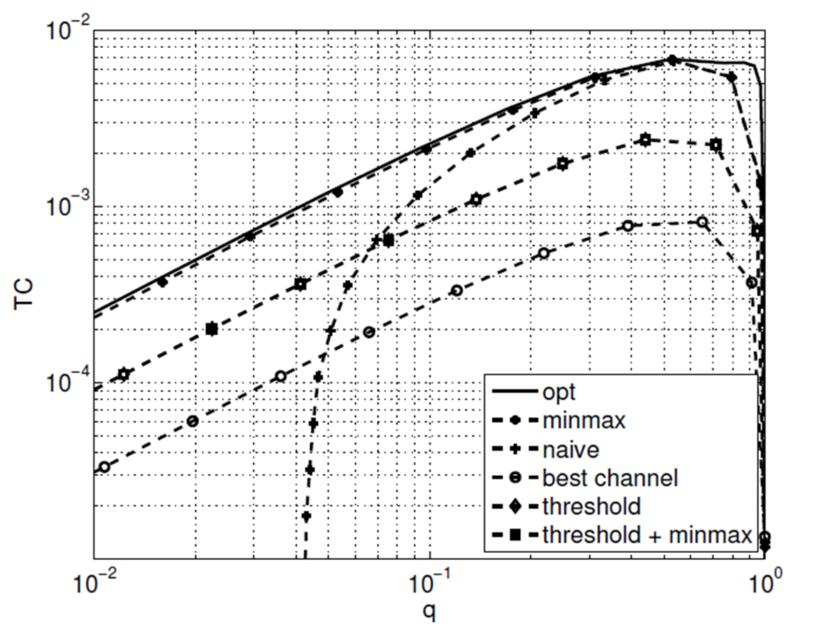
1. naïve, 2. best channel only, 3. soft-adaptive min-max thresholding, and 4. hard-adaptive thresholding

Some results 1/2

Path loss model and Rayleigh model behave differently: Rayleigh fading has non-vanishing outage probability even for $\lambda \rightarrow 0$, due to possible bad fades.

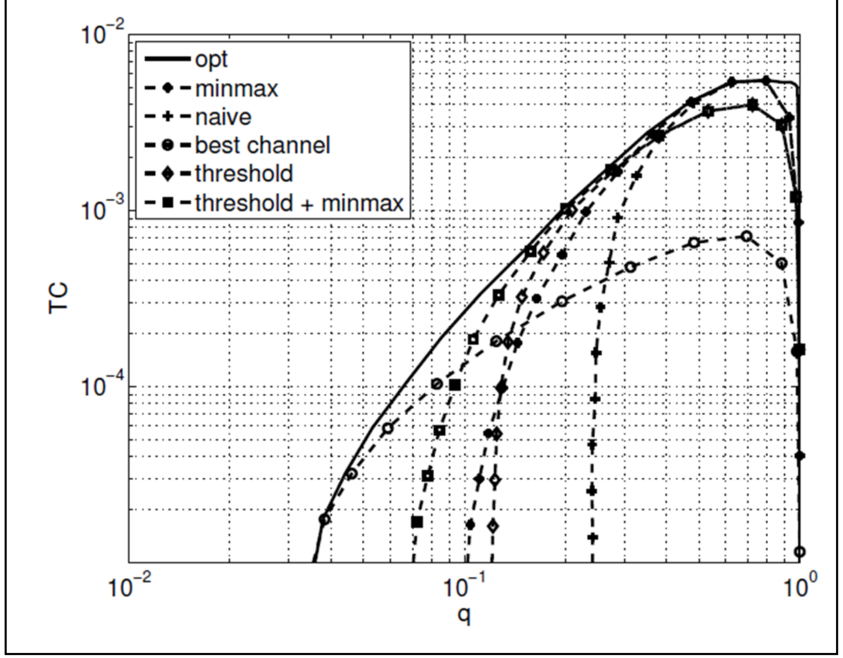
Figure parameters: M=10, r=10, α=4, β=1 and avg. NSR=-5 dB, κ=5 dB, K=3

Path loss model



Low outage: Both optimizations yield same result
Intermediate outage: Thresholding good
High outage: Naïve sufficient

Rayleigh fading model



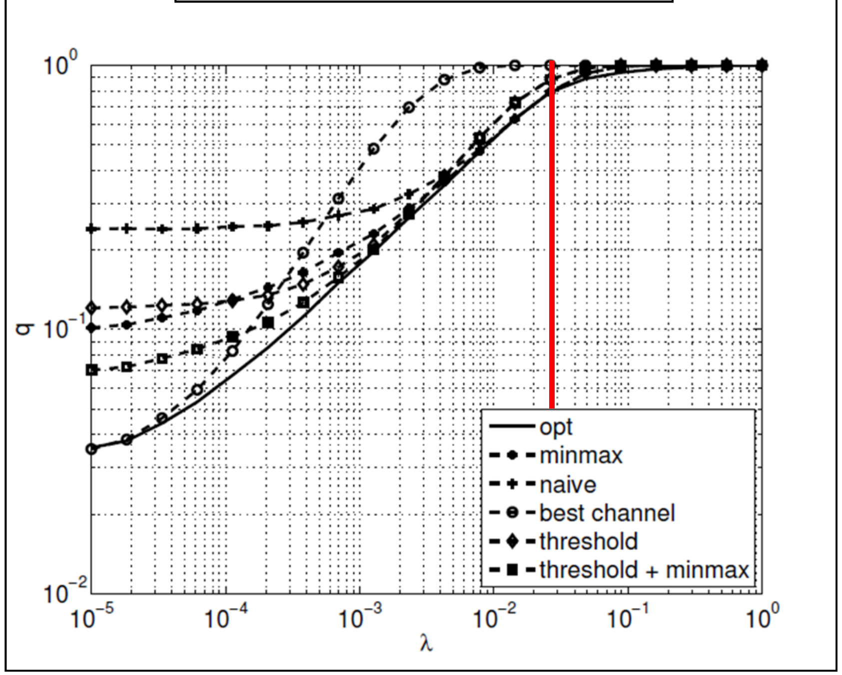
Low outage: Best channel best
Intermediate outage: Thresholding good
High outage: Naïve sufficient

Some results 2/2

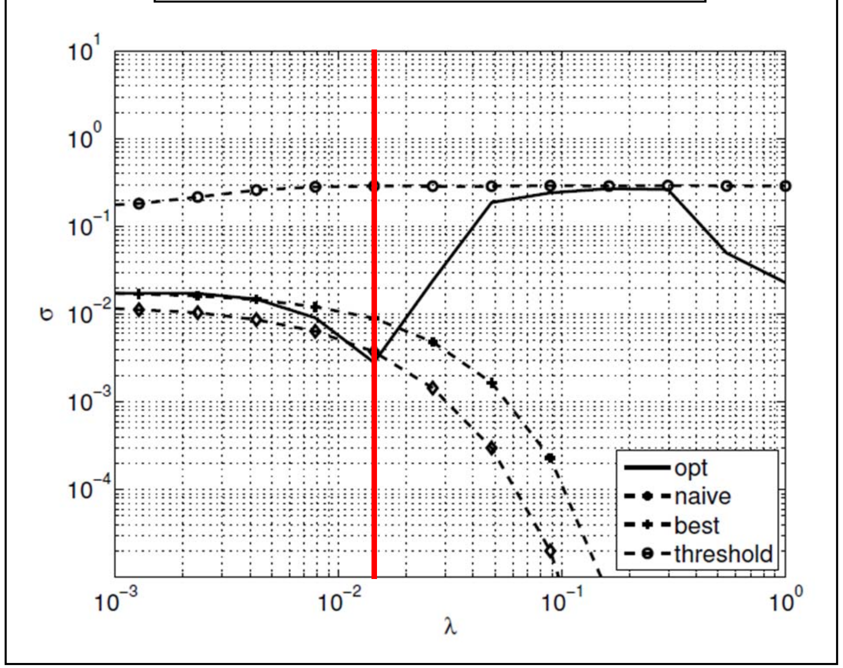
Min-max optimization offers constant outage probability (constant QoS), for other strategies the expected standard deviation depends on the node density.

Figure parameters: *M*=10, *r*=10, α=4, β=1 and avg. NSR=-5 dB, κ=5 dB, *K*=3

Outage probability (Rayleigh model)



Standard deviation of outage probability



Optimization problem becomes non-convex for high λ (note different axes scaling)

Summary: Main points

A good FH-CDMA hopping strategy balances internal and external interference.

1. **Introduced Poisson point process stochastic geometry model for ad hoc networks under external interference**
   - Applications: Analysis of interference avoidance techniques
   - In the paper: Analytical outage probability expressions for optimal strategies in path loss and Rayleigh fading model

2. **Numerical comparison of optimal assignment with practical suboptimal strategies**
   - Naïve hopping, best channel only, thresholding
   - Hard-adaptivity and soft-adaptivity

3. **Protocol design insights**
   - Adaptivity does not offer a gain if node density is high and hence internal interference is dominant
   - If node density is low to average, a min-max strategy with thresholding can achieve close to optimal performance
   - Consistent with mechanism implemented in IEEE 802.15.1

Q&A