Karlsruhe Institute of Technology

A note on Local Receive Channel Scheduling versus Transmit Channel Scheduling in Wireless Ad Hoc Networks

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Overview

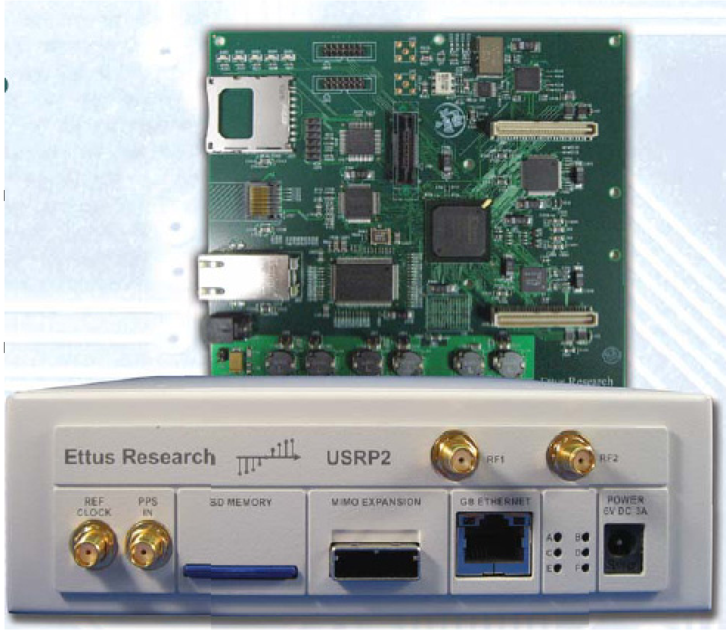
A note on Local Receive Channel Scheduling versus Transmit Channel Scheduling in Wireless Multi-Channel Ad Hoc Networks

- Wireless ad hoc networks: Why multi-channel?
- Modeling using stochastic geometry
- Transmission Capacity with local FDMA scheduling
- Transmit versus Receive Channel Scheduling
- Discussion / Q&A

Wireless Multi-Channel Ad Hoc Networks: Motivation

Every nodes has limited RF bandwidth: multi-channel networks are necessary.

Target platform



e.g. USRP2

Requirements

- **Infrastructureless communication between arbitrary nodes**
- **High robustness against external interference**
- **High number of nodes**

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

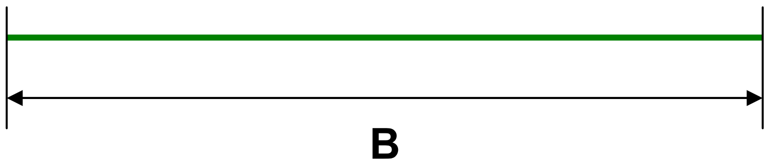
Source: Ettus Research LLC, http://www.ettus.com

Wireless Multi-Channel Ad Hoc Networks: Properties

Multi-channel ad hoc networks substantially differ from single channel networks.

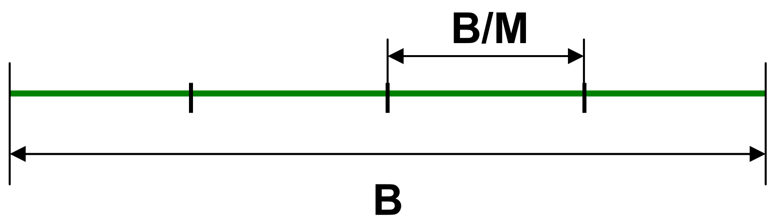
Single channel network

- PHY: More bandwidth is better
- MAC: CSMA/MACAW/IEEE 802.11 …
- Extensive research body available



Multi-channel network

- PHY: How to choose the bandwidth of a single channel?
- MAC: CSMA and derivatives not possible, different solutions needed
- Up until now low relevance in applications, less extensive research body



Multi-Channel Ad Hoc Networks: Research question

What can be gained by local FDMA in ad hoc networks?

Fundamental limits / system design

- What is the optimal split for the operation bandwidth / what is the optimum system bandwidth?
- Which number of nodes can be supported?
- What can be gained by scheduling in the communication range in ad hoc networks?

?

Wireless Multi-Channel Ad Hoc Networks: Modeling

Stochastic geometry offers a possibility to describe ad hoc networks analytically.

System model

- **Node positions of interfering transmitters are described by a homogeneous Poisson point process (PPP).**
- **The PPP model offers analytical tractability and creates a homogeneous interference field.**
- **Metric is Shannon outage capacity; Receiver is assumed to work above an SINR threshold; Interference is AWN**
- **Reference connection (cf. Slivnyak's Theorem) describes the whole network.**

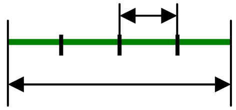
Possible statements

- **Influence of parameters such as bandwidth, path loss exponent, node density, transmission range …**
- **Comparison of protocol strategies such as DSSS-CDMA, FH-CDMA, SIC, FDMA with scheduling etc.**
- **Model averages node positions, if a PPP is a realistic assumption has to be decided on case to case basis**

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

Wireless Multi-Channel Ad Hoc Networks: Modeling

Multi-channel model



SINR

$$\mathrm{SINR} = \frac{\rho r^{-\alpha}}{N_0 B_m + \sum_{i \in \Pi_m(\lambda_m)} \rho |X_i|^{-\alpha}}$$

Outage probability

$$q_m(\lambda_m) = \mathbb{P}\{B_m \log_2(1 + \mathrm{SINR}) \leq R_m\}$$

Transmission Capacity

$$c_m(q_m) = \lambda_m(q_m)(1 - q_m)$$

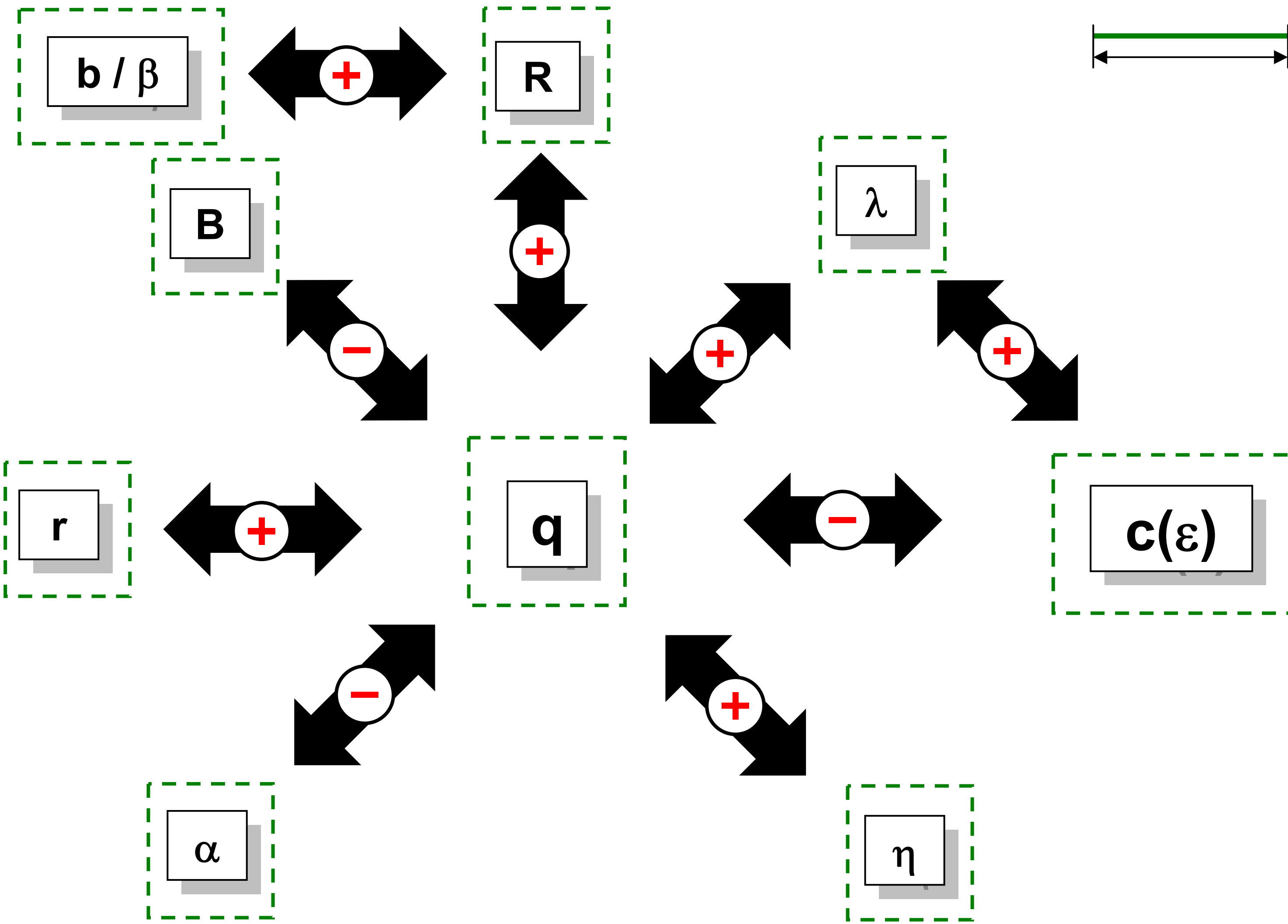
$$c(\epsilon) = \sum_{m=1}^{M} c_m(\epsilon), \epsilon \in (0, 1)$$

- ρ: transmission power
- r: communication distance
- α: path loss exponent
- $\eta_m = N_0 B_m$: noise
- λ_m: interferer density
- X_i: interferer positions
- q_m: outage probability
- $B_m = B/M$: bandwidth
- R_m: transmission rate
- c/c_m: Transmission Capacity

Influence of parameters for a single channel

b / β: spectral efficiency; threshold

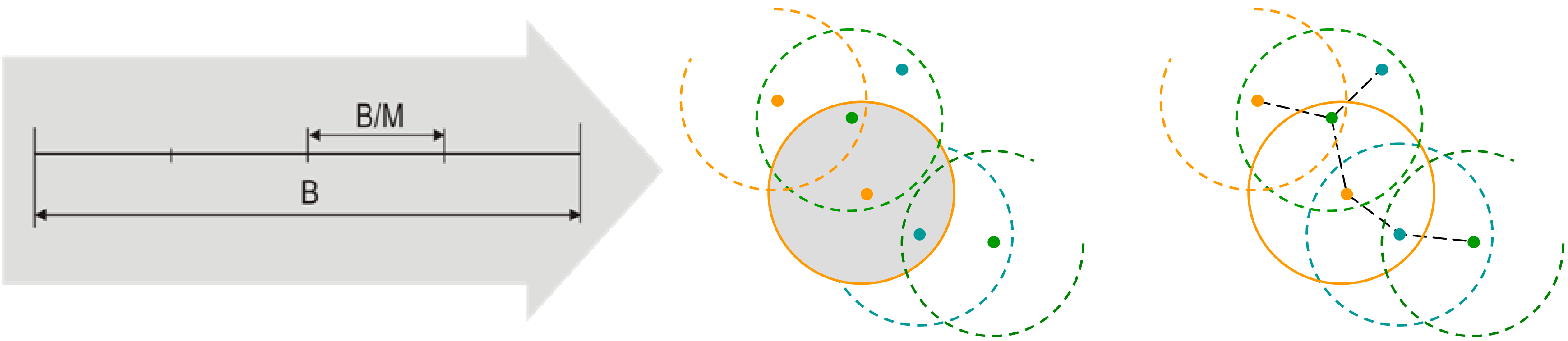
+ Positive influence
− Negative influence



Multi-Channel Ad Hoc Networks: Local FDMA

Neighbors in communication range r use different channels.

Local FDMA in ad hoc networks



Brooks' theorem
▪ Node coloring with M colors possible, if no node has more than M neighbors.

J. Elsner, R. Tanbourgi, F. Jondral: On the transmission capacity of wireless multi-channel ad hoc networks with local FDMA scheduling, International Congress on Ultra Modern Telecommunications and Control Systems, October 2010

Multi-Channel Ad Hoc Networks: Local FDMA

When is locally orthogonal transmission possible on a network scale with high probability?

System model

- **Reference transmission (cf. Slivnyak's Theorem) describes the whole network**
  - **Condition: Local results apply globally.**
  - **Local results apply, if network orthogonalization is feasible with high probability.**
- Node positions are described by a homogeneous Poisson point process.
- **Network is limited to K nodes.**

Network orthogonalization

$$\mathrm{P}\left\{\max\{N_1, N_2, ..., N_K\} \leq M-1\right\} > 1-\epsilon_o$$

$$1-\epsilon_o(M) < \left(\sum_{i=0}^{M-1} \exp(-\lambda_n)\frac{\lambda_n^i}{i!}\right)^K$$

$$= \Phi(M, \lambda_n)^K$$

$$M \geq \Phi^{-1}\left((1-\epsilon_o)^{\frac{1}{K}}, \lambda_n\right)$$

$\lambda_n = \pi r^2 \lambda$: Mean number of neighbors

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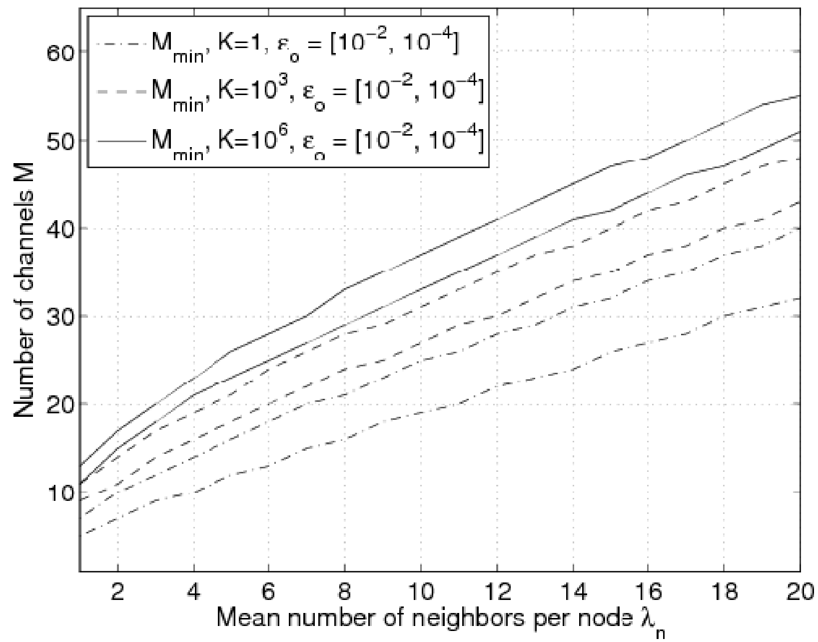
Network orthogonalization



$$M \geq \Phi^{-1}\left((1-\epsilon_o)^{\frac{1}{K}}, \lambda_n\right)$$

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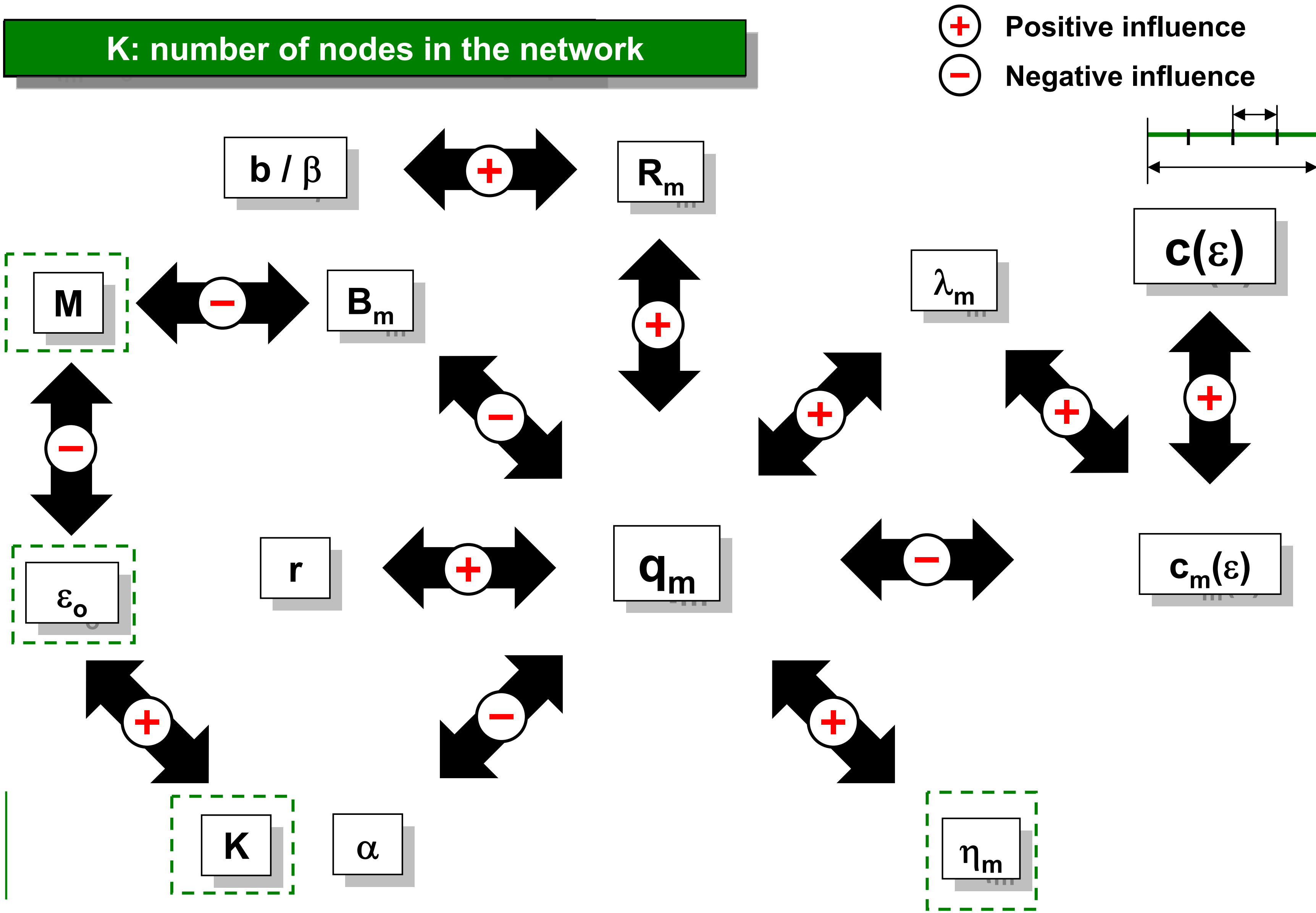
CEL

Influence of parameters in multi-channel model

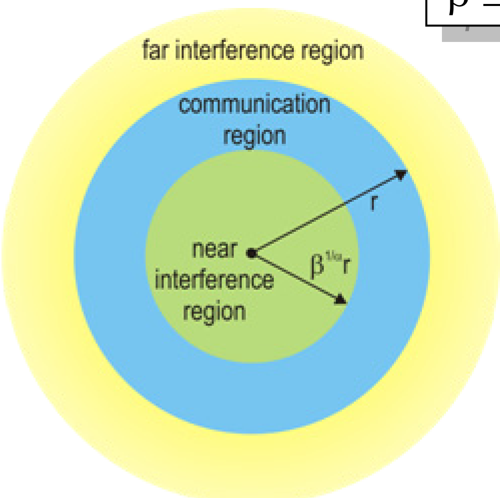
K: number of nodes in the network



Local FDMA: Results

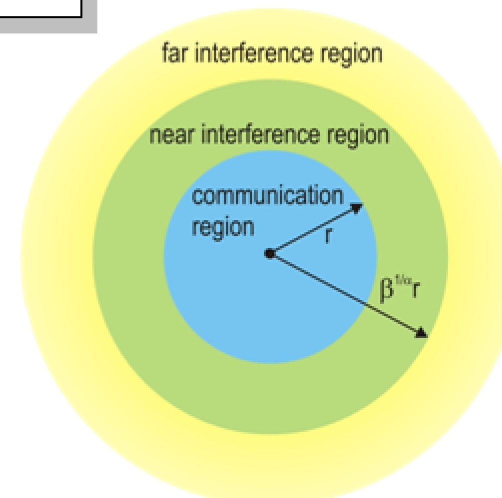
Local FDMA: No analytical solution for SIR distribution, lower and upper bounds needed.

β ≤ 1



$$p_o = \sum_{i=0}^{M-1} \exp(-\lambda_n) \frac{\lambda_n^i}{i!}$$

β > 1



$$1 - q(\lambda) = p_o(\lambda)\mathbb{P}\{Y_r(\lambda) \leq \beta^{-1}\} + (1 - p_o(\lambda)) \mathbb{P}\{\text{no node within } r_s\}\mathbb{P}\{Y_{r_s}(\lambda) \leq \beta^{-1}\}$$

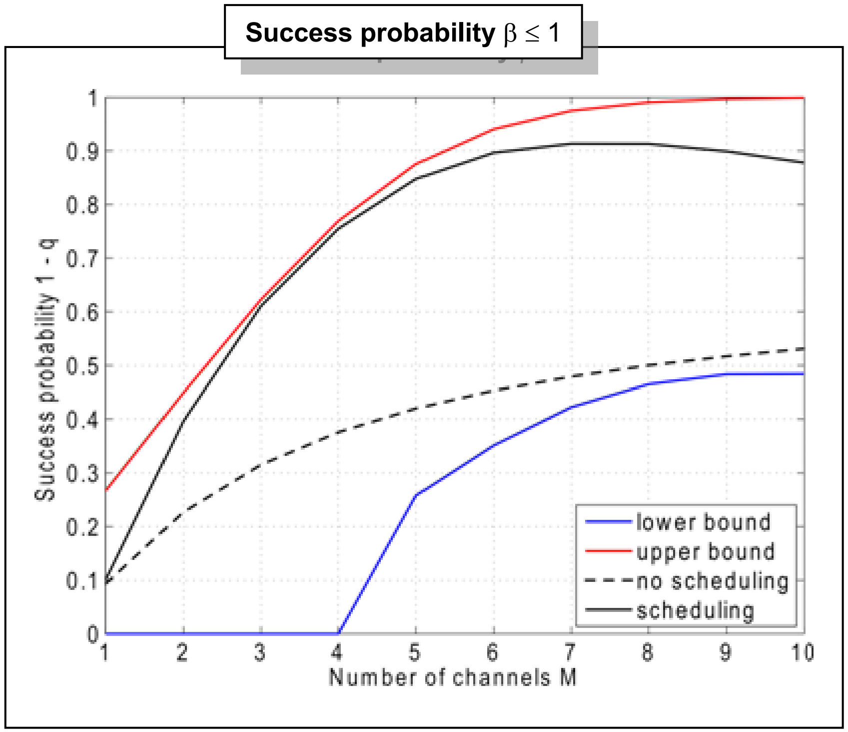
$$1 - q(\lambda) = p_o(\lambda)\mathbb{P}\{\text{no node in annulus}\} \mathbb{P}\{Y_{r_s}(\lambda) \leq \beta^{-1}\}$$

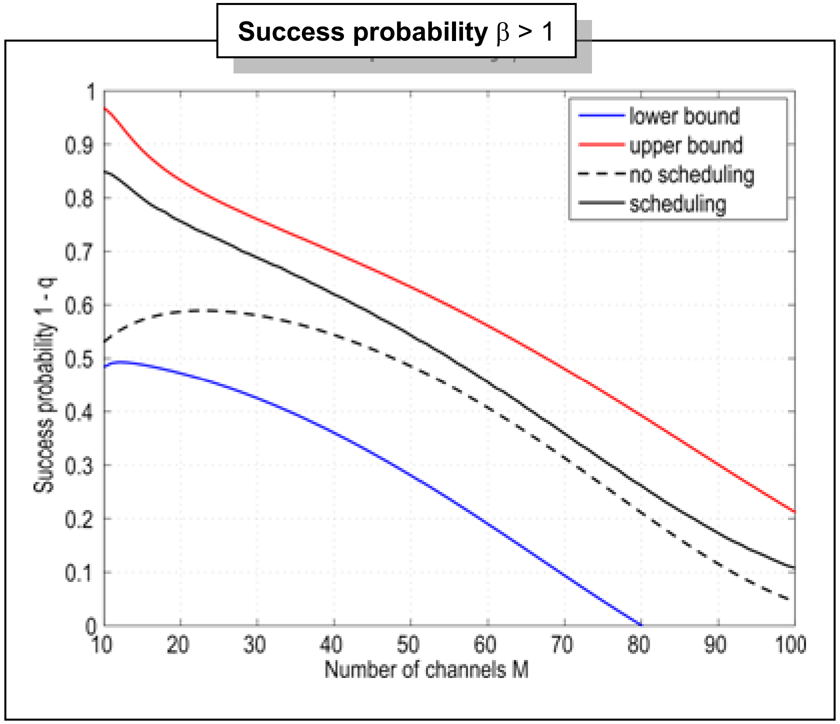
J. Elsner, R. Tanbourgi, F. Jondral: On the transmission capacity of wireless multi-channel ad hoc networks with local FDMA scheduling, International Congress on Ultra Modern Telecommunications and Control Systems, October 2010

Local FDMA: Results

Local FDMA scheduling lowers outage probability.

Figures for $R_m/B = 0.1$, $\lambda_n = 5$, $\alpha = 4$ **and** $r = 10$



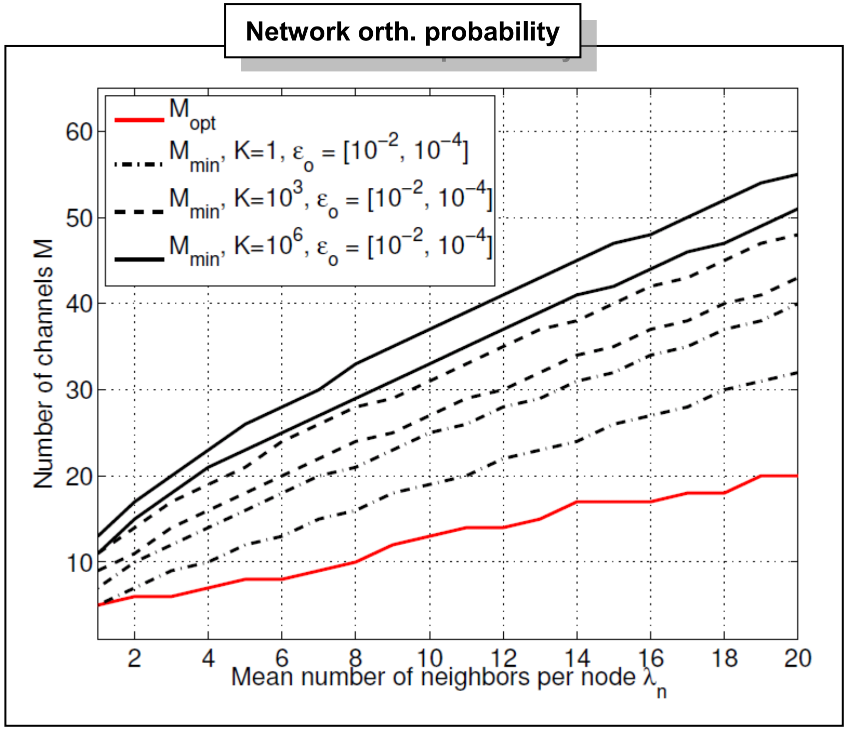


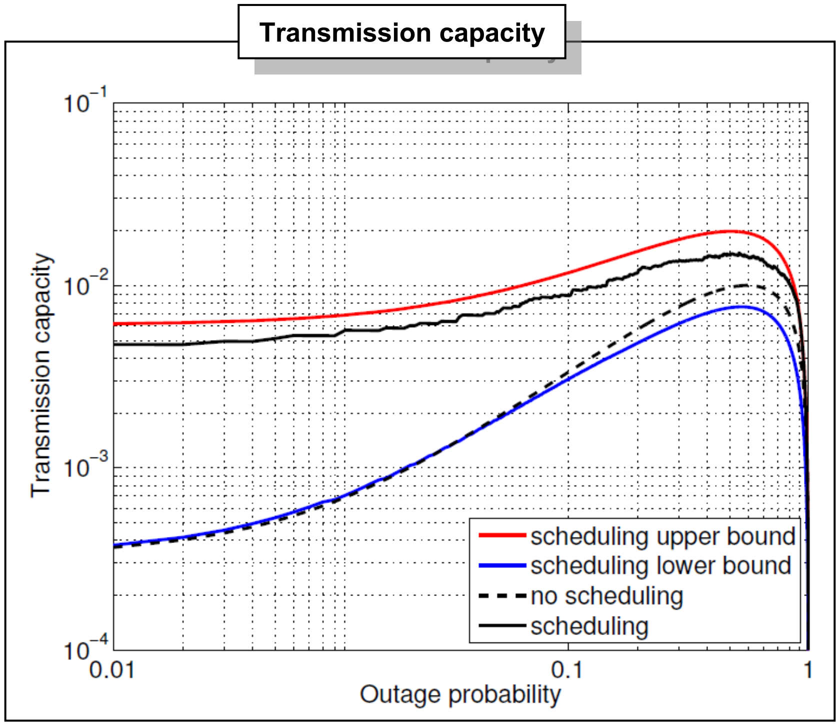
Optimum number of channels now depends on λ

Local FDMA: Results

Local FDMA: Network orthogonalization dominates number of channels.

Figures for $R_m/B = 0.1$, $\lambda_n = 5$, $\alpha = 4$ **and** $r = 10$





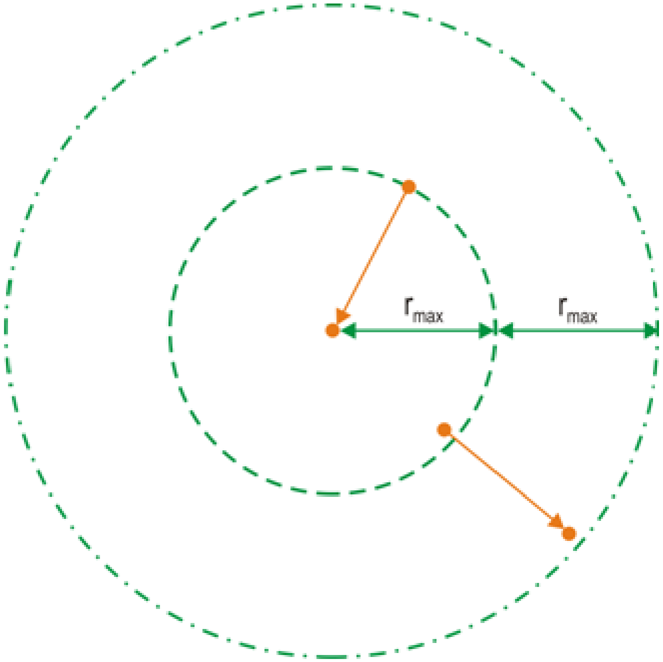
High gains possible (here: factor 1.35 – 13)

Local FDMA: receive versus transmit scheduling

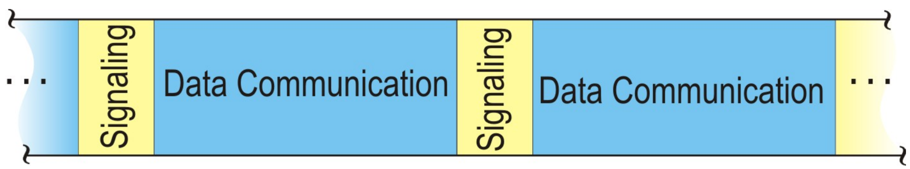
A-priori knowledge of transmit channels to be used not always available.

Medium access with local FDMA

- **To orthogonalize next neighbors, *contention resolution* is necessary.**
- **CSMA und similar methods are not suitable for multi-channel networks**
- **Alternative: Receive channel orthogonalization**



Receive channel orthogonalization within 2 r_{max} leads to transmit orthogonalization within r_{max}



Contention resolution in signaling phase

Local FDMA: receive versus transmit scheduling

Receive channel scheduling has a disadvantage at low densities.

Receive channel scheduling

- **For same scheduling radius r: disadvantages at low densities**
- **Alternative: Scheduling within $2r_{max}$ by e.g.,**
  - **Using lower rate R_s**
  - **Scheduling over several hops**
  - **Using information from non decodable signals (noise level)**

Tx versus Rx Scheduling

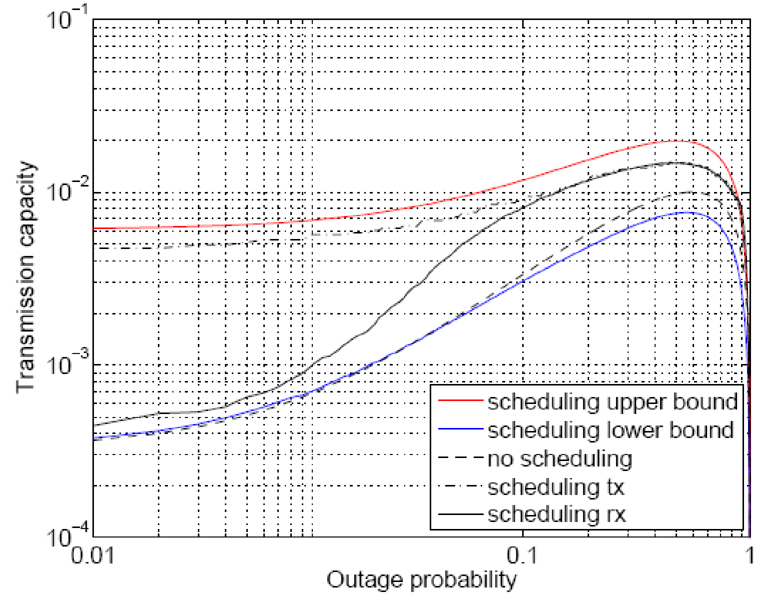


Figure for $R_m/B = 0.1$, $\alpha = 4$, $r = 10$, $K=1000$, $\varepsilon_o=10^{-2}$

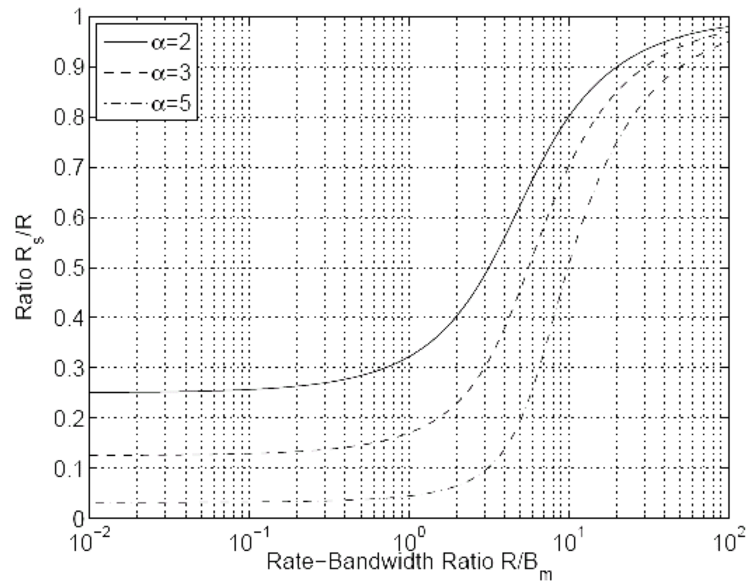
Local FDMA: receive versus transmit scheduling

Receive channel scheduling has a disadvantage at low densities.

Scheduling within $2r_{max}$ with rate R_s

- **Needs to be robust even with uncoordinated medium access (“cold start”)**
- If spectral efficiencies are low, rates need to be lowered significantly, for high spectral efficiencies the rate reduction is minor
  - For small R/B_m: $R_s/B_m \rightarrow 2^{-\alpha}$
  - For large R/B_m: $R_s/B_m \rightarrow 1$
- **Conclusion: High spectral efficiencies (e.g. FH-CDMA systems) are preferable for coordinated access**

Necessary ratio Rs/R for scheduling within $2r_{max}$



On-going research

Algorithms for channel assignment in ad hoc networks and practical aspects.

Theoretical limits

1

- Further research on FDMA: Scheduling beyond the communication range
- Comparison with SIC, *Fading,* MIMO
- Including external interference in the model

FDMA in ad hoc networks

Practical algorithms

2

- Protocol design, PHY/MAC
- Graph coloring algorithms for channel selection
- Describing performance in the PPP model

Discussion / Q&A

Further questions, feedback appreciated:
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