



Transmission Capacity of Wireless Ad Hoc Networks with Multiple Antennas

Marios Kountouris

Wireless Networking & Communications Group

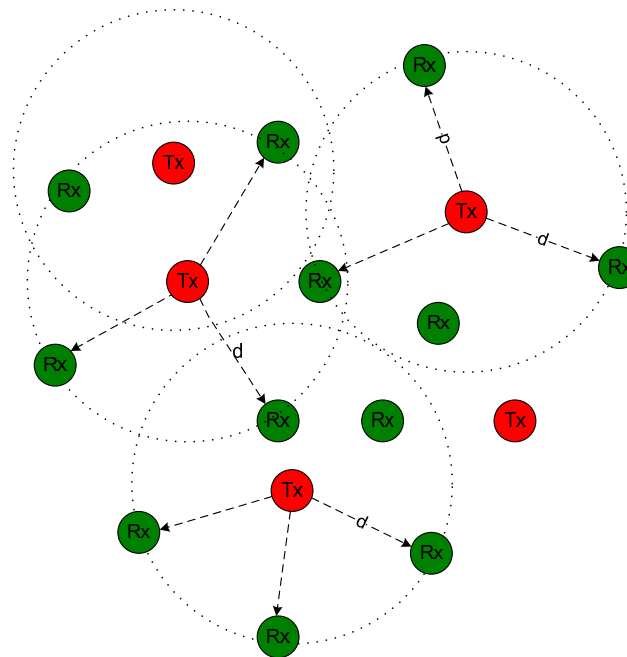
Dept. of Electrical & Computer Engineering

The University of Texas at Austin

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We consider a wireless ad hoc network with multi-antenna nodes



Question: How to efficiently use multiple antennas (degrees of freedom) to enhance network performance?

Answer:

- ▲ receive antenna processing is of cardinal importance.
- ▲ choice depends on the availability of CSI.

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- Introduction
- Network Model
- Transmission Capacity Framework
- Multi-Antenna Wireless Ad Hoc Networks
- Perfect Channel Knowledge
- Linear Precoding with CSIT
- Imperfect Channel Knowledge
- The Way Forward



Talk Outline



▶ Talk Outline

Introduction

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- ▲ Wireless Ad Hoc Networks: Introduction & Motivation
- ▲ **PART I:** Transmission Capacity: what, why and how?
- ▲ **PART II:** SDMA Multi-Antenna Ad Hoc Networks
 - Perfect Channel knowledge
 - Dirty Paper Coding
 - Linear Precoding
 - Limited feedback
- ▲ Concluding Remarks & Perspectives



Wireless Ad Hoc Networks



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- ▲ Ad hoc networks are peer-to-peer with no pre-existing infrastructure
- ▲ The most **general** wireless networks: single-hop, relay, interference, mesh, and star networks are special cases
- ▲ Variety of applications:
 - Home networking
 - Emergency/rescue and medical operational networks
 - Military communications
 - Sensor networks
 - Metropolitan mesh networks
- ▲ Attractive characteristics:
 - Decentralized and mobile
 - Dynamic, highly flexible, and self-organizing
 - Large scale

Network Information Theory



What is the capacity of ad hoc networks?

- ▲ **The Holy Grail:** general end-to-end capacity results for wireless ad hoc networks are difficult to derive!
- ▲ Shannon IT was a Success Story:
 - fundamental limits & design driver
 - relevant benchmark for single-user, BC, MAC channels
- ▲ **BUT ...** links & networks have different capacity characteristics
- ▲ What changes:
 - unbounded delay and reliability not allowed (T-D-R region)
 - spatially dependent nature of the interference
 - spatio-temporal network **dynamics** (need for decompositions)
 - bursty traffic sources, e2e delay constraints, multihop routing, mobility → constantly changing network topology



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Recent Approaches



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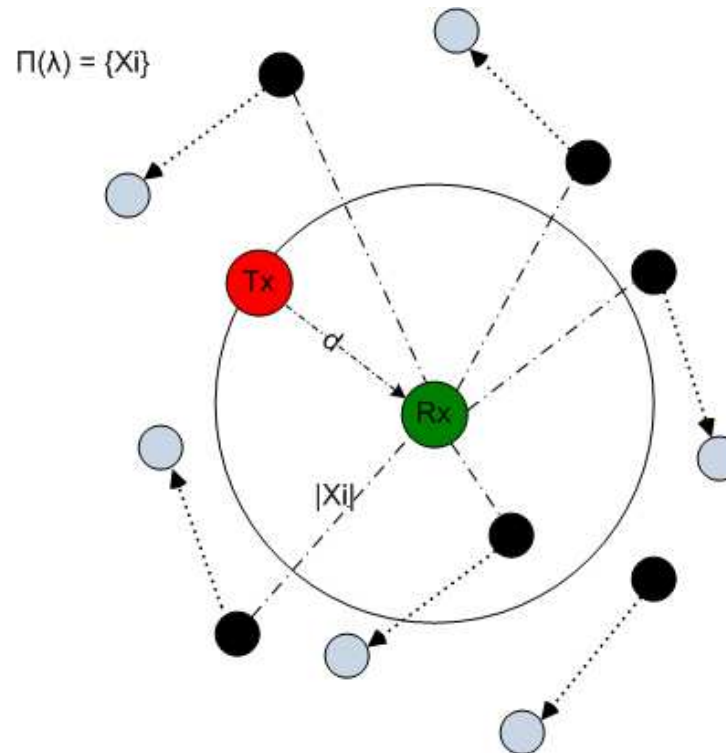
- ▲ Seminal result [GupKum'00]: for K nodes
 - Transport capacity scales at best as $\Theta(\sqrt{K})$ bit-m/s²
 - sublinear in K & per-node capacity $\rightarrow 0$ as $K \rightarrow \infty$
- ▲ Several results so far:
 - Mobility increases capacity ($O(K)$ if delay is not an issue) [GroTse'02]
 - Hierarchical Cooperation, virtual MIMO [OzgLevTse'07]
 - Electromagnetic limits [FraMigMin'07]
 - 'Wireline' Tree Network idea [NieGupSha'08]
- ▲ Deterministic Model & Approximate Capacity for Interference Channels [AveDigTse'07]

Issue: Scaling laws and numerical simulations do not provide sufficient insights

→ **Transmission Capacity** comes to supplement the puzzle!

Network Model

Consider one snapshot in time (single hop)



- ▲ Transmission & end-to-end distances are roughly constant
- ▲ Uncoordinated network (e.g. ALOHA)
- ▲ Tx locations: stationary Poisson point process (PPP) on the plane (*stochastic geometry framework*)



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Outage Probability

▲ Given a choice of system parameters, outage events capture the main network behavior

▲ Outage Probability for a *typical Tx-Rx pair*:

$$P_{\text{out}} = \mathbb{P} \left\{ \frac{\rho H_{00} d^{-\alpha}}{\sum_{i \in \Pi(\lambda)} \rho H_{0i} |X_i|^{-\alpha} + \eta} < \beta \right\} \leq \epsilon$$

ρ	transmission power
H_{ij}	fading coefficient from Tx i to Rx j
d	distance between Tx-Rx pair
α	pathloss exponent ($\alpha > 2$)
η	noise power
$ X_i $	distance from interference i
$\Pi(\lambda) = \{X_i\}$	Poisson point process of interferers with intensity λ (per m^2)
β	SINR/SIR requirement for successful reception
ϵ	outage probability constraint

Transmission Capacity Framework



- ▲ Definition: the maximum intensity λ of successful concurrent transmissions per unit area for which each transmission is successful with probability $1 - \epsilon$

Key metrics:

- ▲ (Network-wide) Outage Probability

$$\pi(\lambda) \equiv \mathbb{P} \{ \text{SINR} < \beta \}$$

$\pi(\lambda) \in [0, 1]$ - continuous monotone increasing in λ

- ▲ Transmission capacity

$$\mathcal{C}(\epsilon) = \pi^{-1}(\epsilon)(1 - \epsilon) \quad 0 < \epsilon < 1$$

$\pi^{-1}(\epsilon) \equiv \lambda_\epsilon$: max. density of transmissions (users/m²)

- ▲ Area Spectral Efficiency

$$\text{ASE} = \lambda_\epsilon(1 - \epsilon) \log_2(1 + \beta) \text{ bps/Hz/m}^2$$

TC depends on interferers' positions & random channel effects



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Implications of TC Framework



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- ▲ TC framework allows for quantification of achievable single-hop rates by focusing on a simplified PHY/MAC model
- ▲ TC allows for intuitive closed-form expressions
- ▲ **Stochastic geometry** models to quantify the multiuser interference
 - relationship between the spatial density and P_{succ} can be determined
- ▲ Homogeneous Poisson distribution of nodes assumption (tractability - more sophisticated results exist)
- ▲ Gives crisp insights into cross-layer design problems (FH vs. DS-CDMA, SIC, power control, bandwidth partitioning, threshold scheduling, network coexistence, cognitive policies)

For details: [WebAndJin'07], [WebAndJin'08]



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SDMA Ad Hoc Networks
SDMA Network Model

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Multi-Antenna Wireless Ad Hoc Networks: point-to-multipoint MIMO links



Motivation and Goals

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- ▲ Extend transmission capacity framework to take into account multi-receiver (SDMA) transmissions
- ▲ Derive the fundamental limits of SDMA communications in wireless ad hoc networks
- ▲ Quantify the throughput gains (*if any*) by sending multiple streams to different receivers (multiuser MIMO)
- ▲ Provide insights on how to use multiple antennas in SDMA ad hoc networks
- ▲ Effect of limited feedback in multi-antenna transmission
- ▲ Any gains in terms of scheduling, delay, and packet forward progress?

SDMA Ad Hoc Networks



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SDMA Ad Hoc Networks

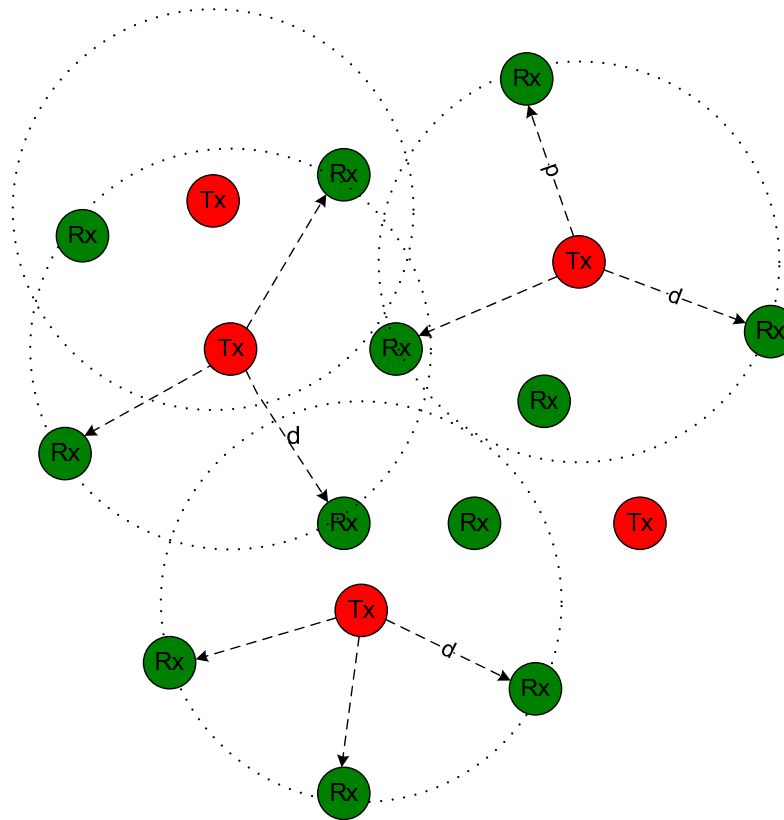
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- ▲ Each transmitter with M antennas communicates simultaneously with $K \leq M$ receivers, each with N receive antennas.
- ▲ Perfect CSIR and error-free, zero-delay feedback channels

SDMA Network Model



The received signal \mathbf{y}_k at receiver $k \in \mathcal{K}$ is given by

$$\mathbf{y}_k = \sqrt{\rho} d^{-\alpha/2} \mathbf{H}_{0k} \mathbf{x}_k + \sqrt{\rho} \sum_{i \in \Pi(\lambda)} |X_i|^{-\alpha/2} \mathbf{H}_{ik} \mathbf{x}_i + \mathbf{n} \quad (1)$$

where $\mathbf{H}_{0k} \in \mathbb{C}^{N \times M}$ is the channel between T_0 and receiver k
 $\mathbf{H}_{ik} \in \mathbb{C}^{N \times M}$ is the channel between receiver k and
interfering transmitters T_i
 \mathbf{x}_k is the normalized transmit signal vector
 \mathbf{n} is complex additive Gaussian noise.

Key metric: Assuming transmission at the Shannon target rate $R = \log_2(1 + \beta)$ bps/Hz, the area spectral efficiency is defined as

$$\mathcal{C}_\epsilon = K \lambda_\epsilon (1 - \epsilon) R \quad \text{bps/Hz/m}^2 \quad (2)$$

and depends on the number $1 \leq K \leq M$ spatial streams sent by each source node.

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Dirty Paper Coding (1/2)

Multi-antenna Receivers

Lemma 1: The maximum contention density under DPC is upper bounded by

$$\lambda_{\text{DPC}} \leq \frac{(4MN)^{2/\alpha}}{\mathcal{I}_M \beta^{2/\alpha} d^2} \left[-\log(1 - \epsilon) + \frac{\eta \beta d^\alpha}{4MN\rho} \right] \quad (3)$$

where

$$\mathcal{I}_M = \frac{2\pi}{\alpha} \sum_{m=0}^{M-1} \binom{M}{m} B(m + 2/\alpha, M - (m + 2/\alpha)) \quad (4)$$

Since $\mathcal{I}_M \sim \pi \Gamma(1 - 2/\alpha) M^{2/\alpha}$ for large M :

Lemma 2: The DPC capacity scales superlinearly as

$$\mathcal{C}_{\text{DPC}} = O(MN^{2/\alpha}) \quad (5)$$

For $M = N$: $\mathcal{C}_{\text{DPC}} = O(N^{1+2/\alpha})$

→ DPC allows for $N^{2/\alpha}$ more concurrent transmissions per unit area as compared to single-stream MIMO communications.

Dirty Paper Coding (2/2)

Single-antenna Receivers

Proposition 1: Transmission to M single-antenna Rx using DPC results in a maximum contention density $\lambda_{\text{DPC}}^{\text{miso}}$ of

$$\lambda_{\text{DPC}}^{\text{miso}} = \frac{\mathcal{F}_M \epsilon}{\mathcal{I}_M \beta^{2/\alpha} d^2} e^{-\frac{\beta d^2}{\rho}} \quad (6)$$

where

$$\mathcal{F}_M = \left[\sum_{k=0}^{M-1} \sum_{j=0}^k \binom{k}{j} \left(\frac{\eta}{\rho}\right)^{k-j} \frac{1}{j!} \prod_{m=0}^{j-1} (m - 2/\alpha) \right]^{-1} \quad (7)$$

- ▲ For large M , $\frac{\mathcal{F}_M}{\mathcal{I}_M} = O(1) \rightarrow$ capacity exhibits linear scaling (i.e. $\mathcal{C}_{\text{DPC}}^{\text{miso}} = O(M)$)
- ▲ Lack of Rx processing \rightarrow no diversity or interference cancellation gain \rightarrow per-user outage probability is $O(1)$



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▶ Dirty Paper Coding (1/2)

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Linear Precoding with CSIT (1/3)



Zero-forcing Beamforming with Antenna Combining

For $M \geq KN$ with $N > 1$

Inter-user interference constraint at each Rx antenna n :

$$\mathbf{h}_{k,n} \mathbf{w}_{j,l} = 0, \forall j \neq k, \forall n, l \in [1, N] \text{ and } \mathbf{h}_{k,n} \mathbf{w}_{k,l} = 0, \forall l \neq n.$$

Proposition 2: The capacity in the small outage constraint regime scales as

$$C_{ZF} = O\left(\frac{(M - KN + 1)^{2/\alpha}}{(KN)^{2/\alpha - 1}}\right) \quad (8)$$

For $M = KN$, we have a scaling of $O((KN)^{2/\alpha})$ (full diversity [HunAndWeb'08]).

For $N > M$

Extra DoF at the Rx side can be exploited to eliminate the inter-node interference.

$$\rightarrow C_{ZF} = O\left(M\left(\frac{N-M+1}{M}\right)^{\frac{2}{\alpha}}\right) = O(M^{1-2/\alpha}) < O(N^{1-2/\alpha}).$$



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Linear Precoding with CSIT (2/3)



Zero-forcing Beamforming with Antenna Selection

The maximum contention density (for $\epsilon \rightarrow 0$) is given by

$$\lambda_{\text{ZF}}^{\text{as}} = \frac{\epsilon}{S'_N \mathcal{I}_M \beta^{2/\alpha} d^2} e^{-\frac{\beta d^\alpha}{\rho}} \quad (9)$$

where $S'_N = \sum_{n=1}^N \sum_{j=1}^n \binom{n}{j} \binom{d}{j} \left(\frac{\eta}{\rho}\right)^{(n-j)} (-1)^{j+1} j^{2/\alpha}$ and \mathcal{I}_M is given by (4).

- ▲ The capacity scales as $\mathcal{C}_{\text{ZF}}^{\text{as}} = O(S_N^{-1} M^{1-\frac{2}{\alpha}})$
- ▲ For $M = N \rightarrow \mathcal{C}_{\text{ZF}}^{\text{as}} = O(M)$ (selection improves the typical channel without amplifying interference)
- ▲ Since order statistics (due to selection) provides an $M^{2/\alpha}$ -fold increase of the received signal power \rightarrow linear capacity growth.



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Zero-forcing Beamforming with Single-antenna Receivers

BF vector of Rx k : $\mathbf{h}_j \mathbf{w}_k = 0, \forall j \in \mathcal{K}, j \neq k$.

Proposition 3: For a random access wireless network in which the Tx spatially multiplexes M single-antenna receivers using ZFBF, the maximum contention density is given by

$$\lambda_{\text{ZF}} = \frac{-\log(1 - \epsilon)}{\mathcal{I}_M \beta^{2/\alpha} d^2} + \frac{\eta \beta^{1 - \frac{2}{\alpha}} d^{\alpha - 2}}{\rho \mathcal{I}_M} \quad (10)$$

where \mathcal{I}_M is given in (4).

- ▲ For large M , the ASE scales as $\mathcal{C}_{\text{ZF}} = O(M^{1 - \frac{2}{\alpha}})$ (same scaling as interference-aware beamforming [HuaAndHeaGuoBer'08]).
- ▲ Regularized channel inversion (MMSE precoding) provides the same $O(M^{1 - \frac{2}{\alpha}})$ scaling but achieving higher SINR target β per user stream.



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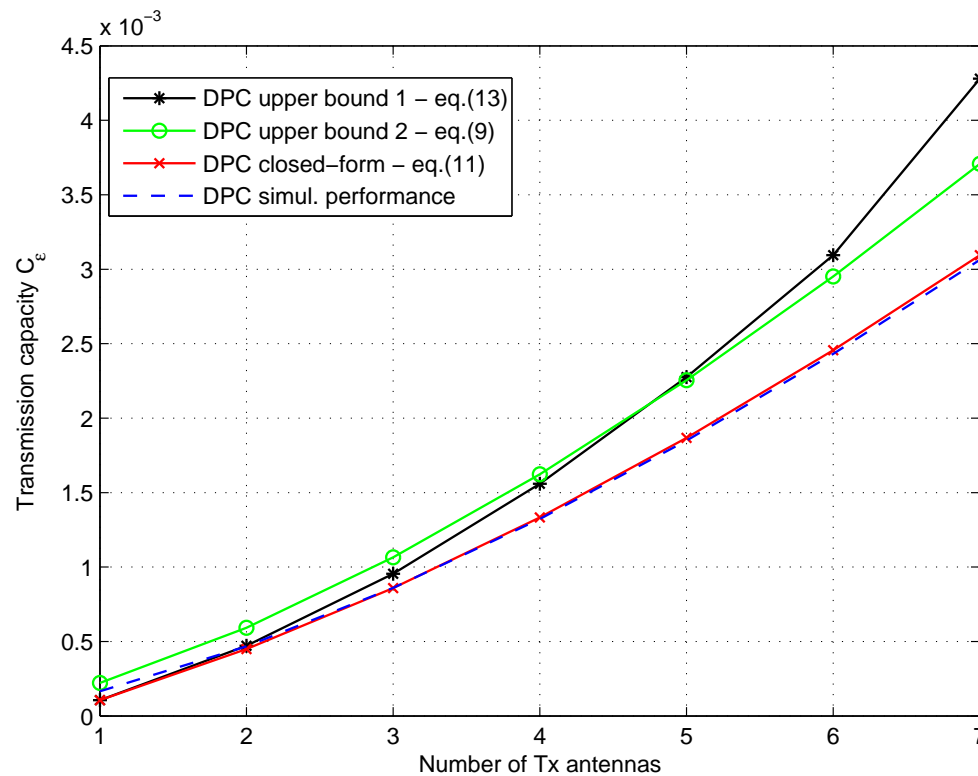


Figure 1: DPC capacity scaling C_{DPC} vs. nb. of Tx antennas ($M = N$) for $\alpha = 4$.

- ▲ Superlinear scaling behavior of DPC with the number of antennas.
- ▲ Tightness of the upper bound depends on the pathloss exponent α and M (being tighter for α decreasing).
- ▲ Substantial gains appear even when only a few streams are transmitted.

ZF Performance Evaluation

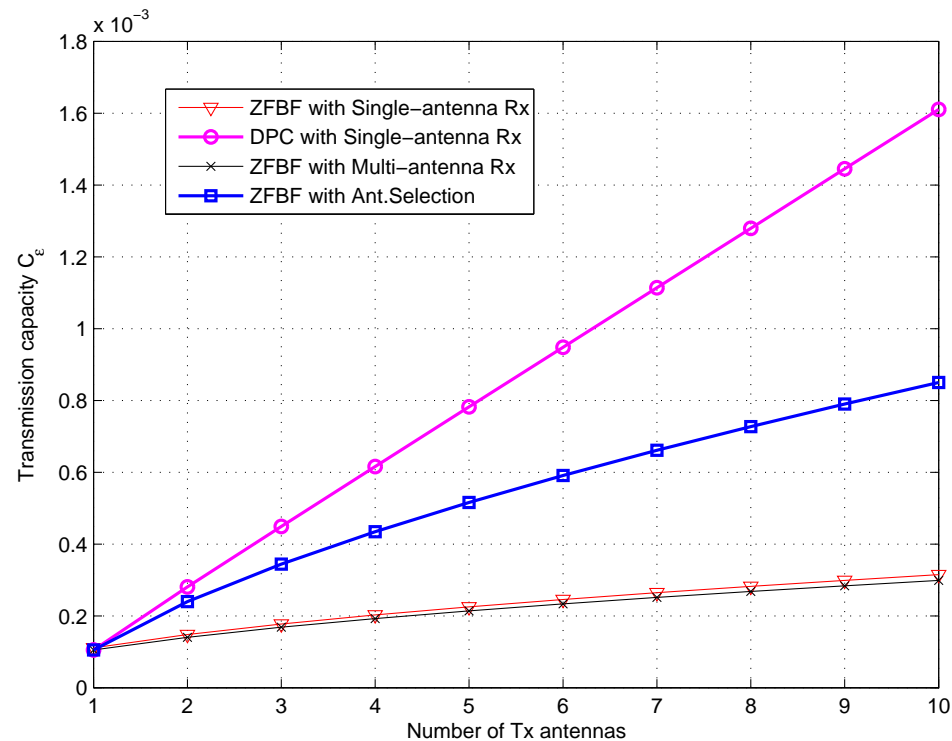


Figure 2: Capacity vs. nb. of Tx antennas for different SDMA precoding techniques ($\alpha = 4$)

- ▲ Linear scaling of MISO DPC and sublinear capacity behavior of linear precoding.
- ▲ Diversity-oriented receive processing combined with linear transmit processing is not sufficient to achieve linear scaling.

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SDMA TC with imperfect CSIT (1/3)



Single-antenna Receivers

- ▲ **Orthogonal Beamforming:** The optimal contention density using OBF with partial CSIT (1 scalar) is given by

$$\lambda_\epsilon = \frac{-\log(1 - \epsilon)}{\mathcal{I}_M d^2 \beta^{\frac{2}{\alpha}}} - \frac{\log(1 + \beta d^{2\alpha})^{(M-1)}}{\mathcal{I}_M d^2 \beta^{\frac{2}{\alpha}}}$$

which results in transmission capacity loss of

$$\Delta_{\text{TC}} = \frac{M(M-1)(1-\epsilon)\log(1+\beta d^{2\alpha})}{\mathcal{I}_M d^2 \beta^{\frac{2}{\alpha}}} = O(M^{2-\frac{2}{\alpha}})$$

- ▲ The number of Tx antennas (streams) for positive network contention density is upper bounded by

$$M < 1 + \frac{\log(1 - \epsilon)^{-1}}{\log(1 + \beta d^{2\alpha})}$$



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Performance Evaluation (2/2)

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SDMA TC with imperfect CSIT (2/3)



Multi-antenna Receivers

- ▲ **Orthogonal Beamforming:** If MRC Rx processing is employed with limited feedback OBF, the outage probability is given by

$$P_{\text{out}} = 1 - \left[\sum_{k=0}^{N-1} \frac{(-s)^k}{k!} \frac{\partial^k}{\partial s^k} (\mathcal{L}_{I_\Phi} \mathcal{L}_Y) \right]_{s=\beta d^\alpha}$$

with

$$\mathcal{L}_{I_\Phi} = e^{-\lambda d^2 \beta^{\frac{2}{\alpha}} \mathcal{I}_M}$$

Laplace transform of PPP interference

$$\mathcal{L}_Y = (1 + s d^\alpha)^{(1-M)}$$

Laplace transform of inter-stream/MU interference

- ▲ Inter-stream interference cancellation is required



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SDMA TC with imperfect CSIT (3/3)



Key messages

- ▲ SDMA transmission capacity is **very sensitive** to CSIT inaccuracy!
- ▲ Single-stream transmission (with diversity) outperforms MISO-SDMA techniques
- ▲ For a target SIR = 0 dB, low ϵ is hard to be achieved with partial CSIT
- ▲ Interference cancellation combined with diversity-oriented receive processing should be envisaged for SDMA ad hoc networks with limited feedback
- ▲ Δ_{TC} grows M times faster than the MISO transmission capacity



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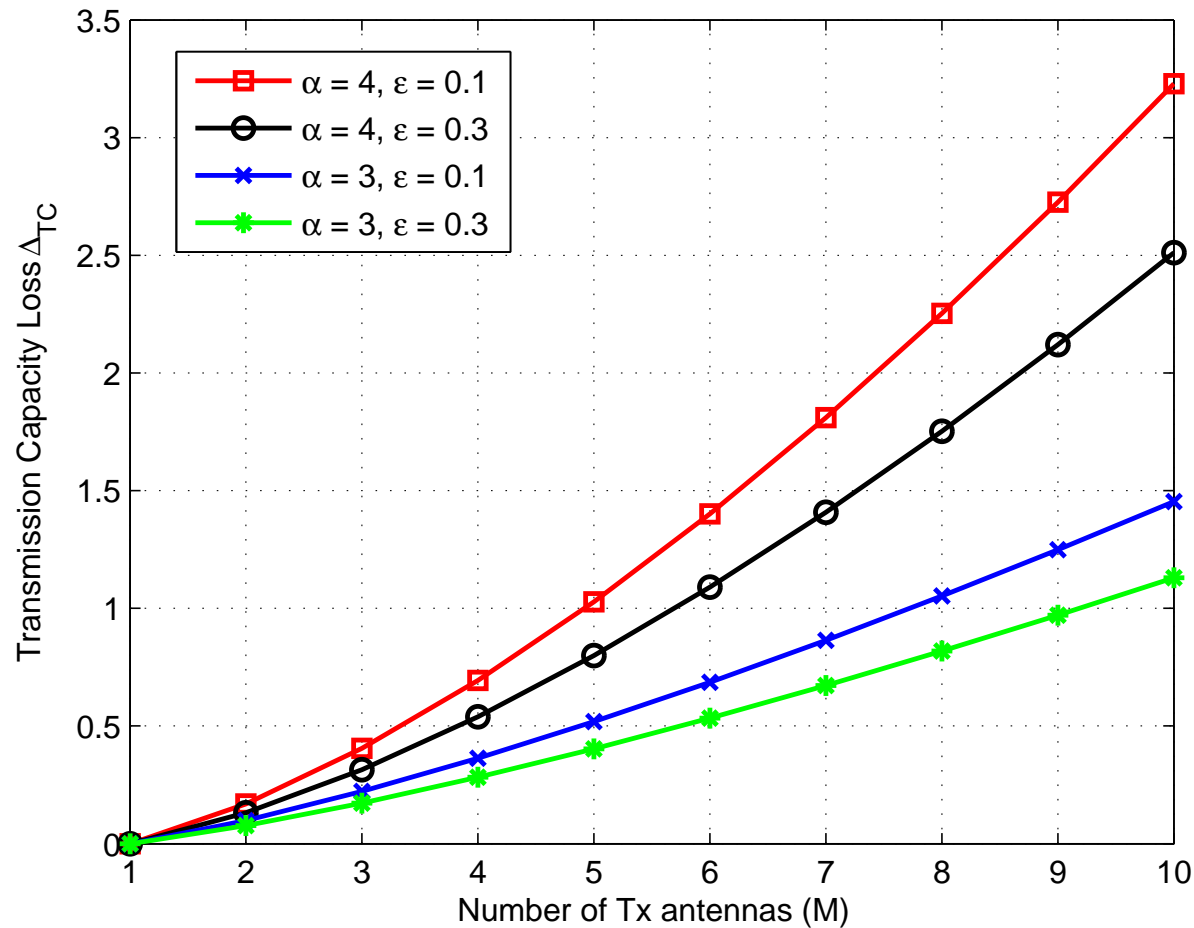


Figure 3: Trans. capacity loss Δ_{TC} vs. # of Tx antennas M

Performance Evaluation (2/2)

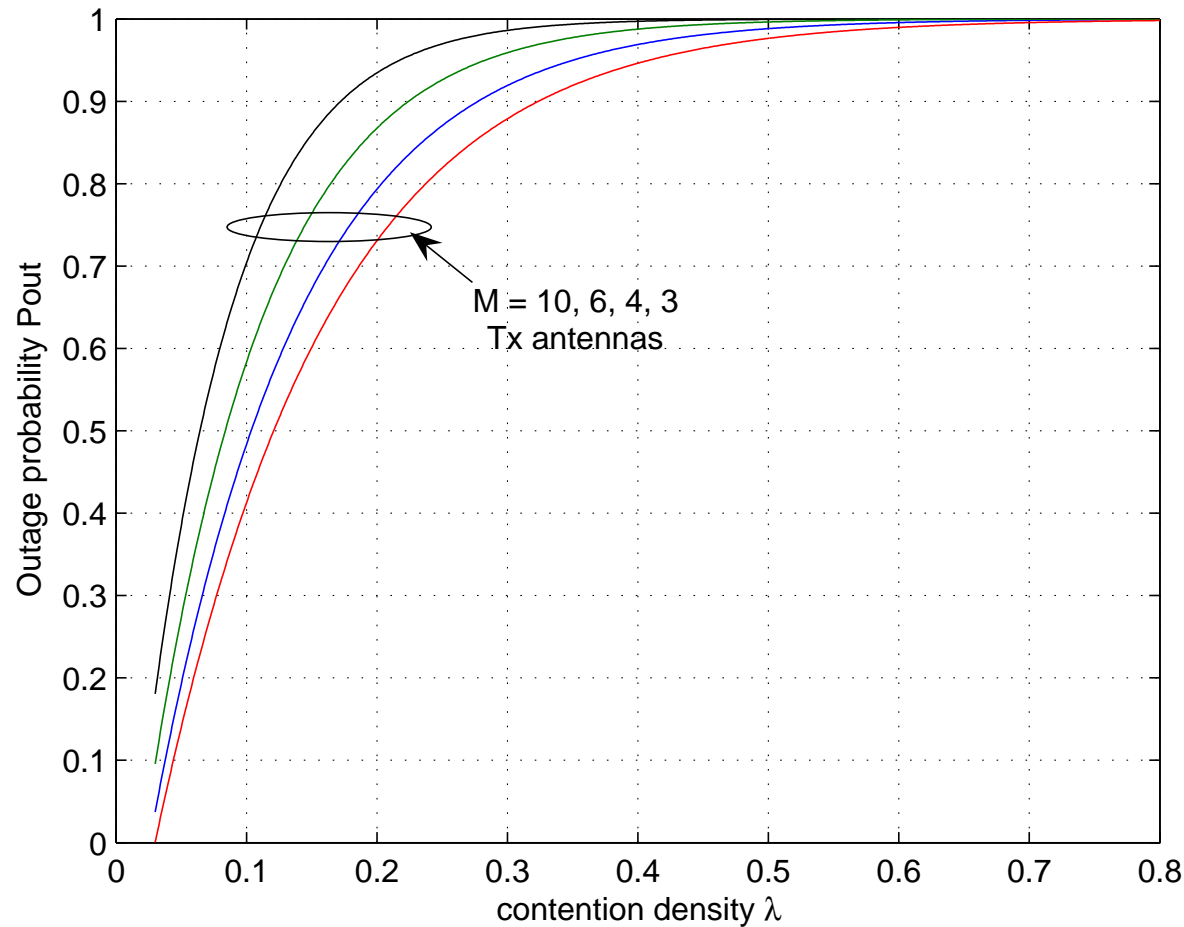


Figure 4: Outage Prob. vs. λ for SDMA with OBF + MRC ($N=2$)

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The Way Forward

Concluding remarks & Perspectives



- ▲ MIMO allows for larger spatial packing of simultaneous transmissions
- ▲ Superlinear capacity increase is achieved with multiple antennas (with perfect CSIT)
- ▲ Limited feedback is very detrimental in SDMA ad hoc
- ▲ More results for codebook-based SDMA techniques - Interplay between capacity and CSIT resolution (# feedback bits)
- ▲ SDMA in ad hoc networks may result in delay/routing benefits
- ▲ Need for novel, MANET-tailored SDMA techniques (interference alignment with partial CSIT??)
- ▲ MAC layer coordination and scheduling to the rescue?



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The Road Ahead

more interdisciplinary flavor required

- ▲ Extension to multihop MANETs (+ incorporate routing)
- ▲ Use of non-Poisson & heterogeneous point process (Cox, hardcore, clustered) to analyze sophisticated MAC strategies (scheduling, CSMA)
- ▲ A unifying analytical framework to account for overhead messaging is critical for a relevant network IT
- ▲ Extend TC framework with mobility (e.g. Lévy random walks, first passage processes)
- ▲ Understanding the unique spatial and temporal dynamics of ad hoc networks is essential



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Thank you!



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