On the Complementary Benefits of Massive MIMO, Small Cells, and TDD

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(joint work with K. Hosseini, S. ten Brink, M. Debbah)

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The data explosion and possible solutions

By 2017, there will be 13 $\times$ more mobile data traffic than in 2012.[1]

Network densification is the only solution to the capacity crunch:

- **Small cells** : + area spectral efficiency scales linearly with the cell density
  − not well suited to provide coverage and support high mobility
- **Massive MIMO** : + interference can be almost entirely eliminated
  − distributing the antennas achieves highest capacity[2]

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Can we integrate the complementary benefits of both in a new network architecture?

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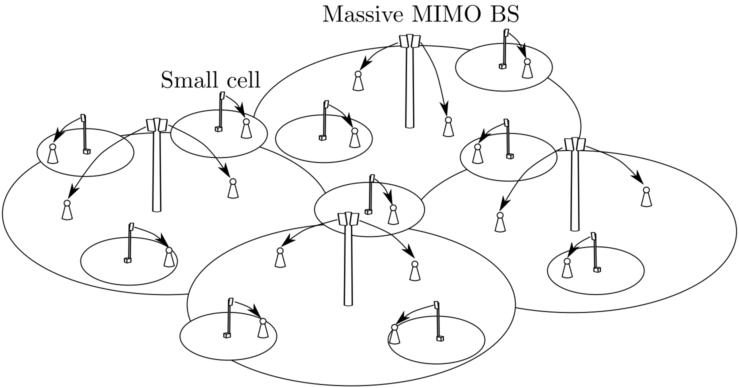
A two-tier network architecture



- Massive MIMO base stations (BS) overlaid with many small cells (SCs)
- BSs ensure coverage and serve highly mobile UEs
- SCs drive the capacity (hot spots, indoor coverage)

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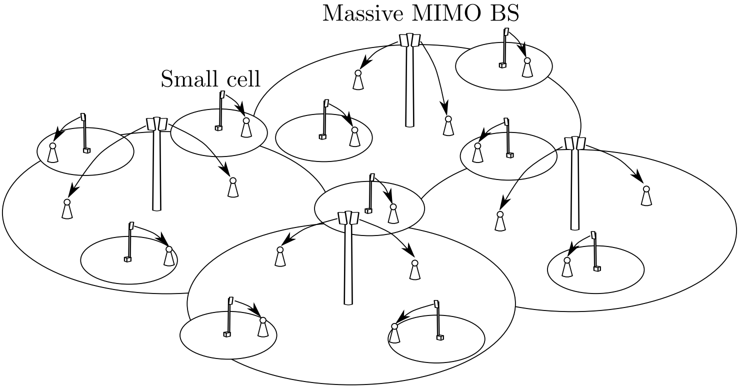

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Intra- and inter-tier interference is the main performance bottleneck.

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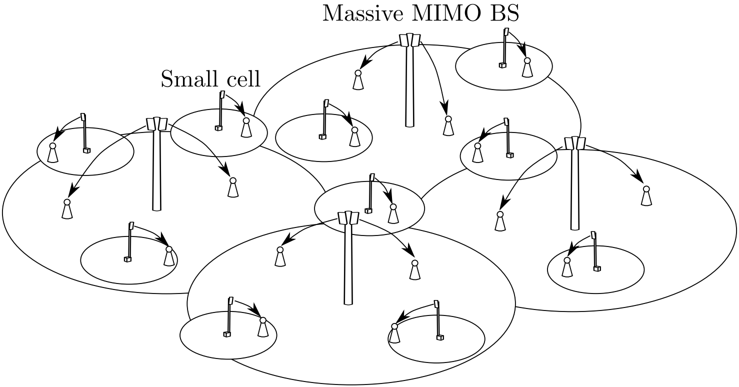

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Intra- and inter-tier interference is the main performance bottleneck.

There are many **excess antennas** in the network which should be exploited!

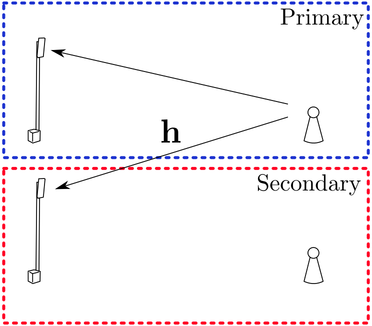
The essential role of TDD

A network-wide synchronized TDD protocol and the resulting channel reciprocity have the following advantages:

- The downlink channels can be estimated from uplink pilots.
  $\rightarrow$ Necessary for massive MIMO
- Channel reciprocity holds for the desired *and* the interfering channels.
  $\rightarrow$ Knowledge about the interfering channels can be acquired for free.

TDD enables the use of excess antennas to reduce intra-/inter-tier interference.

An idea from cognitive radio



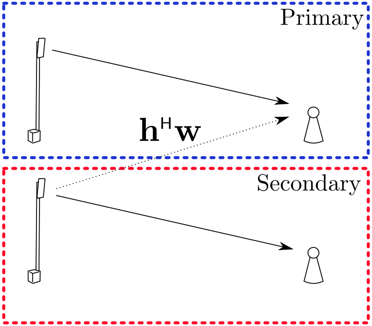
1. The secondary BS listens to the transmission from the primary UE:

$$\mathbf{y} = \mathbf{h}x + \mathbf{n}$$

2. ...and computes the covariance matrix of the received signal:

$$\mathbb{E}\left[\mathbf{y}\mathbf{y}^{\mathsf{H}}\right] = \mathbf{h}\mathbf{h}^{\mathsf{H}} + \mathsf{SNR}^{-1}\mathbf{I}$$

An idea from cognitive radio



3. With the knowledge of the SNR, the secondary BS designs a precoder $\mathbf{w}$ which is orthogonal to the sub-space spanned by $\mathbf{h}\mathbf{h}^{\mathsf{H}}$.

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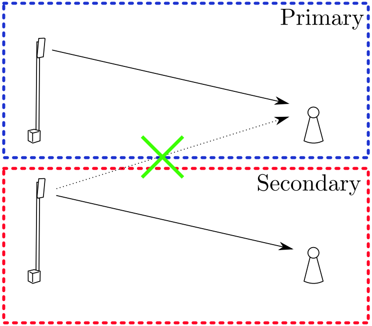
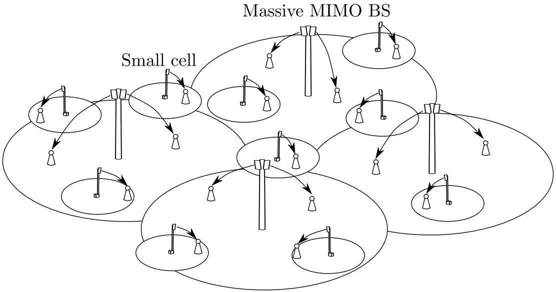


3. With the knowledge of the SNR, the secondary BS designs a precoder **w** which is orthogonal to the sub-space spanned by $\mathbf{h}\mathbf{h}^{\mathsf{H}}$.

4. The interference to the primary UE can be entirely eliminated without explicit knowledge of **h**.

Translating this idea to HetNets



Every device estimates its received interference covariance matrix and precodes (partially) orthogonally to the dominating interference subspace.

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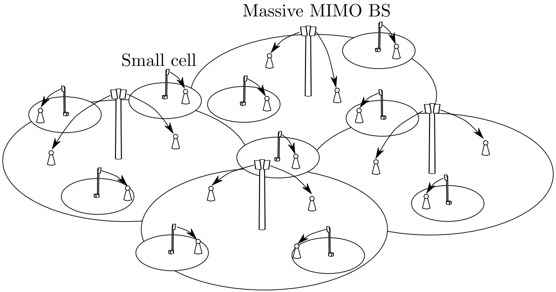

Every device estimates its received interference covariance matrix and precodes (partially) orthogonally to the dominating interference subspace.

Advantages

- Reduces interference towards the directions from which most interference is received.
- No feedback or data exchange between the devices is needed.
- Every device relies only on locally available information.
- The scheme is fully distributed and, thus, scalable.

About the literature

- **Cognitive radio**
  - R. Zhang, F. Gao, and Y. C. Liang, "Cognitive Beamforming Made Practical: Effective Interference Channel and Learning-Throughput Tradeoff," IEEE Trans. Commun., 2010.
  - F. Gao, R. Zhang, Y.-C. Liang, X. Wang, "Design of Learning-Based MIMO Cognitive Radio Systems," IEEE Trans. Veh. Tech., 2010.
  - H. Yi, "Nullspace-Based Secondary Joint Transceiver Scheme for Cognitive Radio MIMO Networks Using Second-Order Statistics," ICC, 2010.
- **TDD Cellular systems**
  - S. Lei and S. Roy, "Downlink multicell MIMO-OFDM: an architecture for next generation wireless networks," WCNC, 2005.
  - B. O. Lee, H. W. Je, I. Sohn, O. S. Shin, and K. B. Lee, "Interference-aware Decentralized Precoding for Multicell MIMO TDD Systems," Globecom. 2008.
- **Blind nullspace learning**
  - Y. Noam and A. J. Goldsmith, "Exploiting spatial degrees of freedom in MIMO cognitive radio systems," ICC, 2012.
- **and many more...**

System model and signaling

- Each BS has N antennas and serves K single-antenna MUEs.
- S SCs per BS with F antennas serving 1 single-antenna SUE each
- The BSs and SCs have perfect CSI for the UEs they want to serve.
- Every device knows perfectly its interference covariance matrix and the noise power.
- Linear MMSE detection at all devices

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- Every device knows perfectly its interference covariance matrix and the noise power.
- Linear MMSE detection at all devices
- The BSs and SCs use precoding vectors of the structure:

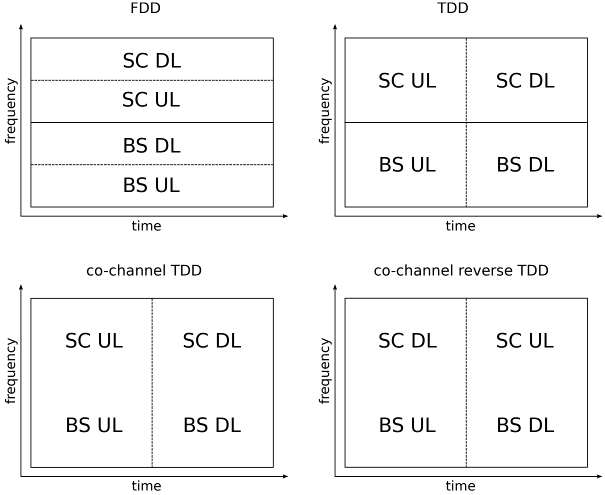
$$\mathbf{w} \sim \left(P\mathbf{H}\mathbf{H}^{\mathsf{H}} + \kappa\mathbf{Q} + \sigma^2\mathbf{I}\right)^{-1}\mathbf{h}$$

  - $\mathbf{h}$ channel vector to the targeted UE
  - $\mathbf{H}$ channel matrix to other UEs in the same cell
  - P, σ^2: transmit and noise powers
  - $\mathbf{Q}$ interference covariance matrix
  - κ: regularization parameter (α for BSs, β for SCs)

About the regularization parameters

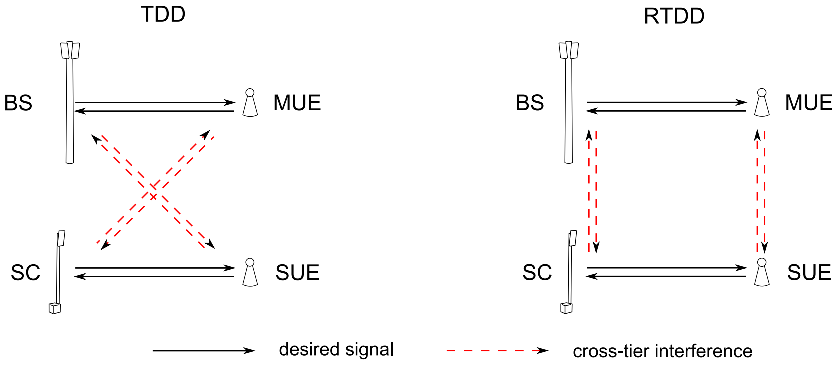
For $\alpha, \beta = 0$, the BSs and SCs transmit as if they were in an isolated cell, i.e., MMSE precoding (BSs) and maximum-ratio transmissions (SCs). By increasing α, β, the precoding vectors become increasingly orthogonal to the interference subspace.

Comparison of duplexing schemes and co-channel deployment



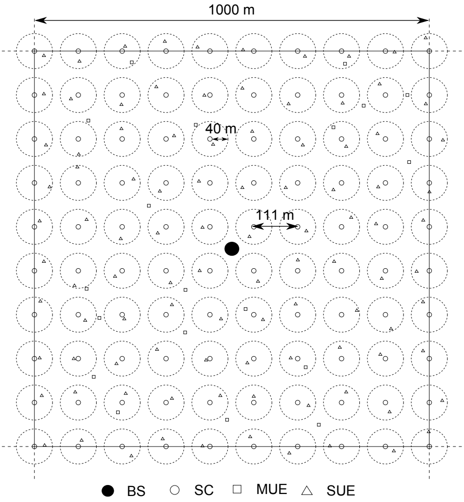
- FDD: Channel reciprocity does not hold
- TDD: Only intra-tier interference can be reduced
- co-channel (reverse) TDD: Inter and intra-tier interference can be reduced

TDD versus reverse TDD (RTDD)



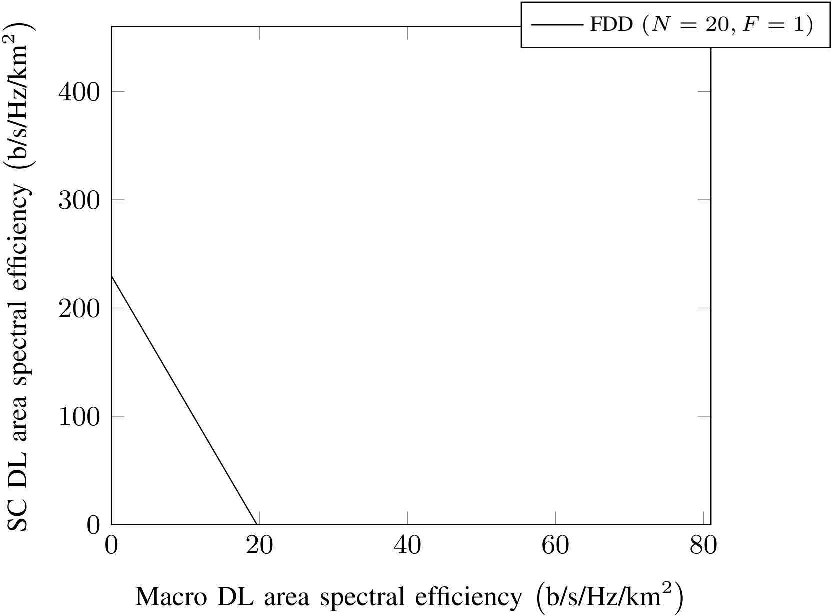
- Order of UL/DL periods decides which devices interfere with each other.
- The BS-SC channels change very slowly. Thus, the estimation of the covariance matrix becomes easier for RTDD.

Numerical results



- 3×3 grid of BSs with wrap around
- $S = 81$ SCs per cells on a regular grid
- $K = 20$ MUEs randomly distributed
- 1 SUE per SC randomly distributed on a disc around each SC
- 3GPP channel model with path loss, shadowing and fast fading, N/LOS links
- TX powers: 46 dBm (BS), 24 dBm (SC), 23 dBm (MUE/SUE)
- 20 MHz bandwidth @ 2 GHz
- No user scheduling, power control
- Averages over channel realizations and UE locations
- TDD UL/DL cycles of equal length

Downlink spectral area efficiency regions



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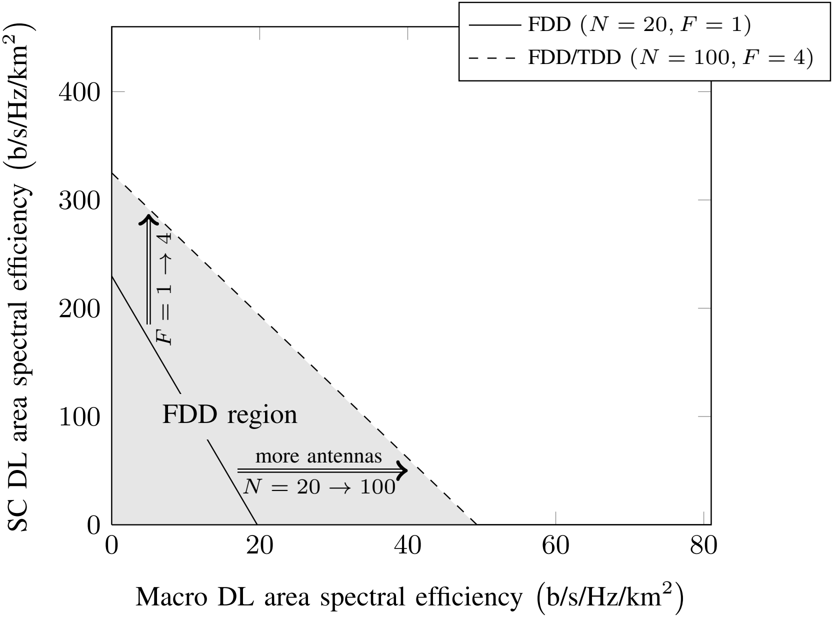

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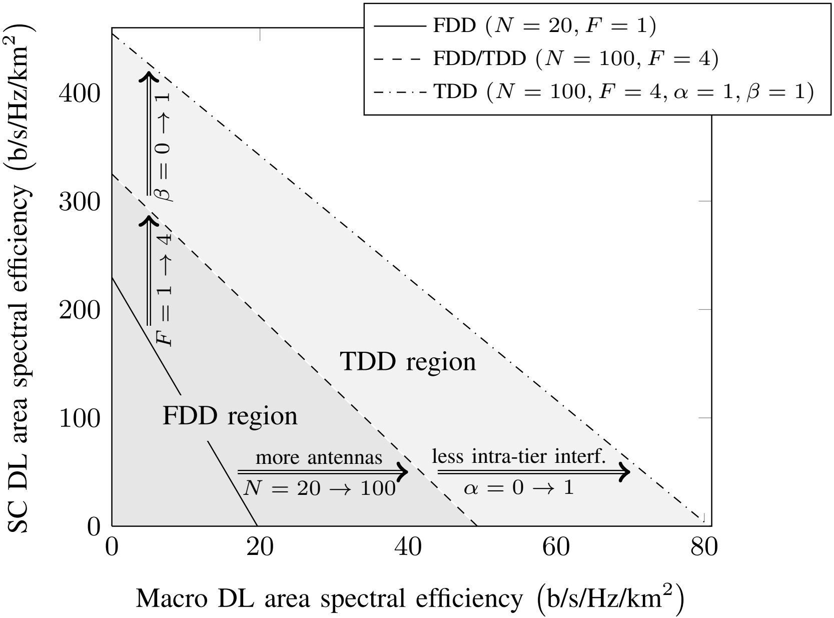

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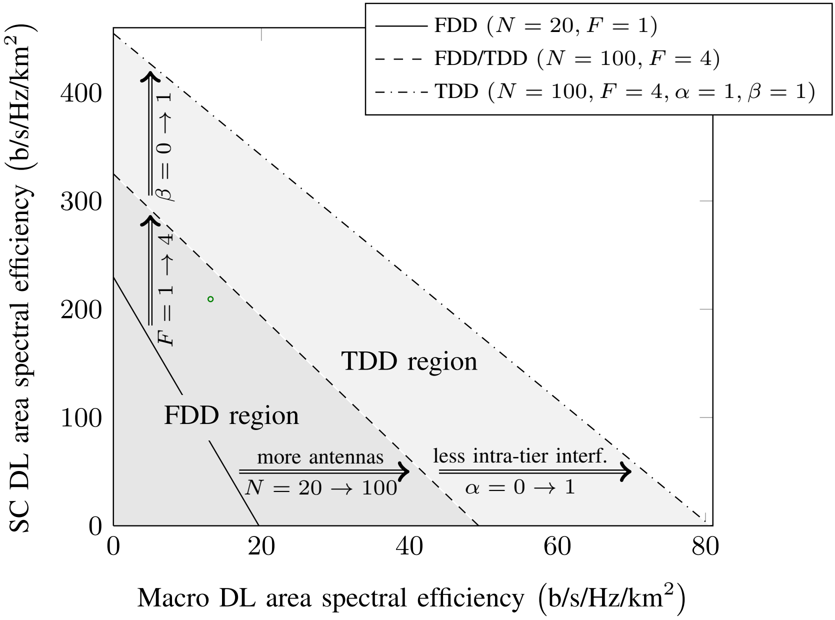

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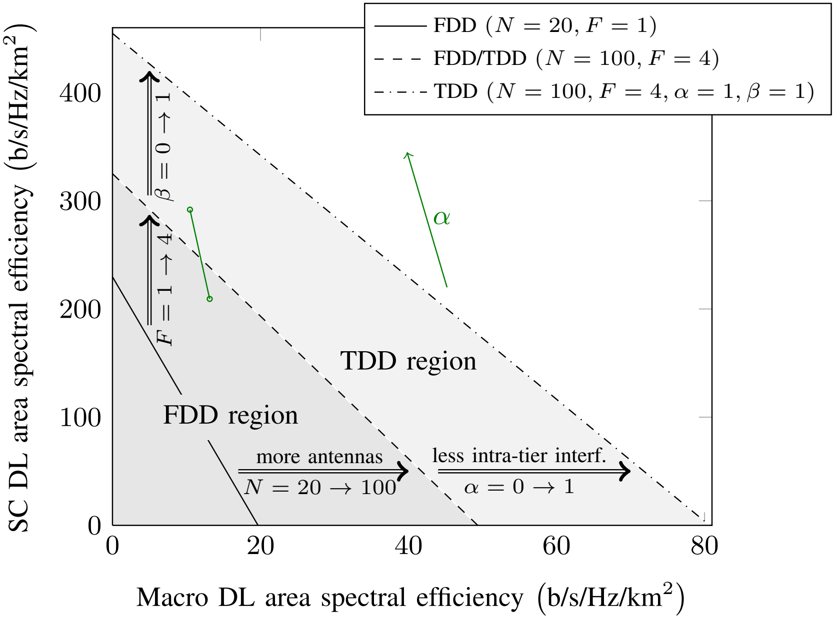

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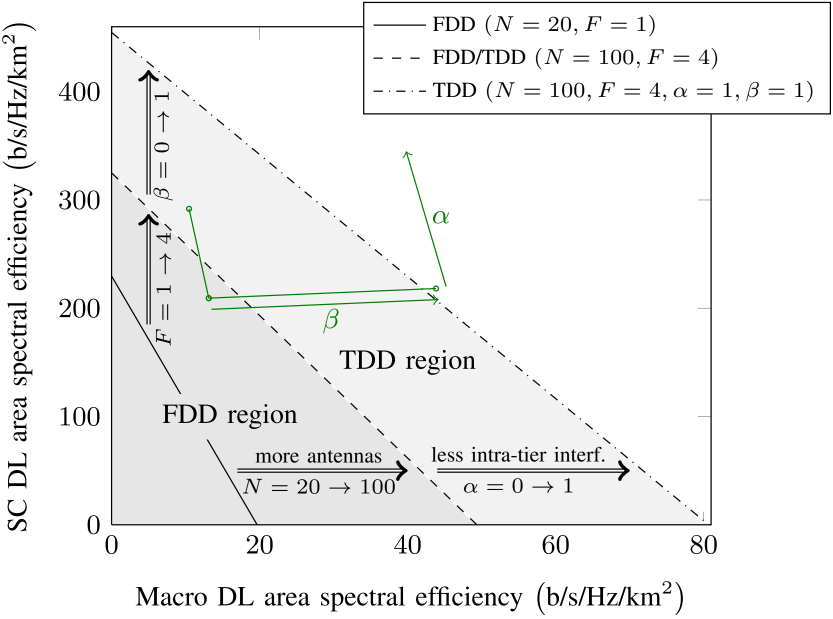

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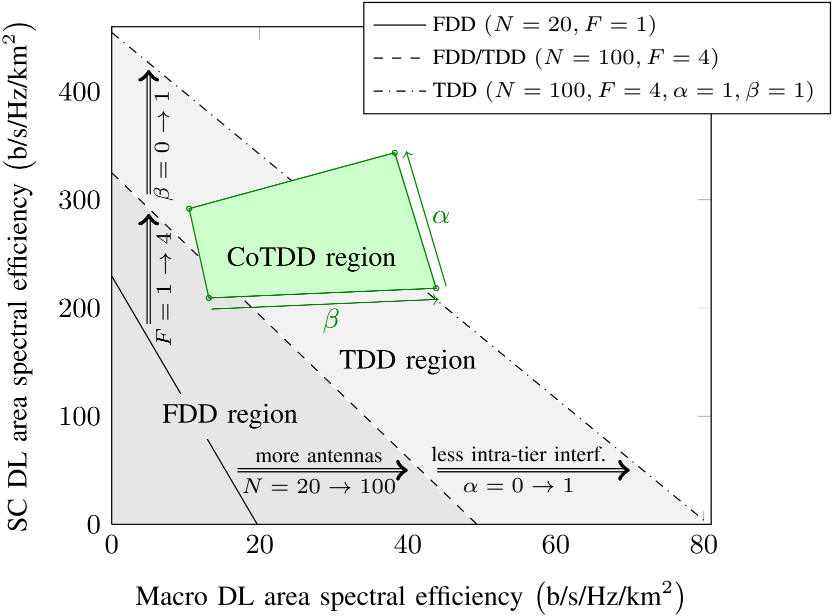

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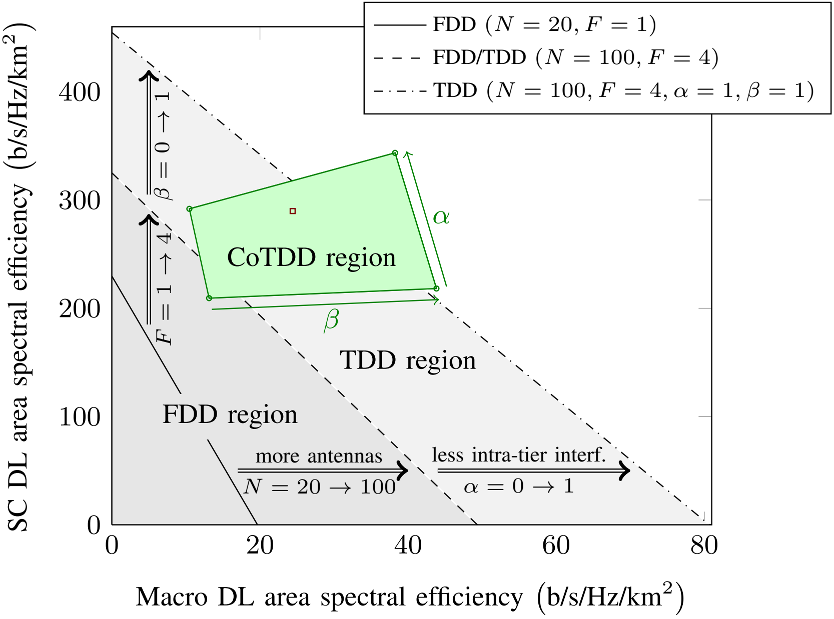

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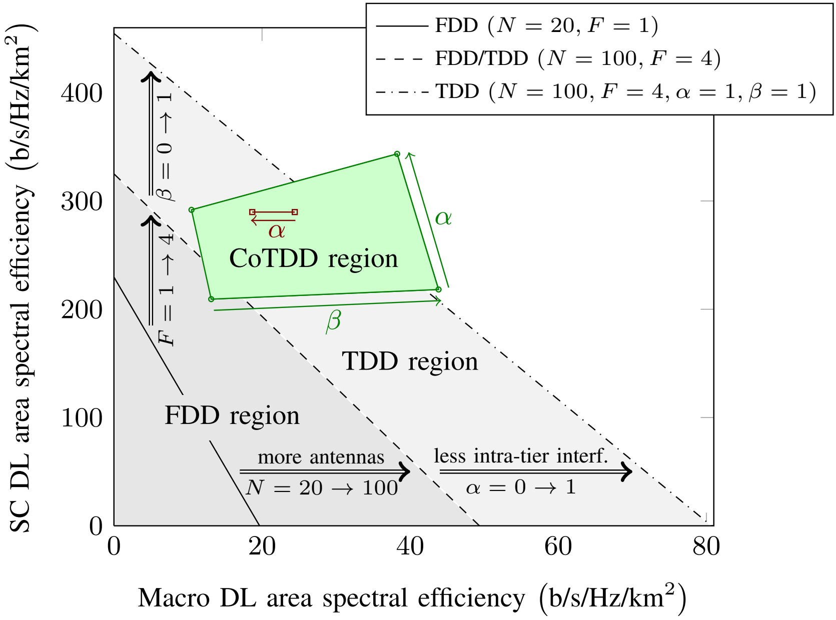

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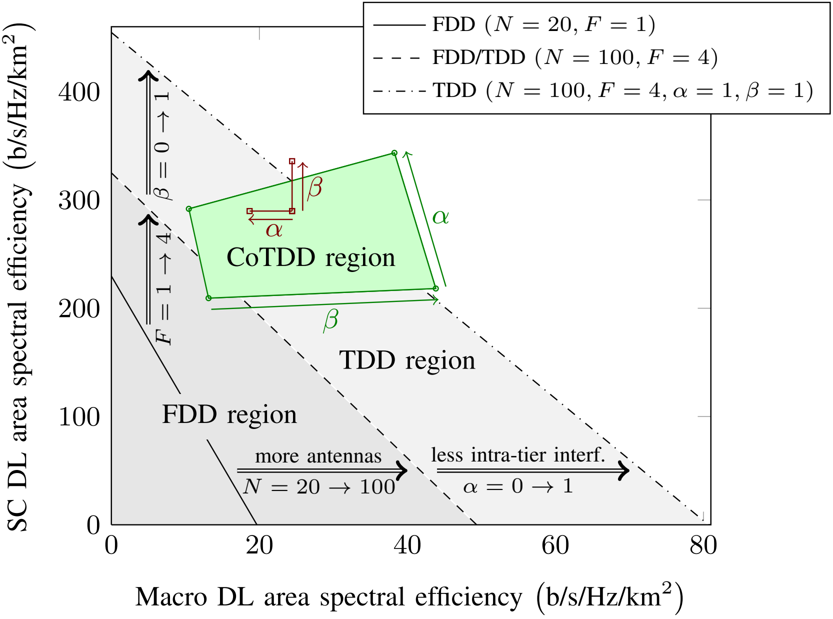

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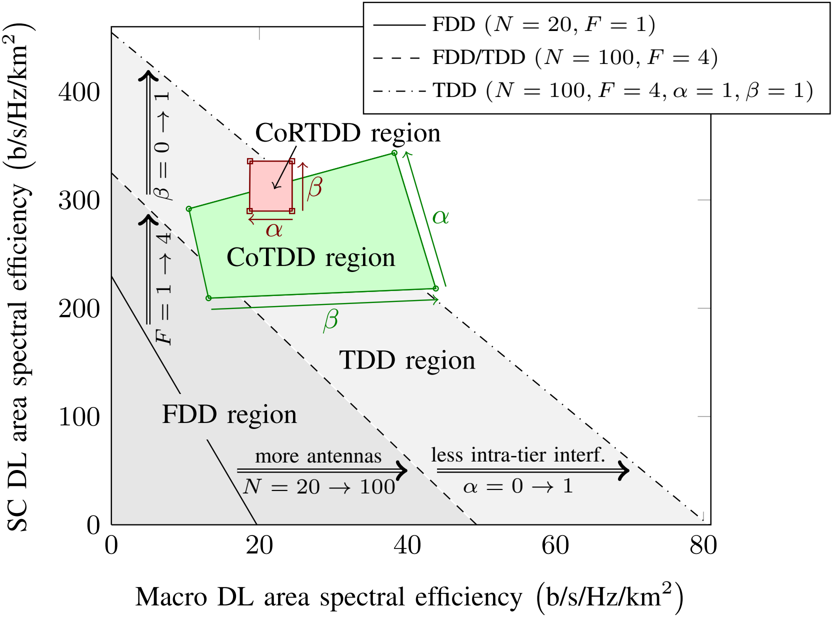
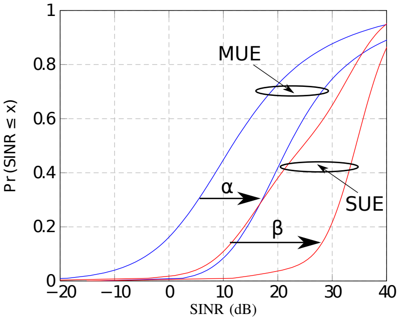
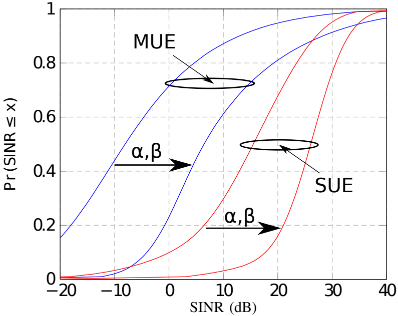


Downlink SINR distribution





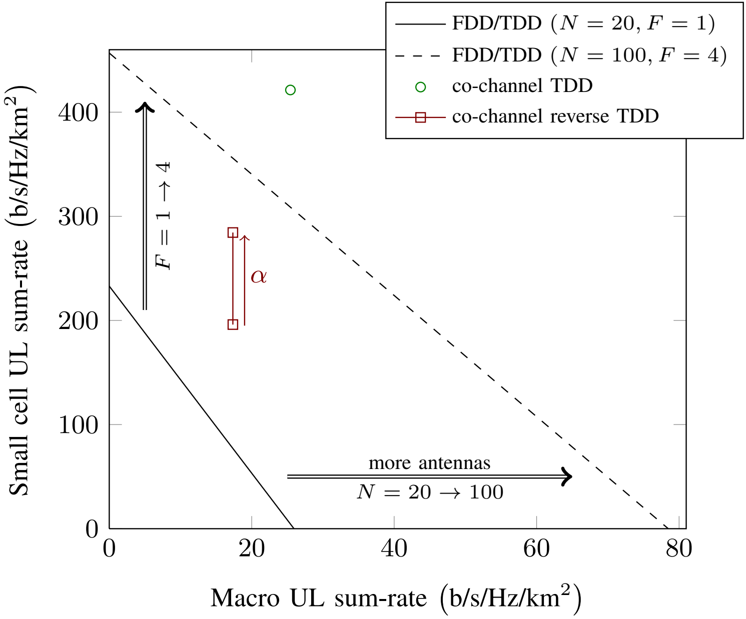
TDD Downlink SINR:

	MUE		SUE	
	$\alpha = 0$	$\alpha = 1$	$\beta = 0$	$\beta = 1$
Mean	13.11	24.13	23.9	33.78
95%	40.38	48.47	40	42.87
50%	11.58	22.01	24.65	34.35
5%	**−8.48**	**7.86**	**6.02**	**22.62**

Co-channel TDD Downlink SINR:

	MUE		SUE	
	$\alpha, \beta = 0$	$\alpha, \beta = 1$	$\alpha, \beta = 0$	$\alpha, \beta = 1$
Mean	−6.29	9.52	14.33	25.45
95%	20.45	35.95	29.88	35.01
50%	−8.06	6.44	15.49	26.05
5%	**−26.64**	**−6.82**	**−6.51**	**13.6**

Uplink spectral area efficiency regions



Observations

- With the proposed precoding scheme, a TDD co-channel deployment of BSs and SCs leads to the highest area spectral efficiency ($\alpha = \beta = 1$, 20 MHz BW):

	DL	UL
Area throughput	7.63 Gb/s/km^2	8.93 Gb/s/km^2
Rate per MUE	38.2 Mb/s	25.4 Mb/s
Rate per SUE	84.8 Mb/s	104 Mb/s

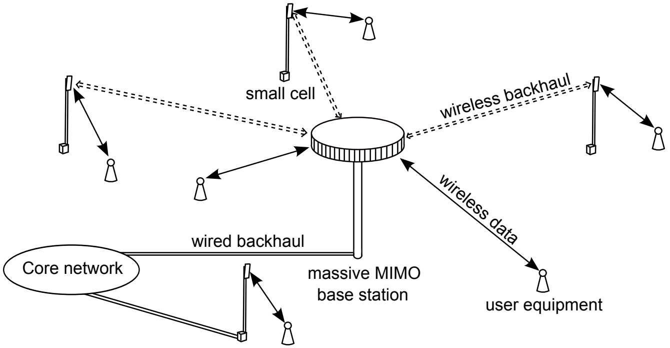
- Even a few "excess" antennas at the SCs lead to significant gains.

- As the scheme is fully distributed and requires no data exchange between the devices, the rates can be simply increased by adding more antennas to the BSs/SCs or increasing the SC-density.

Discussion

- Channel reciprocity requires:
  - Hardware calibration
  - Scheduling of UEs on the same resource blocks in subsequent UL/DL cycles
- The network-wide TDD protocol requires tight synchronization of all devices:
  - GPS (outdoor)
  - NTP/PTP (indoor)
  - BS reference signals
- Channel estimation will suffer from interference and pilot contamination.
- Covariance matrix estimation becomes difficult for large N.
- We have considered a worst-case outdoor deployment scenario with fixed cell association, no power control or scheduling. Location-dependent user scheduling and interference-temperature power control could further enhance the performance.

Massive MIMO for wireless backhaul



- The unrestrained SC-deployment "where needed" rather than "where possible" requires a high-capacity and easily accessible backhaul network.
- Already for most WiFi deployments, the backhaul capacity (10–100 Mbit/s) and not the air interface (54–600 Mbit/s) is the bottleneck.

Why not provide wireless backhaul with massive MIMO?[3]

[3] T. L. Marzetta and H. Yang, "Dedicated LSAS for metro-cell wireless backhaul - Part I: Downlink," Bell Laboratories, Alcatel-Lucent, Tech. Rep., Dec. 2012.

Massive MIMO for wireless backhaul: Advantages

- No standardization or backward-compatibility required
- BS-SC channels change very slowly over time:
  - Complex transmission/detection schemes (e.g., CoMP) can be easily implemented.
  - Even FDD might be possible due to reduced CSI overhead.
- Provide backhaul where needed:
  - Adapt backhaul capacity to the load (support highly variable traffic)
  - Statistical multiplexing opportunity to avoid over-provisioning of backhaul
  - Enable user-centric small-cell clustering for virtual MIMO
- SCs require only a power connection to be operational
- Line-of-sight not necessary if operated at low frequencies

Massive MIMO for wireless backhaul: Is it feasible?

How many antennas are needed to satisfy the desired backhaul rates with a given transmit power budget?

Assumptions:

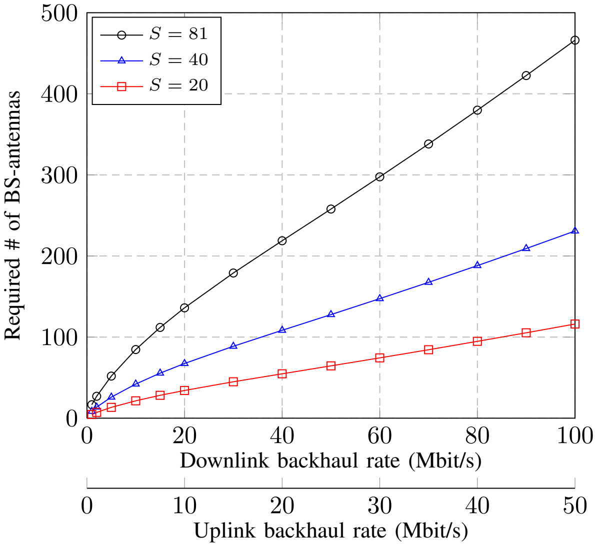
- Every BS knows the channels to all SCs.
- The BSs can exchange some control information.
- Full user data sharing between the BSs is not possible.
- Single-antenna SCs, BSs with N antennas
- TDD operation on a separate band (2/3 DL, 1/3 UL)
- Same modeling assumptions as before

Find the smallest N such that the power minimization problem with target SINR constraints for the multi-cell multi-antenna wireless system is feasible.[4,5]

[4] H. Dahrouj and W. Yu, "Coordinated beamforming for the multicell multi-antenna wireless system," IEEE Trans. Wireless Commun., vol. 9, no. 5, pp. 1748–1759, May 2010.

[5] S. Lakshminarayana, J. Hoydis, M. Debbah, and M. Assaad, "Asymptotic analysis of distributed multi-cell beamforming, in IEEE International Symposium in Personal Indoor and Mobile Radio Communications (PIMRC), Istanbul, Turkey, Sep. 2010, pp. 2105–2110.

Massive MIMO for wireless backhaul: Numerical results



Average minimum number of required BS-antennas N to serve $S \in \{20, 40, 81\}$ randomly chosen SCs with the same target backhaul rate.

Summary

- Massive MIMO and SCs have distinct advantages which complement each other:
  - Massive MIMO for coverage and mobility support
  - SCs for capacity and indoor coverage
- TDD and the resulting channel reciprocity allow every device to fully exploit its available degrees of freedom for intra-/inter-tier interference mitigation.
- A TDD co-channel deployment of massive MIMO BSs and SCs can achieve a very attractive rate region.
- Massive MIMO BSs can provide wireless backhaul to a large number of SCs. The slowly time-varying nature of the BS-SC channels might allow for complex precoding and detection schemes.

For more details:

J. Hoydis, K. Hosseini, S. ten Brink, and M. Debbah, *"Making Smart Use of Excess Antennas: Massive MIMO, Small Cells, and TDD,"* Bell Labs Technical Journal, vol. 18, no. 2, Sep. 2013.

Thank you!