Making Smart Use of Excess Antennas: Massive MIMO, Small Cells, and (the essential role of) TDD

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The data explosion and possible solutions

The data explosion

By 2017, there will be[1]

- $13 \times$ more mobile data traffic than in 2012
- $10,000,000,000$ connected devices
- 2/3 of the total traffic generated by mobile video streaming and communications

Network densification is today the only answer to the capacity crunch

- Small cells : Area spectral efficiency scales linearly with the cell density
- Massive MIMO : Interference can be almost entirely eliminated

Both approaches can significantly reduce the radiated power

Mobility is not anymore limited by coverage but rather by battery life.

[1] Source: Cisco, Yankee

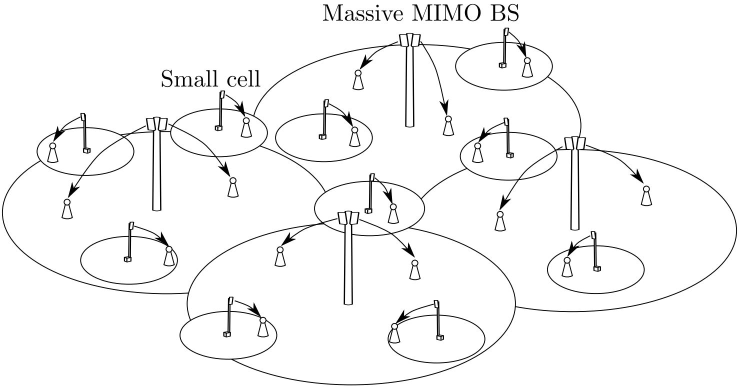
Massive MIMO versus Small Cells

- From a coverage as well as area spectral efficiency point of view, one should **distribute the antennas as much as possible**.[2]
- However, with small cells deployed below the roof tops, it is difficult to
  - ensure coverage
  - support highly mobile UEs
- But, massive MIMO is *particularly* suited to
  - ensure coverage
  - support highly mobile UEs

Can we integrate the **complementary benefits** of both?

[2] H. S. Dhillon, M. Kountouris, and J. G. Andrews, "Downlink MIMO hetnets: Modeling, ordering results and performance analysis," IEEE Trans. Wireless Commun., 2013, submitted. [Online]. Available: http://arxiv.org/abs/1301.5034.

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)

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

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

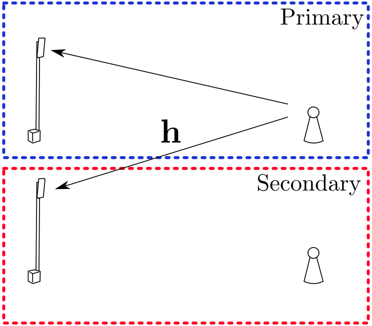
The essential role of TDD

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



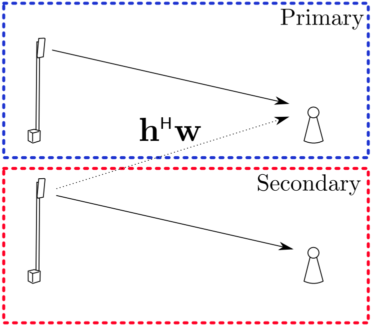
1. The secondary BS listens to the transmission from the primary UE:

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

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

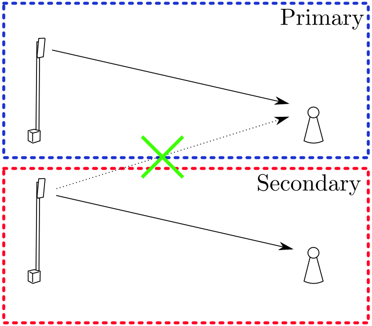
$$\mathbb{E}\left[\mathbf{y}\mathbf{y}^{\mathsf{H}}\right] = \mathbf{h}\mathbf{h}^{\mathsf{H}} + \mathsf{SNR}^{-1}\mathbf{I}$$

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 $\mathbf{h}\mathbf{h}^{\mathsf{H}}$.

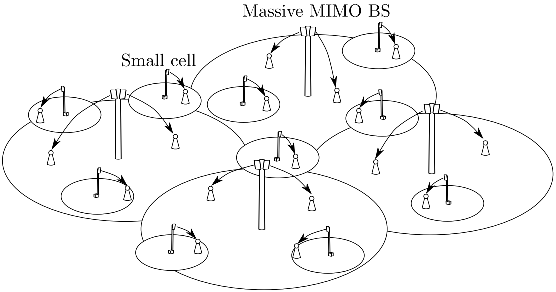
An idea from cognitive radio



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

4. The interference to the primary UE can be entirely eliminated without explicit knowledge of $\mathbf{h}$.

Translating this idea to HetNets



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

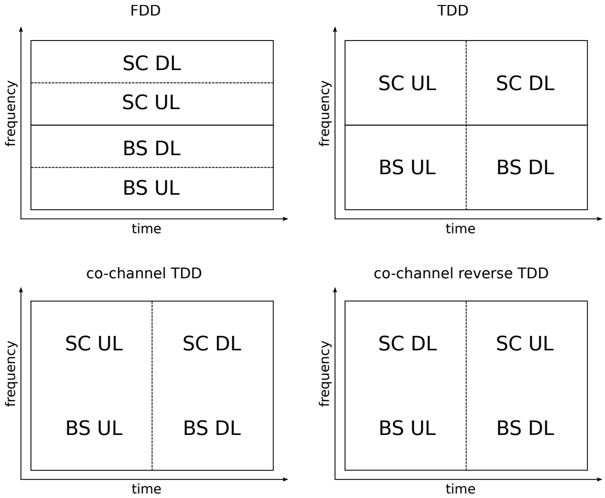
Advantages

- 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

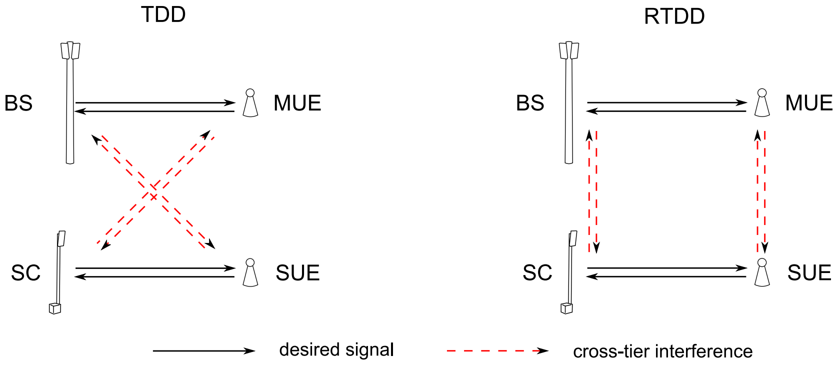
- **Cognitive radio**
  - R. Zhang, F. Gao, and Y. C. Liang, "Cognitive Beamforming Made Practical: Effective Interference Channel and Learning-Throughput Tradeoff," IEEE Trans. Commun., 2010.
  - F. Gao, R. Zhang, Y.-C. Liang, X. Wang, "Design of Learning-Based MIMO Cognitive Radio Systems," IEEE Trans. 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.
  - F. Negro, I. Ghauri, D. Slock, "Transmission techniques and channel estimation for Spatial Interweave TDD Cognitive Radio systems," Asilomar 2009.
- **Blind nullspace learning**
  - Y. Noam and A. J. Goldsmith, "Exploiting spatial degrees of freedom in MIMO cognitive radio systems," ICC, 2012.
- **and many more...**

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.

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
- The BSs and SCs use precoding vectors of the structure:

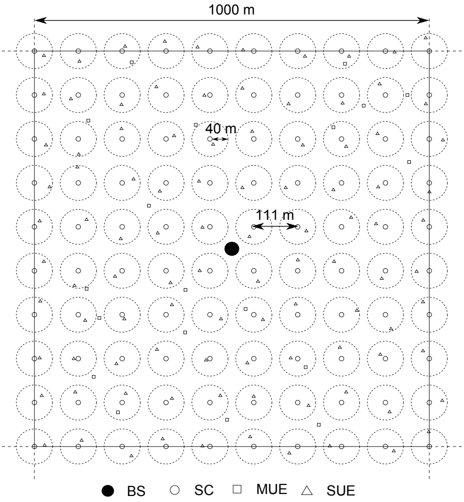
$$\mathbf{w} \sim \left(P\mathbf{H}\mathbf{H}^{\mathsf{H}} + \kappa\mathbf{Q} + \sigma^2\mathbf{I}\right)^{-1}\mathbf{h}$$

  - $\mathbf{h}$ 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

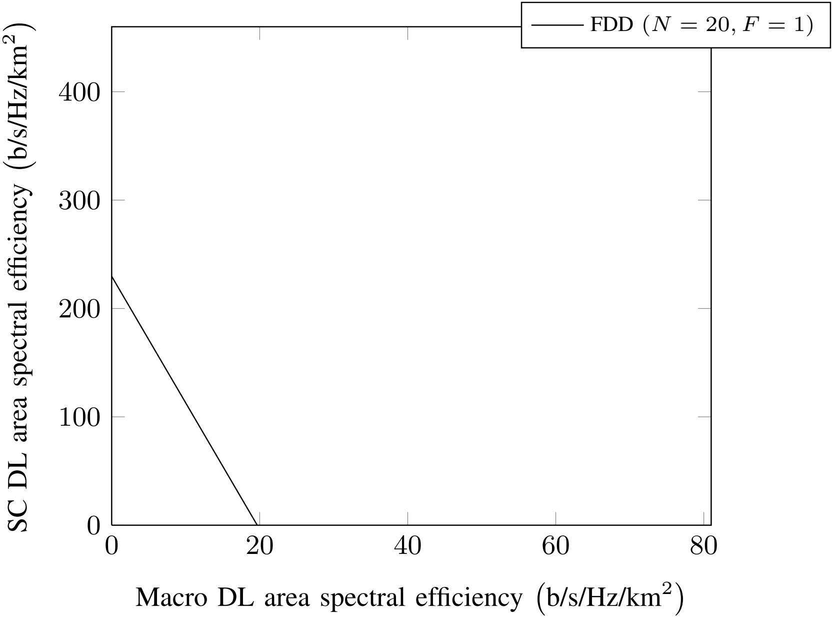
For $\alpha, \beta = 0$, the BSs and SCs transmit as if they were in an isolated cell, i.e., MMSE precoding (BSs) and maximum-ratio transmissions (SCs). By increasing α, β, the precoding vectors become increasingly orthogonal to the interference subspace.

Numerical results

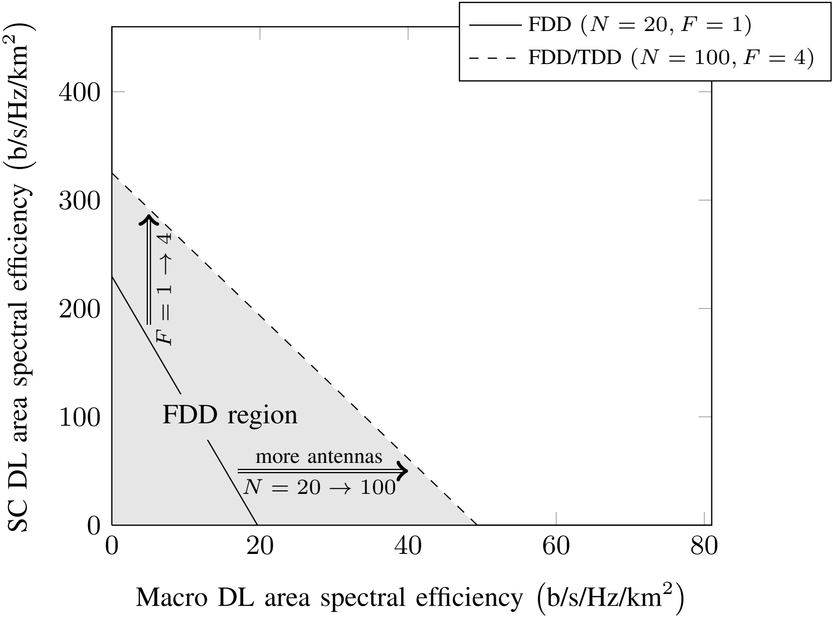


- 3×3 grid of BSs with wrap around
- $S = 81$ SCs per cells on a regular grid
- $K = 20$ MUEs randomly distributed
- 1 SUE per SC randomly distributed on a disc around each SC
- 3GPP channel model with path loss, shadowing and fast fading, N/LOS links
- TX powers: 46 dBm (BS), 24 dBm (SC), 23 dBm (MUE/SUE)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

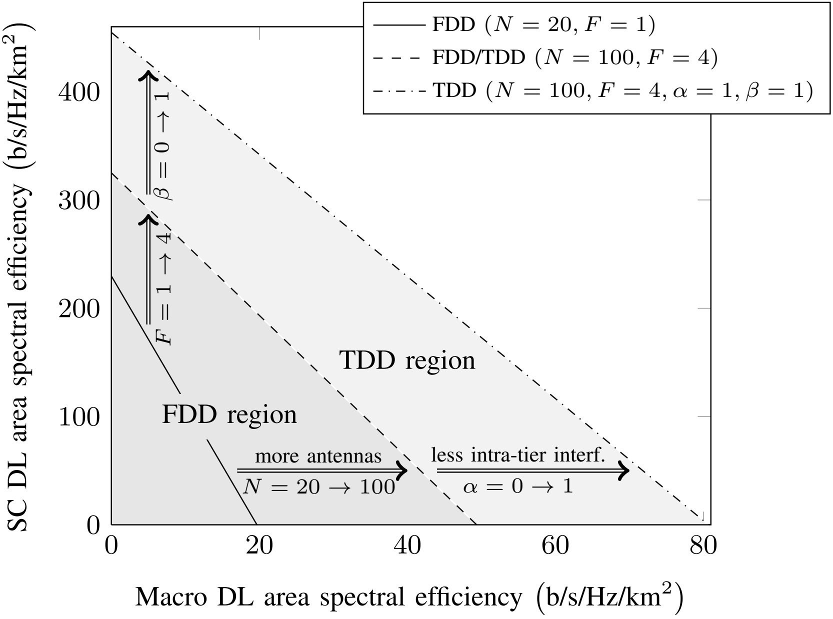
Downlink spectral area efficiency regions



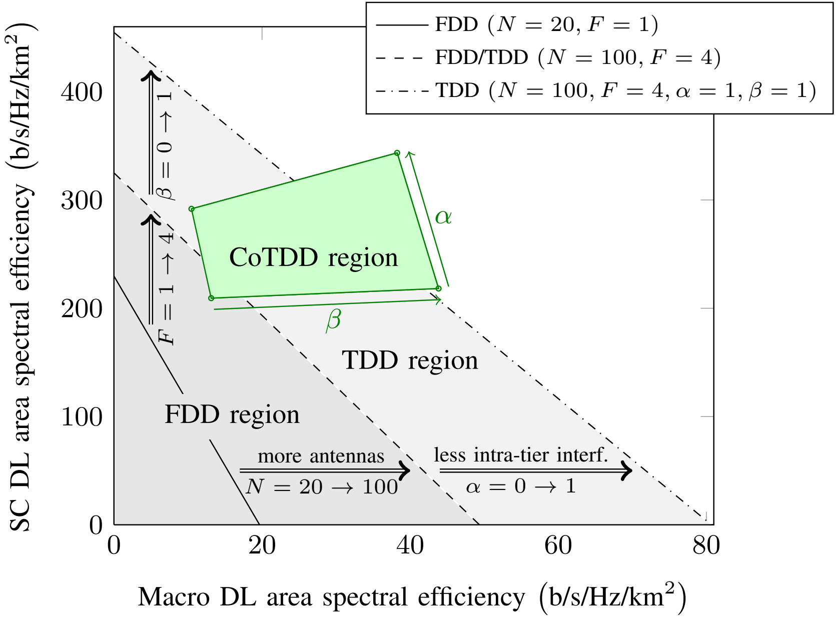
Downlink spectral area efficiency regions



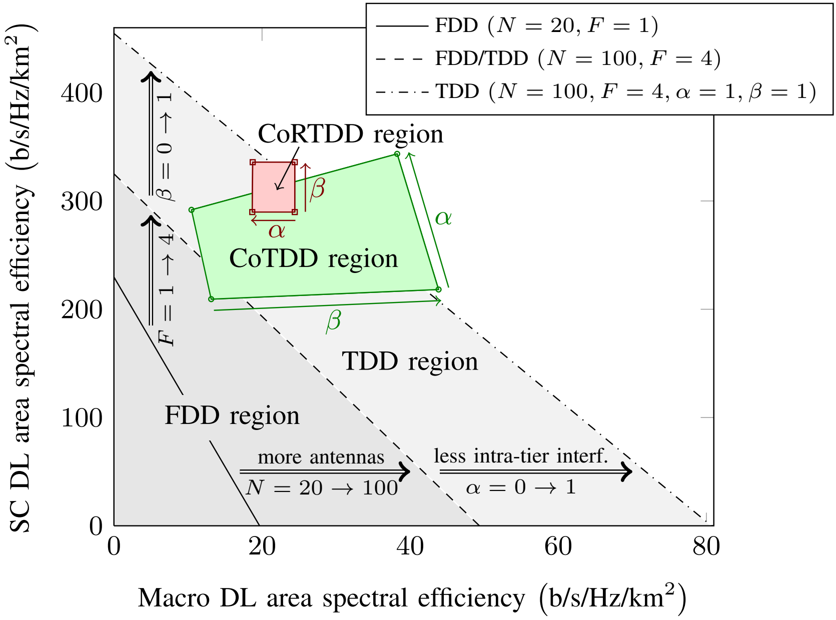
Downlink spectral area efficiency regions



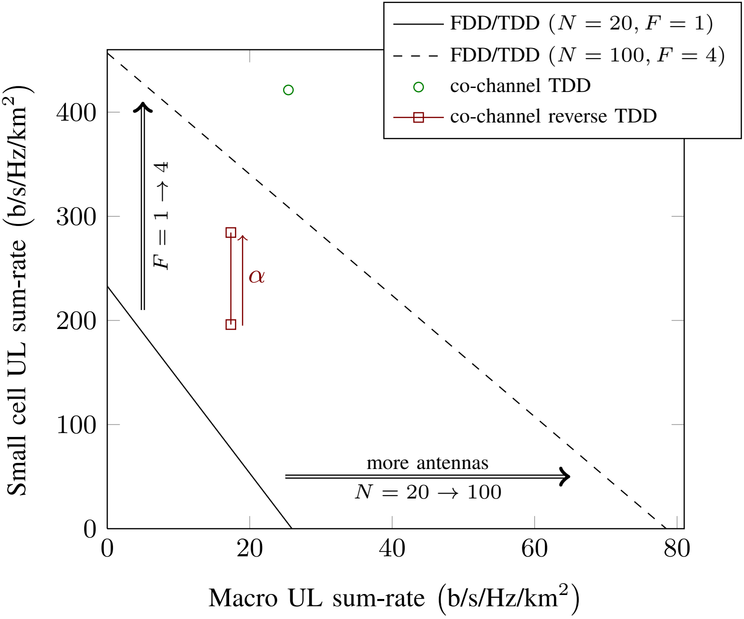
Downlink spectral area efficiency regions



Downlink spectral area efficiency regions



Uplink spectral area efficiency regions



Observations

- Increasing the number of antennas at each device leads to tremendous performance improvements for all duplexing schemes ($N = 20 \to 100$, $F = 1 \to 4$, FDD):

$$+200\,\%\text{ BS UL, }+150\,\%\text{ BS DL, }+100\,\%\text{ SC UL, }+50\,\%\text{ SC DL}$$

- TDD channel reciprocity allows for intra-tier interference reduction ($\alpha, \beta : 0 \to 1$):

$$+50\,\%\text{ BS DL, }+30\,\%\text{ SC DL}$$

- Even **a few "excess" antennas at the SCs leads to significant gains**.
- 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 bandwidth):

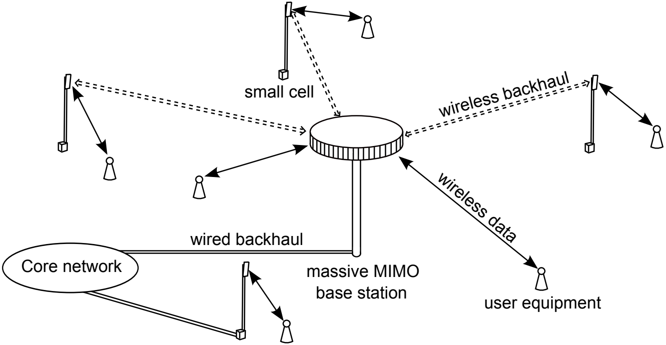
	DL	UL
total	7.63 Gb/s/km^2 (382 b/s/Hz/km^2)	8.93 Gb/s/km^2 (447 b/s/Hz/km^2)
per MUE	38.2 Mb/s	25.4 Mb/s
per SUE	84.8 Mb/s	104 Mb/s

- 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 model 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
  - Statistical multiplexing opportunity to avoid over-provisioning of backhaul
- 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:

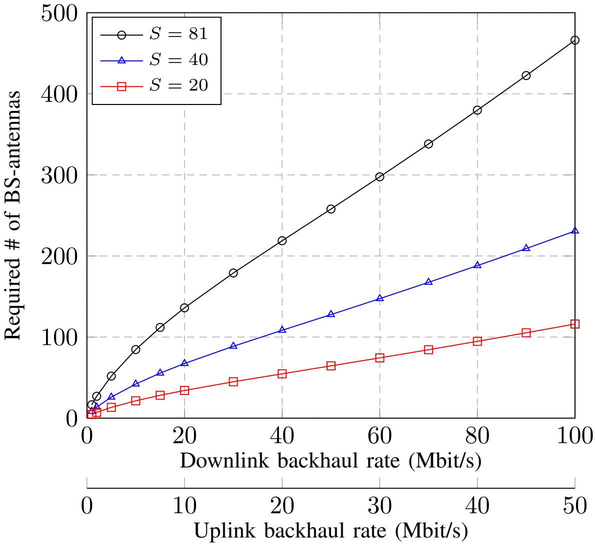
- Every BS knows the channels to all SCs.
- The BSs can exchange some control information.
- Full user data sharing between the BSs is not possible.
- Single-antenna SCs, BSs with N antennas
- TDD operation on a separate band (2/3 DL, 1/3 UL)
- Same modeling assumptions as before

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!