Security Level:

Technical Challenges of Future Massively Deployed Radio Technologies

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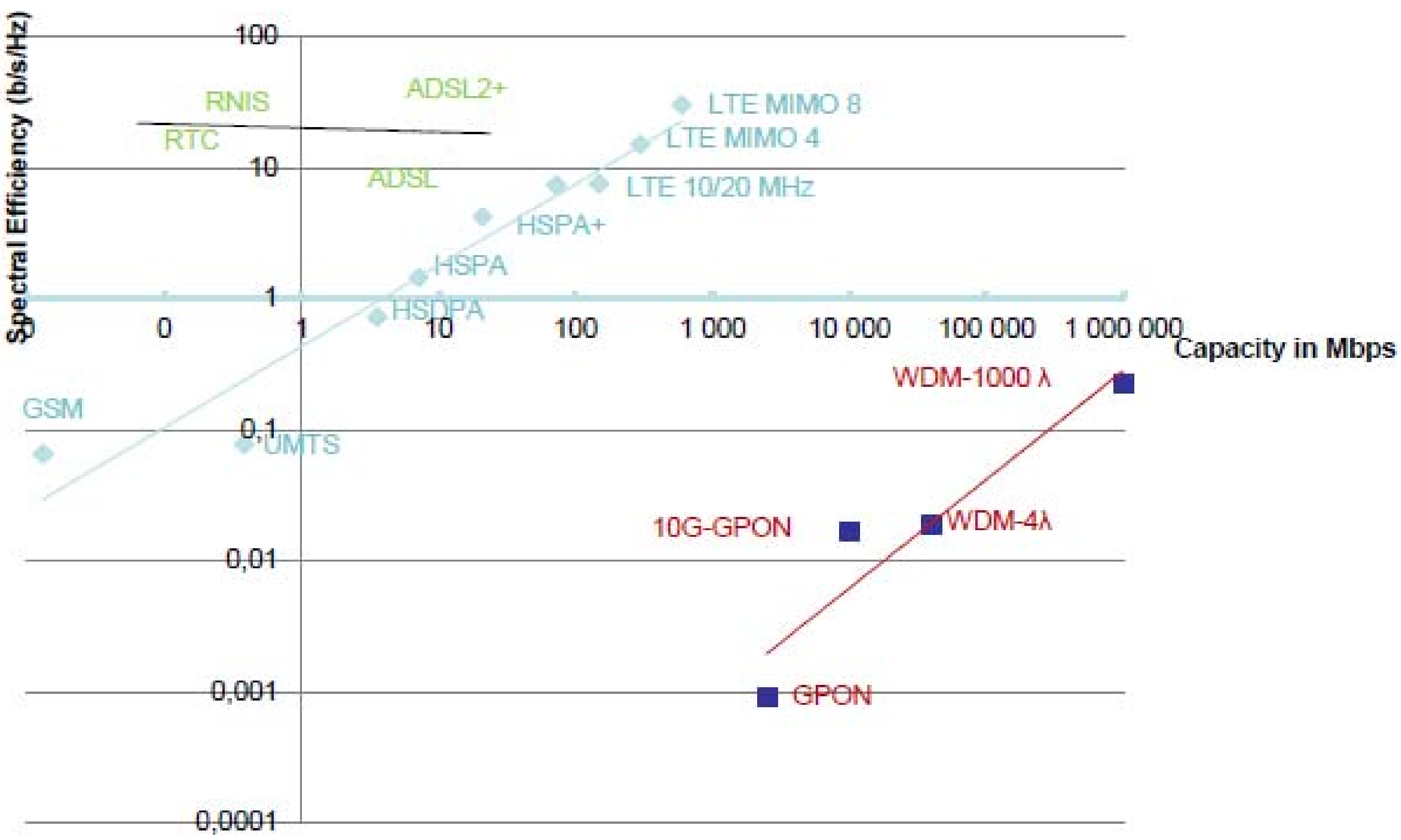
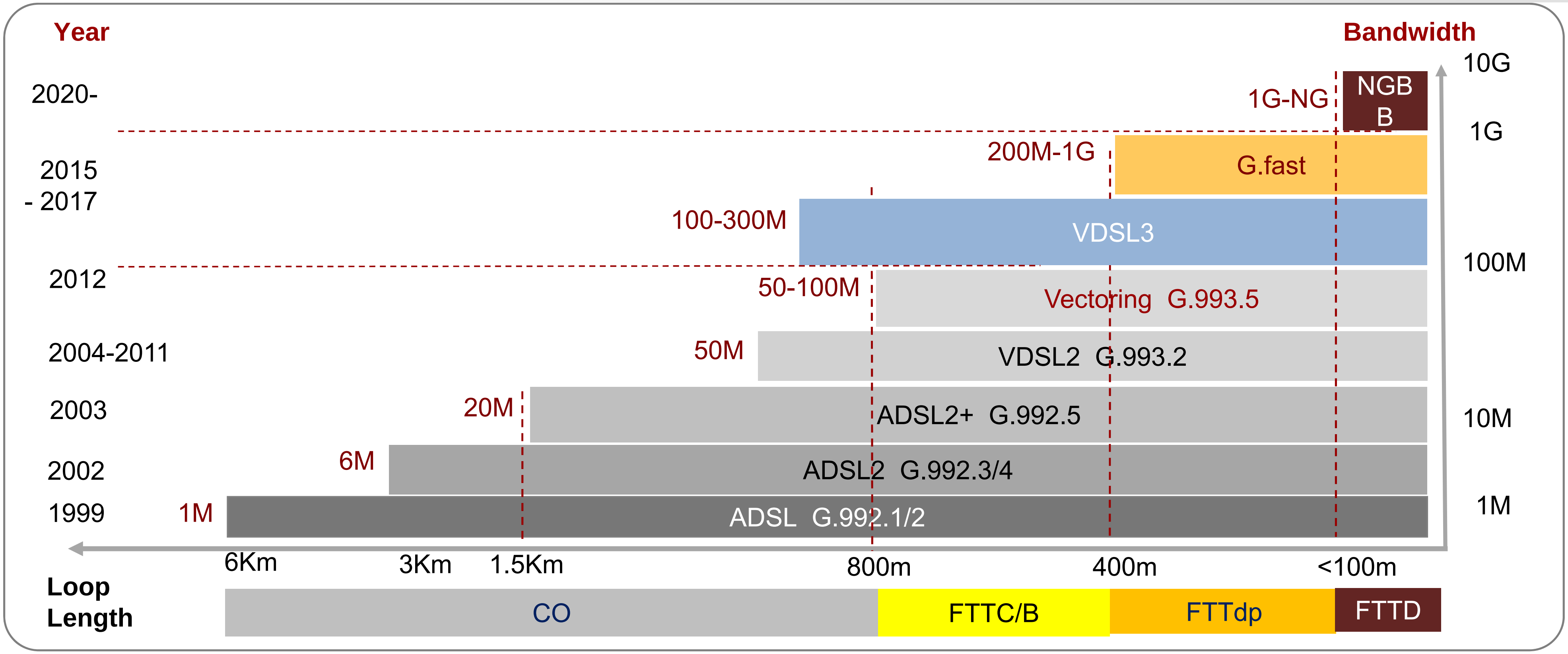
Spectral Efficiency for fixed and Wireless Technologies



Copper Access: History and Future Trend: Continuous Innovations Keep Exploring the Potential of Copper



AF5

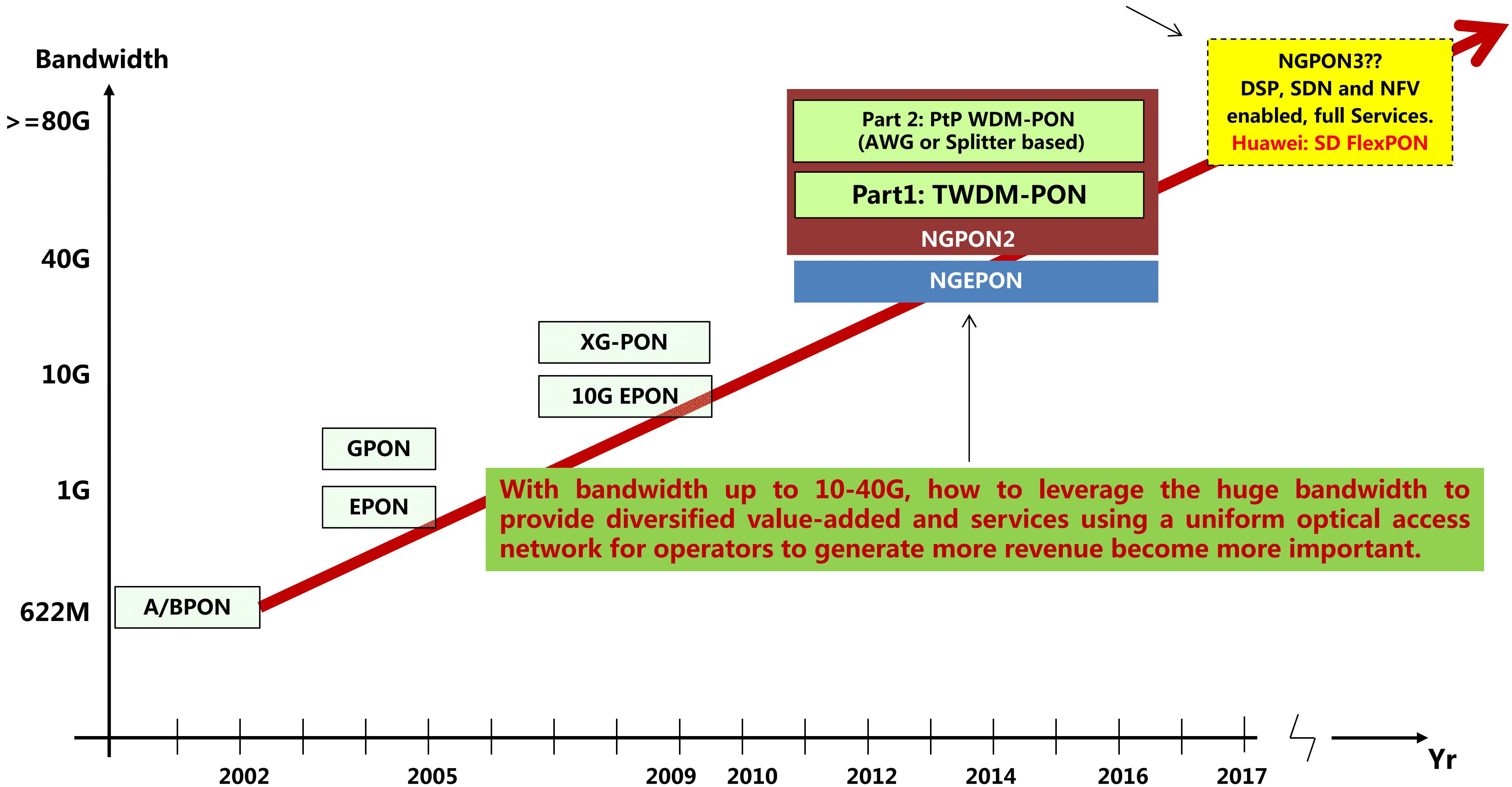
VDSL2	Vectoring	VDSL3	G.fast	NGBB
• **Bandwidth:30-50Mbps** • **Distance:~1000m** • **Scenario: FTTC** • **Mature**	• **Bandwidth:50100 Mbps** • **Distance:300-800m** • **Scenario: FTTC** • **Mature**	• **Bandwidth:100-300Mbps** • **Distance300-1200m** • **Scenario: FTTC** • **Available:2016-2017**	• **Bandwidth:200M-1Gbps** • **Distance:<400m** • **Scenario: FTTB/D/dp** • **Available: 2015-2016**	• **Bandwidth:1-NGbps** • **Distance:<100m** • **Scenario: FTTD/F** • **Multi-pair MIMO?** • **Available: 2020-**

Slide 3

AF5 Put a dash between 50 and 100
A73863; 06/05/2015

Optical Access Trend

Much more flexible OAN will be the Future trend. New technologies such as DSP, SDN and NFV will be involved.



Cable Access Network Trend

Past

Now

Soon

Future

Current Cable (1Gbps):

- **Spectrum:** 5~860MHz;
- **Network:** Analog optical fiber, N+5 Coax, 500~1000HHP;
- **Technology:** D2.0/D3.0, Channel bonding (32DS+8US);
- **Architecture:** I-CCAP, Integrate video and DOCSIS data.

NG Cable (10Gbps):

- **Spectrum:** 5M~1.7GHz;
- **Network:** Digital optical fiber, N+3 Coax, 500~1000HHP;
- **Technology:** D3.1(LDPC+ OFDM/OFDMA), PNM;
- **Architecture:** DCA (Distribute CCAP Architecture), Remote PHY or Remote MAC and PHY.

NG2 Cable (40Gbps):

- **Spectrum:** 5M~6GHz;
- **Network:** FTTLA, N+1 Coax, 100~200HHP;
- **Technology:** 40G Cable (20G DOCSIS + 20G wireless front haul), iCoax(Remote PNM diagnose);
- **Architecture:** Cable 2.0 (Virtual CCAP, and Virtual CPE).

2015 2019 2025

Common Trend of various access technologies

Data rate faster & faster

Data rate	Now	Soon	Future
Copper (dedicated)	100 MBPS	1 GBPS	5-10 GBPS
Cable (shared)	1 GBPS	10 GBPS	40 GBPS
Optical (shared)	2.5 GBPS	10 GBPS	40~400 GBPS

Spectrum wider & wider

Frequency Spectrum	Now	Soon	Future
Copper (dedicated)	30 MHz	100 MHz	>200 MHz
Cable (shared)	860 MHz	1.7 GHz	6 GHz
Optical (shared)	1 lambda x2.5G	4 lambda x 10G	more lambda x >10G

Loops shorter & shorter

Loop length	Now	Soon	Future
Copper (dedicated)	300-1000m	100-300m	<100m
Cable (shared)	1000-2000m	500-1000m	<200m

The Massive Paradigm of Next Generation Radio technologies

- **Massive number of antennas**
- **Massive number of things**
- **Massive bandwidth**

	Massive spectrum	Massive Antennas	Massive Number of things
	?x	?x	?x
	New regulations, cognitive radio, mmWave bands	*Smaller cells, Massive MIMO*	***Non-Orthogonal waveforms*** ***Asynchronous transmissions***

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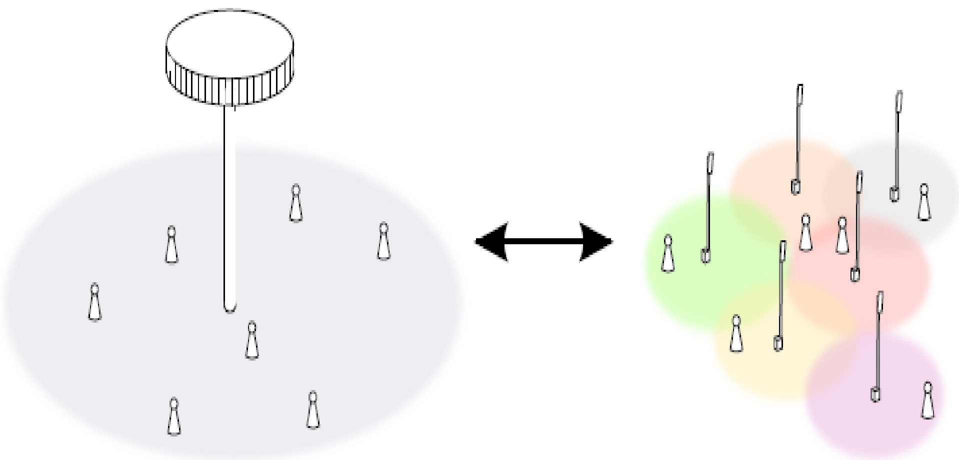
We will focus on Massive Antennas

“David vs Goliath“ or "Small Cells vs Massive MIMO“



How to densify: *“More antennas or more BSs?”*

Questions:

- Should we install more base stations or simply more antennas per base?
- How can massively many antennas be efficiently used?

Example

- Density of UTs: $\lambda_{UT} = 16$
- Constant transmit power density: $P \times \lambda_{BS} = 10$
- Number of BS-antennas: $N = \lambda_{UT}/\lambda_{BS}$
- Path loss exponent: $\alpha = 4$
- UT simultaneously served on each band: $K = \lambda_{UT}/(\lambda_{BS} \times L)$

$\Rightarrow$ Only two parameters: λ_{BS} and L

Table: Average spectral efficiency C/W in (bits/s/Hz)

sub-bands L	$\lambda_{BS} = 1$	$\lambda_{BS} = 2$	$\lambda_{BS} = 4$	$\lambda_{BS} = 8$	$\lambda_{BS} = 16$
1	0.6209	0.8188	1.1964	1.5215	2.1456
2	1.1723	1.2414	1.3404	1.5068	x
4	0.8882	0.8973	1.1964	x	x
8	0.5689	0.5952		x	x
16	0.3532	x	x	x	x

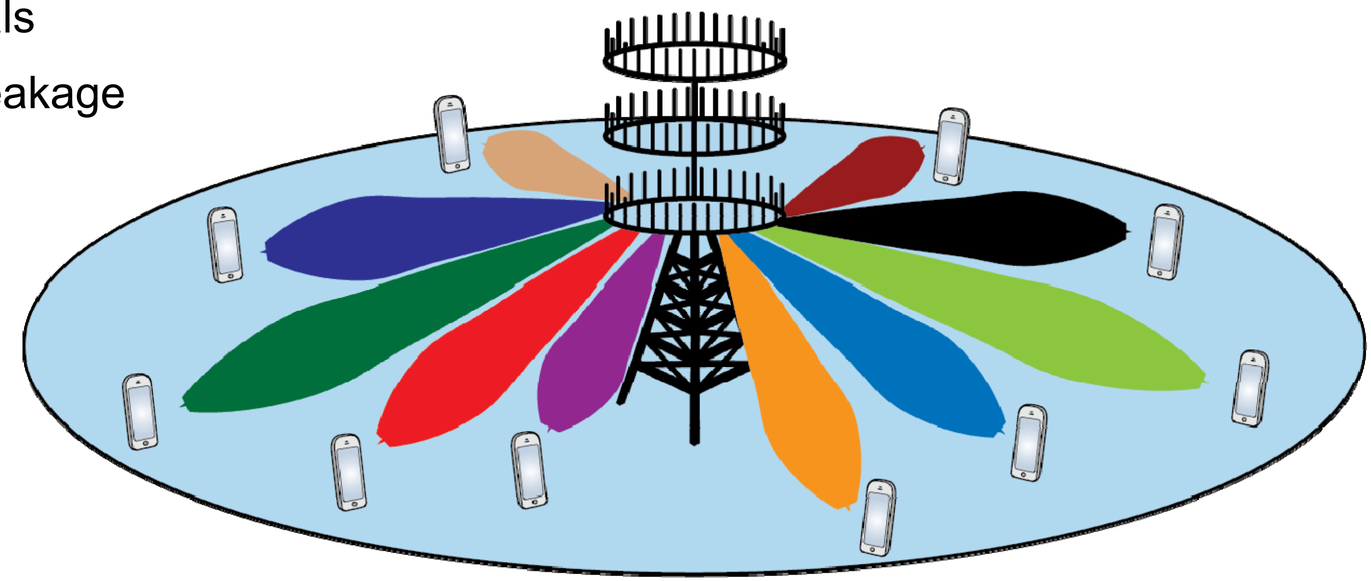
Fully distributing the antennas gives highest throughput gains!

Massive MIMO as one of the operating of 5G

E. Bjornson, L. Sanguinetti, J. Hoydis and M. Debbah, "Designing Multi-User MIMO for Energy Efficiency: When is Massive MIMO the Answer? », IEEE Wireless Communications and Networking Conference (WCNC) 2014, Istanbul, Turkey, **BEST PAPER AWARD.**

Taking Multi-User MIMO to the Next Level

- Network Architecture: Massive MIMO
  - BS with many antennas; e.g., $M \approx 200$ antennas, $K \approx 40$ users
  - Key: Excessive number of antennas, $M \gg K$
  - Very directive signals
  - Little interference leakage



Spectral efficiency prop. to number of users!

$$\min\left(M, K, \frac{\tau_c}{2}\right) \approx K$$

What is the Key Difference from Today?

- Number of Antennas? **No, we already have many antennas!**
  - 3G/UMTS: 3 sectors x 20 element-arrays = 60 antennas
  - 4G/LTE-A: 4-MIMO x 60 = 240 antennas

Typical vertical array:
10 antennas x 2 polarizations

Massive MIMO Characteristics

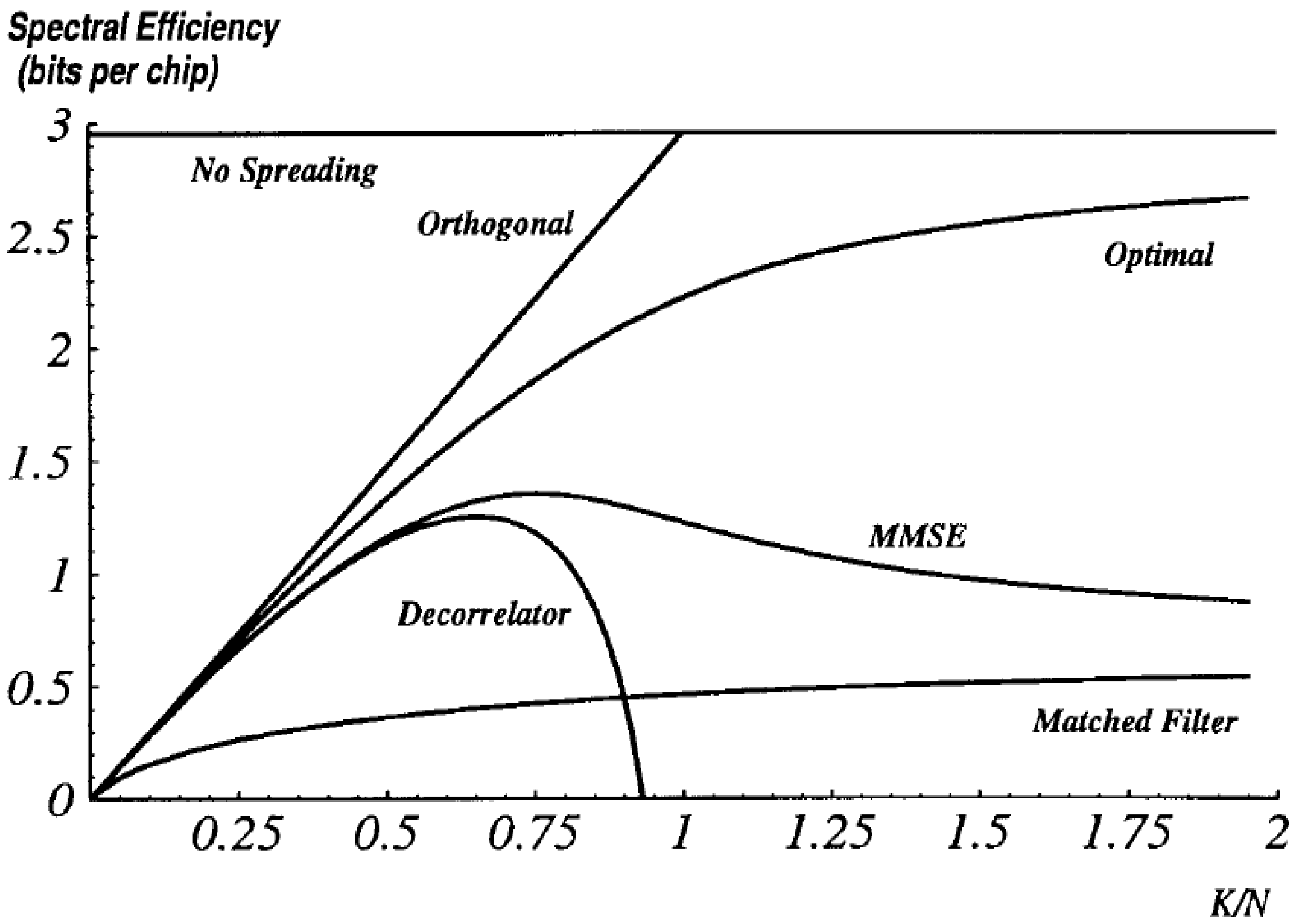
Many small dipoles with transceiver chains

Spatial multiplexing of tens of users

Massive in numbers – not massive in size

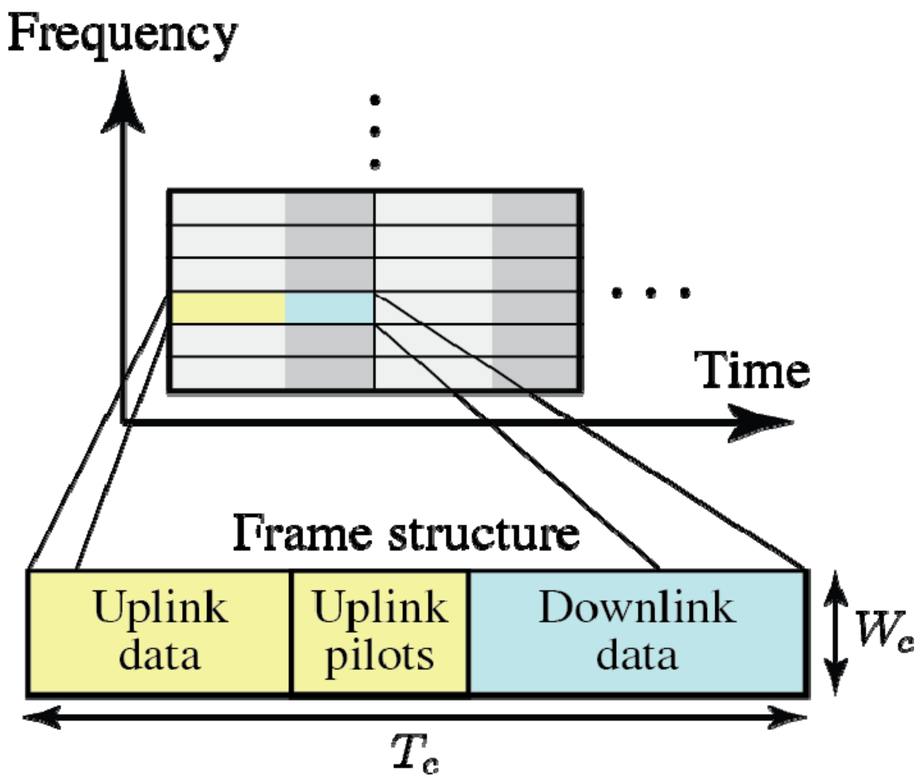
3 sectors, 4 vertical arrays per sector
Image source: gigaom.com

J. Hoydis, S. ten Brink, M. Debbah, "*Massive MIMO in the UL/DL of Cellular Networks: How Many Antennas Do We Need?*," IEEE Journal on Selected Areas in Communications, 2013. **IEEE Leonard G. Abraham Prize**



Massive MIMO Transmission Protocol

- Coherence Blocks
  - Fixed channel responses
  - Coherence time: T_c s
  - Coherence bandwidth: W_c Hz
  - Depends on mobility and environment
  - Block length: $\tau_c = T_c W_c$ symbols
  - Typically: $\tau_c \in [100,10000]$



- Time-Division Duplex (TDD)
  - Downlink and uplink on all frequencies
  - τ_p symbols/block for uplink pilots – for channel estimation
  - $\tau_c - \tau_p$ symbols/block for uplink and/or downlink payload data

Linear or Non-linear Processing?

- Capacity-Achieving Non-linear Processing
  - Downlink: Dirty paper coding
  - Uplink: Successive interference cancellation

Do we need it in Massive MIMO?

Linear Processing

Bad when $M \approx K$

Good when $M/K > 2$

Relative low complexity

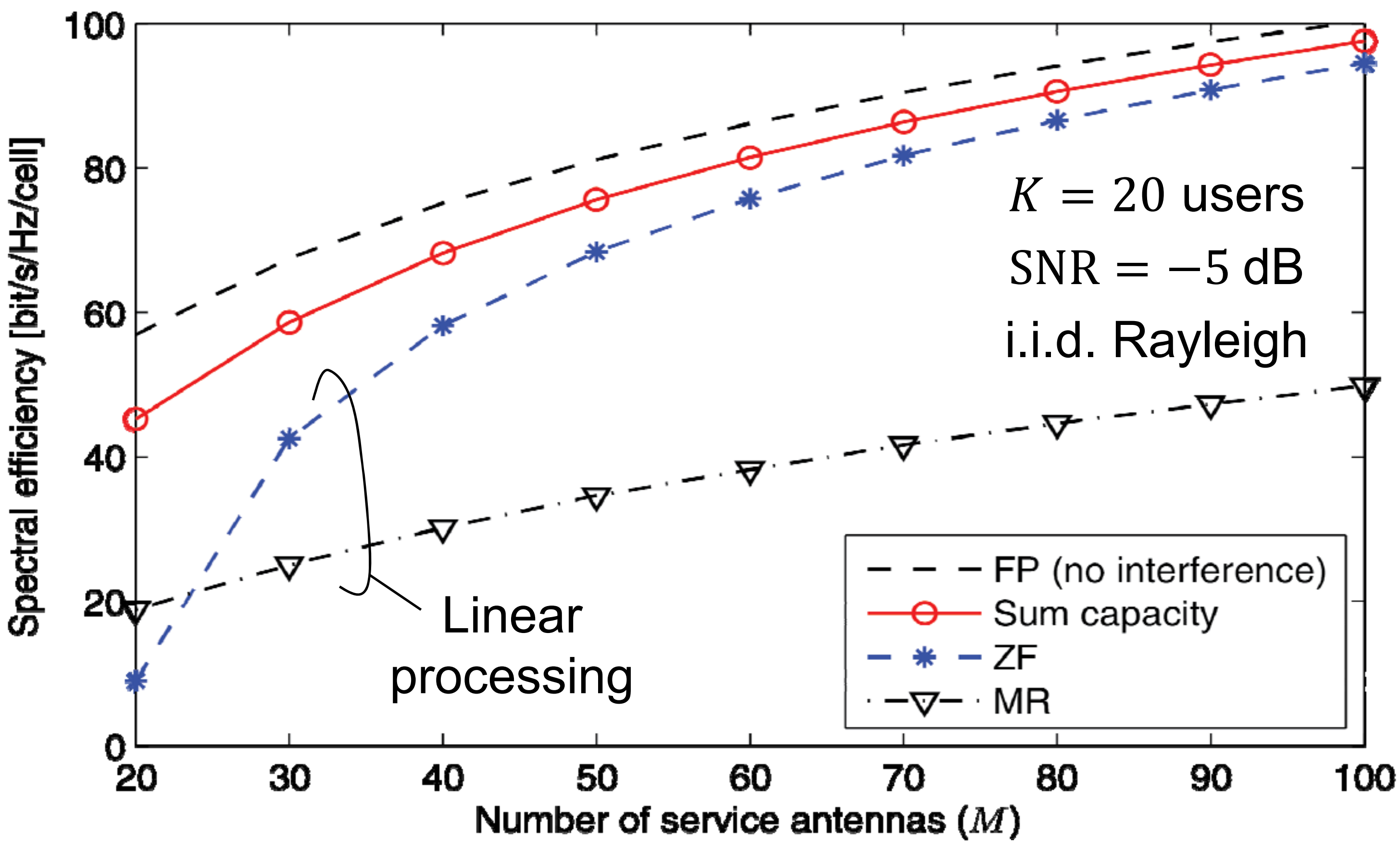
Massive MIMO

Uses linear processing:

Maximum ratio (MR)

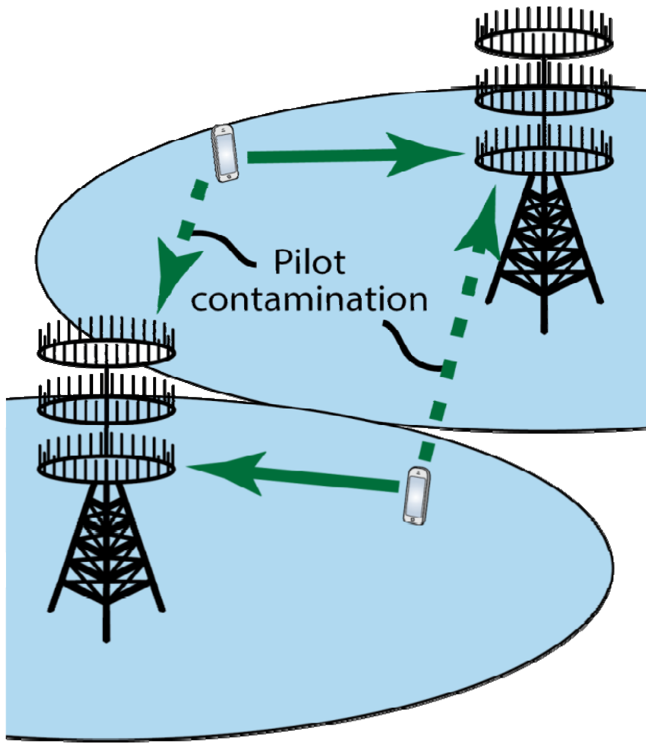
Zero-forcing (ZF)

MMSE



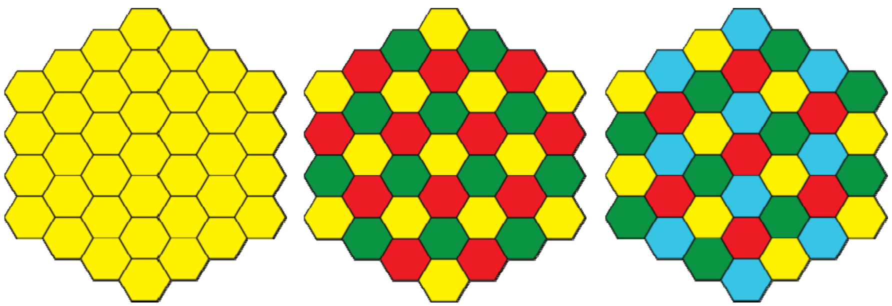
Channel Acquisition in Massive MIMO

- Limited Number of Pilots: $\tau_p \leq \tau_c$
  - Must use same pilot sequence in several cells
  - Base stations cannot tell some users apart:
    Essence of pilot contamination



- Coordinated Pilot Allocation
  - Allocate pilots to users to reduce contamination
  - Scalability $\rightarrow$ No signaling between BSs

- Solution: Non-universal pilot reuse
  - Pilot reuse factor $f \geq 1$
  - Users per cell: $K = \frac{\tau_p}{f}$
  - $\mathcal{P}_j(f)$: Cells with same pilots as BS j
  - Higher $f \rightarrow$ Fewer users per cell,
    but fewer interferers in $\mathcal{P}_j$



Reuse $f = 1$ ***Reuse*** $f = 3$ ***Reuse*** $f = 4$

Asymptotic Limit on Spectral Efficiency

$$\mathrm{SE}_j \to K\left(1-\frac{fK}{\tau_c}\right)\log_2\left(1+\frac{1}{\sum_{l\in\mathcal{P}_j(f)\setminus\{j\}}\mu_{jl}^{(2)}}\right)$$

How Many Users to Serve?

Pre-log factor $K\left(1-\frac{fK}{\tau_c}\right)$ *is maximized by* $K^* = \frac{\tau_c}{2f}$ *users*

Maximal SE: $\frac{\tau_c}{4f}\log_2\left(1+\frac{1}{\sum_{l\in\mathcal{P}_j(f)\setminus\{j\}}\mu_{jl}^{(2)}}\right)$

Try different f *and* $\mathcal{P}_j(f)$ *to maximize the limit*

How Long Pilot Sequences?

$\tau_p = fK^* = \frac{\tau_c}{2}$*:* *Spend half coherence interval on pilots!*

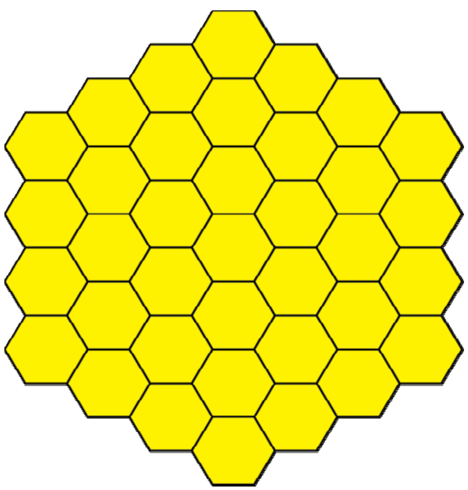
Numerical Results

- Problem Formulation:

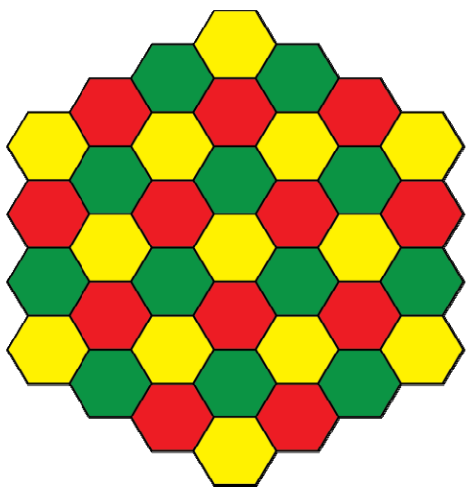
$$\underset{K,\tau_p}{\text{maximize}} \quad \text{total spectral efficiency} \qquad [\text{bit/s/Hz/cell}]$$

for a given M *and* τ_c.

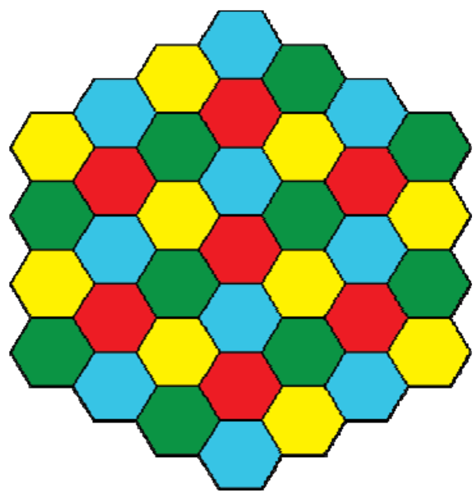
  - Use average spectral efficiency expressions
  - Compute average interference $\mu_{jl}^{(1)}$ and $\mu_{jl}^{(2)}$ (a few minutes)
  - Compute for different K and f and pick maximum (<1 minute)



Reuse $\boldsymbol{f=1}$



Reuse $\boldsymbol{f=3}$



Reuse $\boldsymbol{f=4}$

Assumptions

Pathloss exponent: 3.7

Coherence: $\tau_c = 400$

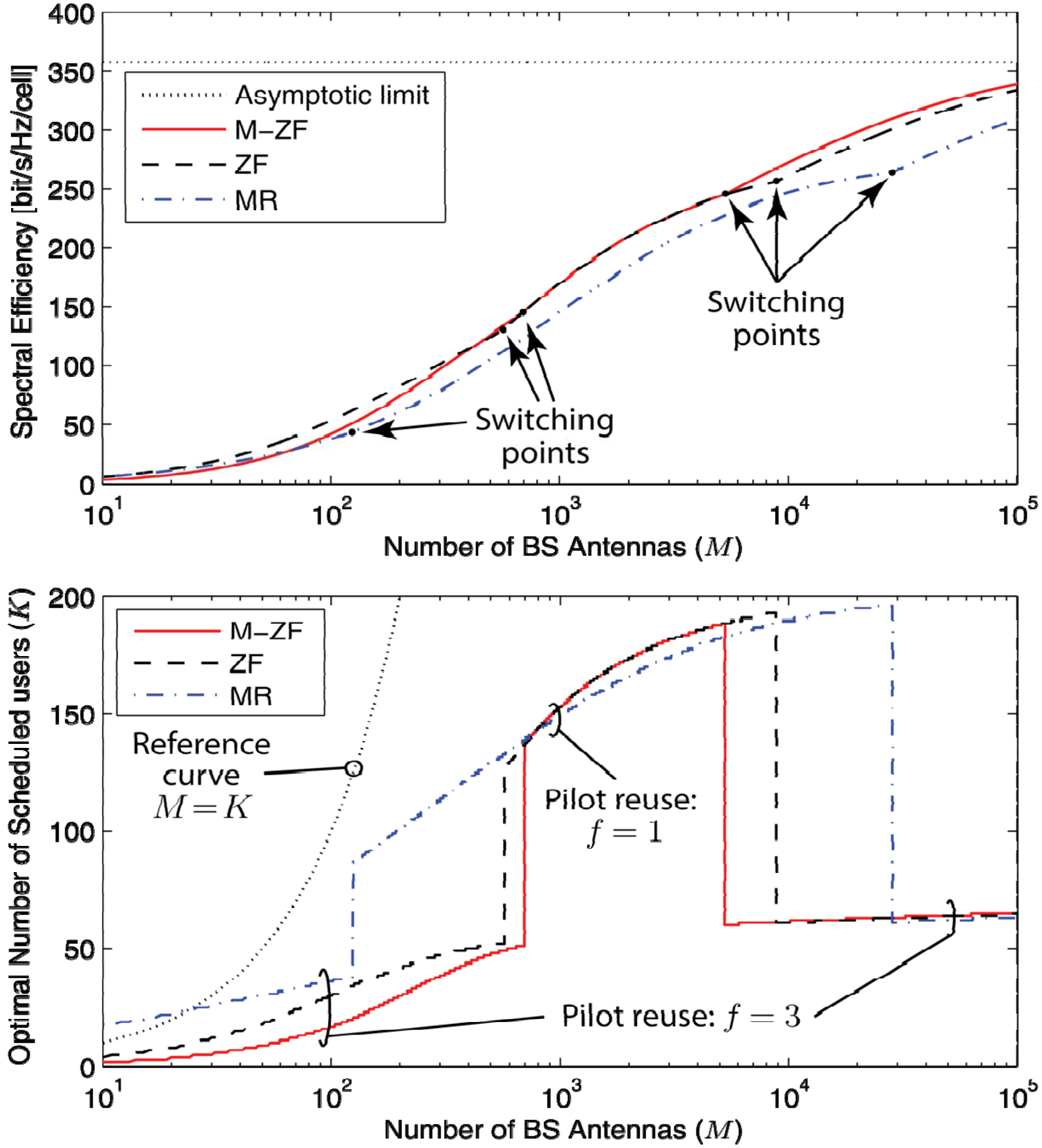
Rayleigh fading

SNR 5 dB

Asymptotic Behavior: Mean-Case Interference

Observations

- *Uniform user distributions*
- *Asymptotic limits not reached*
- *Reuse factor $f = 3$ is desired*
- *K is different for each scheme*
- *Small difference between optimized schemes*
- *Coordinated beamforming: Better at very large M*



Flexible Number of Users

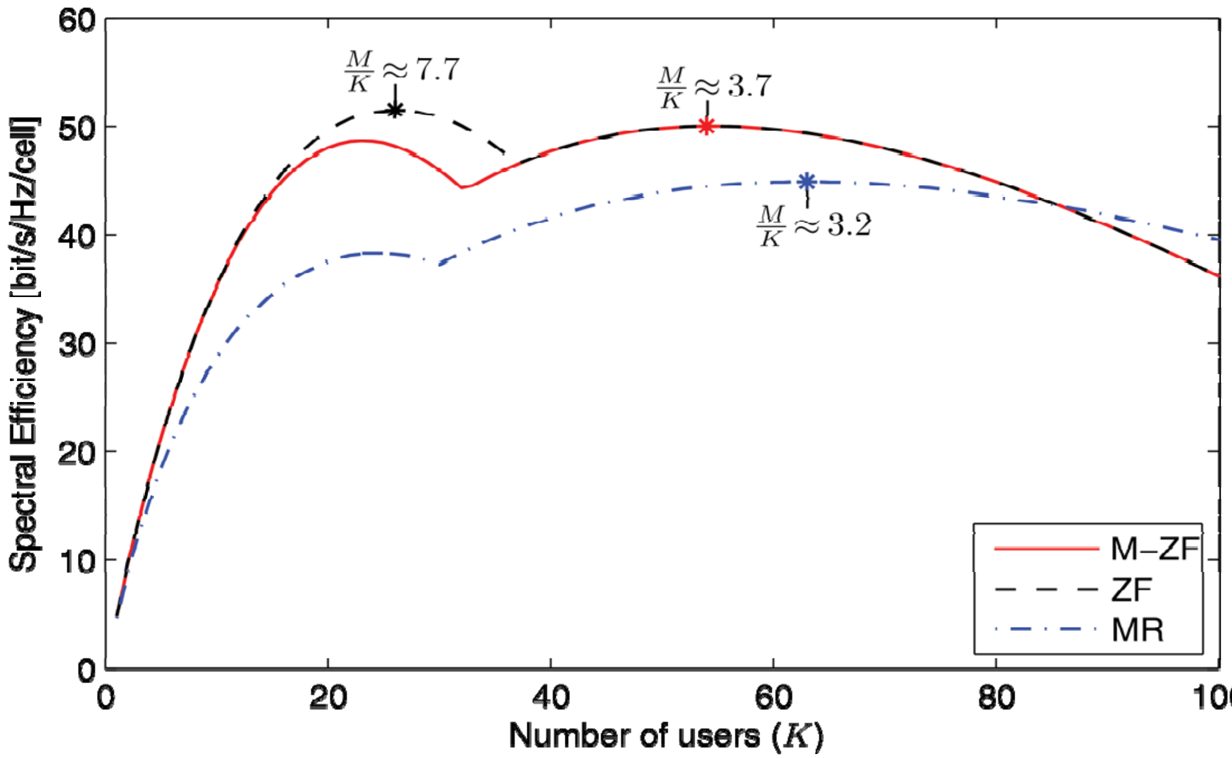
- SE w.r.t. number of users ($M = 200$ antennas)
  - Mean-case interference
  - Optimized reuse factors
  - Equal SNR (5 dB)

Observations

Stable SE for $K > 10$:
Trivial scheduling:
Admit everyone

M-ZF, ZF, and MR provide similar per-cell performance

$M/K < 10$ is just fine!



Spectral Efficiency per User

- User Performance for Optimized System
  - Mean-case interference
  - Optimized reuse factors
  - Equal SNR (5 dB)

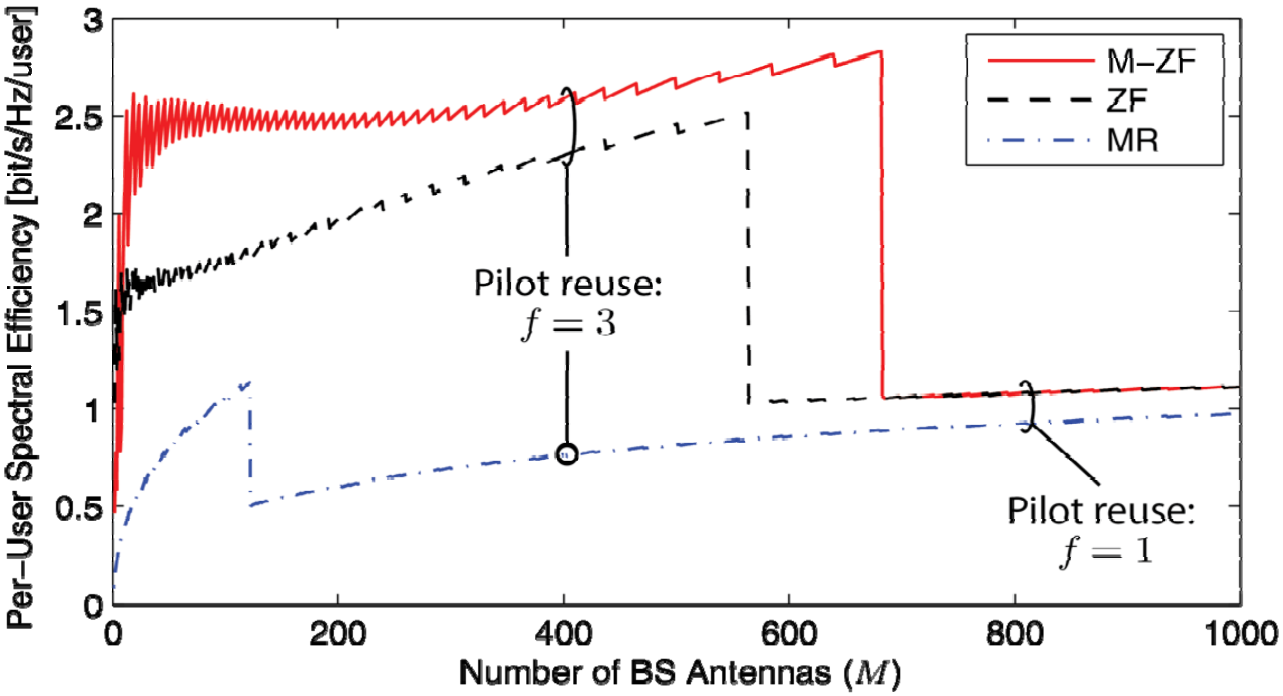
Observations

User performance is modest:

BPSK, Q-PSK, or 16-QAM

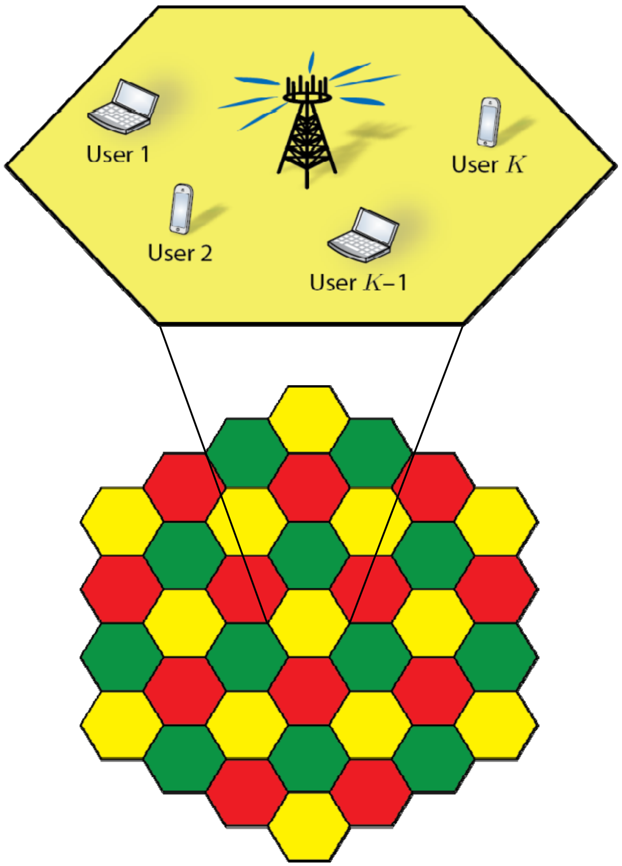
Schemes for different purposes:

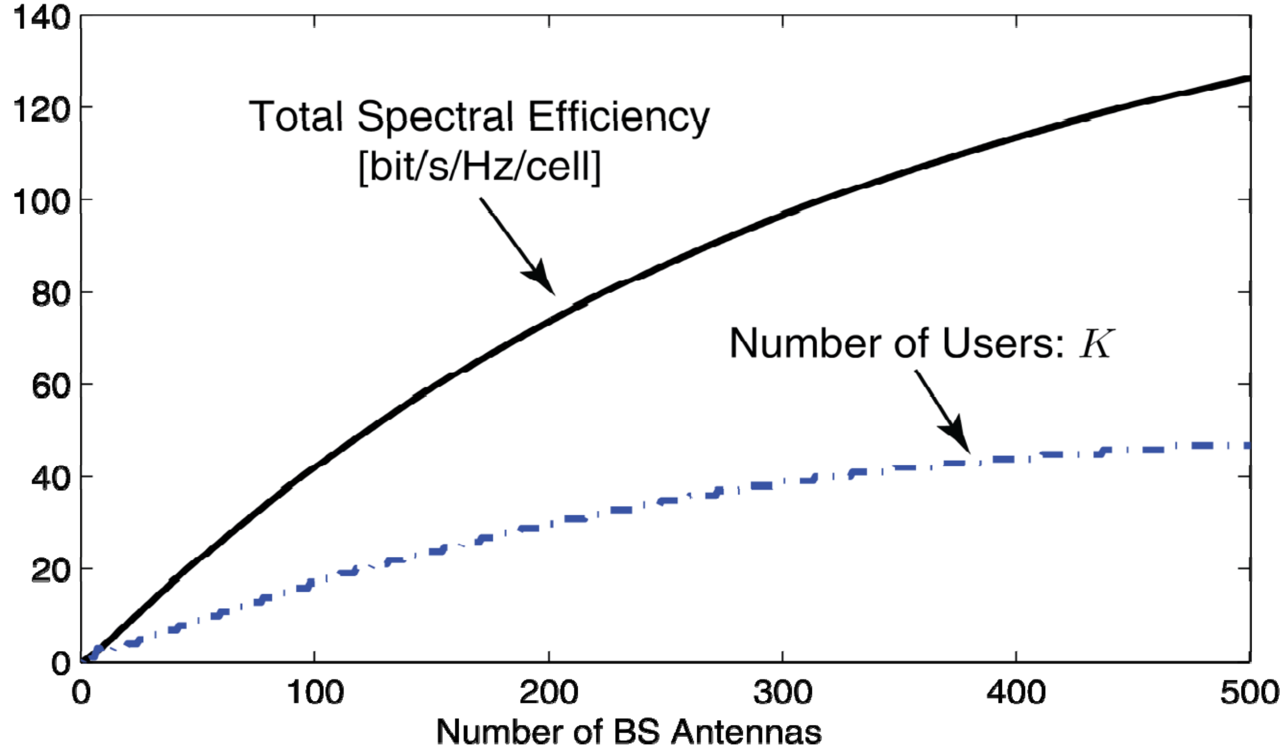
M-ZF > ZF > MR



Also applicable in the downlink!

Anticipated Uplink Spectral Efficiency





Assumptions

ZF processing

Pilot reuse: $f = 3$

Observations

- *Baseline: 2.25 bit/s/Hz/cell (IMT-Advanced)*
- *Massive MIMO,* $M = 100$*: x20 gain* $(M/K \approx 6)$
- *Massive MIMO,* $M = 400$*: x50 gain* $(M/K \approx 9)$
- *Per scheduled user:* ≈ 2.5 *bit/s/Hz*

First Large Scale 5G Field Trial (Chengdu/ China)

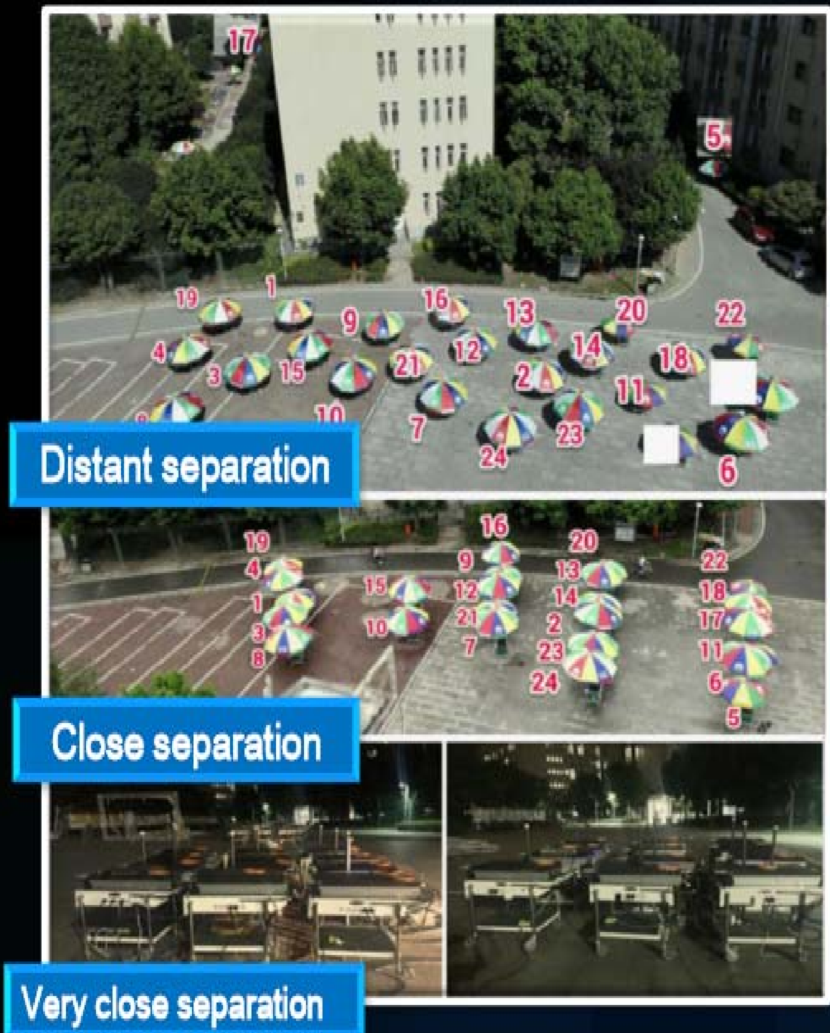
Large Scale Field Test of 5G New Radio Interface

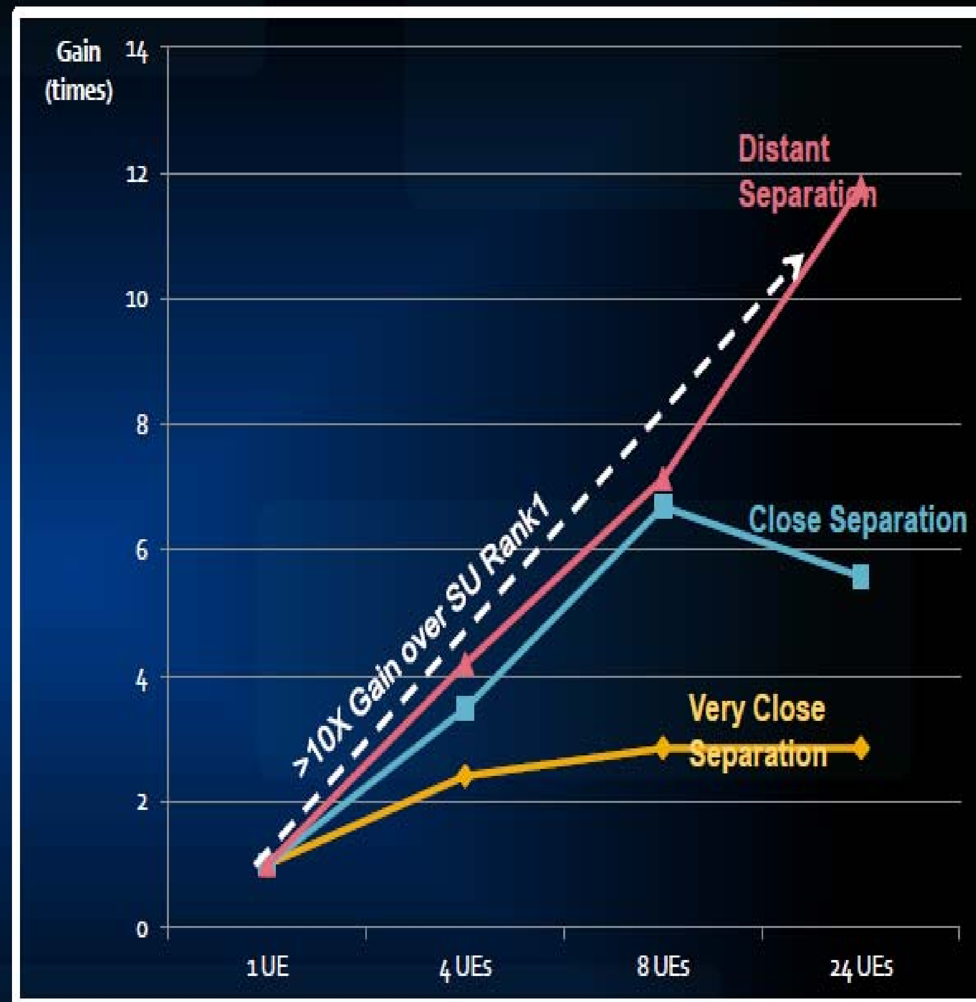
Technologies

- f-OFDM
- SCMA
- Polar Coding
- M-MIMO
- Full Duplex

- 64 TRX
- 100MHz Bandwidth
- 24 UE

m-MIMO with 24 UEs





Cell throughput of MU-MIMO is >10 times to SU-MIMO with single layer

Key References (1/2)

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