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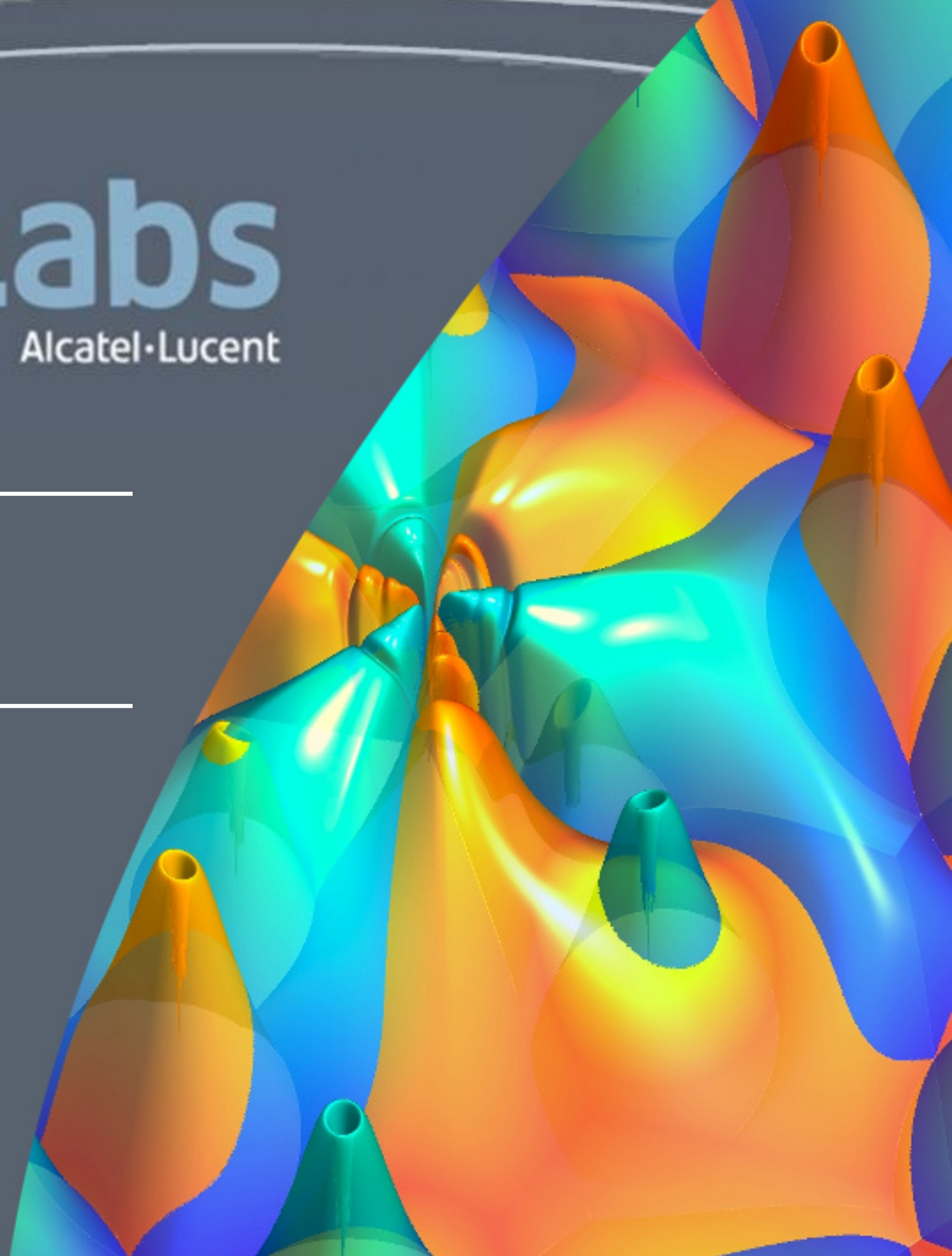
Future Cellular Networks

David Lopez-Perez

Mar. 2015



Agenda

- Trends & Cellular Network Evolution
- Where are we today?
- Where are we heading?
- New macrocell architectures
- Intelligent indoor small cells
- Dense small cell deployments

Agenda

Trends & Cellular Network Evolution

Telecommunications market drivers

New user terminals

New applications

New markets

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Traffic Growth in Wireless Networks

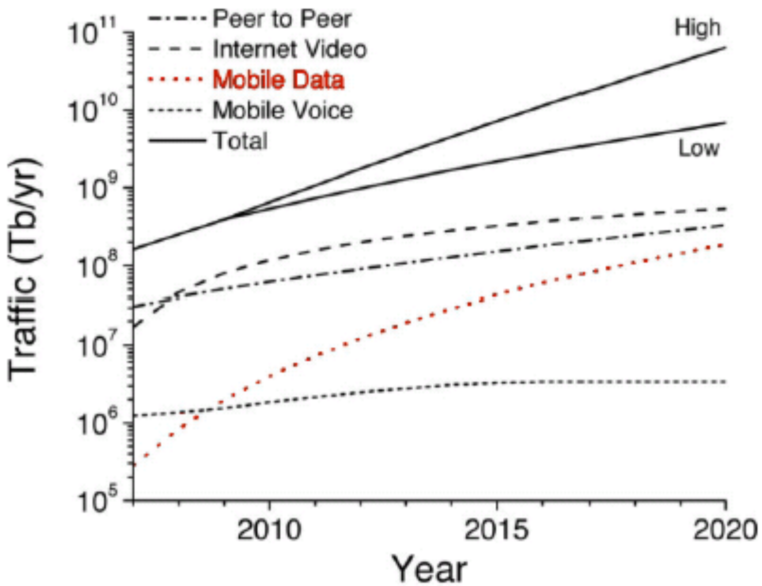
Wireless Network Trends:

- Broad availability of small, highly capable mobile devices
- Users want access to internet and mobile services anytime anywhere
- Exponential increase in wireless capacity demand

Challenges:

- Mobile users are not willing to spend exponentially more money
- Limited available frequency spectrum
- Energy consumption of networks

New mobile devices



Bell Labs traffic predictions for North America

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Historic Capacity Gains in Wireless Networks

Wireless Network Capacity Gains 1950-2000

5x from better voice coding

5x from better MAC and modulation methods

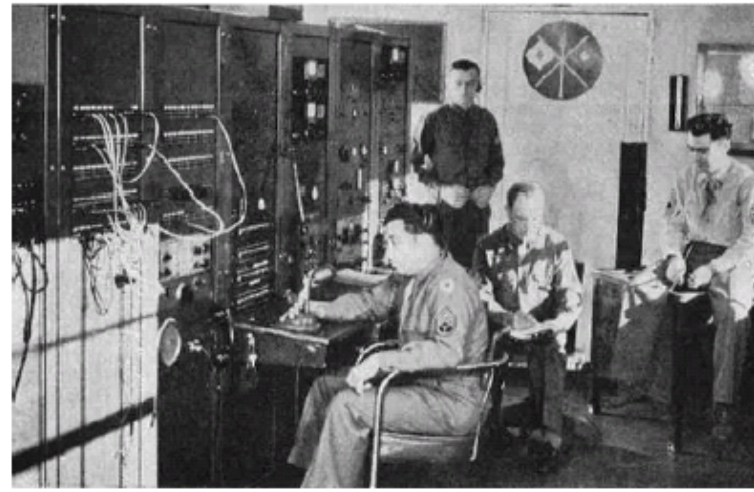
15x by using more spectrum (3 GHz vs 150 Mhz)

2700x from smaller cells

Total gain 1 million fold

Source: William Webb, Ofcom.

We can always further increase spatial frequency re-use by reducing cell size!



US Army Communications Control Center, Pentagon, 1950

AT&T Global Operations Center, 2012

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Future Network Topology & Small Cells today

Alcatel-Lucent Femtocell, and LightRadio Metrocell

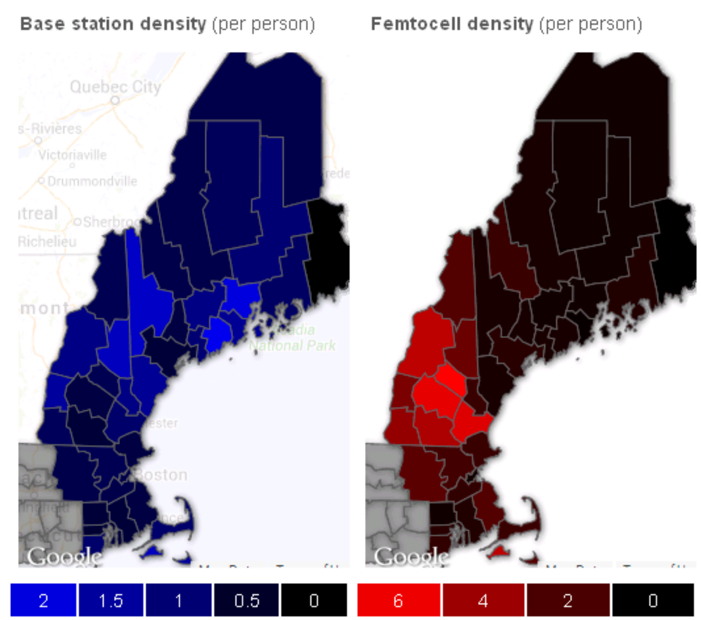
Future Cellular Network Topology:

- Small cells are the solution to the wireless capacity problem
- Macrocells required for coverage

Small Cell Deployments Today:

- Over 6 million small cells deployed, exceeding the number of macrocells worldwide (2012)
- 98% of mobile operators believe that small cells are essential for the future of their networks

Source: Informa Telecoms & Media, 2012



Base station density (base stations per 1000 people)

Femtocell density (femtocell per 1000 people)

Source: Prof. Berthold Horn, MIT; OpenSignalMaps

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Where are we today?

Current Cellular Network Model

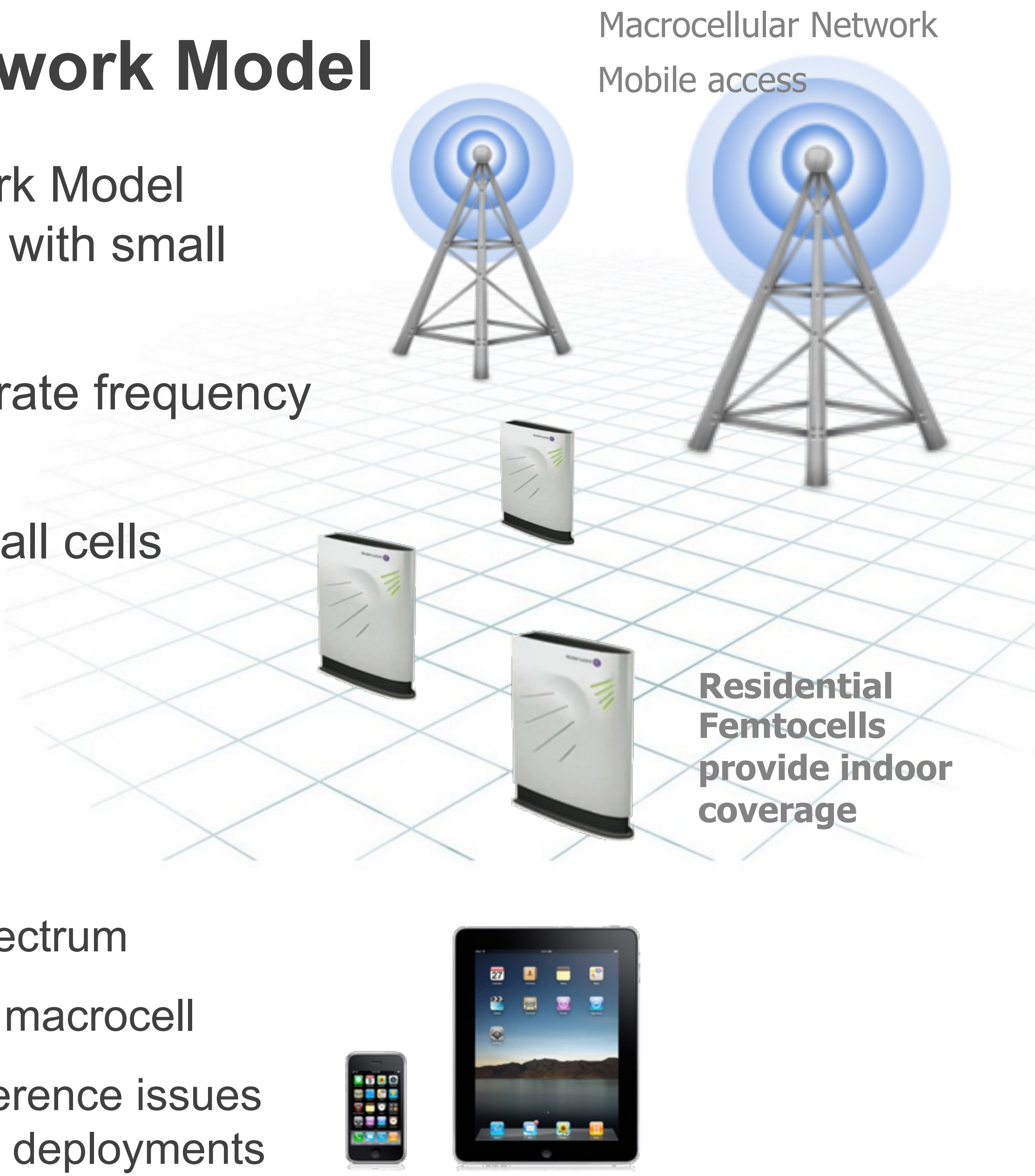
- Predominant Cellular Network Model today consists of macrocells with small cells for indoor coverage
- Small cells transmit on separate frequency band
- Closed access model for small cells

Pros:

- Simple to deploy

Cons:

- Requires large amount of spectrum
- Capacity outdoors limited by macrocell
- Closed access causes interference issues between small cells in dense deployments



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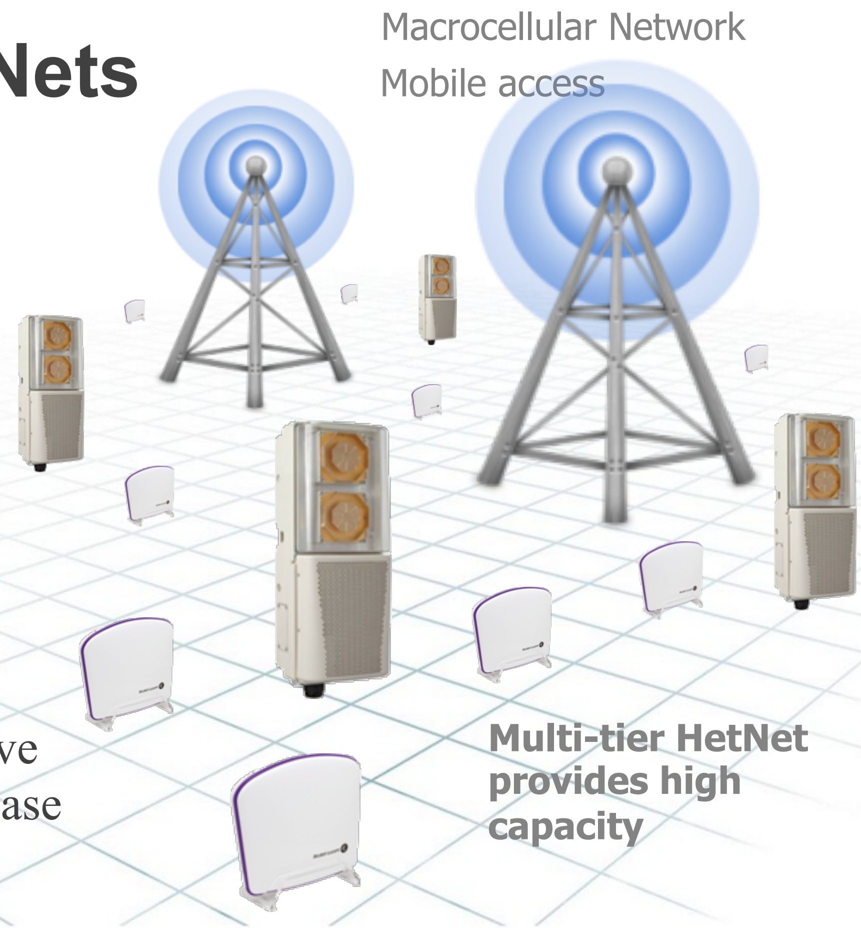
Where are we heading?

Future Dense Multi-tier HetNets



- HetNet deployment where outdoor small cells provide capacity and macrocells ensure area coverage.
- Co-channel deployment
- Public access model for small cells

Pros:

- High frequency re-use } Lower CapEx
- Capacity scales with number of cells } Allows massive capacity increase

Cons:

- More interference
- Requires fast handovers } Potential QoS problem
- Large number of cells may be difficult to deploy and expensive to operate } Increased CapEx & OpEx

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New macrocell architectures

What are we doing outdoors?
If we do more of the same …

Obstruction

Discrimination

Contamination

We need new macrocell architectures

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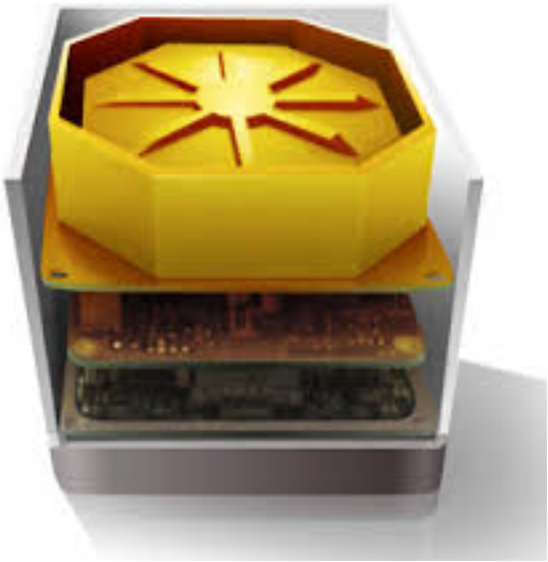
The light radio cube
Build networks with lego pieces …



The cube

We need new macrocell architectures

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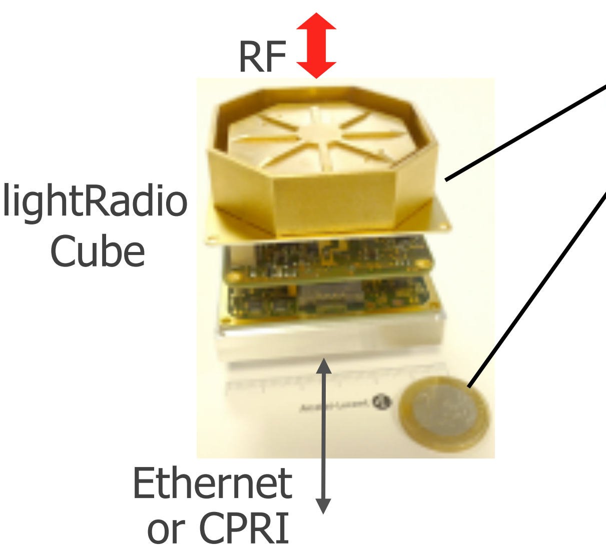
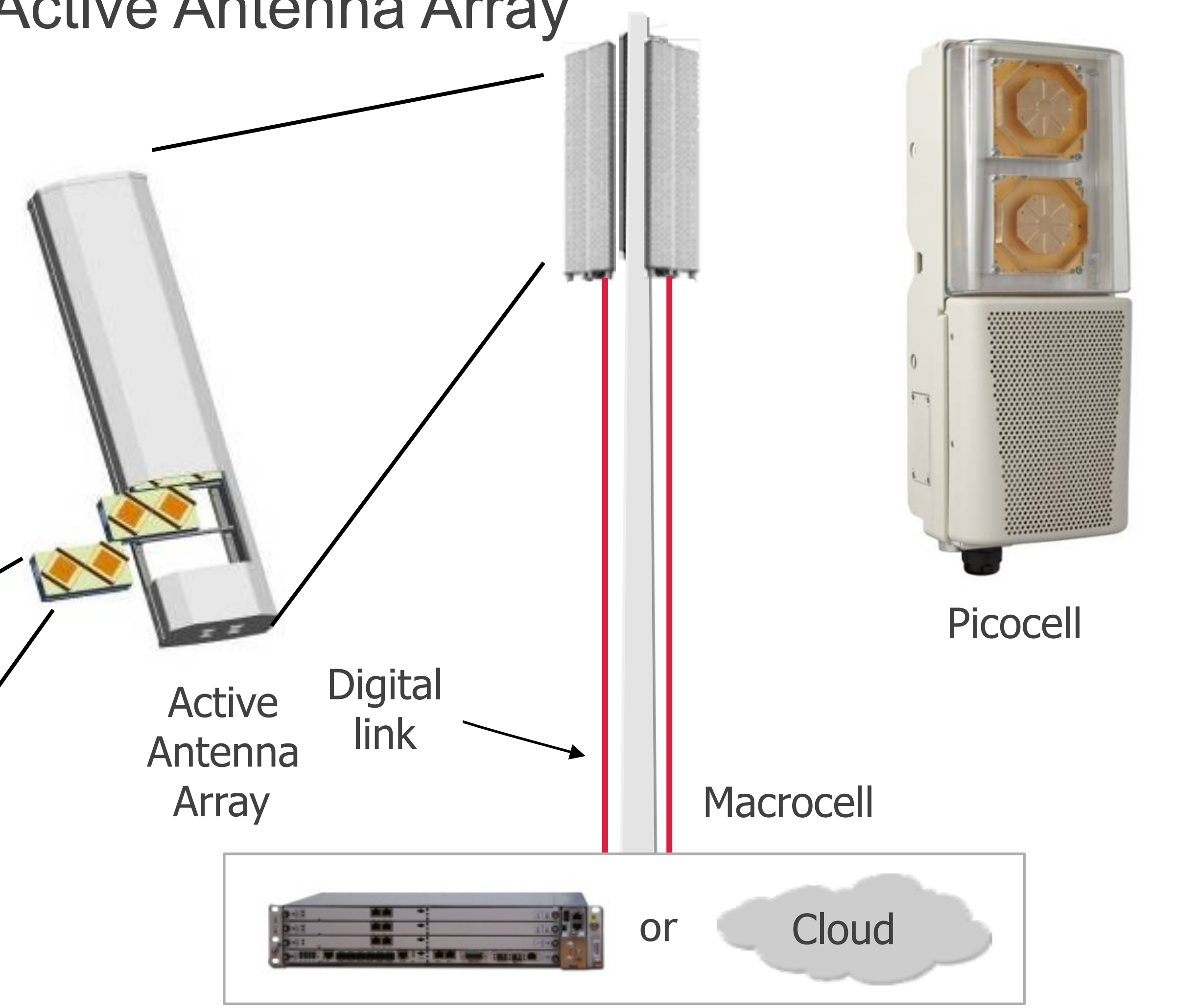
Architecture improvements for macrocells
lightRadio Cube and Active Antenna Array

Characteristics:
- Picocell – Macrocell flexible solutions
- Enables intelligent antenna techniques
- Avoids Cable losses (3 dB)





Flexible deployment - > Leverage power and backhaul infrastructure

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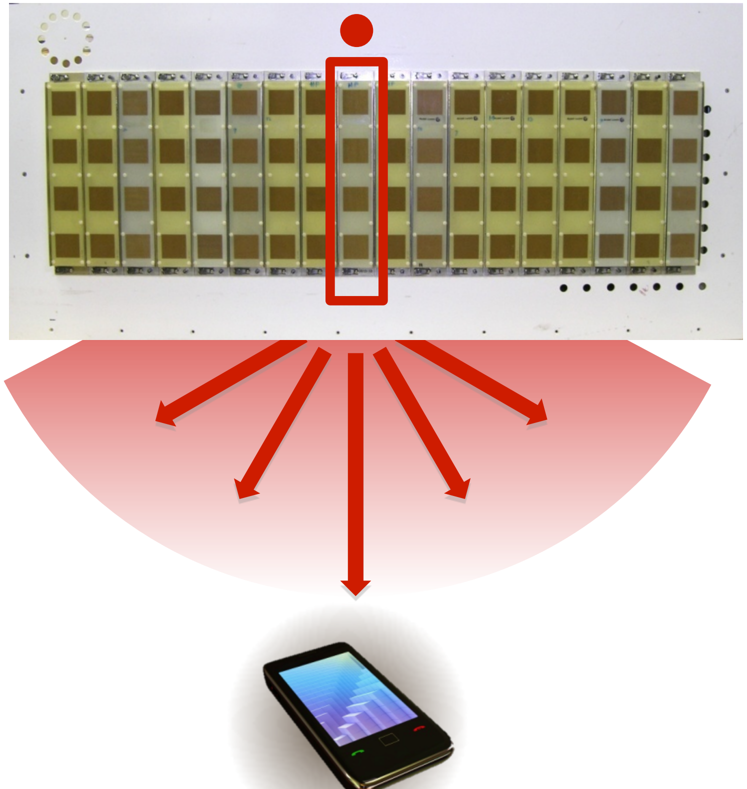
Large Scale Antenna Systems

Reducing Energy Consumption

GreenTouch™

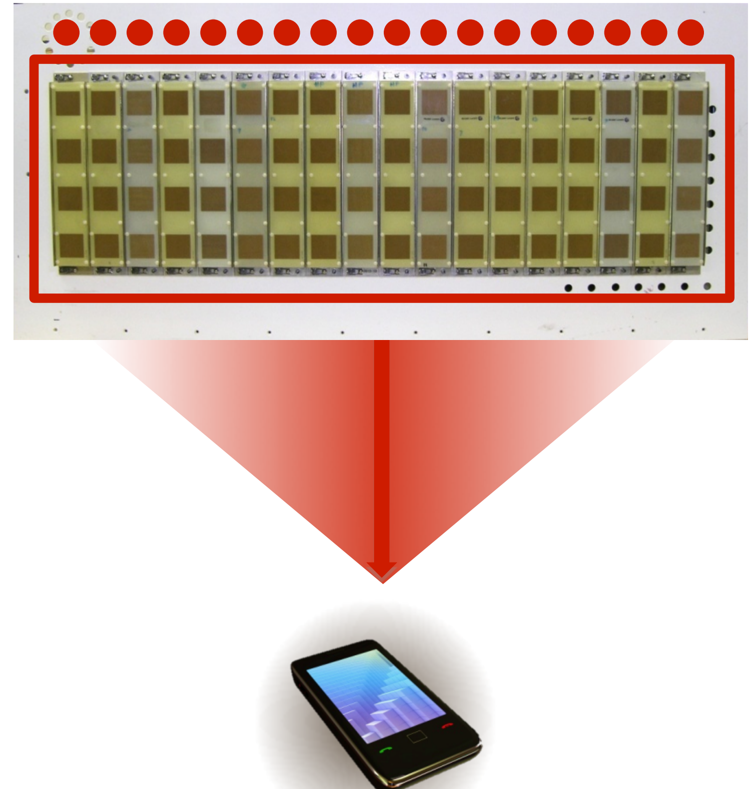
Only one antenna panel is powered to simulate a call to an end-user.

All powered but only at a fraction



End-user

Power used = 16W



End-user

Power used = 1W

Proof of Concept Demonstration, London 2011.
Collaborators: Bell Labs, Freescale, Huawei, imec, Samsung

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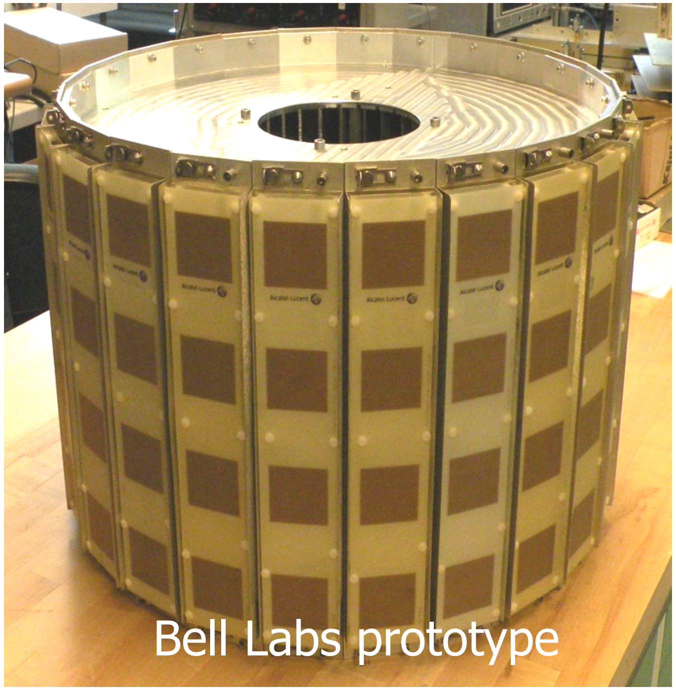
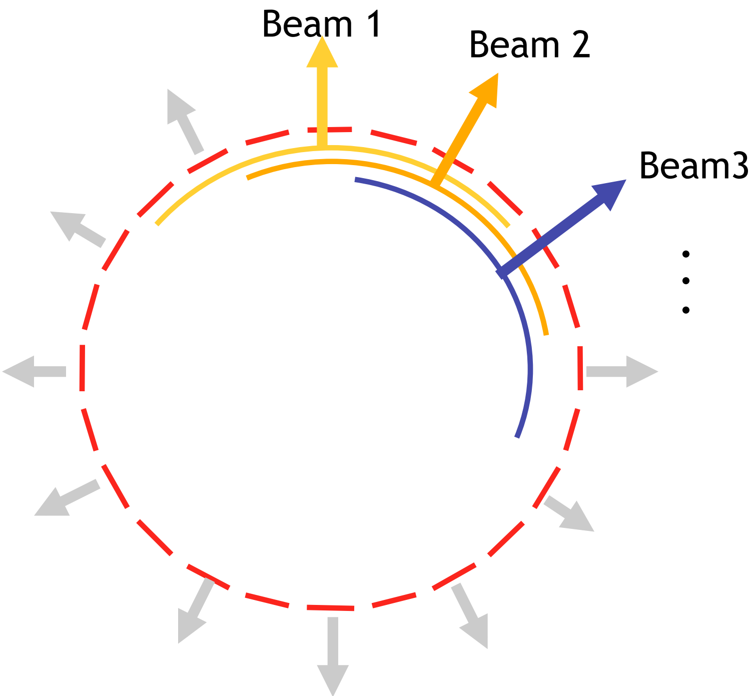
Circular Antenna Array
Higher-order sectorization strategies



24 column Array.
Diameter: ~21″ @2.45 GHz



Each beam/sector is generated using 7 adjacent antenna elements.

Sector offset configuration

D. López-Pérez, H. Claussen and L. Ho, "The Sector Offset Concept and its Applicability to Heterogeneous Cellular Networks," accepted for publication in IEEE Communication Magazine, 2014.

Agenda

Intelligent indoor small cells:

enhanced idle modes

Impact of small cells on the network energy consumption

Energy Facts:

- Telecommunications is a large consumer of energy (e.g., Telecom Italia uses 1% of Italy's total energy consumption, NTT uses 0.7% of Japan's total energy consumption)
- Increasing costs of energy and international focus on climate change have resulted in high interest in improving the efficiency in the telecommunications industry

Opportunity:

Small cells have the potential to reduce the transmit power required for serving a user by a factor in the order of 10^3 compared to macrocells.

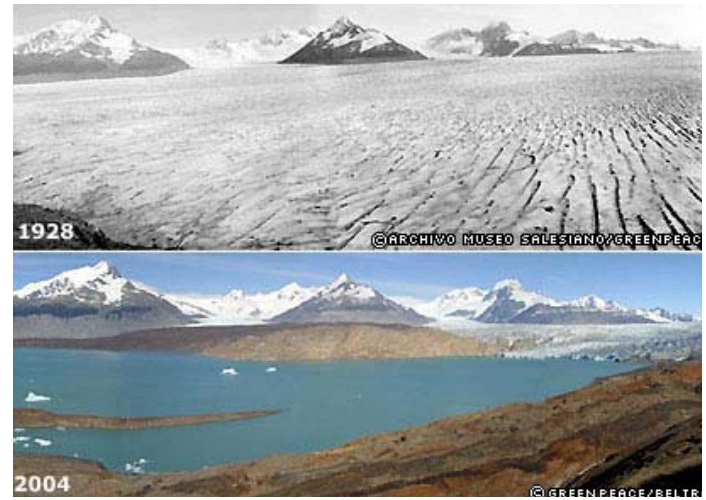
Problem:

Most femtocells today are not serving users but are still consuming power:

50 Million femtos x 12W = 600 MW ⟶ 5.2 TWh/a

Comparison:

- Nuclear Reactor Sizewell B, Suffolk, UK: 1195MW
- Annual UK energy production: ~400 TWh/a



Source: BBC News - How the world is changing

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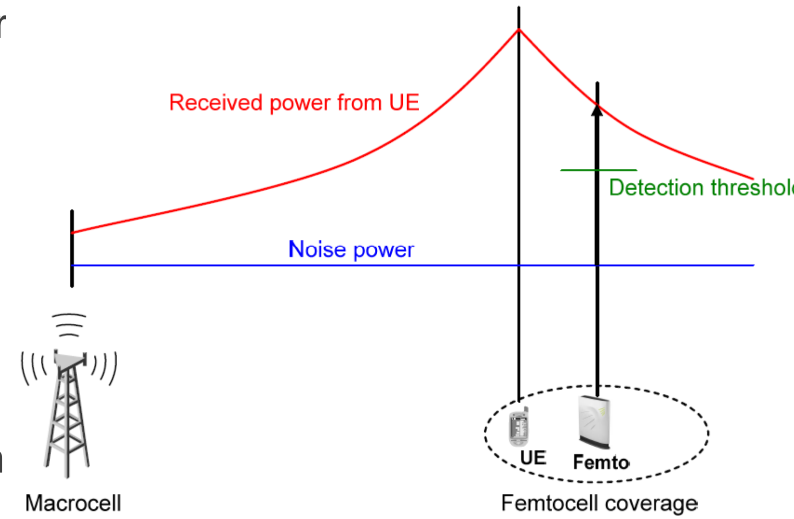
Reducing energy consumption
Idle mode procedures for indoor small cells

When femtocells become more widely deployed, their energy consumption becomes a concern.

Idle mode procedures can:

- Significantly reduce energy consumption
- Reduce power density in the home
- Reduce mobility procedures and associated signalling
- Reduce interference caused by pilot transmission

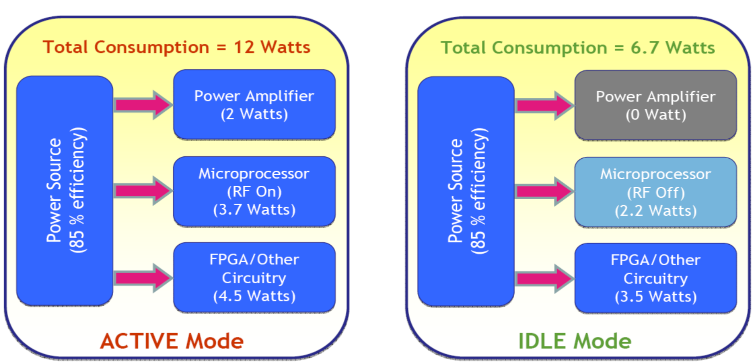


Femtocell activation based on noise rise from active UE allows to activate the femto only for serving a call

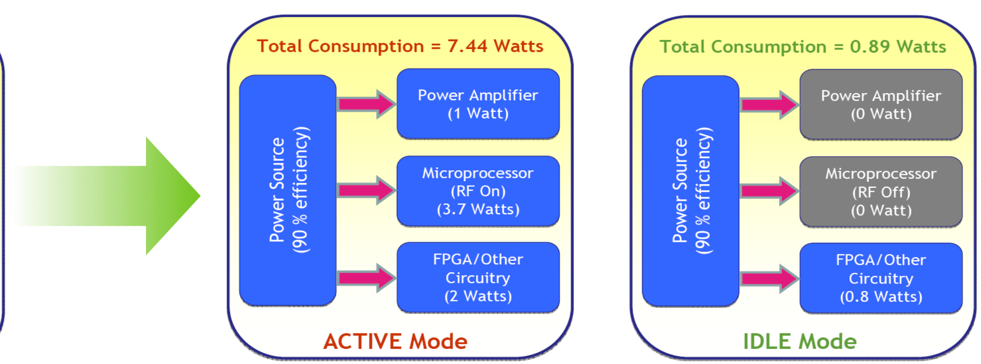
References:

[1] I. Ashraf, L. T. W. Ho, and H. Claussen, "Improving energy efficiency of femtocell base stations via user activity detection," in Proc. IEEE Wireless Communications and Networking Conference (WCNC), Sydney, Australia, Apr. 2010.

[2] H. Claussen, I. Ashraf, and L. T. W. Ho, "Dynamic idle mode procedures for femtocells," Bell Labs Technical Journal, to be published in 2010.



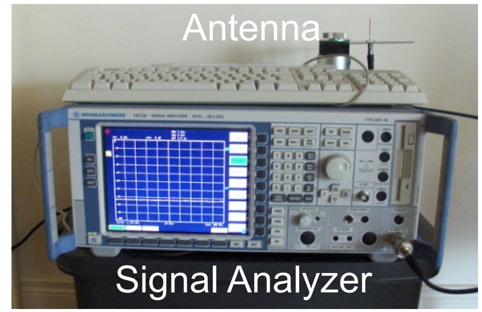
Femtocell energy consumption - Today

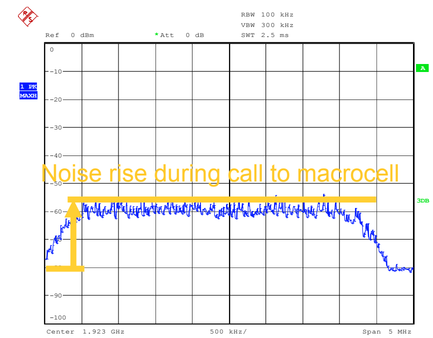


Femtocell energy consumption – Optimized design

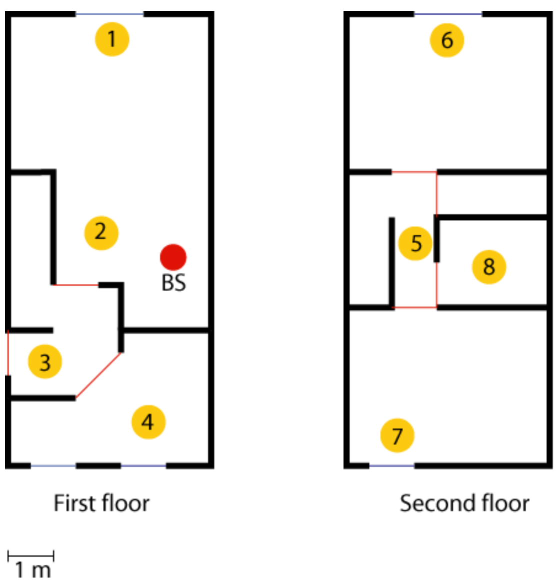
Measurements for noise rise controlled idle modes

Residential house





Measurement equipment and example result



Measurement point	(1) UMTS Vodafone P_N = -90dBm		(2) UMTS Three P_N = -90dBm		(3) GSM O2 P_N = -81dBm		(4) GSM Vodafone P_N = -81dBm	
	S1 Signal	P1 [dBm]	S2 Signal	P2 [dBm]	S3 Signal	P3 [dBm]	S4 Signal	P4 [dBm]
1	6/7	-79	6/6	-61	5/5	-22	4/5	-25
2	6/7	-61	6/6	-52	3/5	-18	3/5	-15
3	6/7	-67	5/6	-57	3/5	-28	3/5	-22
4	6/7	-74	6/6	-70	3/5	-30	3/5	-31
5	6/7	-67	6/6	-65	3/5	-33	3/5	-34
6	6/7	-82	6/6	-75	4/5	-28	4/5	-27
7	6/7	-79	6/6	-68	3/5	-32	3/5	-40
8	6/7	-69	4/6	-57	4/5	-29	4/5	-26

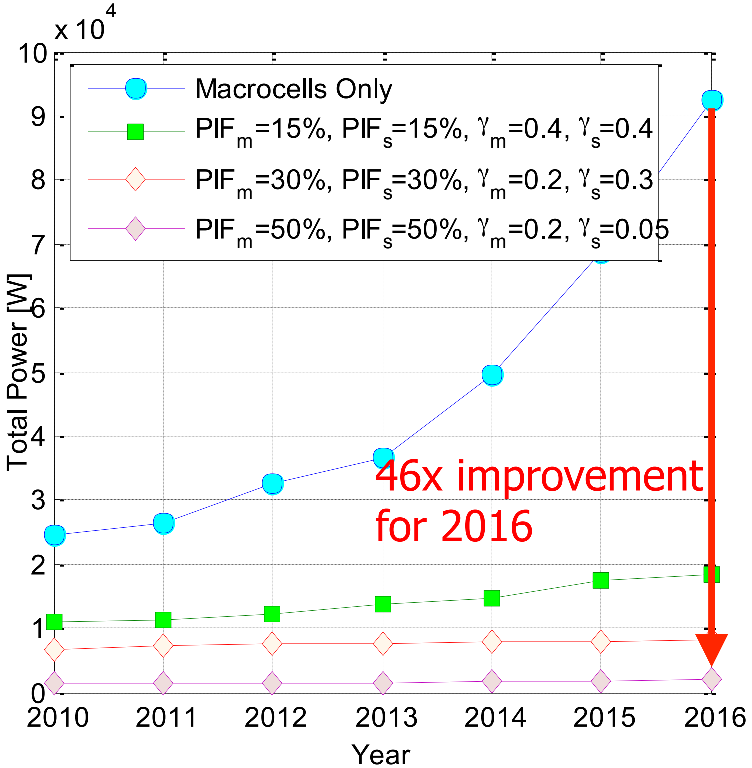
P1...P4 are the measured noise powers during a call of the test mobile to the macrocell.
S1...S4 is the signal strength indicator displayed by the mobile.

All calls for both GSM and UMTS are easily detectable

Small Cells enable significant improvements in energy efficiency

Results

- A mixed macro- and small cell architecture can significantly reduce the energy consumption of cellular networks for high data rate user demand in urban areas where macrocells are capacity limited
- The power consumption can be reduced by up to 60% for high data rate demand in urban areas (2007 technology) [1],[2].
- With more dynamic idle mode control and efficient power scaling with load a 46x efficiency improvement is possible in 2016 [3].



References:

[1] H. Claussen, L. T. W. Ho, and F. Pivit, "Leveraging advances in mobile broadband technology to improve environmental sustainability," Telecommunications Journal of Australia, vol. 59, no. 1, pp. 4.1-4.18, Feb. 2009.

[2] H. Claussen, L. T. W. Ho, and F. Pivit, "Effects of joint macrocell and residential picocell deployment on the network energy efficiency," in Proc. 19th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Cannes, France, Sept. 2008.

[3] R. Razavi and H. Claussen, "Urban small cell deployments: Impact on the network energy consumption," in Proc. IEEE Wireless Communications and Networking Conference (WCNC), Paris, France, Apr. 2012.

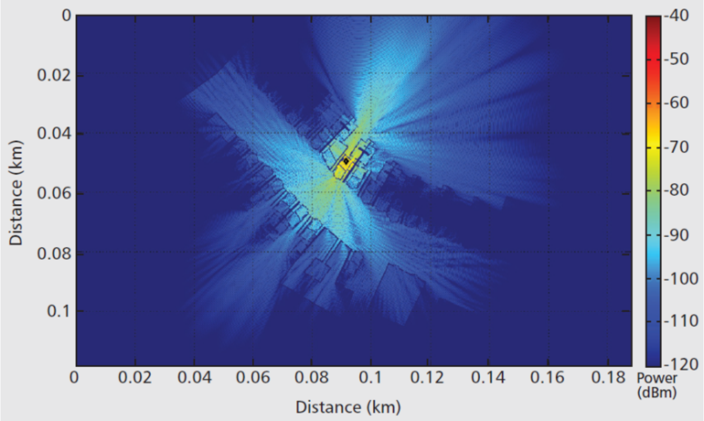
Agenda

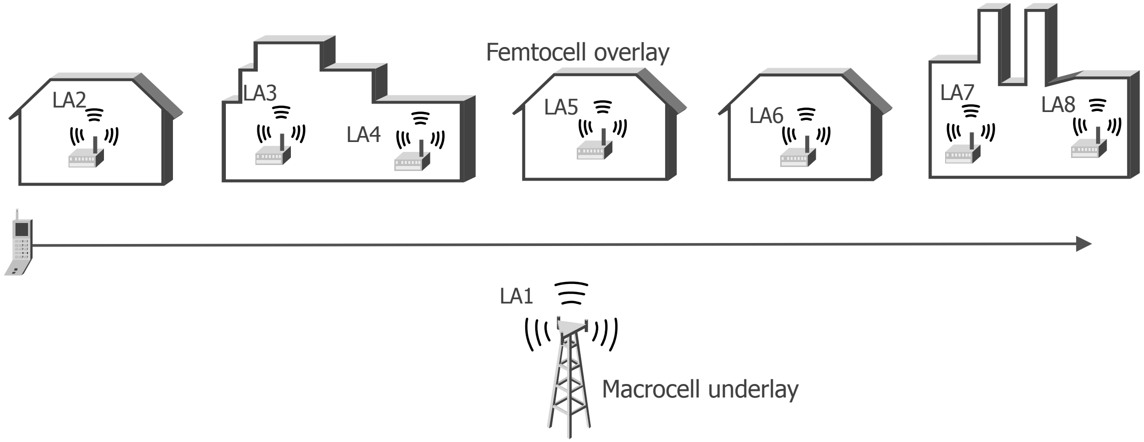
Intelligent indoor small cells:

Optimized coverage

Effects of Small Cell Deployments on the Core Network

- Femtocells deployed in dense urban areas frequently result in mobile macrocell users passing through the coverage of multiple femtocells.
- For public access deployments where femtocells can share a single frequency with the macrocell underlay, handovers of macrocell users into the femtocell are required to prevent dropped calls due to co-channel interference. This can cause very high number of handovers (can increase call drop probability).
- For private access deployments, Location/Routing Area Codes assigned to femtocells needs to be different from the macrocell underlay and neighbouring femtocells to prevent camping of un-registered users. This can cause a very high number of LA/RA update requests.



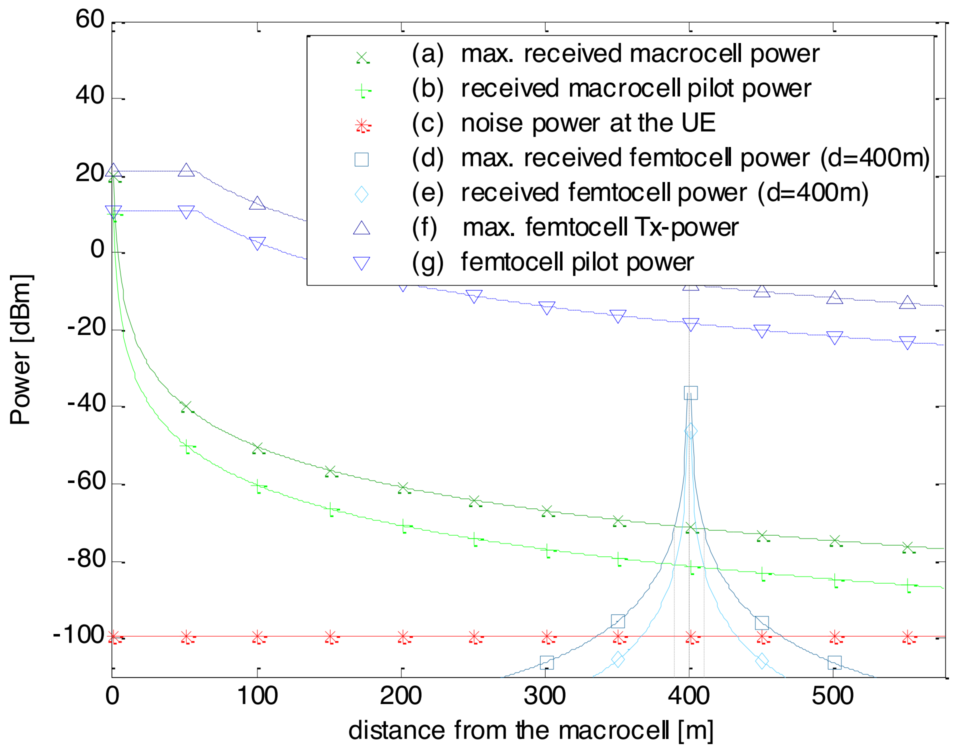


Femtocell coverage needs to be optimized

Coverage optimization based on neighbors transmit power

Initial configuration – Downlink power

- Each femtocell adjusts its transmit power to achieve a SIR of 0 dB with respect to the macrocell at the intended cell radius.
- As a result the DL power is a function of the macrocell radio distance. This ensures the same femtocell range irrespective of the location within the macrocell.



Femtocell power auto-configuration to achieve a pre-defined coverage

$$P_{\text{femto}} = \min\Big(\underbrace{P_{\text{macro}} + G(\theta) - L_{\text{macro}}(d)}_{\text{estimate of recieved macro cell power}} + L_{\text{femto}}(r),\ P_{\max} \Big)$$

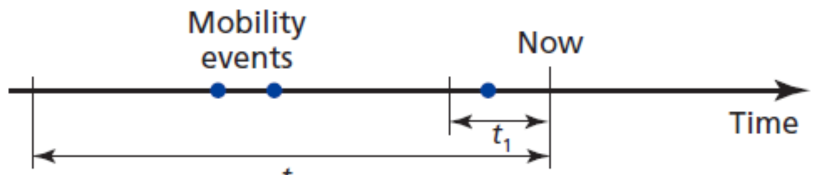
Problem: Best coverage depends on house type and deployment location within the building.

Further optimization required.

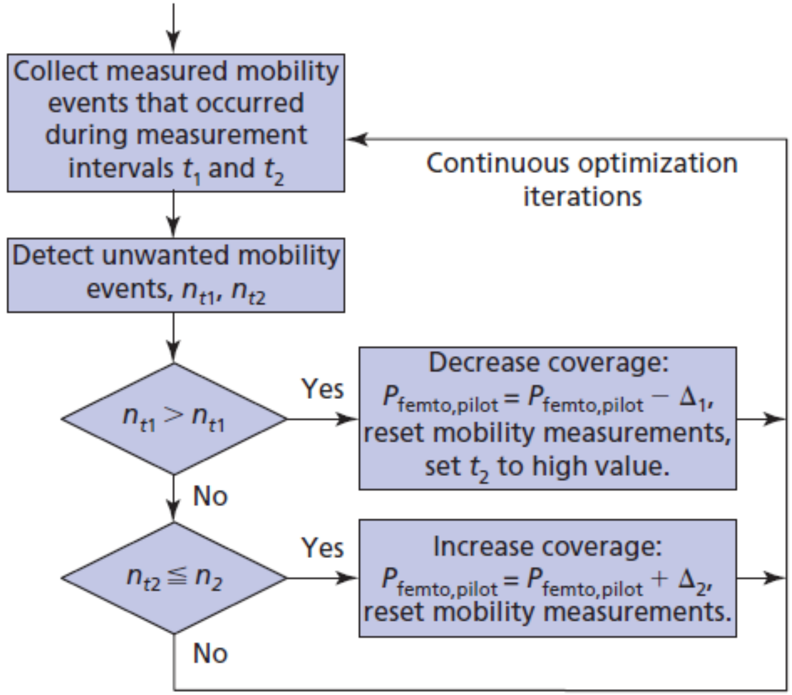
Coverage optimization based on mobility events

Practical self-optimization approach:

- The femtocell classifies handovers in wanted and unwanted handovers dependent on whether the UE is registered.
- If the number of unwanted HO n_{t1} during time t_1 exceeds the maximum allowed number n_1 the pilot is reduced by Δ_1.
- If n_{t2} during time t_2 is smaller than the maximum allowed number n_2 the pilot is increased by Δ_2.
- Here, $n_1 = n_2 = 0$ to prevent all unwanted mobility events.



(a) Measurement intervals



(b) Process for minimizing mobility events of passing users

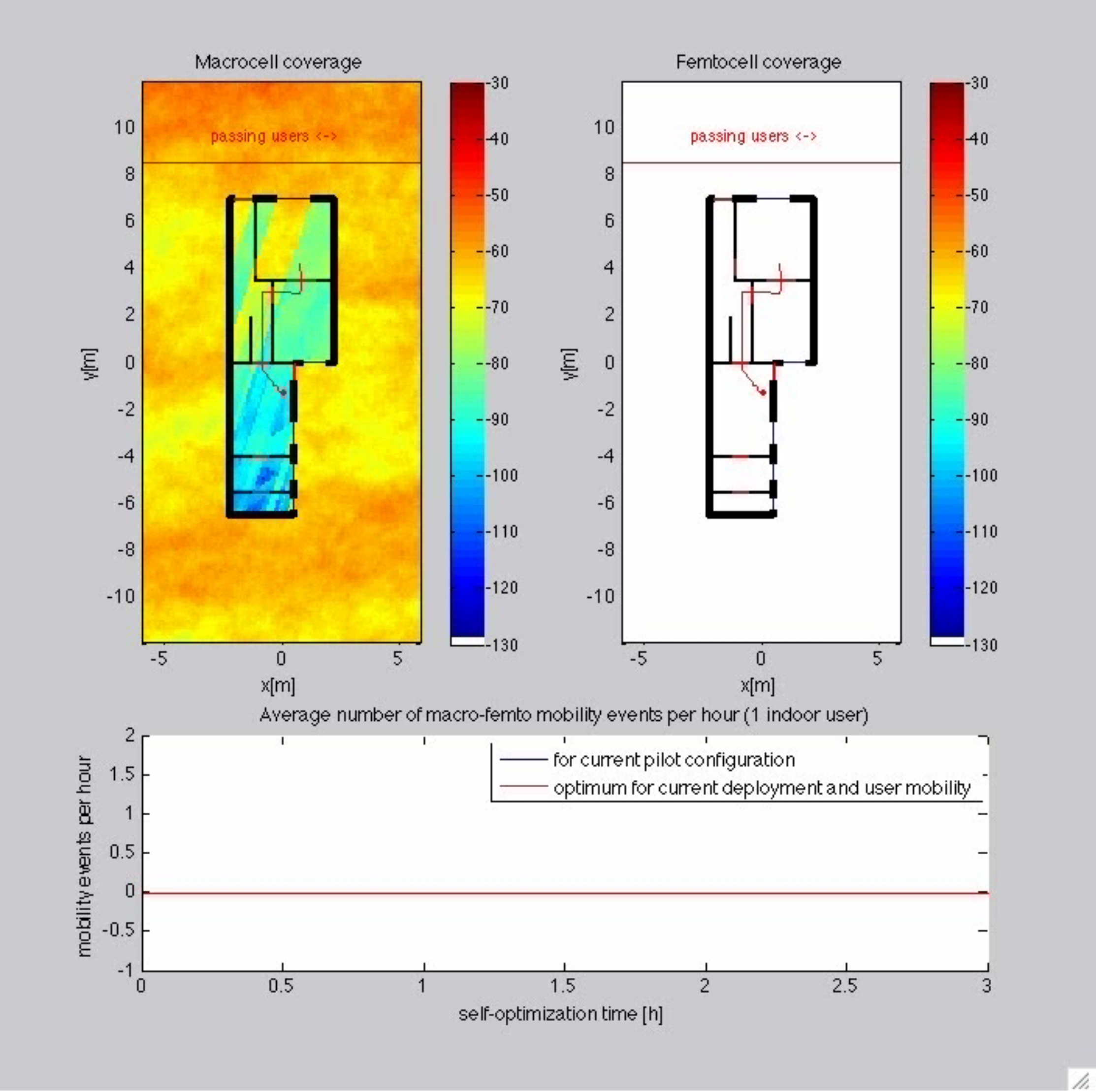
Example of self-optimization process

Overview

- Residential scenario with house facing busy road including indoor and outdoor mobility model.
- Femtocell is deployed in the back of the house
- Initial pilot power setting is auto-configured based on received signal from macrocell
- During operation, mobility event based self-optimization of the coverage is performed

Results

- The optimization results in optimal performance for this scenario
- Full indoor coverage is achieved



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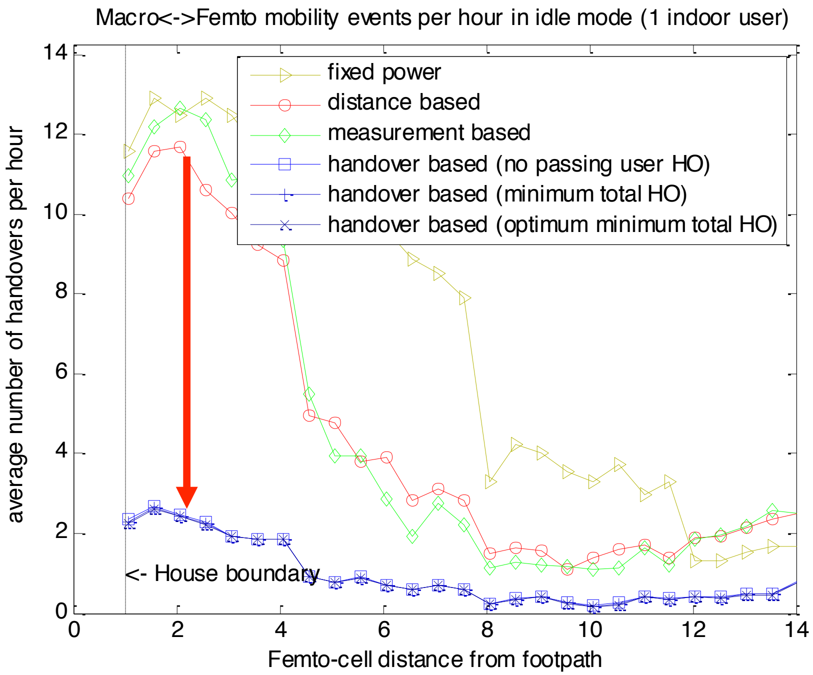
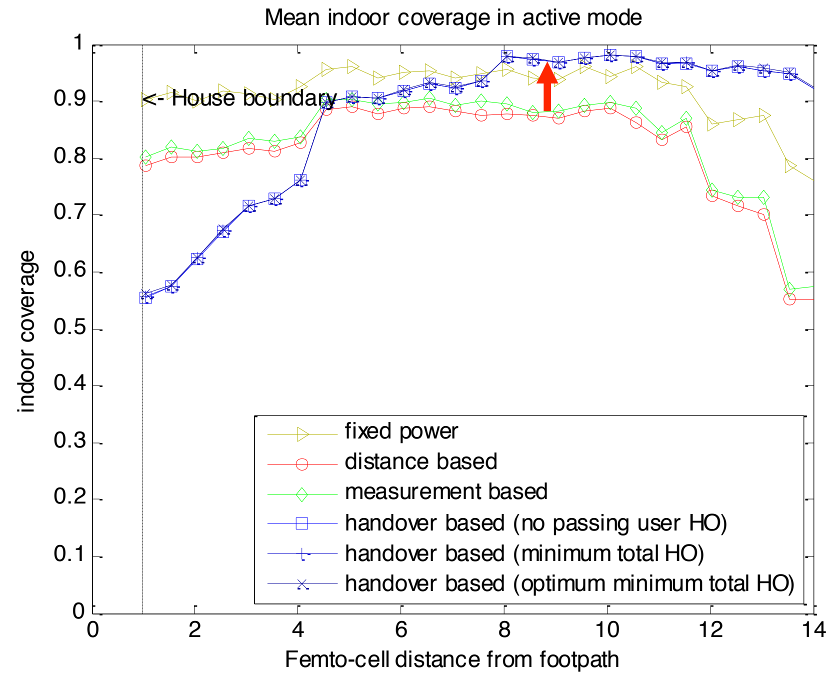
Performance of Coverage Optimization





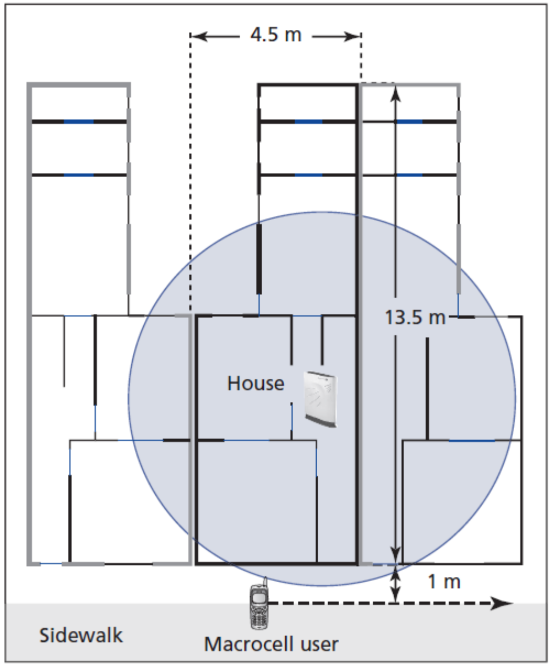
- Handover based self-optimization of coverage can significantly reduce the total number of handover events caused by femtocell deployments.
- Indoor coverage for femtocells deployed in suitable locations is improved compared to simpler methods that aim to achieve a constant cell radius.

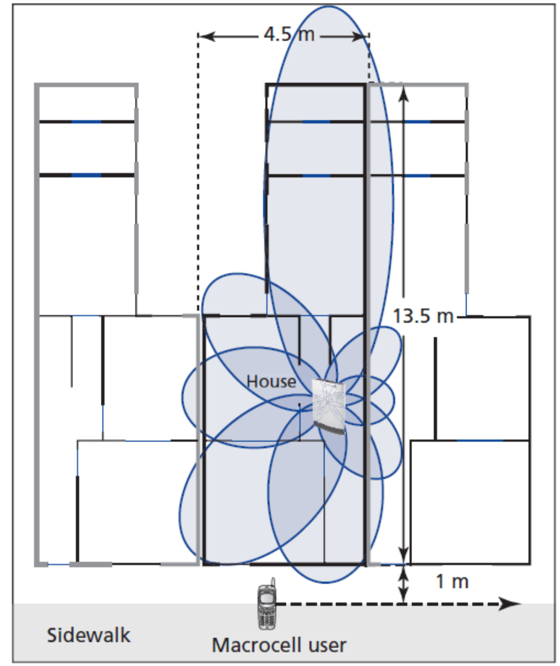
References

[1] H. Claussen, L. T. W. Ho, and L. G. Samuel, "Self-optimization of coverage for femtocell deployments," in Proc. Wireless Telecommunications Symposium (WTS), Los Angeles, USA, Apr. 2008, pp. 278-285.

[2] H. Claussen, L. T. W. Ho, and F. Pivit, "Self-optimization of femtocell coverage to minimize the increase in core network mobility signalling," Bell Labs Technical Journal, vol. 14, no. 2, pp. 155-184, Aug. 2009.

Coverage optimization using multiple antennas





Since the cell radius is constrained such that passing users are not affected, good indoor coverage can only be achieved when the femtocell is deployed in the center of the house.

With multiple antennas the coverage can be better adapted to the house which improves the achievable indoor coverage for different deployment locations without impacting other users

Strong constraints on cost and size

- Due to cost constraints no independent adaptation of lobes feasible at this time. Focus is on switching between multiple gain patterns resulting from combinations of antennas.
- Antenna design must fit into a small femtocell enclosure.

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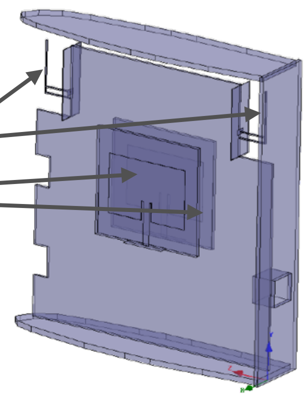
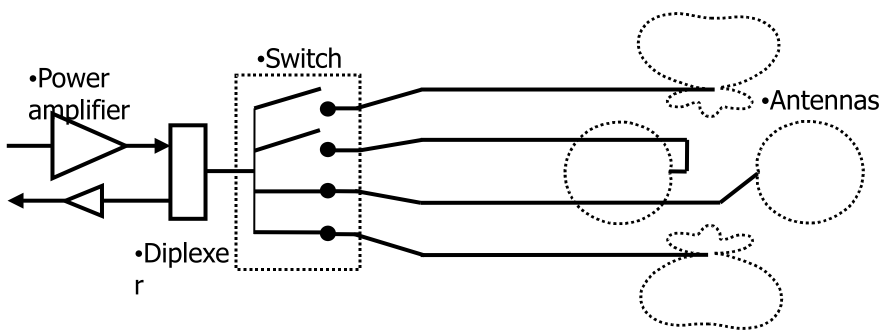
Pattern diversification and null steering using multiple antenna system

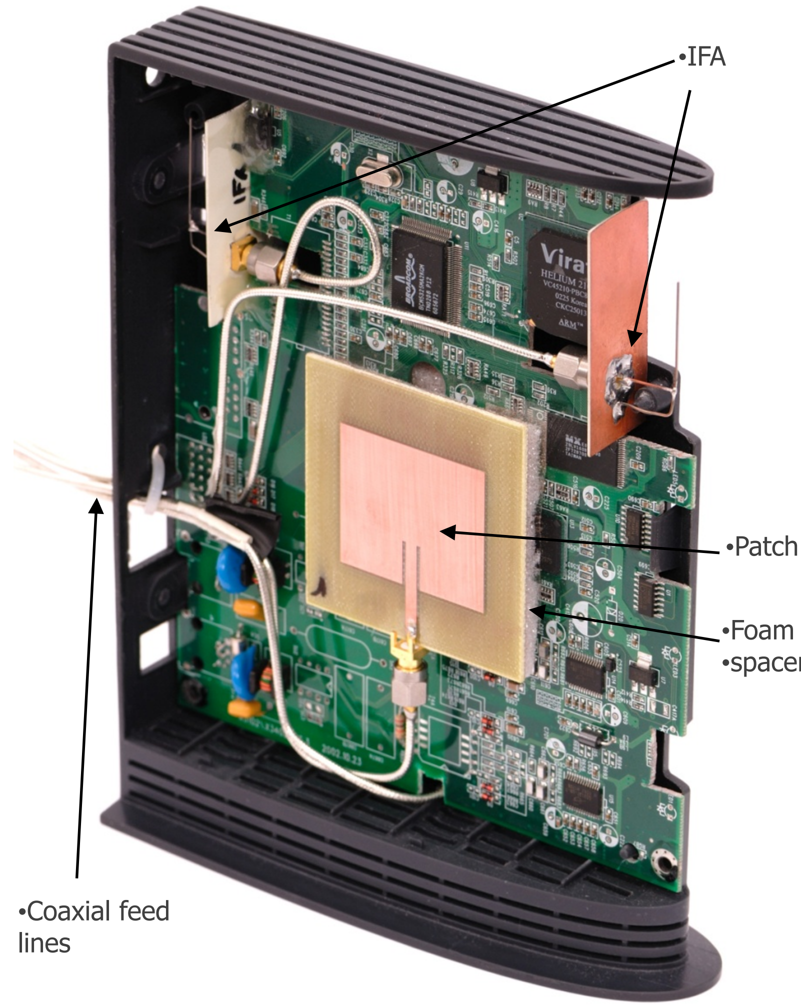
Antenna System Setup:
- 4 Antennas:
  - 2 mono-pole-type (IFA)
  - 2 Patches



Feed network:
- Simple 1x4 Switching Circuit



Cost:
~3 €



Prototype of femtocell antenna system with dummy printed circuit board.

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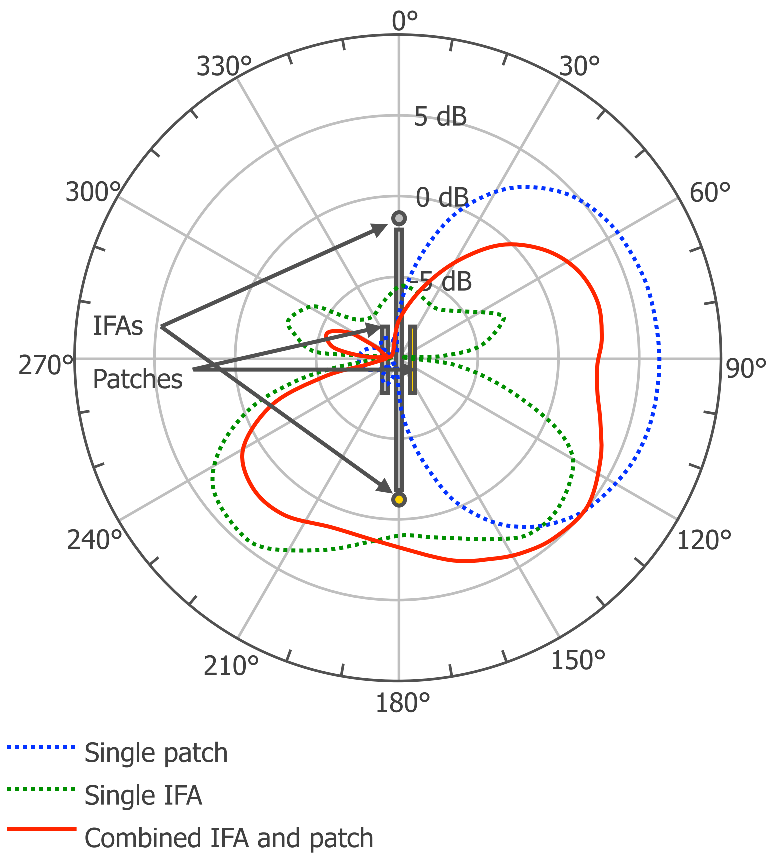
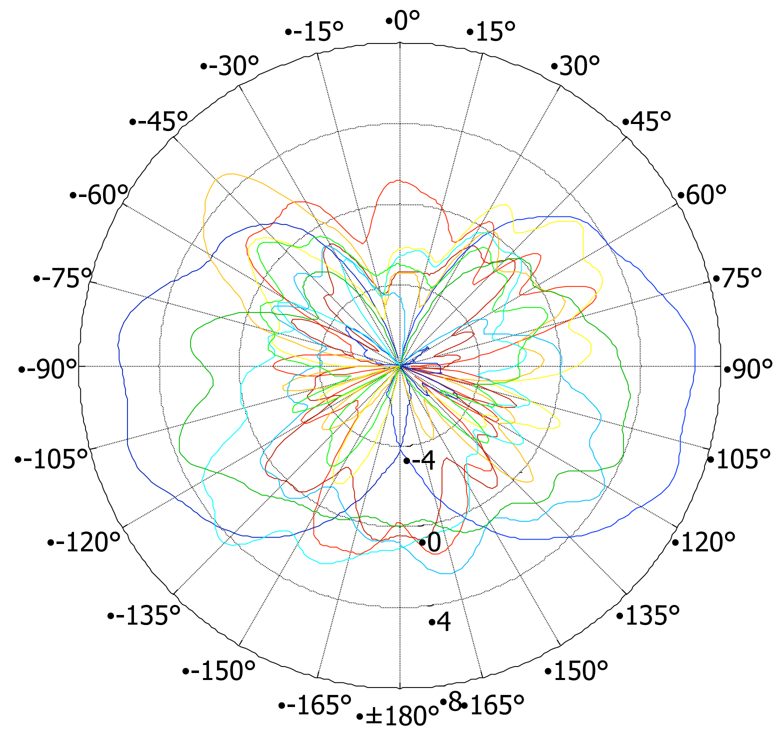
Simulated and measured antenna patterns



IFA—Inverted F antenna

Antenna pattern in decibel of a single patch, single IFA, and of a combination thereof.



Ten measured antenna patterns resulting from selection of one or a combination of two antennas.

High beam versatility enables null steering and exposition reduction

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Algorithm

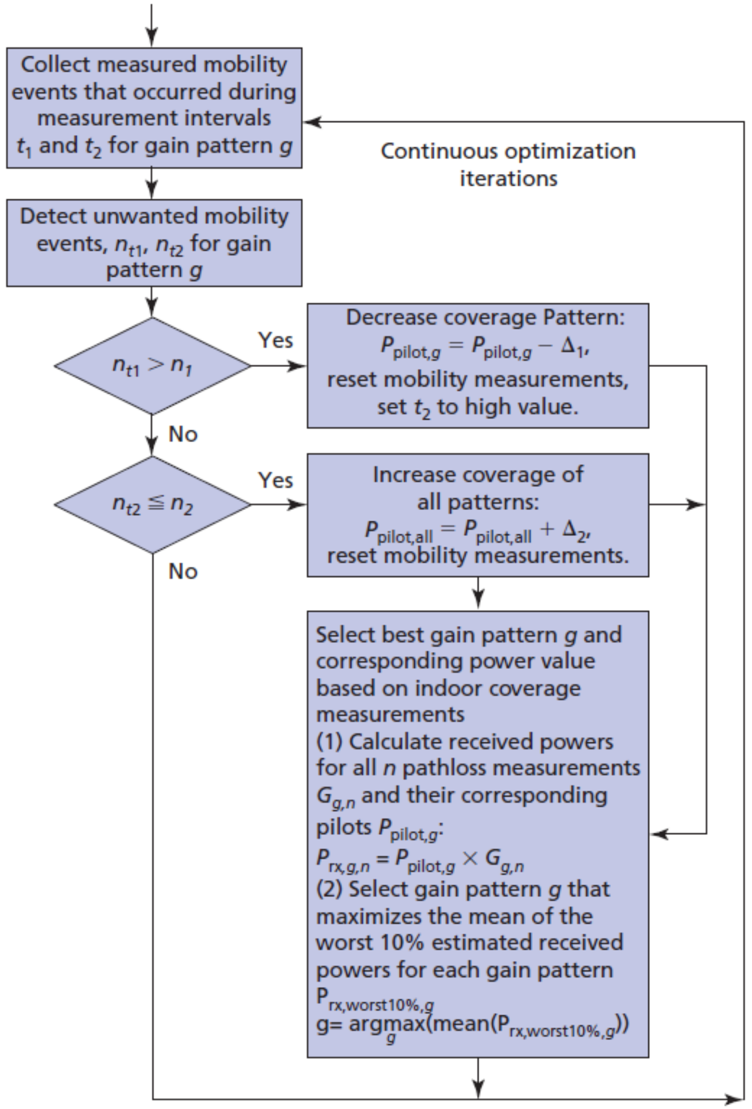
Practical self-optimization approach:

Select the beam pattern and power based on both mobility events and path-loss measurements:

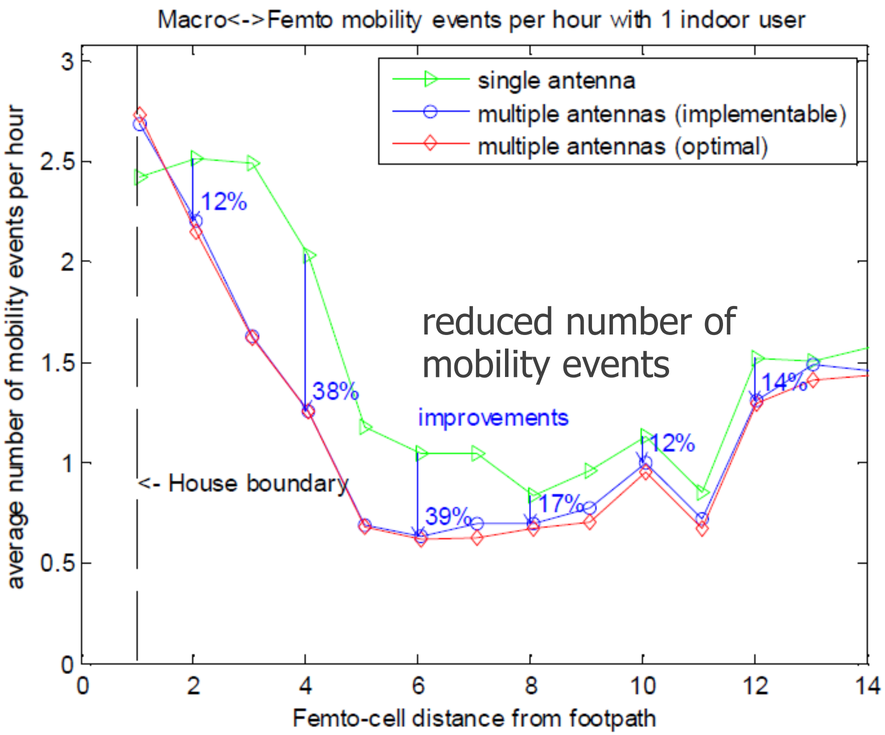
- The femtocell collects path-loss statistics for each gain pattern by periodically switching through all gain patterns when a mobile is connected
- The femtocell collects information on mobility events and classifies them into wanted and unwanted events
- The femtocell uses the above information in an iterative optimization process to determine the best gain pattern and corresponding pilot power level

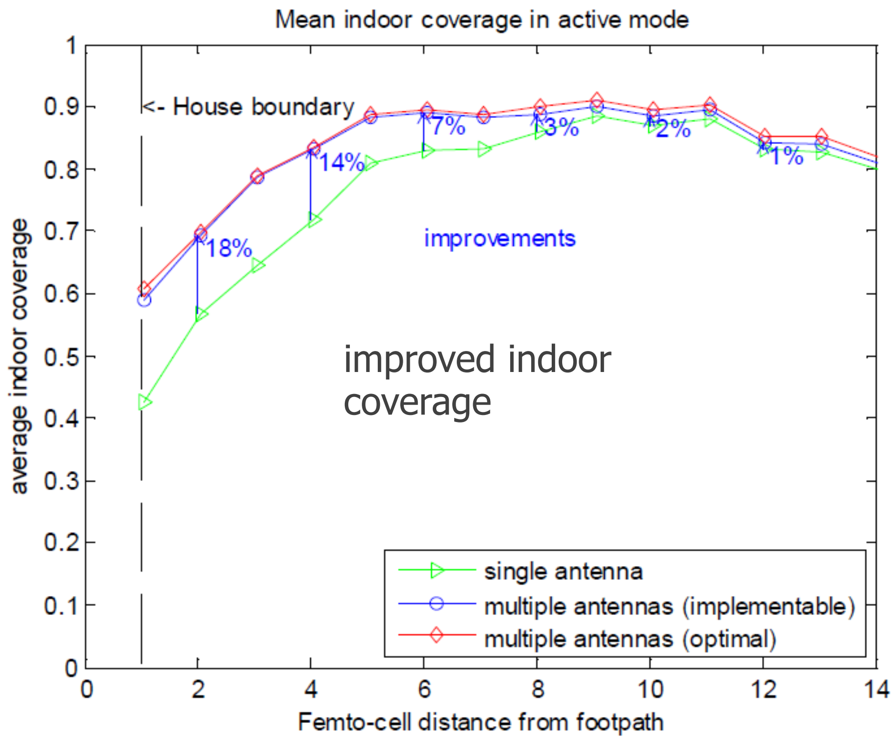
Optimal solution as benchmark:

- Global search over all possible combination to find optimal configuration.
- Good as benchmark, but not suitable for implementation due to slow convergence.



Results: Multi-element antennas





- Multi-element antennas can both reduce the number of mobility events and improve indoor coverage particularly in poor femtocell location choices
- Improvements of more than 20% in performance over single antenna optimization can be achieved for only a small increase in costs
- The flexibility where a femtocell can be deployed and give good coverage is increased, resulting in an improved customer perception of the product.
- The proposed coverage optimization method approaches optimal performance.

References

[1] H. Claussen and F. Pivit, \Femtocell coverage optimization using switched multi-element antennas," in Proc. IEEE International Conference on Communications (ICC), Dresden, Germany, June 2009.

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Agenda

The capacity challenge:

Ultra-dense small cell networks

More is needed

Capacity will continue to grow

Mobile users (NO M2M)

5.3 Billion	9 Billion
2010	2020

M2M Connections

1.4 Billion	4 Billion
2012	2017

Mobile devices in use

7.7 Billion	12.1 Billion
2014	2018

Smartphone users

1.13 Billion	2.5 Billion
2012	2017

Number of mobile devices per business user

1.36	1.95
2014	2018

Mobile app users

1.2 Billion	4.4 Billion
2012	2017

Mobile apps download per year

82 Billion	200 Billion
2013	2017

Mobile data traffic

2.6 Exabytes/ month	15.9 Exabytes/ month
2014	2018

Multiple sources: Statista, Infonetics Research, Radicati, eMarketer, Portio Research,

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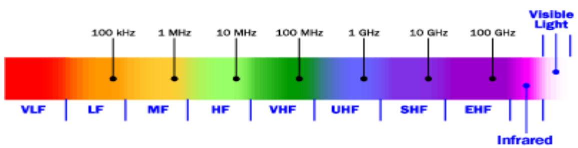
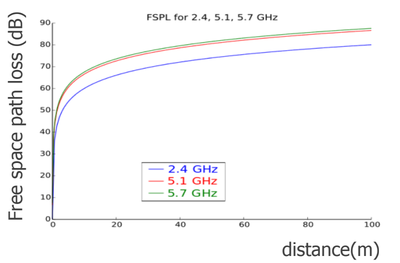
Challenges & Heroes

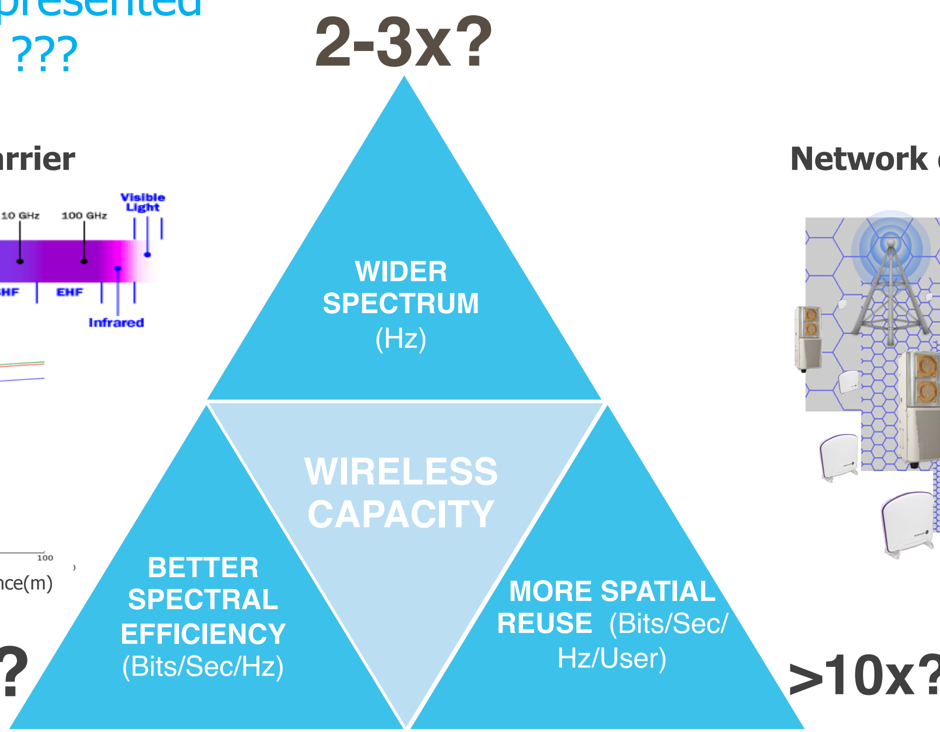
Capacity Demands & Small Cells

Usually this triangle is presented full of questions marks ???

Higher frequency carrier

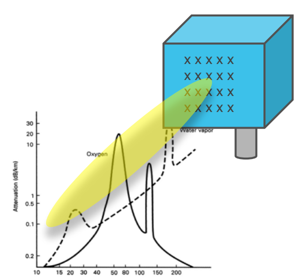






Network densification

More antennas



All these 3 degrees of freedom cannot be infinitively abused, have limitations!!!

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Our research
Objectives

Understand the benefits and limitations of network densification

Analyse its effect together with the use of:
- higher carrier frequencies, and
- more antennas

while considering:
- idle modes (inter-cell interference mitigation), and
- UE density and distribution

Target:
- Find network characteristics to deliver 1Gbps/UE in average
  today's networks provide around 300kbps/UE in average

Putting numbers to Marcus Weldon's triangle has never done before

David Lopez-Perez, Ming Ding, Holger Claussen, Amir Jafari, "***Towards 1Gbps/UE: Understanding Ultra Dense Small Cell Deployments***," submitted to IEEE Communications Surveys & Tutorial, Oct. 2014

Agenda

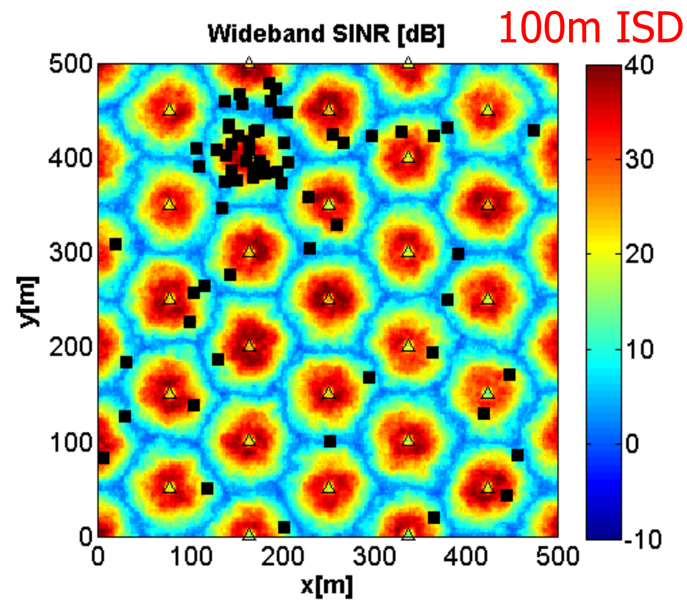
Model

Model
System-level simulation

Current theoretical frameworks fail to catch the required degree of detail!!!

Standard system model with:

- Small cell BS inter-site distances:
  200, 150, 100, 75, 50, 35, 20, 10 or 5m
- Small cell BS carrier frequencies:
  2.0, 3.5, 5.0 or 10GHz
  - Bandwidth = 5% of the carrier frequency
- Small cell BS antenna elements:
  1, 2 or 4 antennas
  - Maximal ratio transmission LTE codebook beam-forming
- Non-uniform outdoor UE distribution
  - 100, 300 and 600 active UEs/km2
  - 50% of UEs clustered



Example of an outdoor hexagonal small cell BS deployment with a non-uniform UE distribution

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Note about Analytical Modeling

Be careful with framework and assumptions

Model

- Homogeneous Poisson Point Process

Assumption

- Single slope path loss model

Result

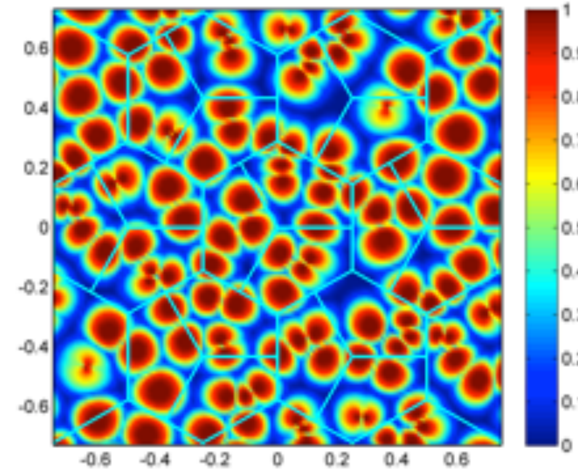
- Coverage probability
independent on the BS density

Conclusion

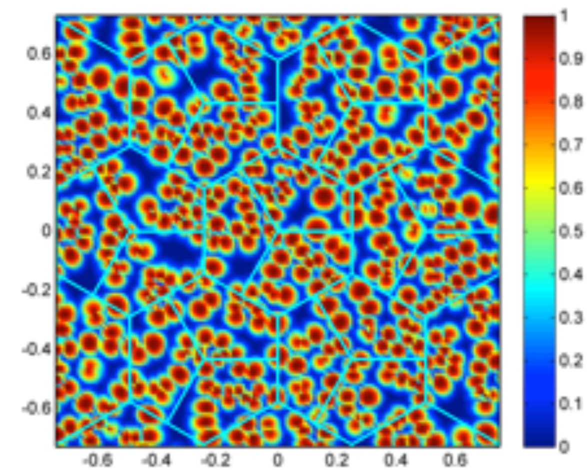
- **BS density does not matter!!!**

The Interference signal grows at the same pace as the carrier signal

Same amount of read and blue



4 small cell per sector



16 small cell per sector

Papers widely cited → conclusion because part of common understanding

Note about Analytical Modeling

Be careful with framework and assumptions

Model

- System level simulation

Assumption

- Probability of line of sight considered

Result

- Coverage probability dependent on the BS density

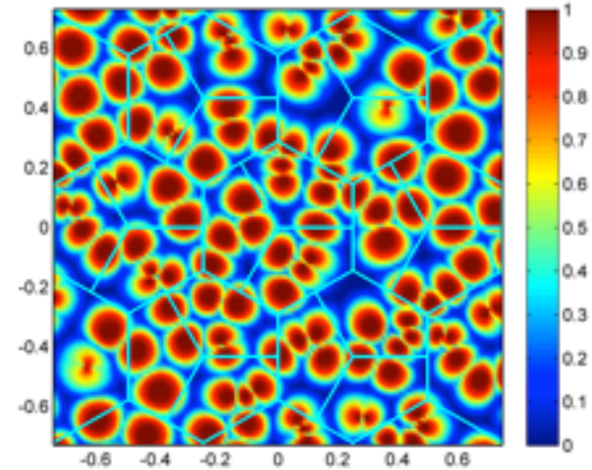
Conclusion

- **BS density does matter!!!**

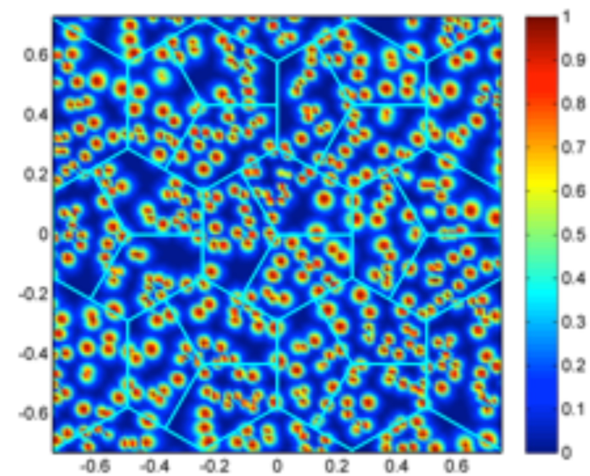
The interference signal grows faster than the carrier signal due to NLOS to LOS transition

Conclusions may be misleading if they are taken out of its context

Different amount of read and blue



4 small cell per sector



16 small cell per sector

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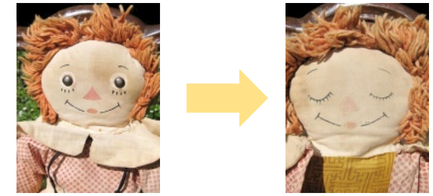
Agenda

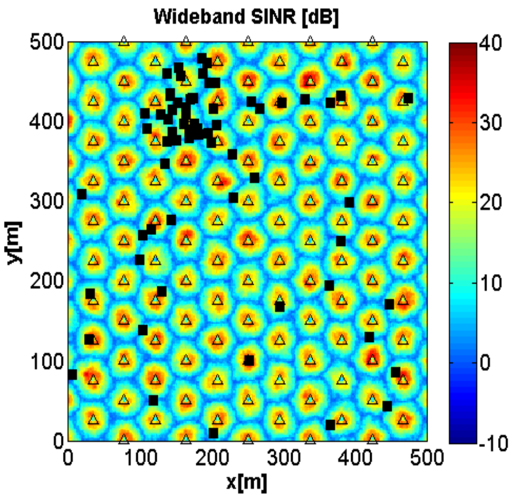
More cells

Densification – idle mode effect

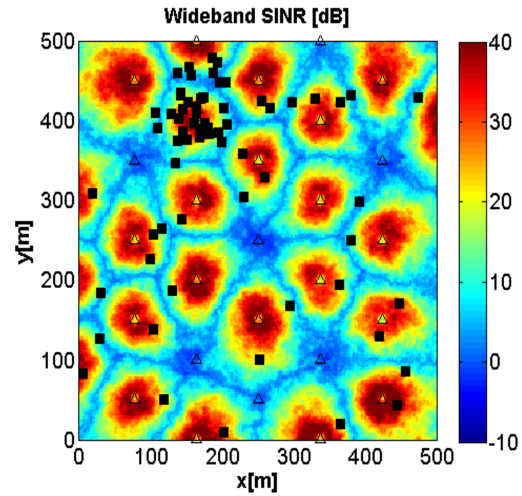


Idle mode OFF

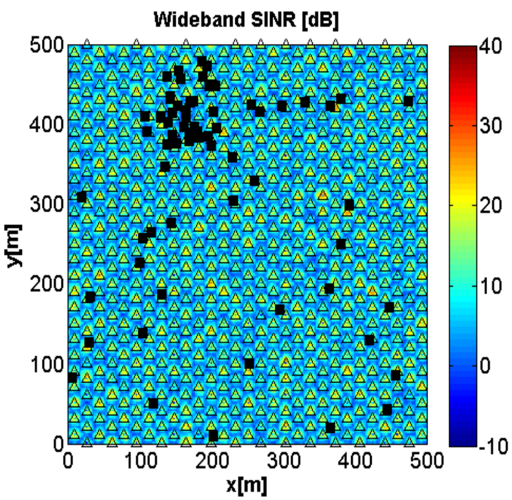
Idle mode ON



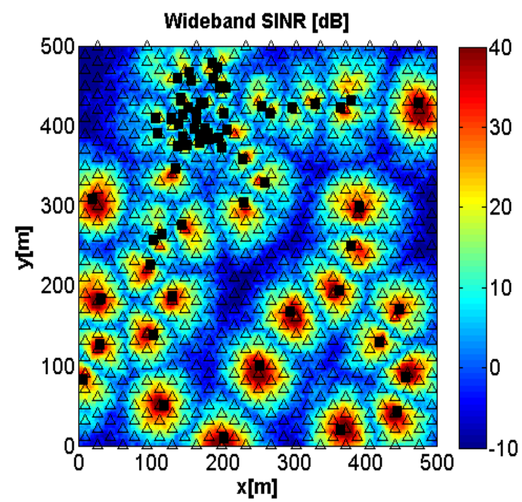
50m ISD



50m ISD



20m ISD



20m ISD

Cells with no UE enter in idle mode, switch off, thus reducing energy consumption and interference

Observations:

Significant change in SINR distribution, median improvement of 6.87 and 14.31dB

Current ICIC techniques cannot deliver such interference mitigation

Transition to noise limited scenarios occurs for very sparse networks (high BS density and low UE density)

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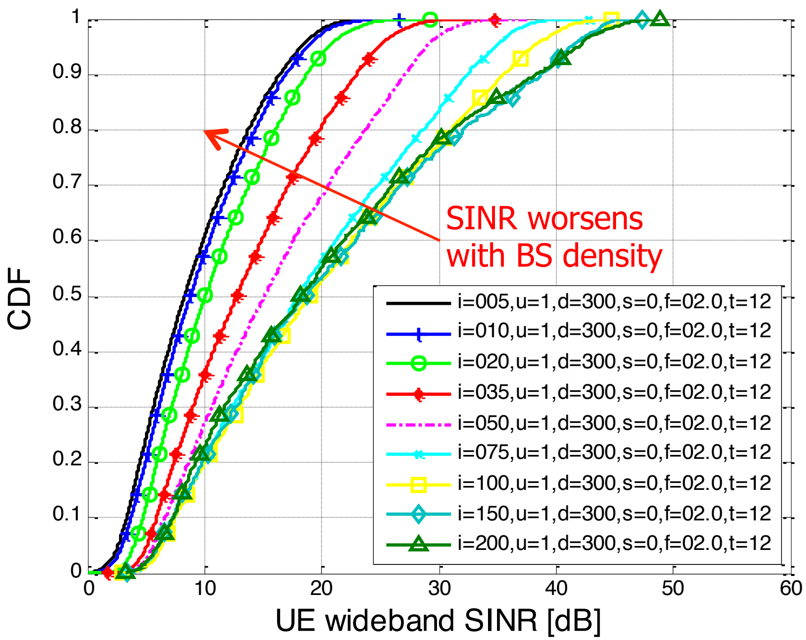
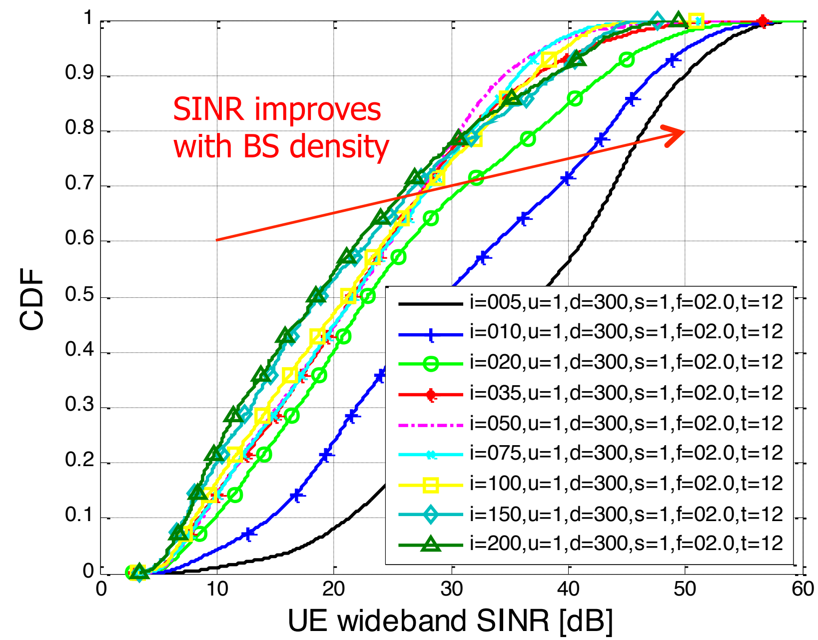
Densification – SINR distribution

Idle mode OFF



Idle mode ON



- Densification affects SINR distribution due to the higher LOS probability, which increases interference

  SINR CDF worsens with densification different conclusion than stochastic geometry modelling guys due to more realistic propagation modelling

- The idle mode reduces interference and thus enhances the UE SINR distribution

  SINR CDF improves with densification

The idle mode changes the trend -> Very high UE SINRs (256QAM needed)

i(isd); d(ueDensity [ue/km2]); u(ueDistribution); s(onOff); f(frequency[GHz]); a(antennas); t(snrTarget[dB])

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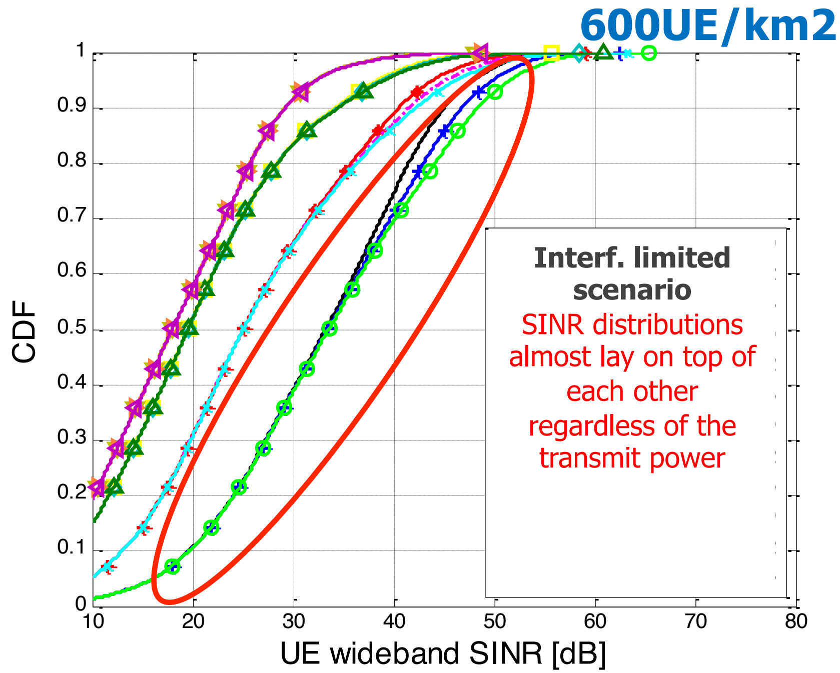
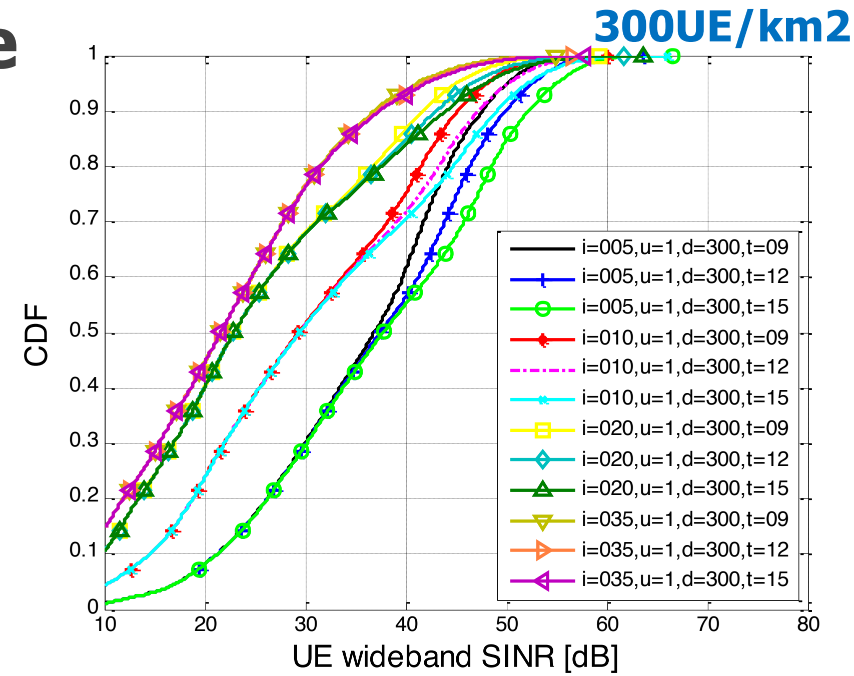
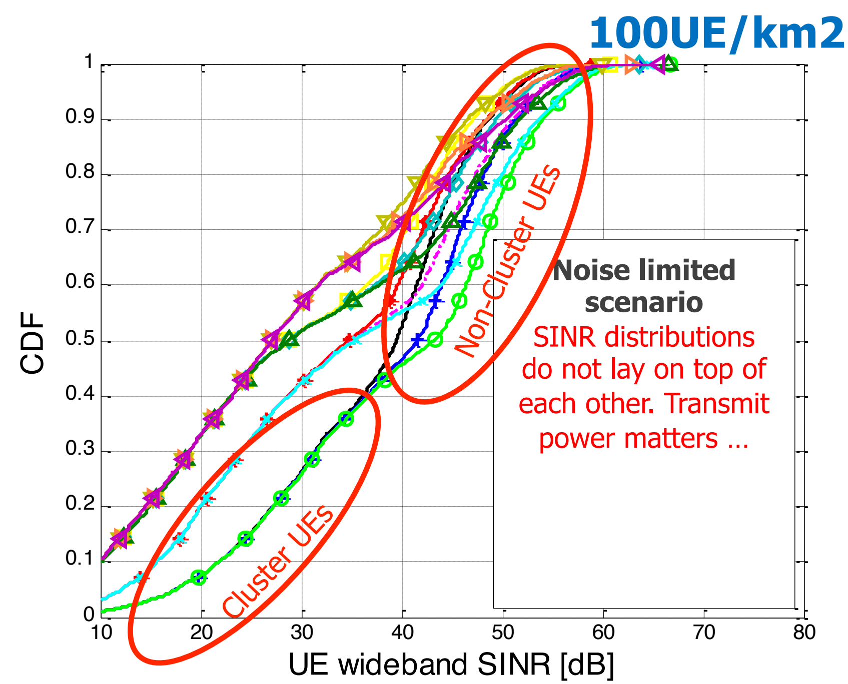
Transition from interference to noise limited scenario







When # active UEs is very low and the cell density is very high, low interference due to idle modes and 50% of UEs (the non-cluster ones) transition from interf. to noise limited

Since this transition occurs in extreme cases, we advise to tune transmit power just to achieve the targeted cell range

The One UE per Cell Concept
The limit of spatial reuse

1 UE per cell is the limit to spatial reuse, capping the cell spatial gains, achieved with an ISD of 35m
in the UK there is 1 hotspot every 11 people

When we reach 1 UE per cell, average TP gain slows down, not so rapidly for the cell-edge UEs

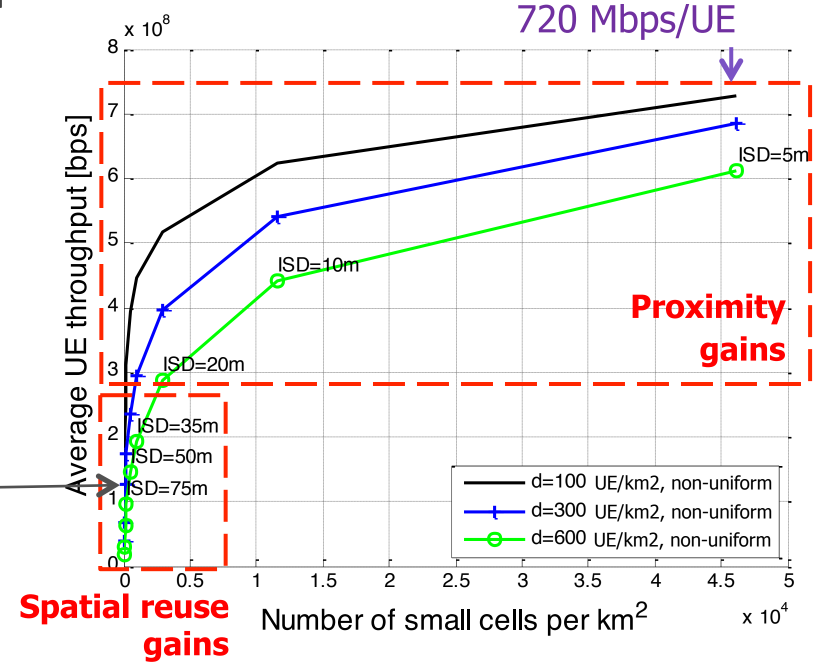
UE-to-BS proximity still provides noticeable capacity gains
drawback: diminishing gains at exponential cost

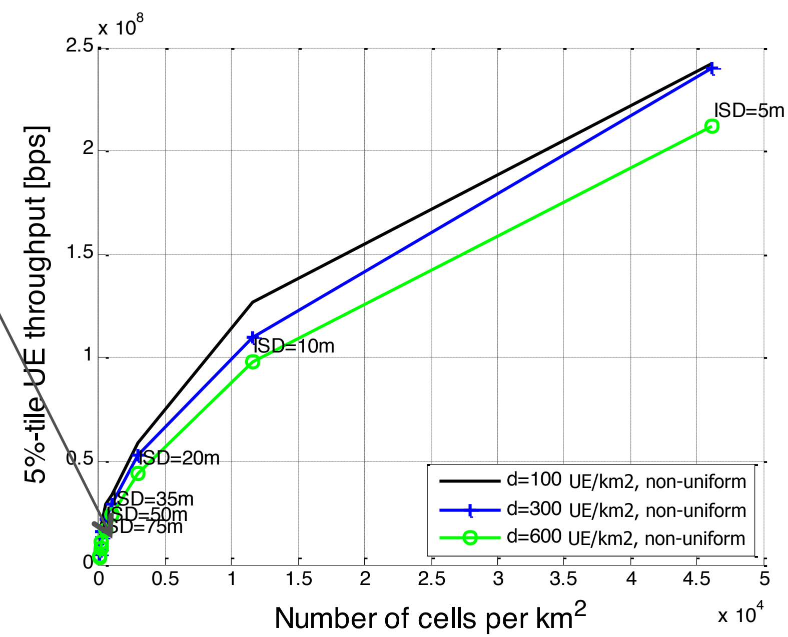
Gains are larger at the cell-edge

Up to 17.56x average capacity gain and 48.00x cell-edge capacity gain

i(isd); d(ueDensity [ue/km2]); u(ueDistribution); s(onOff); f(frequency[GHz]); a(antennas); t(snrTarget[dB])

2GHz, 100MHz, idle mode on, 1 antenna

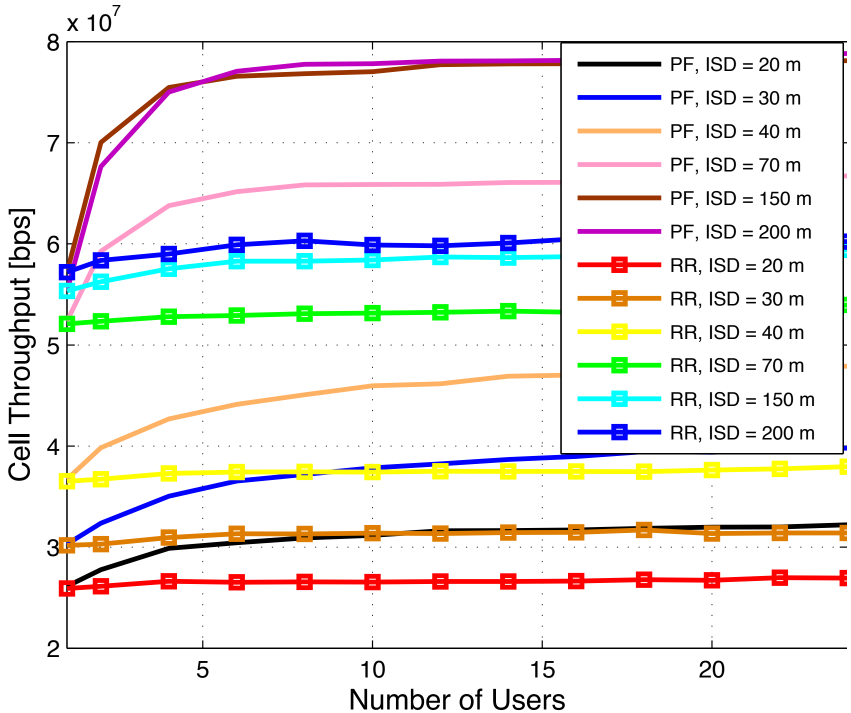


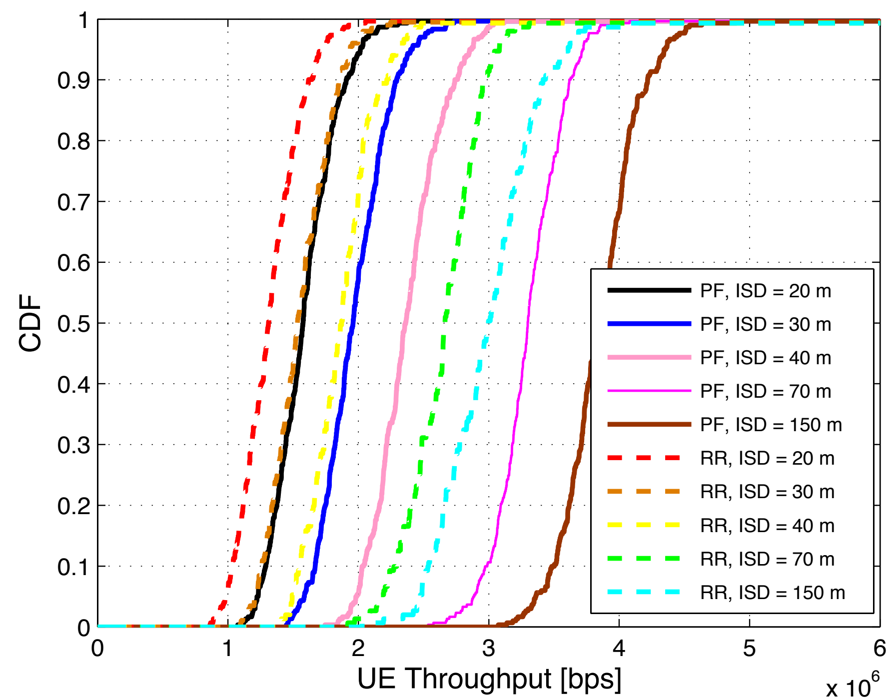


Agenda

Scheduling

Scheduling
Round robin versus proportional fair





- The more cells, the more line of sight (LOS)
- The more LOS, the less channel fluctuations
- Proportional fair starts losing its advantage compared to round robin with densification due to the lower channel fluctuations and thus multi-user diversity gains from 20% to 8% mean UE mean throughput
- Round robin more appealing due to lower complexity???

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Agenda

More bandwidth

Higher carrier frequencies

Linear performance increase with BW

Higher carrier frequencies benefit from lager bandwidth, but the incur higher path losses

Performance scales linearly with the bandwidth, up to 5x average capacity gain with the bandwidth

The higher the density,
the more active cells, but the less tx power/cell

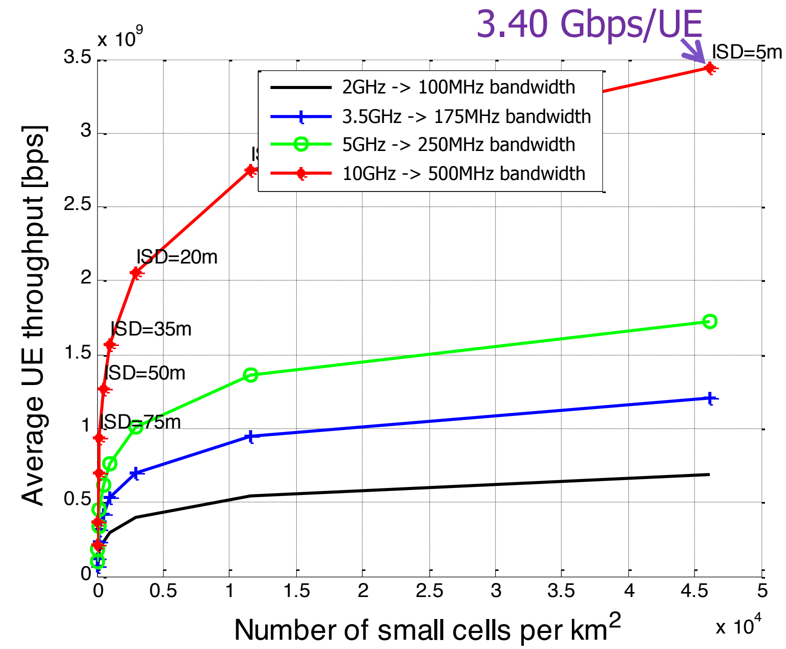
tx power/cell reduction outweighs the more active cells, thus overall network consumption decreases

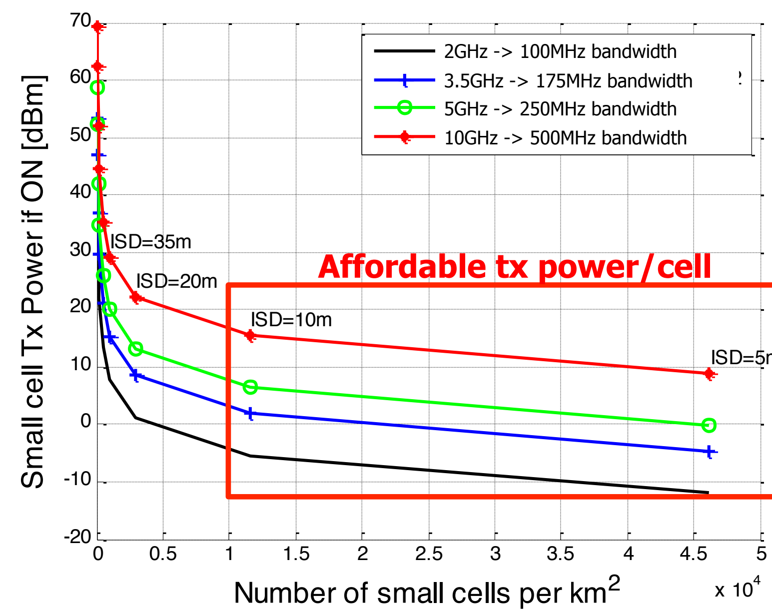
tx power/cell increases with the carrier frequency (more subcarriers, more path loss)

↓

Large bandwidths not suitable for large cells!

300UEs/km2, idle mode on, 1 antenna





Agenda

Scheduling

More antennas

Maximal Ratio Transmission Beam-forming

Horizontal antenna array

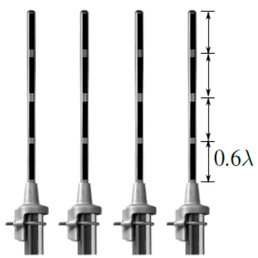
4 vertical dipole arrays with 4 half-lambda dipoles

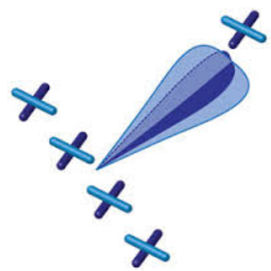
Maximal ratio transmission beamforming

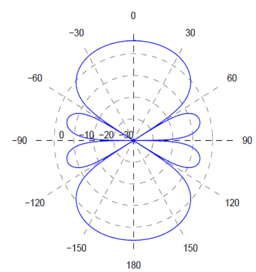
maximizing the RSS of the intended UE

LTE beamforming codebook

reduce overhead





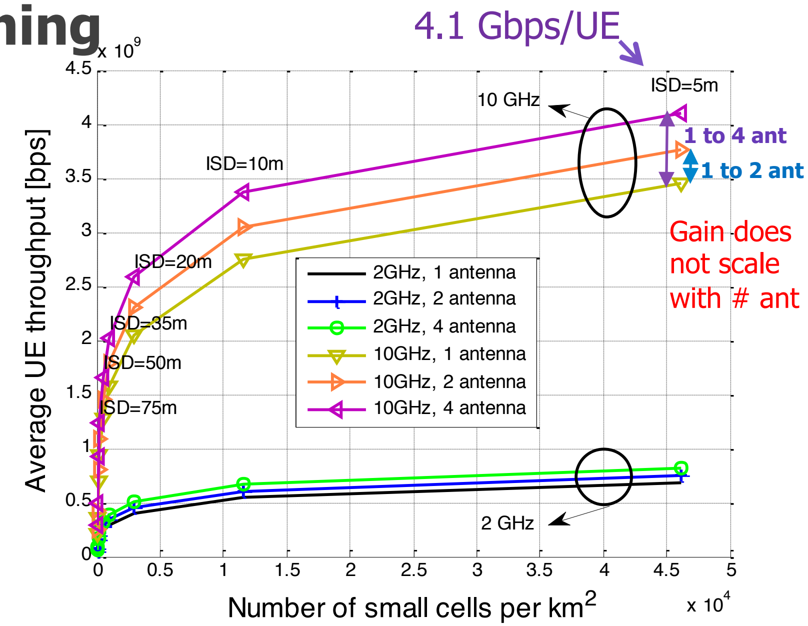


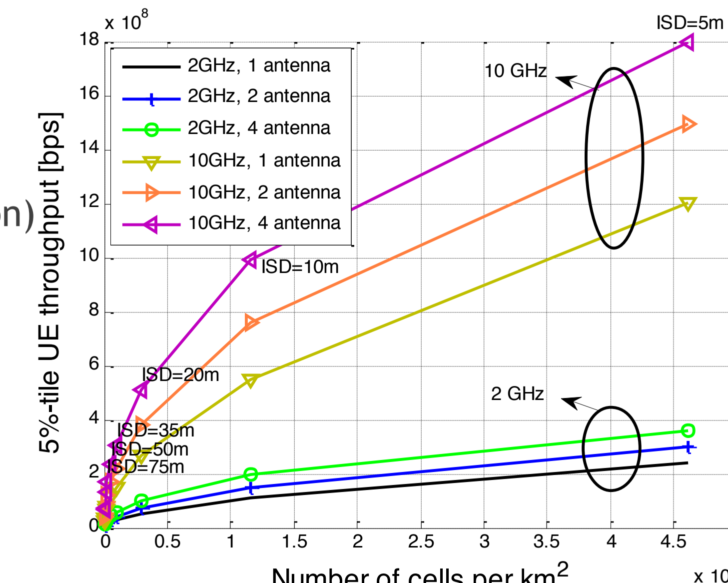
Beamforming gains are:

- larger for larger cell ranges (better carrier signal)
- larger at the cell-edge (better interference mitigation)
- diminish with the number of antennas

- somewhat LOW, up to 1.38x, compared to densification and bandwidth

Research on spatial multiplexing needed!!!



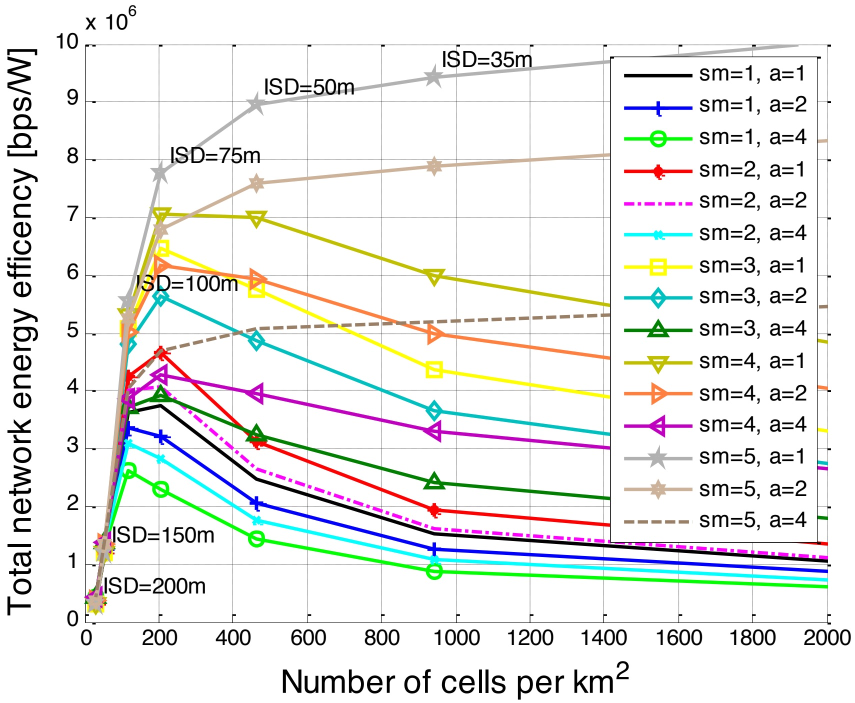


Agenda

Energy efficiency

Energy Efficiency

Renewal energy and energy harvesting



Idle modes: GreenTouch

- sm=1 slow idle mode
- sm=2 shut-down state

More futuristic idle modes:

- sm=3 -> 30% of sm=1
- sm=4 -> 15% of sm=1
- sm=5 -> 0% of sm=1

- Increasing the number of antennas decreases the energy efficiency
- The lower the power consumption in idle mode the larger the energy efficiency
- For sm={1,2,3,4}, the maximum energy efficiency is achieved for ISD = 100 or 75. Energy efficiency decreases for smaller ISDs -> no energy efficient
- For sm=5, the energy efficiency increases with the densification. Energy harvesting could be used to power the cell while in idle mode -> energy efficient

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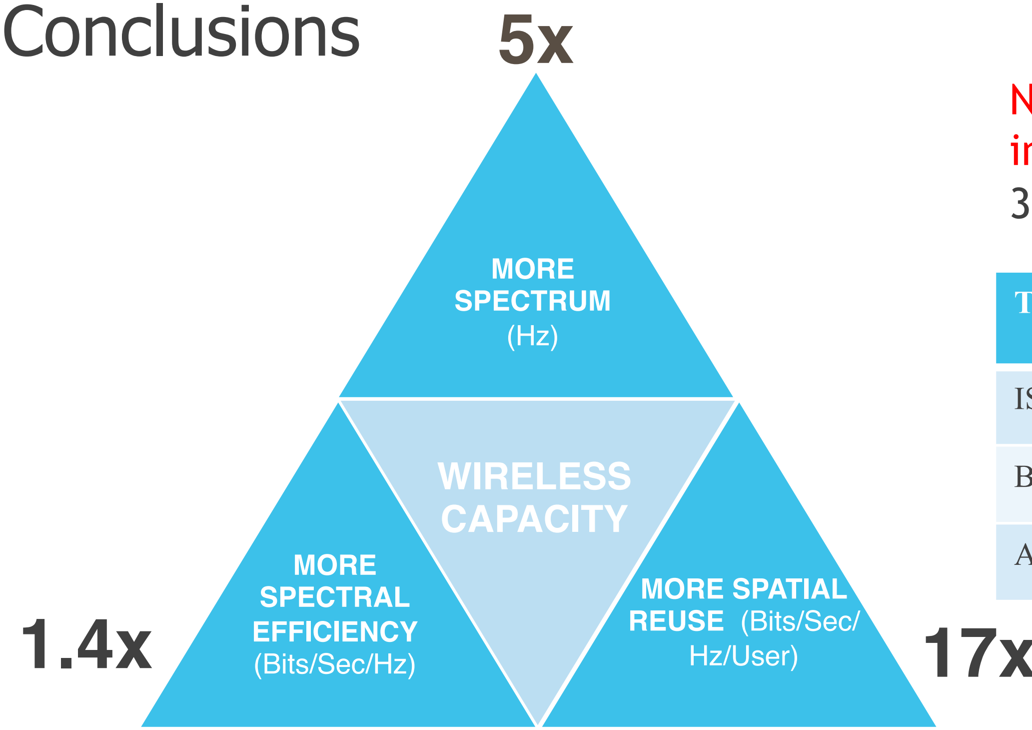
Agenda

Conclusions

The Great Challenge

Conclusions



Network configurations to achieve the indicated targets
300UE/km2, non-uniform distribution

Target	0.5 Gbps/UE		1 Gbps/UE	
ISD(m)	≈75	≈35	≈75	≈35
Bandwidth (MHz)	250	175	500	250
Antennas (#)	2	2	4	4

Ongoing and future work:

- Study cost efficiency
- Impact of cell size on multi-user diversity (proportional fair vs. round robin)
- Impact of cell size on spatial multiplexing (MIMO schemes in LOS presence)
- Comparison to WiFi, and investigation of licensed assisted access (LTE-U)

David Lopez-Perez, Ming Ding, Holger Claussen, Amir Jafari, "***Towards 1Gbps/UE: Understanding Ultra Dense Small Cell Deployments***," submitted to IEEE Communications Surveys & Tutorial, Oct. 2014

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