# Challenges and Opportunities with mmWave and sub-THz Communications in 5G and Beyond

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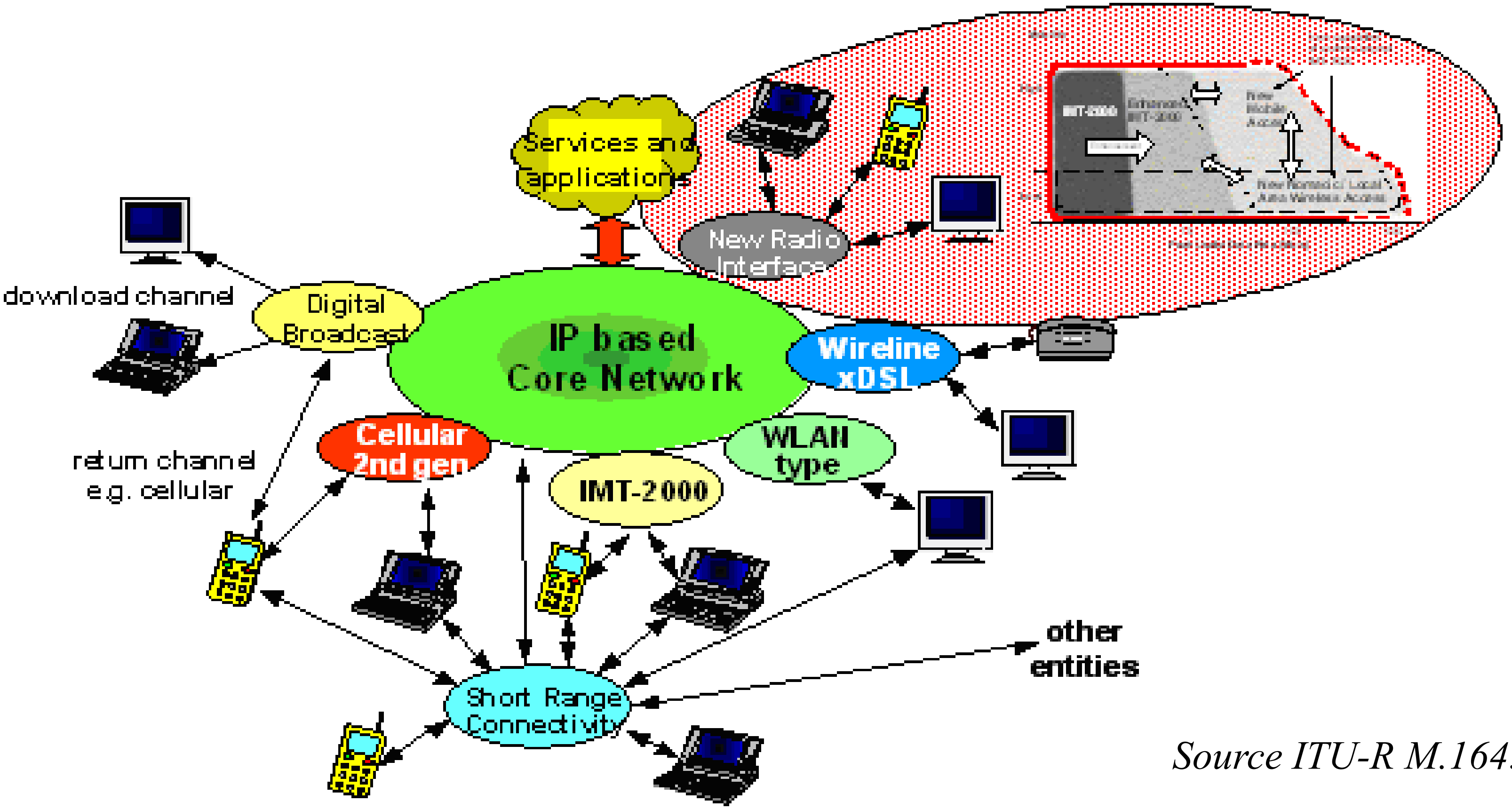
# Outline

- European research towards 4G and beyond
  - The WINNER System concept towards towards IMT Advanced standards
  - Evolution of 4G networks – cooperative and moving networks
- Introduction to the EU FP7 METIS project towards 5G
- Challenges and opportunities with mm-wave communications in 5G
  - Introduction to EU H2020 5GPPP and the mmMAGIC project
  - Research at Chalmers
- Conclusions

# Background: ITU-R Vision for Systems Beyond 3G




*Source ITU-R M.1645*

Integrate existing and evolving access systems on a *packet-based* platform to enable cooperation and interworking.

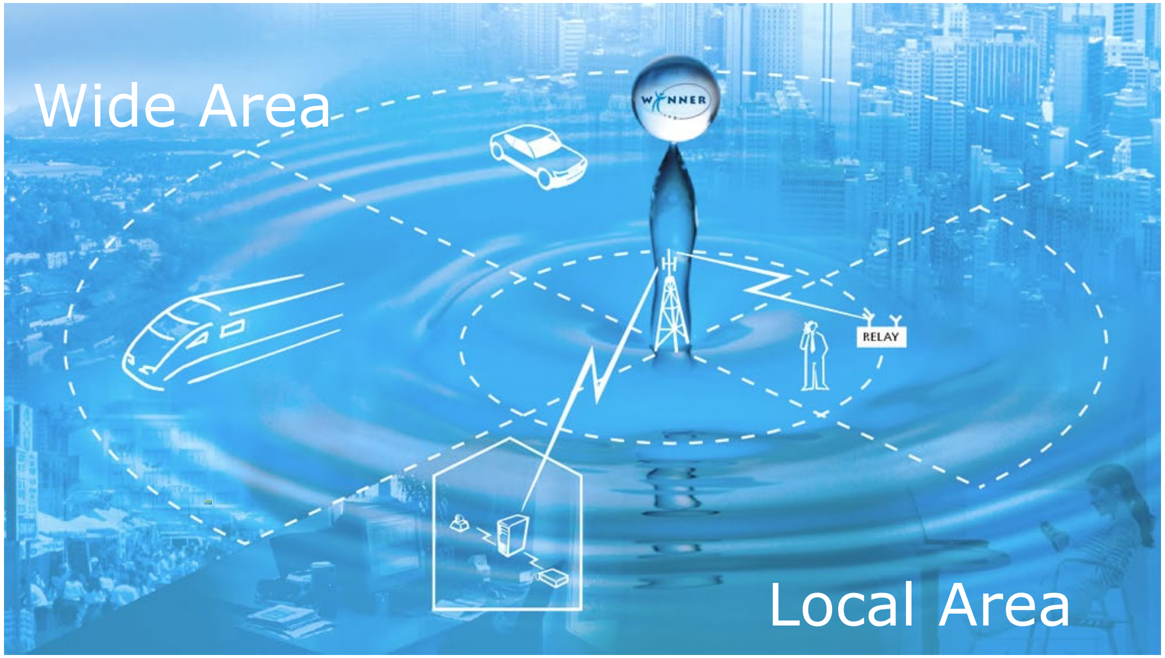
"Optimally connected anywhere, anytime"

# The WINNER Vision: Ubiquitous Radio System Concept

Is based on a
**common radio interface**

that will
**adapt to user needs and scenarios**

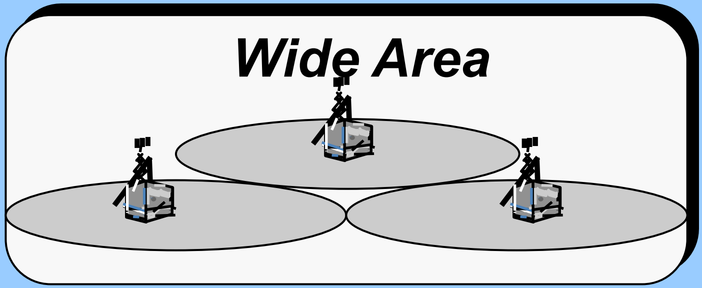
by utilising
**different modes of a common technology**

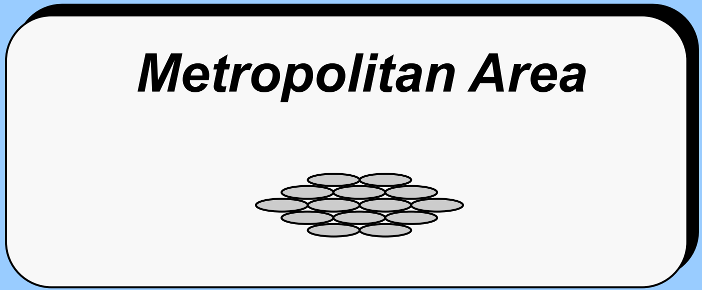


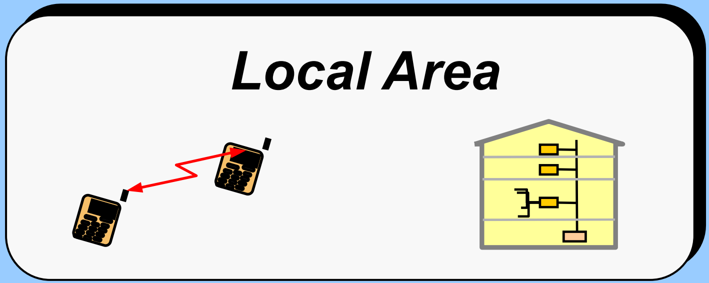

**covers the full range of scenarios**

- Provides a significant improvement compared to current systems in terms of performance, efficiency, coverage and flexibility
- Makes efficient use of the radio spectrum to minimise the cost-per-bit by combining the technologies researched in an efficient way
- Cost competitive infrastructure and terminals with efficient TCP/IP support

# The WINNER System Concept: Multiple Deployment Scenarios



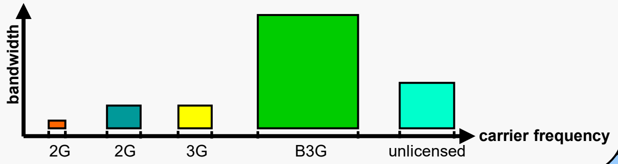

- **Wide Area**
  - Medium traffic demand
  - Cellular, large cells
  - Range issue
- **Metropolitan Area**
  - High traffic demand
  - Cellular, midsize cells
  - Range issue
- **Local Area**
  - High data rate demands
  - Isolated, small cells
  - Indoor, P2P

Source: WINNER

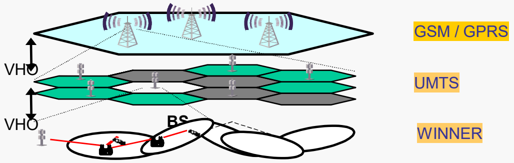
# The WINNER System Concept: Requirements

*User-centricity*

*Spectrum Flexibility*




*Cooperation*

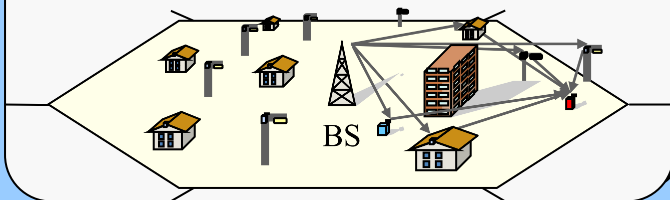



- **User-centricity**
  - Adaptivity on user basis
  - Wide range of applications
- **Spectrum Flexibility**
  - Paired / unpaired
  - Shared / flexible use
  - Different bands
- **Cooperation**
  - Legacy networks
  - Resource management

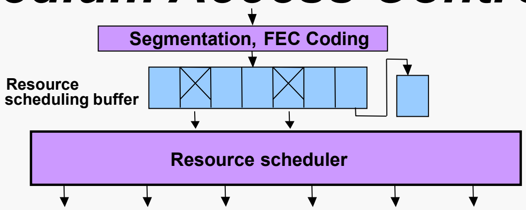
Source: WINNER

# The WINNER System Concept: Key Technologies

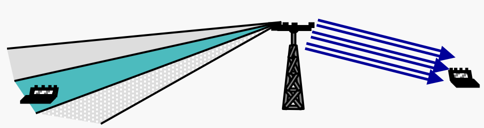
*Multihop Deployment*




*Medium Access Control*




*Spatial Processing*

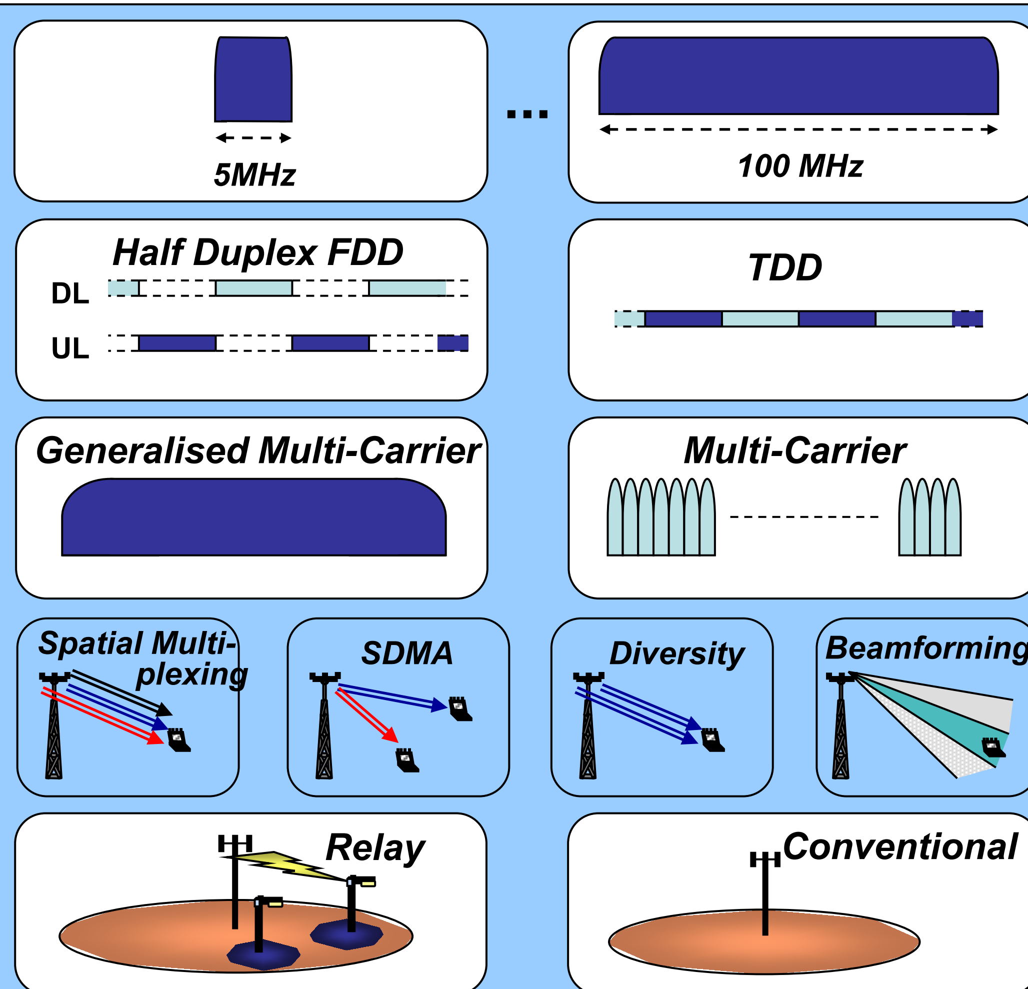


- **Multihop Deployment**
  - Solution to the range issue (WA, MA)
  - Rapid low cost deployment
- **Medium Access Control (MAC)**
  - Resource use optimisation
  - Opportunistic scheduling
  - Interference mgmt / Spectrum sharing
- **Spatial Processing**
  - Capacity / Range / Robustness
  - Interference mgmt / SDMA
  - Throughput maximisation (MIMO)

Source: WINNER

# The WINNER System Concept: Key Radio Interface Components

- Spectrum
- Duplex
- Adaptive Transmission
- Advanced Antennas
- Relays

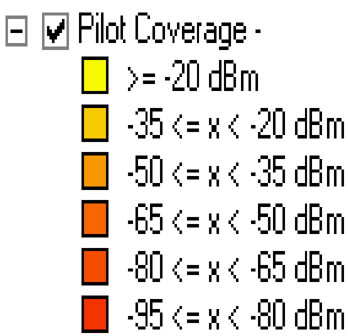


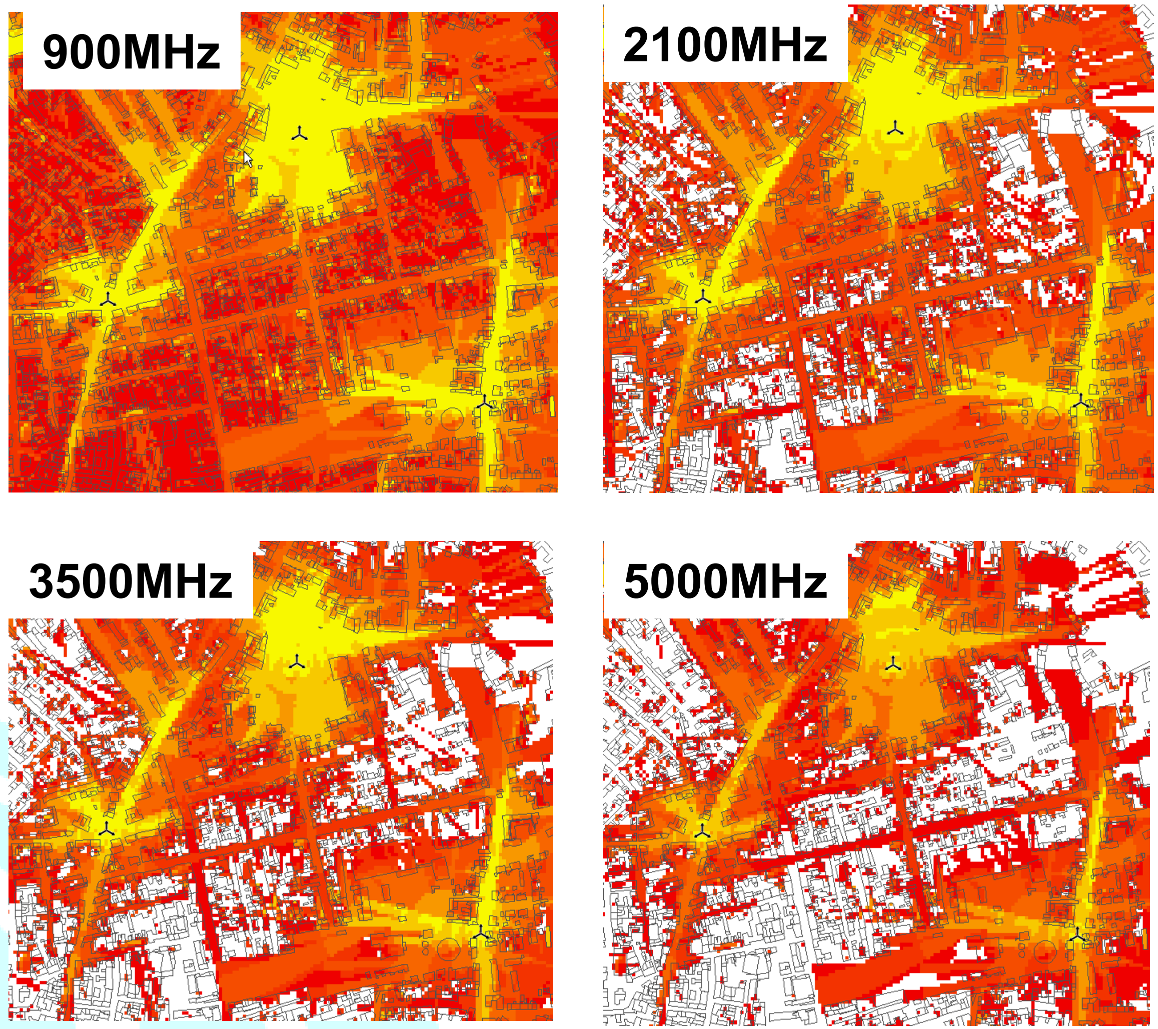

*Adaptive configuration of radio interface components (modes) for optimal usage.*

# Why Relays/Node Densification? The Impact of Carrier Frequency

Higher frequency bands provide
- more spectrum
- but lower coverage

**Will be even worse at mm-wave frequencies!**

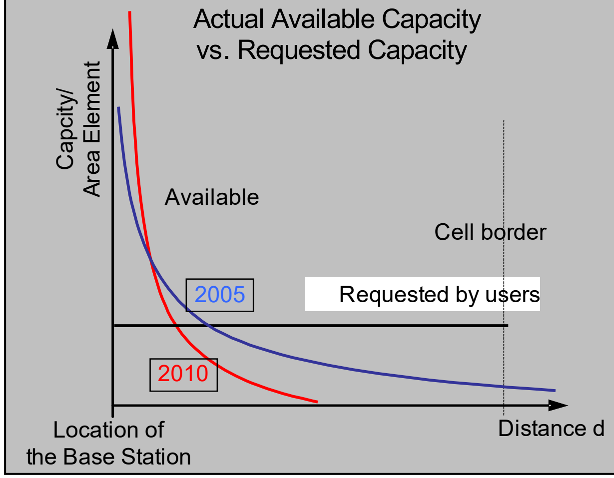


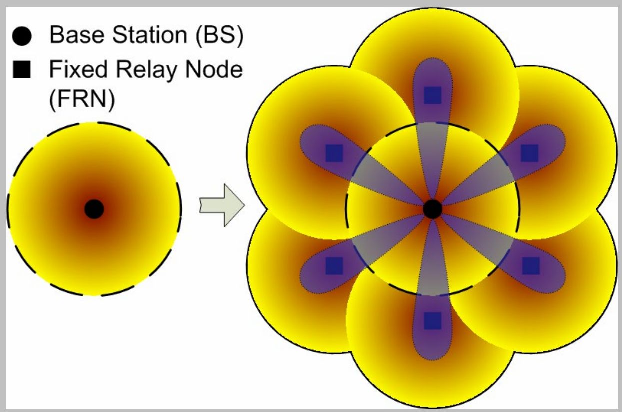

Source: Vodafone

# Fixed Layer 2 Relay Nodes

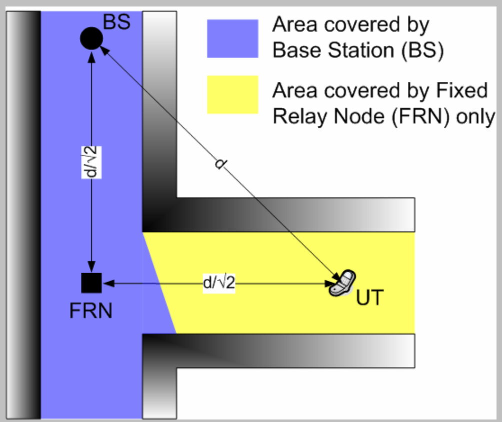
## Capacity drops with distance to BS



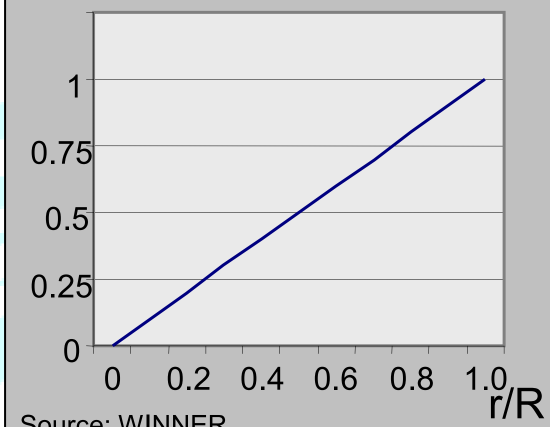

## Relays for Coverage extension



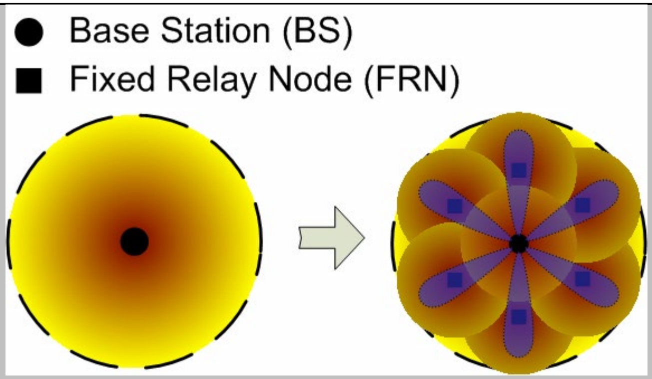

## Relays to cover shadowed areas



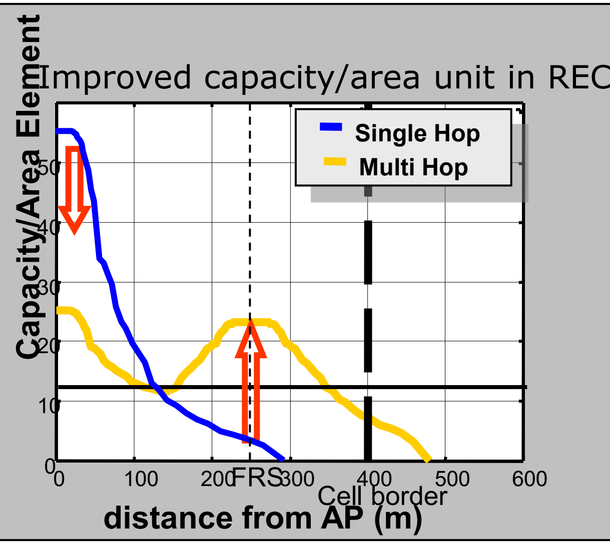

Normalized number of users
vs distance




Source: WINNER



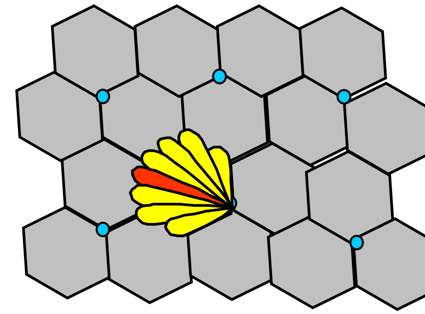

Relays to make capacity in cell more uniform

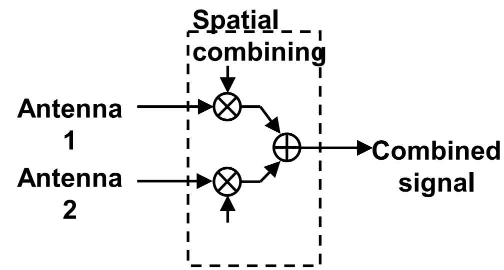


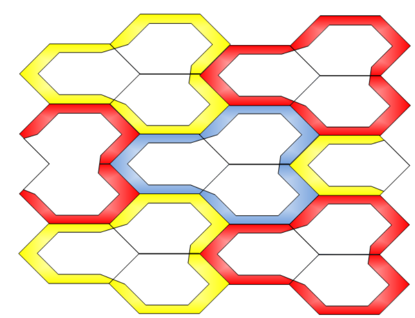
# Interference Mitigation



- Intercell interference is a major challenge in wide area deployments, in particular with frequency reuse 1.
- The most suitable Interference mitigation techniques identified were:
  - Downlink: transmit beamforming (GoB) in conjunction with receivers having interference suppression capabilities, e.g. Interference Rejection Combining (IRC).
  - Uplink: Receivers with interference suppression capabilities, e.g. IRC.
  - Common Control Channels: Resource partitioning such as Fractional Frequency Reuse.
- Scheduler co-design with interference mitigation techniques is of crucial importance, in particular for cell edge users

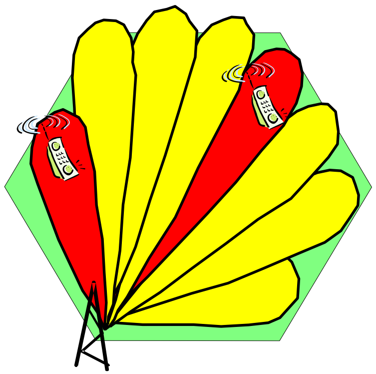




# System Spectral Efficiency vs Satisfied Users

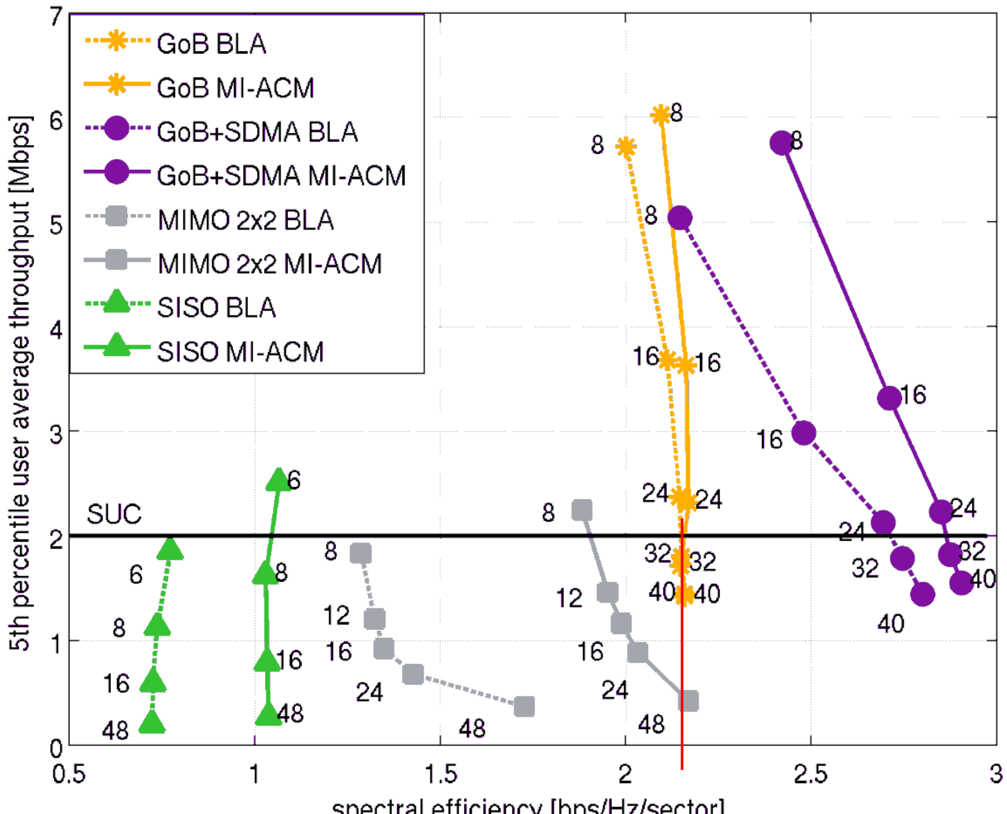
- Spatial Division Multiple Access (SDMA) implemented with Grid-of-Beams (GoB)



- Wide Area Deployment
- 4x2 Antennas Downlink
- Gain over SISO ~x3
- 4x2 SDMA+GoB ~2.5-2.9 bits/s/Hz/sector
- Proportional Fair scheduling

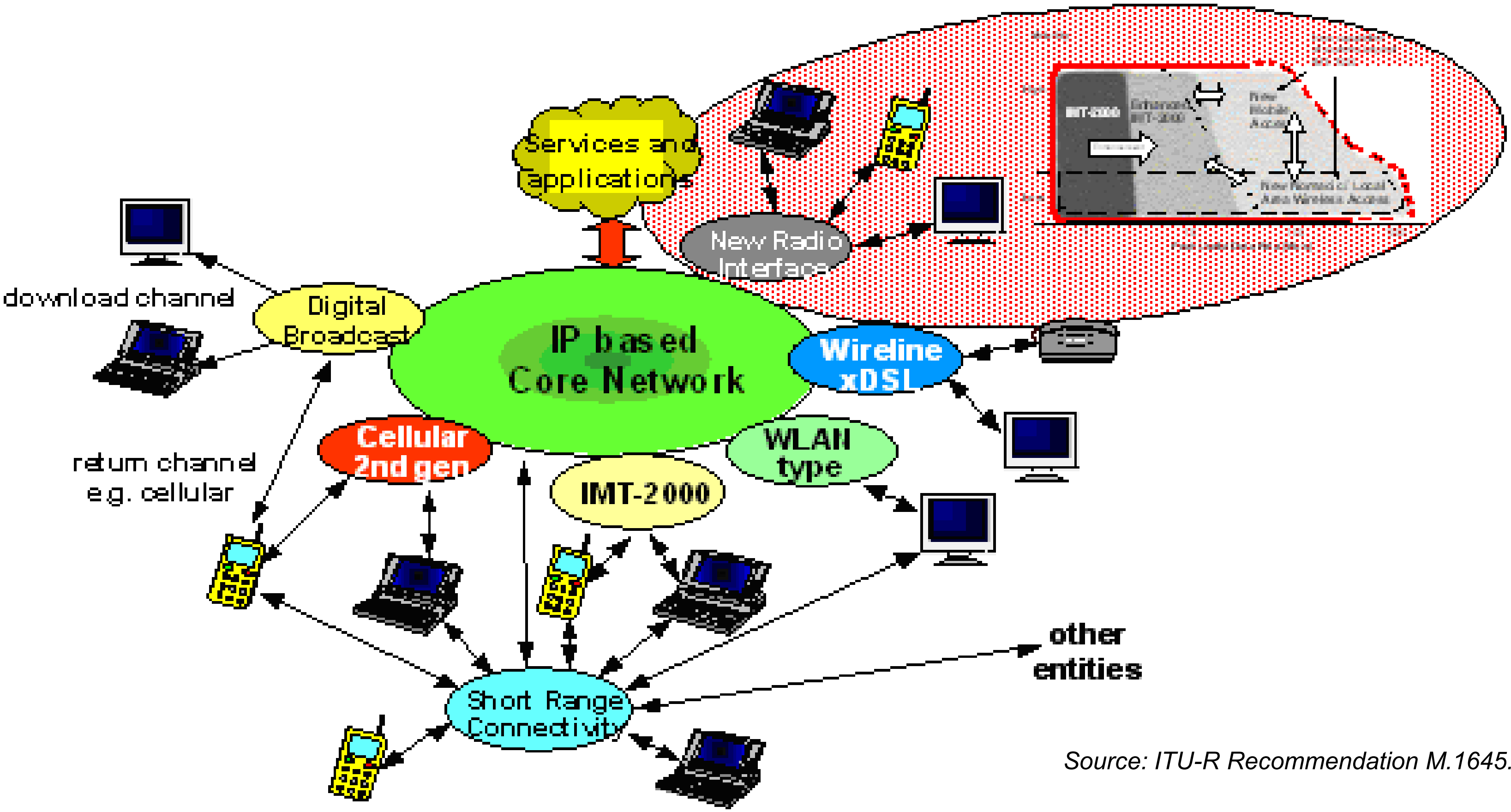
- Satisfied User Criterion (SUC)

**Wide area scenario, 2x50 MHz @ 3.95 GHz**




*Source: WINNER*

# Recall: the 4G Vision

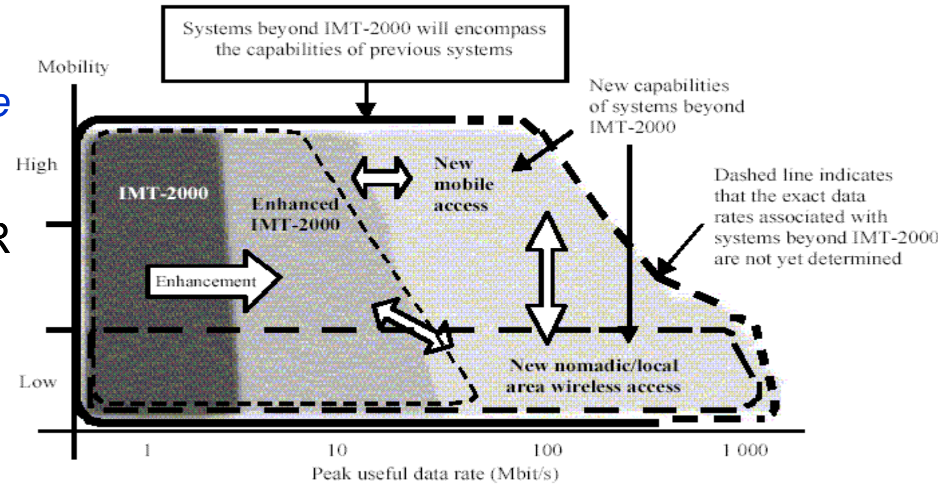



Source: ITU-R Recommendation M.1645.

Integrate existing and evolving access systems on a *packet-based* platform to enable cooperation and interworking - *"Optimally connected anywhere, anytime"*

# ITU-R IMT-Advanced

- International Telecommunications Union – Radiocommunications (ITU-R) defines *mobile radio system families*.
- Spectrum is typically allocated to these ITU-R system families.
- ITU-R Mobile Telecommunications – Advanced, IMT-Advanced, is the "4G" systems family.
- IMT-Advanced defines capabilities which go further than that of IMT-2000 "3G" systems.
- IMT-Advanced was previously known as "Systems beyond IMT-2000", and is the realization of the "4G" vision.
- For "5G", the ITU-R system family is called IMT-2020.




Downlink peak spectral efficiency is 15 bit/s/Hz
Uplink peak spectral efficiency is 6.75 bit/s/Hz.

**Cell spectral efficiency**

| Test environment [1] | Downlink (bit/s/Hz/cell) | Uplink (bit/s/Hz/cell) |
|---|---|---|
| Indoor | 3 | 2.25 |
| Microcellular | 2.6 | 1.80 |
| Base coverage urban | 2.2 | 1.4 |
| High speed | 1.1 | 0.7 |

*Source: ITU-R Recommendation M.1645, M.2134.*

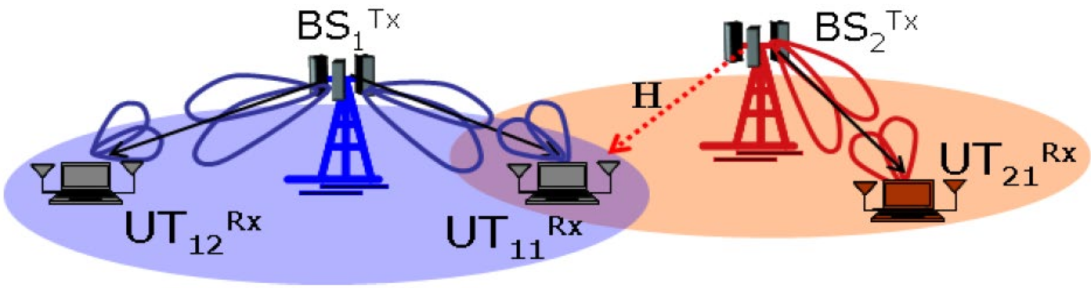
# Ok, Access Network is Ready!
## (3GPP LTE Advanced rel. 10)

*Well, … maybe not…*

IMT Advanced requirements at cell edge:

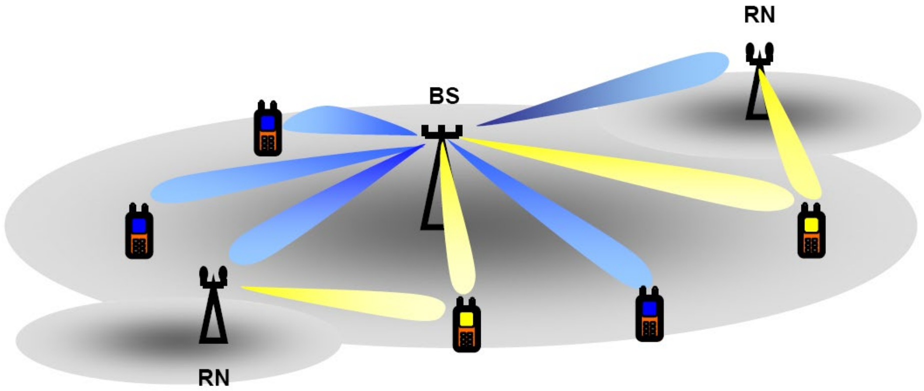
**Cell edge user spectral efficiency**

| Test environment[1] | Downlink (bit/s/Hz) | Uplink (bit/s/Hz) |
|---|---|---|
| Indoor | 0.1 | 0.07 |
| Microcellular | 0.075 | 0.05 |
| Base coverage urban | 0.06 | 0.03 |
| High speed | 0.04 | 0.015 |



# Capacity Where Needed: Coordinated Multi-Point Operation

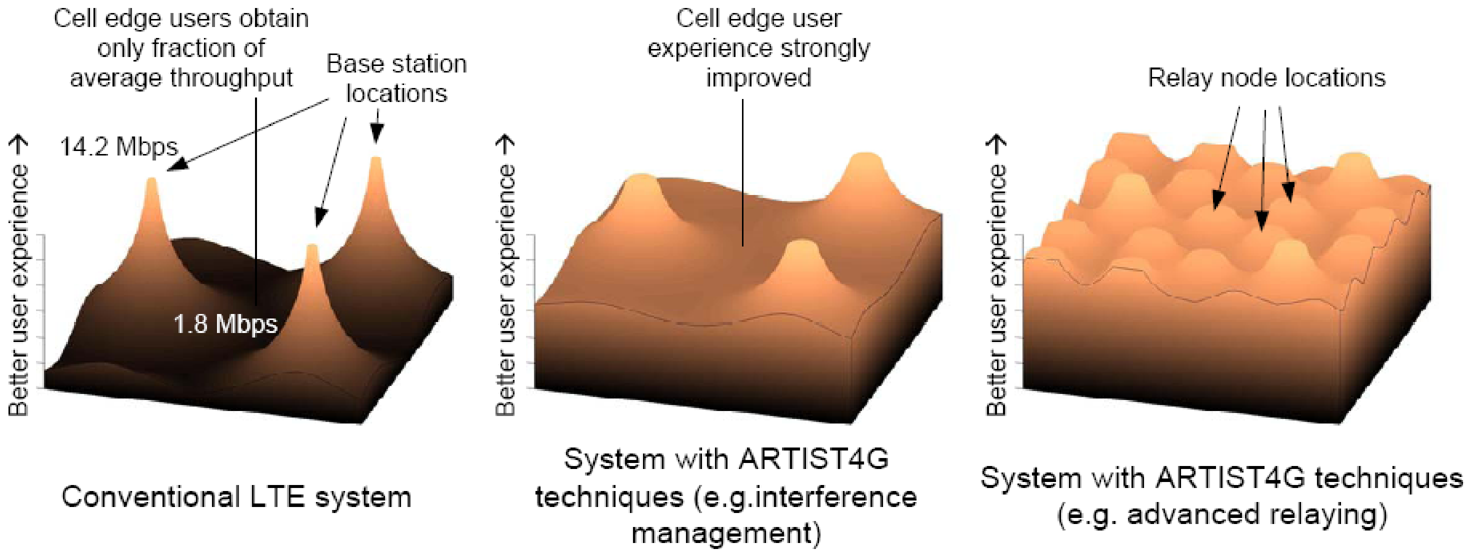
- New cellular structures with *Coordinated Multi-Point* (CoMP) schemes:
  - Potential to make *capacity more smooth* and movable to where users are
  - Coordinate and collaborate over multiple 'cells' for *macro-diversity* and *interference avoidance*
  - Adapt using advanced channel knowledge of distributed antennas to *improve network capacity*



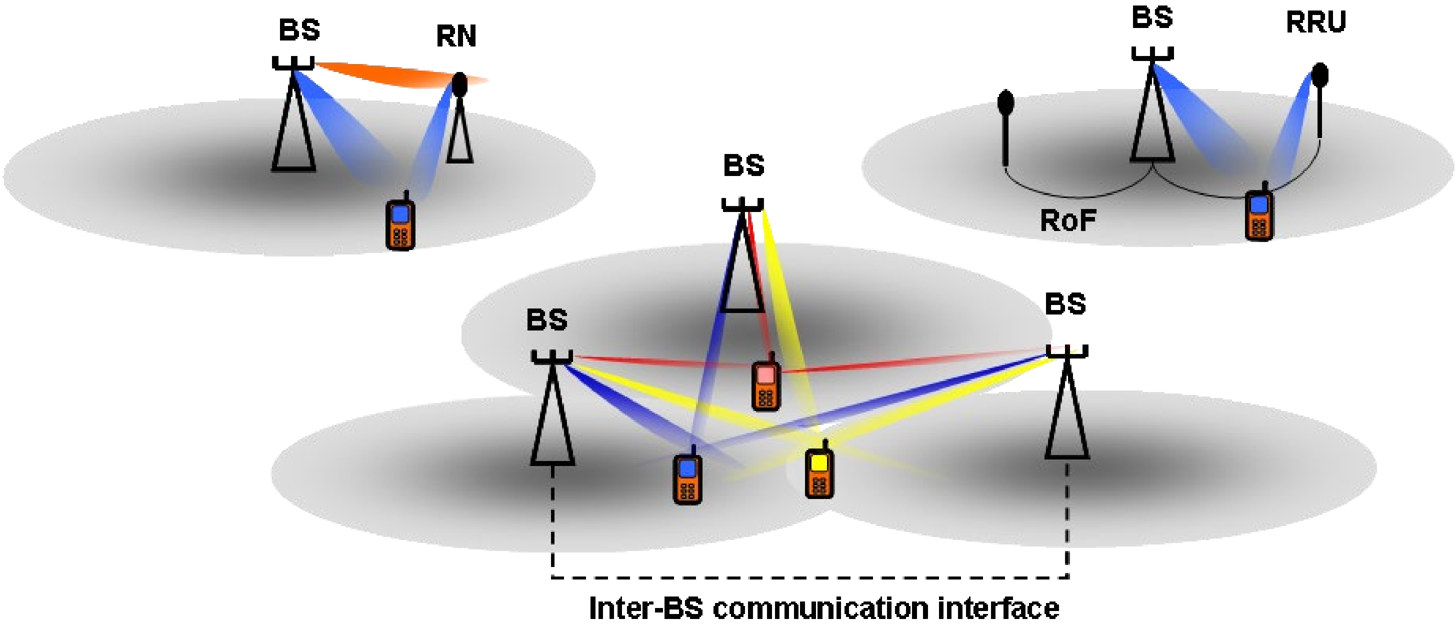

*Illustrations source: WINNER+*

# Coordinated Multi-Point (CoMP)

- Coordinated scheduling/beamforming over multiple cells has the potential to lower the interference levels in a frequency reuse one system
- Coordinated multi-cell transmission and reception has the potential to improve the outage capacity and to smoothen the capacity over the cell areas.



# The CoMP Architectures



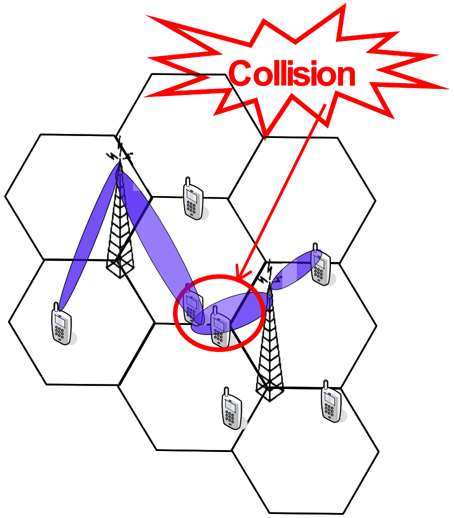

Three types of coordinated entities can be considered:

- Remote Radio Units (RRUs)
- Cells with intra-Base Station (BS) or inter-BS coordination
- Relay nodes (RNs)

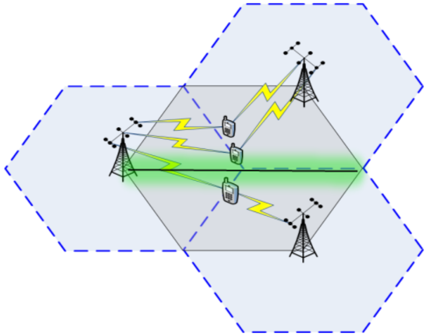
Combined multi-cell coordination with BSs, RRUs, and RNs in each cell.

# CoMP Approaches and Algorithms

- Coordinated scheduling and/or beamforming
  - Data to a single user is instantaneously transmitted from *one* of the transmission points.
  - Scheduling decisions are coordinated to control e.g. the interference generated in a set of coordinated cells.
  - Requires exchange of control data only between nodes



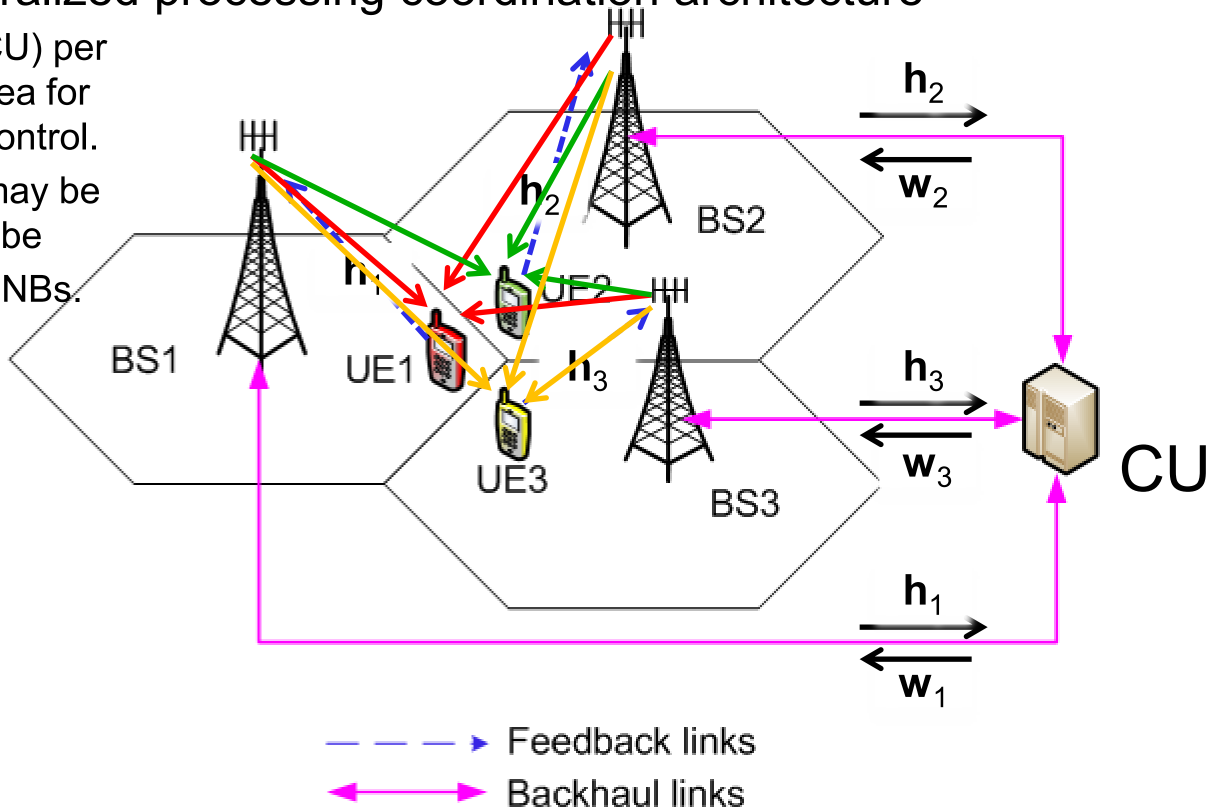

- Coordinated joint processing/transmission
  - Data to a single user is simultaneously transmitted from *multiple* transmission points, e.g. to improve the received signal quality and/or cancel actively interference for other users.
  - Requires exchange of user data as well
  - Macro-diversity gains can be obtained with low exchange of control data, but joint processing gains requires rather large exchange of control data



# CoMP Architectures

## Centralized processing coordination architecture

- Central Unit (CU) per cooperation area for transmission control.
- Data queues may be centralized, or be distributed to eNBs.

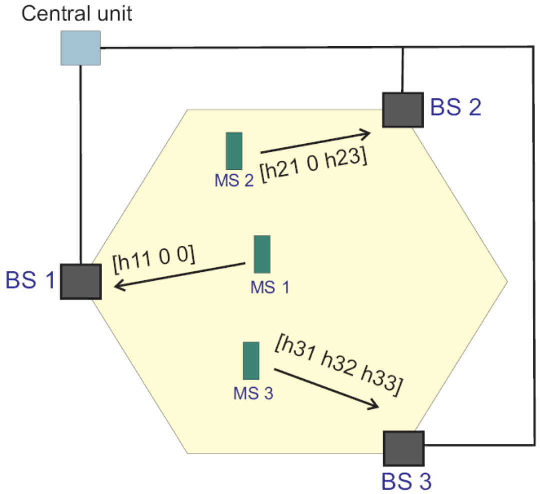



$$\mathbf{H} = \begin{bmatrix} \mathbf{h}_1 \\ \mathbf{h}_2 \\ \mathbf{h}_3 \end{bmatrix}$$

$$\mathbf{W} = \begin{bmatrix} \mathbf{w}_1 \\ \mathbf{w}_2 \\ \mathbf{w}_3 \end{bmatrix}$$

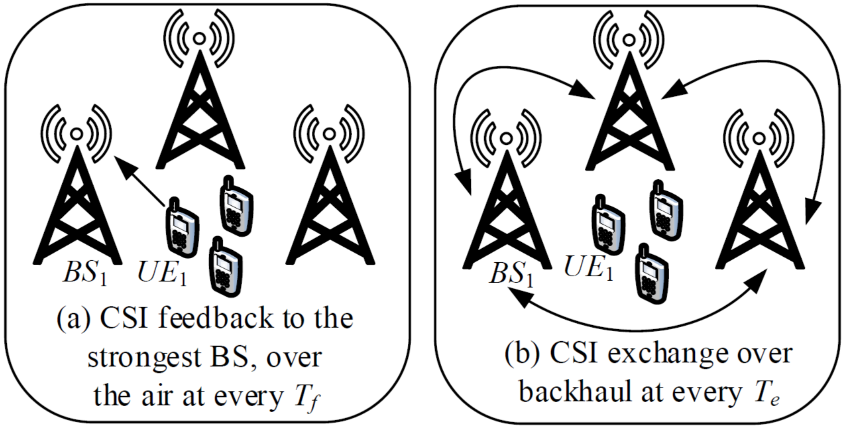
- A star-like network
- Coordinated BSs are connected to a control unit (CU) via backhaul links
- Total latency for an entire transmission loop, $\Delta t^C = \Delta F + \mathbf{2}\Delta B$

# Adaptive CoMP: Partial Joint Processing (PJP)




- *Sub-clusters* of base stations are defined for each user in the cluster, e.g. based on a channel gain *threshold mechanism*.
- Multiuser interference is introduced, but *less* requirements on *feedback* and *backhaul* are needed
- Possible to find *robust* close to optimum PJP schemes that lowers feedback and backhaul load

*T. R. Lakshmana, A. Tölli, R. Devassy, T. Svensson, "Precoder Design with Limited Feedback and Backhauling for Joint Transmission", IEEE Transactions on Wireless Communications, vol.PP, no.99, pp.1-1*




- User specific CSI update rate
- Possible to harvest a large part of the cooperation gains

*T. R. Lakshmana, A. Tölli, T. Svensson, "Improved Local Precoder Design for JT-CoMP with Periodical Backhaul CSI Exchange Corresponding Author: Mr. Tilak Rajesh Lakshmana", IEEE Communications Letters, To appear*

# CoMP Relative Performance Gains (ideal CSI)

Main evaluation case: 4 Tx, 2 Rx antennas, 3 site (9 cell) CAs

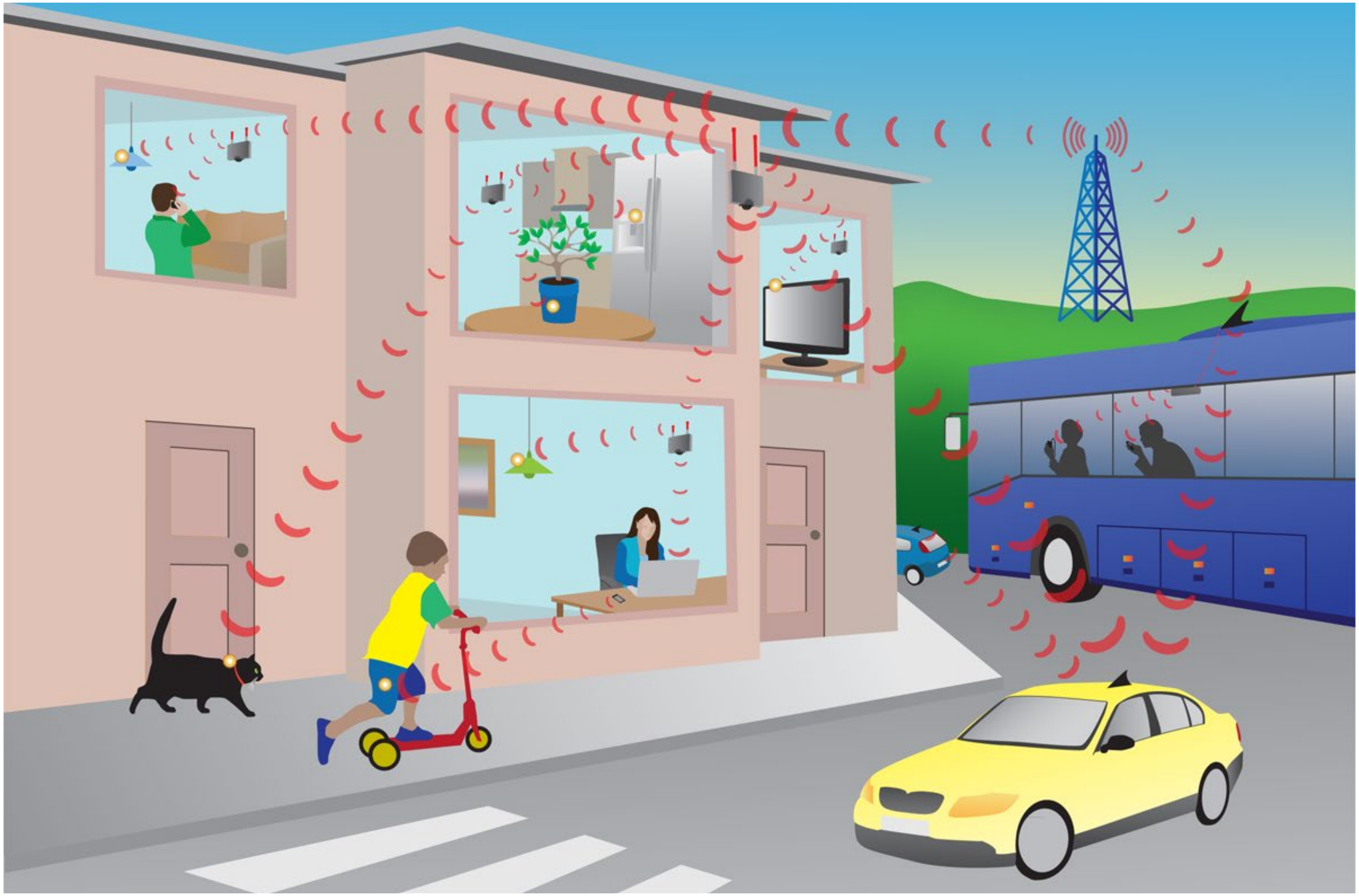
| | **SINR** [dB] | | **Spectral efficiency** bits/s/Hz/cell | **SE gain** [%] |
|---|---|---|---|---|
| | cell edge | average | | |
| Network wide CoMP [(1)] | - | - | **8 / 15**[(2)] | **160** |
| Network wide CoMP with nonlinear precoding[(1)] | - | - | **11 / 20** | **250** |
| 3GPP MU-MIMO | - | - | **3.1** | **0** (reference) |
| 3GPP JP-CoMP | - | - | **4.0** | **30** |
| 9-cell CoMP [(3)] | **-2** | **12** | - | - |
| + cover shift [(3)] | **4** | **17** | - | - |
| + IF floor shaping [(3)] | **12** | **23** | - | - |
| + 2-stage scheduler [(4)] | **5** | **15** | **7.5 / 13** [(2)] | **140** |

SINRs [dB] for single UE per cell

Artist4G D1.4, *Interference Avoidance Techniques and System Design*, June 2012. https://ict-artist4g.eu

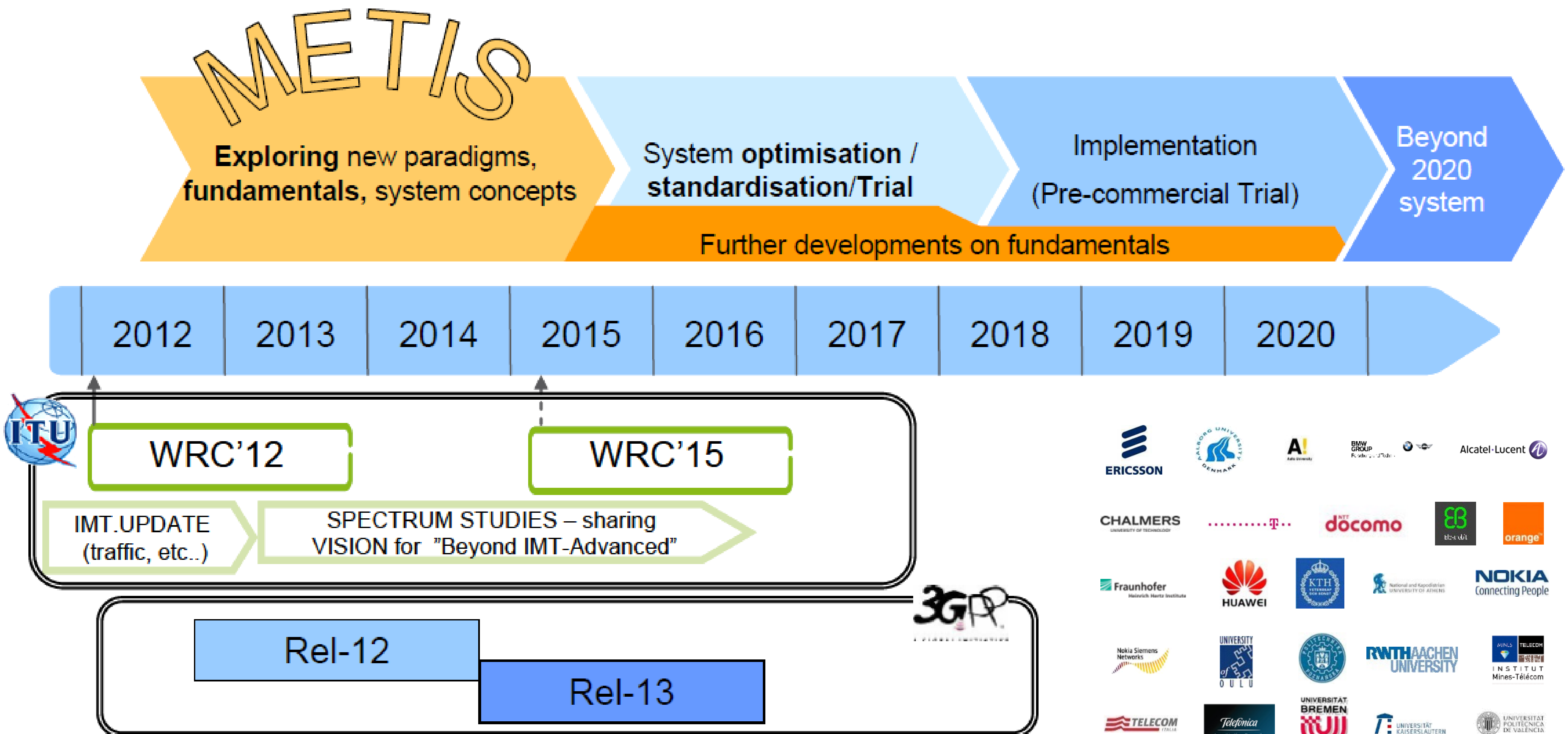
(1) Simulation conditions are not fully comparable; higher values are for nonlinear precoding
(2) Values after backslash ignore LTE overhead of 43%;
(3) SINR for single UE per cell and for 4x2;
(4) SINR for 2 to 3 out of 10 simultaneously scheduled UEs per cell and 4x2 configuration
Perfect transmitter CSI assumed in all evaluations above.

# Wireless Communications in Dense Heterogeneous Networks



# METIS Overall Objectives

**Lay** the foundation & **Ensure** a global forum & **Build** an early global consensus for beyond 2020 “5G”mobile & wireless communications



# METIS Overall Technical Goal

A system concept that, relative to today, supports:

› 1000 times higher mobile data volume per area,

› 10 times to 100 times higher number of connected devices,

› 10 times to 100 times higher typical user data rate,

› 10 times longer battery life for low power Massive Machine Communication (MMC) devices,

› 5 times reduced End-to-End (E2E) latency.

*Source: METIS Deliverable D1.1 "Scenarios, requirements and KPIs for 5G mobile and wireless system", https://www.metis2020.com/*

# METIS Scenarios and Test Cases

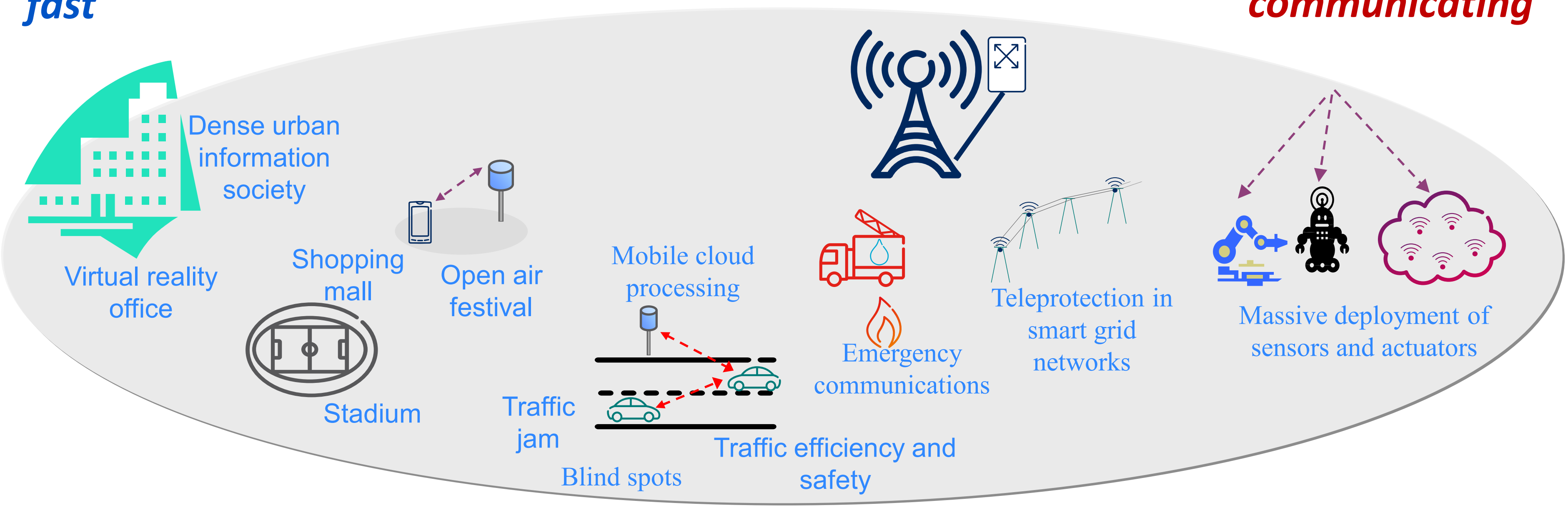
***Amazingly fast***

***Great service in a crowd***

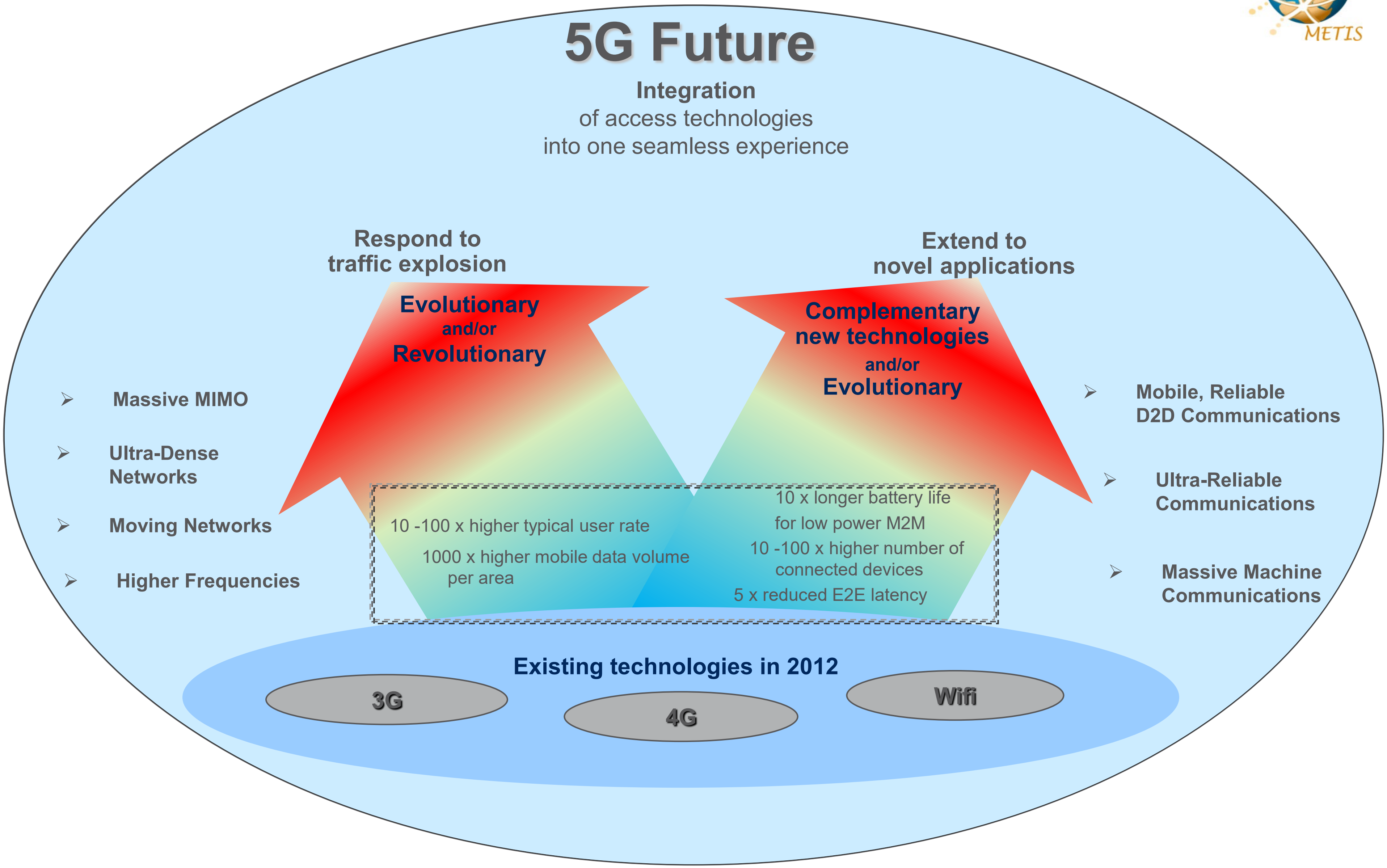
***Best experience follows you***

***Super real-time and reliable connections***

***Ubiquitous things communicating***




*Source: METIS Deliverable D1.1 "Scenarios, requirements and KPIs for 5G mobile and wireless system", https://www.metis2020.com/*



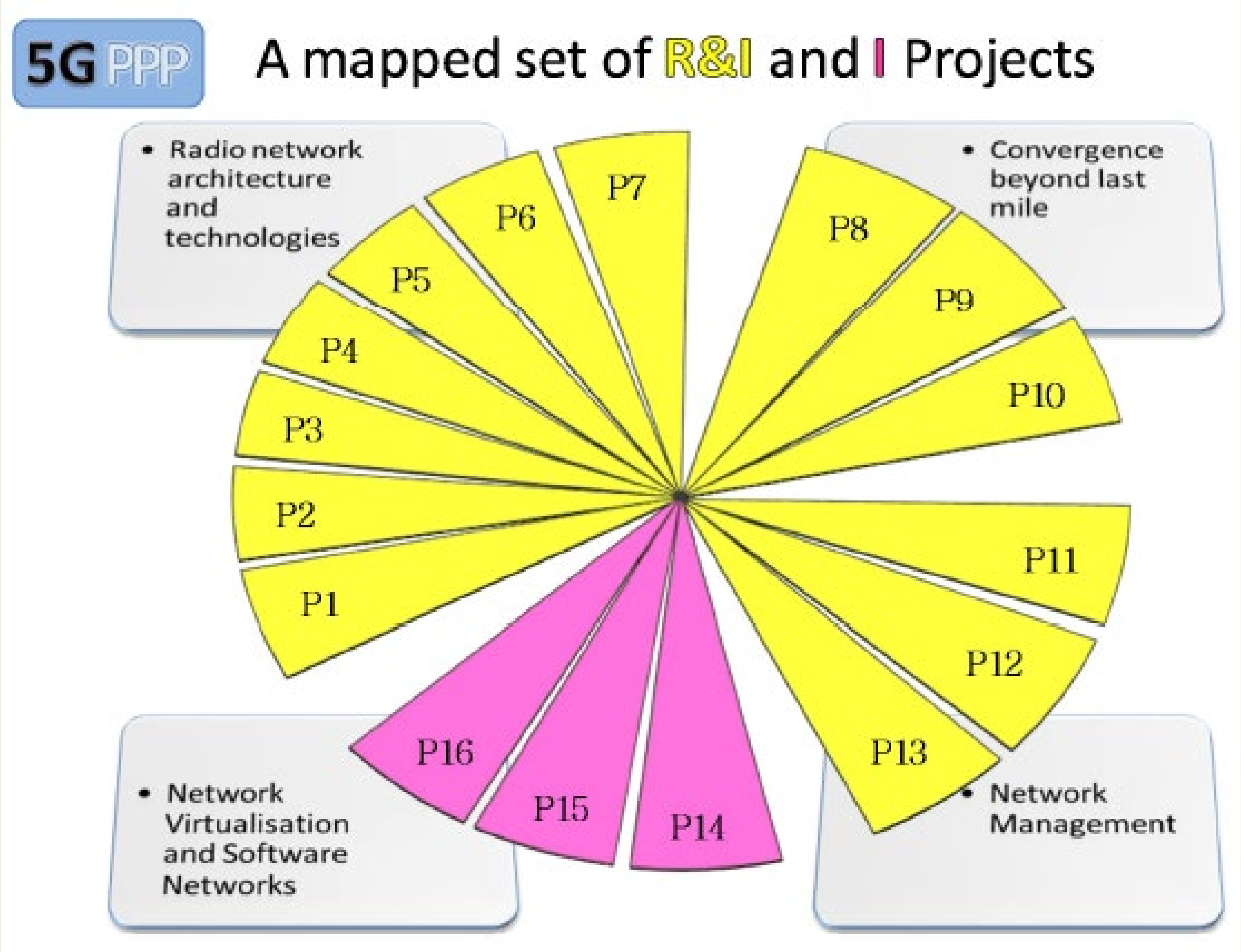
5G Future
Integration
of access technologies
into one seamless experience
Respond to
traffic explosion
Evolutionary
and/or
Revolutionary
Extend to
novel applications
Complementary
new technologies
and/or
Evolutionary
Massive MIMO
Ultra-Dense Networks
Moving Networks
Higher Frequencies
Mobile, Reliable D2D Communications
Ultra-Reliable Communications
Massive Machine Communications
10 -100 x higher typical user rate
1000 x higher mobile data volume per area
10 x longer battery life for low power M2M
10 -100 x higher number of connected devices
5 x reduced E2E latency
Existing technologies in 2012
3G
4G
Wifi

# Challenges and Opportunities with mm-wave Communications in 5G

# Outline

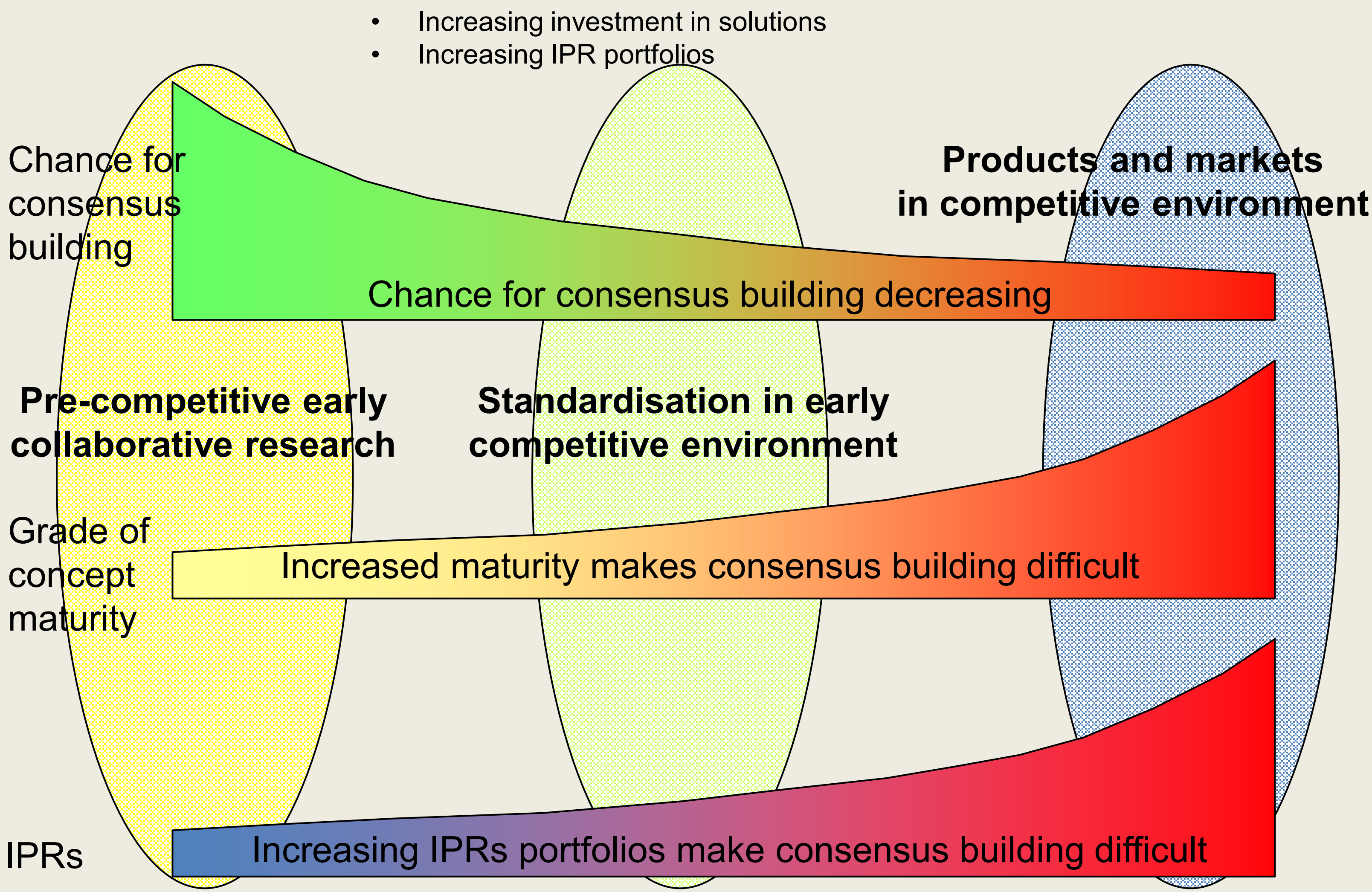
- The European road to 5G new air interface:
  - Overview of the 5G infrastructure public private partnership (5G PPP)
  - The EU H2020 mmMAGIC project
- Some research highlights at Chalmers

# Pre-structuring Model Approach




http://5g-ppp.eu/

# Why Competitive Organisations are Collaborating




- Thus, important to build international consensus building at an early stage!

# mmMAGIC

Duration: 24 months
Budget: EURO 8.26M
Coordinator: Maziar Nekovee, Samsung
Technical Manager: Peter von Wrycza, Ericsson

https://5g-mmmagic.eu

UHD TV/streaming

Immersive and interactive 3D services

Ultra-responsive mobile cloud

Ultra-dense deployment

Multicast support

Self-backhaul/front-haul support

WRC'19 & 3GPP Head-start

3GPP ITU


## mm-wave Based Mobile Radio Access Network for Fifth Generation (5G) Integrated Communications

### Horizon 2020 Public Private Partnership Consortium

**Coordinator: Samsung Electronics, Europe Ltd.**
**Technical Management: Ericsson AB**

SAMSUNG, Ericsson, Alcatel-Lucent, intel, HUAWEI, NOKIA NETWORKS, orange, Telefónica

cea leti, Fraunhofer Heinrich Hertz Institute, imdea networks

Aalto, University of BRISTOL, CHALMERS UNIVERSITY OF TECHNOLOGY, TECHNISCHE UNIVERSITÄT DRESDEN

KEYSIGHT TECHNOLOGIES, ROHDE&SCHWARZ, qamcom

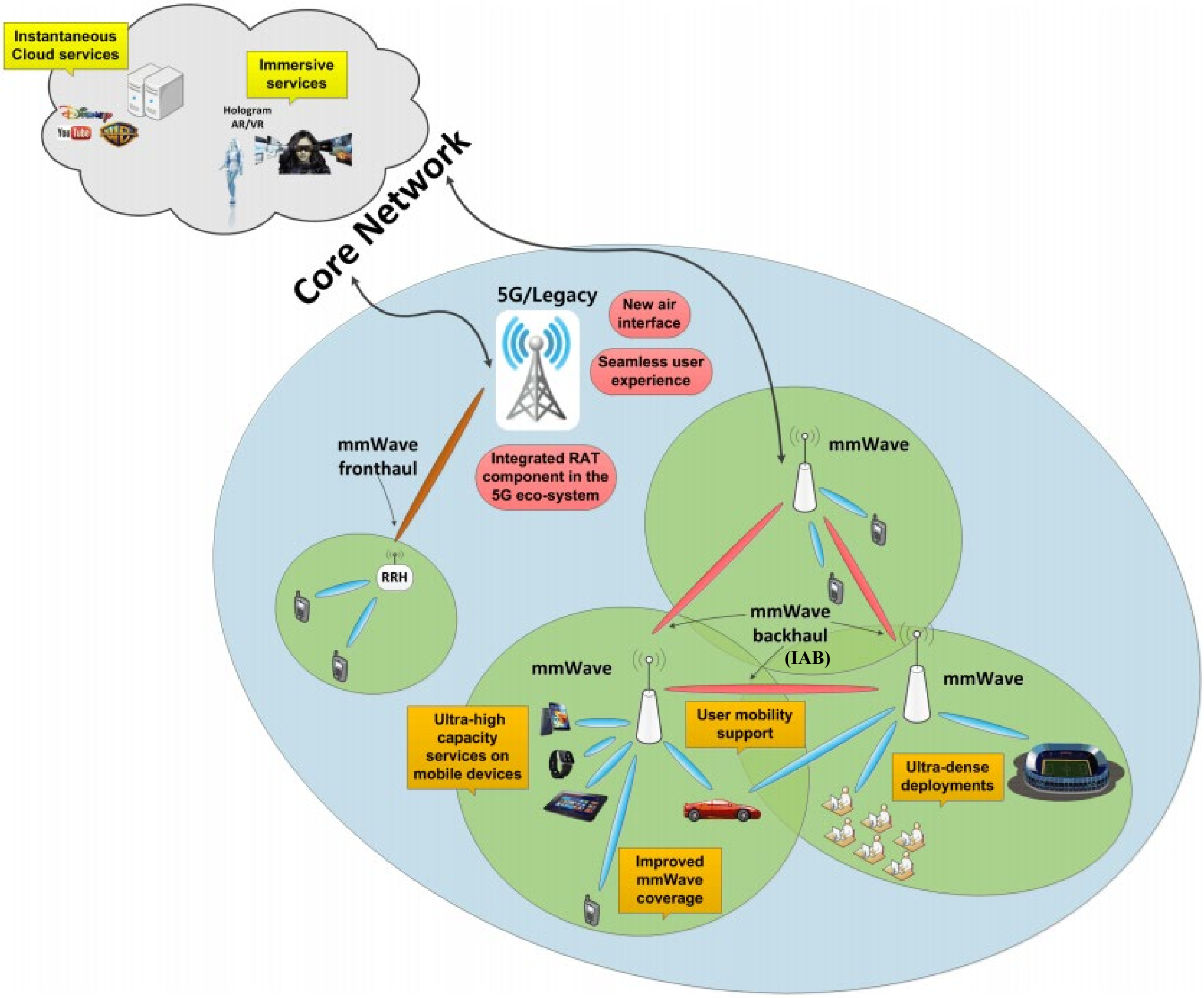
Advisory Board

Agence Nationale des Fréquences, BNetzA, Viestintävirasto Kommunikationsverket Finnish Communications Regulatory Authority, Ofcom, PTS

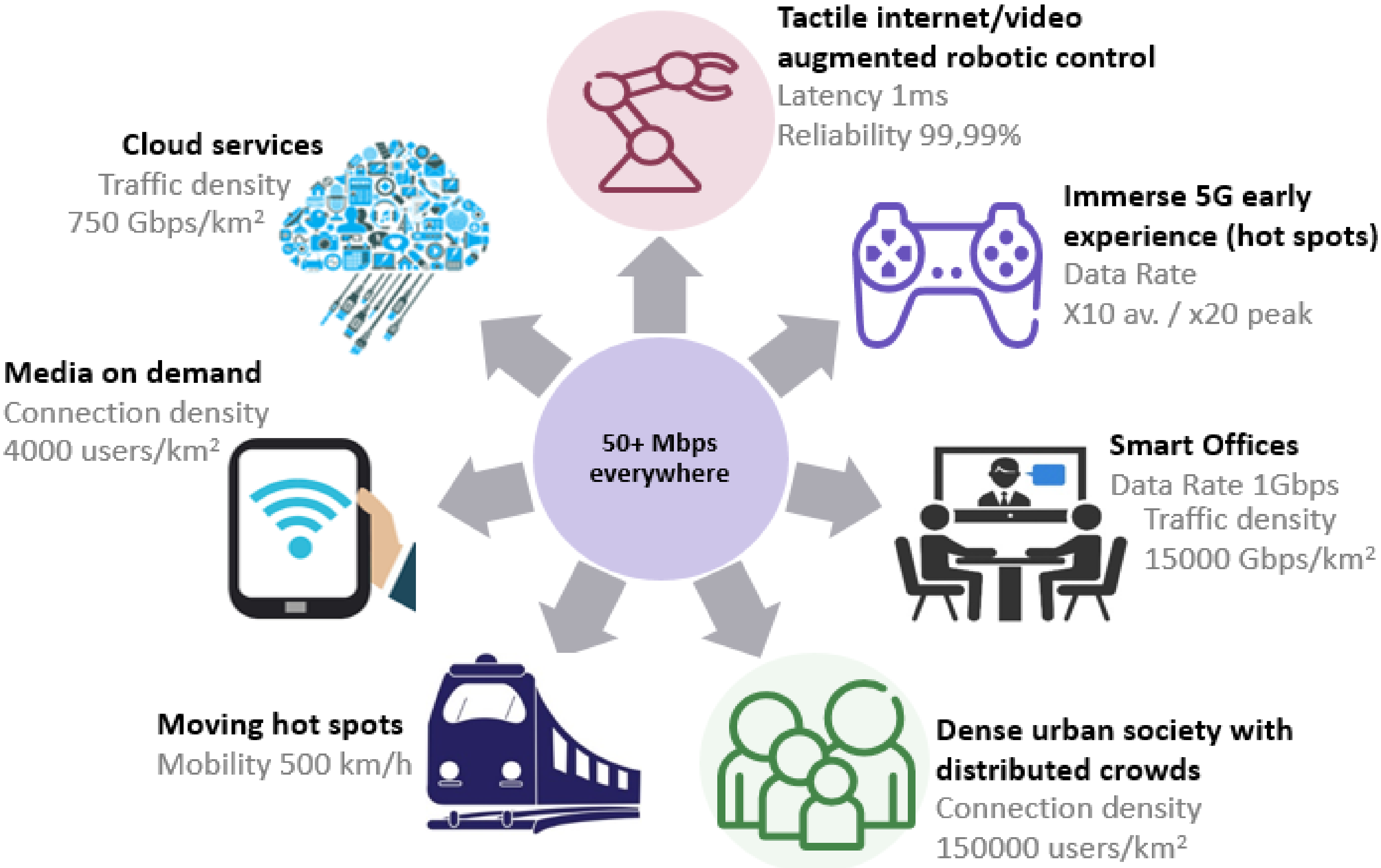
# Project Objectives and Expected Outcome

- **Investigate** suitable frequency ranges (6-100 GHz) for extremely high capacity mobile broadband services
  - **Standards-ready** mobile radio interface operating in mm-wave frequencies (6-100 GHz), paving the way for a European head-start in 5G standards, including 3GPP and ITU-R
- **Conduct** measurements and develop accurate channel models for identified candidate frequency ranges
  - **Comprehensive** mm-wave channel models suited for regulatory and standards fora usage, ITU-R working groups and 3GPP
- **Develop** novel mobile radio access technologies for 5G systems in frequency above 6 GHz
- **Demonstrate** feasibility of the developed concepts
  - **Demonstrator** including advanced visualization of mm-wave based mobile broadband systems operating in **real-life** service provisioning scenarios & **hardware-in-the-loop** demonstrations
- **Interface/collaborate** with other 5G PPP projects, towards achieving a common set of 5G PPP KPIs
  - **Inputs** to the EC/5G-PPP Infrastructure Association in preparation of WRC 18/19 and contributing to the ITU-R evaluation work on IMT above 6 GHz

# Objectives and Features



# 8 Use Cases in mmMAGIC



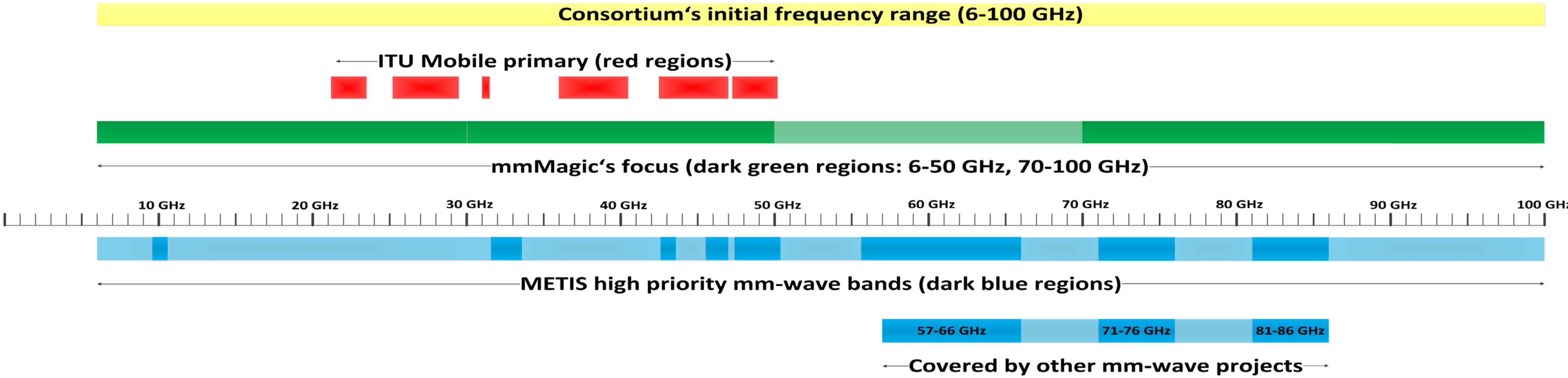

mmMAGIC

https://bscw.5g-mmmagic.eu/pub/bscw.cgi/d54427/mmMAGIC_D1.1.pdf

# Advantages of mm-waves for Selected Use Cases

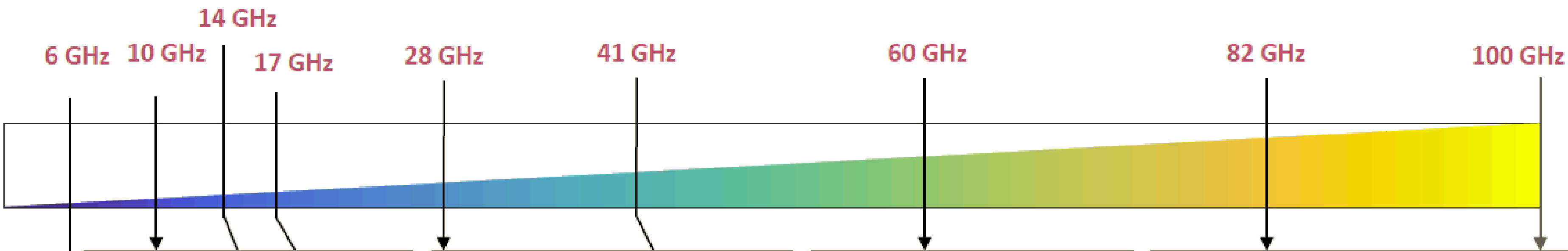
- Possibility to find wide contiguous bandwidth => potentially high data rate and low latency
- The high directionality of antennas needed for mmWave transmissions causes less interference to other systems
- Unfavourable propagation characteristics allows dense frequency reuse

# Spectrum Considerations




- The analysis was conducted in the first instance to the 6-50 GHz frequency range, where mobile allocations already exists, and to the 70 - 100 GHz frequency range
- Factors included in the selection of the most suitable frequency bands for mm-wave communications
  - available technology hardware components
  - presence of incumbent systems and possible interference-mitigation techniques
  - potential for global harmonization
  - available and required contiguous bandwidth
  - transmit power, antenna characteristic and beamforming options
  - existing mobile-communication services
  - sharing and coexisting possibilities with other radio technologies and services,
  - …

# mmMAGIC Measurement Bands and Scenarios




**BW: 150 MHz @ 5.8 GHz**
1) Street canyon (EAB)
2) O2I (EAB)
3) Office (EAB)

**BW: 125 MHz @ 10 GHz, 700 MHz @ 10.25 GHz**
1) Street canyon (HHI, Orange)
2) Open square (Orange)
3) O2I (HHI, Orange)
4) Office (HHI)
5) Shopping mall (HHI)
6) Airport (HHI)
7) Stadium° (HHI, optional)
8) Metro (HHI)

**BW: 500 MHz @ 14.25 GHz, 200 MHz @ 14.8 GHz**
1) Street canyon (Aalto, EAB)
2) Open square (Aalto)
3) O2I (EAB)
4) Office (EAB)
5) Airport (Aalto)

**BW: 125 MHz @ 17 GHz**
1) Street canyon (Orange)
2) Open square (Orange)
3) O2I (Orange)

**BW: 900 MHz @ 27.45 GHz, 500 MHZ @ 28 GHz, 2 GHz @ 28.5 GHz**
1) Street canyon (HHI, Aalto, EAB)
2) Open square (Aalto)
3) O2I (HHI, EAB)
4) Office (EAB, CEA, HHI)
5) Shopping mall (HHI)
6) Airport (HHI, Aalto)
7) Subway (HHI, Aalto)
8) Stadium° (HHI)
9) Metro (HHI)

**BW: 2 GHz @ 41.5 GHz**
1) Street canyon (HHI)
2) O2I (HHI)
3) Office (HHI)
4) Shopping mall (HHI)
5) Airport (HHI)
6) Stadium° (HHI)
7) Metro (HHI)

**BW: 2-4 GHz @ 60 GHz**
1) Street canyon (EAB, Aalto)
2) Open square (UoB, Orange, Aalto)
3) O2I (EAB)
4) Office (UoB, EAB, CEA)
5) Shopping mall (UoB)
6) Airport (Aalto)

**BW: 2 GHz @ 82.5 GHz (100 GHz)**
1) Street canyon (HHI, Aalto)
2) Open square (Aalto, UoB)
3) O2I (HHI)
4) Office (HHI: 82.5/100 GHz, CEA, UoB)
5) Shopping mall (HHI: 82.5/100 GHz, UOB)
6) Airport (HHI: 82.5/100 GHz)
7) Stadium° (HHI, 82.5/100 GHz)
8) Metro (HHI: 82.5/100 GHz)

QuaDRiGa SW
http://quadriga-channel-model.de/

° Optional scenario

mmMAGIC

# Need of Suitable HW Impairment Models

Behavioral/statistical models at various investigation levels

- Power amplifiers (HPA, LNA)
- Phase noise
- I/Q Imbalance
- A/D, D/A converters
- Phase shifters
- Antenna models

Effective models after Compensation techniques

| | Needs /Abstraction level | | |
|---|---|---|---|
| RF/HW Impairment | **Waveforms (WP4) / behav. Physical models** | **TRX Architectures (WP5)/ behav. & stat. models** | **System Simulation (WP3)/ stat. models ; tables & black box** |
| Power Amplifier | Behavioral models, e.g. Volterra Series (1) | Behavioral and statistical models, e.g. Bussgang, Possibly on symbol-level: SISO-models (1) MIMO models (2) | Statistical model, SINR-table (0) |
| Phase noise | Multiplicative phasor with phase as filtered noise -based on literature. Basic models (1) | Impact of LO distribtion method (3) | SINR table. |
| | Adaptation of coefficients to SOTA mmWave local oscillators (2) –and Matlab implementation of the model (3) | | |
| | | Additive noise –waveform dependent. Known for OFDM SISO (1). Adaptation to new waveforms, SOTA local oscillators and MIMO needs (2) | . |
| I/Q Imbalance | Behavioral models (1) | Behavioral models (1) | Add noise (0) |
| A/D, D/A | Behavioral model: white noise model (1) | Behavioral model: white noise model (1) | Additive noise (0) |
| Phase-Shifters | Behavioral model (0) | Behavioral model (0) | Add noise (0) |
| Antennas | Large array wideband radiation patterns, efficiency, beamforming (2) | Large array wideband radiation patterns, efficiency, beamforming (2) Large array S-parameters (2) | |
| Channel | Raw data and or geometric stochastic models (3) | Raw data and or geometric stochastic models (3) | Stochastic models (3) |

# *Need for Evolved Hardware Impairment Models*

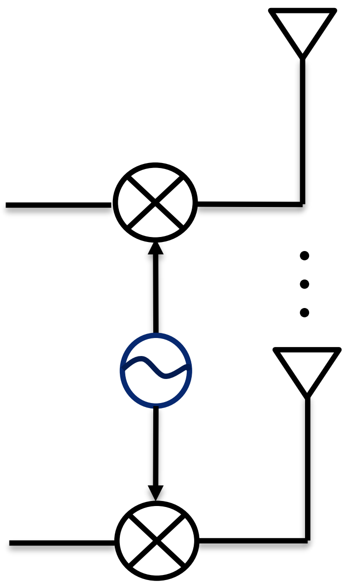
(0) Not available
(1) Existent
(2) Extension in mmMagic
(3) mmMagic contribution

https://bscw.5g-mmmagic.eu/pub/bscw.cgi/d95056/mmMAGIC_D5_1.pdf

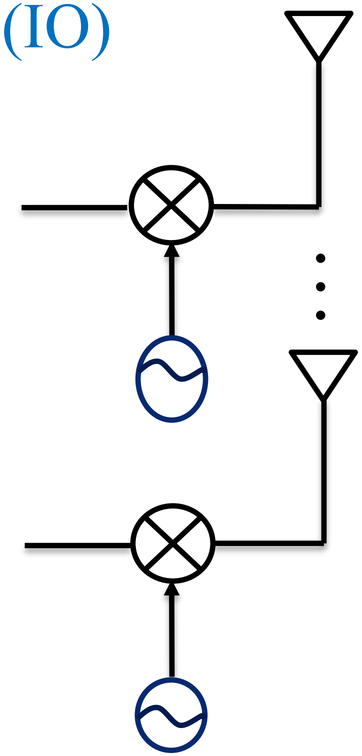
# Impact of non-ideal oscillators

Phase noise effects for two alternative oscillator implementations

## Common oscillator (CO)



## Independent oscillators (IO)

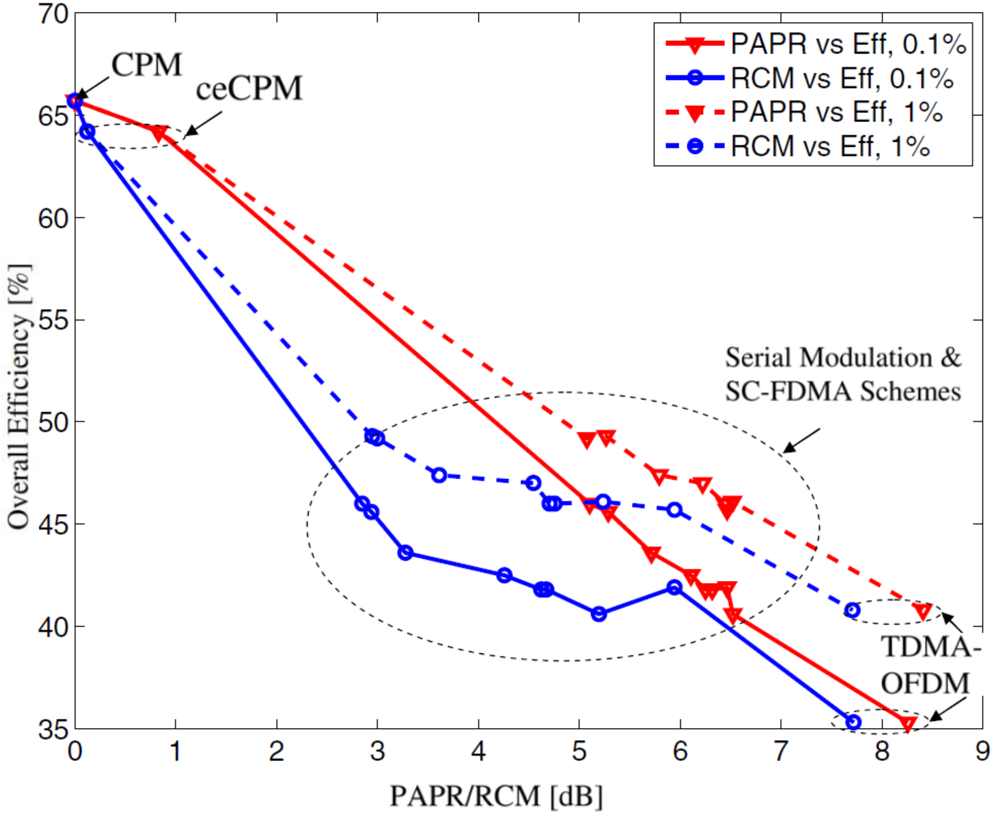


- Tx PN and Rx PN of CO have the same inter-carrier interference (ICI) influence on beamforming MIMO-OFDM.
- Tx PN and Rx PN of IO can have different influences depending on the number of Tx and Rx antennas.
- PN of IO can be alliviated by having more antennas. That is not the case for CO.
- It is easier to track the CO PN. Hence, with effective PN mitigation, the CO case outperforms the IO case.

*X. Chen, F. Chao, Y. Zou, A. Wolfgang, T. Svensson, "Beamforming MIMO-OFDM Systems in the Presence of Phase Noises in Millimeter-Wave Frequencies", IEEE WCNC'2017 mmMAGIC workshop, Mar 2017, San Francisco, USA.*

# High Power Amplifier (HPA) Overall Efficiency vs Envelope Metrics

- Maximum overall efficiency vs mean PAPR and Raw Cubic Metric with 1% and 0.1% clipping level




$$\eta_A = \frac{P_{Out}}{P_{DC} + P_{In}}$$

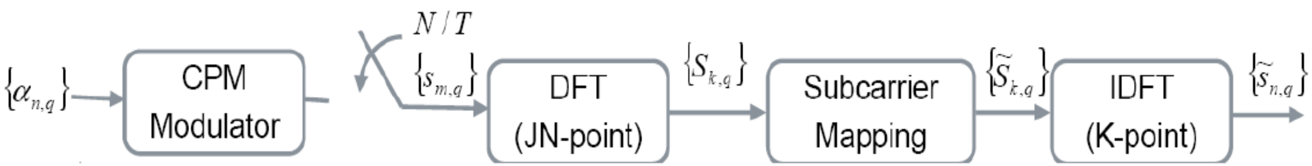
- $P_{In}$: RF power at the input of the HPA
- $P_{Out}$: resulting RF output power
- $P_{DC}$: power at the DC input of the amplifier, $P_{DC} = V_{DC} \cdot I_{DC}$.

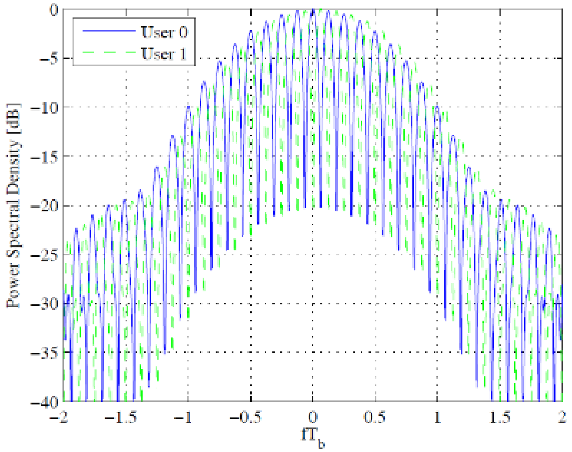
- HPA overall efficiency increases monotonically with decreasing Peak-to-Average-Power Ratio (PAPR) and Raw Cubic Metric (RCM)
- Constant (CPM) and constrained envelope (ceCPM) modulation schemes are substantially more efficient compared to OFDM, with serial modulation schemes in between.
- However, end-to-end energy efficiency might still not be better, due to more compact signal space (open question).

- Low PAPR enables low cost HPAs
- High HPA efficiency implies low heat dissipation enabling tight integration in transceiver in small form factor without cooling

*T. Svensson, T. Eriksson, "On Power Amplifier Efficiency with Modulated Signals", VTC2010-Spring, May 2010, Taipei, Taiwan*

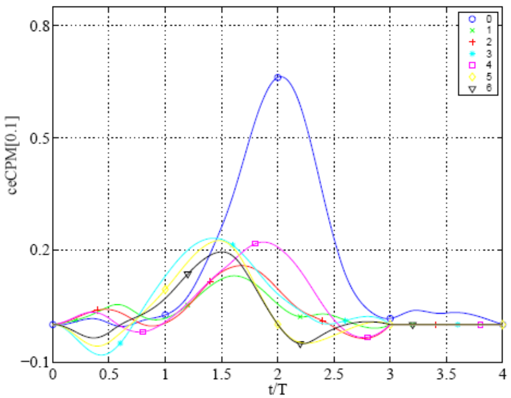
# Low PAPR wideband spread frequency interleaved waveform: Continuous Phase Modulation based Precoding of SC-FDMA (CPM-SC-FDMA)

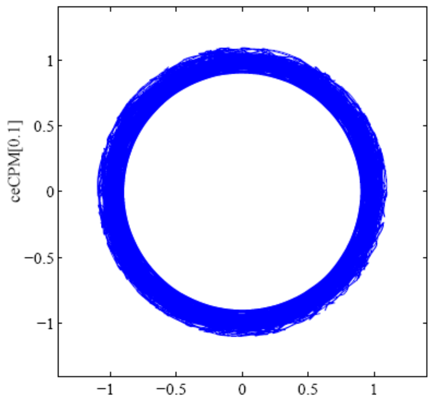


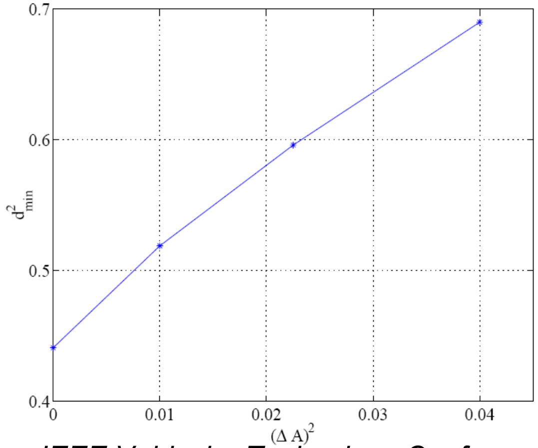




*M.P. Wylie-Green, E. Perrins, T. Svensson,"Introduction to CPM-SC-FDMA: A Novel Multiple-Access Power-Efficient Transmission Scheme," Communications, IEEE Transactions on , vol.59, no.7, pp.1904-1915, July 2011*

# Low PAPR narrowband: Constrained Envelope Continuous Phase Modulation (ceCPM)

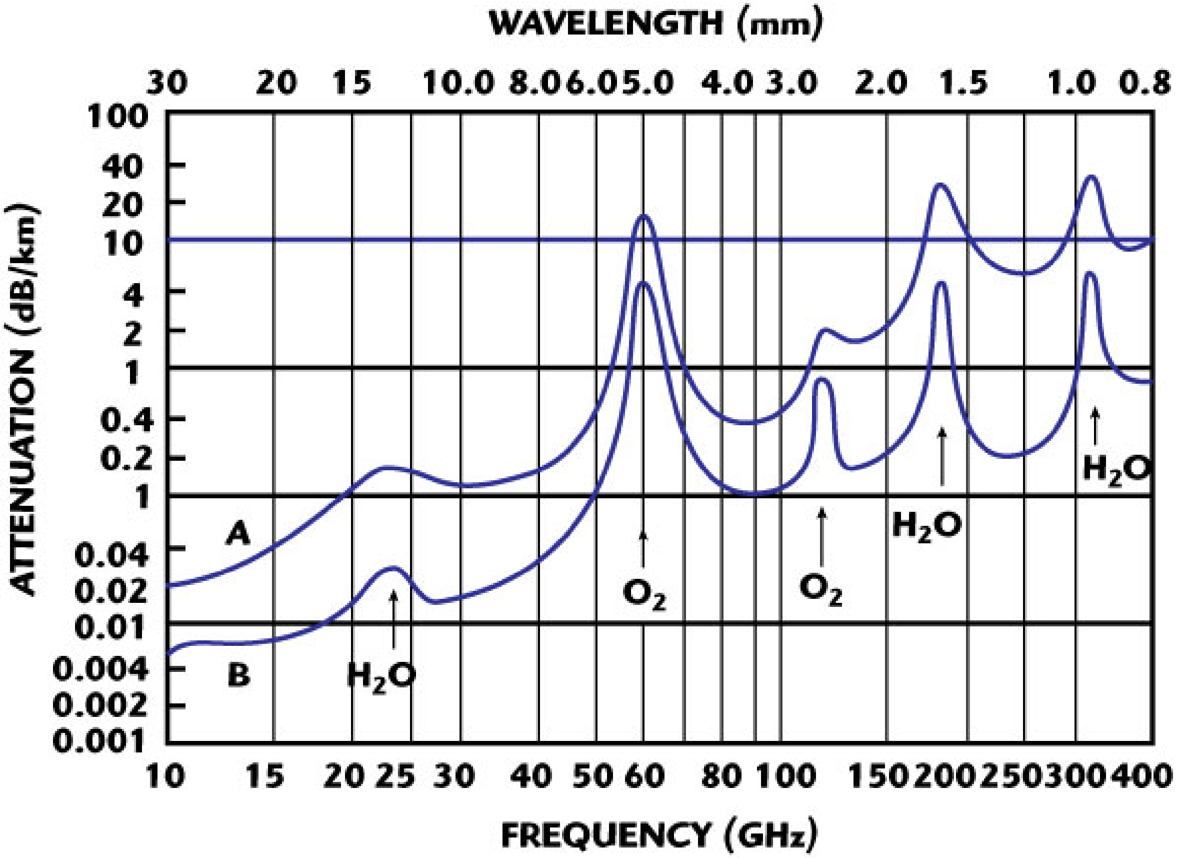



*T. Svensson and A. Svensson, “Constrained envelope continuous phase modulation,” in Proc. IEEE Vehicular Technology Conference, vol. 4, Jeju, Korea, 2003, pp. 2623–2627.*
*T. Svensson, A. Svensson, “Design and Performance of Constrained Envelope Continuous Phase Modulation”, (Invited paper). Proceedings IEEE 4th International Waveform Diversity and Design Conference, Feb 2009, Orlando, Florida.*

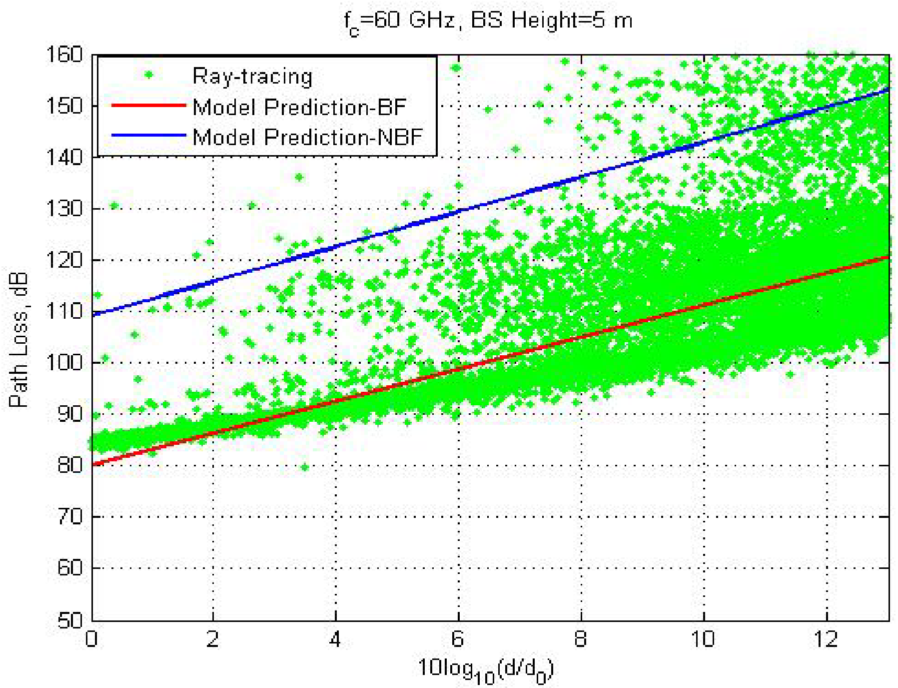
# Attenuation at mm-wave Frequencies



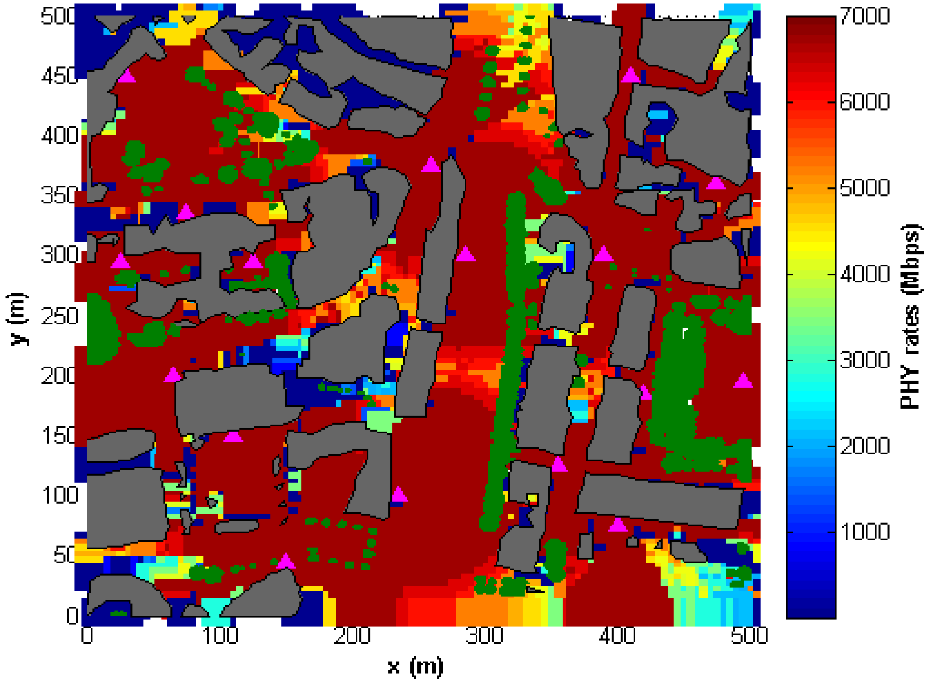

Average atmospheric absorption of MMWs: (A) Sea Level: T = 20°C, P = 760mm, $H_2O$ = 7.5 g/m³ (B) 4 km altitude: T = 0°C $H_2O$ = 1 g/m³

*Source: Microwave Journal: http://www.microwavejournal.com/legacy_assets/FigureImg/AR_4772_Fig02_L.jpg*

# Coverage and Throughput Prediction at 60 GHz mm-wave using Ray Tracing



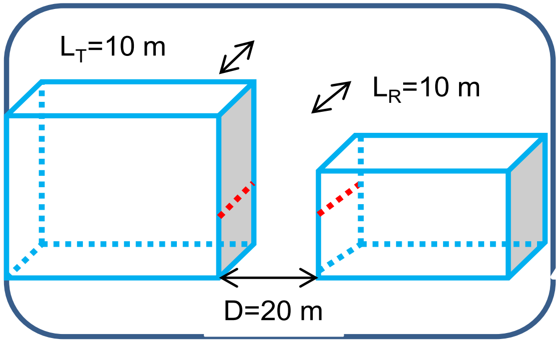

Path-loss with respect to distance for mm-wave outdoor system



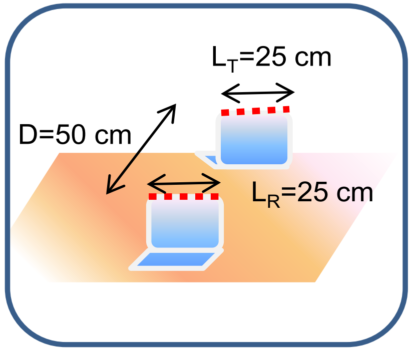

Throughput estimation using 17 BSs [ABA+15].

- *D5.1 "Initial multi-node and antenna transmitter and receiver architectures and schemes" March 2016, https://5g-mmmagic.eu*
- *[ABA+15]: Abdullah, N.F.; Berraki, D.; Ameen, A.; Armour, S.; Doufexi, A.; Nix, A.; Beach, M., "Channel Parameters and Throughput Predictions for mmWave and LTE-A Networks in Urban Environments," inVehicular Technology Conference (VTC Spring), 2015 IEEE 81st , vol., no., pp.1-5, 11-14 May 2015*

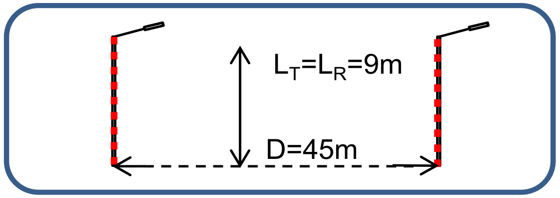
# Massive MIMO at Both Tx, Rx (MMIMMO)



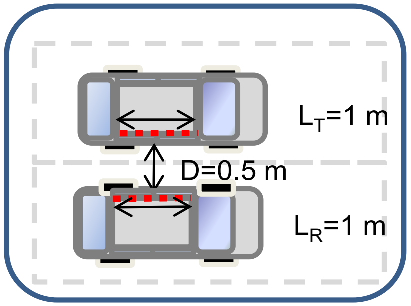

scenario 1: communicating buildings, **N=512, f=30.72GHz**



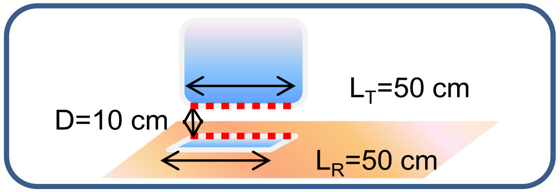

scenario 3: communicating laptops, **N=32, f=76.8GHz**




scenario 2: communicating lamp posts (these are heights and separations in France), **N=256, f=42.7GHz**




scenario 4: side-to-side communicating cars (non moving), **N=256, f=38.4GHz**




scenario 5: communicating laptop-screen, **N=512, f=61.4GHz**

Legend:

Uniform linear antenna array

## Friis transmission equation

transmit power

wavelength

$$P_{RX} = P_{TX} G_{TX} G_{RX} \left(\frac{\lambda}{4\pi r}\right)^2$$

received power

gain of transmit and receive antennas

separation distance

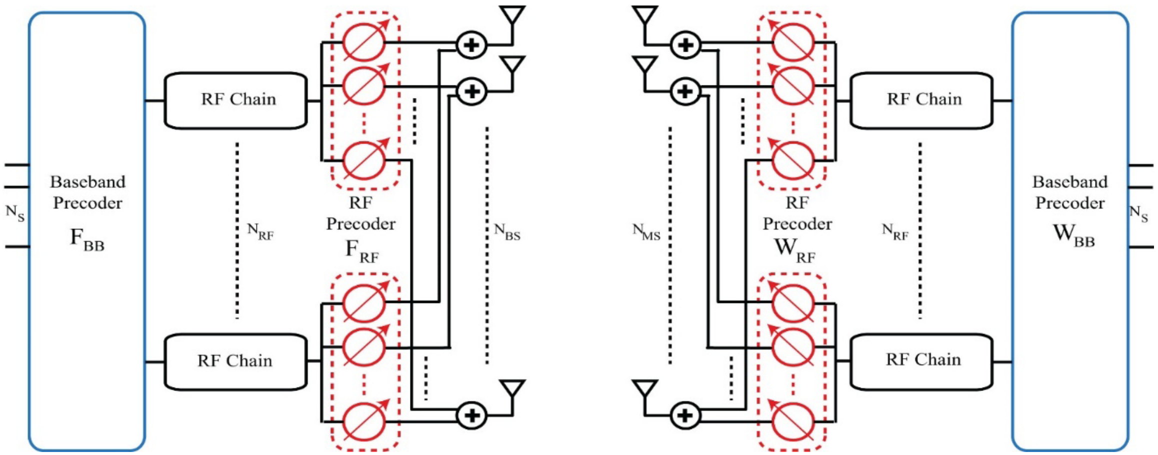
"Free space path loss"

Hundreds of bits/s/Hz possible using "Block Discrete Fourier TransForm based Spatial Multiplexing with Maximum Ratio Transmission" (B-DFT-SM-MRT)

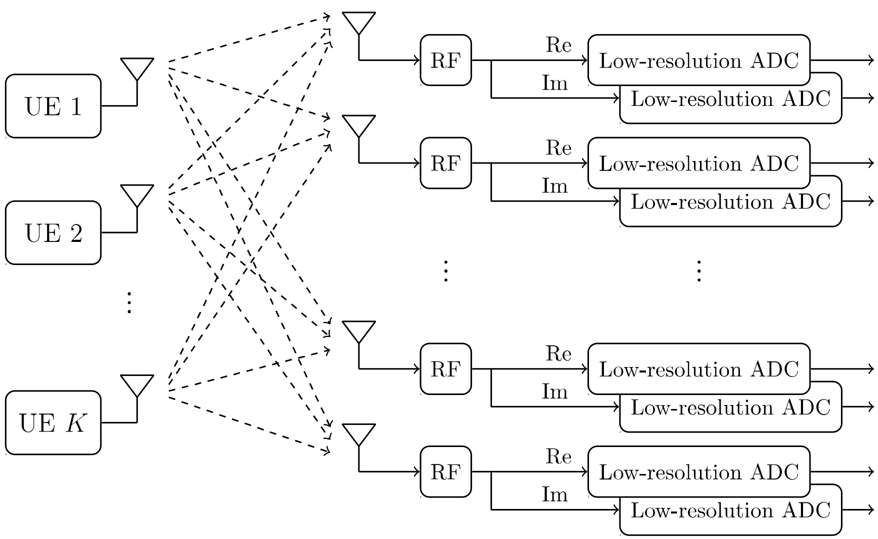
*D.-T. Phan-Huy, P. Ratajczak, R. D'Errico, A. Clemente, J. Järveläinen, D. Kong, K. Haneda, B. Bulut, A. Karttunen, M. Beach, E. Mellios, M. Castaneda, M. Hunukumbure, T. Svensson, "Massive Multiple Input Massive Multiple Output for 5G Wireless Backhauling", IEEE Globecom'2017 ET5GB workshop.*

*Source: D5.1 "Initial multi-node and antenna transmitter and receiver architectures and schemes" March 2016, https://5g-mmmagic.eu*

# Hybrid and Low-precision Beamforming for Massive MIMO




© O. El Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. Heath, “Spatially sparse precoding in millimeter wave MIMO systems,” IEEE Transactions on Wireless Communications, vol. 13, no. 3, pp. 1499–1513, March 2014

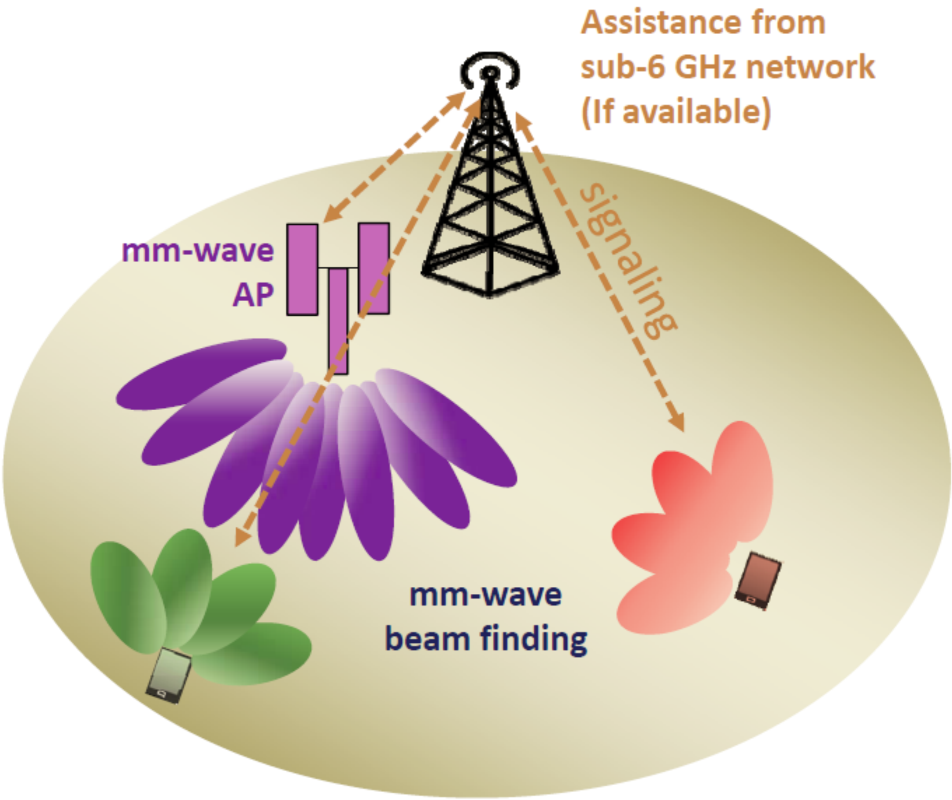



***Low resolution DACs also at transmitter?***
***Might increase uncontrolled interference!***

*© C. Studer and G. Durisi, “Quantized massive MU-MIMO-OFDM uplink,” Sep. 2015. [Online]. Available: http://arxiv.org/abs/1509.07928*

# Initial Access and Beam Tracking

- **Design KPI's**
  - Access delay
  - Access ratio
  - Overhead
  - Complexity
  - Availability and accuracy of context information
  - Standalone/non-standalone operations support
  - Antenna configurations support




- Exploit sub-6 GHz coverage
- Exploit contexual information
- Coupling beamforming and initial access
- Support different transceiver/antenna configurations

*Source: mmMAGIC WP4 presentation, ETSI workshop, Sophia-Antipolis, Jan 28, 2016*

***Beam finding/tracking – the key for enabling low latency mm-wave access!***

# Initial Access (IA) Phases

Initial Access (IA) Phase at mm-wave frequencies [1]:

**Cell Discovery (Beam Sweeping)**

- Broadcast signaling
  - The AP transmits synchronization signals and cell-related information
- Directional antennas for achieveing sufficient link margin
  - Beam sweeping required for coverage

**Random Access and Resource Allocation (Beam Alignment)**

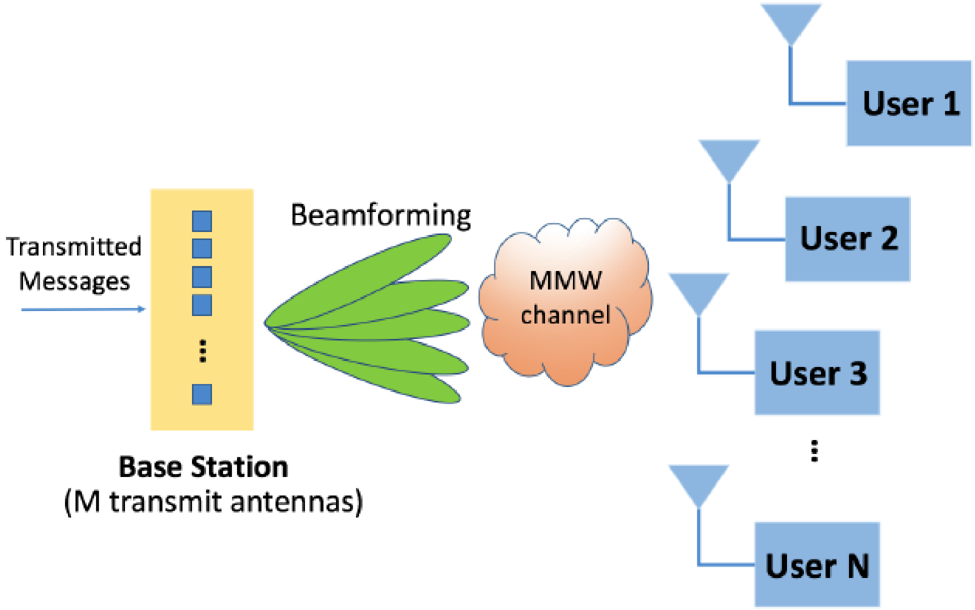
- Contention-based access
  - The UE transmits a preamble over the shared random access channel
- Beam alignment
  - AP and UE find suitable transmit/receive directions
- Time, frequency, and spatial resources are allocated for the UE

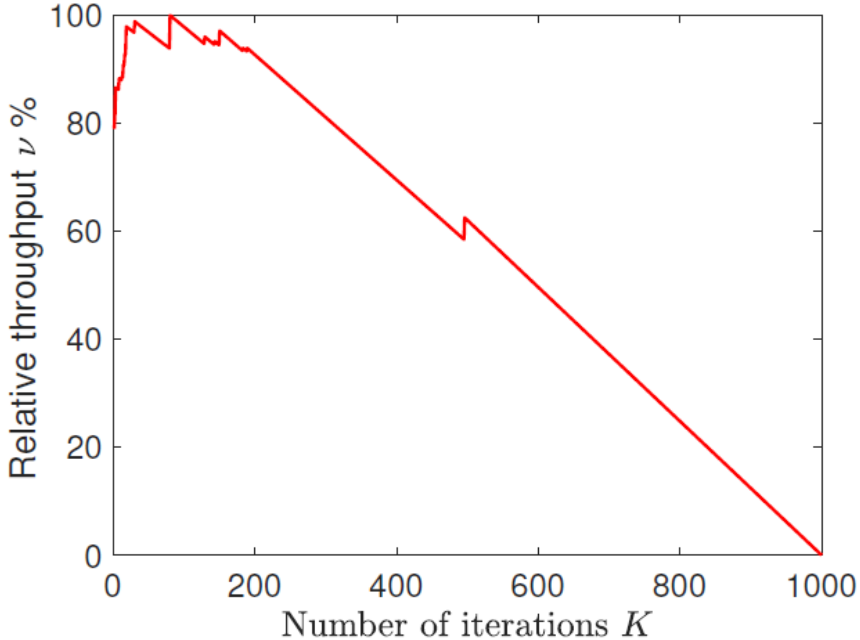
**Beam Refinement and Tracking for Mobility Management**

- Beam refinement
  - Further AP/UE beam alignment for rate maximization
- Beam tracking
  - AP and UE beams need to be rapidly updated due to channel variations (user mobility)

[1] “mmMagic Project D4.2, Final radio interface concepts and evaluations for mm-wave mobile communications.” [Online]. Available: https://bscw.5g-mmmagic.eu/pub/bscw.cgi/d214055/mmMAGIC_D4.2.pdf

# Illustrative Initial Access Result

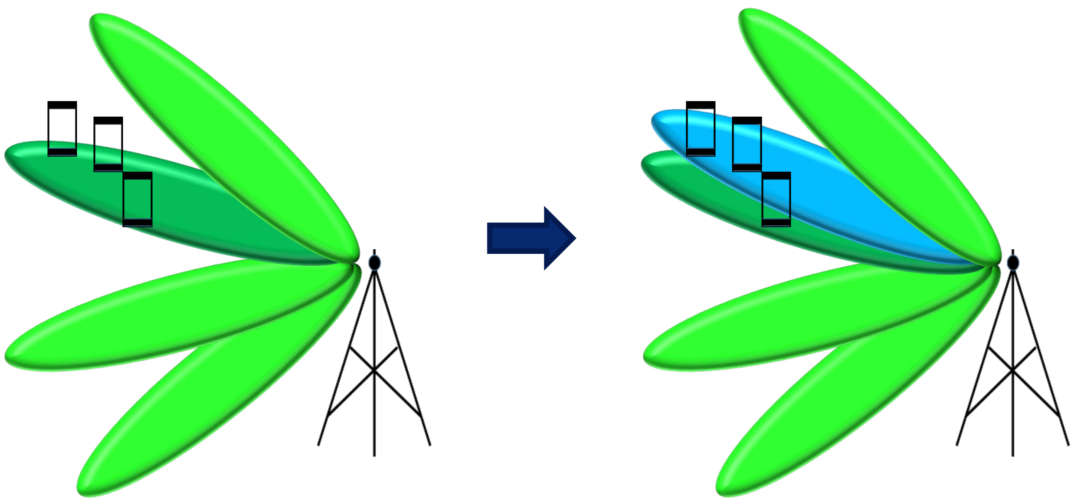




(a) System performance with delay ($\alpha = 0.001$)

*H. Guo, B. Makki, T. Svensson, "A Genetic Algorithm-based Beamforming Approach for Delay-constrained Networks", IEEE WiOpt'2017, May 2017.*

*H. Guo, B. Makki, T. Svensson, "A Comparison of Beam Refinement Algorithms for Millimeter Wave Initial Access",PIMRC'2017 workshops. Montreal, Canada, Oct 2017.*

# Genetic Algorithm (GA)-based Search

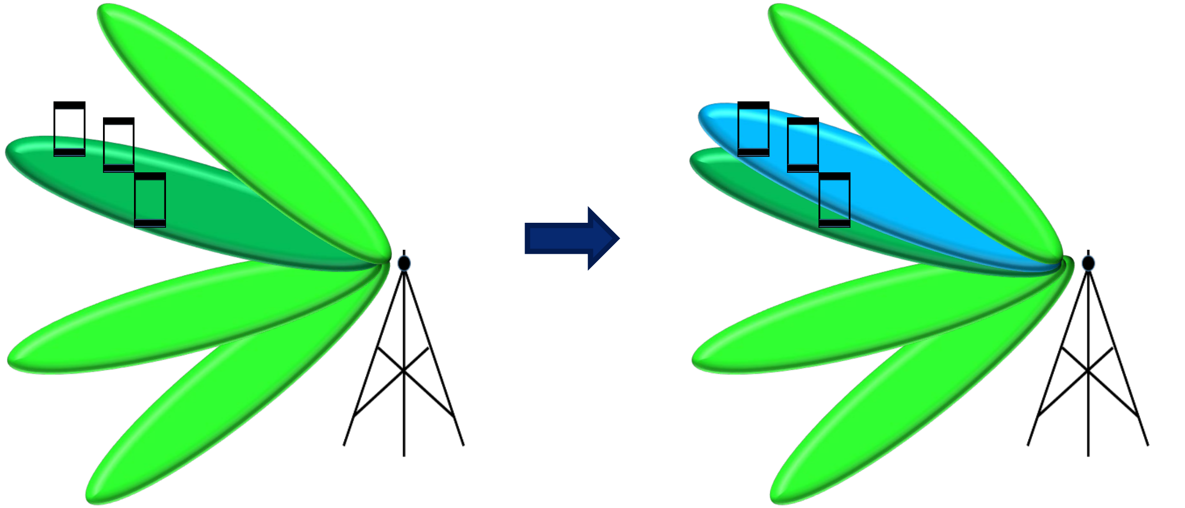


Step 1 Find the Queen.

Step 2 Adjust the Queen by making small changes to the queen/replacing random columns.

B. Makki, T. Svensson, G. Cocco, T. de Cola, and S. Erl, "On the throughput of the return-link multi-beam satellite systems using genetic algorithm-based schedulers," in Proc. IEEE ICC'2015, London, UK, Jun. 2015, pp. 838–843.

# Tabu Search

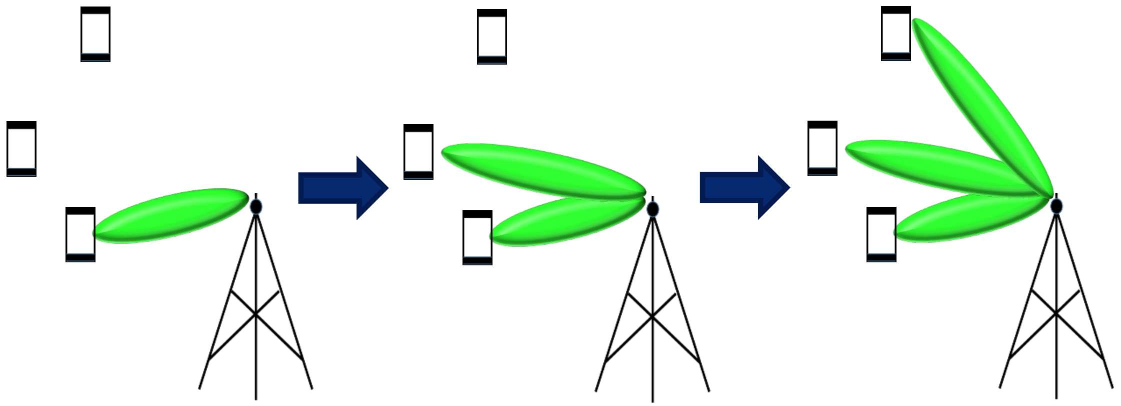


Step 1 Find the Queen.

Step 2 Adjust the Queen by changing columns to their neighbors.

X. Gao, L. Dai, C. Yuen, and Z. Wang, "Turbo-like beamforming based on tabu search algorithm for millimeter-wave massive mimo systems," IEEE Trans. Veh. Technol, vol. 65, no. 7, pp. 5731–5737, Jul. 2016.

# Link-by-link Search



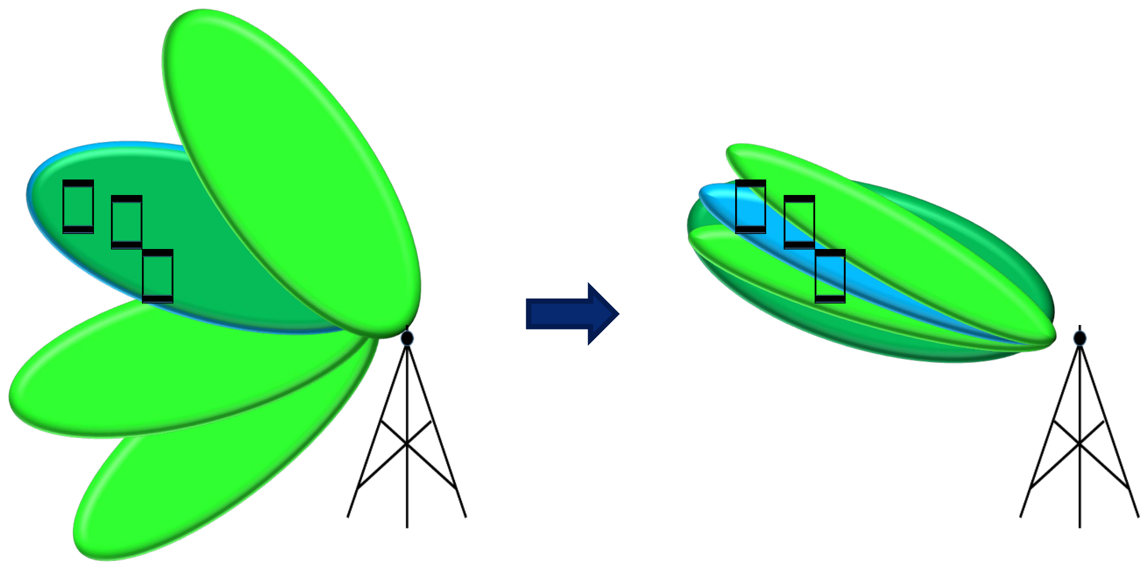
Step 1 BF for user 1.

Step 2 BF for user 2 (with interference from user 1).

Step 3 BF for user 3 (with interference from user 1 and user 2).

J. Qiao, X. Shen, J. W. Mark, and Y. He, "MAC-layer concurrent beamforming protocol for indoor millimeter-wave networks," IEEE Trans. Veh. Technol, vol. 64, no. 1, pp. 327–338, Jan. 2015.

# Two-level Search

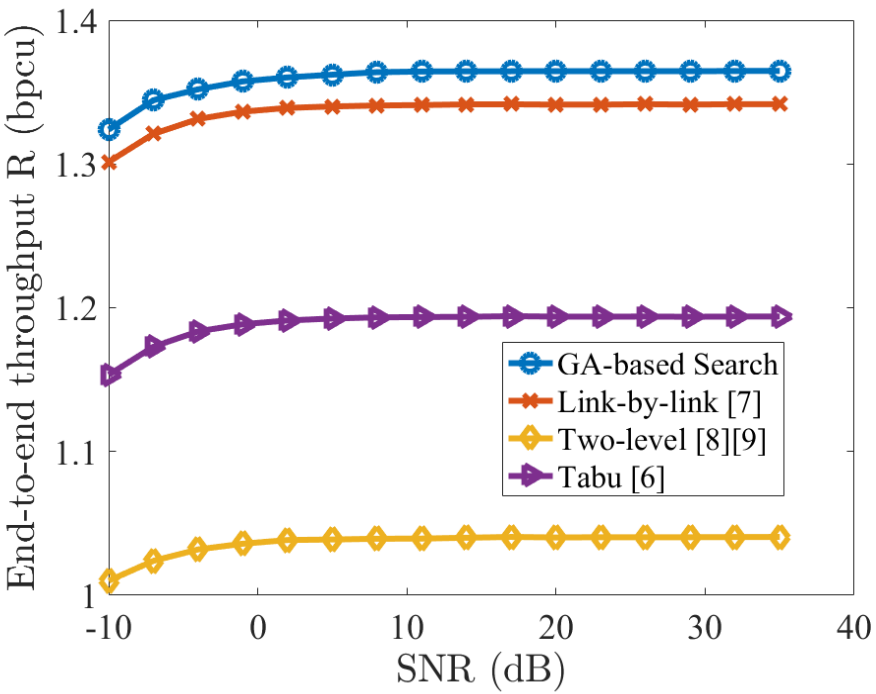


Step 1 Find the Queen roughly by wide beams in the first-level codebook.

Step 2 Steer to narrow beams by the second-level codebook.

S. Hur, T. Kim, D. J. Love, J. V. Krogmeier, T. A. Thomas, and A. Ghosh, "Multilevel millimeter wave beamforming for wireless backhaul," in Proc. IEEE GLOBECOM'2011, Houston, Texas, USA, Dec. 2011, pp. 253–257.
L. Chen, Y. Yang, X. Chen, and W. Wang, "Multi-stage beamforming codebook for 60GHz wpan," in Proc IEEE ICST'2011, Harbin, China, Aug. 2011, pp. 361–365.

# Simulation Results




| M \| N | GA | Tabu | Link-by-link | Two-level |
|---|---|---|---|---|
| 32 \|12 | 502 | 498 | 307 | 501 |
| 32 \| 8 | 500 | 501 | 288 | 498 |
| 32 \| 4 | 488 | 502 | 261 | 500 |

- Comparison of the considered schemes in terms of $R$. $M$ = 32, $\tau$ = 4, $N$ = 12, $k$ = 0, $d$ = $1$, $\theta$ = -4 dB. Collaborative users.
- The GA method outperforms the state-of-the art schemes.
- The average numbers of required iterations are insensitive to $M$ and $N$. Link-by-link search has the lowest complexity.

H. Guo, B. Makki, and T. Svensson, “A comparison of beam refinement algorithms for millimeter wave initial access,” in Proc. IEEEPIMRC’2017 Workshop, Montreal, QC, Canada, Oct 2017, pp. 1–7.

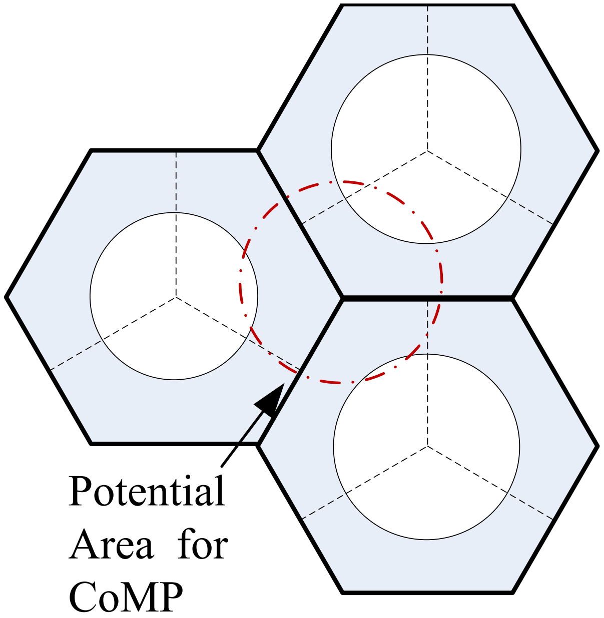
# Revisit: Towards a Framework for Realistic CoMP

## Based on

- Realistic channel knowledge, pilot overhead and feedback rates
- Backhaul awareness
- Application (QoS) aware performance metrics (KPIs)

## Enablers

- Multi-link channel estimation/prediction schemes
- Robust metric-aware beamforming
- Adaptive (user centric) clustering
- Power control and resource allocation
- Inter-cluster interference coordination
- Backhaul limitations awareness
- User grouping and scheme/mode selection
- Dynamic multi-mode CoMP schemes



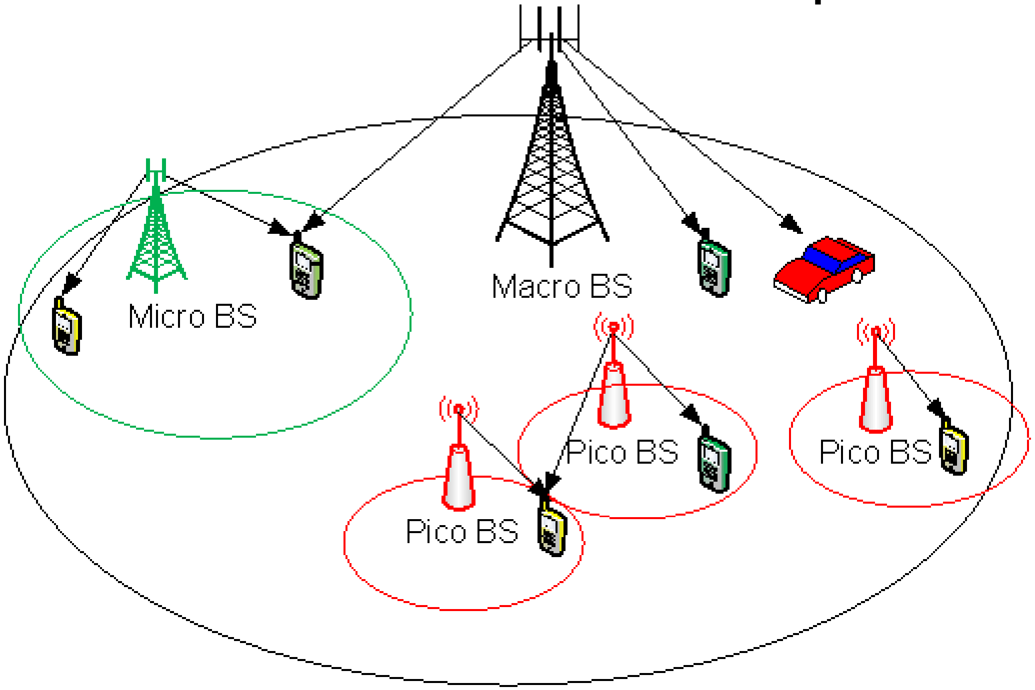

mm-wave: unstructured networks, unreliable backhauling, constrained/imprecise beamforming, smaller cells with more frequent handover, high requirement on energy efficiency…

# Potential of Multi-node Cooperation in mm-wave Systems

- With narrow beamforming mm-wave links, potentially less need for interference coordination(?), but also less knowledge of CSI
- Standalone (Homogeneous)
  - Macro-diversity gains towards shadowing/blocking
  - Power gains: potential EIRP limited
  - Increase multipath and thus (distributed) MIMO rank to better support (distributed) spatial multiplexing and massive MIMO gains at sparse mmWave channels
  - Spider handover
  - Load balancing
- Non-standalone (Heterogeneous macro/mm-wave) adds:
  - Low latency and robust out-of-band control
  - Coverage of mm-wave blind spots
  - Hybrid links for macro-diversity and rain fading diversity
- Integrated design of mm-wave backhaul and access can enable efficient user data delivery for cooperative communications

***To assess the potential, angular dependency and spatial correlation in the channel models are critical.***

# Potential of Multi-node Cooperation in mm-wave Systems



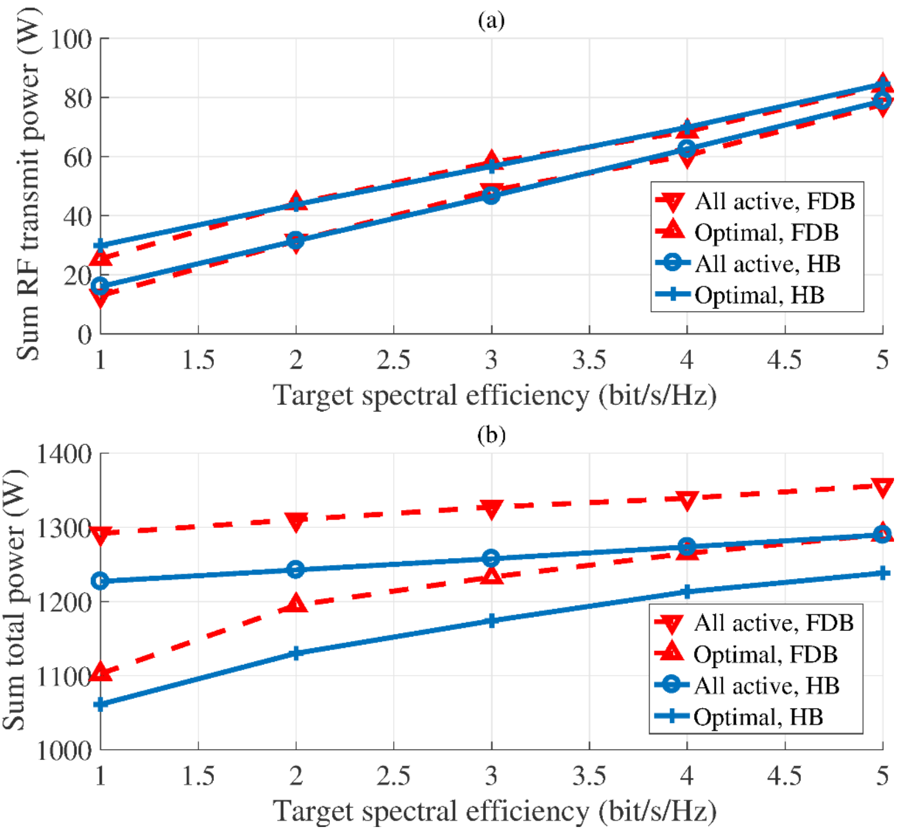

- Standalone mm-wave BSs
- Non-standalone, macro-BS assisted
- Integrated design of mm-wave backhaul and access can enable efficient user data delivery for cooperative communications

**Jointly optimize the precoding, load balancing and BS operation modes for improving the network energy efficiency, using <u>spatial multi-flow</u> => Low CSI exchange needed**

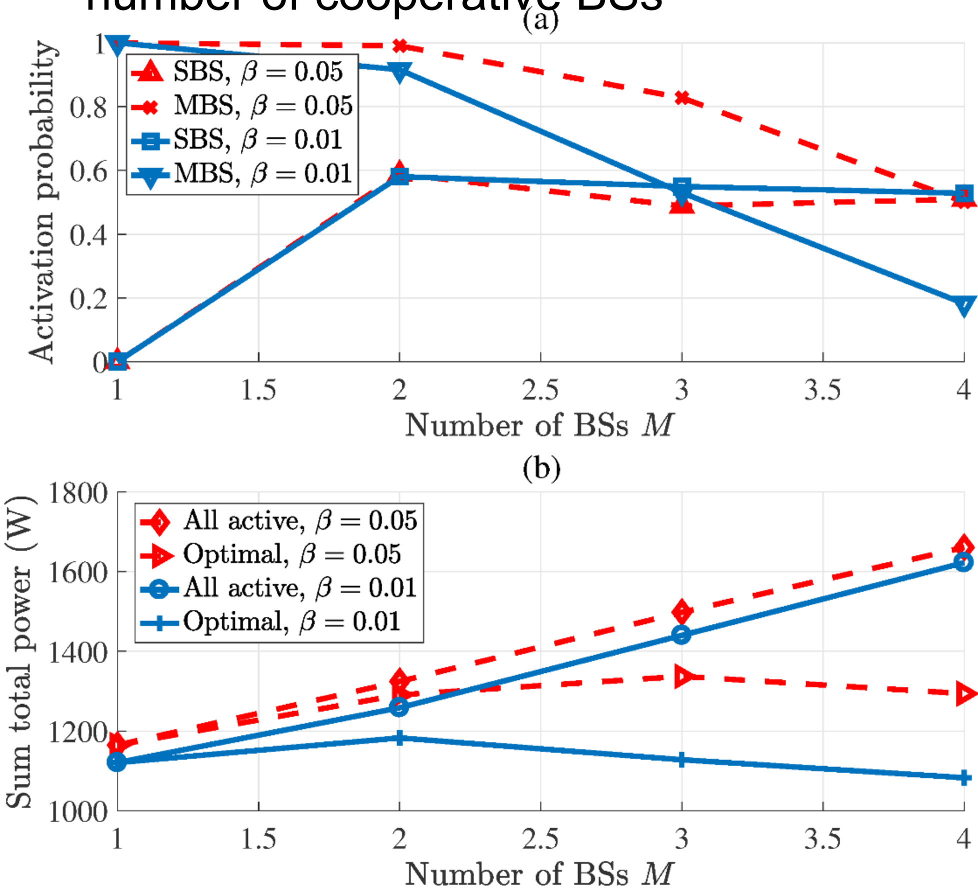

- ***C. Fang, B. Makki, J. Li, T. Svensson, "Coordinated Hybrid Precoding for Energy-efficient Millimeter Wave Systems", SPAWC'2018, Invited paper***
- *J. Li, E. Bjornson, T. Svensson, T. Eriksson, M. Debbah, "Optimal design of energy-efficient HetNets: joint precoding and load balancing," in Communications (ICC), 2015 IEEE International Conference on , vol., no., pp.4664-4669, 8-12 June 2015* ***Best paper award***
- *J. Li, E. Bjornson, T. Svensson, T. Eriksson, M. Debbah, "Joint Precoding and Load Balancing Optimization for Energy-Efficient Heterogeneous Networks," in Wireless Communications, IEEE Transactions on , vol.14, no.10, pp.5810-5822, Oct. 2015*

# Key Findings: Coordinated Hybrid Precoding for Energy-efficient Millimeter Wave Systems

## Sum RF transmit power and sum total power of all BSs

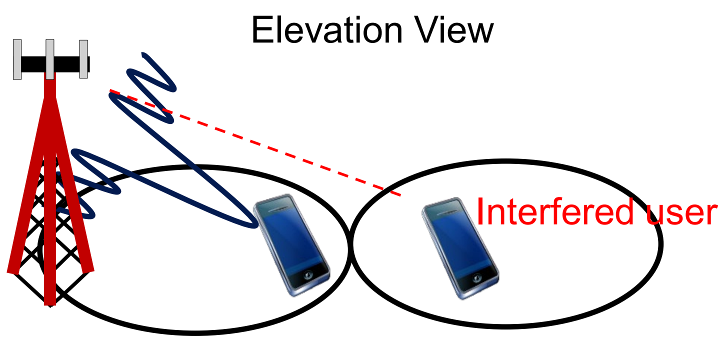



## BS activation probability versus the number of cooperative BSs

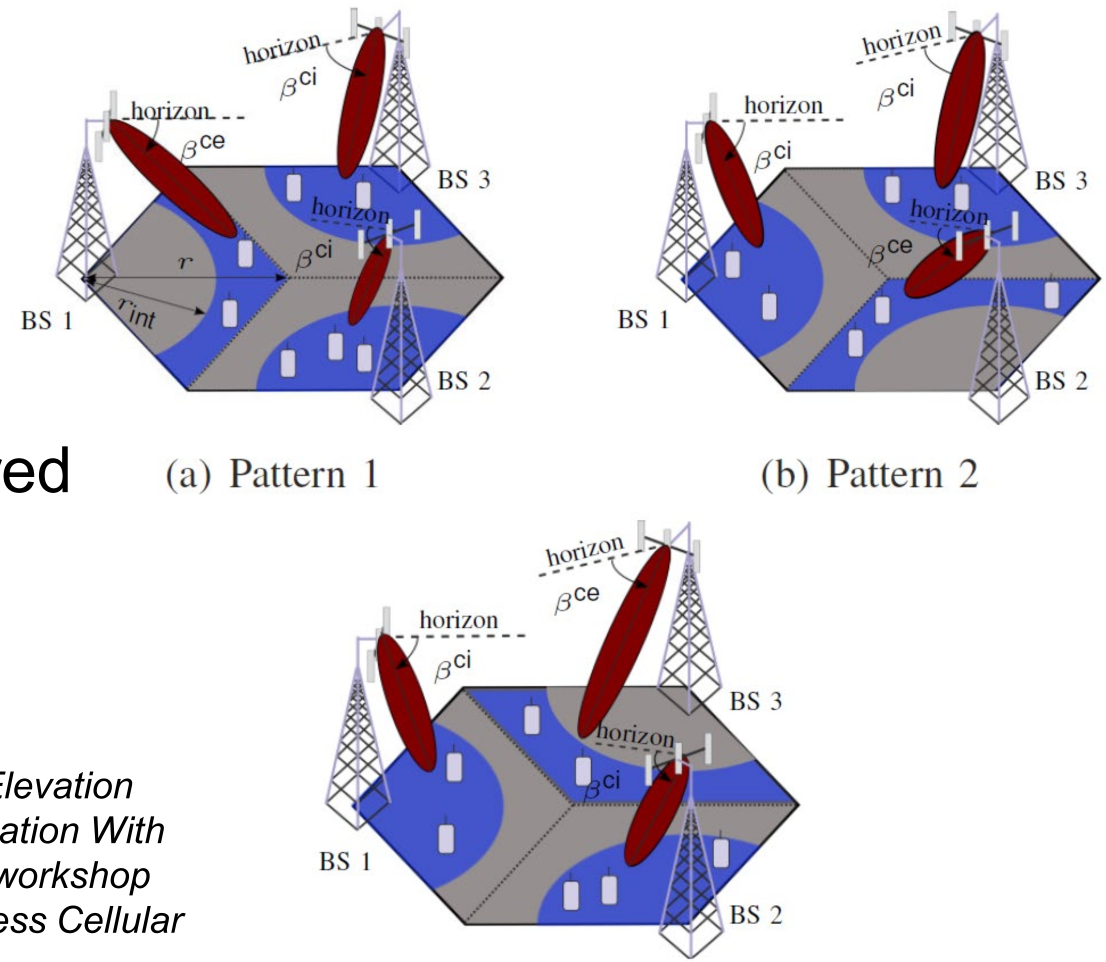



- *C. Fang, B. Makki, J. Li, T. Svensson, "Coordinated Hybrid Precoding for Energy-efficient Millimeter Wave Systems", SPAWC'2018,* ***Invited paper***

# Vertical Coordination



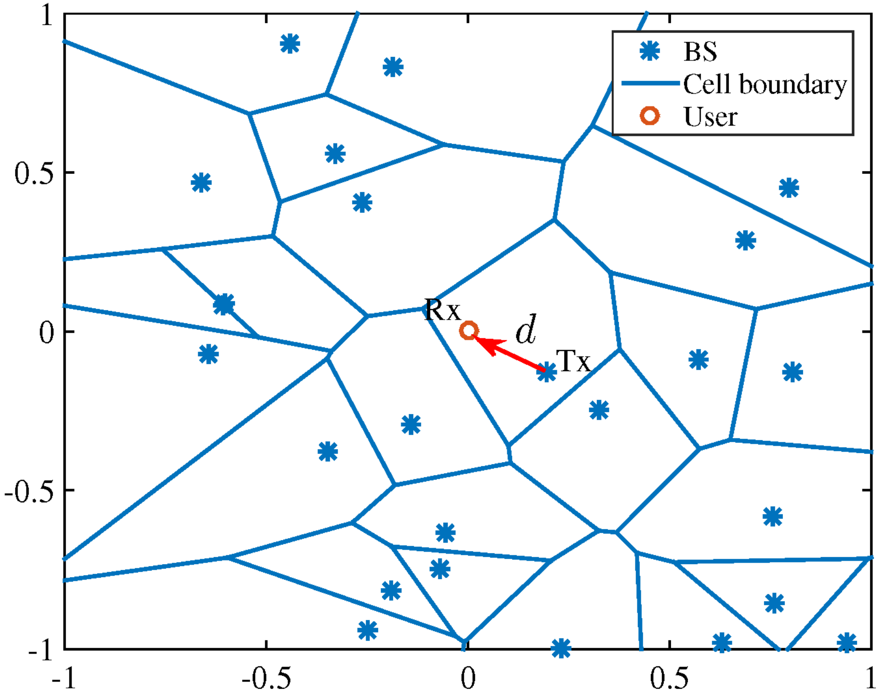

- No CSI exchange required




(a) Pattern 1 (b) Pattern 2 (c) Pattern 3

- *N. Seifi, M. Coldrey and T. Svensson, "Elevation Plane Spatial Multicell Interference Mitigation With no CSI Sharing", IEEE Globecom 2015 workshop on Emerging Technologies for 5G Wireless Cellular Networks, Dec 2015.*

# Analysis of Unstructured Networks



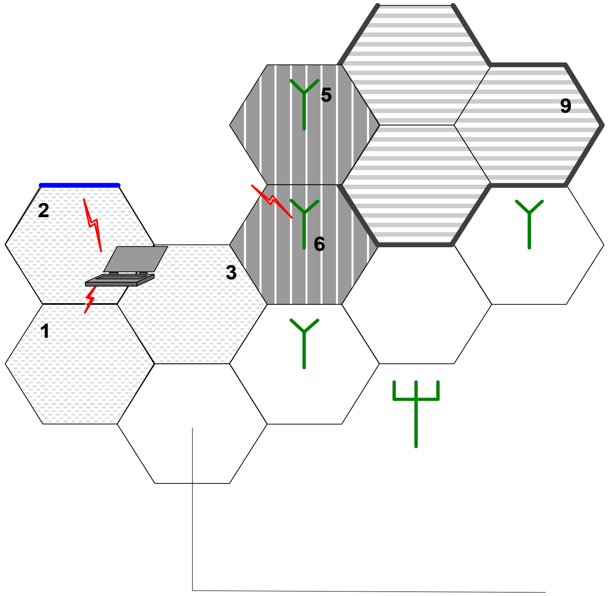

- Transmitter and/or receiver locations are modelled by a homogeneous Poisson point process (PPP) with density λ.
- Network-wide performance metrics can be analyzed
- User-specific performance metrics can also be analysed in case of moving networks

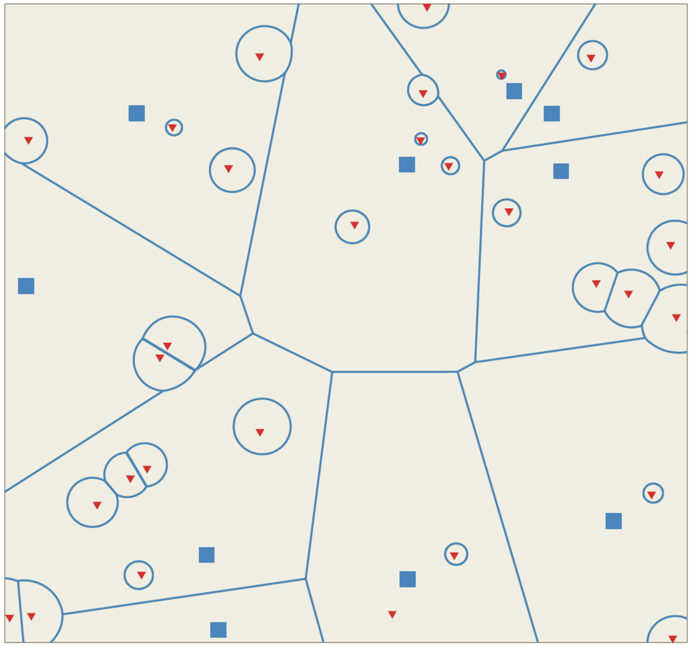
- C. Fang, B. Makki, T. Svensson, "HARQ in Poisson Point Process-based Heterogeneous Networks", IEEE Vehicular Technology Conference (VTC2015-Spring), 2015, Glasgow, Scotland
- B. Makki, C. Fang, T. Svensson, M. Nasiri-Kenari, "On the performance of amplifier-aware dense networks: Finite block-length analysis", International Conference on Computing, Networking and Communications (ICNC 2016), Workshop on Computing, Networking and Communications (CNC), Kauai, Hawaii, USA, Feb. 2016.
- Y. Hong, X. Xu, M. Tao, J. Li, T. Svensson, "Cross-tier Handover Analyses in Small Cell Networks: A Stochastic Geometry Approach", ICC'2015
- C. Fang, B. Makki, T. Svensson, "'On the Performance of the Poisson-Point-Process-Based Networks with no Channel State Information Feedback", submitted IET Communications
- C. Fang, B. Makki, X. Xu, T. Svensson, "Analysis of Equal Gain and Switch-and-stay Combining in Poisson Networks with Spatially correlated Interference", submitted to IEEE Transactions on Wireless Communications

**We plan to include also unreliable wireless backhauling, building on:**

- Z. Mayer, J. Li, A. Papadogiannis, T. Svensson, "On the Impact of Control Channel Reliability on Coordinated Multi-Point Transmission", EURASIP Journal on Wireless Communications and Networking, Feb 2014.
- Z. Mayer, J. Li, A. Papadogiannis, T. Svensson, "On the Impact of Backhaul Channel Reliability on Cooperative Wireless Networks", IEEE International Conference on Communications, ICC 2013, Budapest, Hungary, June 2013.

# Multi-Beam Cooperation with Mobility – in Unstructured Beam-centric mmWave Networks



Equal long-term averaged biased DL-RSS coverage Boundaries (ESBs) in a two-tier small cell network with macro cells (blue squares) and small cells (red triangles).

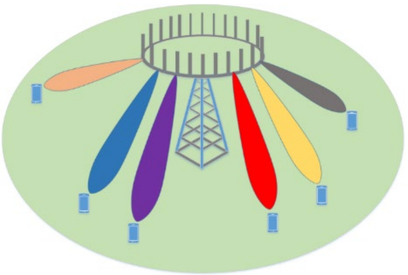
- *Y. Hong, X. Xu, M. Tao, J. Li, T. Svensson, "Cross-tier Handover Analyses in Small Cell Networks: A Stochastic Geometry Approach", ICC'2015*

- Fixed Group Cell: AP1 controls 3 fixed group cells of size 3
- Slide Group Cell: In AP2, the group cell serving MT4 is dynamically reconfigured in order to follow the movement of the user

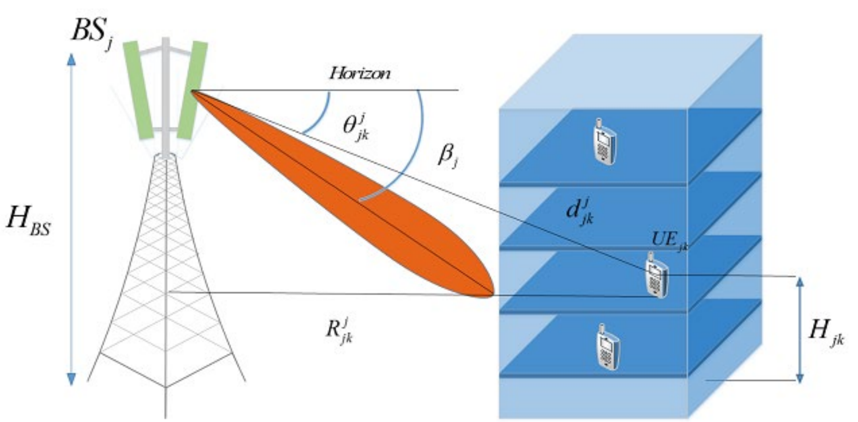
Left illustration is taken from:

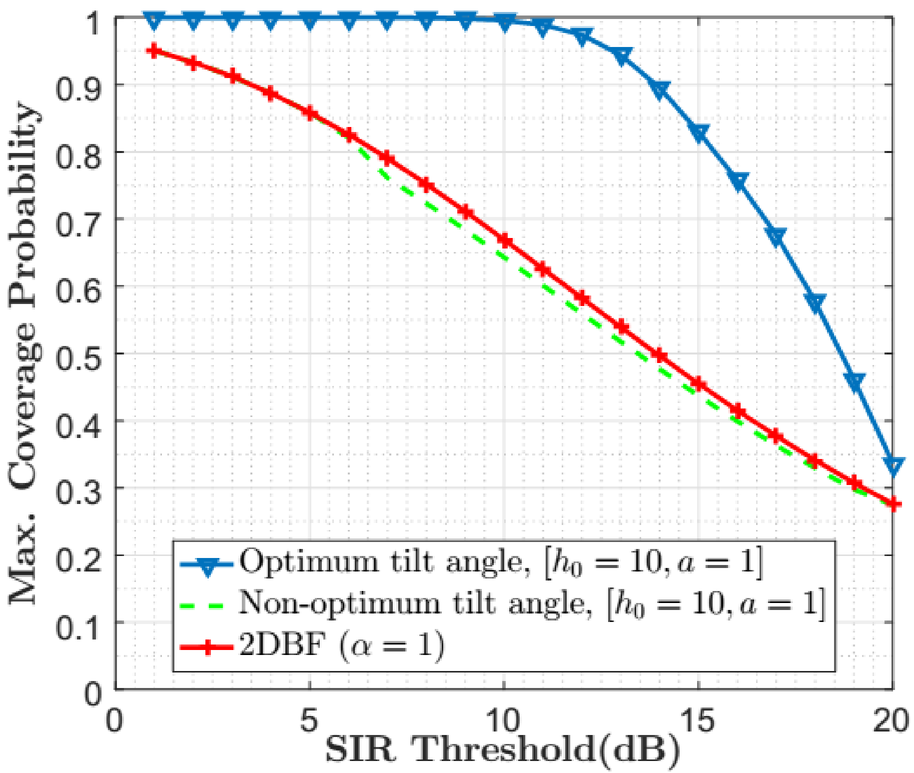
- *X. Xu, X. Tao, C. Wu and P. Zhang, "Capacity and Coverage Analyses for the Generalized Distributed Cellular Architecture-Group Cell," 2006 International Conference on Communications, Circuits and Systems, Guilin, 2006, pp. 847-851.*

# Impact of User Height on the Coverage of 3D Beamforming-Enabled Massive MIMO systems



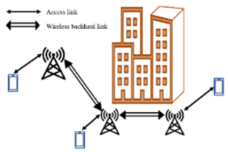
- Uplink of a cellular network
- 3DBF enabled massive MIMO BS
- Using Stochastic Geometry
- Random (PPP) distributed BSs
- Users distributed in 3D space
- Different **user height**



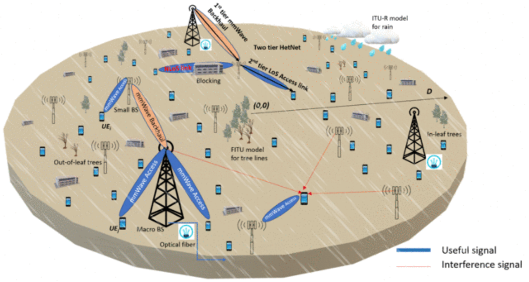

*M. Baianifar, S. Khavari, S.M. Razavizadeh, T. Svensson, "Impact of User Height on the Coverage of 3D Beamforming-Enabled Massive MIMO systems", PIMRC'2017 workshops. Montreal, Canada, Oct 2017.*

# Integrated Access and Backhaul (IAB)




## Arguments for IAB

- Network resources flexibility
- Network cost reduction
- Time-to-market reduction
- Controlled interference also in the backhaul/fronthaul




## System model

Node/BS Distribution

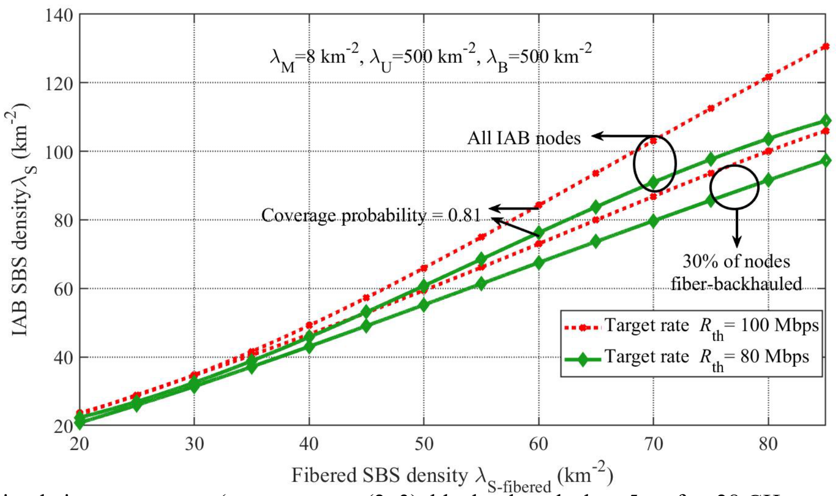
- Finite homogeneous poisson point processes (FHPPP) for macro BS density ($\lambda_M$), small BS density ($\lambda_S$), blockers ($\lambda_B$) and users ($\lambda_U$).
- Two-tier HetNet on a circular plane

Blocking model

- Germ grain model
- OpenStreetMap 3D

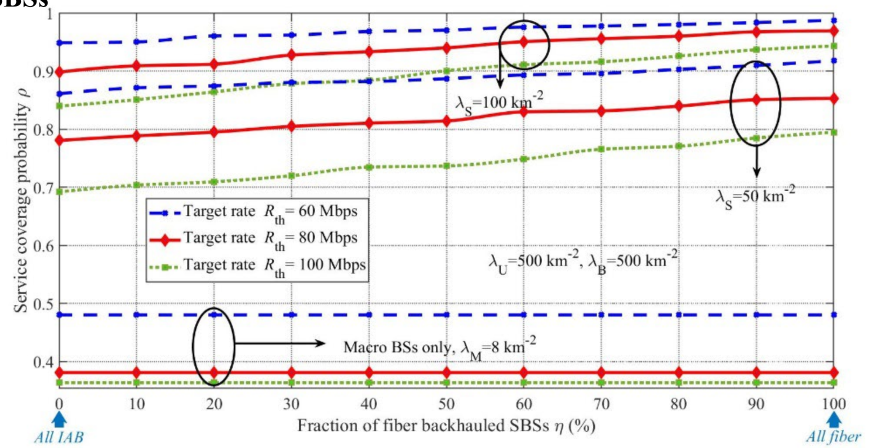
Rain model: ITU-R Rec 8.38-3

**IAB nodes density providing same coverage probability as fiber-backhauling**




- Simulation parameters: ($\alpha_{LOS}$ ; $\alpha_{NLOS}$ = (2; 3), blocker lengths $l_B$ = 5 m, $f_c$ = 28 GHz, bandwidth= 1 GHz and $P_{MBS}$; $P_{SBS}$; $P_{UE}$ = (40; 24; 0) dBm.

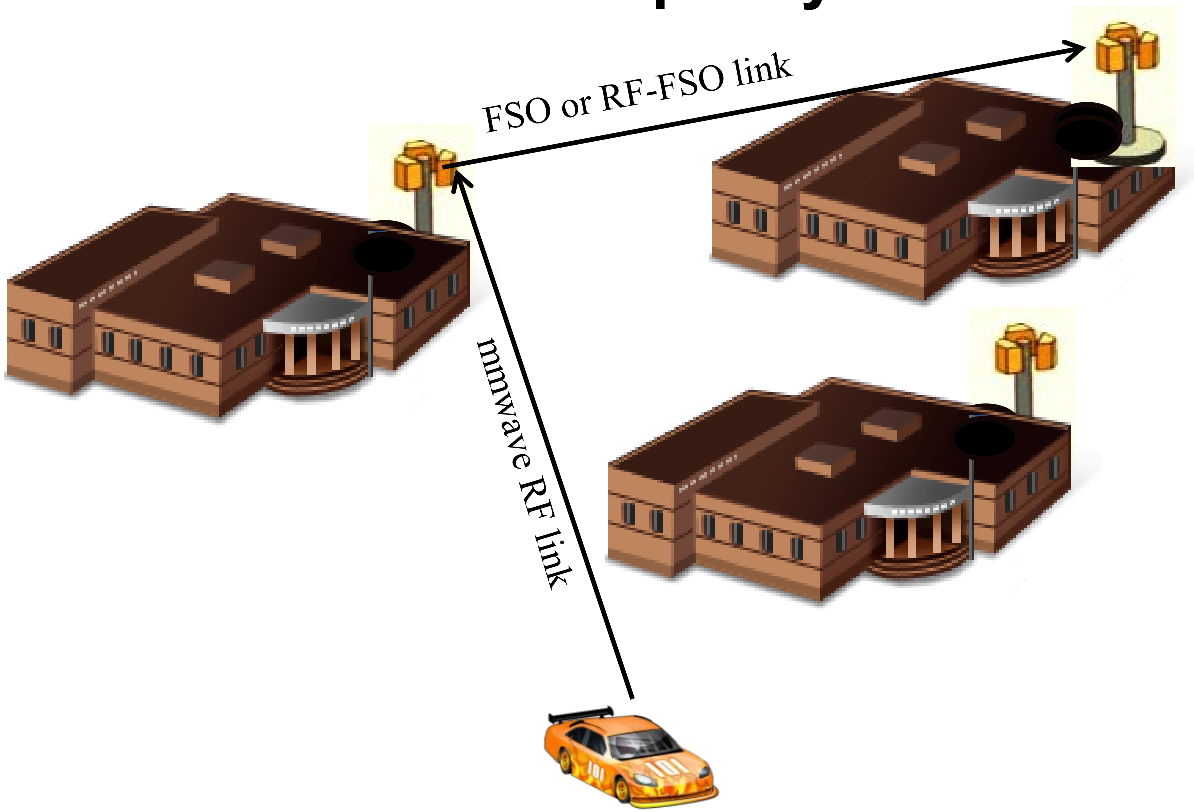
**Service coverage probability as a function of percentage of fiber-backhauled SBSs**




- Simulation parameters: ($\alpha_{LOS}$ ; $\alpha_{NLOS}$) = (2; 3), blocker lengths $l_B$ = 5 m, $f_c$ = 28 GHz, bandwidth= 1 GHz and $P_{MBS}$; $P_{SBS}$; $P_{UE}$ = (40; 24; 0) dBm.

*C. Madapatha, B. Makki, C. Fang, O. Teyeb, E. Dahlman, M. S. Alouini, T. Svensson, "On Integrated Access and Backhaul Networks: Current Status and Potentials", IEEE Open Journal of the Communications Society (OJ-COMS), vol. 1, pp. 1374-1389, 2020. arXiv: https://arxiv.org/abs/2006.14216.*

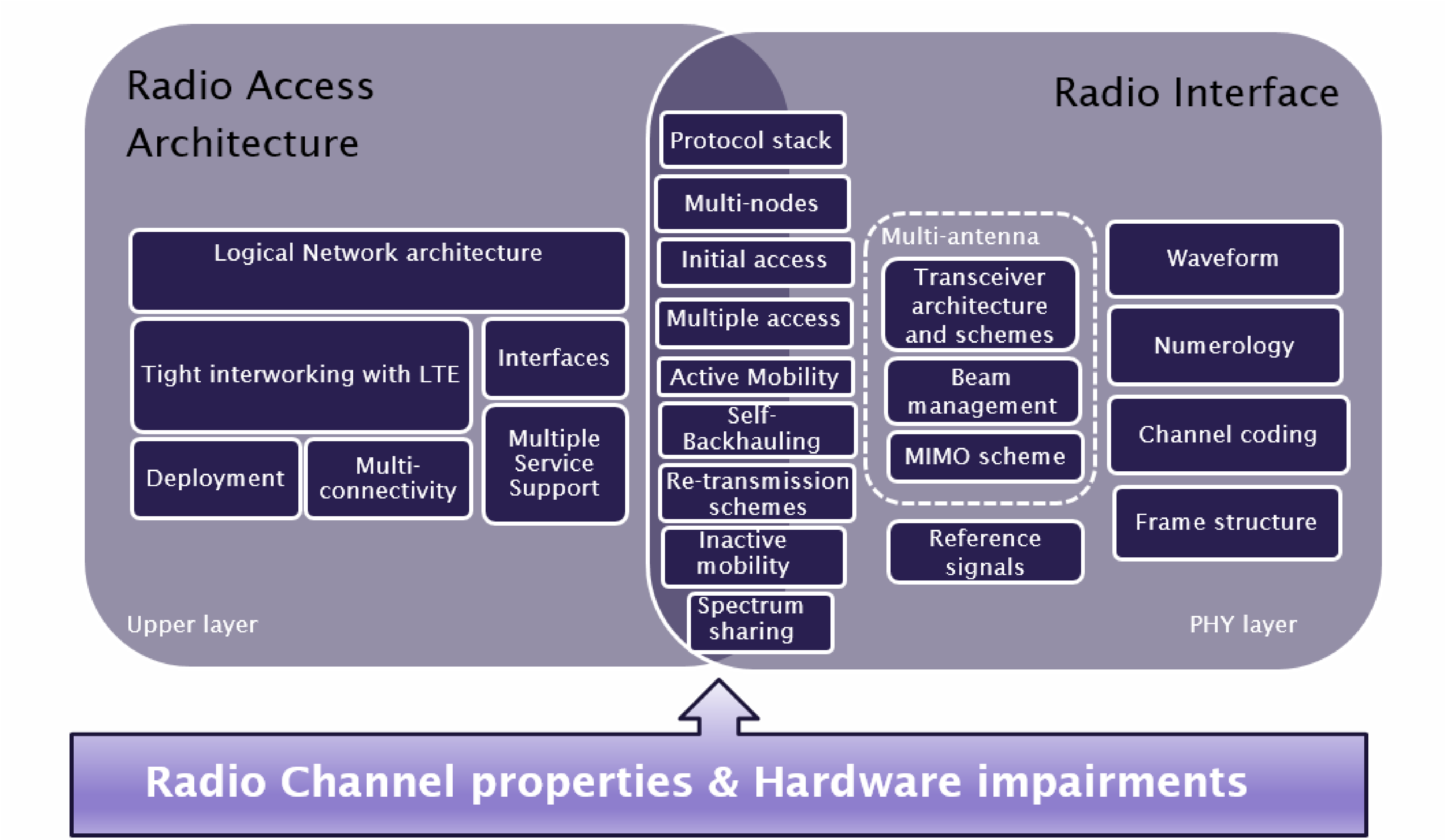
# Hybrid RF-FSO Multi-hop Links to Boost Robustness and Capacity with Wireless Backhauling




*Joint RF-FSO with HARQ provides substantial throughput and outage gains.*


- B. Makki, T. Svensson, M. Brandt-Pearce, M.S. Alouini, "On the Performance of Millimeter Wave-based RF-FSO Multi-hop and Mesh Networks", IEEE Transactions on Wireless Communications, vol. 16, no. 12, pp. 7746-7759, Dec. 2017.
- B. Makki, T. Svensson, T. Eriksson, M.S. Alouini, "Performance Analysis of ARQ-based RF-FSO Links", IEEE Communications Letters, vol. 21, no. 6, pp. 1253-1256, June 2017.
- B. Makki, T. Svensson, T. Eriksson, M.S. Alouini "On the Performance of RF-FSO Links with and without Hybrid ARQ", IEEE Transactions on Wireless Communications, vol.PP, no.99, pp.1-1, 2016.

# mmMAGIC System Concept




https://bscw.5g-mmmagic.eu/pub/bscw.cgi/d54427/mmMAGIC_D6.6.pdf

# mmMAGIC Key Results

- System concept building on the logical architecture and protocol stack of LTE-A RAN.
- Standalone or non-standalone deployment - dense deployment with multi-node coordination important in standalone.
- Initial access procedure periodically repeated and consisting of three phases: cell discovery phase, random-access phase, and beam refinement and/or tracking.
- Multiple access in spatial domain (SDMA) is recommended optimized also for scheduling between backhaul and access traffics, for Integrated Access-Backhaul (IAB), but TDMA most likely be the first choice at early deployments.
- Active and idle mode mobility supported to avoid unnecessary initial access procedures.
- Fast HARQ protocols proposed for single-hop and multi-hop scenarios.
- Scalable OFDM waveform and numerology and flexible frame structure for low delays and robustness towards HW impairments were developed.
- Hybrid beamforming was selected for the transceiver architecture, based on a simplified sub-array architecture. (Some promising results for low precision MIMO was shown, still less mature.)
- A complete 6-100 GHz channel model was developed including new important features such as enhanced blockage modelling, incorporation of ground reflection effects, improved cluster modelling, and large-scale parameters, based on a large amount of consolidated measurement and simulation data, publicly available in the QuaDRiGa SW, http://quadriga-channel-model.de/.
- 16 contributions to 3GPP and 6 to ITU-R have been acknowledged.
- mmMAGIC additionally proposed solutions of interest for further standardization on: spectrum sharing pooling, initial access and beam tracking schemes, mm-wave cell clustering, integrated backhaul and access, and frame structure.

# Summary

## mm-wave for access/backhaul/fronthaul

- Access to mm-wave wide frequency bands is a key enabler for 5G access, backhaul and fronthaul to meet the requirements in key 5G scenarios
- Macro-assisted mm-wave *mobile* communication seems feasible
- Stand-alone is more challenging - cooperative multi-node mm-wave communications with limited CSI might be a crucial enabler
- Access-backhaul/fronthaul convergence is an opportunity
- Accurate channel models and HW-impairment models are important input to the design of mm-wave (cooperative) transceiver schemes
- Timely input to ITU was important for proper allocation of mm-wave frequency spectrum bands and definition of IMT-2020