Cognitive Radio+ for 5G and Beyond

Sonia Heemstra de Groot/Ignas Niemegeers
ECO/CWTe
Faculty of Electrical Engineering

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CWTe
Centre for Wireless Technology Eindhoven

TU/e Technische Universiteit **Eindhoven** University of Technology

Where innovation starts

What will be the role of CR in 5G?

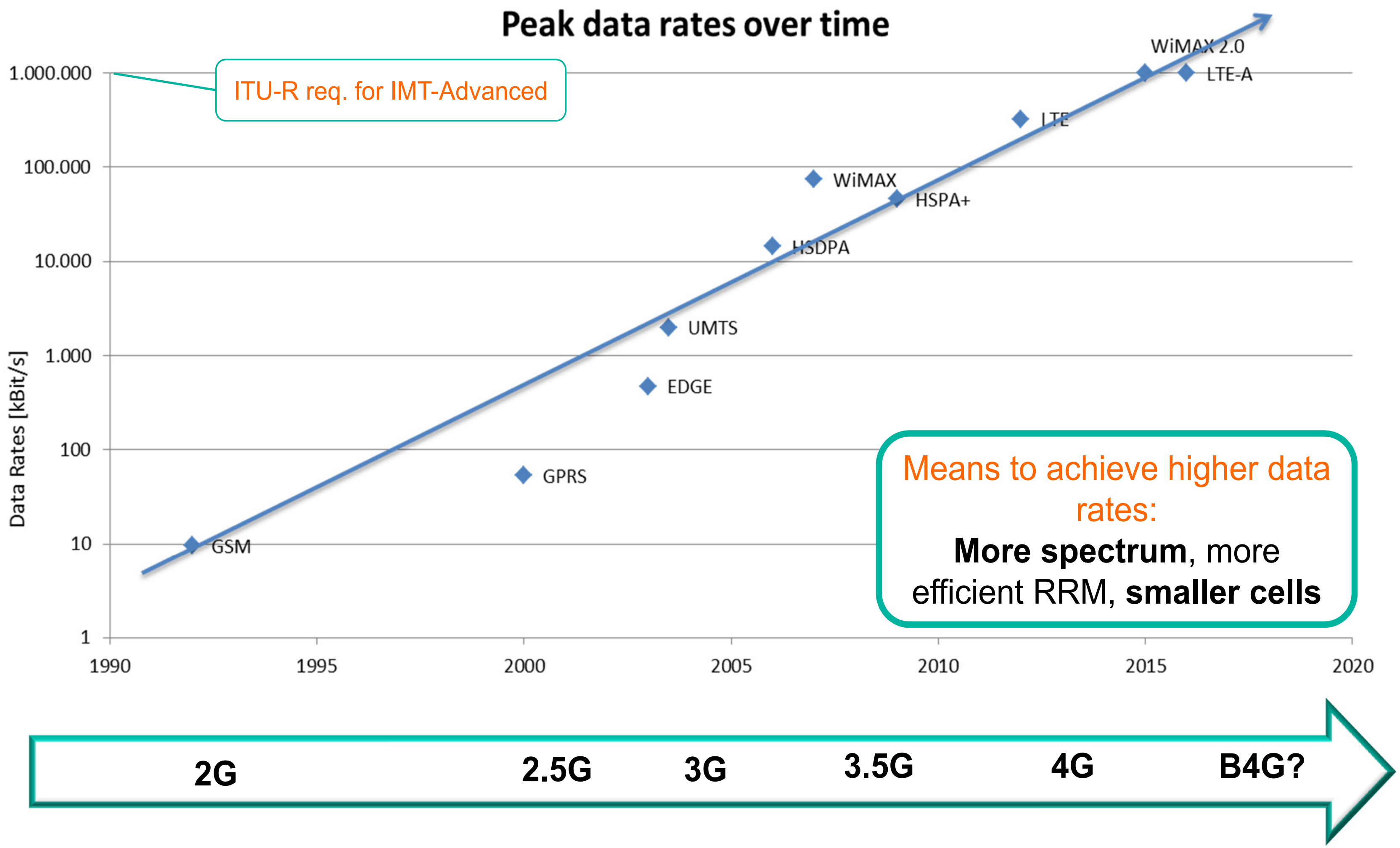
- Will CR in 5G be a key technology or a nice-to-have feature?
- Wouldn't 5G loose its edge if CR spectrum access became dynamic and without guarantees?
- Do we need to extend the concept of CR beyond spectrum?

Outline

- What is 5G?
  - Drivers, goals, and challenges of 5G
  - Enabling technologies
- CR in 5G
- Broadening the CR concept
- Research on CR and CR+ at TU/e
  - CWTe
  - CR at CWTe
  - Extending cognition to other layers
- Conclusions

5G
DRIVERS, CHALLENGES, AND GOALS

Cellular Evolution



Source: NEC – Andreas Maeder, Feb 2012

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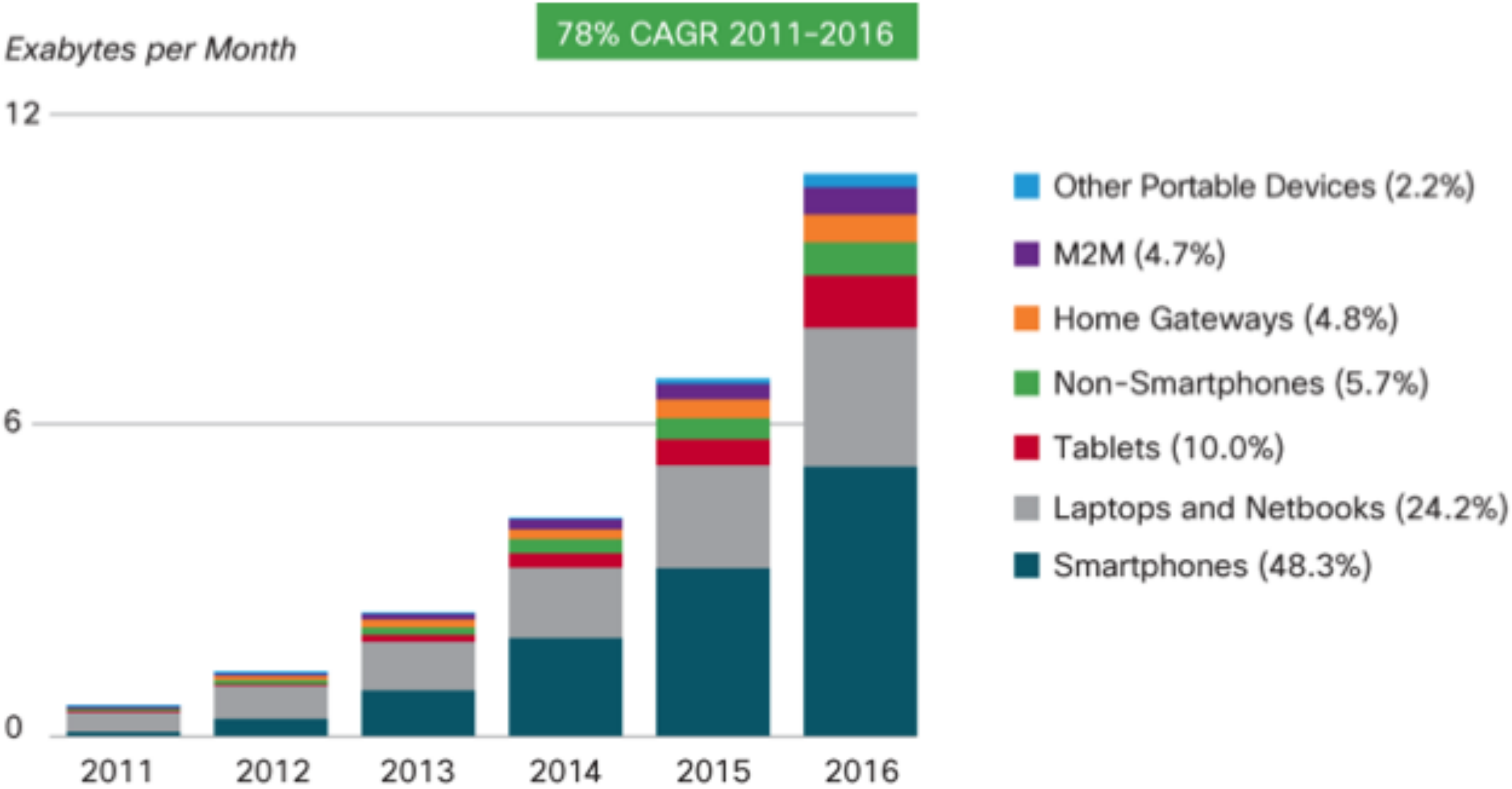
What drives 5G?

- **Mobile data demand will continue to increase**
  - Growth of existing applications
    - e-mail, file transfer, real-time audio (VoIP), video[1] (2013: 66% of IP traffic, 2018: 79% ;more and higher data rates)
  - New applications and new ways of doing things
    - Instant Messaging (IM) … with big files: lots of short connections, high data rates
    - Internet-of-Things (IoT) and Machine-to-Machine (M2M): massive numbers of devices and connections, little data

      > 50 billions of connected devices in 2020[2]
    - Critical applications- e.g., health, safety and security, traffic systems: guaranteed QoS

[1]Cisco Visual Networking Index: Forecast and Methodology, 2013–2018
[2]http://www.ericsson.com/res/doc/whitepaper/wp-50-billions.pdf

Cisco's traffic prediction



Figures in legend refer to traffic share in 2016.
Source: Cisco VNI Mobile, 2012

Multiple challenges

- **Exploding traffic volume**

  Mobile data traffic growth > 24-fold between 2010 and 2015, > 500-fold between 2010 and 2020[1].

- **Random and diverse traffic**
  - Uneven distribution of traffic across space and time
  - Peak-to-mean traffic in fixed Internet up to 100:1; greater ratios expected for mobile broadband
  - Diversity of applications with very different QoS requirements
- **Control plane load (IoT, IoE)**
- **Low cost**
- **Energy efficiency**

[1]Nakamura, et al , "Trends in Small Cell Enhancements in LTE Advanced," IEEE Communications Magazine, Feb 2013.

Goals*

Data Rates	1-10Gbps
Capacity	36TB/month/user
Spectrum	Higher frequencies
Energy	~10% of today's consumption
Latency	<1ms (e.g., tactile internet)
D2D capabilities	NSPS, ITS, resilience, …
Reliability	99.999% within time budget
Coverage	20 dB of LTE (e.g., sensors)
Battery	~10 years
Devices per area	300.000 per access node

Ultra dense networks (Data Rates – D2D capabilities)

Ultra reliable communications (Latency – Coverage)

Ultra dense networks (Coverage – Devices per area)

*EU 2020 METIS Project

5G
TECHNOLOGIES

Enabling Technologies (1)

- **Dense Heterogeneous Networks (HetNets)**
  - **Macro cells combined with**
  - **Small cells: picocells and femtocells**
    increase of spectral efficiency, improved coverage, reduction of transmit power
  - **Separation of data and control planes**
    connectivity with two BS: macro for control, small cell for transport
  - **Multiple radio-access technologies**
    including unlicensed and licensed shared access
  - **Device-to-device communication (D2D)**
    increase energy efficiency, decrease interference, increase coverage

Enabling Technologies (2)

- **Self-Organizing Networks (SONs)**
  - Self-configuration: neighbor discovery , coordinated selection of parameters, e.g., cell identity, Tx-power, time-frequency resource sharing
  - Saving of OPEX by reducing human interventions
  - SON needed for small cells where the number of deployed nodes could be very high
- **Software Defined (Cellular) Networks**
  - Directly programmable architecture
  - Simplified network management and control
  - Simplified introduction of new services or configuration changes
  - Fine-grained resource control

Enabling Technologies (3)

- **Massive/3D MIMO and distributed MIMO**
  - Dramatic increase of capacity and improved radiated energy-efficiency
  - 3D Beamforming
- **Indoor positioning**
  - Additional information can help in resource allocation, and service improvement
  - Enabler of new applications
- **Intelligent user-device assistance**
  - Sensing, relaying, etc.
  - Machine learning
  - Intelligent Transport System paradigm?

Enabling Technologies (4)

- **Spectrum opportunities**
  - **Millimeter wave**
    - Frequency range 30 to 300 GHz
    - Existing solutions, e.g., IEEE 802.11ad, WiGig alliance, Wireless HD and 802.15.3c
    - Huge increase in data rates and cell capacity.
  - **Visible light communications (VLC)**
    - Omnipresence of LEDs: signaling and illumination
    - LEDs offer significant potential for modulation
    - No EMI with RF, unregulated spectrum, worldwide available, enhanced privacy, ……
  - **Shared spectrum/Cognitive radio**

Control Issues in exploiting new technologies

- **Essential and increasing role of control information**
- **Importance of backhaul/fronthaul network, e.g., capillary optical infrastructure**
- **Role of end devices (research topic)**

COGNITIVE RADIO IN 5G

Why may CR be interesting for 5G?

- Some bands are significantly underutilized
- Cost of dynamically leasing spectrum is expected to be much lower than purchasing a licensed band
- Allows expansion of spectrum at a much lower cost
- Coping with overload traffic

Cognitive cellular networks

Use of licensed and cognitive radio resources

- **Licensed radio resources (cellular bands)**
  - Small bandwidth
  - High transmit power
  - High reliability
- **Cognitive radio resources**
  - Potentially broad bandwidth
  - Low transmit power
  - Low reliability

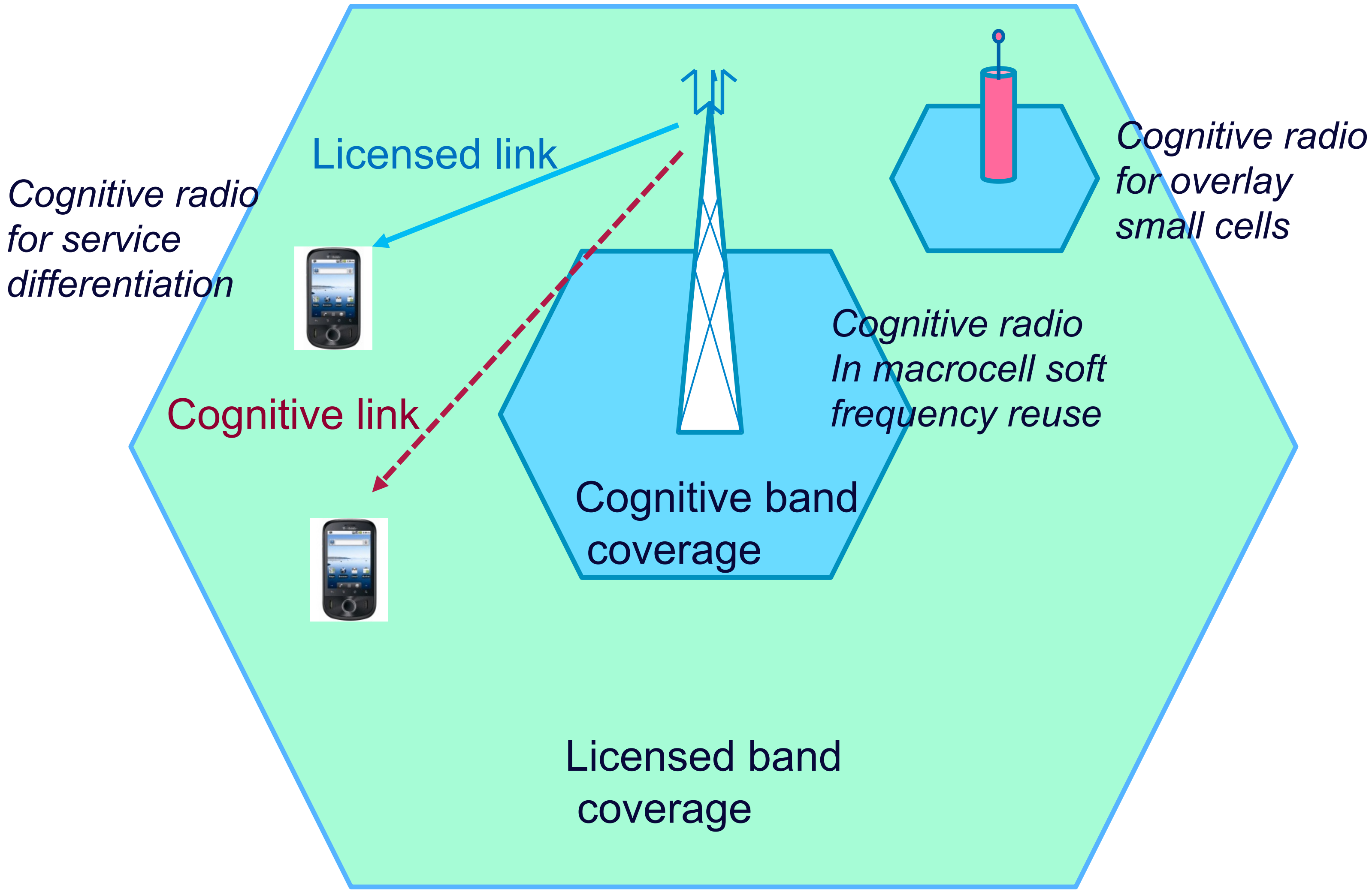
Challenge: How to use those complementary resources to optimize system performance?

Architectures of Cognitive Cellular Networks

- **Non-Cooperative Architecture**
  - Two separated networks at the physical layer
  - Integration at upper layers

- **Cooperative Architecture**
  - Combined used of licensed and CR resources to form a single integrated network
  - Using cooperative communication principles (coordinated relaying by users)
  - Major performance gains possible

Non-cooperative architecture*



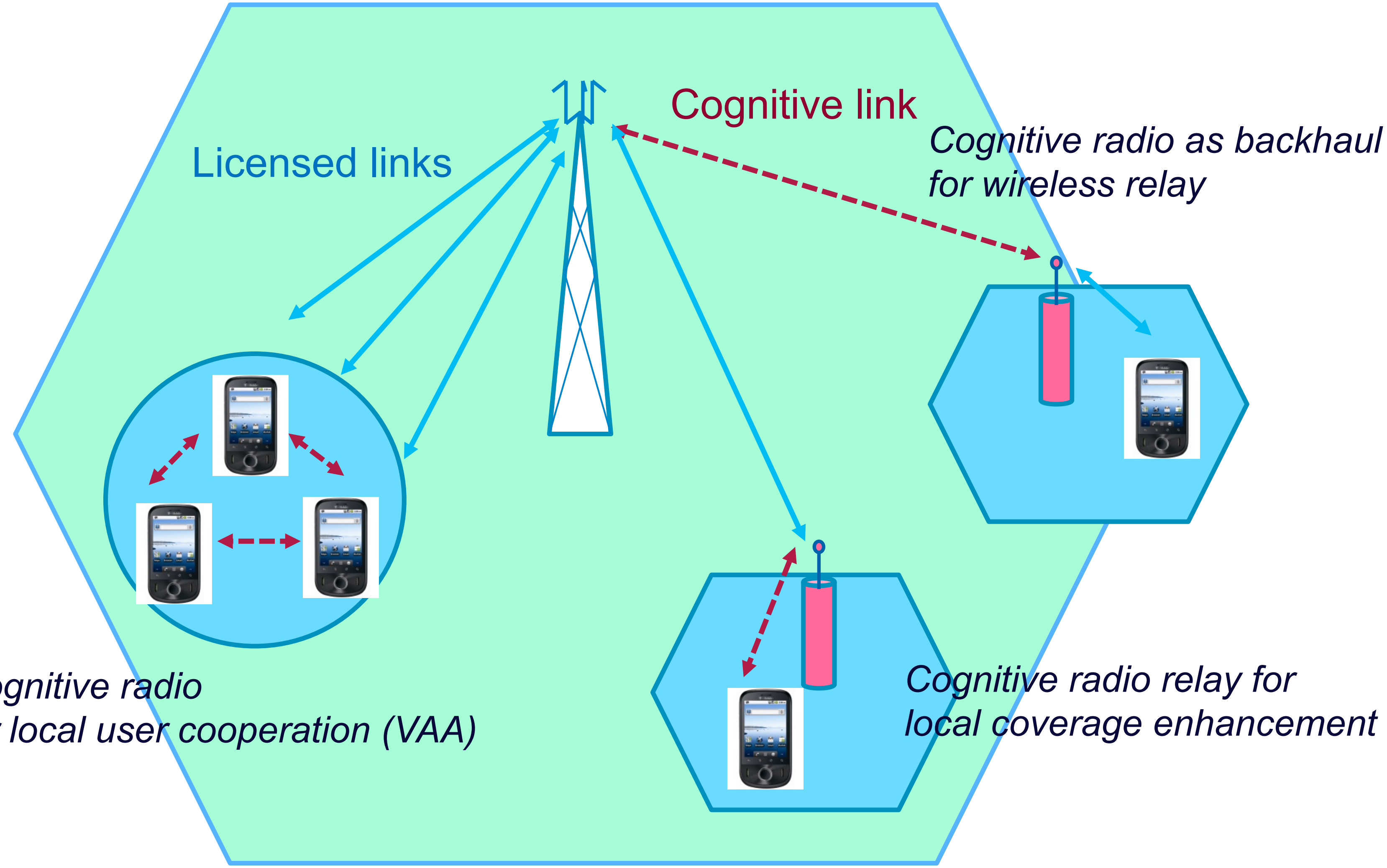
* X. Hong et al "Cognitive Radio in 5G: A Perspective on Energy-Spectral Efficiency Tarde-off, IEEE Comm. Mag. July 2014

Non-cooperative architecture

- **Usage scenarios**
  1. **Power-limited cognitive radio resources for users near the macro-cell; licensed resources for users far away.**
  2. **Service differentiation: licensed resources for strict QoS demands and CR for relaxed QoS**
  3. **Cognitive small cells (femtocells) using CR to cover traffic hot spots or coverage gaps.**

Actively advocated by various major industrial players!

Cooperative architecture*



** X. Hong et al "Cognitive Radio in 5G: A Perspective on Energy-Spectral Efficiency Tarde-off, IEEE Comm. Mag. July 2014*

Cooperative architecture

- **Usage scenarios**
  1. **Cognitive relay for capacity enhancement**
     - Communication to BS with licensed resources; CR for local coverage
     - Communication to BS with CR; local coverage with licensed resources: no modification for conventional user devices
  2. **Virtual Antenna Array (VAA)**
     - Virtual MIMO in licensed band: performance gains

Spectrum sharing

- **Uncoordinated secondary use**

  Primary user has no knowledge of secondary user(s)

- **Semi-coordinated secondary use** (database access, cognitive pilot channel):

  Primary user is aware of secondary users' existence

- **Coordinated (Authorized/Licensed Shared Access (LSA))**
  - Controlled licensed sharing
  - Coordinated binary use by either the operator or the incumbent
  - Predictability for investment security and QoS; and it protects the incumbent.
  - Geo-location databases and policy control mechanisms
  - Supported by many operators

Future Spectrum Landscape (METIS view)

- **Multiple bands with different regulatory modes**
- **Dedicated licensed spectrum complemented by various forms of spectrum sharing**

* METIS Project

5G

BROADENING THE CR CONCEPT

CR+

- Dynamic and opportunistic use of the spectrum will not be enough to cope with the 5G demands and the scarcity of wireless spectrum
- More adaptability needed to battle interference
- A combination of power control, selecting the right frequency, multi-hop, relaying, space division, localised intelligence
  - mm-waves: high propagation loss is exploited
  - multi-hop: minimizing interfered region
  - space division: from tri-sector to (optical) pencil beam *)
  - '*intelligence per mm*^{3}' is scaling faster than data rate

Opportunities beyond spectrum sensing

- **Real-time adaptability at all system levels**

  Network adapts waveform, configuration, spectrum bands, transmit power, but also routing and topology of wireless and wired components

- **Cognitive networks and user devices**

  "A network with a cognitive process that can perceive current network conditions, plan, decide, act on those conditions, learn from the consequences of its actions, all while following end-to-end goals"[1] + user device intelligence

- **Device relaying and cooperative communications**

  One or multiple devices play the role of relay. Cooperative diversity, the occupied spectrum and participating nodes are opportunistically determined according to capabilities and environment.

- Dynamic **"fluid wireless network**" without predetermined topology and spectrum allocation.

[1]Thomas, R.W. et al. (2005), "Cognitive networks", *Pro. of the First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks,*

Key enablers

- Massive deployment of sensors in the environment, and in the user devices
- Computing capabilities of some user devices
- mm-wave technology, cognitive routing techniques like OpenFlow, advanced space division (e.g., pencil beams), and the generic increase of ‘intelligence per mm3’
- Fibre-optical backbone as the ICT-nervous system of the infrastructure

CR+

- **Broader interpretation of the CR concept:**

  Awareness, adaptation, and intelligence at all system levels

- **It that a broadening of the CR concept?**

Cognitive radio

- **Mitola (1999) said it:**

  "The point in which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs"

  Or a broader interpretation?

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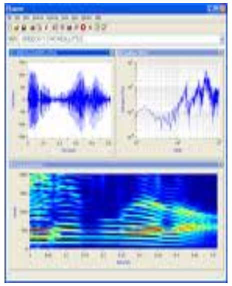
Structure of the CWTe

 +  +  + 

Antennas + Propagation:

EM group
Prof. Tijhuis

Circuit Design (analog, mixed & digital)

MsM group (mixed)
Prof. Van Roermund
Prof. Baltus (Director CWTe)

ES group (digital)
Prof. Basten

Digital Signal Processing

SPS group
Prof. Bergmans

Network Protocols

ECO
Prof. Koonen
Prof. Liotta
Prof. Heemstra de Groot
Prof. Niemegeers

CWTe Programs

- **Ultra-high data rates**
  - High Frequencies (>= 60GHz)
  - High data rates (100Gbps)
  - Beamforming with many elements @ low cost
- **Ultra-low power**
  - Small (< 1mm^3)
  - Low-cost (< $0.20)
  - Battery-less sensors/controls
- **Short range THz observation**
  - Vision: small, low-cost short range
    3D spectroscopic imaging
  - Applications: medical, automotive, security, gaming, etc.

CR Research
PAR4CR PROJECT

What is Par4CR?

- **FP7 IAPP project**
- **Focus:**
  - Knowledge exchange
  - Evolution Software-Defined → Cognitive Radio
  - PHY, Wideband operation
- **October 2010 - September 2013**
- **Partners:**

CATENA, NXP, IMST, CATENA

Industry

TNO, ESIEE ENGINEERING, TU/e, ITE

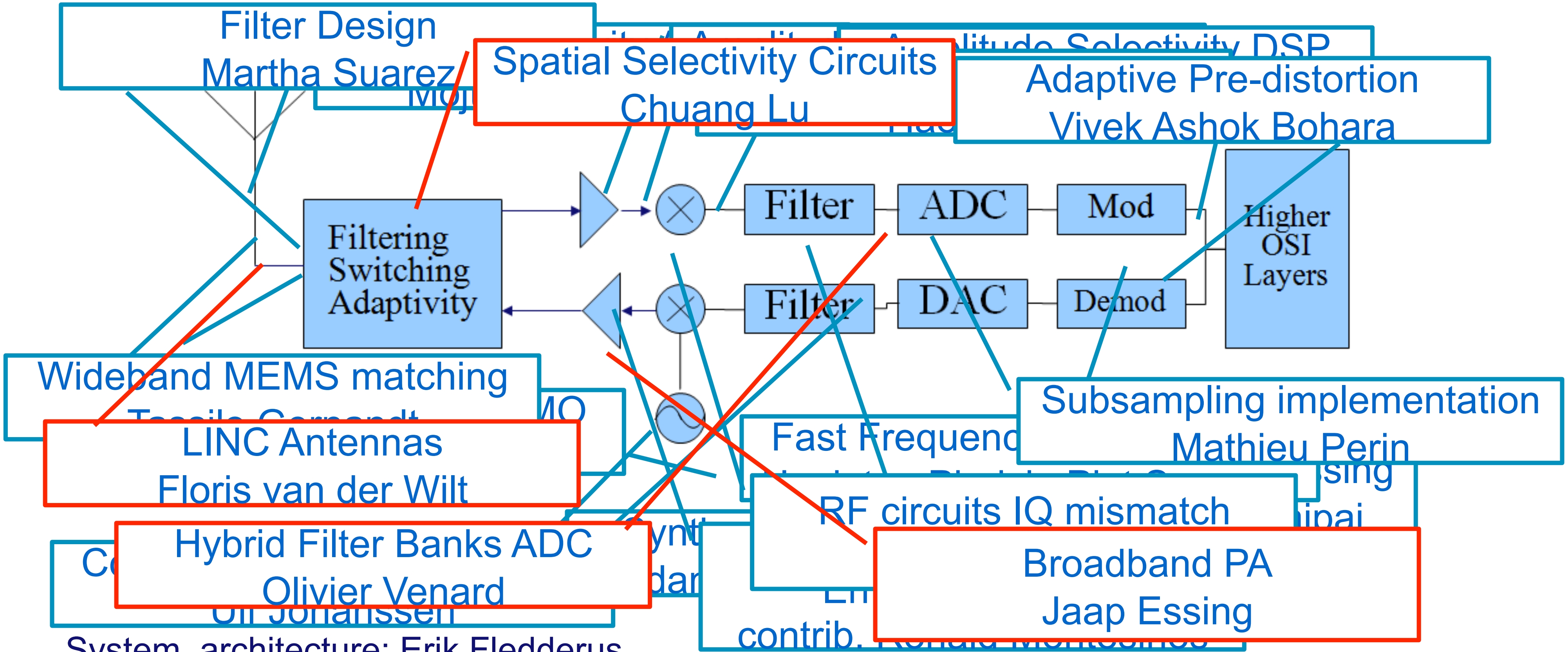
Academia

Par4CR Research Objective

To develop a new architecture for software-defined radio as a step towards cognitive radio

based on wideband operation of transmitter and receiver

The Complete Picture: Overlays



System architecture: Erik Fledderus

RX architecture: Olga Zlydareva, Martha Suarez, contributions Mathieu Perin

TX architecture: Corinne Berland and Martha Suarez; Sandeep Kowgli (BTS)

System simulation: Mazen Abi Hussein

Integration Techn. Comparison: Sidina Wane

Validation: Pooh Ling + all

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Other complementary research

- Electro-optical Communication Group
  - Autonomous networking (Prof. A. Liotta)
  - RoF techniques for adaptive and cost-effective communication platforms (Prof. Ton Koonen)
  - Management and control of RoF-based networks (Prof. S. Heemstra de Groot, Prof. I.G. Niemegeers)

Autonomic networks (1)

- Using machine learning and autonomic computing to address complex network problems
  - Future Internet
  - Mechanisms for enabling spontaneous connectivity, opportunistic communication, self-learning and self control.
  - Cognitive networks


The Cognitive Net Is Coming

The Internet will break down without new biologically inspired routing

By Antonio Liotta

Illustrations by L-Dopa

A. Liotta, **The Cognitive Net is Coming**, IEEE Spectrum, Vol.50(8), pp.26-31, August 2013, IEEE http://bit.ly/spectrum_LIOTTA

Autonomic networks (2)

- **Implementation of machine learning onto small sensors**

  Proof that a sensor can learn complex patterns automatically within just 20Kbytes of RAM and an inexpensive CPU[1,2]

- **Machine learning for proactive adjustment**

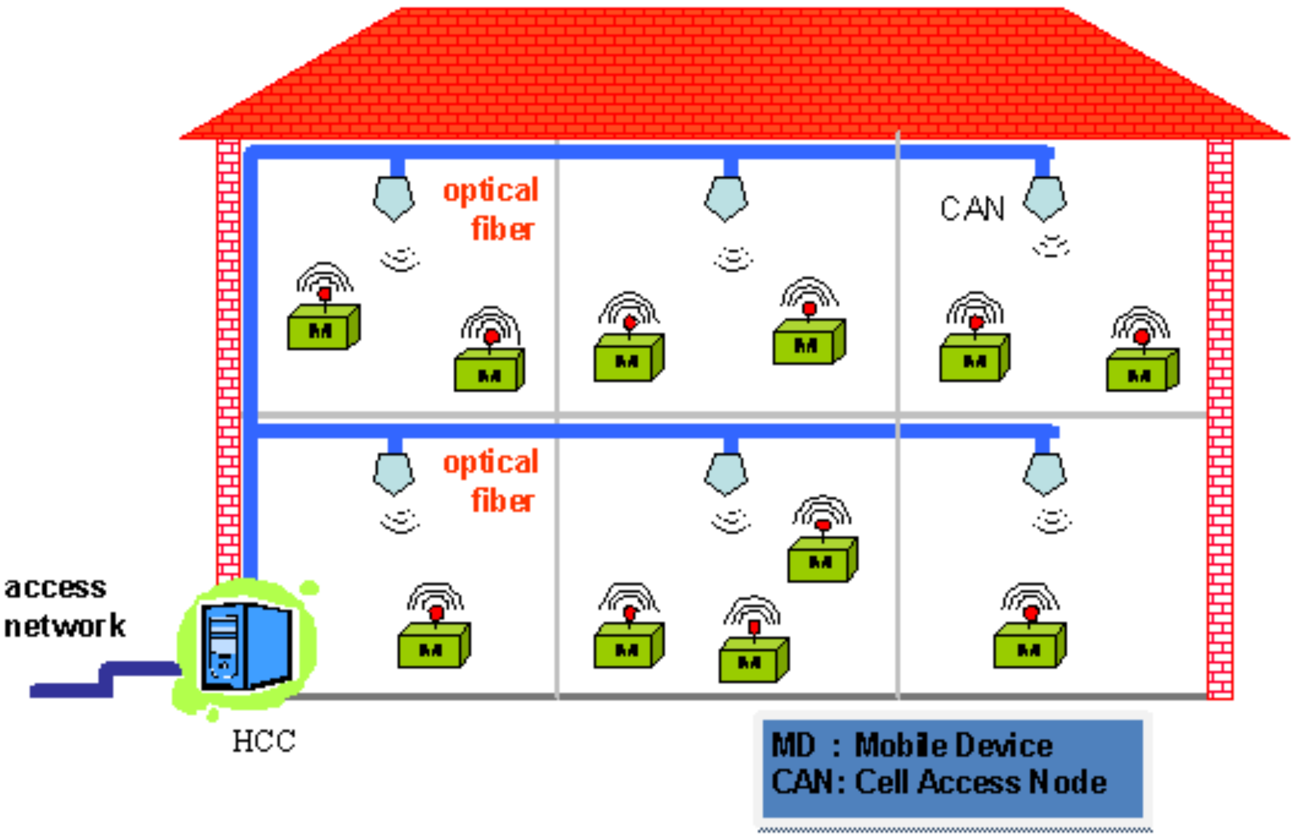
  Devices make predictions about traffic patterns and interference levels, and adjust accordingly in a proactive way

[1]*HHWJ Bosman, **A Liotta**, G Iacca, HJ Wörtche, "Anomaly detection in sensor systems using lightweight machine learning"" Proceedings of the 2013 IEEE International Conference on Systems, Man, and Cybernetics*

[2]*H Bosman, G Iacca, HJ Wortche, **A Liotta**, "Online Fusion of Incremental Learning for Wireless Sensor Networks", IEEE International Conference on Data Mining Workshop (ICDMW), 2014,*

RoF adaptive communication platform

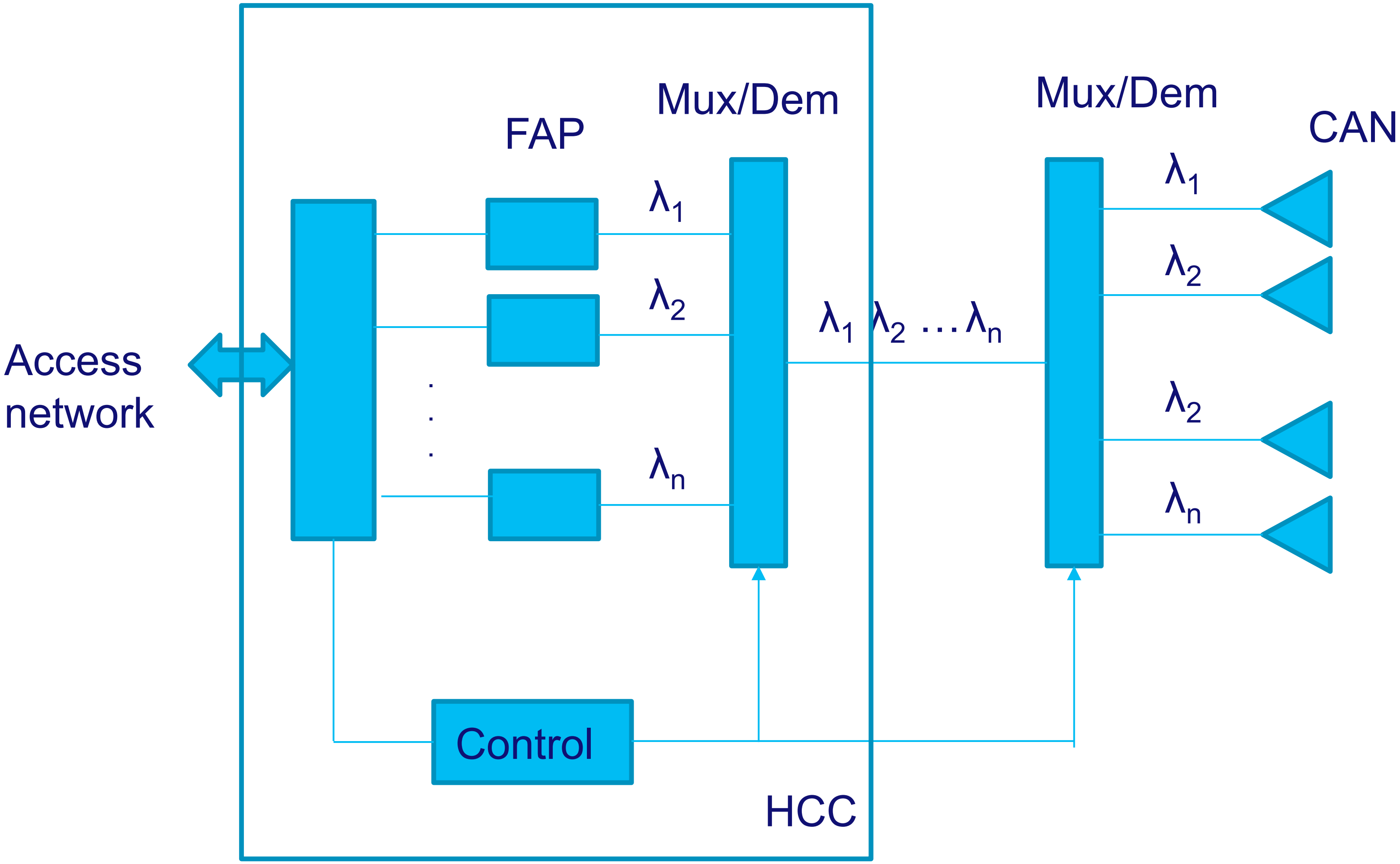
- **High-capacity and mobility**
- **Lower transmission powers**
  - Health, energy preservation, battery lifetime
- **Ease of management and maintenance**
  - Centralized location of radio equipment
  - Remote software upgrades
- **Cost effective**
- **Future proof**
- **Combined with (dense WDM and wavelength routing)**
  - Support of multiple services and providers
  - Flexible and dynamic capacity allocation



MEANS concept for dynamic ad-hoc fiber-wireless in-door networking

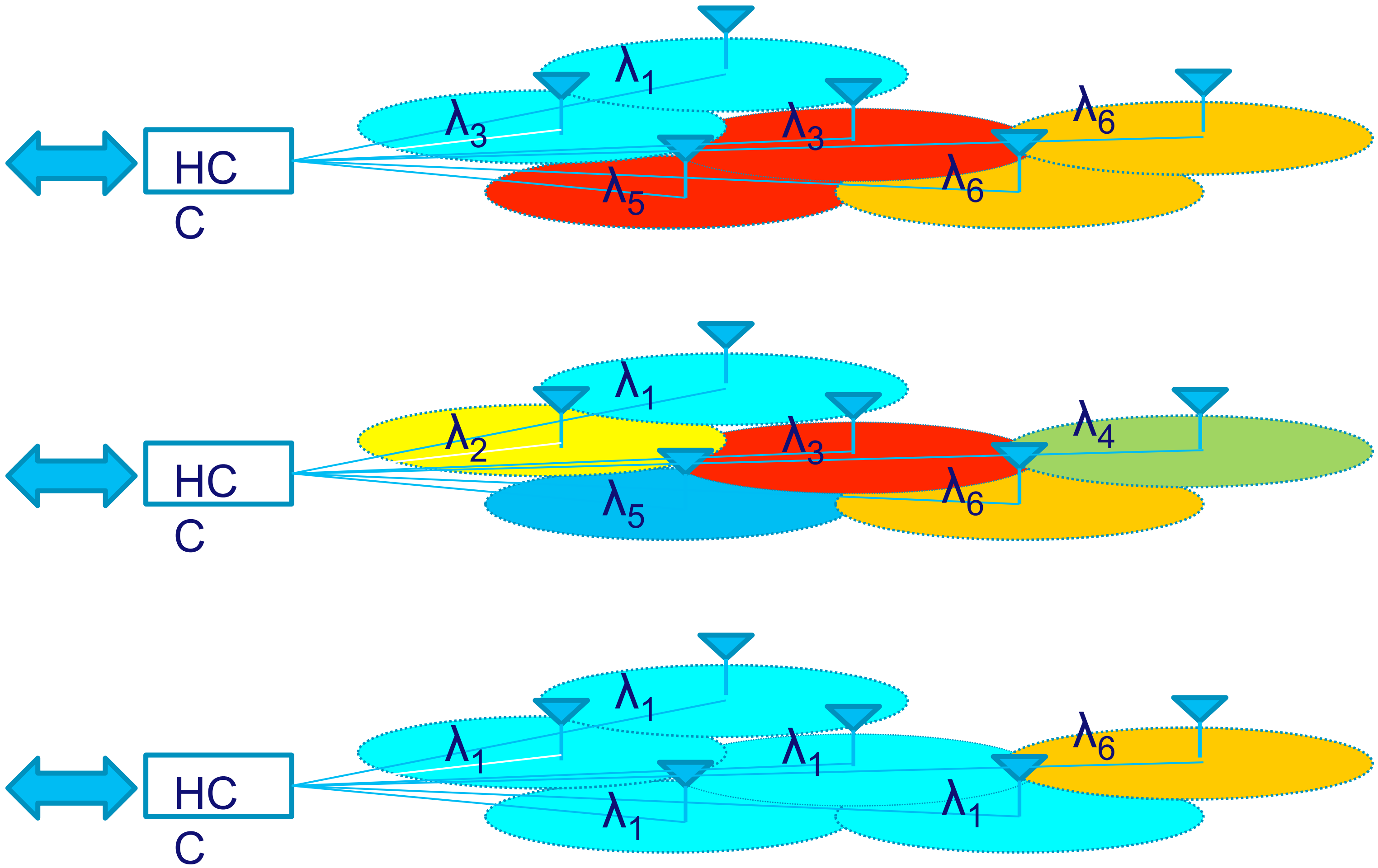
* *Project lead by ECO (T. Koonen)*

Conceptual architecture

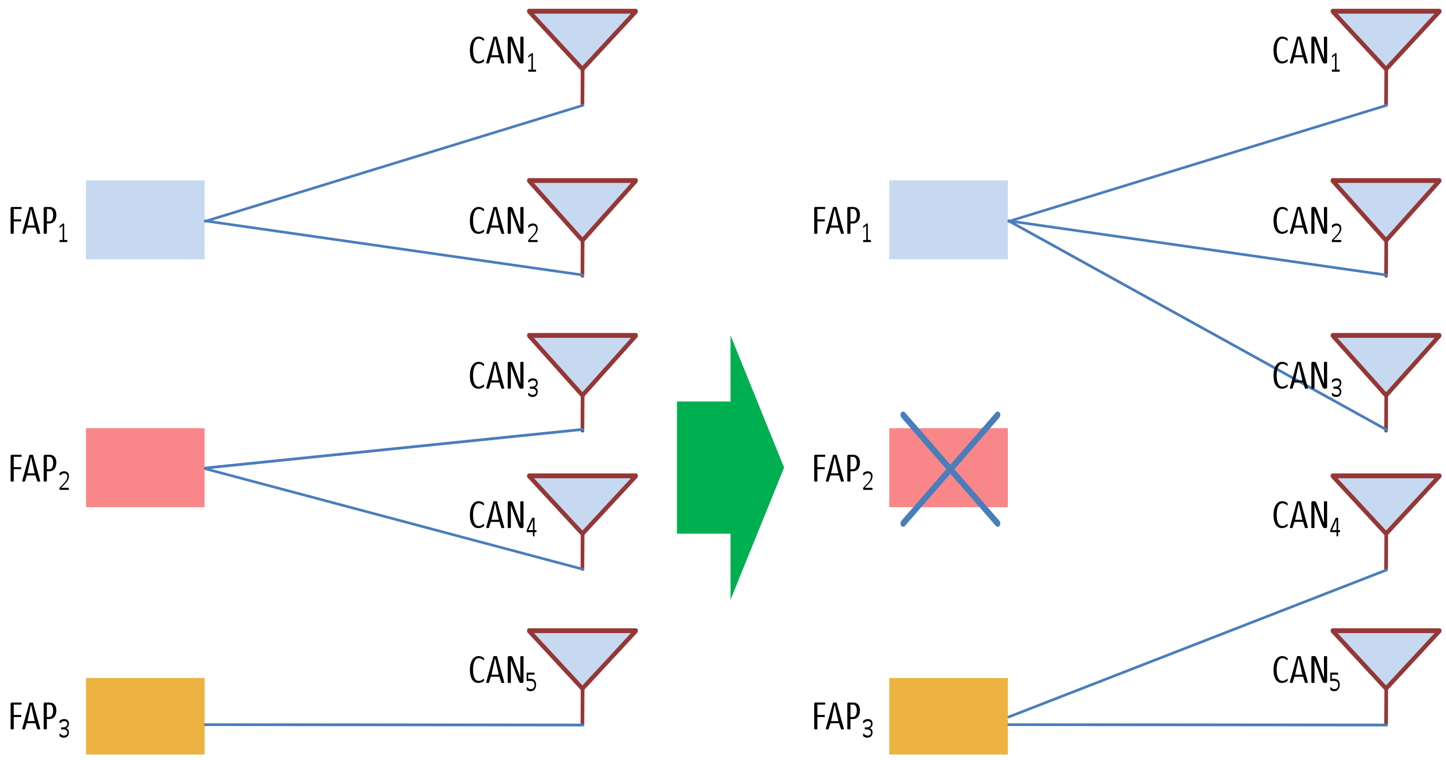


Observe that the FAP may contain SDR interfaces

Flexible capacity allocation



Topology reconfiguration



Default CAN assignment

Re-assignment after failure

Reassignment of CANs to FAPs due to FAP failure (or for energy saving)

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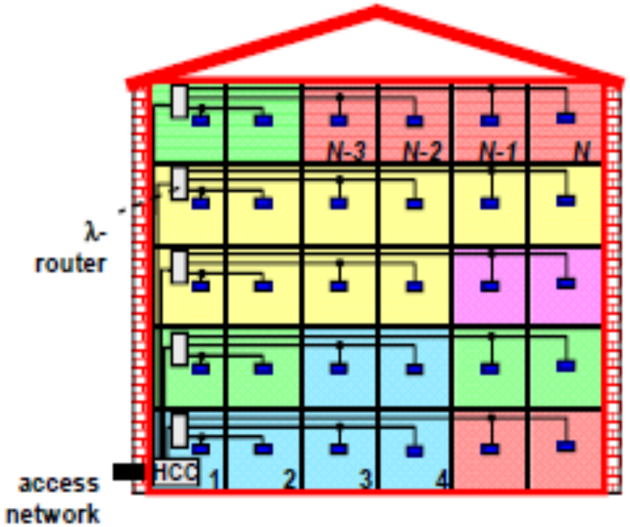
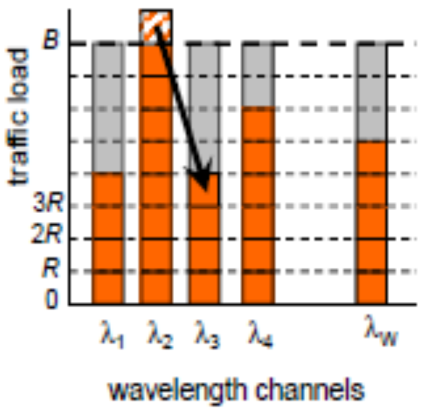
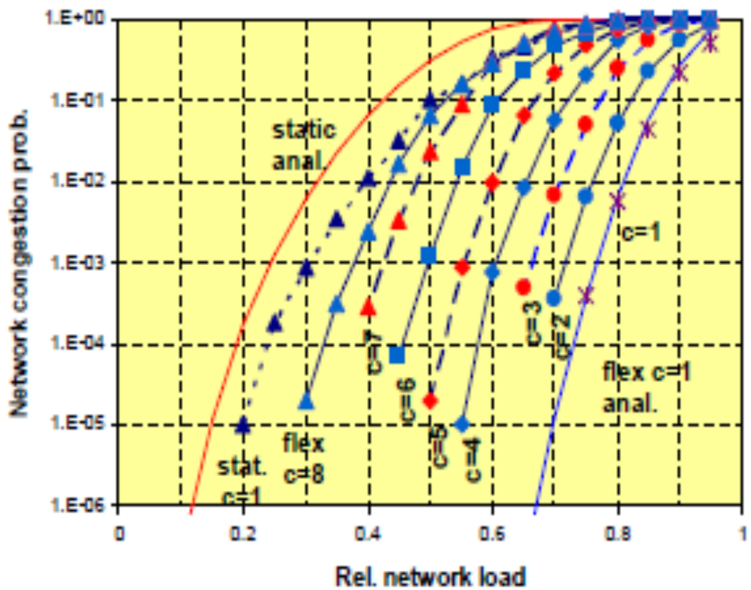
Dynamic capacity allocation in RoF networks*

- **Example: λ-routing for dynamic allocation of radio capacity to living units**







*Koonen et al, OFC 2011, JLT Feb 2014

CONCLUSIONS

Conclusions

- **5G driven by evolution of present use cases and disruptive new use cases, imposing requirements that cannot be met by evolving the present infrastructure**
- **There is an important potential role for cognitive radio**
- **If we use a broader interpretation, the role if cognitive radio in 5G is even more prominent.**
- **Working on building blocks for the future generation (cognitive) mobile networks**

With thanks to

- **Antonio Liotta**
- **Ton Koonen**
- **Peter Baltus**
- **Erik Fledderus**