Pushing the envelope of wireless technology

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CWTe Research Retreat
12 October 2016

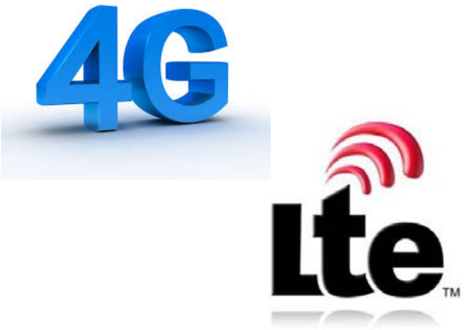
Centre for Wireless Technology Eindhoven

Technische Universiteit Eindhoven University of Technology

Where innovation starts

WHERE ARE WE NOW?

Where are we now? Mobile networks- 4G



LTE, LTE Advanced

- **Faster broadband**
- **Higher capacity**
    - OFDM/SC-FDMA
    - Flexible support for wider channels (up to 100 MHz)
    - More antennas (MIMO)
    - Channel aggregation for higher data rates
- **Peak data rate**
    - 300+ Mbps/75 Mbps (LTE)
    - 1Gbps/500Mbps (LTE advanced)
- **Low latencies**
- **Simplified core network (All IP)**

Where are we now? WLAN - WiFi

- IEEE802.11/a/b/g/n/ac
  - 2.4GHz and 5GHz
  - ac: MU-MIMO-OFDM
    up to 1.69 Gbps/stream (160 MHz, 8 antennas/AP, 2/STA)
- IEEE802.11ad
  - 60 GHz
  - Up to 6.75 Gbps/stream
- IEEE802.11p
  - Optimized for Car 2X communication - ITS
  - 5.9 GHz

Where are we now? Evolution towards IoT

- **Short range**

ZigBee®

4.0 Bluetooth®

- **Long range low power**

SIGFOX™

LoRa™

6LoWPAN

IPv6-based Low-power Wireless Personal Area Networks

2G 3G

IEEE802.11ah HaLow

Where would we like to go?

Broadband multimedia messaging

Extreme HD video steaming

Holographic watch

Haptic holography

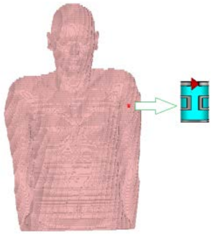
Virtual teleportation

Connected vehicles

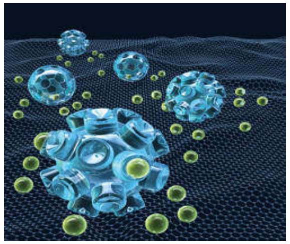
Autonomous driving

Fully autonomous vehicles

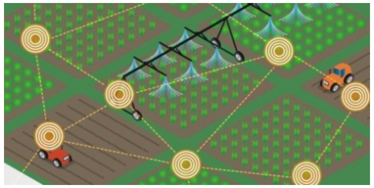
Internet of everything



Implantable antenna



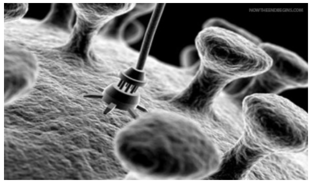
Nano IoT



Smart farming

Implantable wearables

In body networks



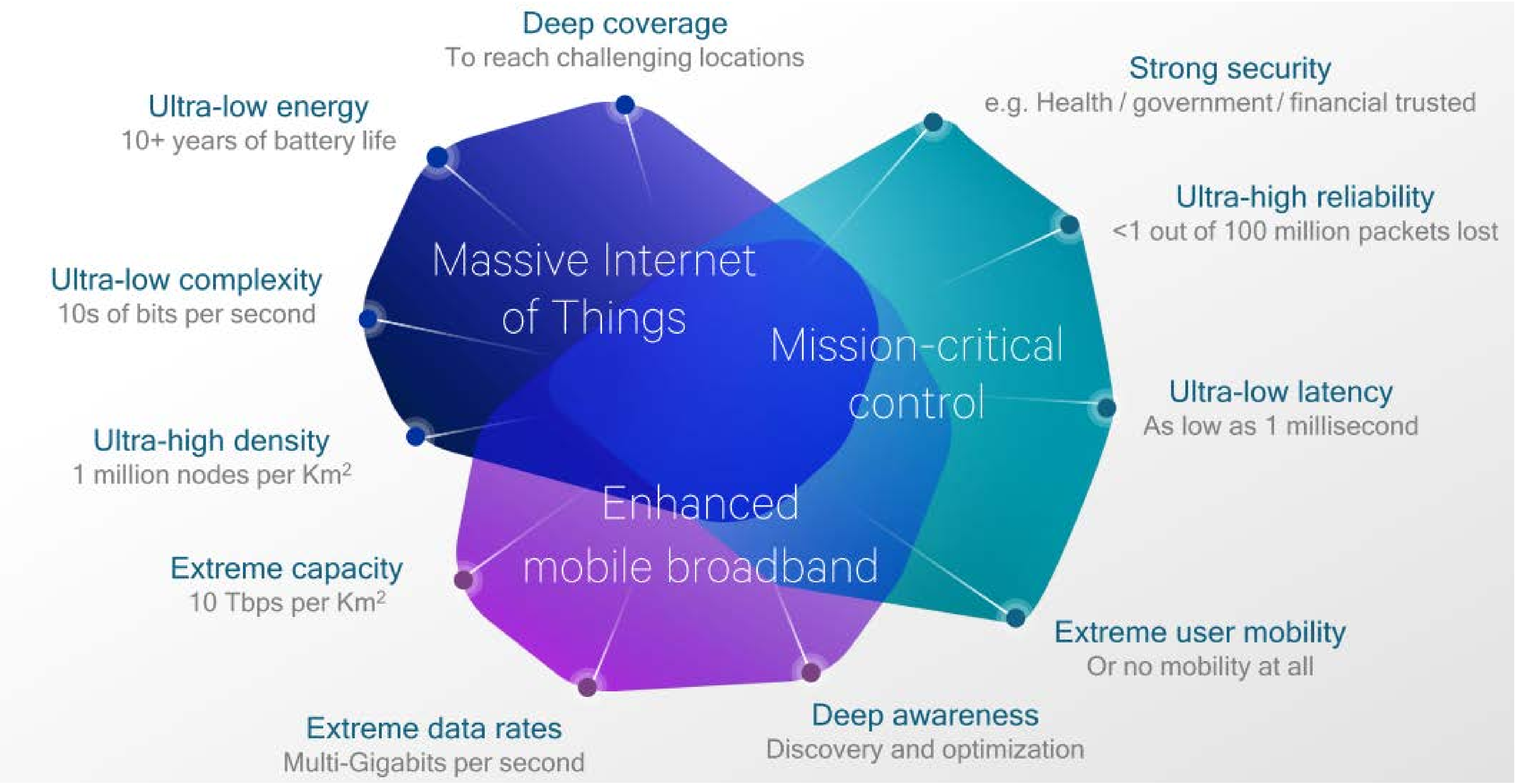
Nano swarms

2016 **2020** **2024** **2028** **2030** **2034**

Next Step 5G

REQUIREMENTS

Extreme variation of requirements*



**From Qualcomm Technologies, Inc. February 2016*

Unified spectrum

Sub GHz: Long range massive IoT

1GHz to 6GHz: Wider bandwidth for enhanced mobile BB and mission critical

Above 6GHz. mmwave: Extreme bandwidth, shorter range extreme broadband

5G
CHALLENGES

Multiple challenges

- Exploding traffic volume
- Random and diverse traffic
- Explosive growth of connected devices
- Control plane load (IoT, IoE)
- Low cost
- Energy efficiency

5G
TECHNOLOGIES

Timeline for 5G

5G Phase 1

5G Phase 2

6G and beyond

2020

2025

2030

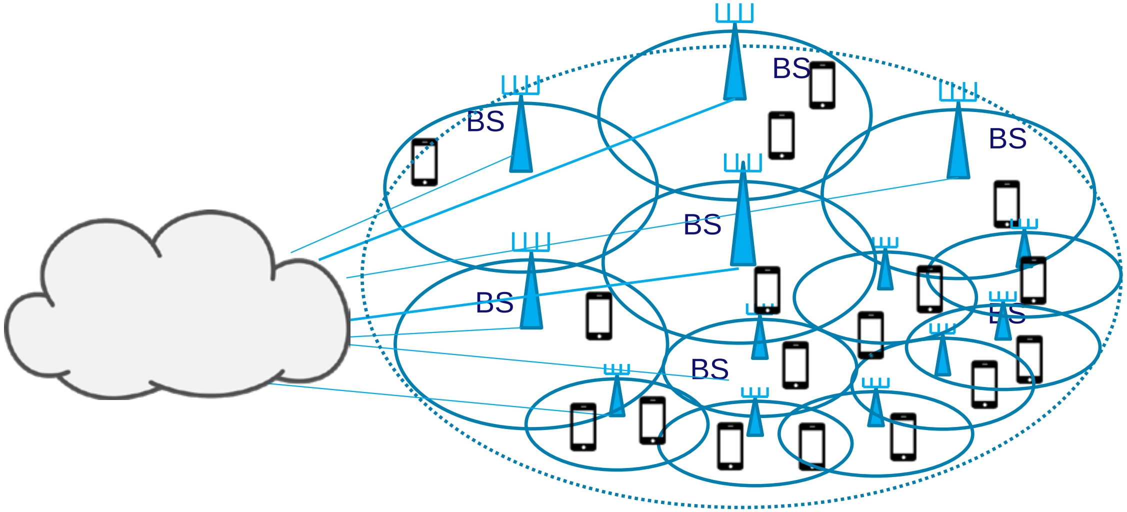
Using spectrum
allocated in WRC
2015 below 6GHz

Adding spectrum
allocated in WRC
2019 above 6GHz

New generation

5G Key technological components - Network

- **Ultra Dense Heterogeneous Networks**
  - **Macro cells combined with**
  - **Small cells: picocells and femtocells**
    increase of spectral efficiency, improved coverage, reduction of transmit power



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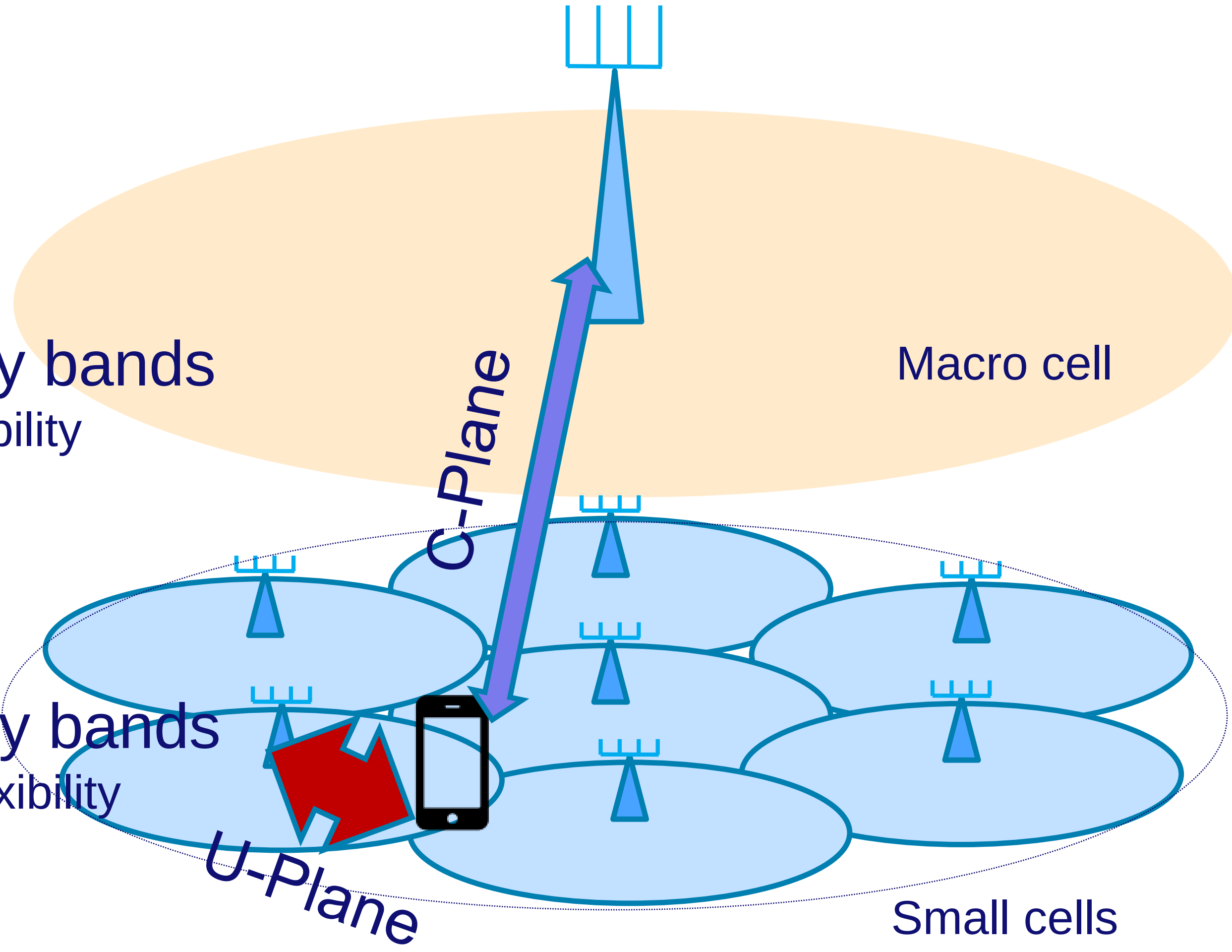
  - **Separation of data and control planes**

    connectivity with two BS: macro for control, small cell for transport

C/U Plane split



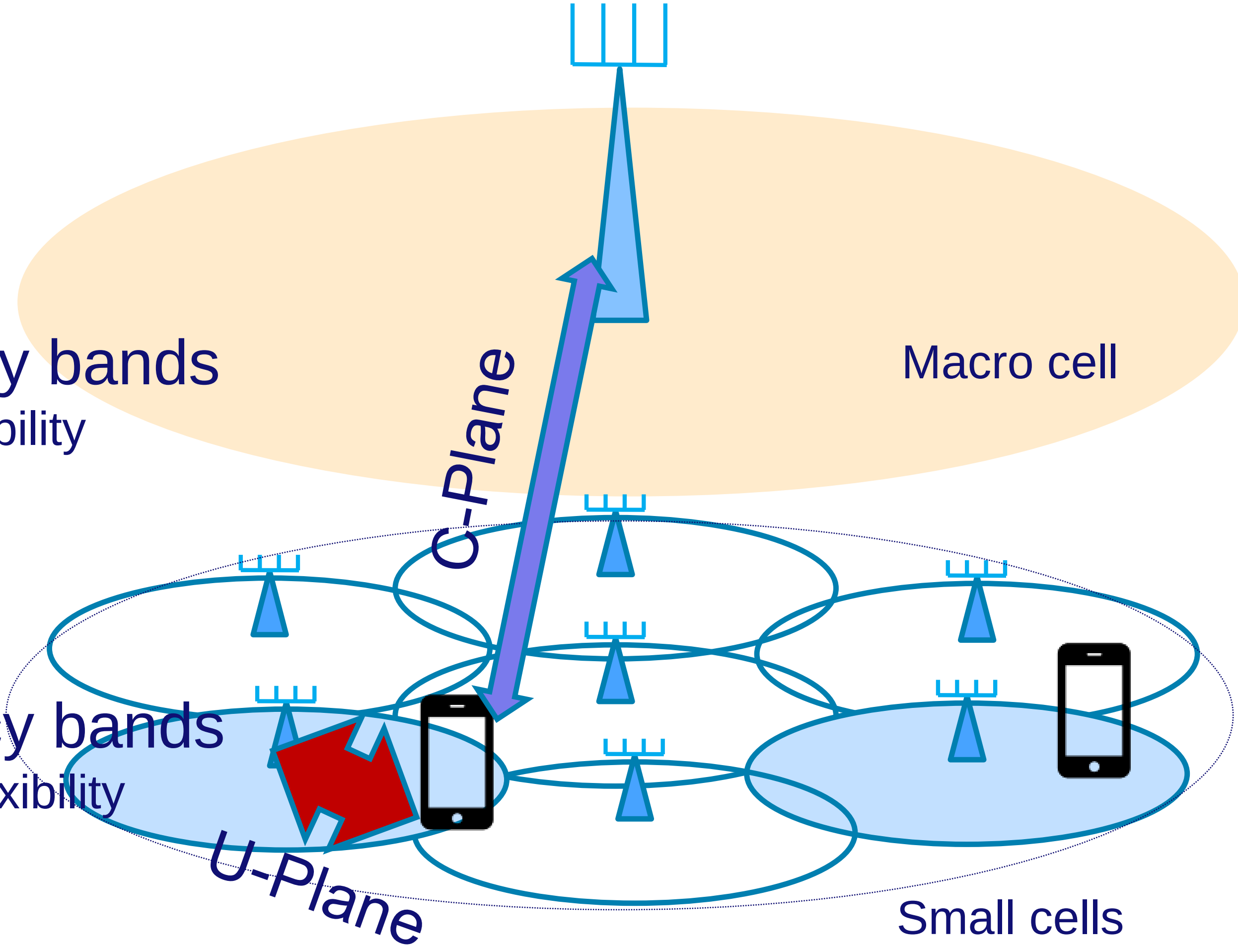
Lower frequency bands

Connectivity and mobility

Higher frequency bands

Higher data rate + flexibility

C/U Plane split



Lower frequency bands

Connectivity and mobility

Higher frequency bands

Higher data rate + flexibility

Energy efficiency: Switching cells on/off according to the demand

5G Key technological components - Network

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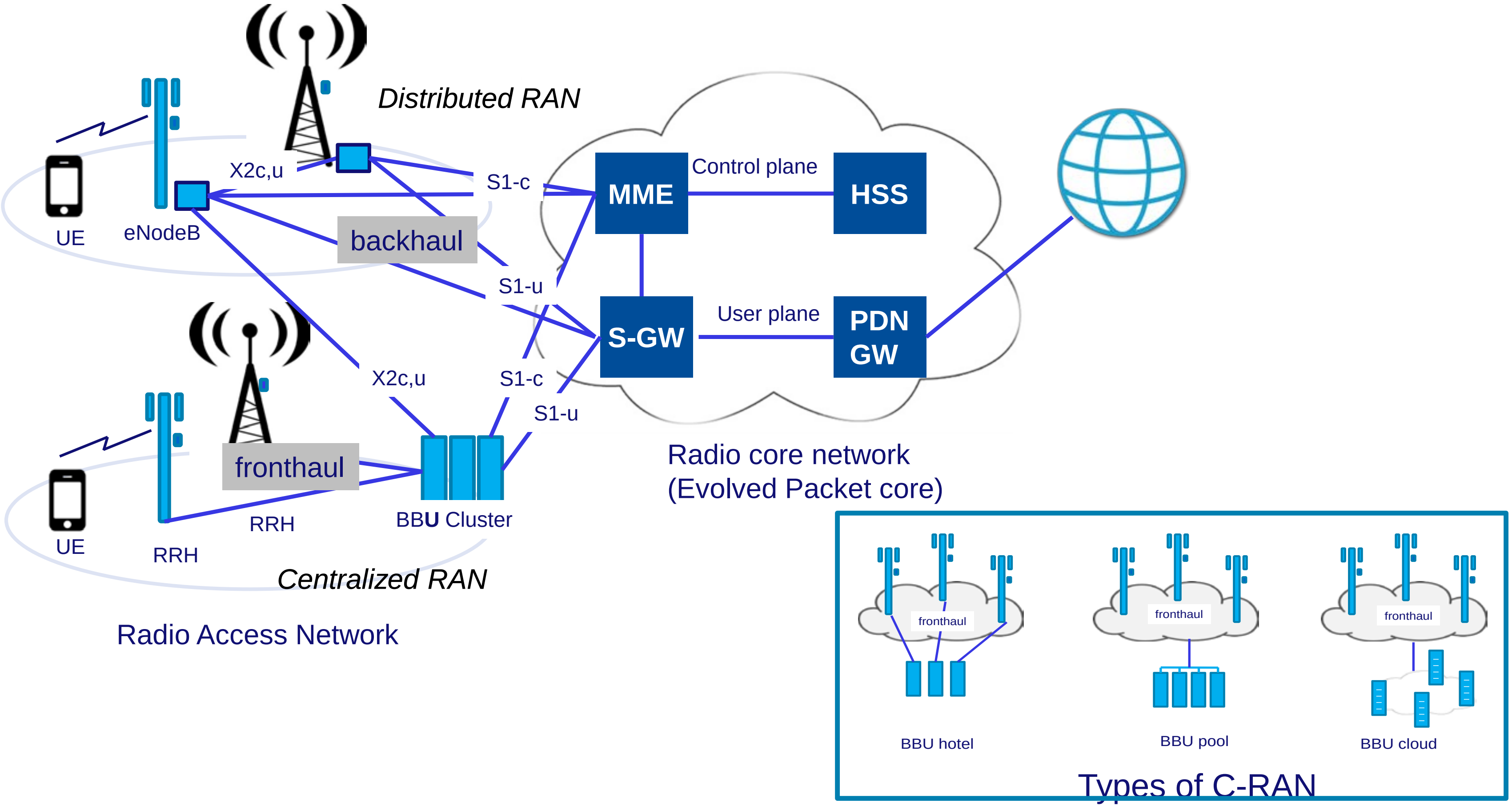
  - **Small cells: picocells and femtocells**
    increase of spectral efficiency, improved coverage, reduction of transmit power
  - **Separation of data and control planes**
    connectivity with two BS: macro for control, small cell for transport
  - **Multiple radio-access technologies**
  - **Device-to-device communication (D2D)**

5G Key technological components - Network

- **Cloud or Centralized RAN (C-RAN)**

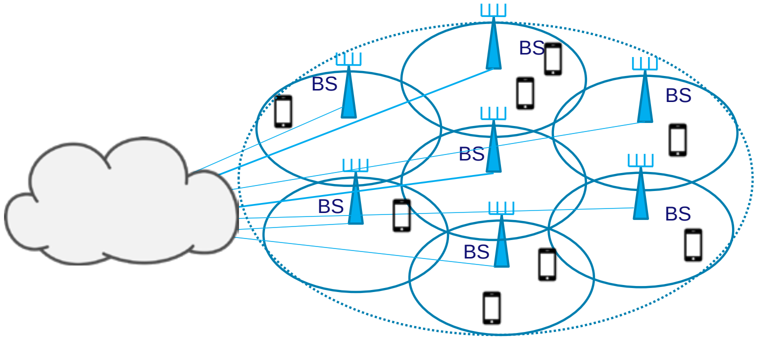


5G Key technological components - Network

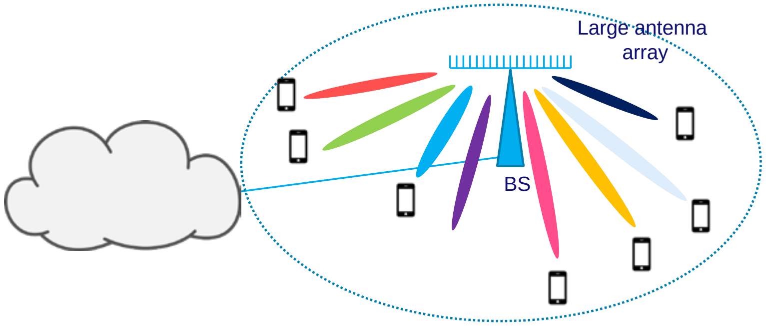
- **Cloud or Centralized RAN (C-RAN)**
  - OPEX and CAPEX benefits
  - Simplified implementation of advanced radio transmission techniques that require inter-cell cooperation
  - Sharing of processing capacity among multiple antenna sites
- **Software Defined (Cellular) Networks**
  - Virtualization - NFV
  - Directly programmable architecture

5G Key technological components - Radio

- **Massive MIMO**
  - Extension to traditional MIMO utilizing a very large number of antennas and spatial multiplexing
  - Several spatial streams
  - Dramatic increase of capacity and improved radiated energy-efficiency



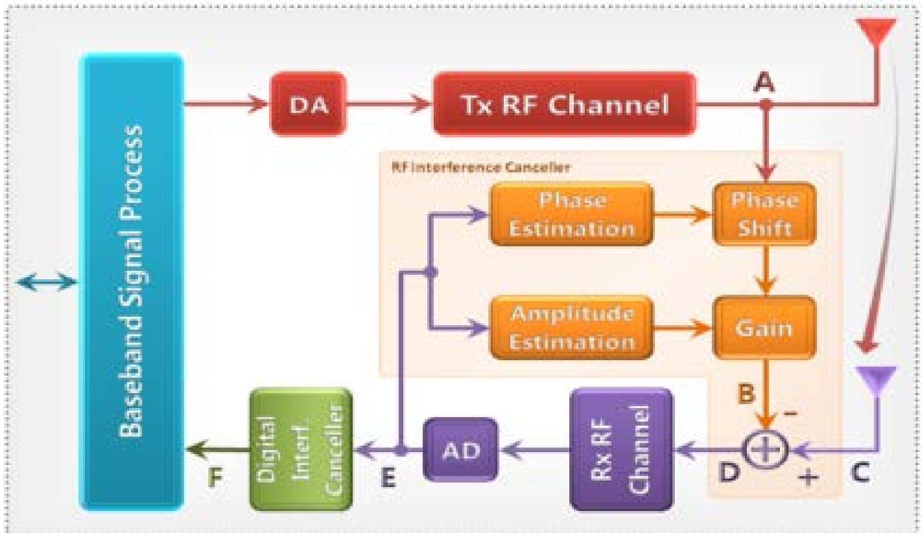
Small cells



Massive MIMO

5G Key technological components - Radio

- **Full duplex**
  - Simultaneous receptions and transmission
  - Doubling spectral efficiency
  - Self-interference cancellation – 120 dB for outdoor

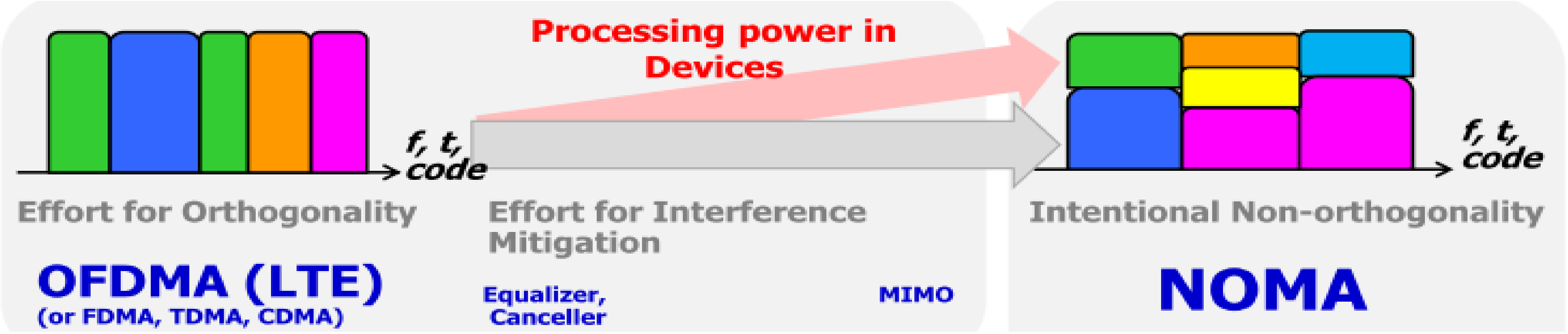


Self-interference cancellation Procedure[1]

[1]*Source: 5G White paper Future Mobile Communication Forum*

5G Key technological components - Radio

- **Alternative Multiple Access**
  - Non-Orthogonal Multiple Access (NOMA)



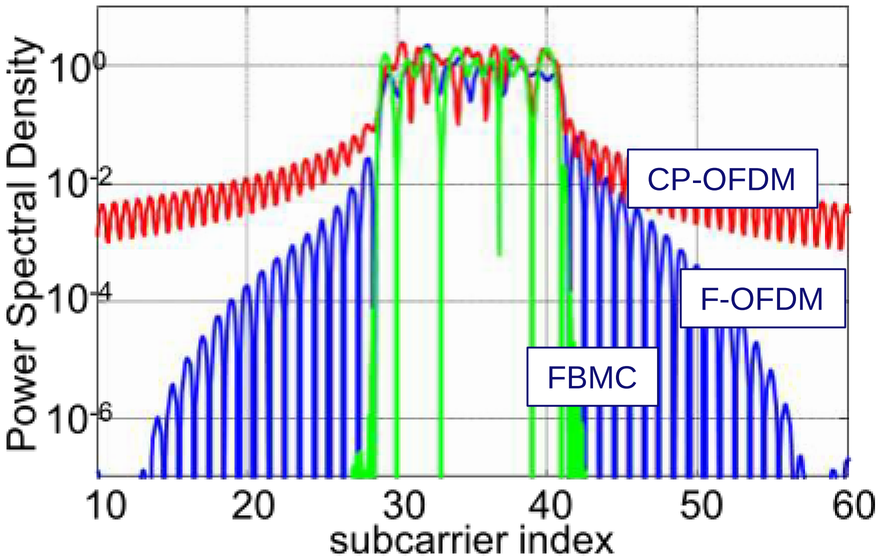
- Increase spectral efficiency
- Combined with SIC at the receiver
- Increase of complexity

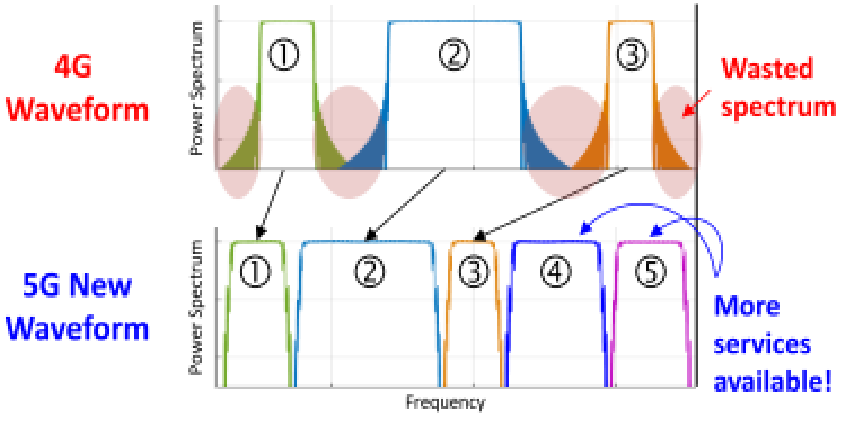
Source: T. Nakemura, Towards 5G Deployment in 2020 and Beyond

5G Key technological components -Radio

- **Alternative waveforms**
  - Flexible waveforms to support both broadband and IoT
  - New waveforms to significantly reduce the out-of-band leakage
    - Filter bank multicarrier and filtered OFDM as alternative to CP-OFDM

Waveform





Source: T. Nakemura, Towards 5G Deployment in 2020 and Beyond

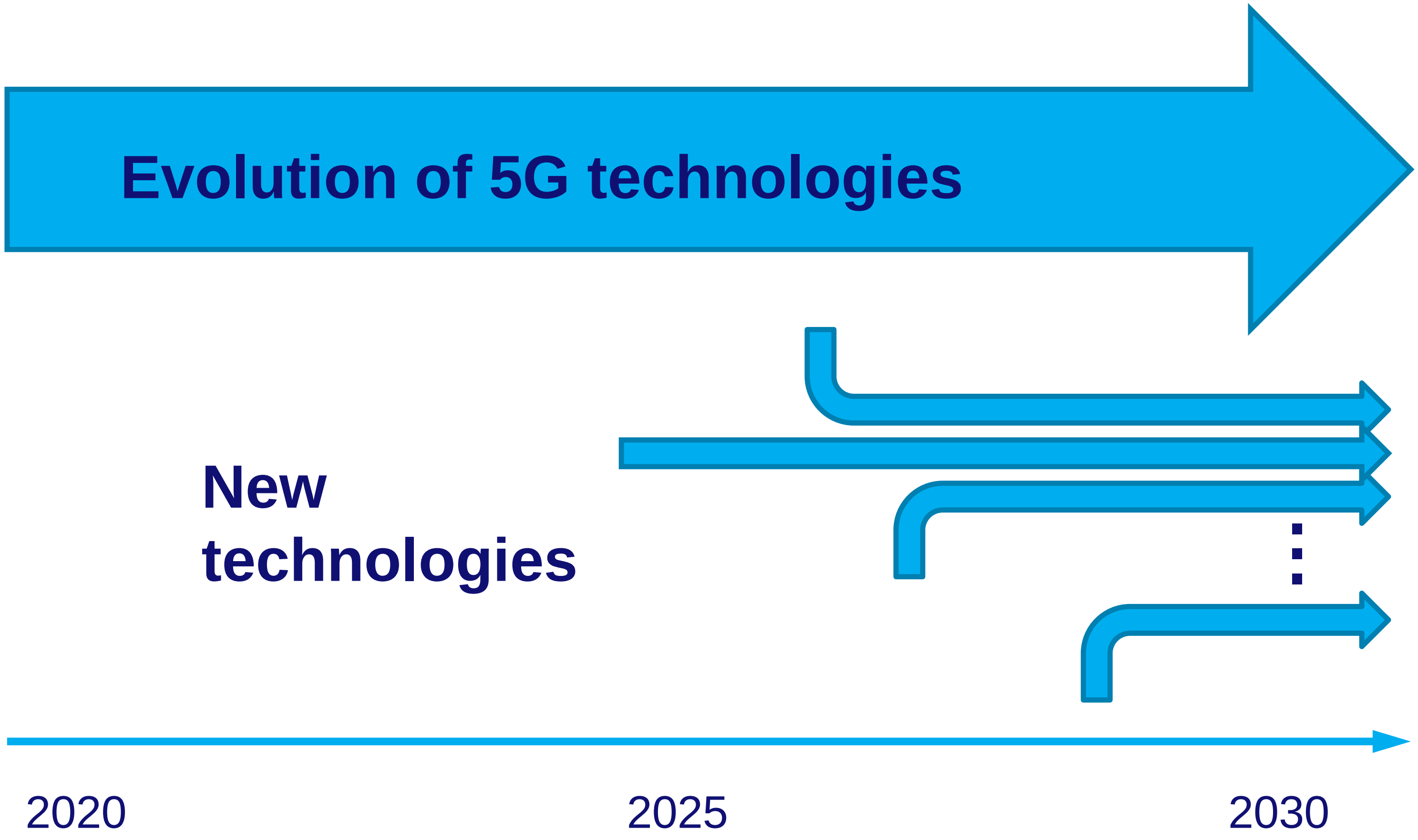
Advanced 5G and Beyond

TECHNOLOGIES

5G + Requirements

- Perception of “Infinite” capacity
  - Ultra-high data rates
  - Massive scalability to millions of devices
- Coverage
  - Ubiquitous consistent user experience in time and location
- Convenience
  - Extreme low latency (interactive services, tactile internet, remote surgery)
  - Long battery life/ ultra-low energy consumption

Wireless Research for Beyond 5G



Evolution of 5G technologies

New technologies

⋮

2020

2025

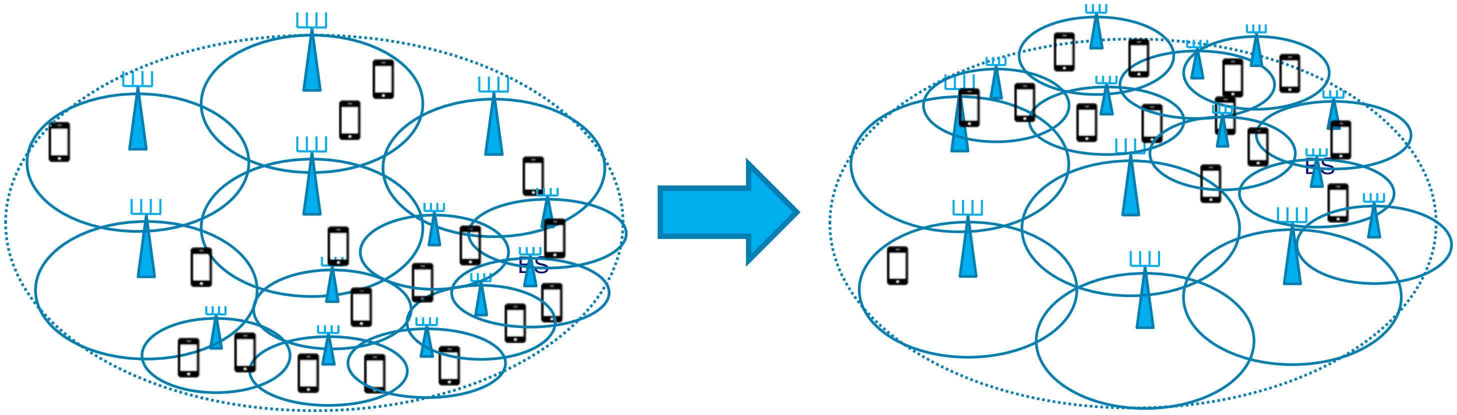
2030

Wireless Research for 5G+ (1)

- Evolutionary techniques
  - Increase spectral and energy efficiency
  - Flexible allocation of capacity
  - Advanced radio coordination techniques, e.g., distributed massive MIMO

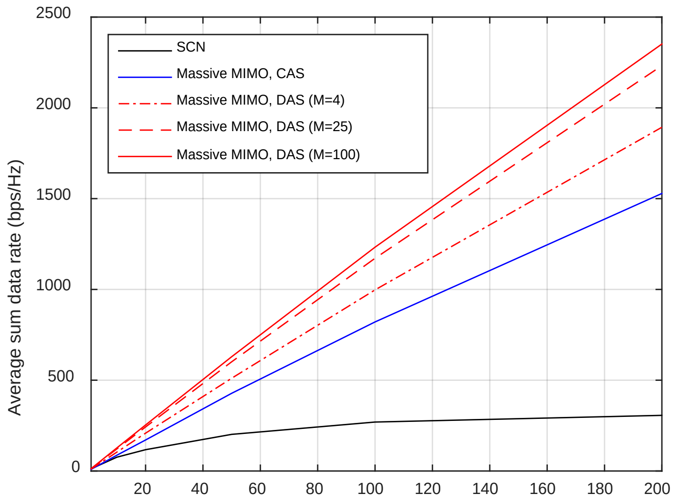
5G+: Flexible allocation of capacity

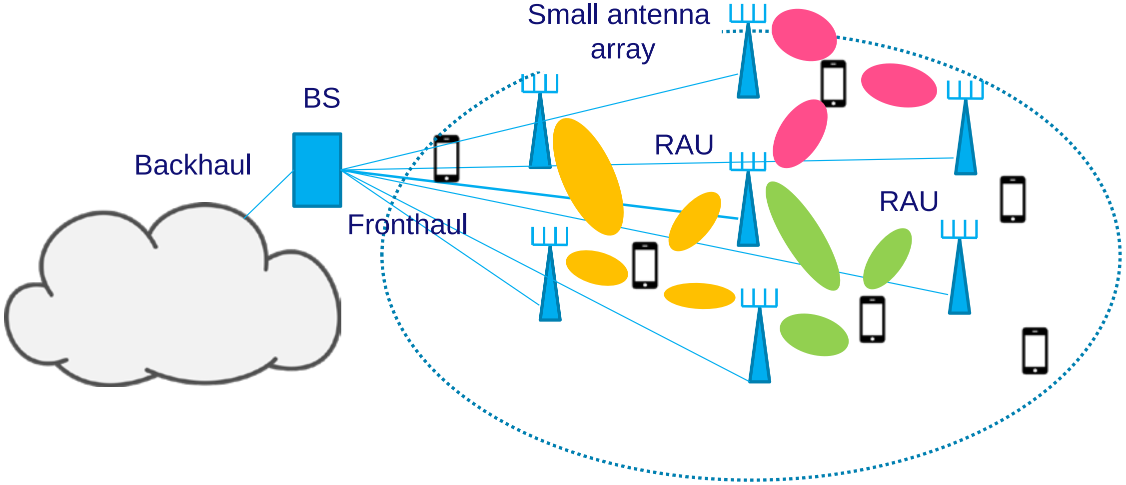
- Radio network dynamic reconfiguration
- Adaptive density of active antennas
- Different network overlays for different traffic classes
- Moving cells
- Wireless back/front haul



5G+: Distributed Massive MIMO

- **Higher energy and spectral performance than centralized**
  - **More channel orthogonality**
  - **Lower transmit power levels**
  - **Mitigation of line-of-sight blockage**





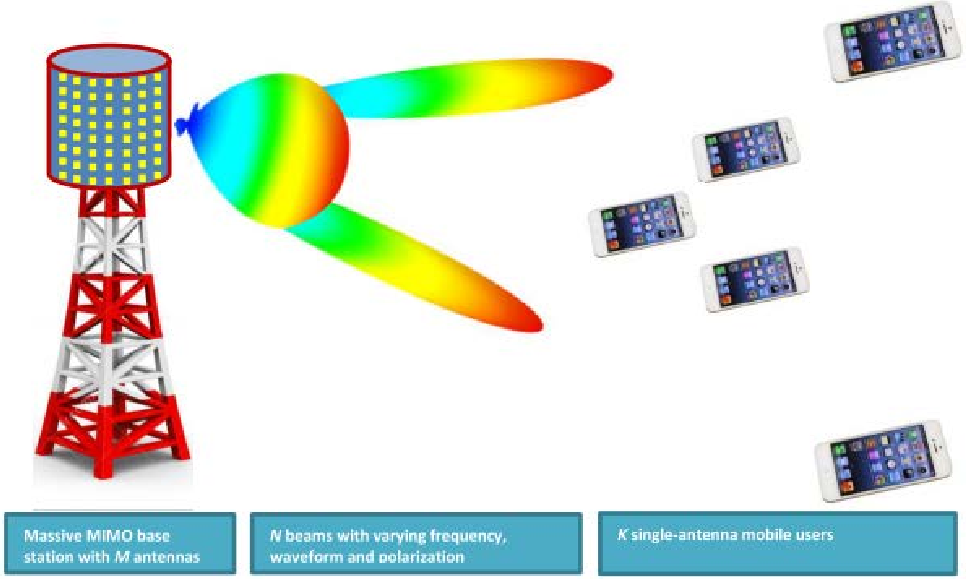
Figures from work Dr. Qing Wang, I.Niemegeers, S.M. Heemstra de Groot massive MIMO vs SCN in indoor environment (100mx100m), total number of antenna elements = 400 and f= 5 GHz

Wireless Research for 5G+ (2)

- **Use of higher spectral bands**
  - **30GHz – 300GHz**
  - **Communication and sensing**
    - Cellular radar
  - **Accurate positioning/localization**
  - **Optical wireless communication**
    - Visible light communication (VLC)
    - IR communication
  - **THz systems for sensing and communications**

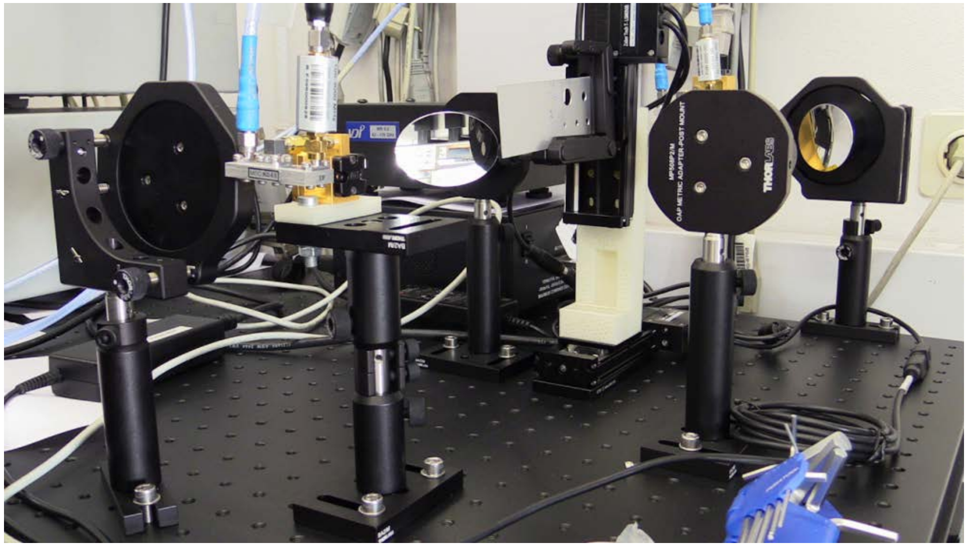
5G+ Antenna technology

- **H2020 SILIKA Project (Prof. B. Smolders)**
  - **mmwave multi-antenna systems for energy-efficient and low cost base stations for 5G wireless infrastructure**



Technologies for very high carrier frequencies

THz Systems



THz lab set up - Dr. M. Matters

presenteerde om het delen van transportmiddelen te faciliteren. Dat is wenselijk, omdat de gemiddelde bezettingsgraad van voertuigen de afgelopen twintig jaar met zo'n 10 % is afgenomen. Sharif Azadeh ontwierp een systeem waarin passagiers kunnen aangeven welke reis (waarheen en wanneer) zij willen maken en of zij

keuze verandert onder invloed van gezondheidsbeleid.'
De hoeveelheid data die je in modellen kunt stoppen lijkt schier oneindig, maar worden ze daar ook nauwkeuriger van? Volgens Chorus zijn eenvoudige modellen op hoofdlijnen vaak al 90 % nauwkeurig. Maar dat maakt die laatste 10 % niet minder interessant. TW
www.heart2016.org/

wege de logistiek en de windbelasting de grootste uitdaging. Het 55 m lange en 560.000 kg wegende val werd met twee drijvende bokken naar een locatie elders gebracht om daar gerenoveerd te worden. Ondertussen worden alle evenwichts- en bewegingskabels van het val vervangen. Eind dit jaar moeten alle werkzaamheden klaar zijn. TW
https://goo.gl/Ys3QGc

Boeken lezen met terahertzstraling

Eerste prototype
Negen pagina's diep

INDRA WAARDENBUG

ICT Onderzoekers van MIT zijn erin geslaagd om met een zelf ontwikkeld systeem door de eerste negen pagina's van een stapel papier te kijken. Het systeem maakt hiervoor gebruik van terahertzstraling, elektromagnetische straling met een golflengte tussen die van infrarood- en microgolfstraling. Met hun onderzoek, waarvan zij de eerste resultaten onlangs publiceerden in het blad Nature Communications, bouwen de wetenschappers voort op een technologie om door enveloppen heen te kijken zonder deze te openen.
Het prototype bestaat uit een terahertzcamera die ultrakorte pulsen uitzendt. Een ingebouwde sensor in de camera detecteert de reflectie van deze pulsen. Deze reflectie ontstaat doordat er zich minuscule luchtzakjes van 20 µm diep tussen de pagina's bevinden. Het verschil in refractie tussen lucht en papier zorgt voor de terugkaatsing van de terahertzstraling. Met behulp van een door de onderzoekers ontwikkeld algoritme blijkt de afstand tussen de verschillende bladzijden te bepalen. Hierbij kijkt het systeem naar de tijd tussen het uitzenden en het ontvangen van de straling. Daarnaast is het algoritme in staat om letters te identificeren, zelfs als de beelden vervormd zijn, of er delen van letters ontbreken.
Met het prototype konden de onderzoekers succesvol door de eerste twintig pagina's komen. Doordat het signaal deels wordt geabsorbeerd en deels heen en weer kaatst tussen de verschillende pagina's, is het signaal echter na negen pagina's zo zwak dat achtergrondruis het overstemt.
De onderzoekers willen nu de nauwkeurigheid van de detectoren verbeteren en de stralingsbron versterken. TW
https://goo.gl/rWDg7H

BARMAK HESHMAT

THz Imaging

Terahertz band: Next frontier for wireless communications

Wireless Research for 5G+ (3)

- **Network intelligence/cognitive networks**
  - To deal with extreme large number of devices
  - To deal with high level of system complexity and uncertainties
  - Machine learning techniques
  - Self-organizing systems/autonomous, and self evolving systems

Network intelligence

- **Cognitive networks (Prof. A. Liotta)**
  - Automatic anomaly detection based on machine learning (running directly inside the sensor).
  - IoT playground with accurate monitoring, logging and analytics

Wireless Research for 5G+ (4)

- **Device miniaturization**
- **Extreme low power/ battery-less**
  - Cell powered devices and systems
- **Wearable electronics, flexible electronics, implantable electronics**

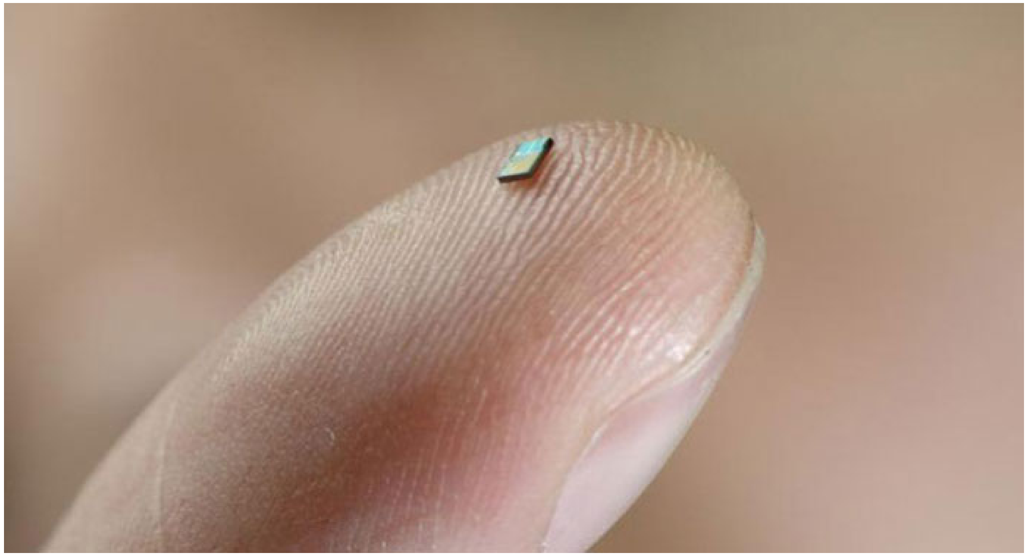
  In-body, on-body, from-body communication
- **Intelligence/sensing/communication embedded in the body and in the environment**

Extremely low-power devices

- **Pushing the limits of miniaturization and ultra-low power**

  CWTe –Premiss (Dr. Hao Gao)

  60GHz energy harvesting temperature sensor

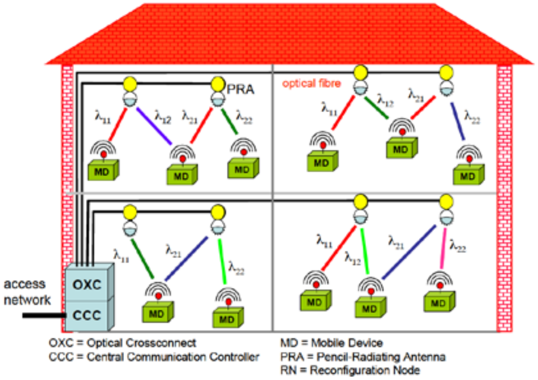


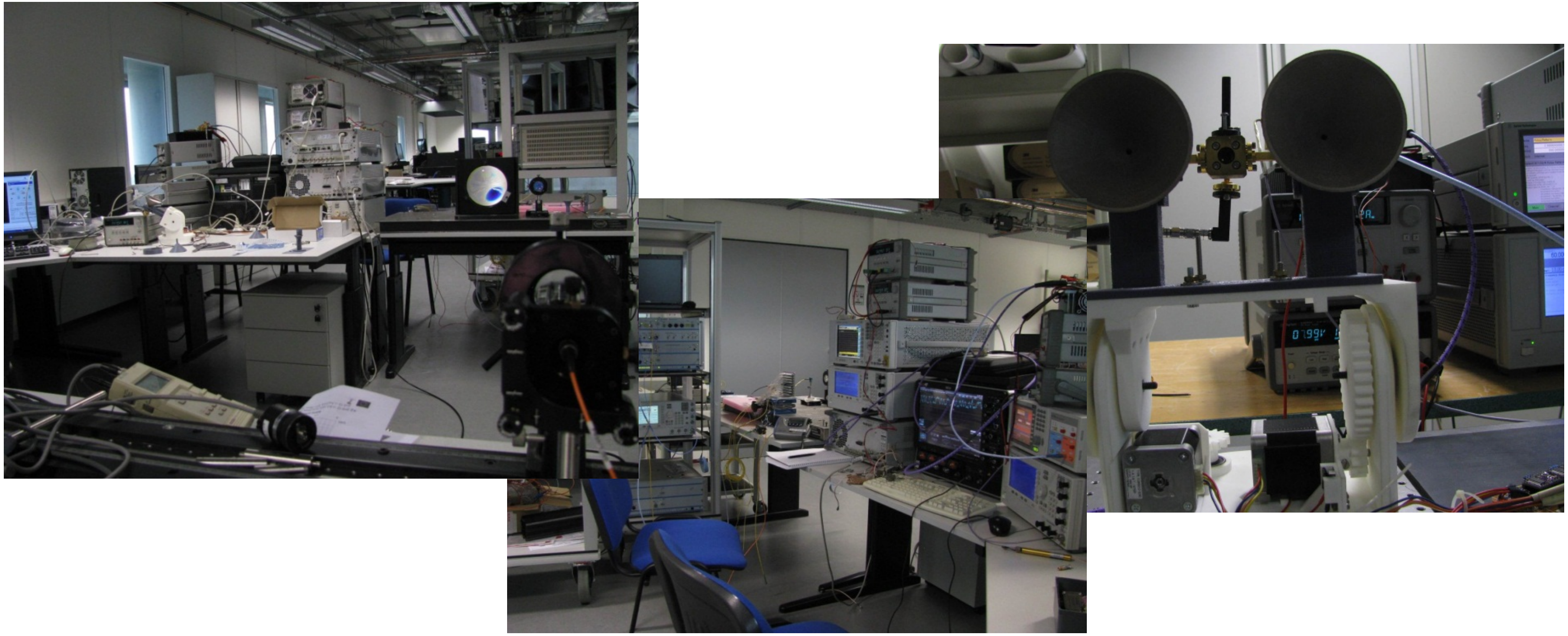
Wireless Research for 5G+ (5)

- **Close interworking wireless/optical communication**
  - Optical will be needed because of capacity and latency
  - Dynamic transport/routing for provision of capacity on demand
  - Optical-wireless communication

Optical technologies

- **Browse project – T. Koonen et al**
  - Multiple dynamically-steered free-space optical beams
  - flexible mmwave radio communication techniques

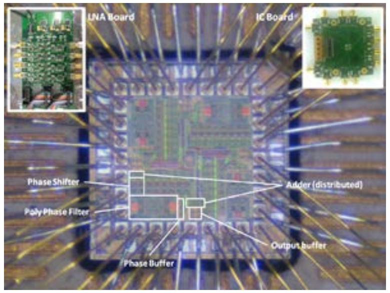




CWTe
ROLE AND AMBITION

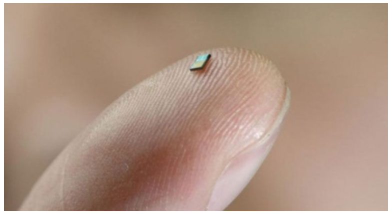
CWTe Programs

- **Ultra-high data rates**
  - High Frequencies (>= 60GHz)
  - High data rates (1Tbps)
  - Beamforming with many elements @ low cost



Integrated beamformer in CMOS

- **Ultra-low power**
  - Small (<< 1mm^3)
  - Low-cost
  - Battery-less sensors/controls

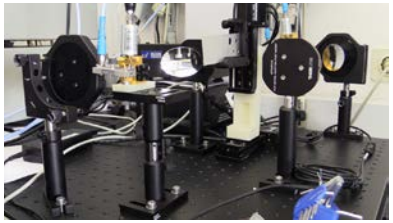


Premiss sensor

- **THz Systems**
  - small, low-cost short range

    3D spectroscopic imaging

    Communication



THz lab setup

Architectures, algorithms and protocols to create dynamically adaptable, energy efficient and reliable networks offering on-demand the full range of services required by 6G applications as those above

UHDR Roadmap Top Level

Vision

Broadband multimedia messaging

Extreme HD video steaming

Holographic watch

Haptic holography

Virtual teleportation

Seemingly infinite capacity everywhere

Technologies

Large MIMO
Cell densification
Self organizing networks
RoF

Distributed Massive MIMO
Massive autonomous networks

THZ communication

Instantaneous networks

Nano antennas
Nano transceivers

THz channel models

Optically-supported communication techniques

In-body wireless networks

Unified spectrum use

Ultra-high resolution positioning

Zero latency communications

Integrated sensing and communication

Probabilistic approaches

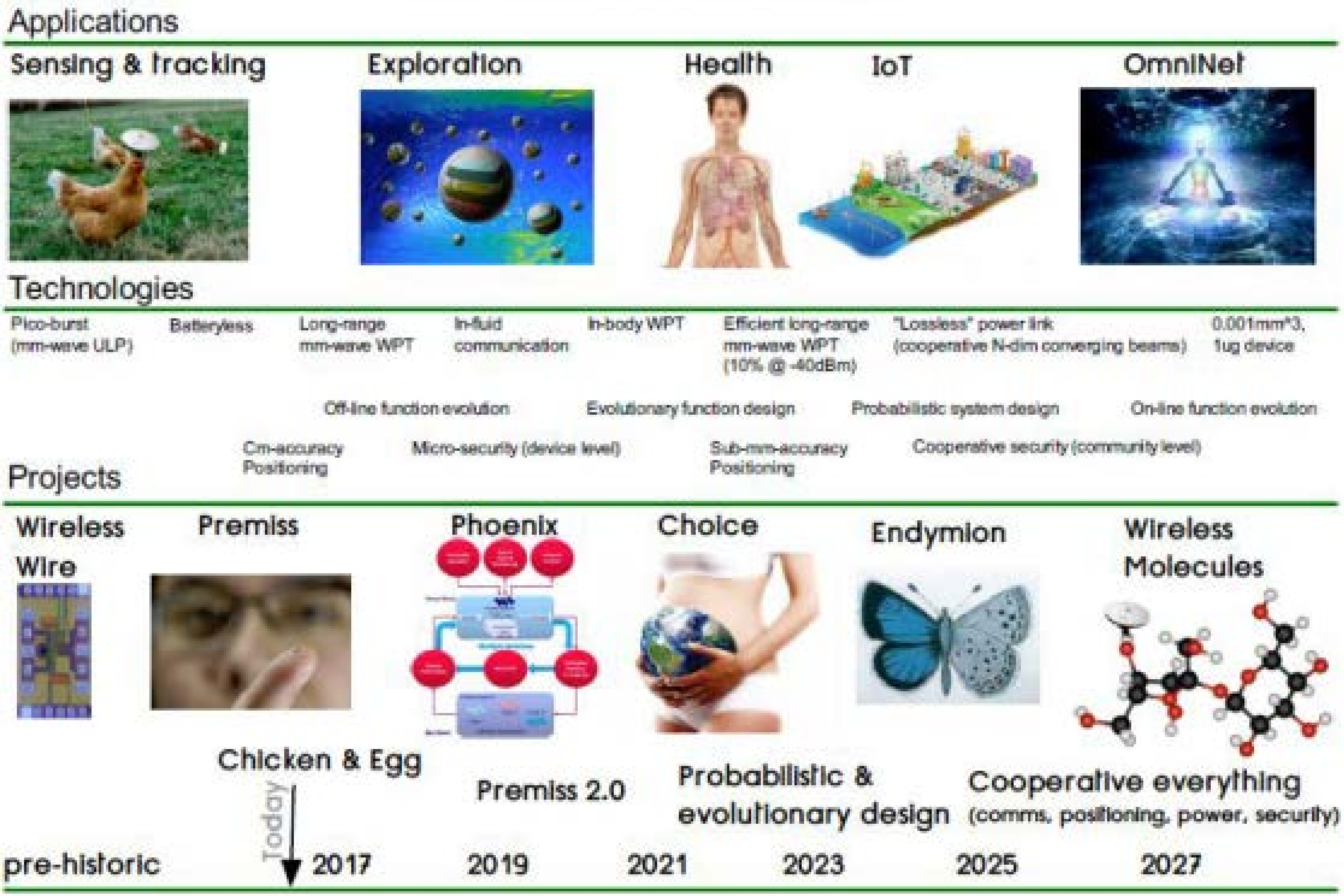
Evolutionary networking

Privacy and security enhancing techniques

Evolutionally subsystems

2017 **2019** **2021** **2023** **2025** **2027**

ULP Roadmap Top Level



Applications

Sensing & tracking

Exploration

Health

IoT

OmniNet

Technologies

Pico-burst (mm-wave ULP)

Batteryless

Long-range mm-wave WPT

In-fluid communication

In-body WPT

Efficient long-range mm-wave WPT (10% @ -40dBm)

"Lossless" power link (cooperative N-dim converging beams)

0.001mm^3, 1ug device

Off-line function evolution

Evolutionary function design

Probabilistic system design

On-line function evolution

Cm-accuracy Positioning

Micro-security (device level)

Sub-mm-accuracy Positioning

Cooperative security (community level)

Projects

Wireless Wire

Premiss

Phoenix

Choice

Endymion

Wireless Molecules

Chicken & Egg

Premiss 2.0

Probabilistic & evolutionary design

Cooperative everything (comms, positioning, power, security)

Today

pre-historic

2017

2019

2021

2023

2025

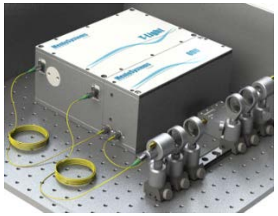
2027

Centre for Wireless Technology Eindhoven

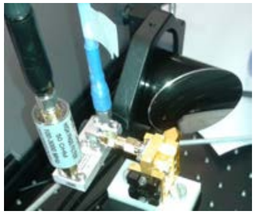
THz Systems Roadmap Top Level

Expert lab equipment → Professional equipment → Autonomous sensors → Consumer

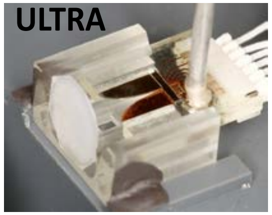
THz-TDS



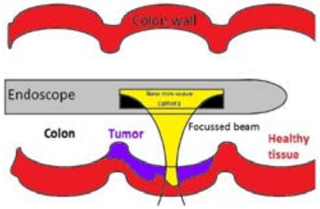
Free-space



Integrated spectrometer



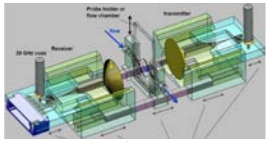
THz-endoscope



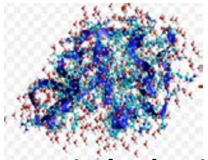
Integrated into other equipment
Implanted into the body
Non-expert use enabled
Integrated signal processing/computing

THz Analysis → THz manipulation

Company: Swissto12



Micro-fluidics



Protein hydration sensing

THz medication

Performance
Sensitivity/Selectivity/Miniaturization

Accessibility : Ease of use / Price

Lab Analysis

Solid material analysis

Contaminant detection e.g. water, metal particles

Gas analysis

Microfluidics

Nonlinear spectroscopy

Living cells/bacteria

Molecular interaction (e.g. drug-protein, antibiotic-bacteria)

Medical

Pathology

THz endoscopes, catheters, guidewires

Implantable sensors

THz sensor surface

Body fluid analysis (e.g. blood)

Breath analysis

Process control

Layer integrity, paint/coating

Contamination detection: e.g. metal particles

Food control

Solvation dynamics

Humidity + drying process control: paint/powders/food/ wood/paper

Medication testing

Consumer

Air-quality

Spectroscopy on mobile devices

Home healthcare

Food quality

Cosmetics / skin care

Electronic pills

CONCLUSION

Final Remarks

- 5G is a big step to advance wireless systems
- Still a lot to be done to accomplish the vision
- But we will need a lot more to enable extreme broadband, ultra reliable, extreme low latency, and ultra low energy wireless systems
- CWTe working on key research areas
  - Using interdisciplinary approach because
    - Technology for the future is not enough
    - To achieve the vision we need to work towards future systems

Thank you!