6G: Requirements, Enabling Technologies, Use Cases and Impact on Future Internet Architecture

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The 15th Workshop on Mobility in the Evolving Internet Architecture (MobiArch)
ACM MobiCom 2020

Centre for Advanced Communications, Mobile Technologies and IoT @ University of Sussex

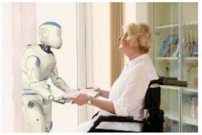
University of Sussex

- Founded in 1961
- 15,000 students from over 140 countries, 1/3 postgraduates
- 35% international students
- 3 Nobel Prize Winners
- 12 Schools

30mm

Sensors/IoT

V2X



Health and Care

Content

- Where are we with 5G?
  - 5G standardisation
  - 5G Spectrum
  - 5G mm-wave technology
- Use cases beyond 5G/6G
- Beyond 5G/6G enabling technologies
- Native AI for 6G Radio access design
  - Deep Neural Networks for model-free PHY design
- Harnessing THz Spectrum for beyond 5G/6G
  - Reconfigurable meta-surfaces for THz beam-forming and beam tracking
- Internet evolution beyond-5G
- Conclusion and collaboration opportunities

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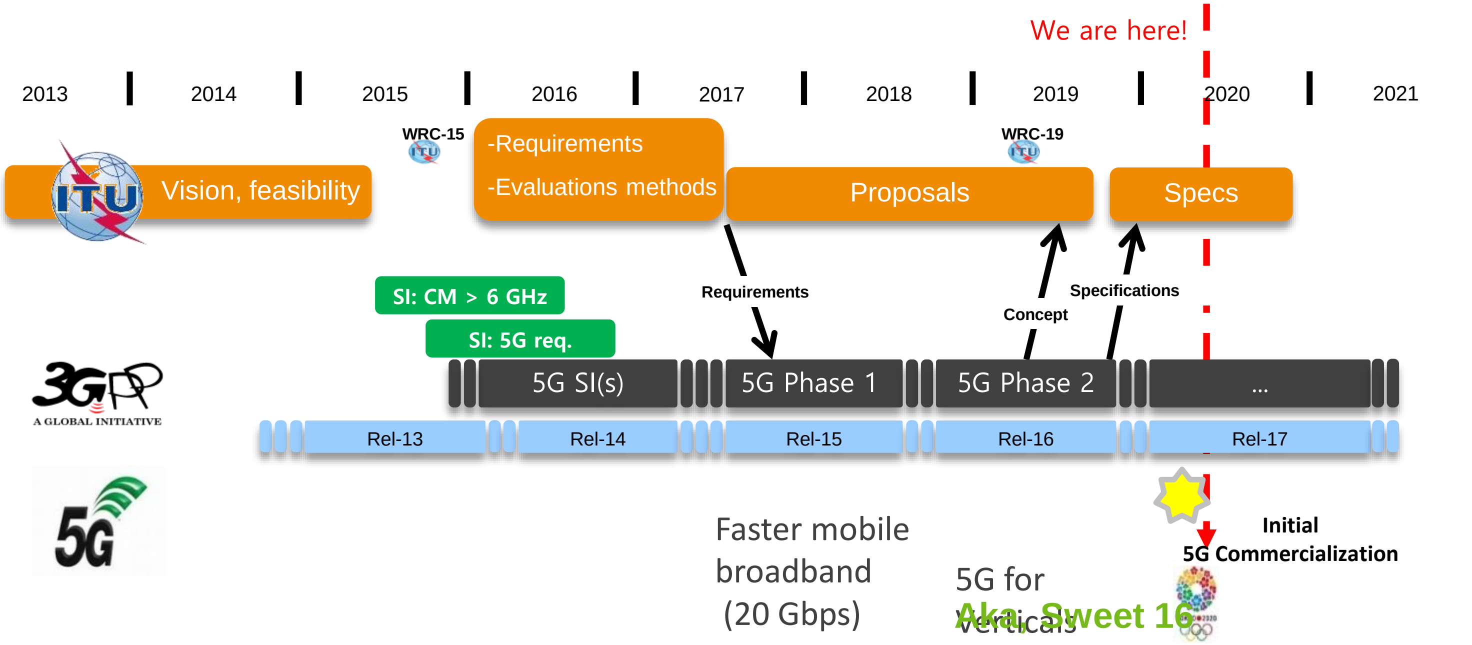
5G Industry Timelines



3-6 months delay due to covid-19 is expected

5G spectrum allocation

600 MHz	LTE/5G	North America
700 MHz	LTE/5G	APAC, EMEA, LatAm
3.3-3.4	LTE/5G	APAC, Africa, LatAm
3.4-3.6	LTE/5G	Global
3.55-4.2	LTE/5G	US
3.6-3.8	5G	Europe
4.5	5G	Japan China
28	5G	US, Korea Japan
39	5G	US
24.25-27.5	5G	WRC-19 band
31.8-33.4	5G	WRC-19 band (Fra, UK)
~40,~50,~70	5G	WRC-19 bands

3GPP Rel 17

Full coverage with <1 GHz

Dense urban high data rates at 3.5 – 4.5 GHz

Hotspot 10 Gbps at 28/39 GHz

Future mmwave options

IoT

Fixed-Wireless Access e.g. Verizon

Towards 6G

~Tbps peak data rate

6G Requirements

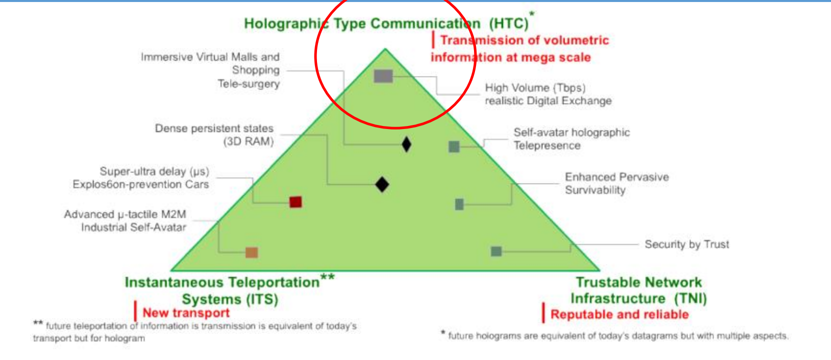
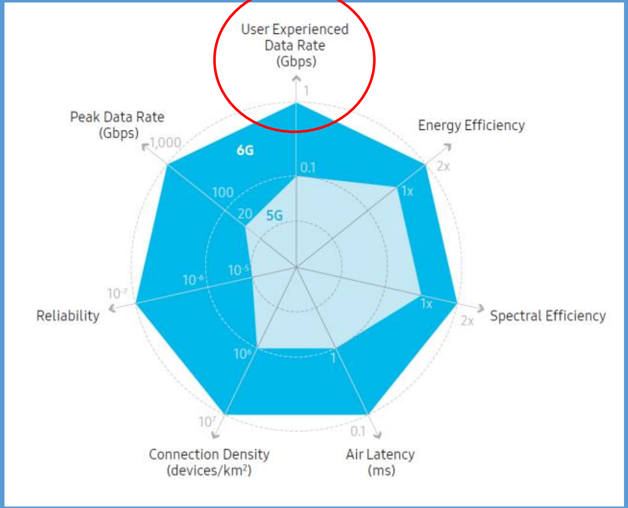


Figure 4: Capabilities for the Future applications

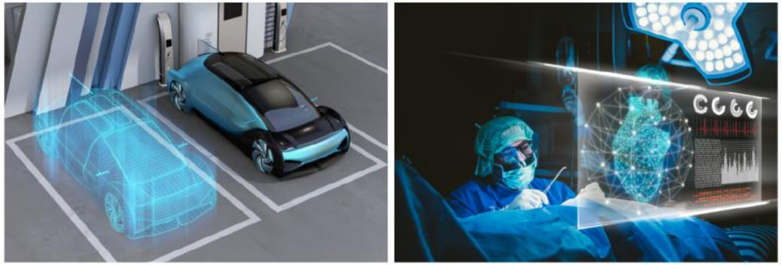


Source: Huawei Internet 2030 Vision (2019)

Source: Samsung 6G Vision (July 2020)

6G Use Cases (ultra high data rate)

Holographic Communications



Digital Triplet/Digital Human

Throughput goes up

4K/8K HD: 35Mbps~140Mbps → band width → VR/AR: 25Mbps~5Gbps → band width → Hologram: 4 Tbps~10 Tbps

To duplicate 1mX1m area for digital twin we may need 0.8Tbps assuming 100ms periodic updates

Horizon Europe

NetWorld 2020

New Technologies for “New Verticals”

Future Digital Health and Care

Future Transportation

Future Robotics

Future interfaces

Smart Networks and Services

New Working Group
All welcome

Artificial Intelligence and Machine Learning for Core and RAN

Native AI for Beyond 5G/6G

AI at the RAN:

- Intelligent initial access and handover
- Dynamic beam management with reinforcement learning
- **Physical Layer Design with deep neural networks**

AI at the fronthaul

- Traffic pattern estimation and prediction
- Flexible functional split for C-RAN

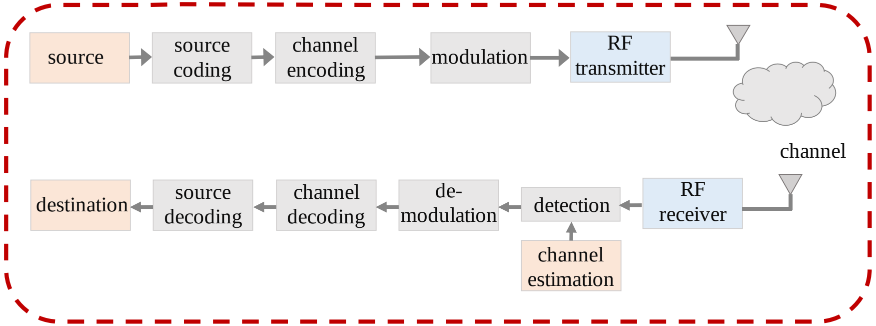
AI at the core:

- Automated operations
- Next generation NFV and SDN
- Reconfigurable core-edge split
- **Cognitive core**

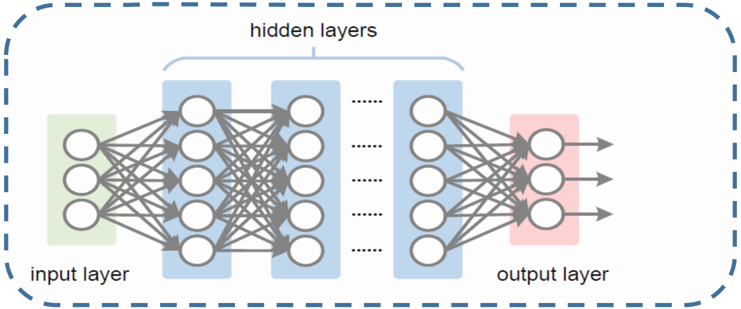
Other general AI applications (RAN, Core or end-to-end network)

- Energy efficiency according to dynamic traffic pattern etc.
- End to end service orchestration and assurance (customized SLA for example)
- End to end Service optimization, prioritization

- **Conventional PHY Design (3G, 4G, 5G)**
  - 3G and 4G design was for known applications (voice, video, data) and deployment scenarios
  - 5G should work for yet unknown applications (verticals) and deployment



- **AI- Based PHY (beyond 5G/6G)**
  - Holistic optimization of the entire PHY processing blocks
  - Data-driven, end-to-end learning solution so reduces design cycle
  - Can adapt to changing applications and deployment environments (including channel)
  - Data-driven, end-to-end learning solution so reduces design cycle



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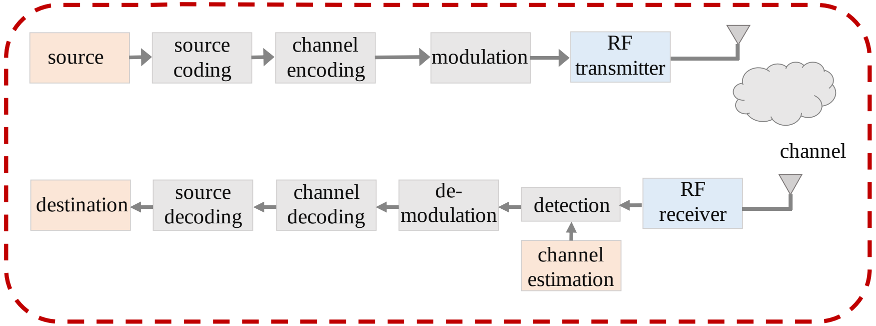

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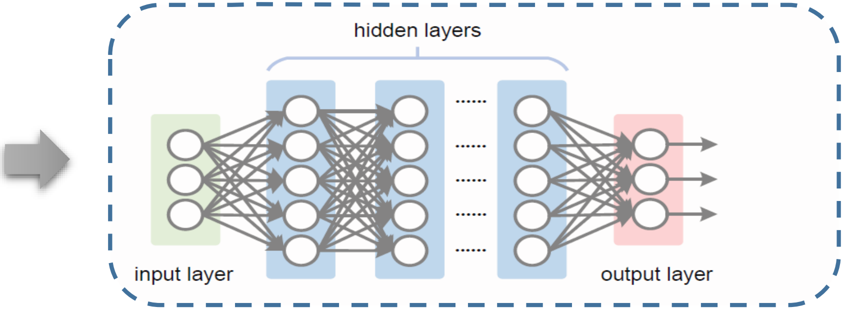

Algorithms

The structure of the AE:

Block name	Layer name	Output Dim
Block name	input:	M
	Dense+eLu	M
	Dense+Linear	$2n$
	nomalization	$2n$
Channel	Noise	$2n$
Decoder	Dense+ReLU	M
	Dense+Softmax	M

Name	$[\sigma(u)]_i$	range
ReLU	$\max(0, U_i)$	$[0, \infty)$
Tanh	$\tanh(U_i)$	(-1, 1)
Softmax	$\frac{e^{u_i}}{\sum_j e(u_j)}$	(0, 1)

The ARL algorithm estimates the interference (α).

With the predicted α, channel function is updated. Then signals are decoded.

The proposed ADL algorithm:

Algorithm 1: DRL to predict the interference

Input : • AE model and specifications: n, k, batch size, epochs number, optimizer, learning rate, etc
• the training data set l_{in}
• the variance of channel noise σ^2

Output: • the estimated interference parameter α

Initialize:
Set AE model parameters (e.g., $n \leftarrow 4$, $k \leftarrow 4$, $M \leftarrow 4$)
for i in range (training data samples) **do**
  Set $x = f(s_i) \in \mathbb{R}^{2n}$, $s_i \in \{1, 2 \ldots M\}$, encoding
  Create and Set $\hat{y}(n)$ for receiver layer
  for i in range (numble of guessing α) **do**
    DNN layer to training the data set
    Recovery pilot signal $\hat{s}_i$ according to a guessing α
    Calculate *reward* $\hat{R}_i$ according to Eqs. (5) and (6)
Set confidence interval of $\hat{R}_i$ and predict α
Update DNN layer with α according to Eqs. (7) to (10)

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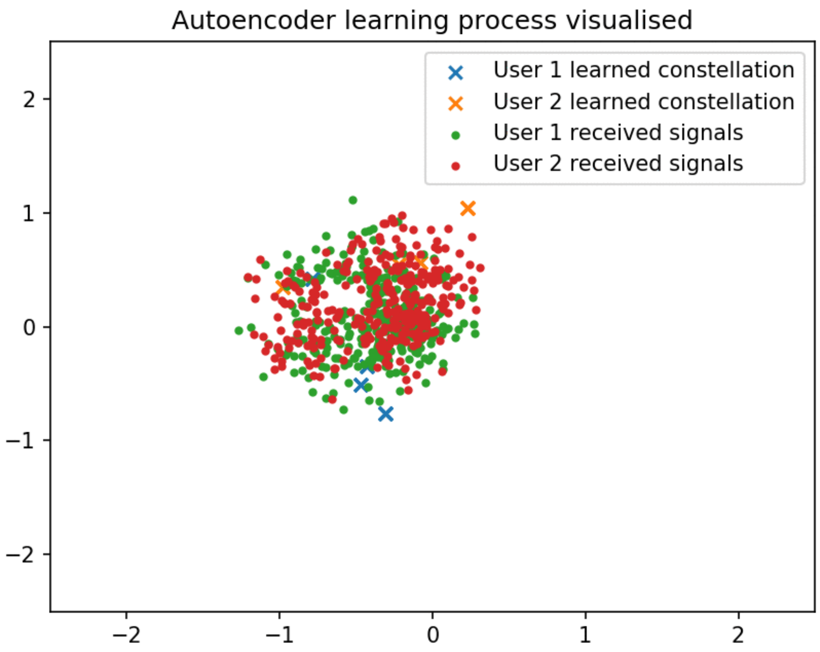
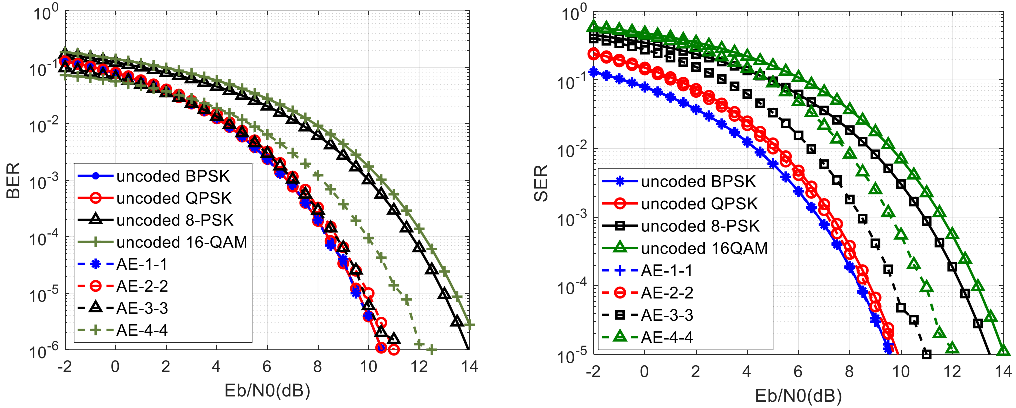
Two-user DL based distributed auto encoder implementation

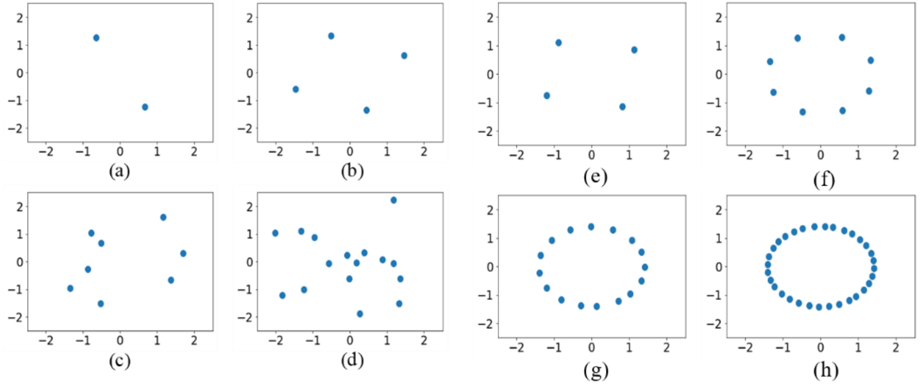


- An Deep Learning based auto encoder for the scenario of a two-user interference channel: the visualization demo of the constellation evolving as the network learns, alongside the received signals for each user.

Numerical results and analysis



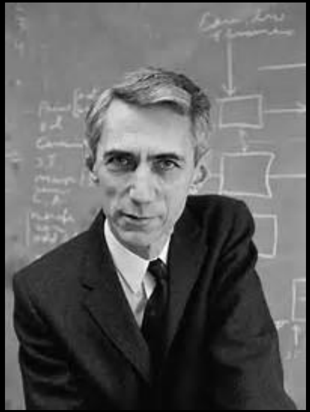
Bit error rate and symbol error rate vs SNR (E_b/N_0) for the AE and other modulation schemes (single user case).



Learned AE constellation produced by AE for single user case: (a) AE-1-1, (b) AE-2-2, (c) AE-3-3 and (d) AE-4-4. (e) AE-1-2, (f) AE-1-3, (g) AE-1-4, (h) AE-1-5.

Towards terabit per second mobile connectivity

Shannon Capacity Formula



Claude Shannon
A Mathematical Theory
Of Communications
1948

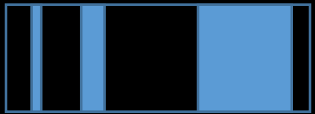
bandwidth of the channel

$$C = B \log_2 (1+S/N)$$

Channel capacity in bits/s

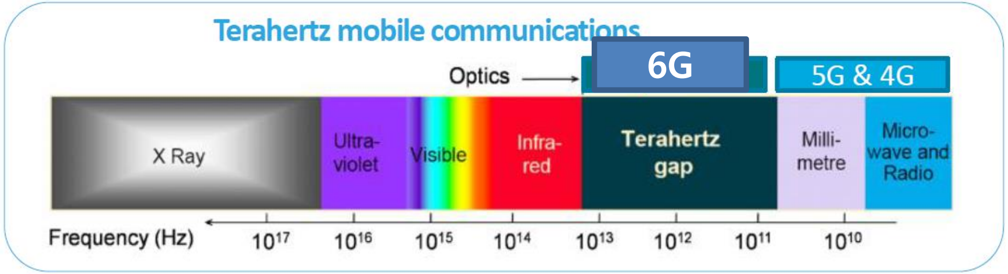
MIMO, OAM

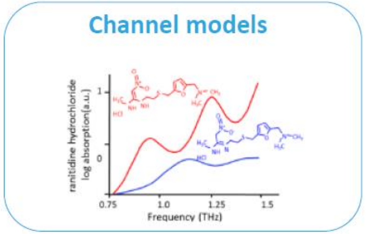
signal-to-noise ratio

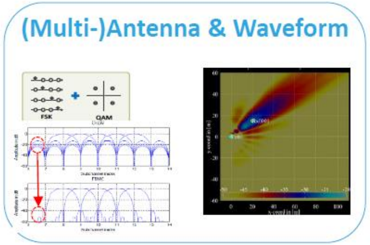


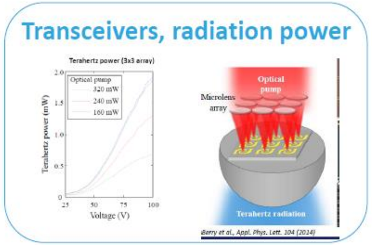
Where to find new spectrum for 6G?

- WRC19 agenda item 1.15 "Possible use of the band 275-455 GHz by land mobile and fixed services"
- 17 Mar 2019 - The **FCC** has unanimously voted to clear "terahertz wave" frequencies for experimentation that could one day represent **6G** connectivity.
- 17 Jan 2020 – **Ofcom** We are proposing to enable greater access to Extremely High Frequency (EHF) spectrum in the **100**-200 **GHz** frequency range...





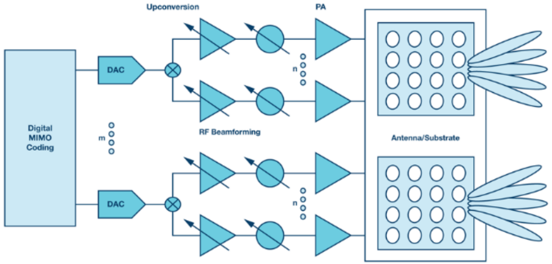




Three fundamental RF challenges of THz communication for 6G

The 6G Multi-Antenna Technology Challenge

5G multi-antenna technology: Phased array antennas with hybrid beamforming



Hybrid beamforming/Digital beamforming

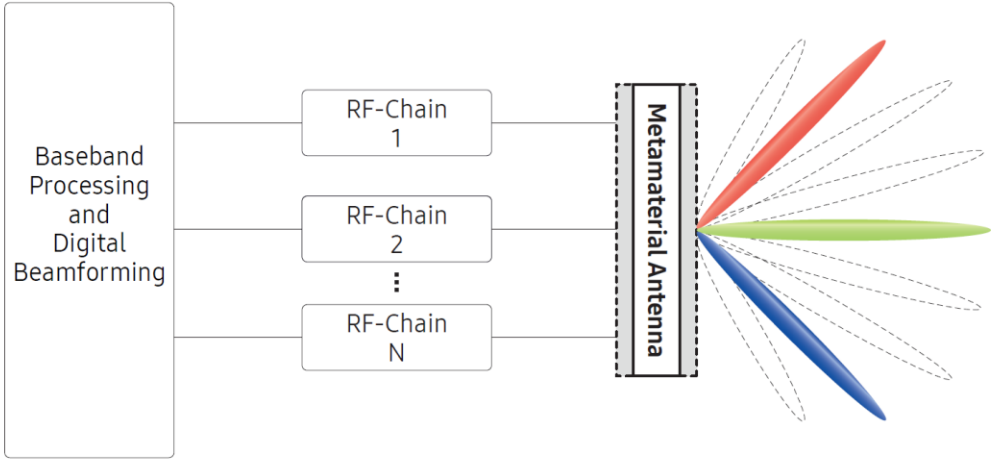
- **Scalability!**
- **Energy consumption**
- **Complexity**

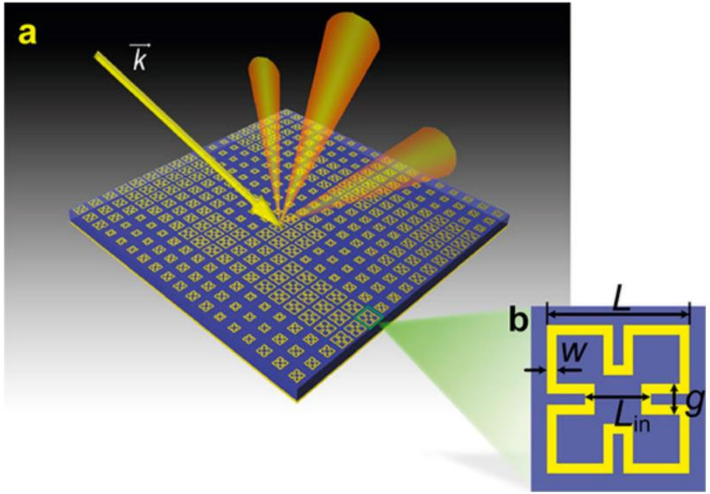
250m @28 GHZ

Samsung 5G Fixed-Wireless Access Trials, London 2018, 1024 antenna elements!

Frequency	Relative Pathloss	Antenna Gain (linear domain)	#Antenna Elements
2.8 GHz	1 (as reference)	1	~1
28 GHz	100	100	~1000
280 GHz	10000	10000	~100,000

Meta surfaces for THz antenna technology

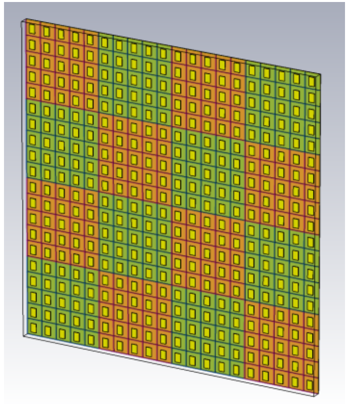




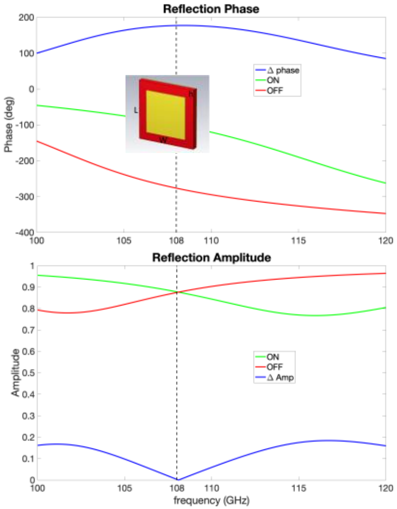
Hybrid Beam-forming with meta-surfaces

Reconfigurable meta-surface reflect array

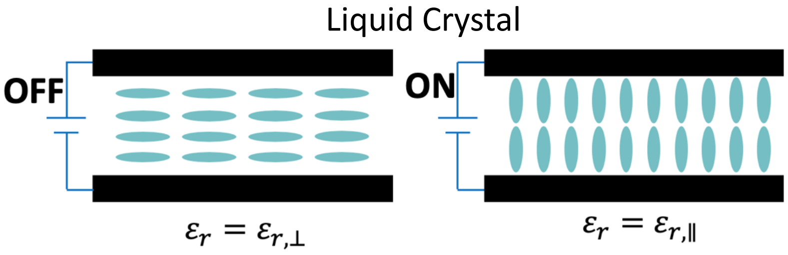
▪ Liquid Crystal Based Reconfigurable Metasurface



Full device: the simulated full device consists of 20x20 semi-passive patch antenna elements, each containing a LC substrate that is electronically controlled via biases.



Unit cell: the unit cell has 2 states: ON/OFF. The reflection phase/amplitudes are optimized for these 2 states at the operation frequency of 108GHz



Liquid Crystal (LC): the liquid crystal substrate is controlled via voltage bias, aligning the molecular orientations of the LC, which in turn changes the effective permittivity of LC. This change in the substrate permittivity shifts the resonant frequency of the antenna, and given the that incident wave is kept at the same frequency of 108 GHz, the effect of change in permittivity is translated into change in phase, which is essential to shaping the wavefront.

- Amplitude optimized for maximal value and minimal difference between ON/OFF state
- Phase optimized for 180 degree difference between ON/OFF

Cross-platform routine

Algorithm 1: Matlab script to optimise unit cell dimensions

Input: S11p - S11 phase; S11a - S11 amplitude; hu, hl - LC height lower/upper bound; Wl, Wu - patch antenna width lower/upper bound; pl, pu - phase difference lower/upper bound; al, au, adm - amplitude lower/upper bound and amplitude difference margin
Output: h, W - Unit cell height and width optimised for close to 180 degrees phase difference, and maximal reflection amplitude (minimal difference) of both states

initialise pu, pl, au, al;
for *h=hl* $\rightarrow$ *hu* **do**
  for *W=Wl* $\rightarrow$ *Wu* **do**
    S11P{h,W}=S11p_{on}{h,W}-S11p_{off}{h,W};
    S11A{h,W}=S11a_{on}{h,W}-S11a_{off}{h,W};
  end
end
Result $\leftarrow$ Find (S11a $\geq$ al) and (S11a $\leq$ au) and (S11A $\leq$ adm) and (S11P $\geq$ pl) and (S11P $\leq$ pu);
Result = Sort Result;
h, W $\leftarrow$ Result

Algorithm 2: Matlab script for GA optimisation on beam-steering pattern synthesis

Input: LOC - index location of desired peak
Output: Matrix_f - final configuration/population
Initialise Matrix with random 1's and 0's;
while *(Counter $\leq$ max generation) or (cost $\leq$ max accepted)* **do**
  Compute E with Matrix;
  LOC_E $\leftarrow$ peak index of E;
  cost $\leftarrow$ |LOC - LOC_E|^2;

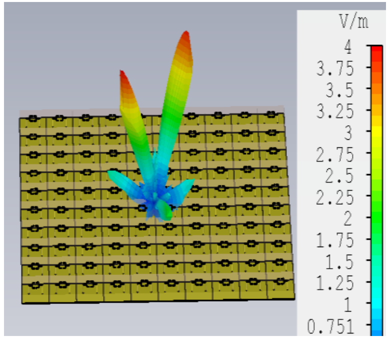
  Matrix_new $\leftarrow$ crossover, mutation, inversion on Matrix;

  compute E_new with Matrix_new;
  LOC_E_new $\leftarrow$ peak index of E_new;
  cost_new $\leftarrow$ |LOC - LOC_E_new|^2;

  if *cost_new < cost* **then**
    update Matrix with Matrix_new
  end
end

Algorithm 3: VBA script to initialise structure in CST according to configuration

Input: FILE - configuration of ON/OFF, 20 by 20 matrix
Output: Full device model updated according to ON/OFF configuration and ready for full wave simulation
Initialise 20 by 20 structure with permittivity ε undefined;
while *not end of line* **do**
  A $\leftarrow$ read current line;
  B $\leftarrow$ split(A) with delimiter;
  for *counter1, counter2* **do**
    Matrix(counter1,counter2)=B(counter1,counter2);
    update counters;
  end
end
for *i=1:20* **do**
  for *j=1:20* **do**
    if *Matrix(i,j)==1* **then**
      $\varepsilon_{i,j}$=2.46; $\tan\delta = 0.02$;
    else
      $\varepsilon_{i,j}$=3.28; $\tan\delta = 0.015$;
    end
  end
end



1) → 2) → 3) → 4)

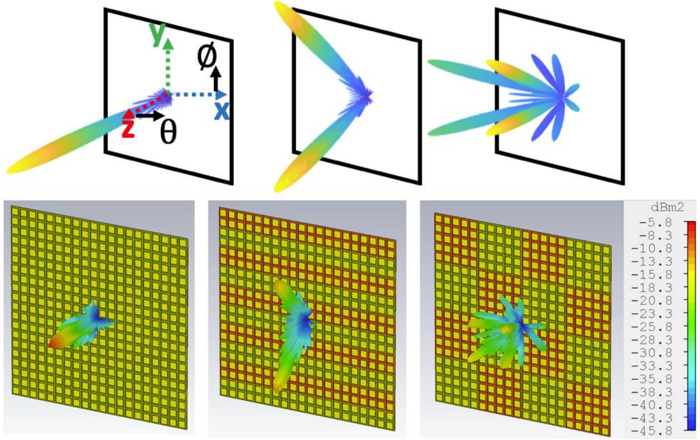
1) The unit cell structure is preliminarily designed and then simulated with periodic boundary conditions for optimal paramenters

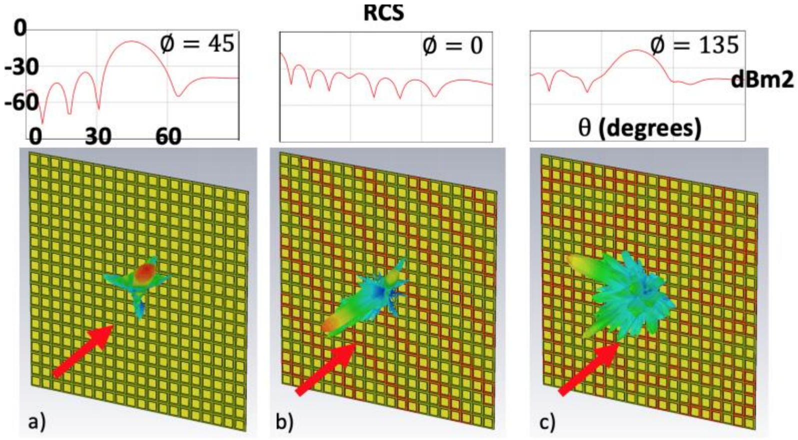
2) GA algorithm is used to find the opmital configuration of ON/OFF states for specific beam-profile

3) VBA script is use for automating the construction of the full device in CST environment given the configuration solutions.

4) Full wave simulation is performed in CST Studio Suite. The whole process is then repeated for other beam profiles.

Full device – plane wave, normal incidence





a) given a normally incident planewave, the theoretical farfield from the ON/OFF configurations shown in b). b) full-wave simulations of the farfields. ON: green, OFF: red

a) given a off-set incident plane wave and corresponding ON/OFF configurations, the radiation pattern at the plane of main lobe. b) the full wave simulation of the far-fields

- -5.8 dBsm gives linear RCS of 263,026 mm^2, which corresponds to approximately 28dB gain
- progressive phase can be implemented easily to achieve beam-steering, where GA has been tested utilised to find the optimal configurations

Internet evolution beyond-5G

Standardization Activities on Internet evolution

- IETF DetNet WG: main activity on IP-layer/DetIP solutions, e.g.,
  - https://datatracker.ietf.org/doc/rfc8655/ (RFC8655: DetNet Architecture)
  - https://datatracker.ietf.org/doc/rfc8578/ (RFC8578: DetNet use cases)
  - https://datatracker.ietf.org/doc/draft-ietf-detnet-bounded-latency/ (latency models)
  - https://datatracker.ietf.org/doc/draft-ietf-detnet-data-plane-framework/ (data plane framework)
  - https://datatracker.ietf.org/doc/draft-ietf-detnet-ip-over-tsn/ (DetNet IP over TSN)
  - https://datatracker.ietf.org/doc/draft-qiang-detnet-large-scale-detnet/ (large-scale DetNet forwarding, as described in previous slide)
- ITU-T SG13
  - *Proposal for High Precision & Deterministic IP Networking and Communication: Network requirements and functional architecture* as input into SG13 for new work items in 2021 and beyond
- ETSI
  - Non-IP Networking (NIN): Concentrates on candidate network protocol technologies that could be alternatives to TCP/IP

-TCP/IP is bandwidth wasteful when it comes to radio access networks. This was already seen in 4G but

-Ultra-reliable ultra-low latency requirement of beyond 5G cannot be satisfied over current IP architecture
-Security especially for verticals is a must but IP has many built-in vulnerabilities
- Vertical applications are not best effort, they need deterministic versus probabilistic services availability
-Current mobile Internet fragmentation into islands of 5G private networks and networks slices
-Need a revamp of TCP/IP Internet architecture.

Ethernet Based Deterministic Networking Technologies

OSI Layer 3 Technology

Suitable for large-scale network

Deterministic IP for large-scale Deterministic Network

– Beyond hop-limit, adapt to large scale networking
– Performance: 10μs latency per hop, 20μs jitter E2E
– Being standardized in IETF DetNet workgroup

OSI Layer 2 Technology

TSN (Time-Sensitive Networking) and Industrial Ethernet Tech.

– Performance: 1-5μs low latency, 1μs jitter E2E
– Well recognized and accepted among OT players
– Standardized in IEEE 802.1

Good for small-scale network

OSI Layer 1.5 Technology

XE (X-Ethernet)

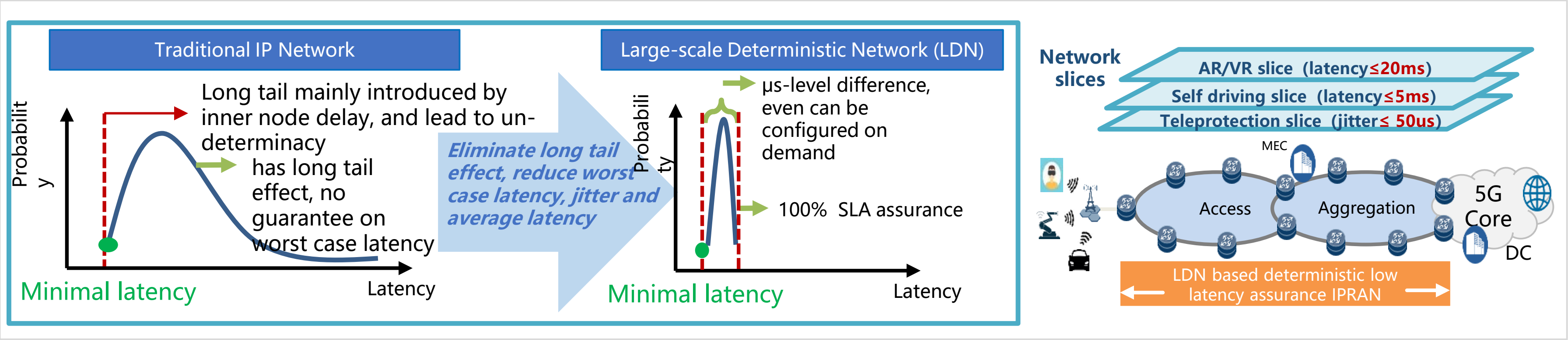
– Work on layer between PHY and MAC, bit-block exchange
– Performance: 1-2μs ultra low latency, 50ns ultra low jitter
– Capable of carrying industrial Ethernet protocols transparently, such as industrial Ethernet implement, PROFINET, EtherCAT, EtherNet/IP

Source: Dr David Lou, Huawei R&D

Large-scale Deterministic Networking

Source: Dr David Lou, Huawei R&D

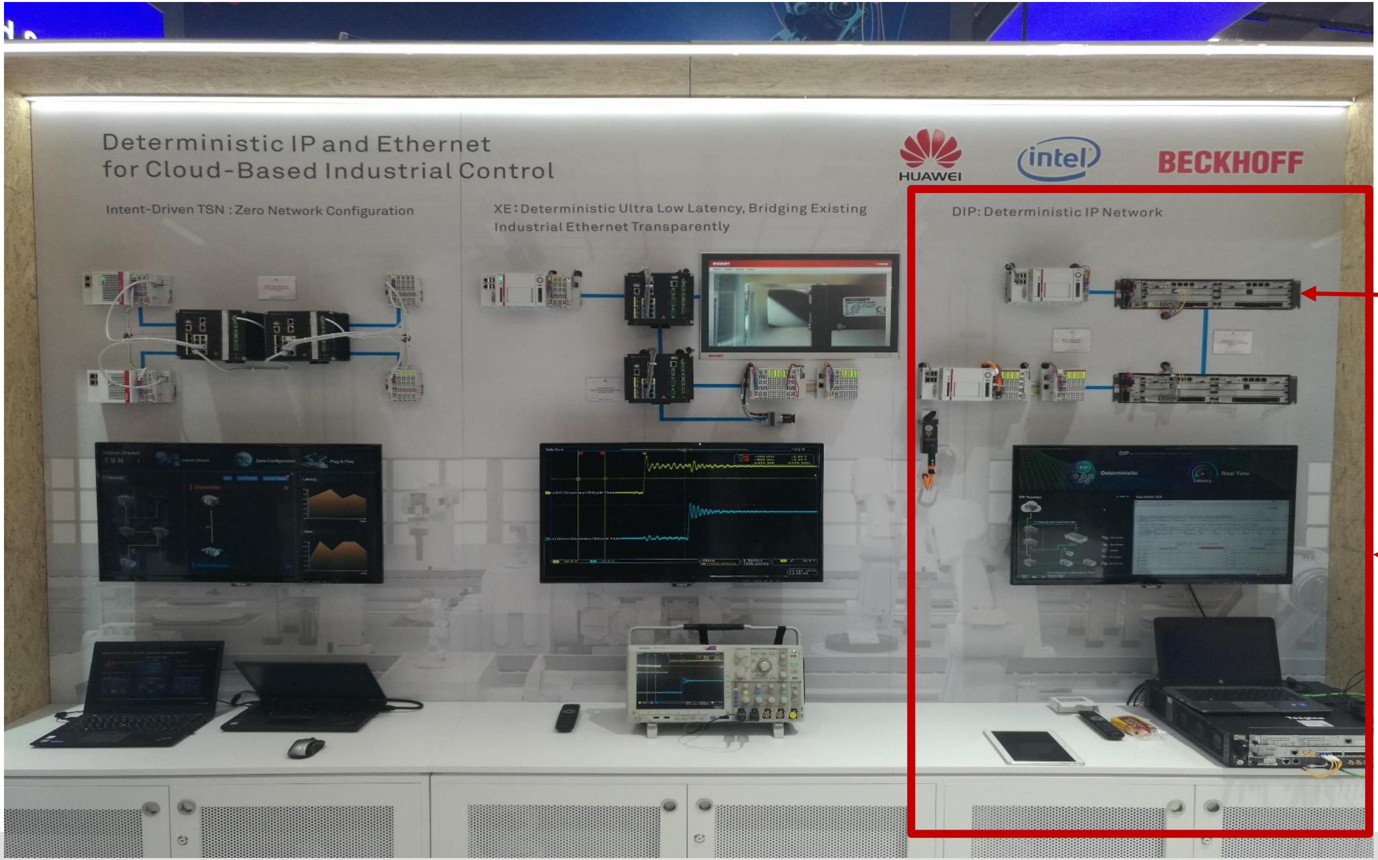
The large-scale deterministic networking focuses on deterministic data paths that operate over Layer 2 bridged and Layer 3 routed segments, where such paths can provide bounds on latency, loss, and packet delay variation (jitter), and high reliability.



It supports massive nodes to achieve deterministic forwarding jitter at microsecond level. It is being standardized in IETF, and compatible with 5G seamlessly.

Collaboration with Beckhoff – HMI 2018

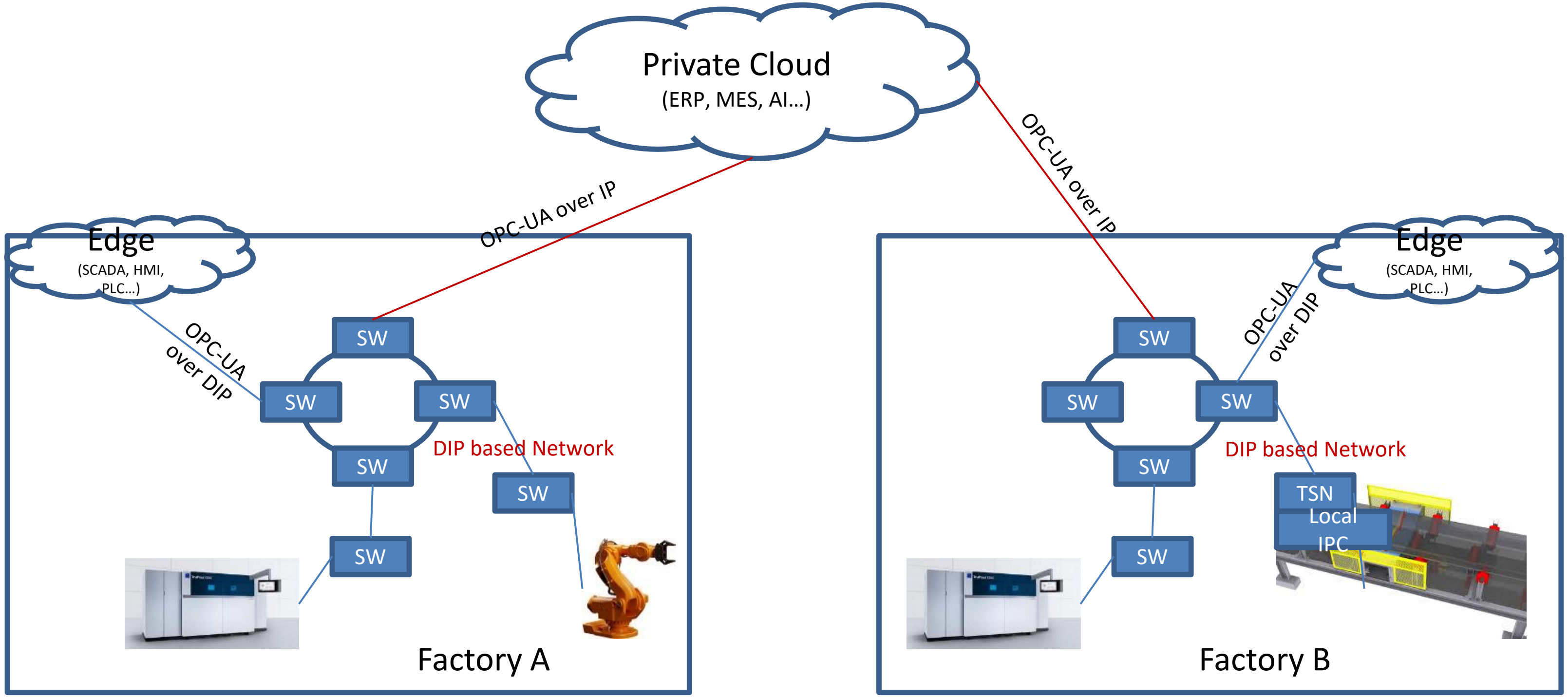
Source: Dr David Lou, Huawei R&D



DIP Router

Beckhoff IPC controls a servo motor at a cycle time of 2ms over a deterministic IP network (emulated by 2 DIP routers)

Smart Factory Vision Enabled by Deterministic IP based Network



Outlook and collaboration opportunities

- Research on concepts, technologies and spectrum for 6G has already started, with standardisation likely to Kick-off c.a 2025 onwards, (e.g. 3GPP and ITU)
- Tbps connectivity and "new verticals" are lthe ikely key drives
- Many candidate technologies are being discussed, some of these are covered by my team and wider collaborators (in Green)
  - THz communication
  - AI and machine-learning embedded in RAN and Core
  - Open RAN architecture
  - Next Generation Internet > ITU 2030, NetWorld 2020 WG on New Technologies for New Verticals
  - Quantum Internet

Horizon Europe

EPSRC

THE ROYAL SOCIETY

2020 NETWORLD

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Thank You!

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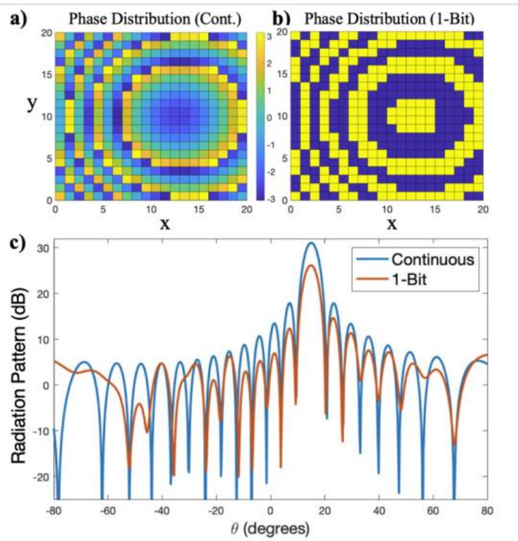
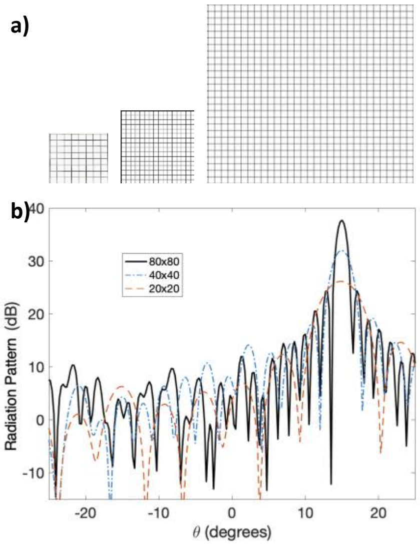
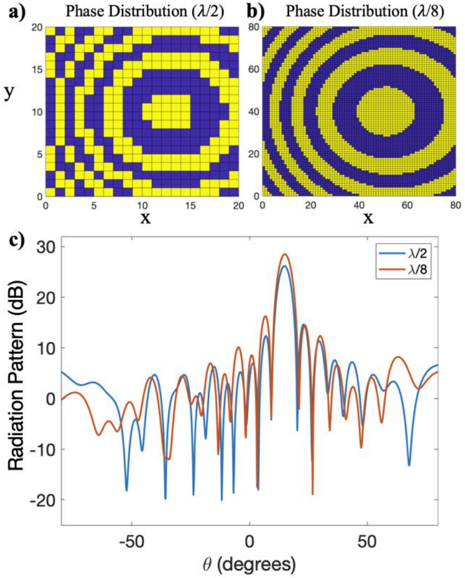
Full device – scalability analysis



a) & b) the phase distribution of continuous and binary unit element surfaces. c) the radiation pattern of the two.



a) the dimension comparison between three different surfaces (20x20, 40x40, 80x80). b) the radiation pattern.



a) & b) the phase distribution of half-wavelength and quarter-wavelength spacing surfaces. c) the radiation pattern.

- The effects on directivity from using a continuous phase distribution versus binary
- The effects on directivity from overall device size/aperture
- The effects on directivity from sub-wavelength spacing