Intelligent Environments to Realize Communication in 5G Beyond Wireless Systems

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REFERENCES

C. Liaskos, S. Nie, A. Tsioliaridou, A. Pitsillides, S. Ioannidis, I. F. Akyildiz.

"A New Wireless Communication Paradigm through Software-controlled Metasurfaces"

IEEE Communication Magazine, Sept. 2018.

C. Liaskos, A. Tsioliaridou, A. Pitsillides, S. Ioannidis, I. F. Akyildiz.

"Using any Surface to Realize a New Paradigm for Wireless Communications"

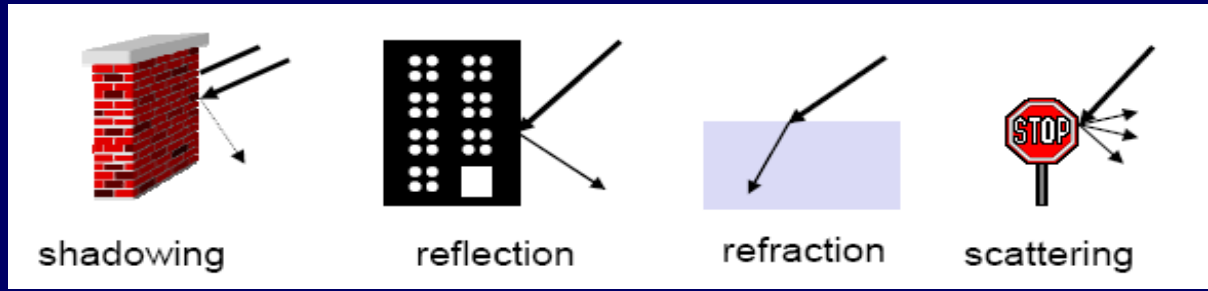
Communications of the ACM, Nov. 2018.

Patent applied for.

WIRELESS COMMUNICATIONS CHANNEL PROBLEMS

EM waves undergo multiple uncontrollable alterations as they propagate through a wireless environment.

- Free space path loss
- Signal absorption



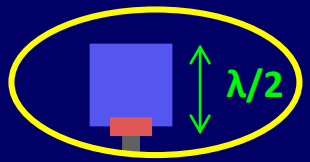
- Interference
- NLOS
- Fading
- Doppler Effects
- Distance esp. for 60GHz and TeraHertz bands
- Coverage
- Energy Consumption
- Security (Eavesdropping)

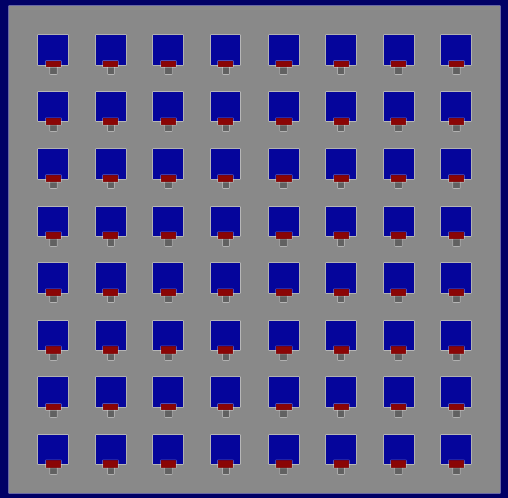
CONVENTIONAL APPROACHES

- PHY Layer solutions, e.g., adaptive antenna, MIMO, beamforming, adaptive modulation, dynamic spectrum allocation, encoding and plethora of MAC and ROUTING protocols
- Although successful, they all have separate degrees of efficiency
- Also the random channel behavior still greatly affects the performance !!

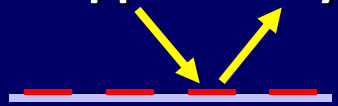
POSSIBLE SIMPLE SOLUTION

Reflectarrays





Supports only:



Normal Reflection

EU-FET PROJECT: VISORSURF

PROGRAMMABLE METASURFACES: (2017-2021)

http://www.visorsurf.eu

- FET Project: Very competitive 3%
- 6 Million Euro (4 years)
- Wireless Communication environments with ambient intelligence, ASICs, NanoMaterials (Graphene and Metamaterials)
- Support of Low (1GHz) to Very high Frequencies includ.60 GHz-10THz
- Partners:

FORTH Foundation for Research & Technology - Hellas

University of Cyprus

Aalto University

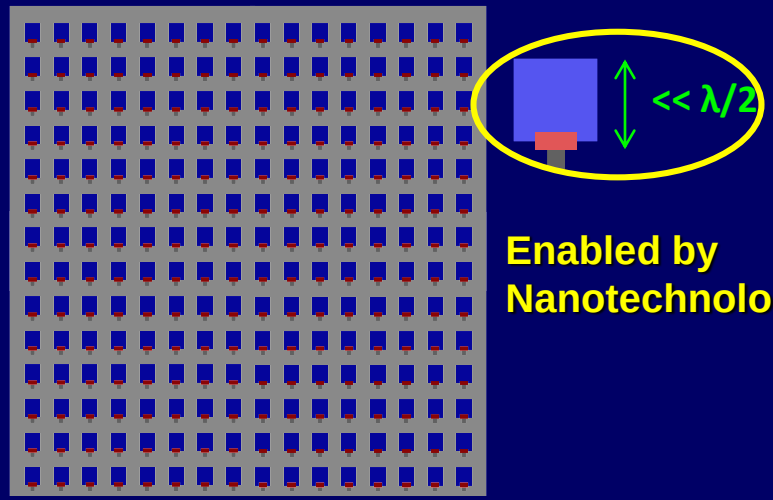
UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Fraunhofer Gesellschaft

Signal GeneriX Ltd Advanced Signal Solutions

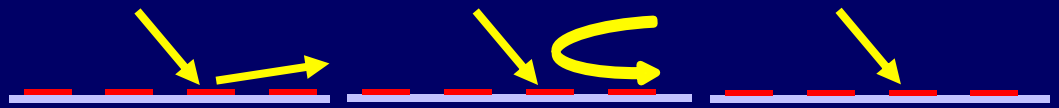
OUR SOLUTION:
HYPERSURFACES/INTELLIGENT WALLS

Metasurfaces



Enabled by Nanotechnology

Additionally supports:



Controlled reflection Polarized reflection Absorption



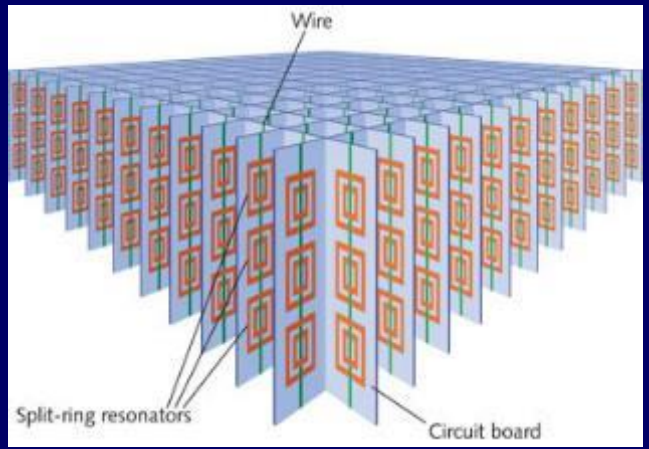
HYPERSURFACES:
PROGRAMMABLE (INTELLIGENT) WIRELESS ENVIRONMENTS



- Programmable Wireless Environments comprised of a networked tiles
- Tiles are called HyperSurfaces
- Multiple HyperSurfaces are used to coat objects such as walls, doors, ceilings, etc.
- They interconnect automatically, resulting in a controlled environment
- A CONTROLLER calculates and decides for optimal interaction type per HyperSurface → to best fit the needs of communicating devices.

METAMATERIALS

- A metamaterial ("beyond") is a material engineered to have a property that is not found in nature
- Manipulation of EM waves: block, absorb, enhance, or bend waves, to achieve benefits that go beyond what is possible with conventional materials
- Their precise shape, geometry, size, orientation and arrangement gives them their smart properties
- Uses repeating patterns of meta atoms (copper strips) deposited on an insulator material









META-ATOM PATTERNS

META-ATOM is repeated periodically over a surface

METASURFACES (2D counterparts of MetaMaterials)

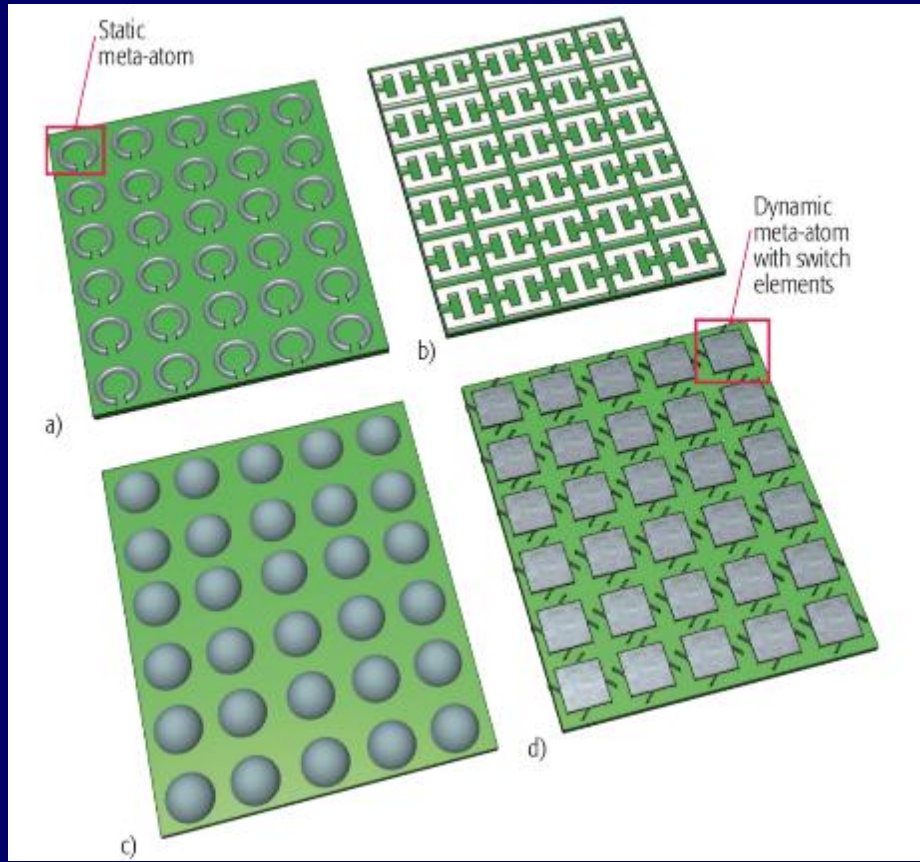
When EM waves impinge on a meta- surface it creates currents in it via induction.

a) Total current pattern within the surface is fully defined by the meta-atom geometry and composition.

d) Current pattern also depends on the states of the switching elements.

The inducted current also creates a response field, following the laws of EM.

The meta-atoms are engineered to provide a custom response field.



META-ATOM CHARACTERISTICS

- Meta-atom size and the thickness of the tile → important design factors

  → define the maximum frequency for EM wave interaction

- As a rule of thumb, meta-atoms are bounded within a square region of

  $\lambda/10 \leftrightarrow \lambda/5$,

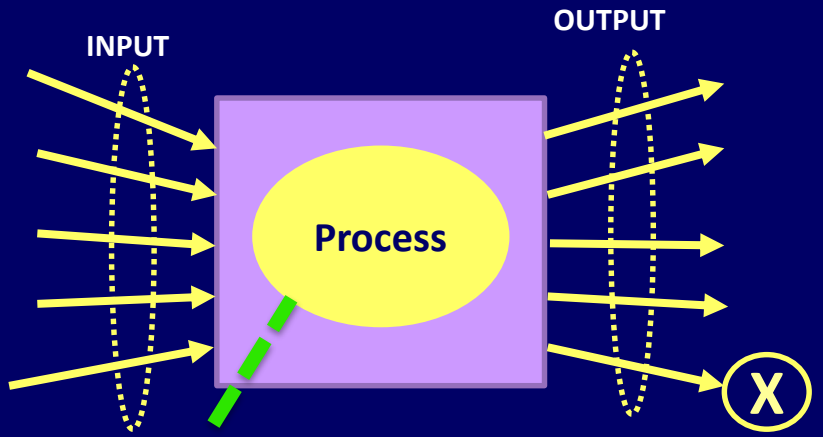
  where λ is the EM interaction wavelength

- E.g., in 5 GHz, the meta-atom size → ~8x8 mm

- Dynamic meta-atom designs → well studied subject in PHYSICS !

RESULT: METASURFACES

Completely re-engineer incoming EM waves



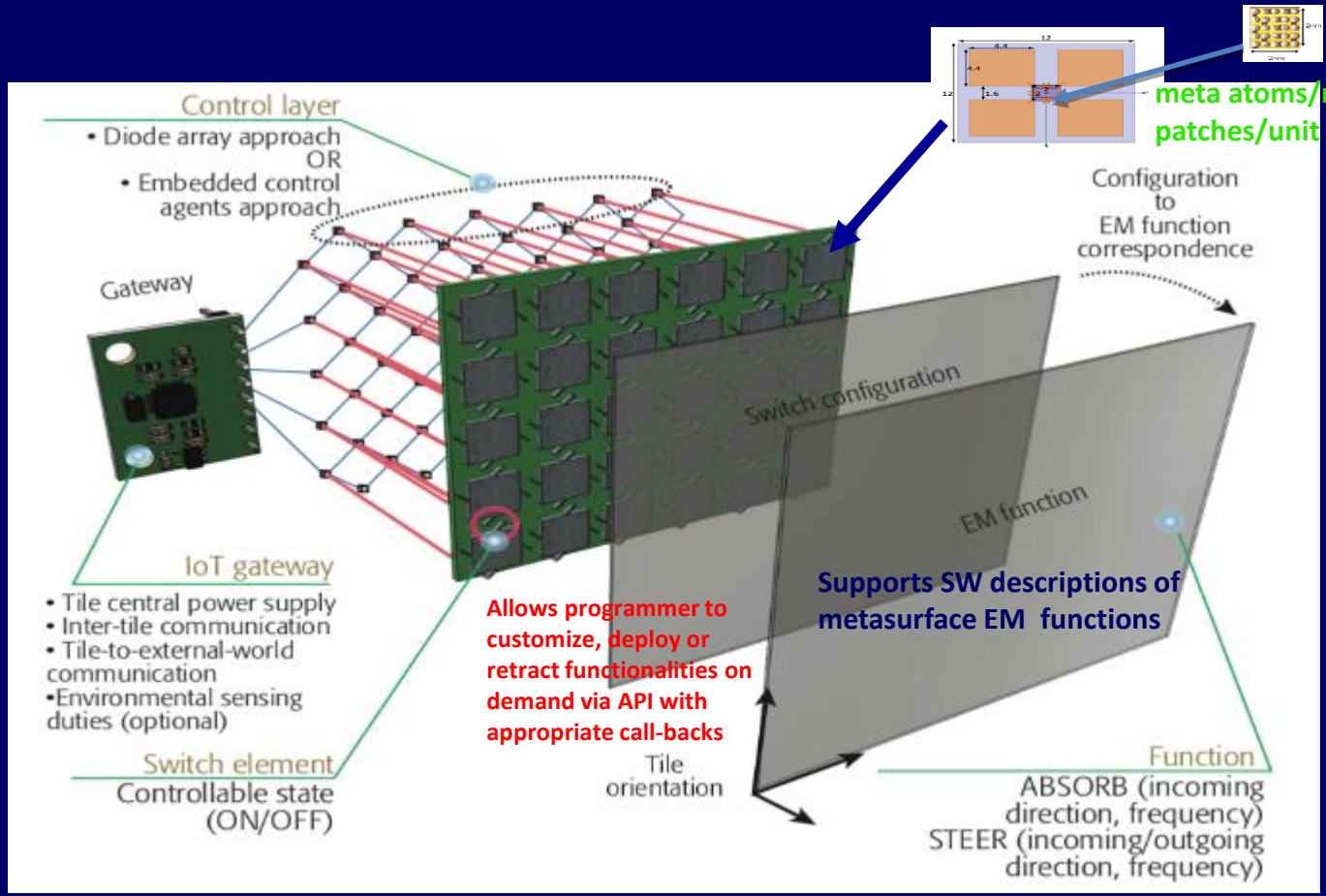
STEER, ABSORB, POLARIZE, SPLIT,
FREQ_FILTER, ALTER_PHASE, FOCUS,
CUSTOM EM/MAG FIELD at output(s)

HYPERSURFACES: PROGRAMMABLE WIRELESS ENVIRONMENTS

- HSF tile is envisioned as a planar, rectangular structure that can host metasurface functions over its surface with programmable control
- Comprises a stack of virtual and physical components

HYPERSURFACES: PROGRAMMABLE WIRELESS ENVIRONMENTS

Gateway: specifies HW & protocols that enable bidirectional communication between controller NW and external world and communication between the tiles



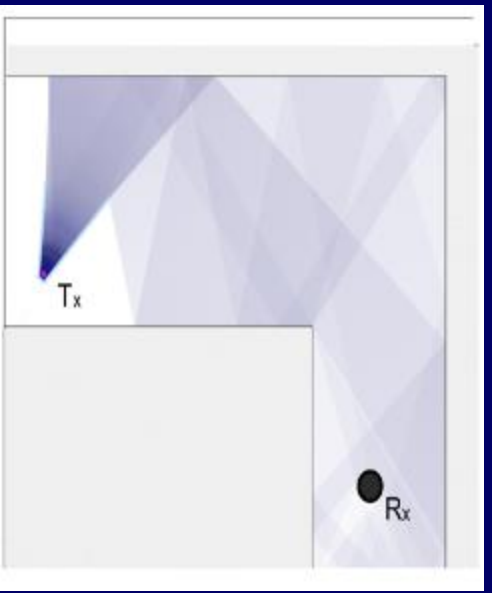
HSF TILES

- Walls, doors, ceilings etc. can be coated with HSF-tiles
- Can enable to re-engineer impinging waves in SW-defined manner
- Can affect each tile in such a way that the impinging rays can be manipulated, e.g., reflected in any desired direction.

- Minimal HyperSurface thickness is in the region of

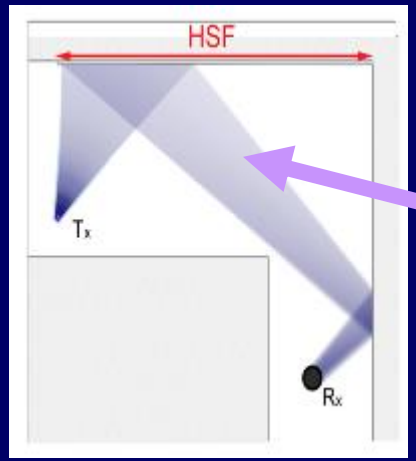
$\lambda/10 \leftrightarrow \lambda/5$.

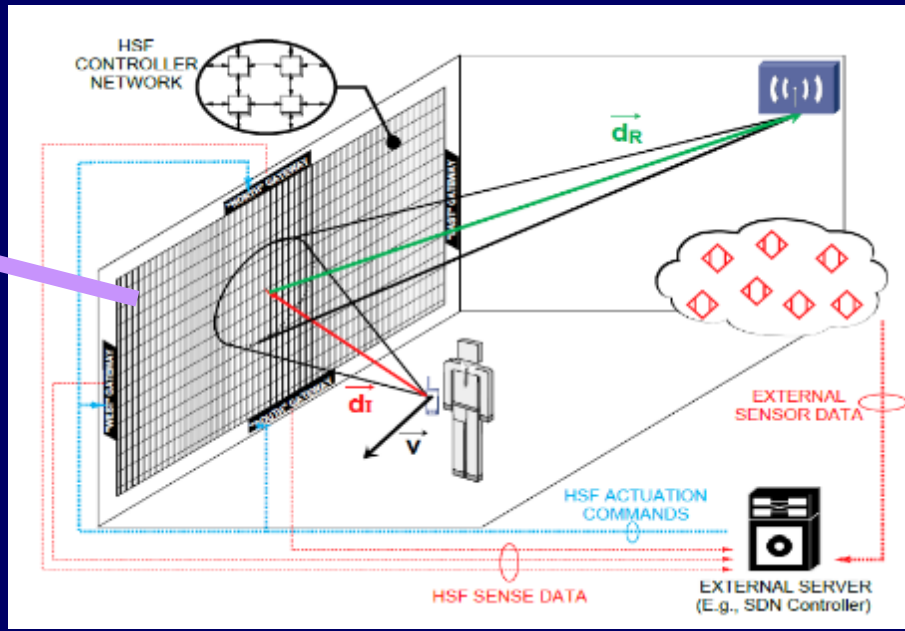
HYPERSURFACES:
PROGRAMMABLE WIRELESS ENVIRONMENTS



without HSF

with HSF





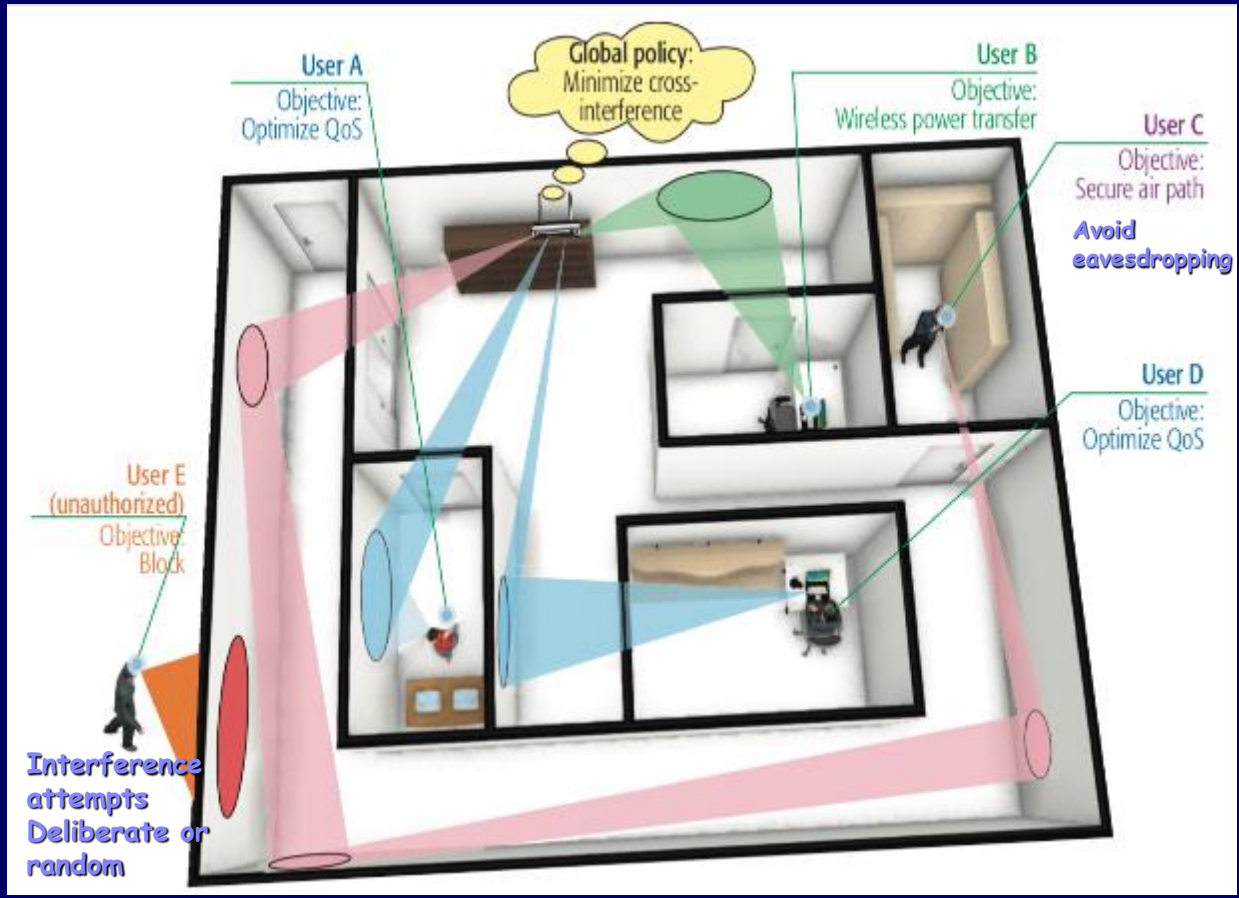
EXAMPLE: HYPERSURFACES USE CASES

A & D receive max S/I power levels by carefully focusing the EM waves in a lens- like manner and avoiding mutual interference.

B targets max WPT using a combination of custom wave steering and focusing

For C, the environment establishes a "private air route," that avoids all other users to reduce the risk of eavesdropping.

Finally, the unauthorized user E is blocked by instructing the environment to absorb his/her emissions

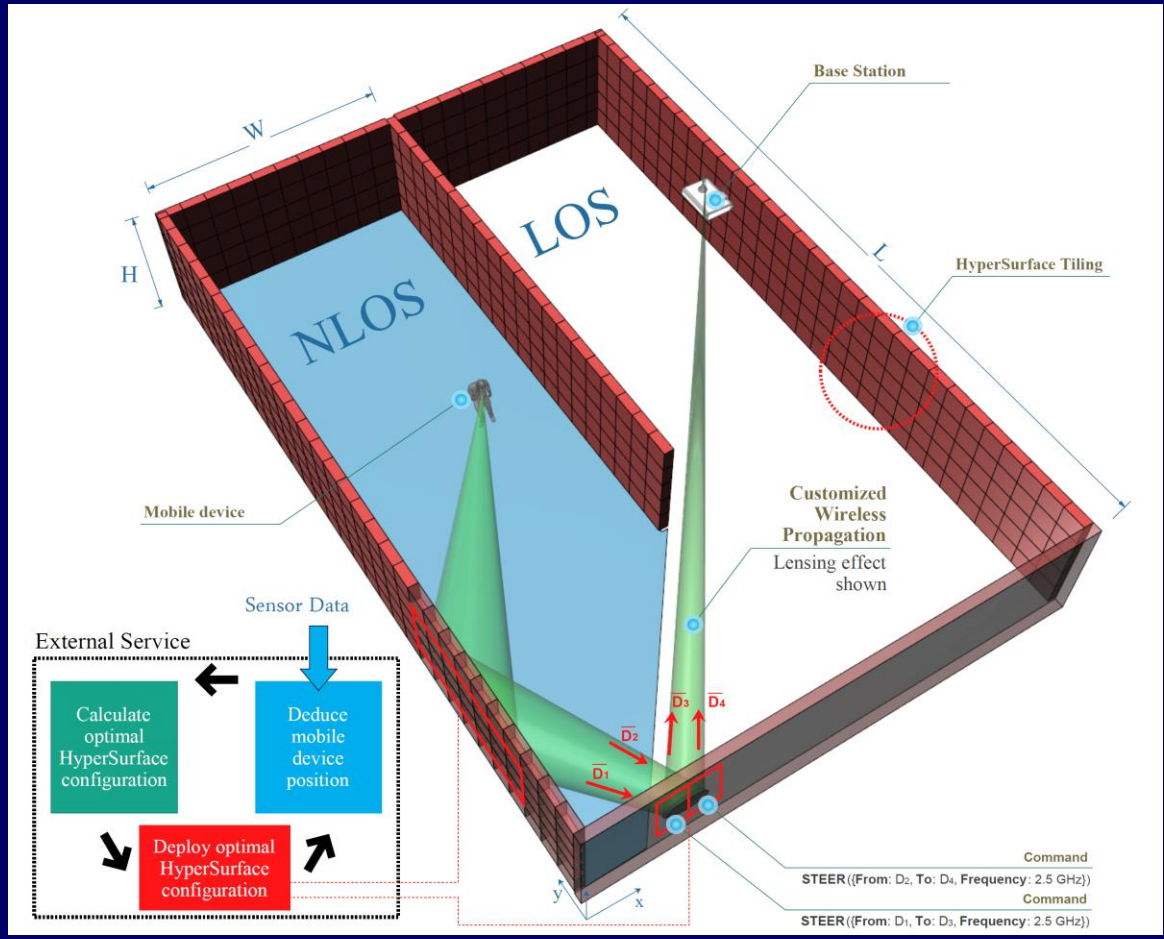


OPERATION PRINCIPLE

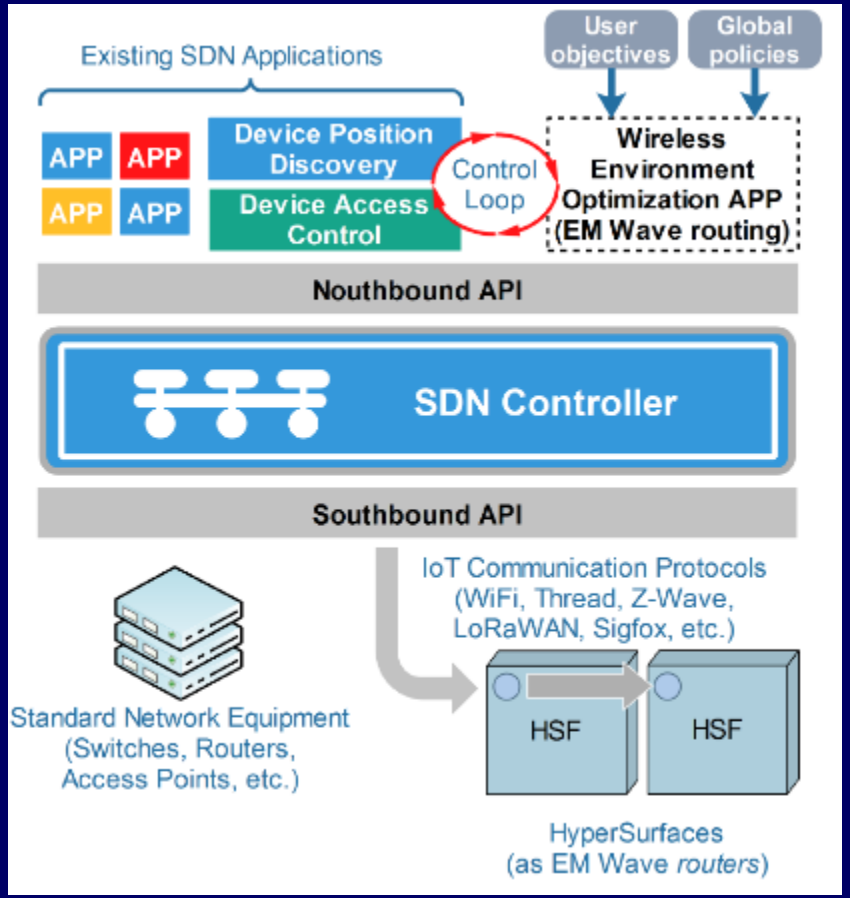
A user device is located in a place with low signal quality, i.e., NLOS.

Hypersurfaces are instructed to:

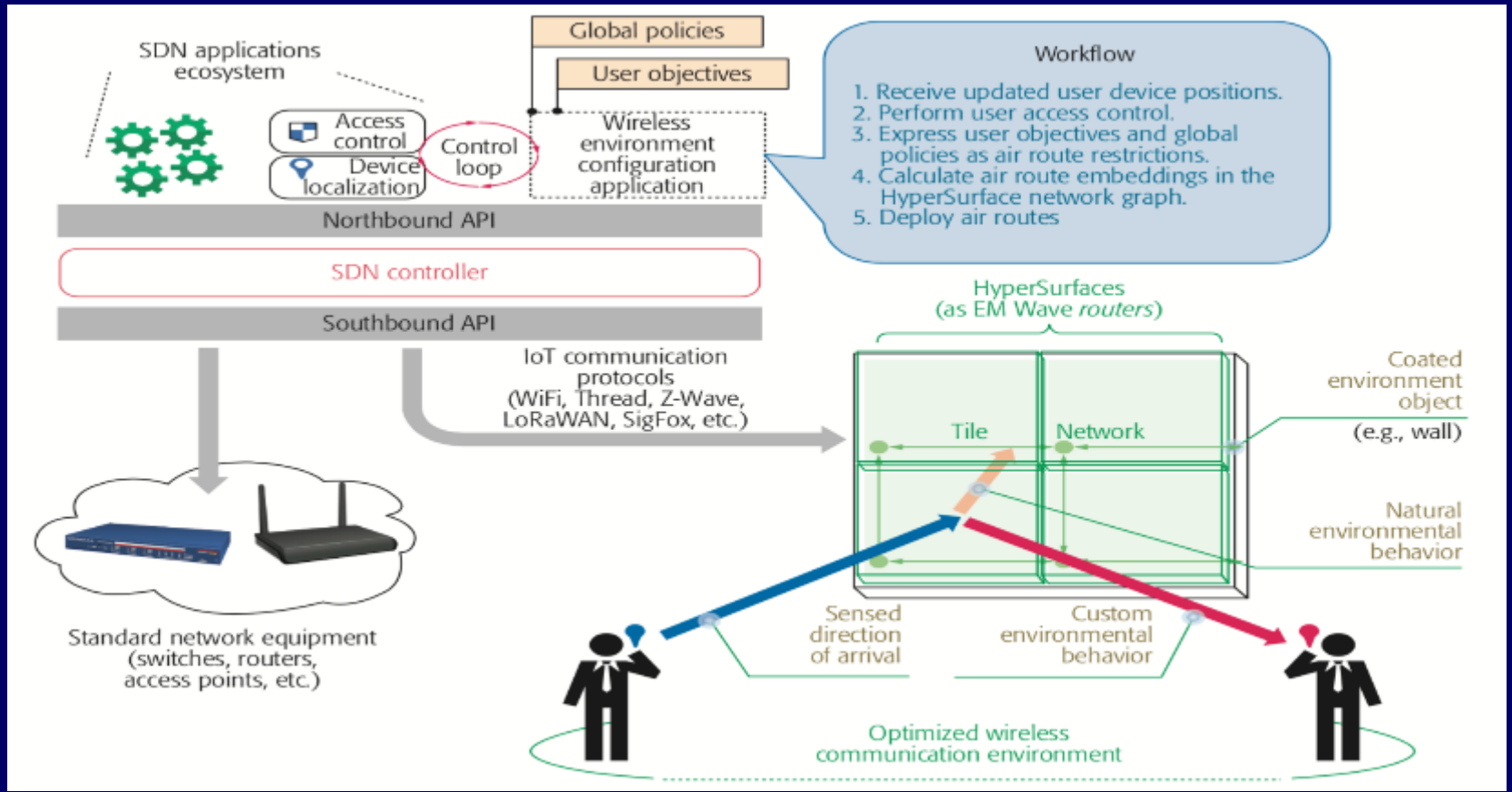
- Create a direct path between the device and the access point, and
- Ensure that the emitted energy is containedin this path without losses, allowing for max data transfer rates.



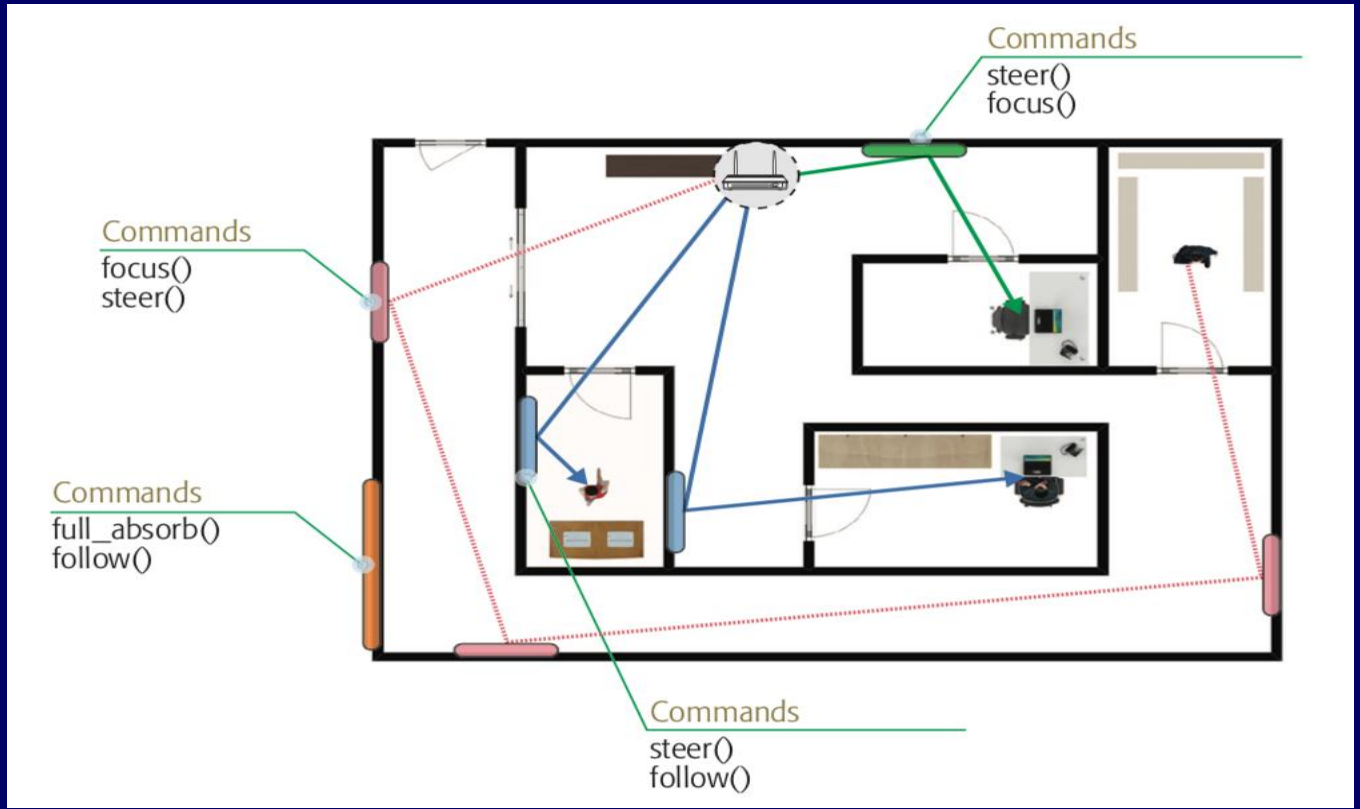
INCORPORATION TO EXISTING SDN-INFRASTRUCTURE



SOFTWARE DEFINED NETWORKING CONTROL



EXAMPLE WIRELESS ENVIRONMENT CONFIGURATION PROCESS AS A ROUTING PROBLEM

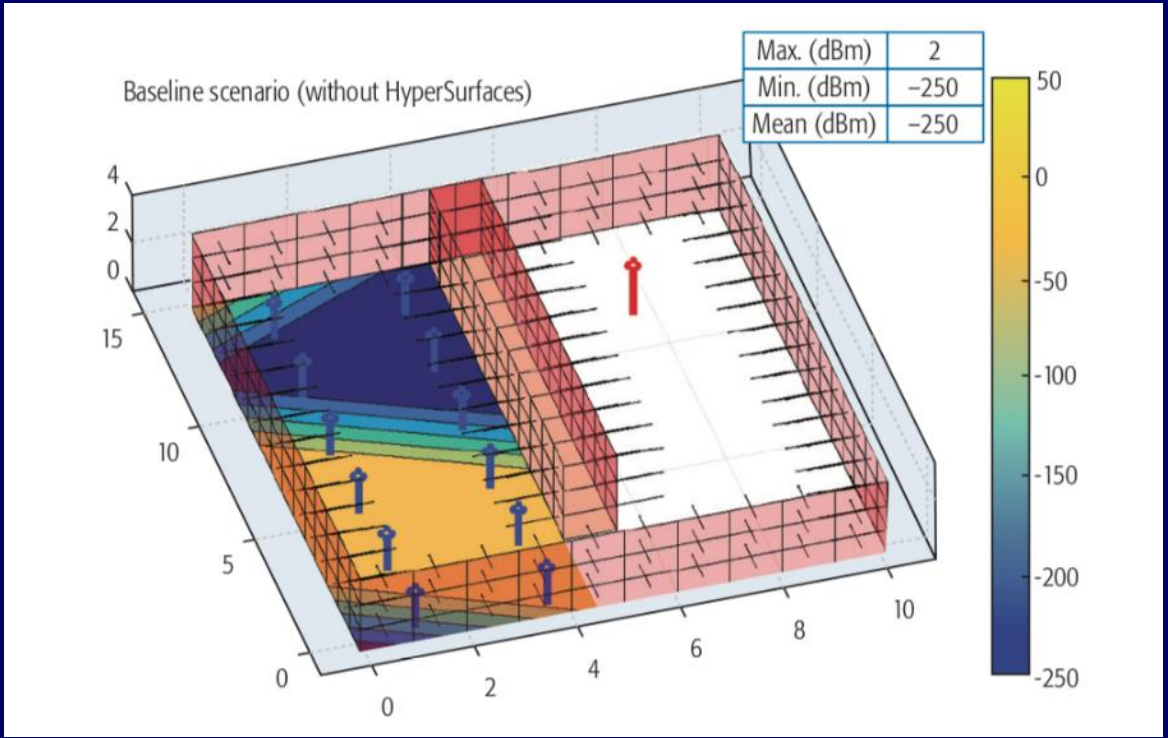


SIMULATION RESULTS

- Full 3D ray-tracing demonstrates potential of the proposed approach
  - H = 3 m, corridor L = 15m and W = 5m, middle wall L = 12m, and 0.5m wall thickness
  - Floor and ceiling are plain surfaces composed of concrete.
  - Walls coated with 222 1×1m HyperSurface tiles

- The room is divided by a middle wall (with a length of 12 m and a thickness of 1 m) into two sections (i.e., LOS and NLOS), each with a width of 4.5 m

SIMULATION ENVIRONMENT



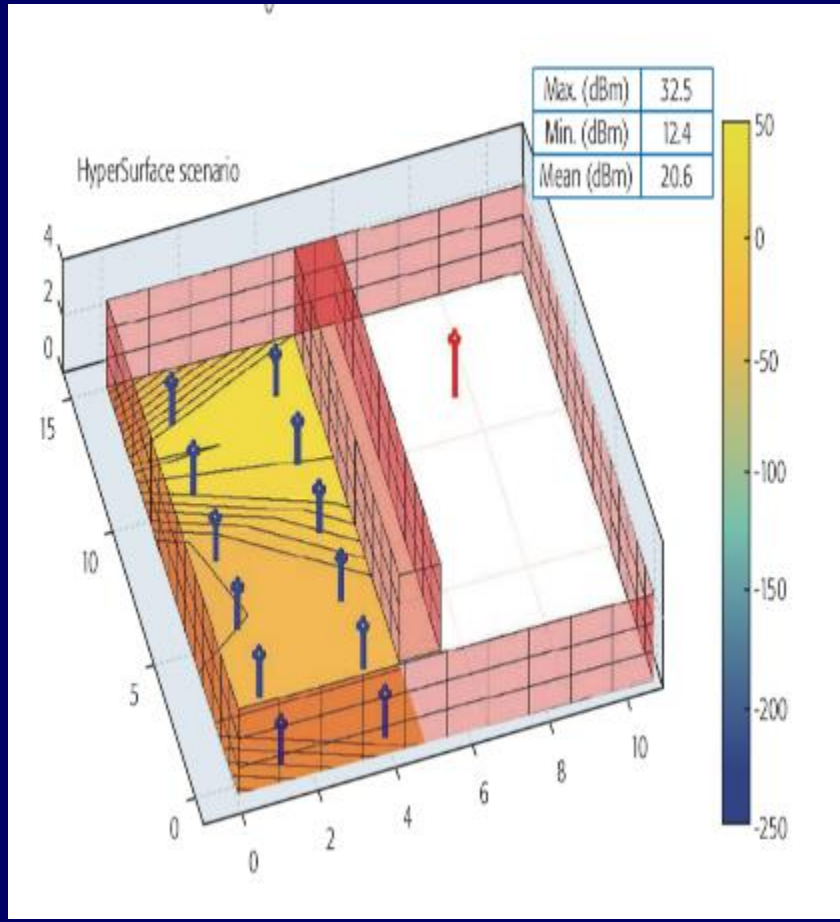
- The average received power over the 12 receivers is –75 dBm, while the minimum power is –250 dBm and is below the threshold allowed by the ray-tracer, implying disconnected areas.
- The receivers in the upper right and bottom left corners are not covered in this setup.

SIMULATION ENVIRONMENT

- All walls are coated with HyperSurface tiles with a size of 1 × 1m
- An EM transmitter, with a height of 2 m (RED) located on one side of the room and equipped with a half-dipole antenna and transmits at 60 GHz with 25 MHz BW
- Transmission power is set to 100 dBm.
- In total 12 receivers (BLUE) are uniformly distributed on the NLOS side of the room with the same height of 1.5 m and half-dipole antennas.

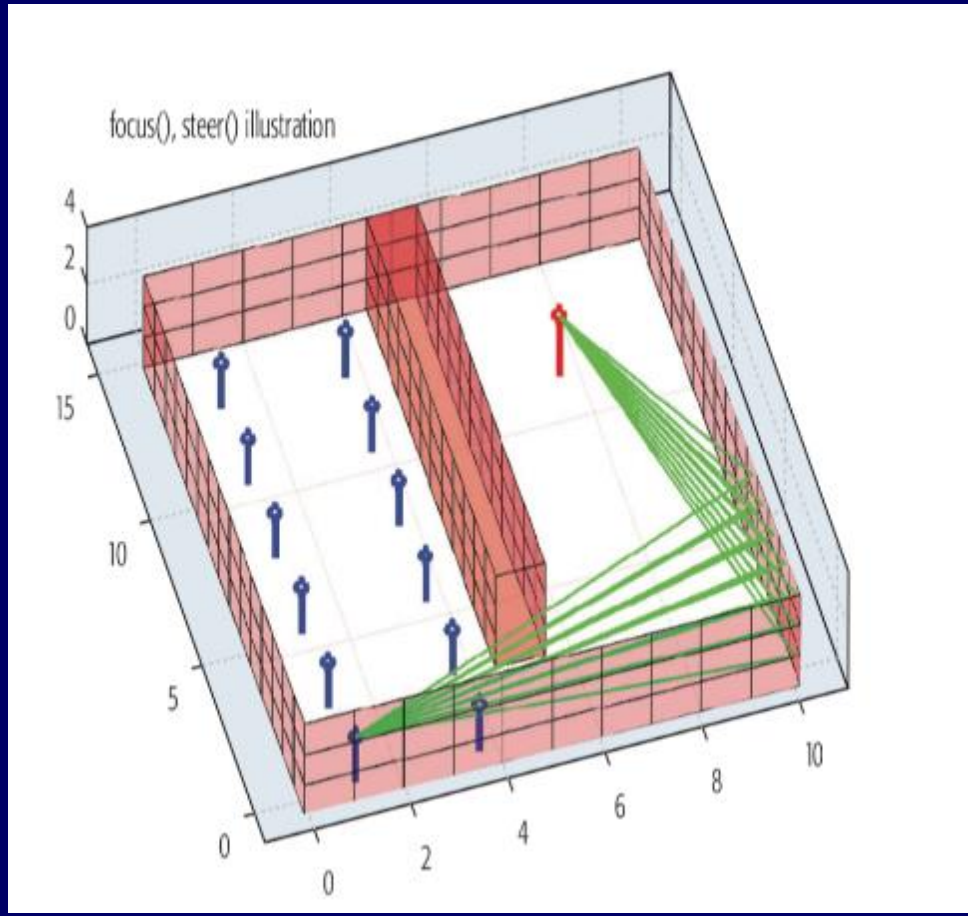
All receivers are in good coverage with the obvious leverage of an average received power of 20.6 dBm.

Also, there are maximum and minimum received powers of 32.5 dBm and 12.4 dBm, respectively.



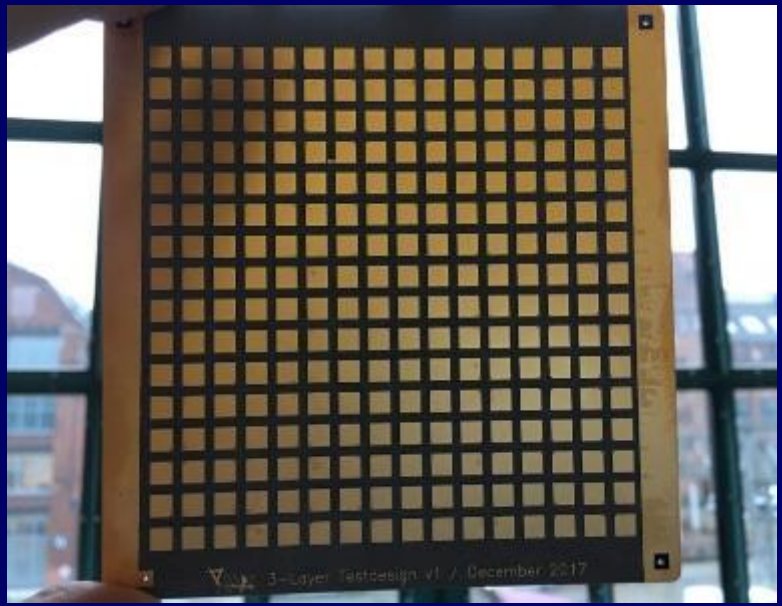
TUNING THE HYPERSURFACES

- Begin with the most distant receiver (top right position) and assign focus and steer commands to the tiles that offer the shortest air route.
- Example of a single focus and steer function deployment.
- The tiles with green paths, impinged upon, will adjust their azimuth and elevation angles to focus the signals from transmitter to desired receiver.



PROTOTYPING

COURTESY OF FRAUNHOFER INSTITUTE BERLIN



- First prototype is ready for evaluation
  - Software & Hardware
- More prototypes to follow:
  - Exotic ASIC solutions
  - Graphene-based, THz control

- Paving the way for smart, connected materials with programmable physical properties
  - Internet of Materials

CONCLUSION

- HyperSurface concept is applicable to any frequency spectrum and wireless architecture
- Solving the corresponding path loss, fading, interference, and NLOS problems in general using HyperSurfaces constitutes a promising research path
- Such directions can further focus on indoor and outdoor communication environments

CONCLUSION

- From probabilistic to deterministic channel control
- From coarse-grained to extremely fine-grained channel control
- Outsource some MAC and networking functions from devices to environment
- From a protocol stack to a thin, ambient, HW hypervisor
- Achieve “direct-wired-grade” performance for wireless communication

RESEARCH DIRECTIONS

- Tile Architecture
  - Metasurface designs with wide tunability range
  - Optimized electronic and networking design of switch controllers to yield fast tile reconfiguration, minimal energy consumption & manufacturing cost
- Inter-tile Networking
  - Fast, energy-efficient wireless environment reconfiguration, supporting a wide range of user mobility patterns
- Tile Control Software
  - Complexity, modularity and interfacing capabilities

RESEARCH DIRECTIONS

- Dynamic meta-atoms that can interact with THz modulated waves need to be designed
- This has been shown to be possible for graphene-based metasurfaces
- The tile sensing accuracy and re-configuration speed must also match the extremely high spatial sensitivity of THz communications, calling for novel, highly distributed tile control processes

FURTHER RESEARCH DIRECTIONS

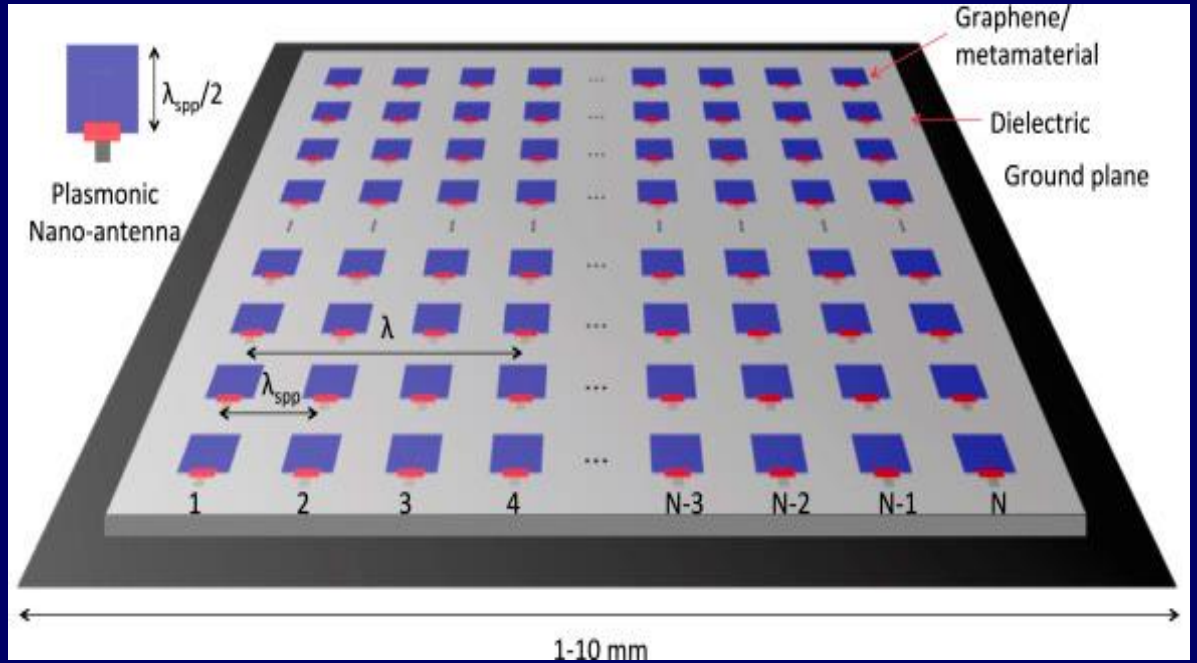
- End-to-end system 3D modeling and analysis
- Deployment strategies for indoor and outdoor scenarios
- Efficient user beam discovery and beam routing algorithms
- AI and Machine Learning Algorithms
- Fabrication and experimental testing

ALTERNATIVE SOLUTION: ULTRA-MASSIVE MIMO

I. F. Akyildiz and J. M. Jornet

"Realizing Ultra-Massive MIMO Communication in the (0.06–10) TeraHertz Band"
Nano Communication Networks, (Elsevier) Journal, Vol. 8, pp. 46-54, March 2016;
U.S. Patent 15/211,503 awarded on Sept. 7, 2017.

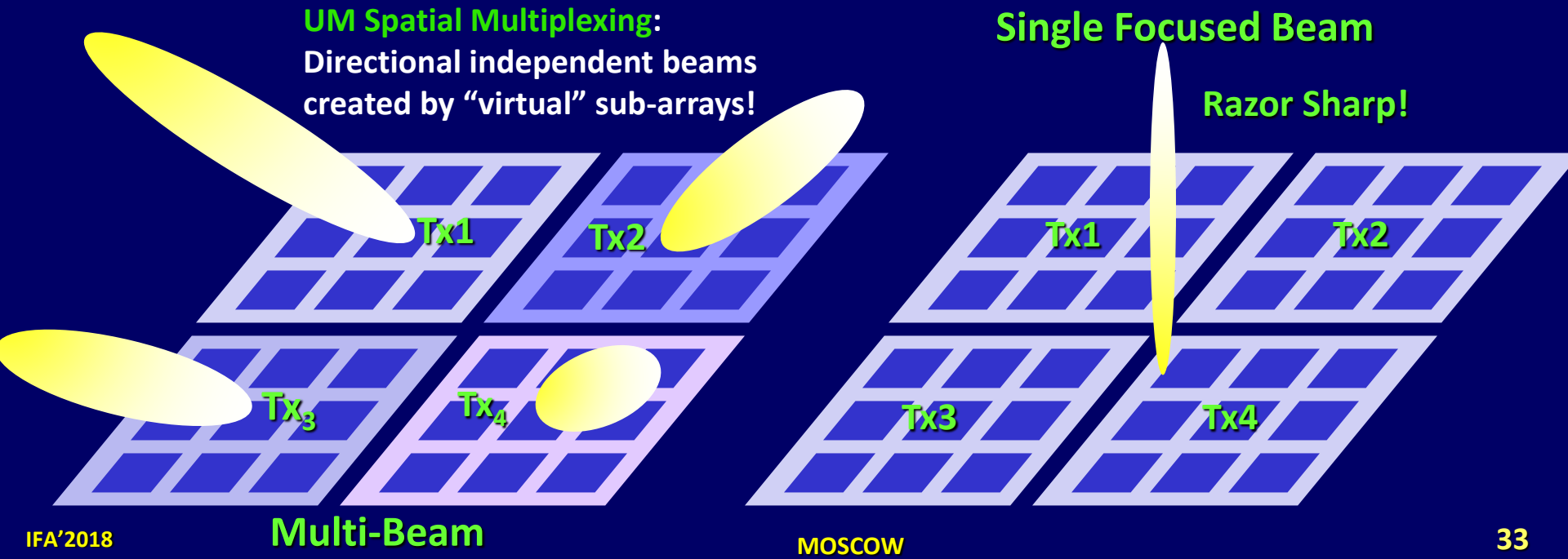
- **1024x1024 Antenna Element Array**



A square uniform plasmonic nano-antenna array

DYNAMIC MASSIVE MIMO

- By properly feeding the antenna elements, the antenna array can be dynamically switched among different modes



MULTI-BAND MASSIVE MIMO

A nano-antenna array can be designed to communicate over multiple transmission windows simultaneously by electronically tuning the response of fixed-length plasmonic nano-antennas

