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Components for Beyond-5G physical and network layers

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Contents

- Applications and requirements
- Physical layer
  - (sub-)Terahertz communications
  - (Cell-free) Massive MIMO
  - Orbital Angular Momenta (OAM)
  - Reconfigurable Intelligent Surfaces (RIS)
  - Orthogonal Time Frequency Space (OTFS) modulation and multiple access
  - Machine Learning for wireless
- New Verticals
  - V2X and 3D systems
  - Joint communication and sensing (JCAS)
  - Joint Communication, Computation, and Caching

Applications

- eXtentded Reality (XR)
  - Advanced gaming
  - Virtual reality
  - Augmented reality
  - Holography

- Extreme coverage extension
  - For emergency communication
  - For operation in remote areas
    (e.g., mining operations)
  - Remote ship operation
  - Covering underserved areas

Applications

- Telemedicine
  - From online consultation
    to remote robotic surgery

- Industry 4.0
  - More efficient industry by
    fast reconfiguration
  - “live” guidance to workers on
    what to do

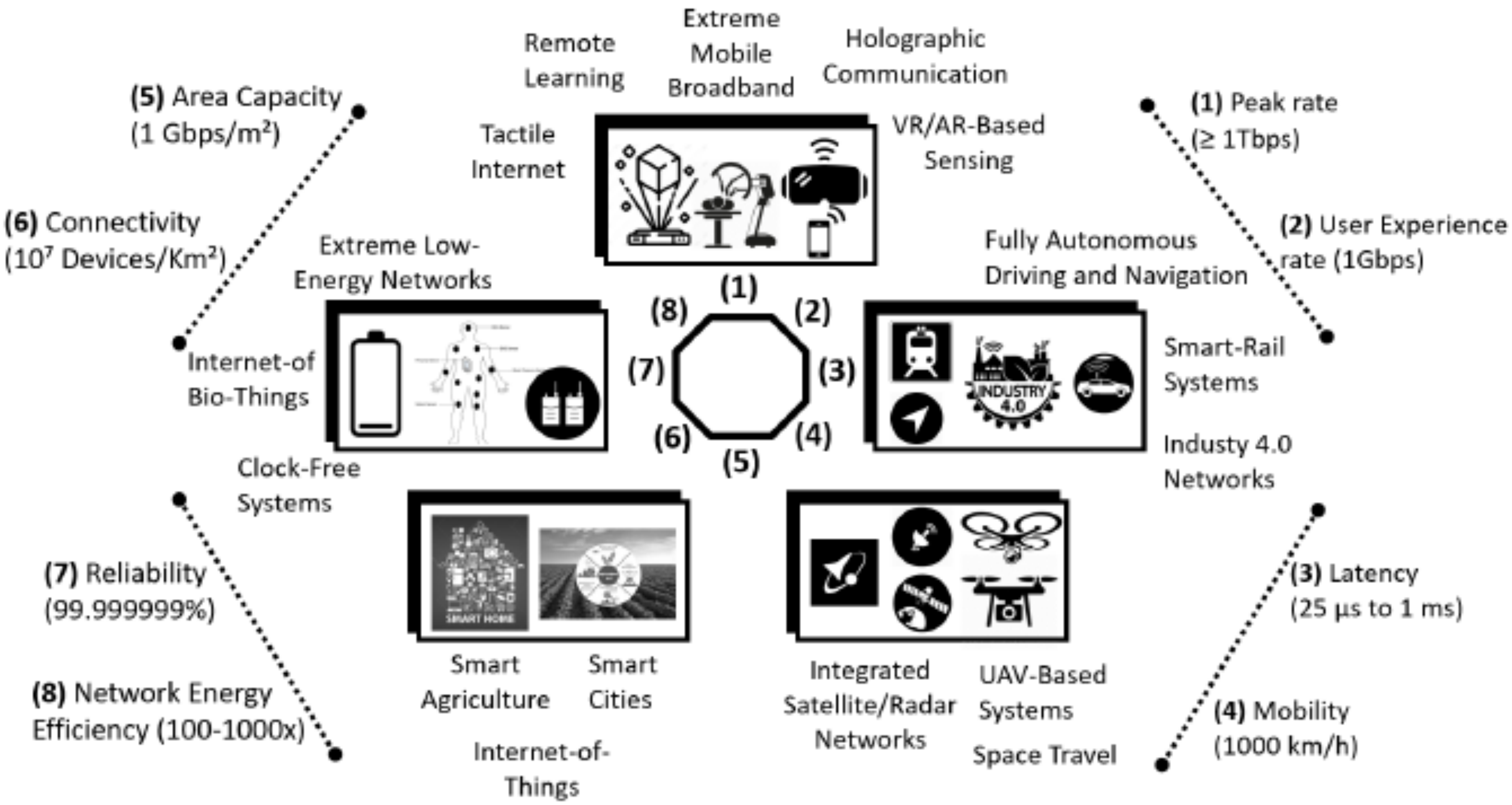
Applications

- Autonomous Driving
  - Reduction of accidents
  - Reduction of traffic jams
  - Elimination of “lost” time

- Smart City
  - Higher efficiency
  - Reduced energy consumption and pollution
  - Automatic reporting of issues

From 5G to 6G

- New applications drive requirements for new approaches



[*with* Tataria et al. 2021, Proc. IEEE]

Increase data rate: new spectrum in THz

THz communication promises and challenges

- Promises
  - Large amounts of fallow spectrum at >100 GHz
  - Frequency regulators have started assigning to users
  - Large number of antenna elements fit into small form factor

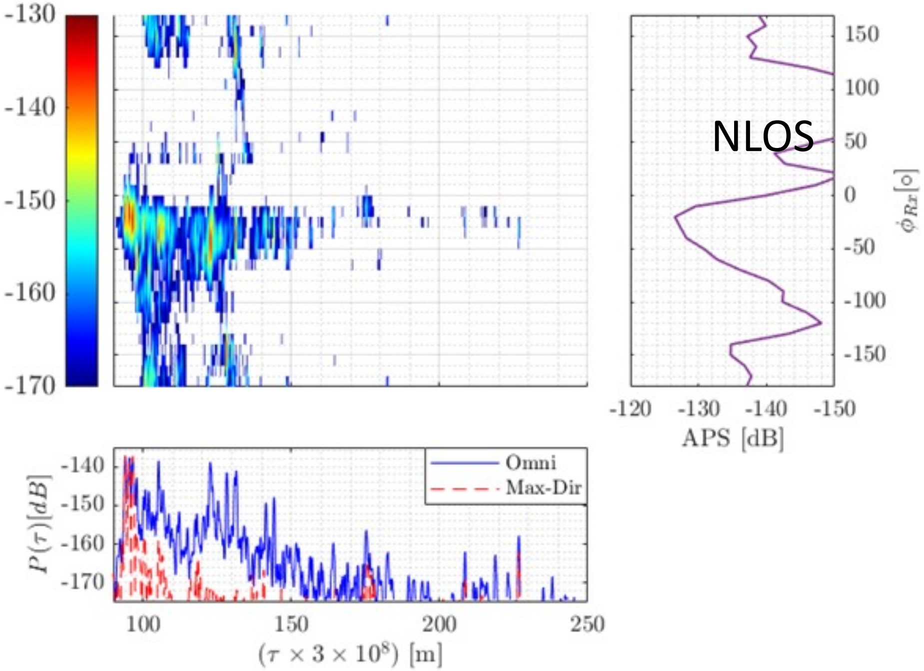
  -> Extremely high data rates and high user densities
  enabling applications not feasible with other technologies
- Challenges
  - Higher attenuation and other difficult propagation channel conditions
  - Low-cost semiconductor technology and transceiver design
  - Are we hitting the limits on array sizes?
    - For constant antenna area, number of antenna elements needs to increase
    - For increased bandwidth, noise power increases
    - -> Arrays at THz need many more elements

THz channels measurements

- Indoor channels
  - Pioneering work by *Kuerner et al*
  - Strong specular reflections in office
  - Long delay spreads in corridors
- Outdoor microcellular channel (1 GHz BW)
  - Pathloss coefficient low (~2) even in NLOS
  - 1 Gbit/s possible over 100 m
  - High sensitivity to shadowing
  - Delay spread can be 10s of ns
    - Even for directional DS
    - Need equalizer
  - Large number of clusters

  ➔Large angular spread

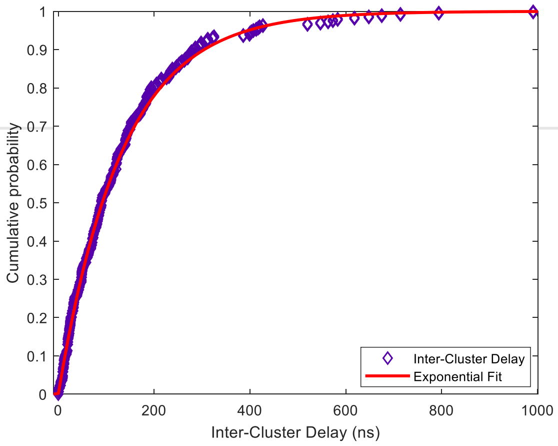
Sample APDP



[Molisch et al. 2024, WCM], [*with* Abbasi et al. 2022, 2023] [*with* Gomez et al. 2022]

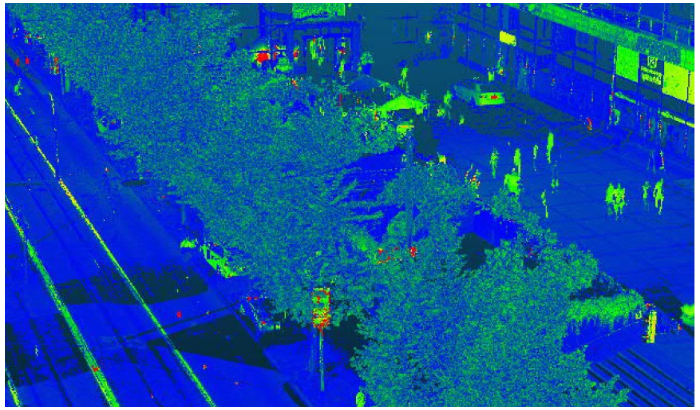
THz channel modeling

- Statistical models
  - Traditional COST approach: inter-cluster and intra-cluster

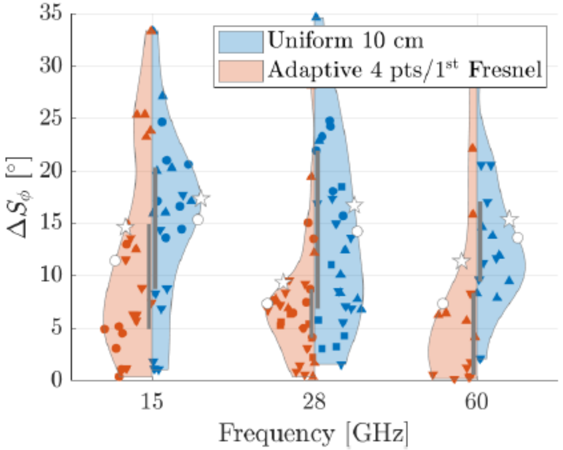


[*with* Abbasi et al, in preparation]

- Point cloud simulations (*Haneda et al.)*
  - Must model fine details, including diffuse scattering, blockage of first Fresnel zone
  - Must improve efficiency of ray tracing, e.g., visibility matrix (*Degli'Esposti et al)*, adaptive point cloud density



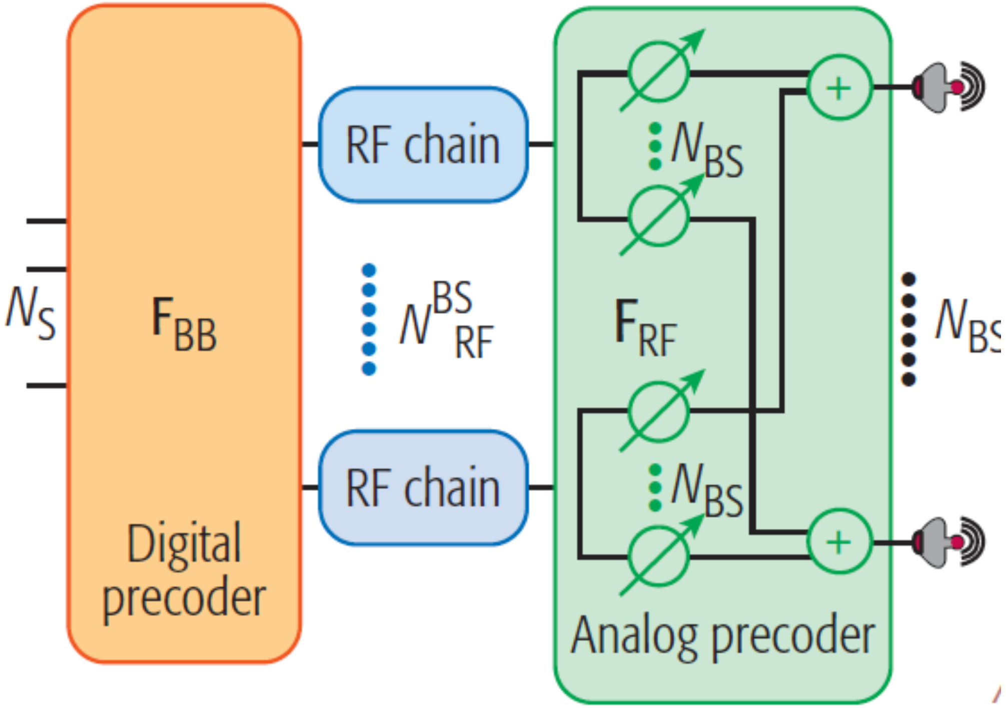
[*with* Koivumaki et al. 2021]



[*with* Koivumaki et al. 2024]

Hybrid beamforming

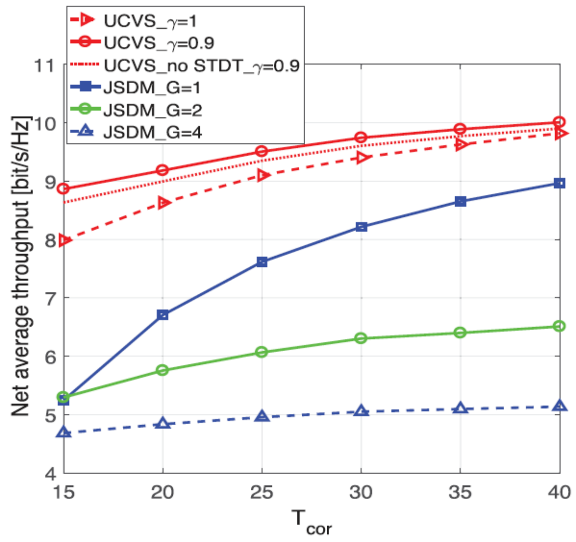
- Combine analog with digital beamforming to reduce number of RF chains without significant performance loss



- Invented in early 2000s at MERL: [Molisch and Zhang 2004], [*with* Zhang et al 2005] (using instantaneous CSI), [*with* Sudarshan et al. 2006] (using average CSI).

Hybrid beamforming research still ongoing

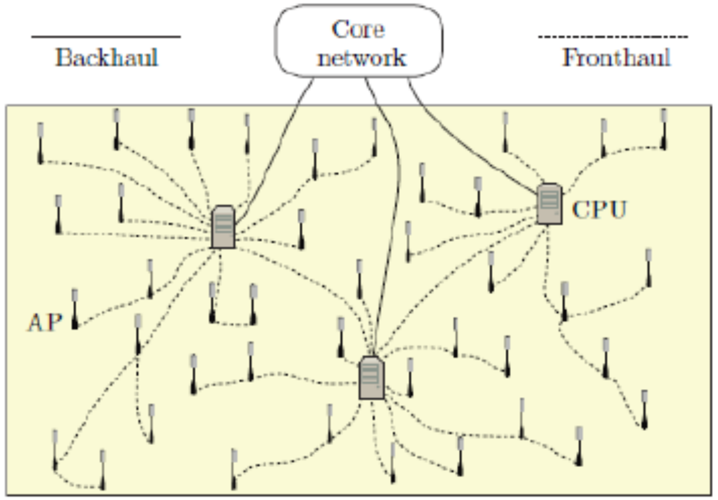
- Different structures and their performance
  - Full array vs array of subarrays vs intermediate
  - Combination of arrays and switches
  - JSDM Joint Spatial Multiplexing and Diversity
  - JPTA Joint Phase Time Arrays
- Adaptation algorithms in multi-user setting
  - Grouping/scheduling of UEs critically impacts performance
- Efficient channel estimation
- Energy minimization
- Combination with low-resolution ADCs
- Recent trend: holographic MIMO



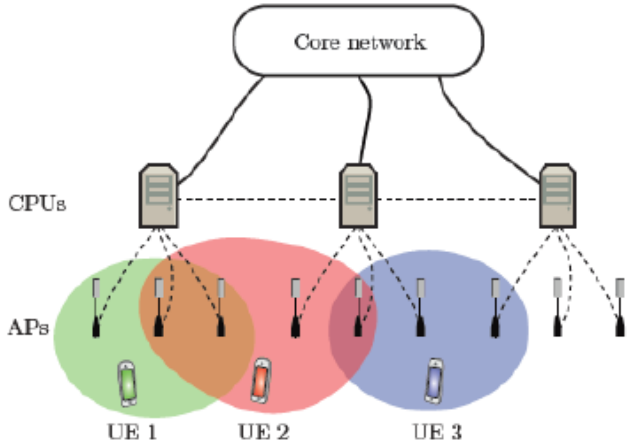
[*with* Li et al. 2018]

Increase datarate: distributed mMIMO

- Origin in base station cooperation, network MIMO, CoMP, Cloud RAN,…
- Elimination of intercell interference
- Enhanced macrodiversity
- Many new theoretical problems
  - Capacity: often handled with stochastic geometry
  - Combination algorithms (MRC, ZF,…)
  - Limited front haul capacity
  - Scalability: dynamic AP association
  - …..
  - and new channel models

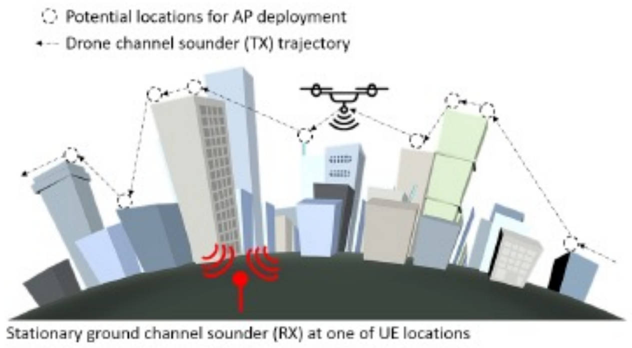


[Demir et al. 2021]



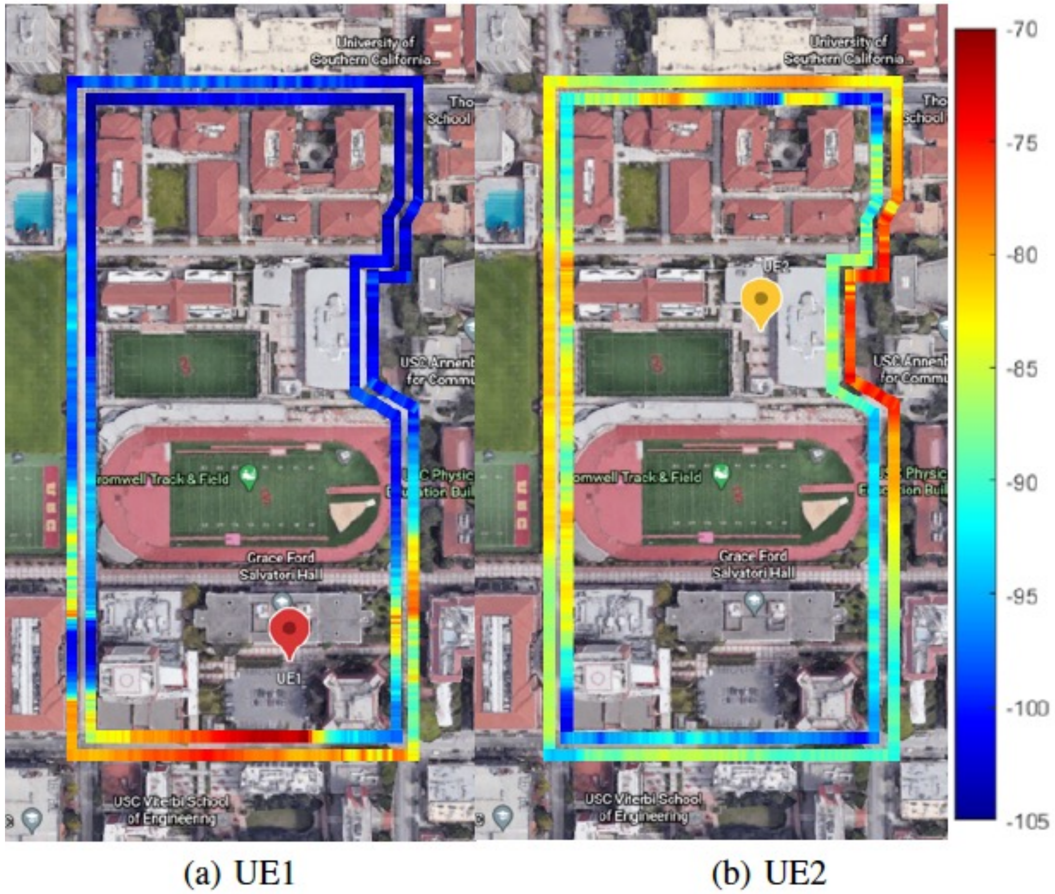
How to measure distributed mMIMO channels

- Use of drone to measure massive distributed AP arrays



[*with* Choi et al. 2022 WCNC]

Measurement data are publicly available

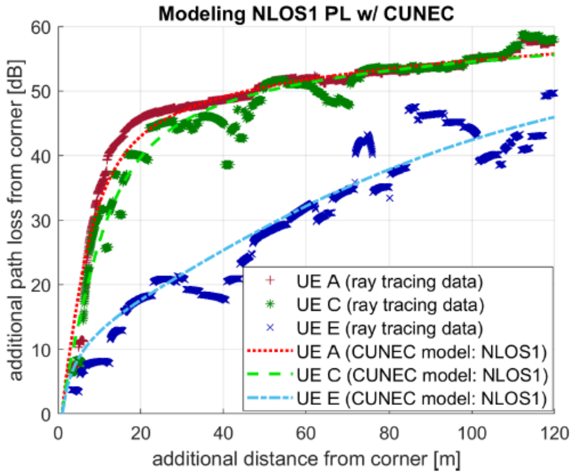


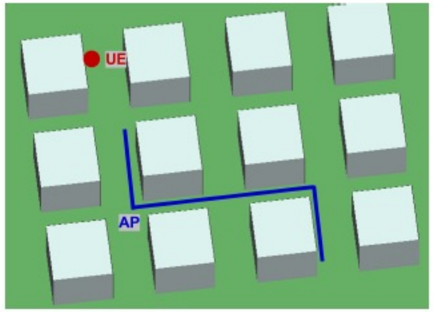
(a) UE1 (b) UE2

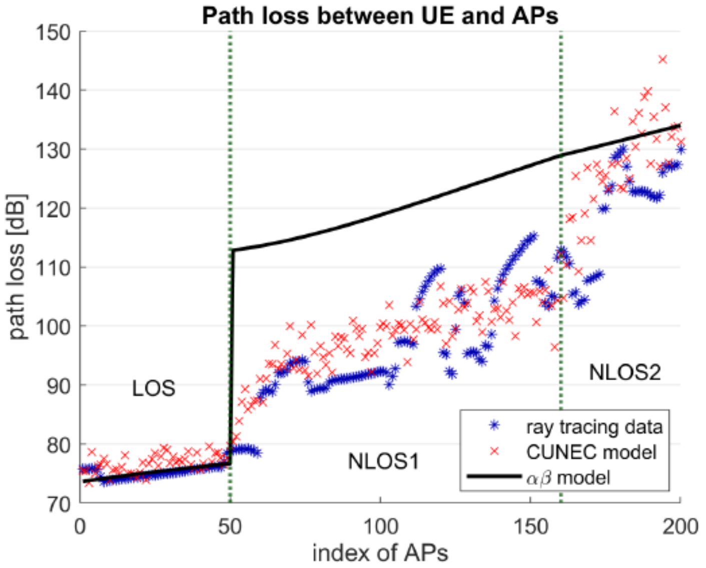
Virtual array moved by drone allows measurement of very large distributed AP arrays

Distributed mMIMO channel model

- Standard model:
  - Euclidean power law
  - Independent shadowing from APs
- Measured results
  - Pathloss depends on street
  - Shadowing along trajectory for both AP and UE
  - Shadowing correlated between APs
- -> new channel model: CUNEC
  - Pathloss, shadowing correlation depends on whether APs are in the same or different streets
  - Transition regions must be modeled
  - Parameterization from measurements and/or ray tracing





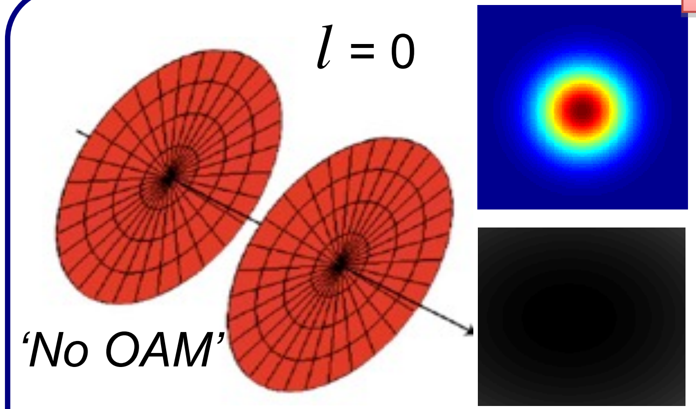


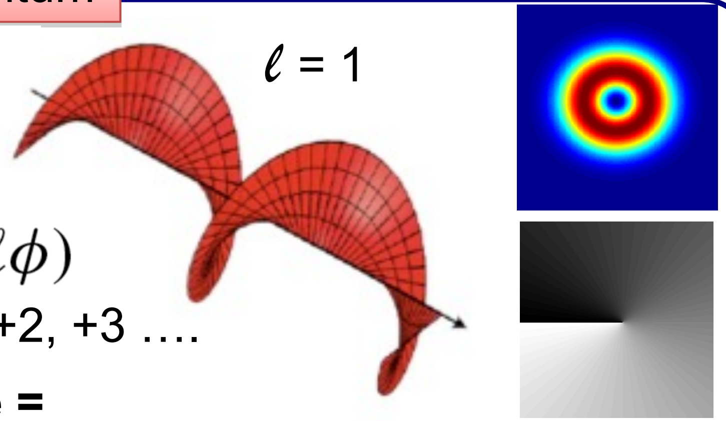
[*with* Choi et al. 2022 Globecom]

Increase data rate: OAM

OAM well suited for multiple data streams on point-to-point LOS links

Orbital Angular Momentum

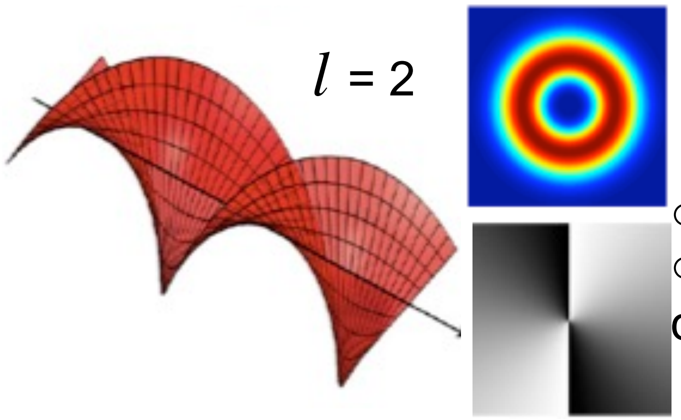


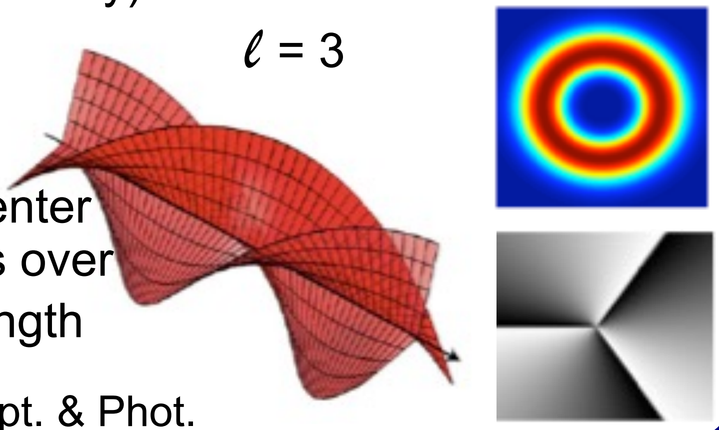


$$\phi(r, \phi) = \exp(i\ell\phi)$$

ℓ = …. -3, -2, -1 ,+1, +2, +3 ….

# of states possible = infinite , …. (theoretically)



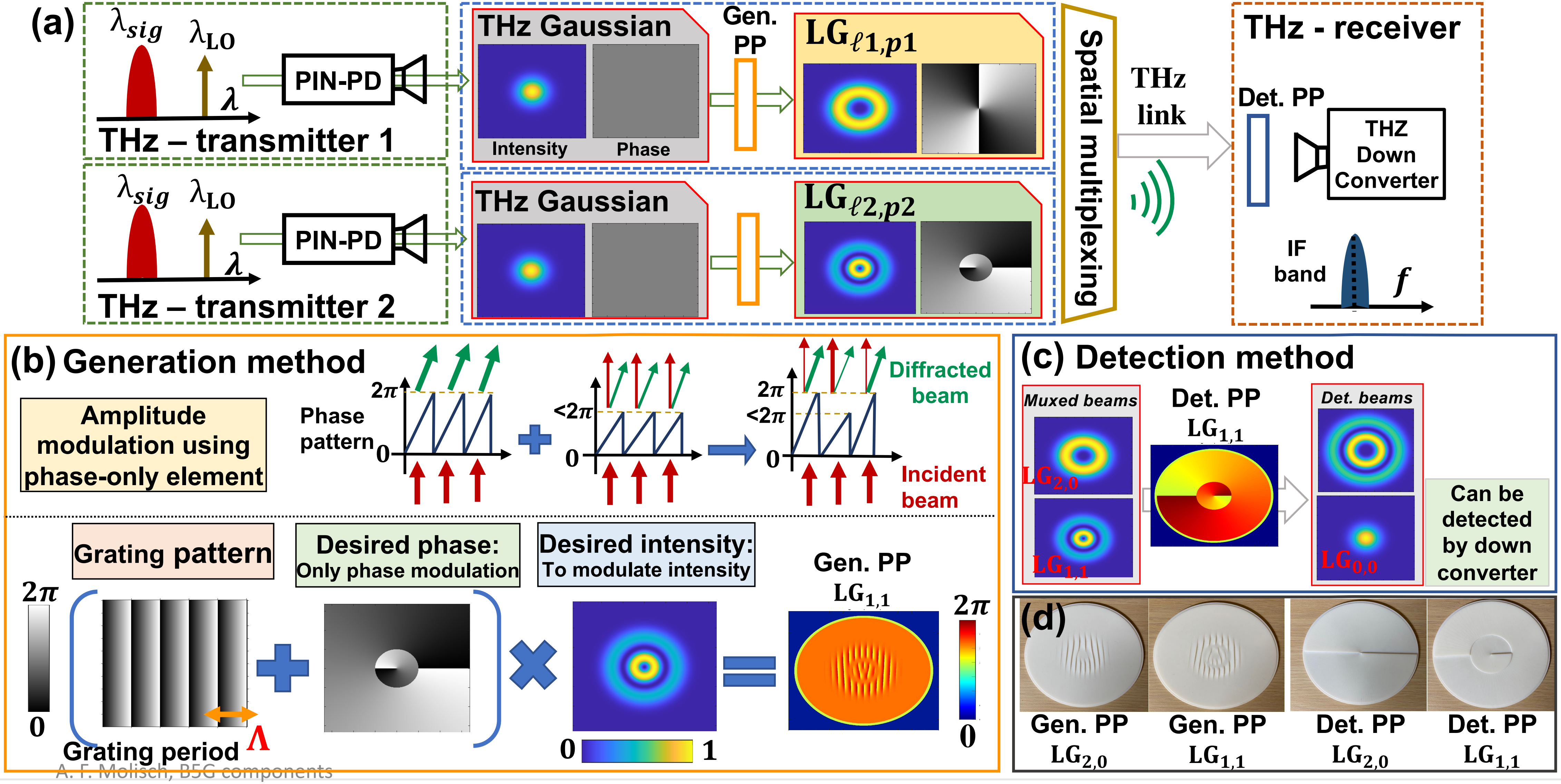


- Intensity null at the center
- Phase spirals 'l' times over distance of one wavelength

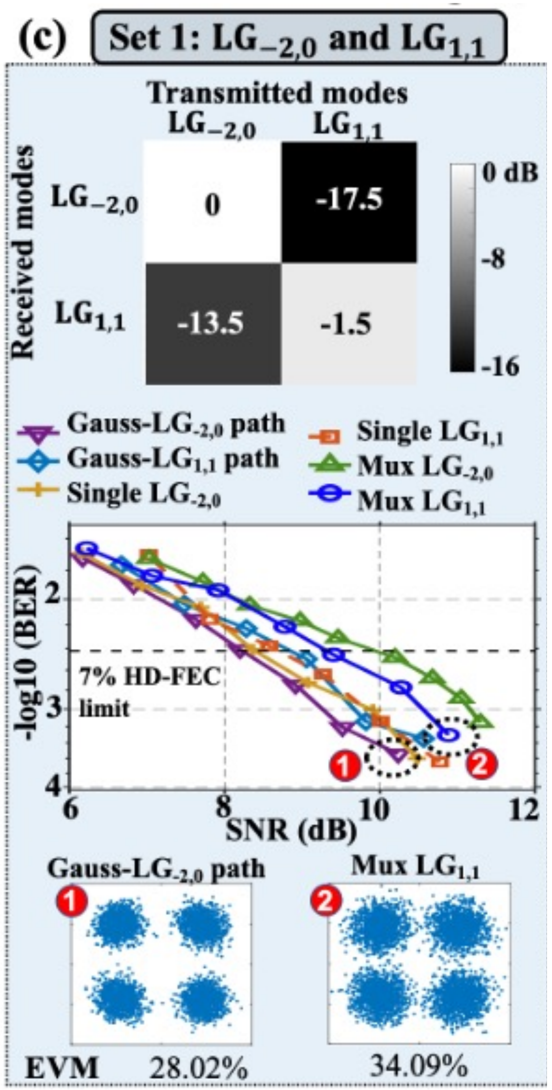
[Yao, et al. 2011 Adv. in Opt. & Phot.

Block diagram for OAM multiplexing

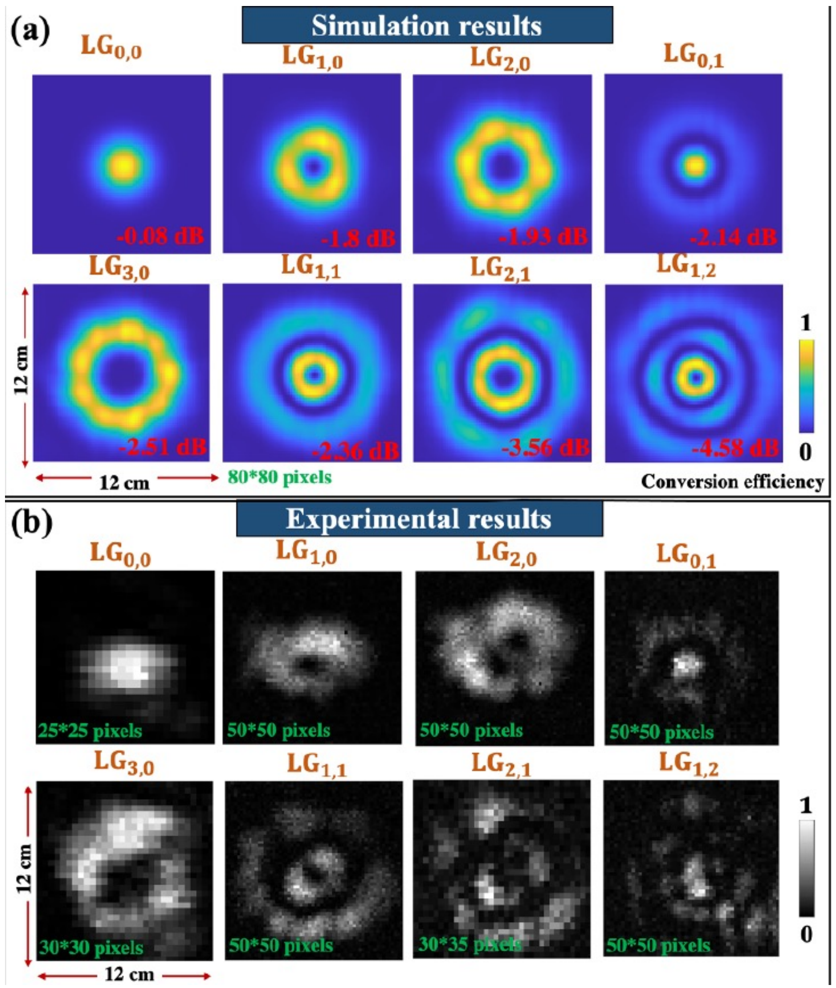
[*with* Minoofar, et al., 2021].



Sample results OAM



More modes from
2-D Laguerre-Gauss

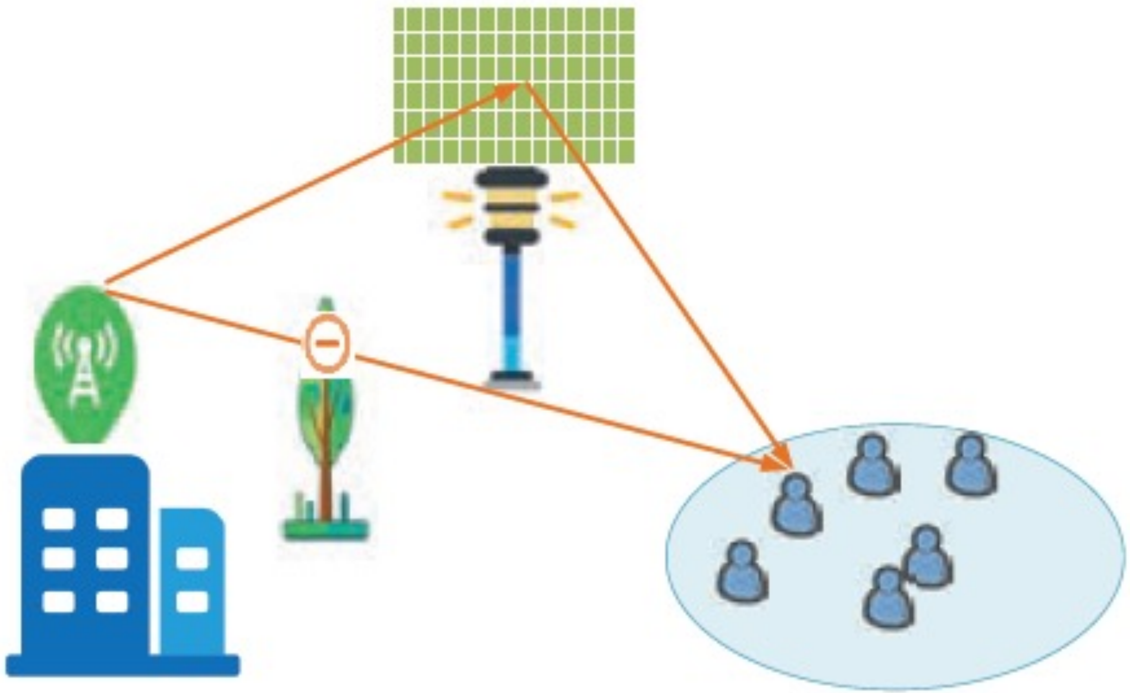


- Sources of intermodal interference
  - Imperfect phase plates/detectors
  - Radial offset
  - Finite aperture
  - Turbulence
  - Multi-path
  - Blockers in path

[*with Minoofar, et al.*, 2021].

Increased data rate: RIS

- Reconfigurable intelligent surface



[Liu et al. 2022]

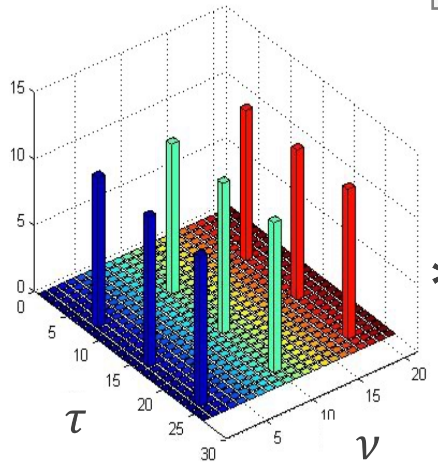
- Advantages
  - No conversion to baseband
  - Relatively simple control
- Drawbacks
  - Required real estate larger than for relay
  - Still needs power supply
  - More complicated processing and channel estimation

- OTFS is a modulation in the delay-Doppler domain (dual to OFDM)

- Modulation in delay-Doppler domain "sees" a channel that is stable and identical for all symbols
- Equivalently, novel 2D basis functions spread information symbols over both time and frequency
- Full diversity
- Averages out channel fluctuations, and thus does not need CSIT

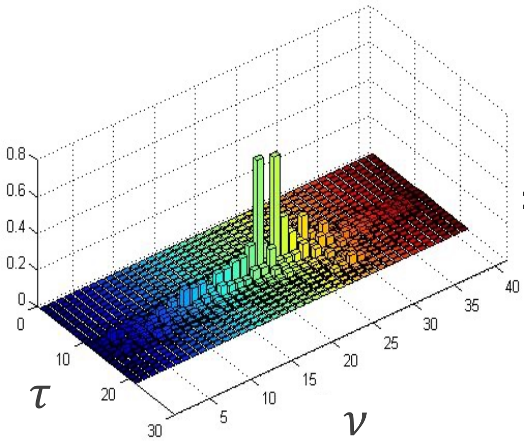
Convolution of transmit symbols with channel spreading function

$$x_{\tau,\nu} * h(\tau,\nu) = y_{\tau,\nu}$$



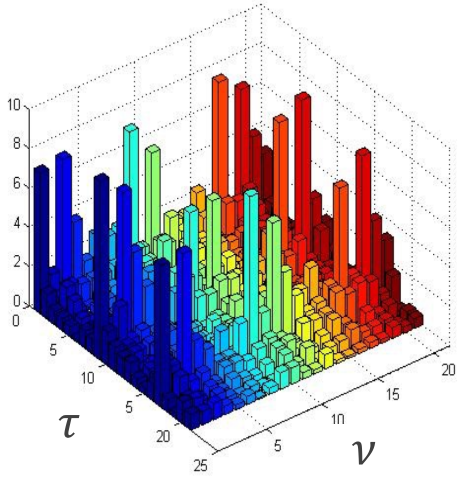
Transmitted OTFS QAM Symbols

*



Delay-Doppler Impulse Response

=

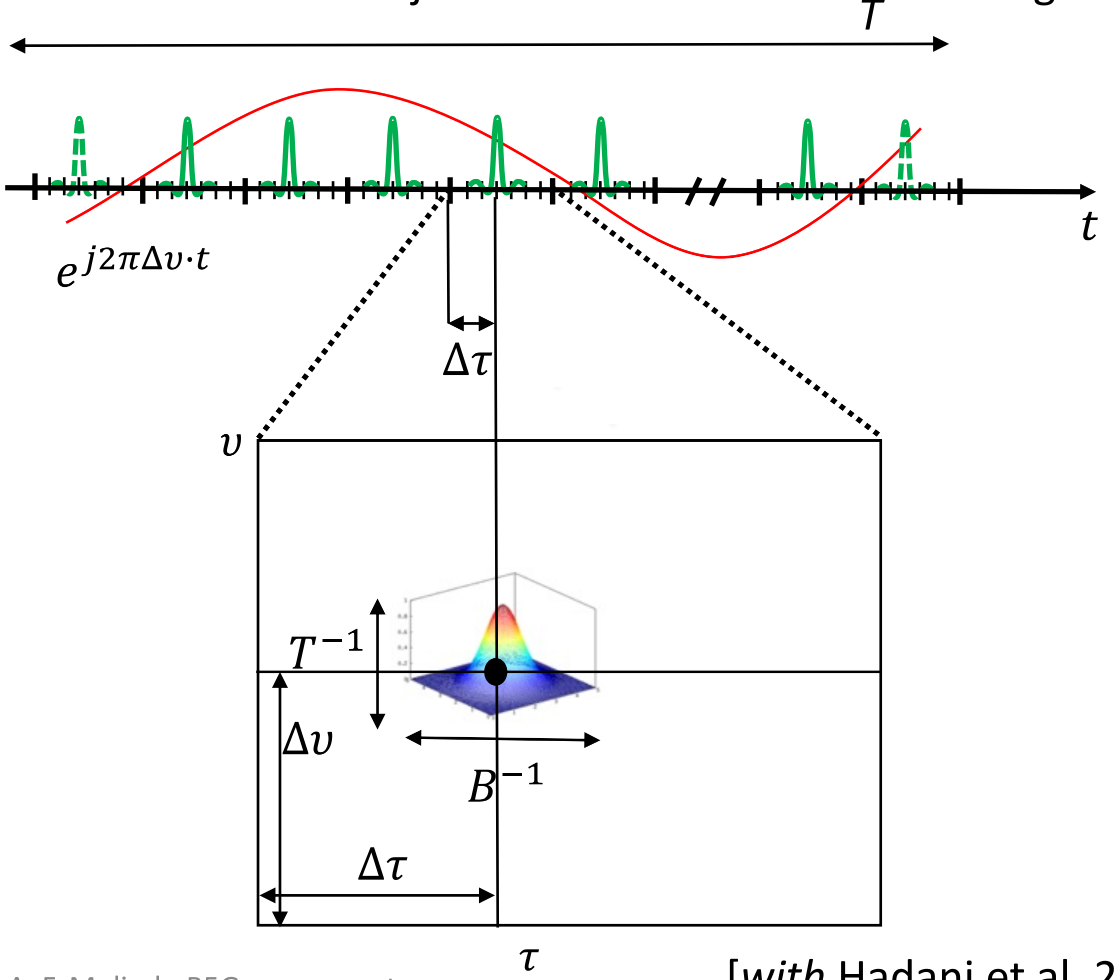


Received OTFS Symbols

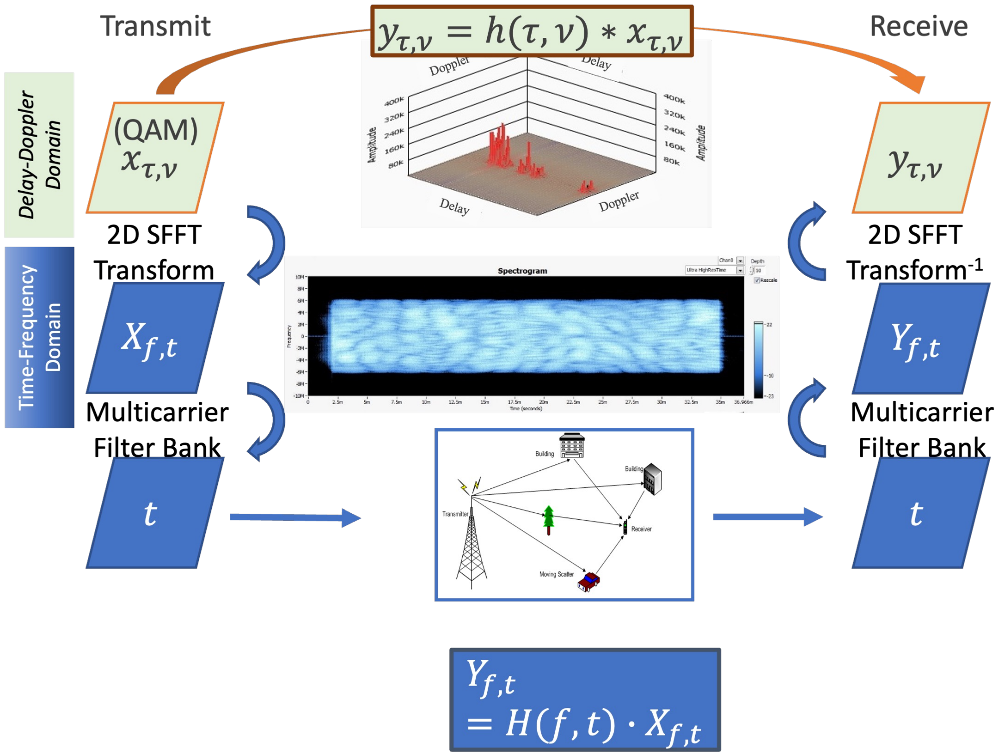
[*with* Hadani et al. 2017]

OTFS interpretation

- OTFS waveform
  - Identical to Doppler pulse radar
  - Well suited for joint communication and sensing



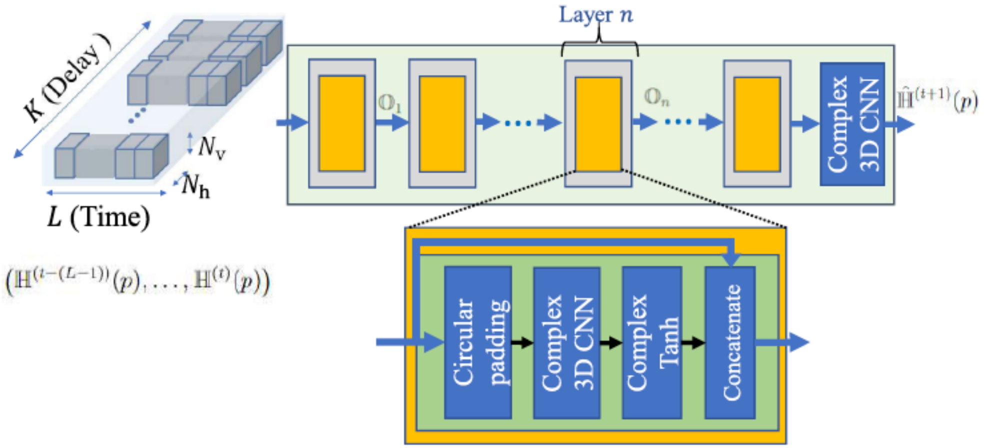
Implementation as overlay



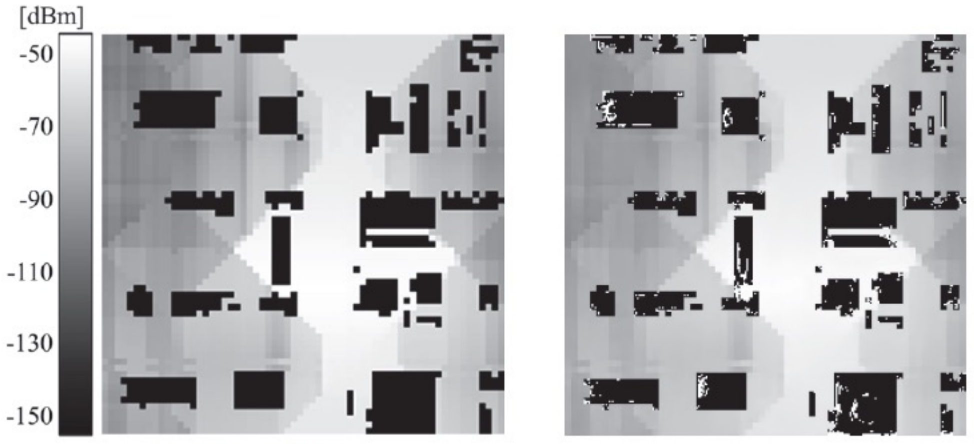
[*with* Hadani et al. 2018]

ML for propagation

- Can be divided into
  - Real-time channel prediction for system operation
    - More important with schedulers, beamformers, etc., becoming more complex
  - Coverage prediction without ray tracing
    - For denser networks, CF-mMIMO, etc.
  - Channel modeling
    - Potentially more accurate than statistical models
- All learning strategies require understanding of the physics of propagation
  - Selection of neural network structure
  - Preprocessing of data
  - Training strategy and amount of required data
  - Data augmentation



[*with* Burghal et al. 2023]



(a) Ground Truth (d) Predicted (PMNet)

[*with* Lee et al. 2023]

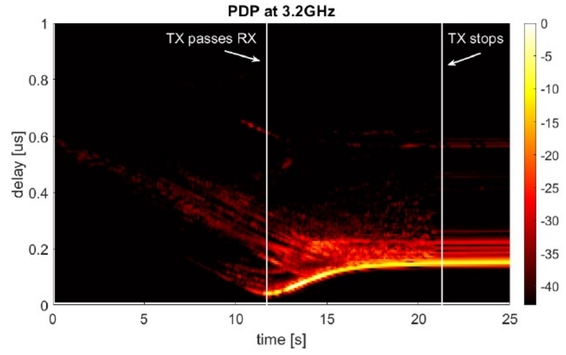
ML for other application

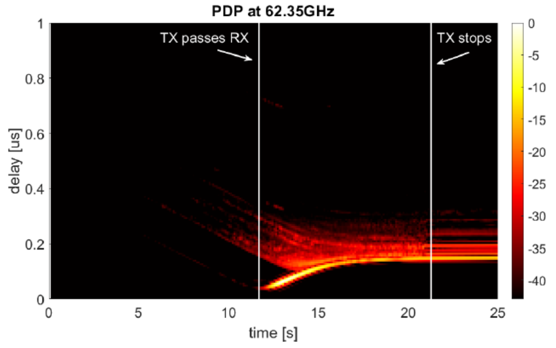
- ML is everywhere
- Best application for:
  - NP-hard problems
  - Operation where simplified analytical models don't hold
    - Real channels
    - Nonlinearities
    - Stochastic processes with non-Gaussian characteristics and/or non-ideal ACF
  - Incorporate physics and known analytical solutions as much as possible
- Examples
  - Antenna selection
  - Modulation/coding
  - Scheduling
  - Routing

V2X

- Ongoing since 2000, battle 802.11p vs 3GPP
- Now increased emphasis on high throughput and JCAS
- Challenges
  - PHY: beamforming, channel estimation, channel extrapolation
  - MAC: scheduling (especially for V2V)
  - Networking: fast handover
- Research avenues
  - Machine learning at all layers
  - Stochastic geometry (mixture of line and point processes)
  - New MAC formats
  - ….

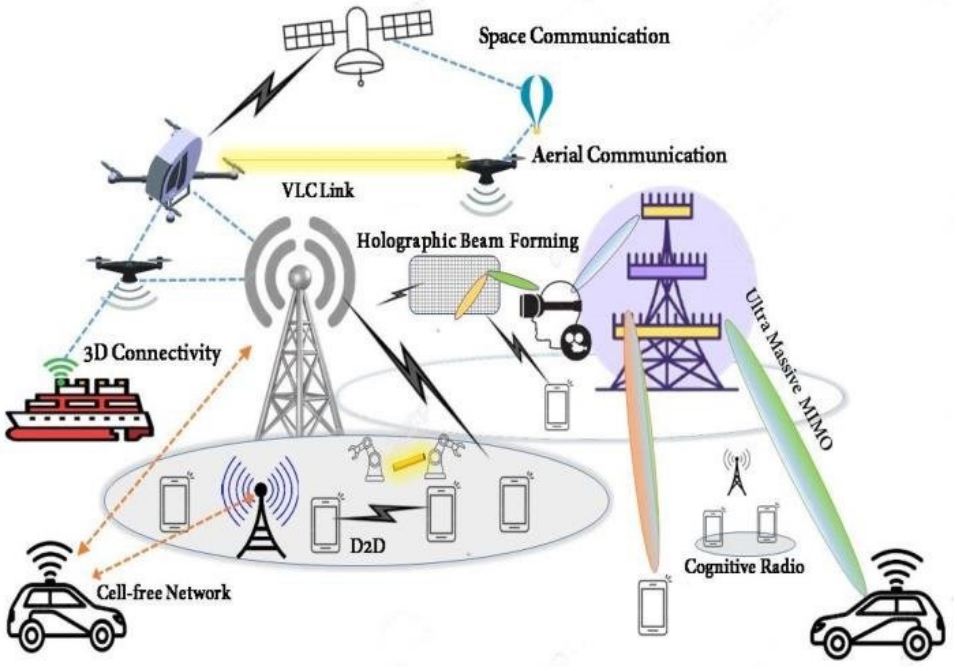
[with *Hofer* et al. 2021]





3D networks

- Coordination of
  - Transmission
  - UAV trajectories (for both efficiency and lifetime)
  - Ability to relay to satellites
- Research challenges
  - Channels (as always…)
  - UAV trajectory planning
  - PHY layer challenges on links (e.g., Doppler shift in satellite link)



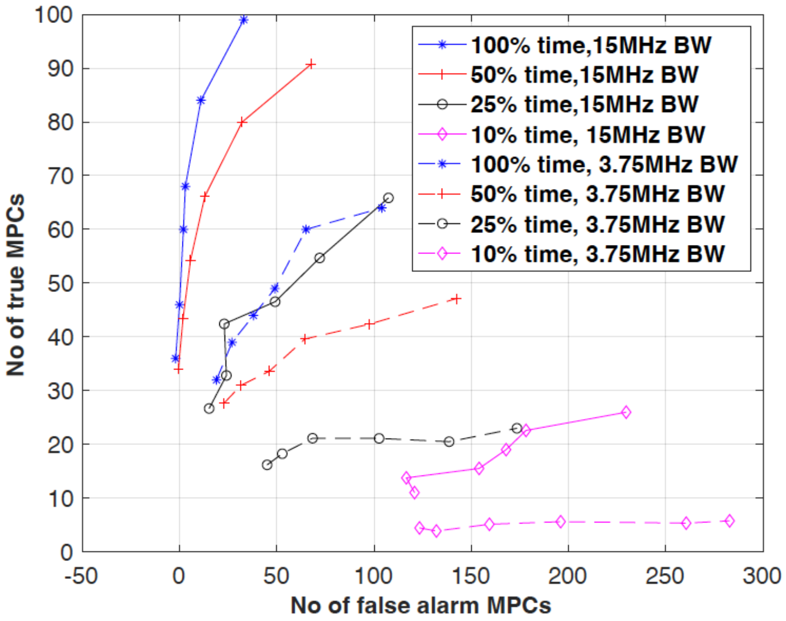
[Bhat et al. 2021]

Joint Communication and Sensing (JCAS)

- Goals:
  - Better spectrum usage
  - Better use of infrastructure
- Orthogonalization
  - Orthogonalization in time/space
    - Spatial database
    - Listen before talk
  - Orthogonalization in signal space
- System co-design
  - Use of radar signals for communication
  - Use of communication signals for radar
    - Information-bearing
    - Pilot tones and synchronization signals
  - Development of joint waveform

JCAS Example

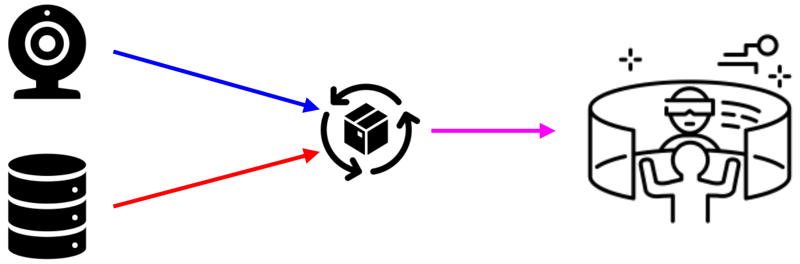
- Example: use of cellular reference signals for radar
  - LTE is better than NR
  - Dedicated signals vs "already specified"
- Ambiguity function analysis
  - Unpredictable placement of RS in time-frequency

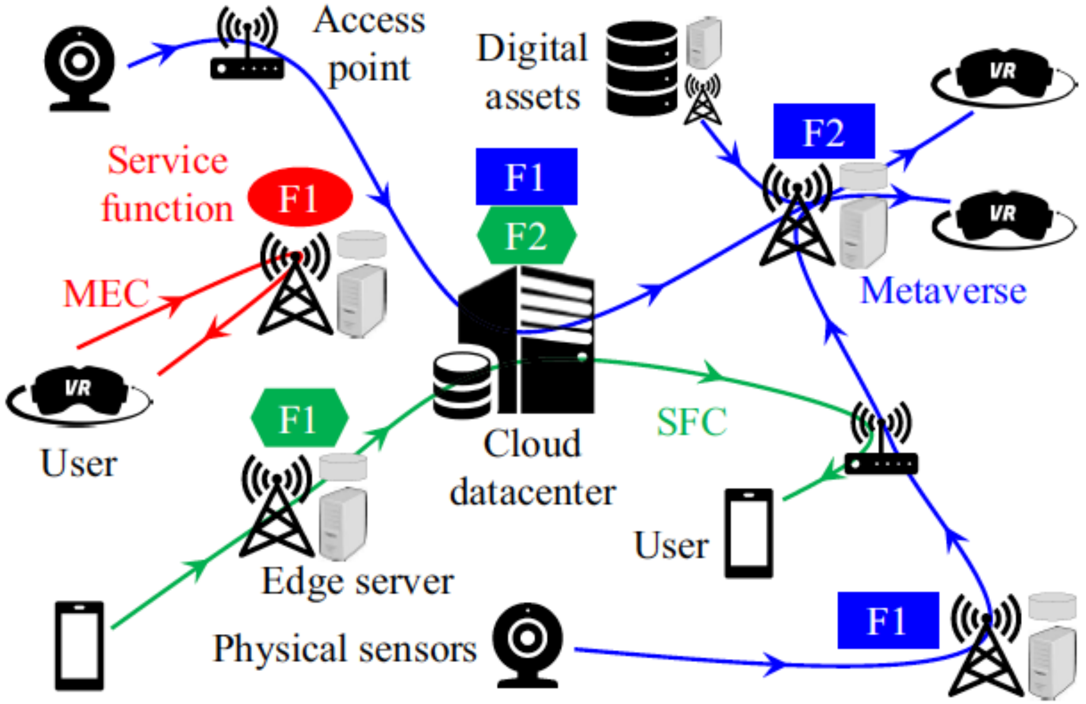


[*with* Nataraja et al., 2024]

Joint Computation Communication Caching (3C)

- Metaverse applications will require combination of all three
- General network structure





[with Cai et al. 2022a*]*

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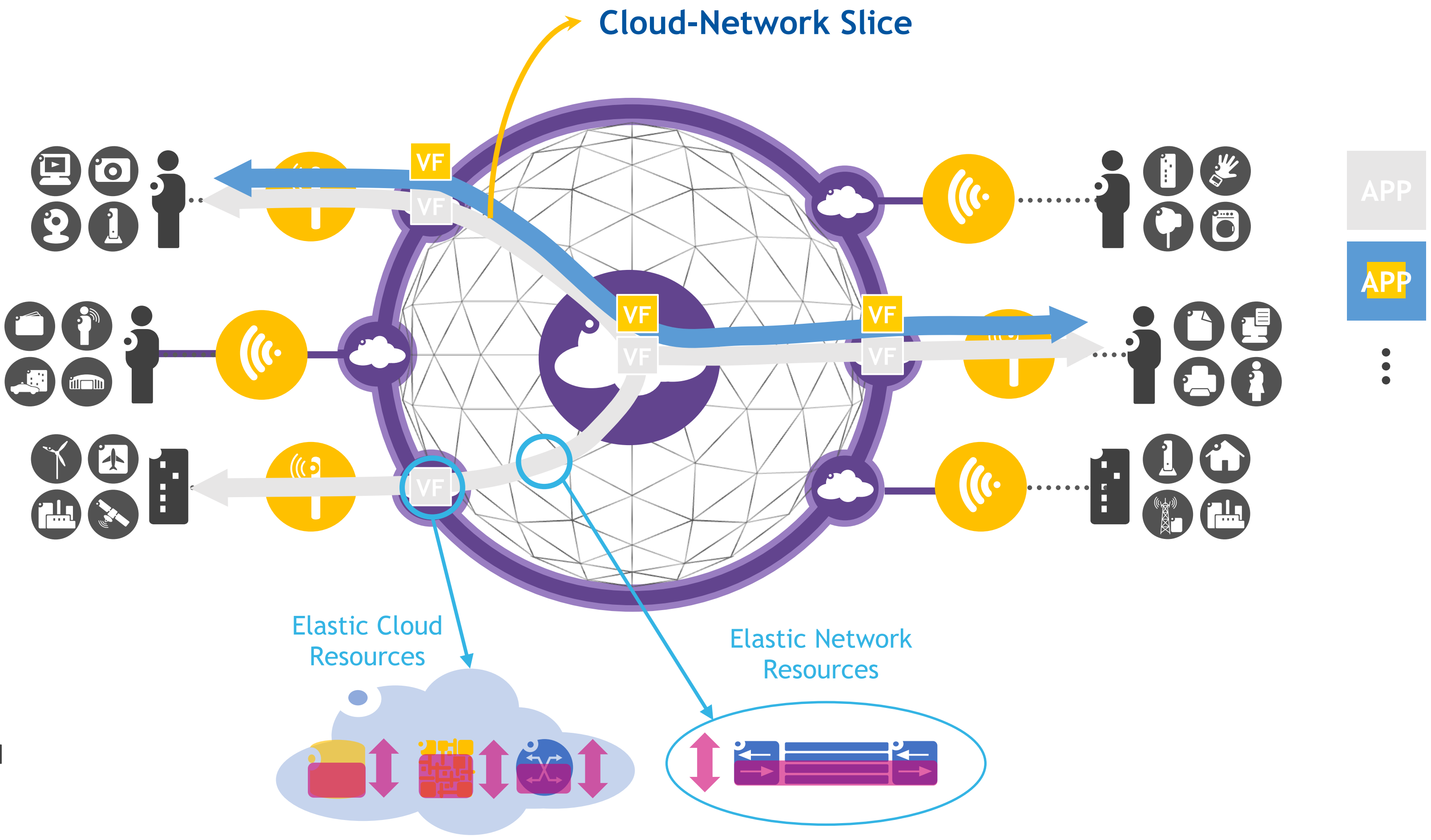
Optimization of data flows

- Cloud-Network OS
  - Network function virtualization (NFV)
  - Software defined networking (SDN)

- Next-generation services
  1) Virtual Networks
     - 5G slices
  2) System Automation
     - Smart home/building/factory/city
     - Autonomous transportation/logistics
  3) Augmented Experience
     - VR/AR, interactive/immersive media, connected gaming, metaverse



[with Cai et al. 2022a*]*

3C types of problems

- Distributed Edge computing:
  - Special case of 3C: source and destination are same node
- Strict delay constraints
- Multicasting
- Robustness to infrastructure outages
- Multimodal transmission (combined wired/wireless)
- Security in 3C networks

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Summary

- B5G is on its way
- Applications will drive technology
- Innovations will range from physical layer to applications
  - New frequency ranges (THz)
  - MIMO (including hybrid beamforming, distributed massive MIMO, OAM, RIS)
  - Machine learning (for channels, PHY, MAC, networking)
  - V2X and 3D systems
  - Joint communication and sensing, and new waveforms (including OTFS)
  - Joint communication, computation, and caching
- Lots of exciting work to be done

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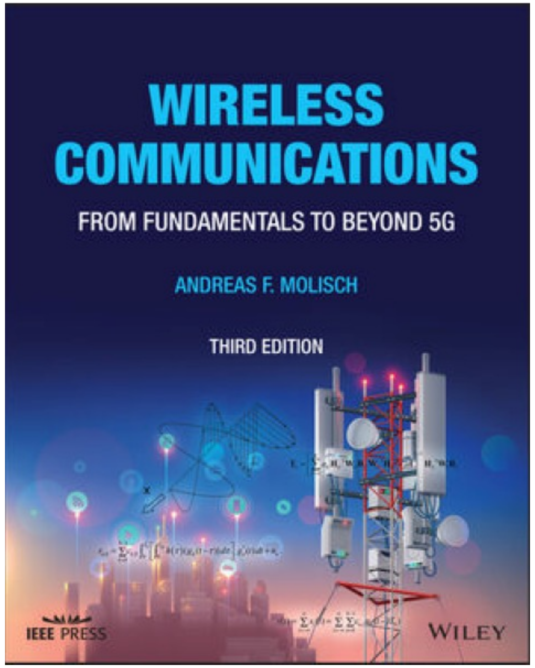

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