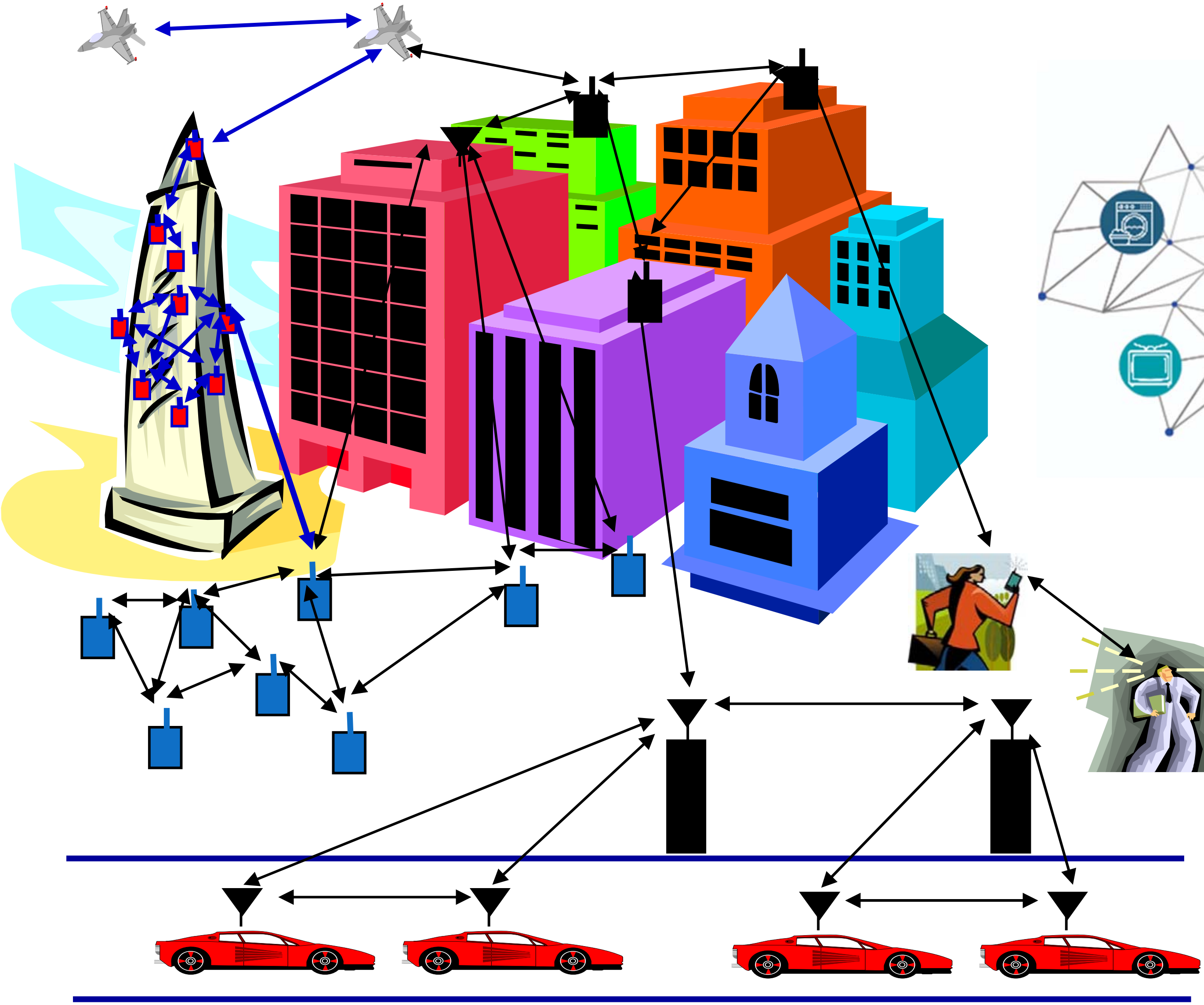
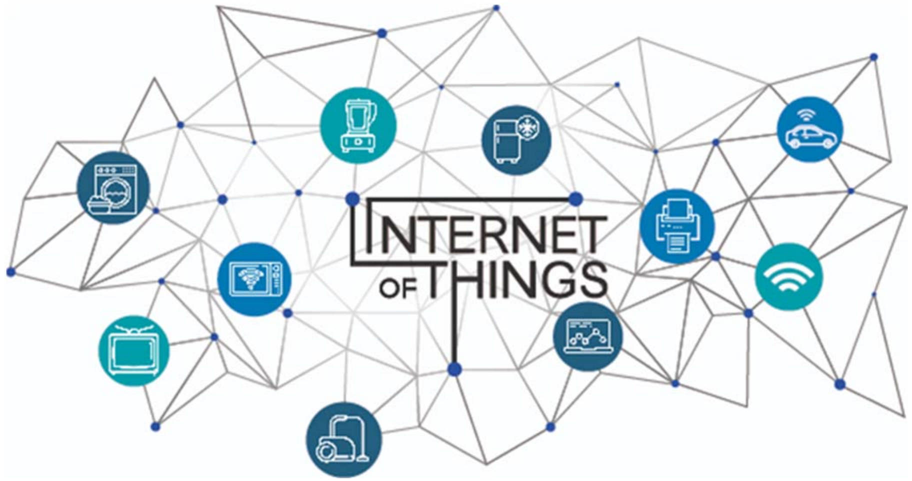
Disrupting Next G

ICASSP Plenary Lecture
June 6, 2023
Rhodes, Greece

Future Wireless Networks

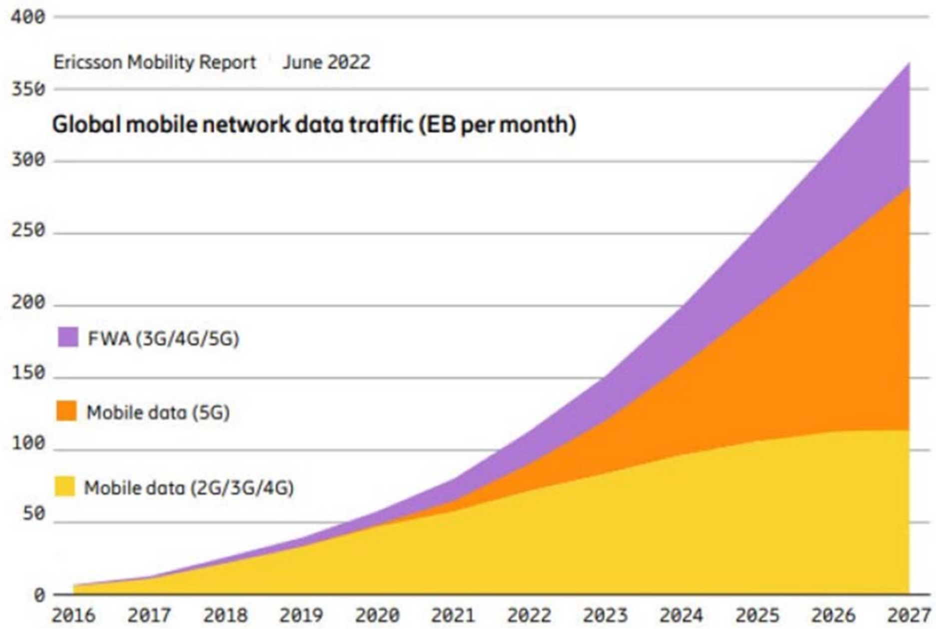
Ubiquitous Communication Among People and Devices

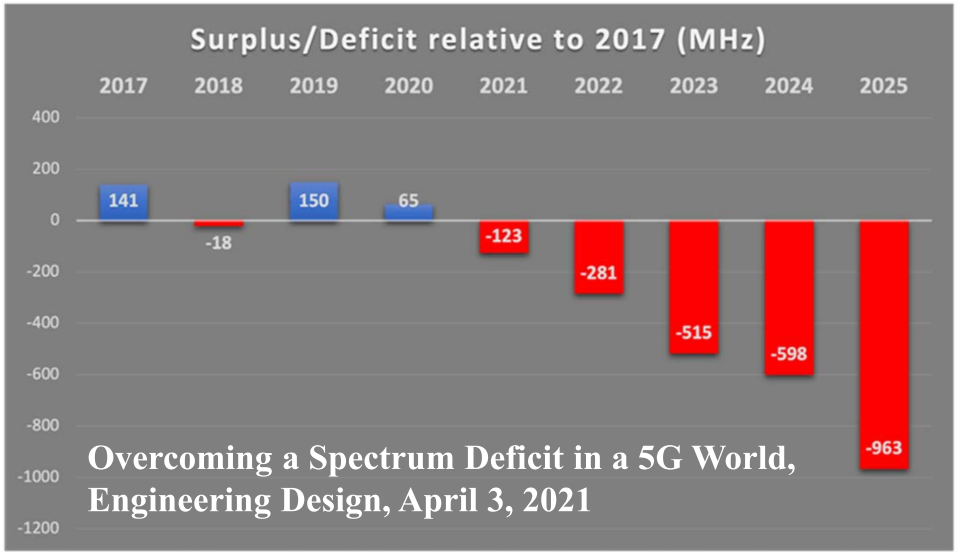




Next-Gen Cellular/WiFi
Smart Spaces/Cities
Autonomous Vehicles
“Enhanced” Reality
Body-Area Networks
Massive Sensing
All this and more …

The Licensed Airwaves are “Full”

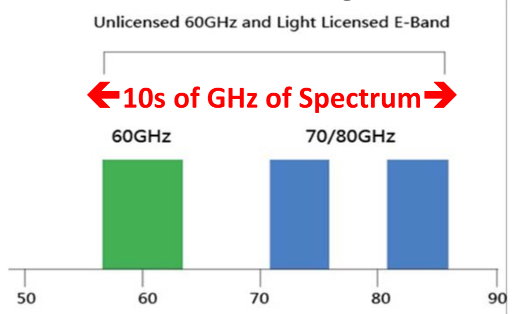




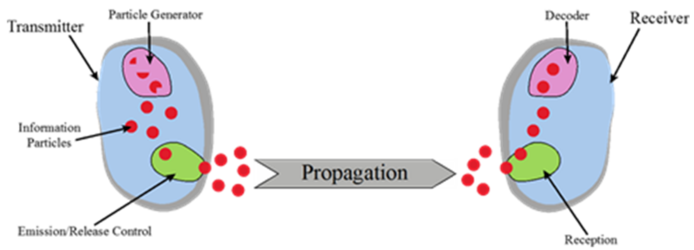
Overcoming a Spectrum Deficit in a 5G World, Engineering Design, April 3, 2021

Also have Wifi

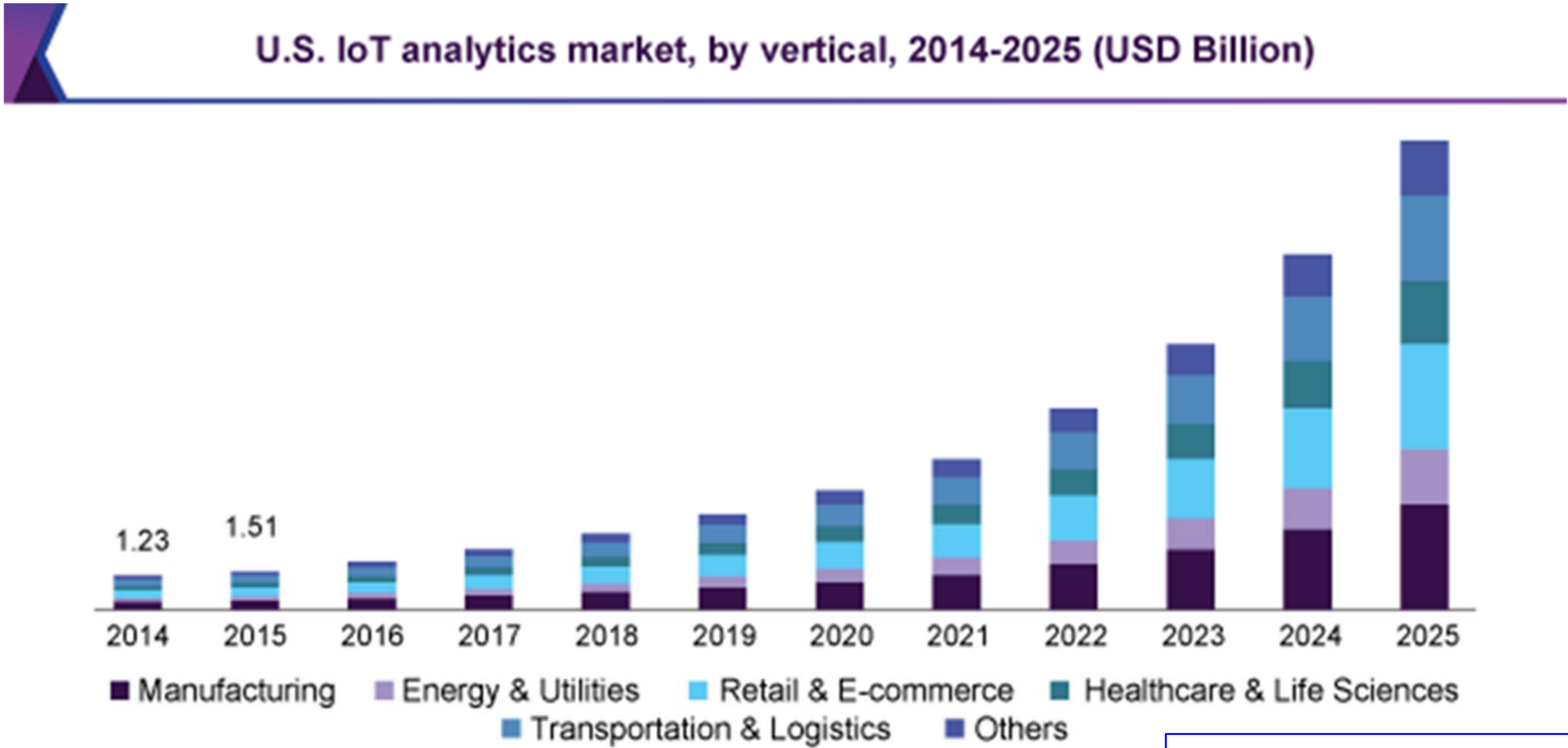
And mmW/THz



And molecular



On the Horizon, the Internet of Things

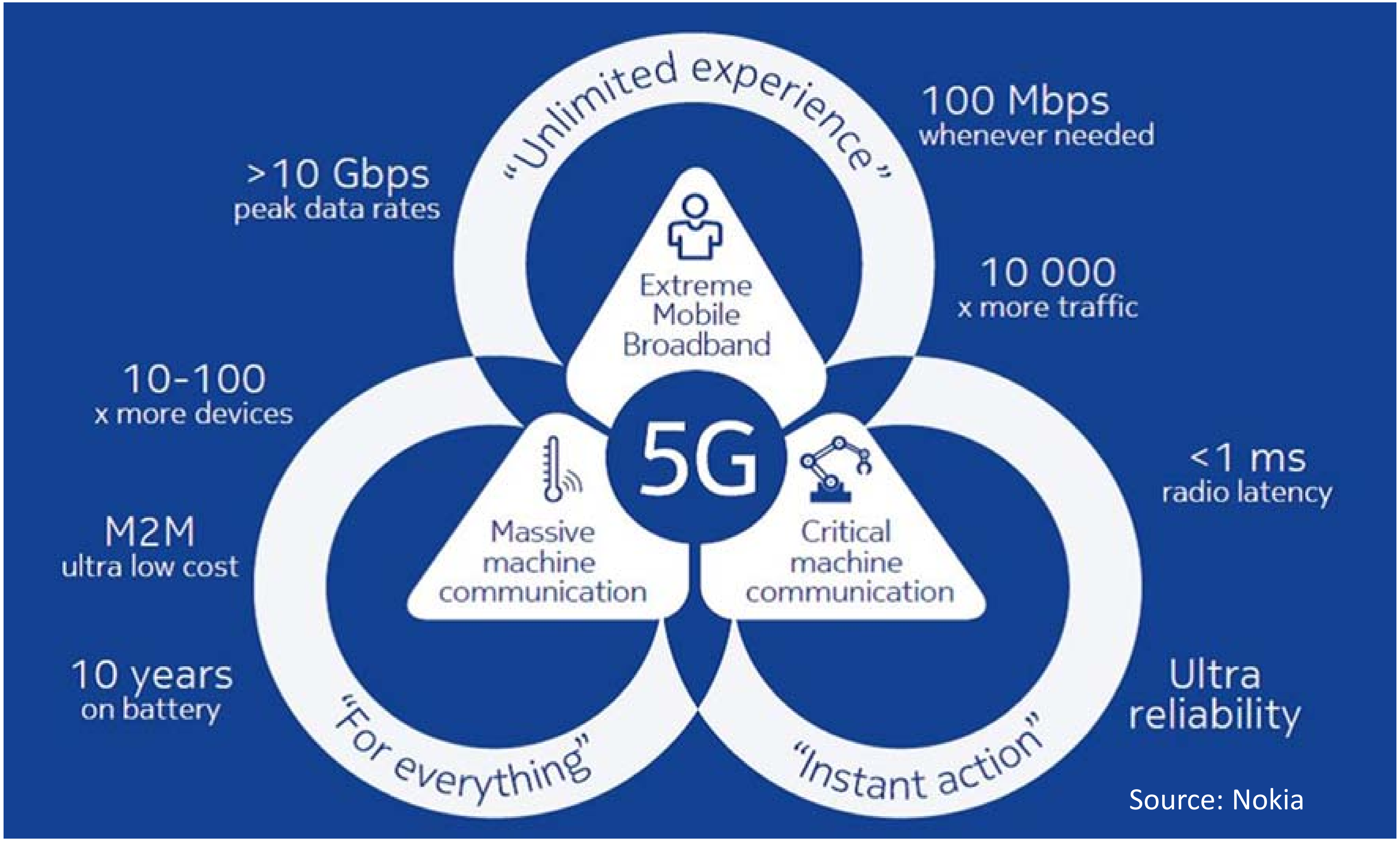


Source: Grand View Research
Report ID: GVR-2-68038-142-9

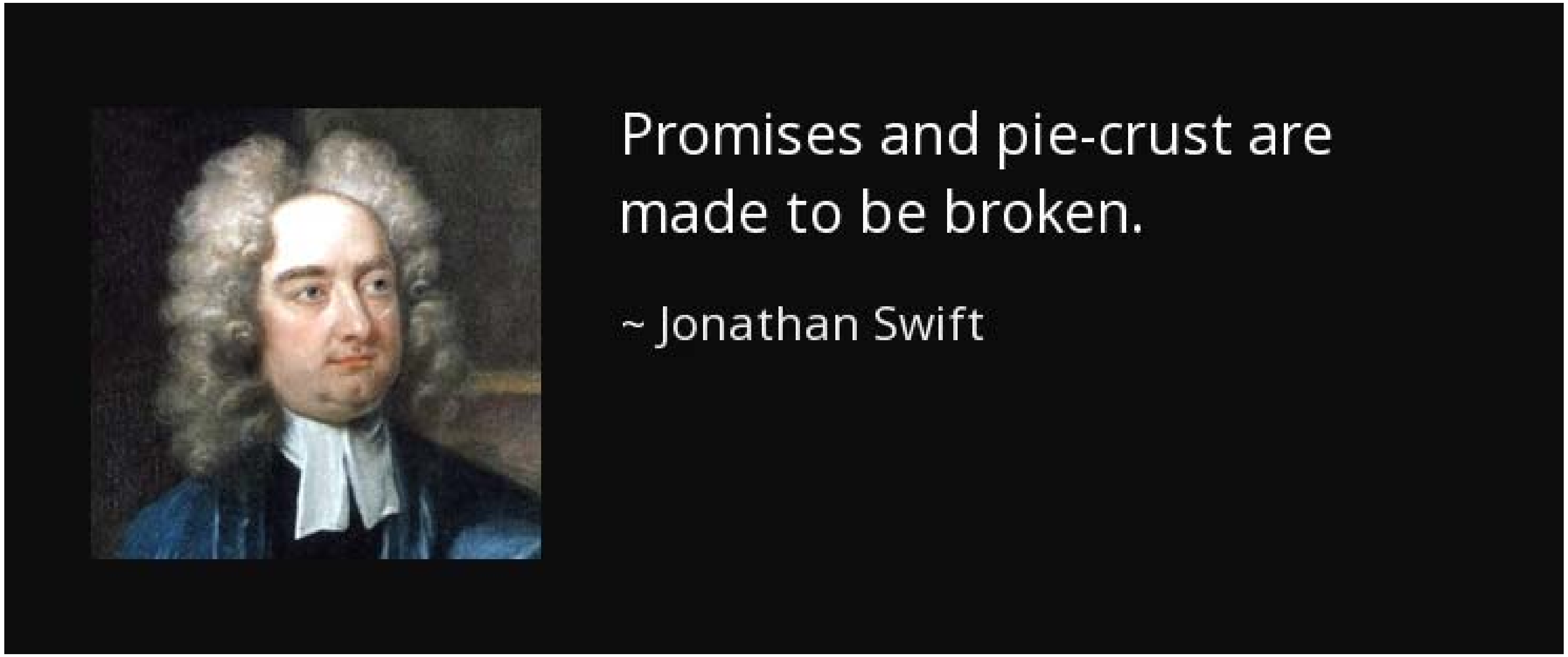
- Different requirements than smartphones
  - Low rates, latency, energy consumption
  - Also security, privacy, and resilience

Promise of 5G

Challenges: high data rates, low energy, low latency



Source: Nokia

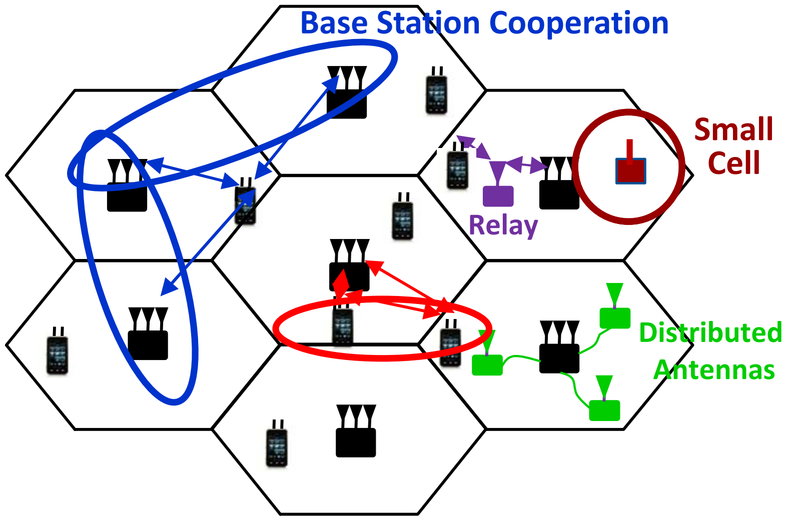


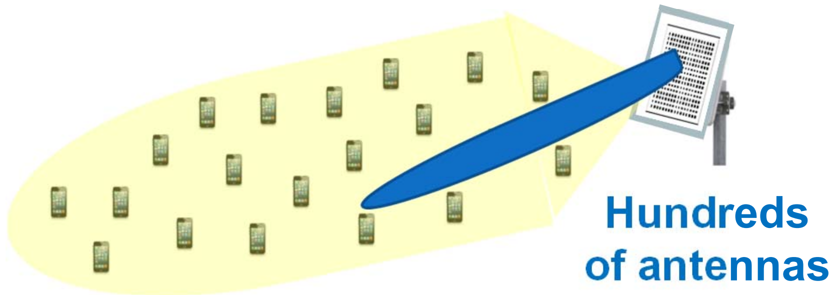
Especially in wireless standards, as it drive the next G

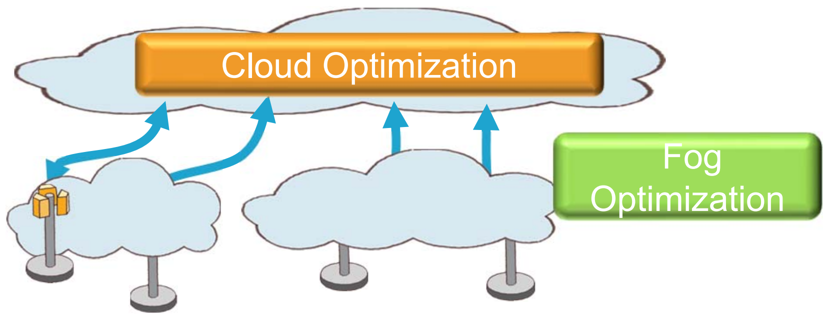
Enabling Technologies for NextG networks

- Rethinking cellular system design
- Rethinking backbone network design
- Utilizing more spectrum (mmw/THz)
- Very low power radios
- Massive MIMO
- New PHY and MAC techniques
- Multihop routing
- Edge computing and caching
- Cloud and fog optimization
- Security, privacy and resilience
- Machine learning

Can’t ML enable everything?

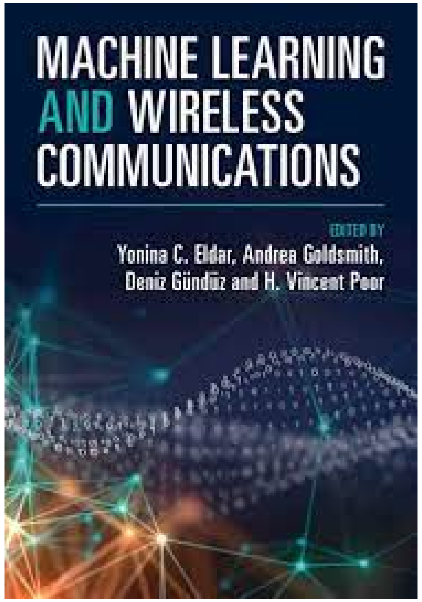


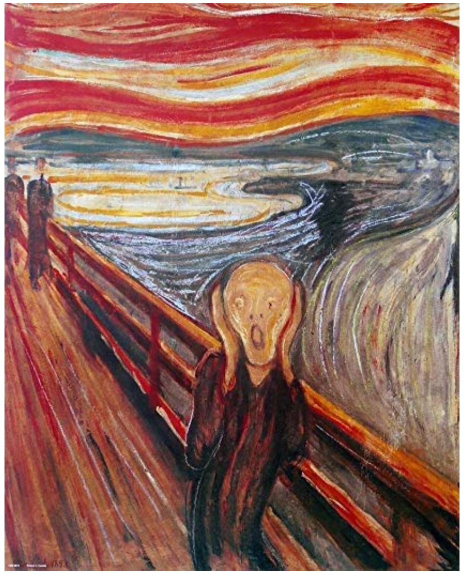




ML Today is a Bandwagon

Should we jump on?



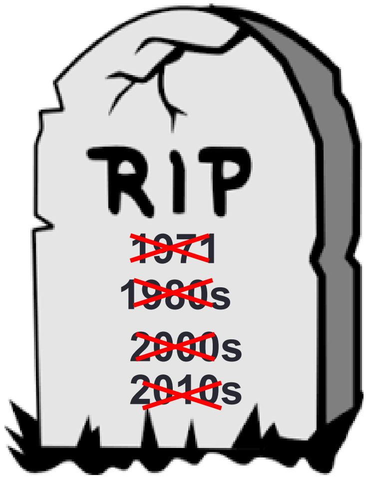


Or run screaming?

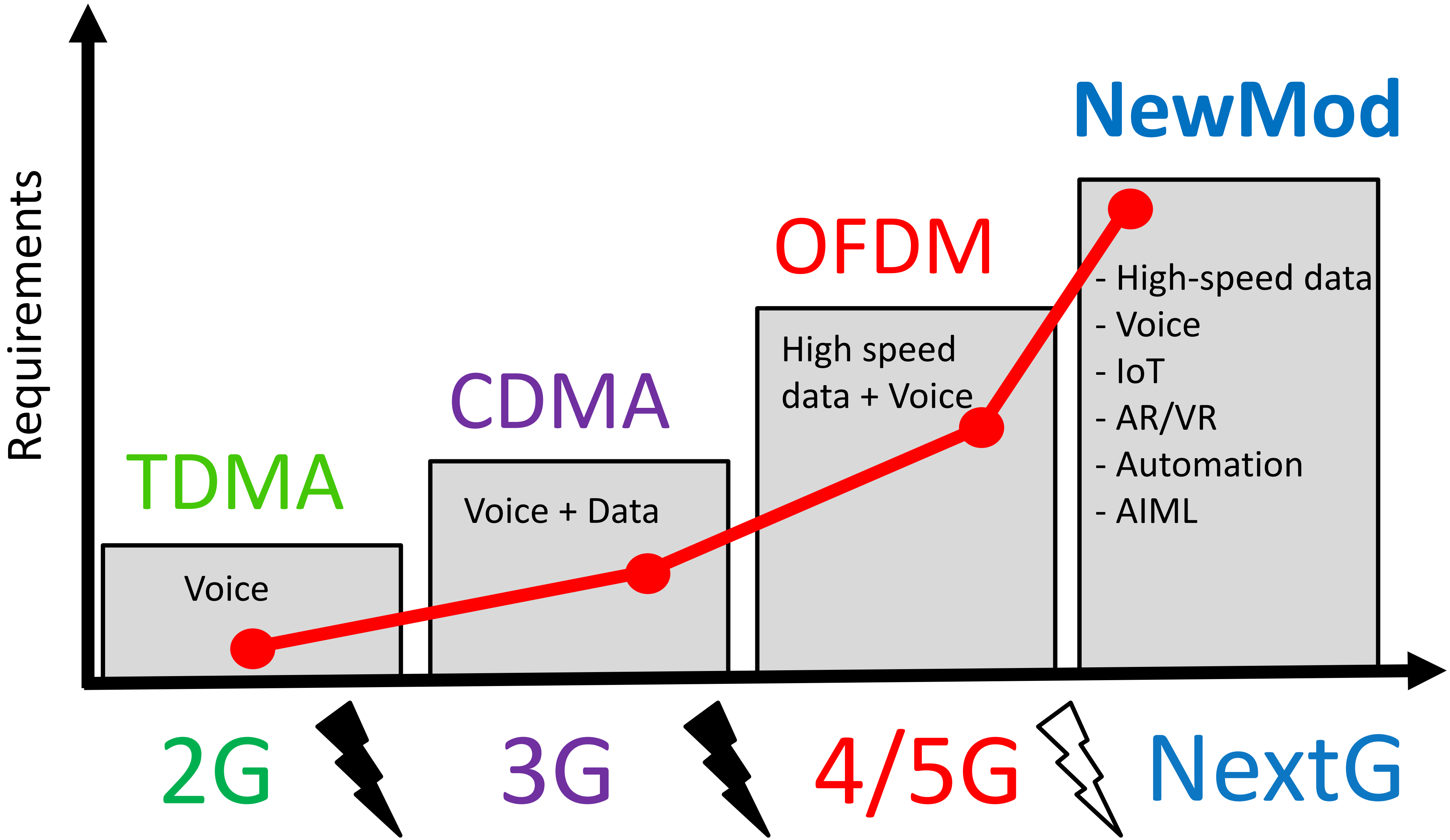
- ML will play an important role in NextG design/operation
  - ML can "beat" theory in PHY-layer design (equalizers, encoding/decoding)
  - ML may provide approximate solutions to intractable network resource allocation problems
  - ML may provide breakthroughs in security, privacy and resilience
  - ML may provide the key to breakthroughs in cross-layer design

New PHY and MAC Techniques

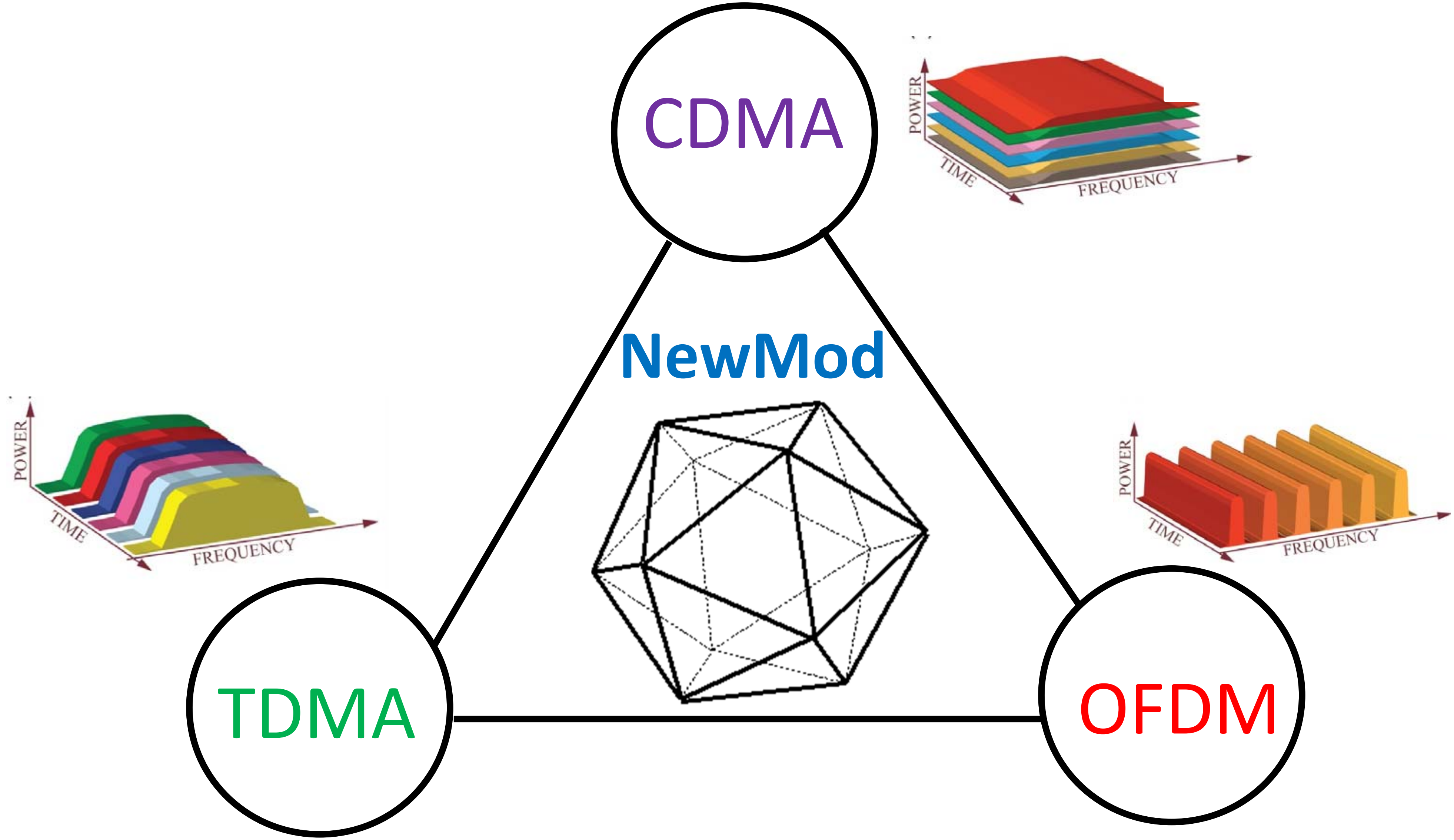
- New Waveforms
  - More bandwidth/energy efficient/robust to changing channels
  - More flexible and efficient subcarrier allocation
- New Coding Techniques
  - New channels and new waveforms
  - New requirements (low latency and low complexity)
- New Detection Techniques
  - Lower complexity, robust to impairments, blind
- New Multiple Antenna Techniques
  - New space-time modulation, coding, and detection methods
  - Massive MIMO
- New Access Techniques
  - Efficient (non-orthogonal) access
- Machine learning in PHY/MAC design and operation



Waveform Disruption



Data can be modulated onto different domains: *time, frequency, doppler, delay*

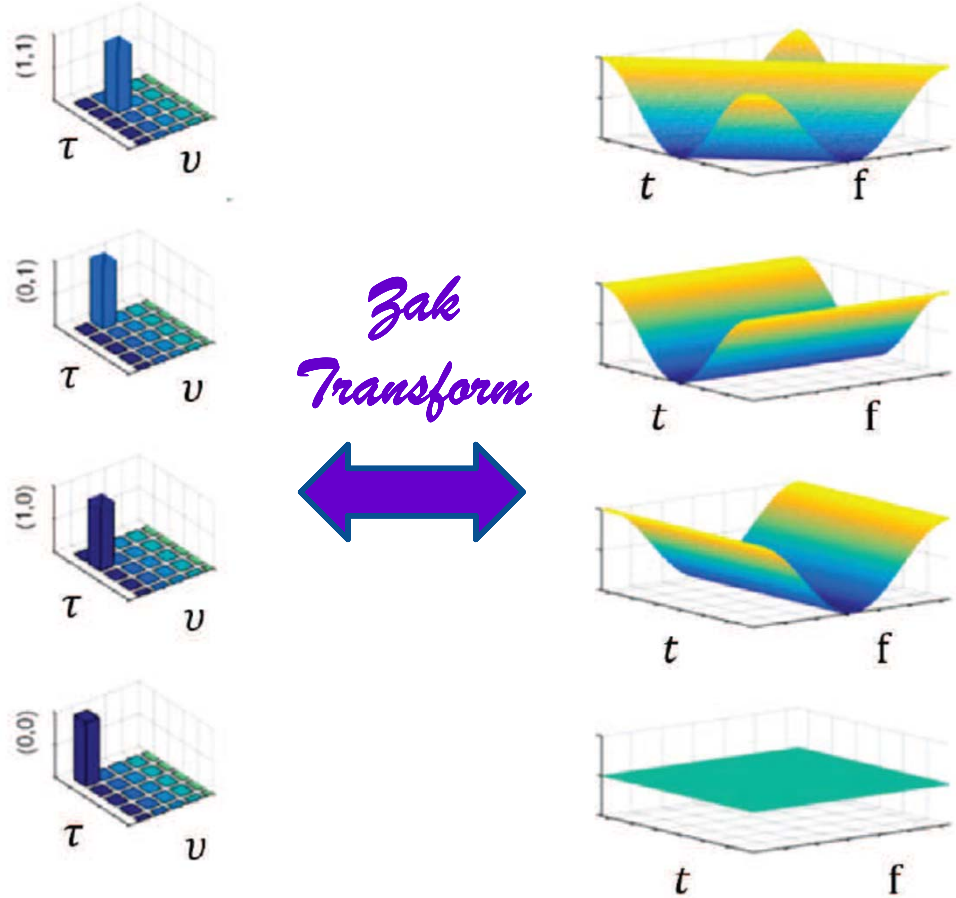


One Strong Candidate: Orthogonal Time-Frequency-Space Modulation (OTFS)*

Data adaptively modulated in delay-Doppler domain

Delay-Doppler Domain

Zak Domain

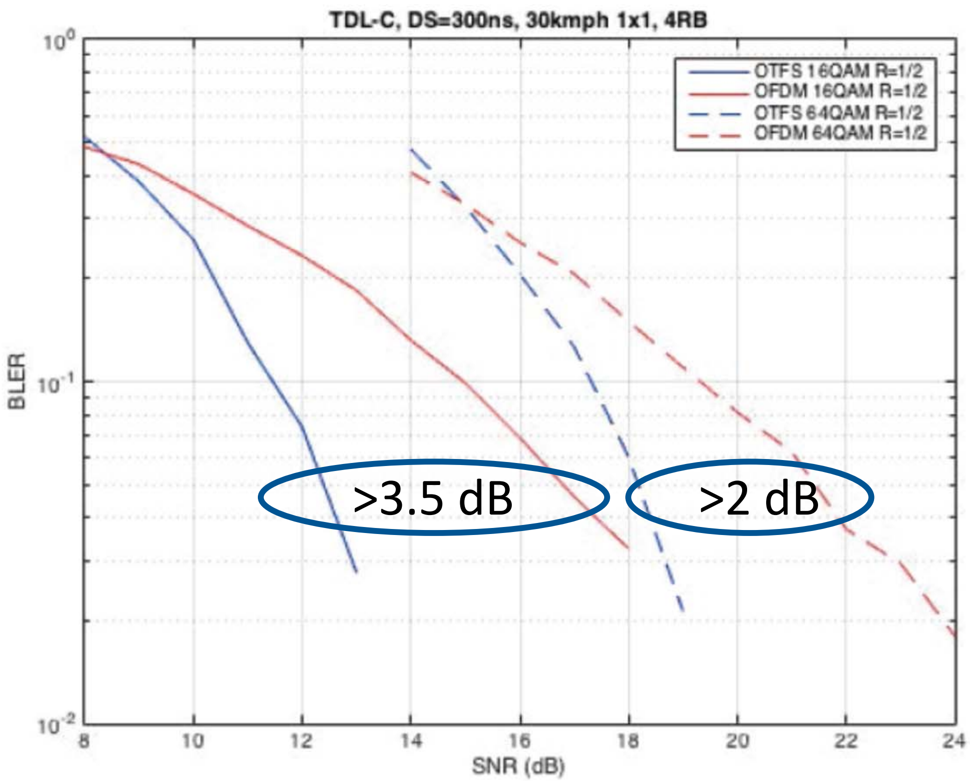


Time-Frequency Domain

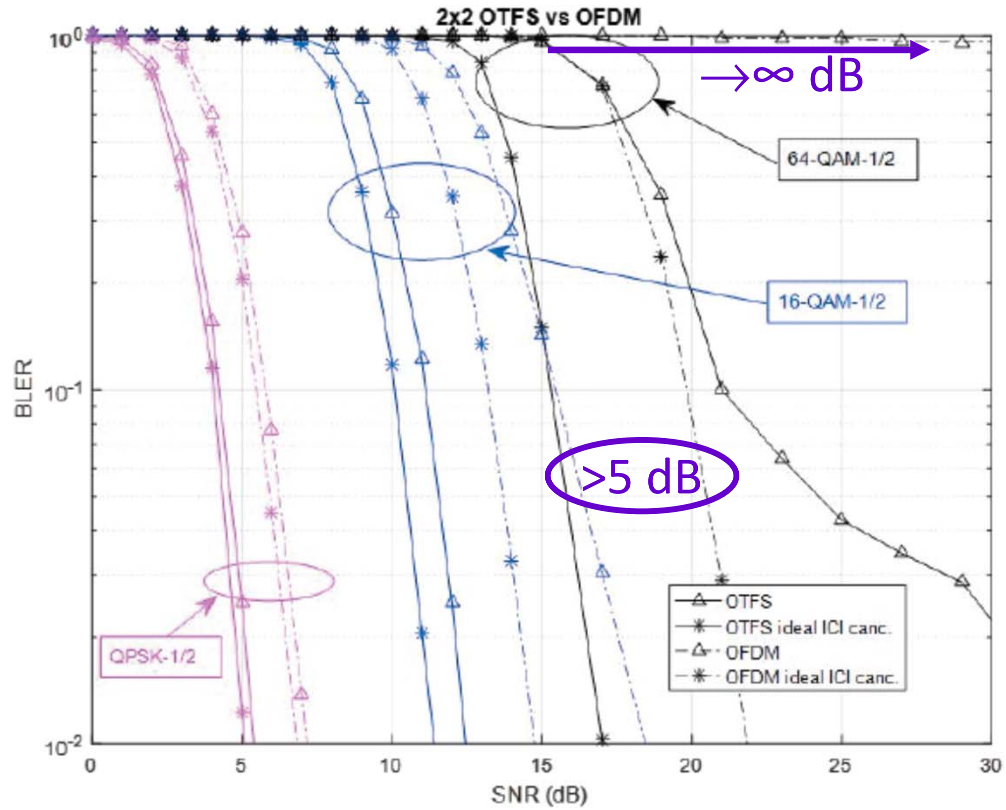
All symbols spread over entire time-frequency channel; obtain full diversity

***Orthogonal Time Frequency Space Modulation, Hadani et. al., WCNC'17 & Arxiv**

OFDM vs OTFS Performance

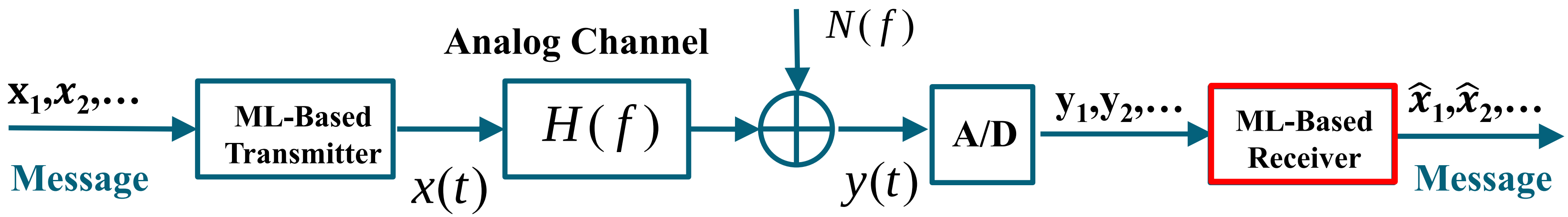


Short packets, 1x1, 16/64 QAM, 30 km/h



Long packets, 2x2, 4/16/64 QAM, 500 km/h

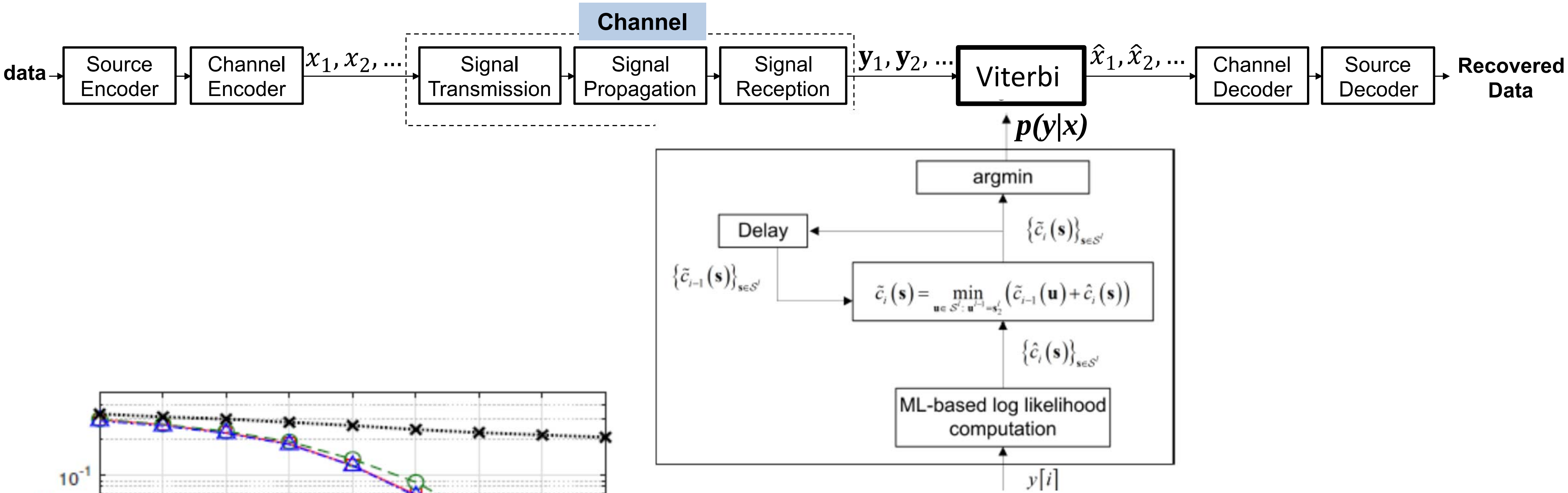
ML-Based Receiver Design

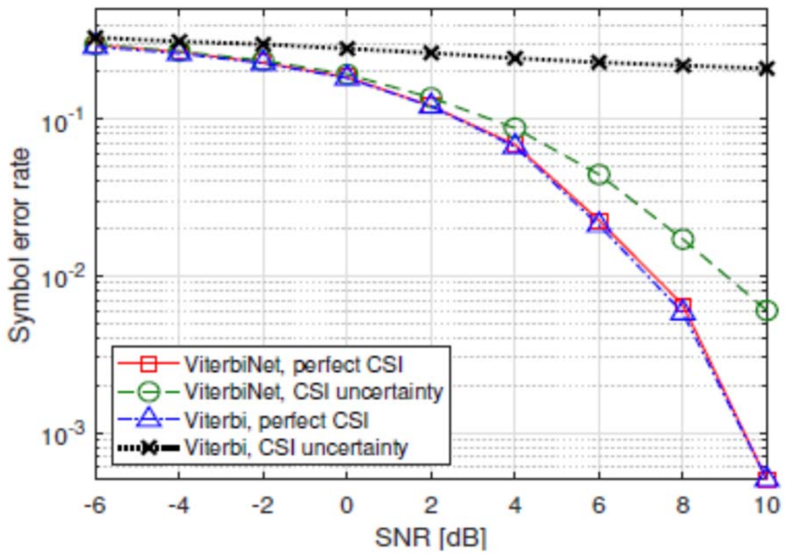


- PHY transmitter and receiver design typically based on a mathematical channel model
  - Accurate channel models may not be known
  - Models may not enable computationally efficient PHY algorithms (decoding, detection, message recovery)
- How does ML-Based RX design solve this?
  - No need for channel model or its parameters
  - Learn the RX design directly from data
  - Solution is robust to estimation error
  - Requires large amount of training (many x_is)

ViterbiNet:

Standard Viterbi with ML to learn p(y|x)



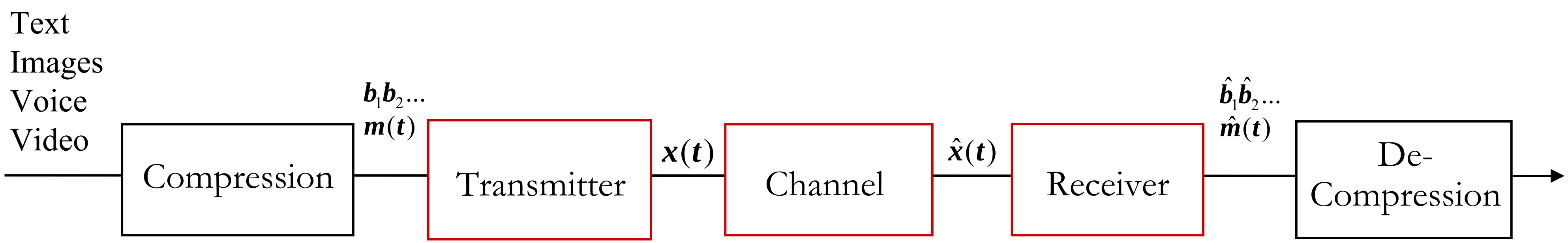


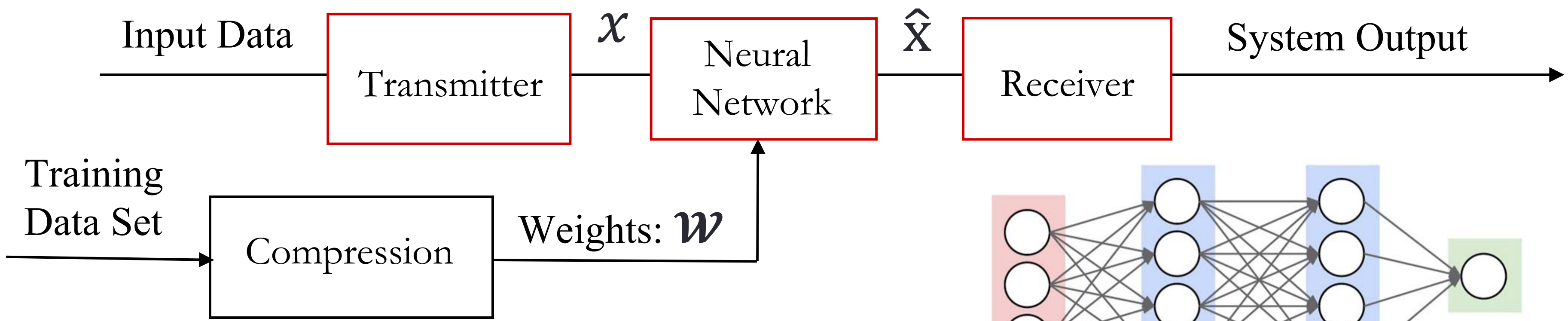
Much faster training and lower complexity than end-to-end ML-based receiver design

Joint work with Eldar, Farsad, Shlezinger

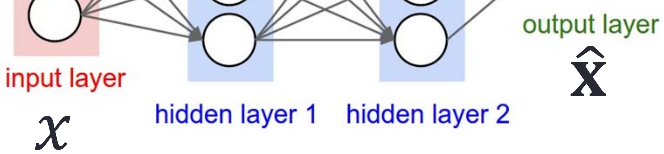
Neural Nets as a Communication System

- Classic Communication System

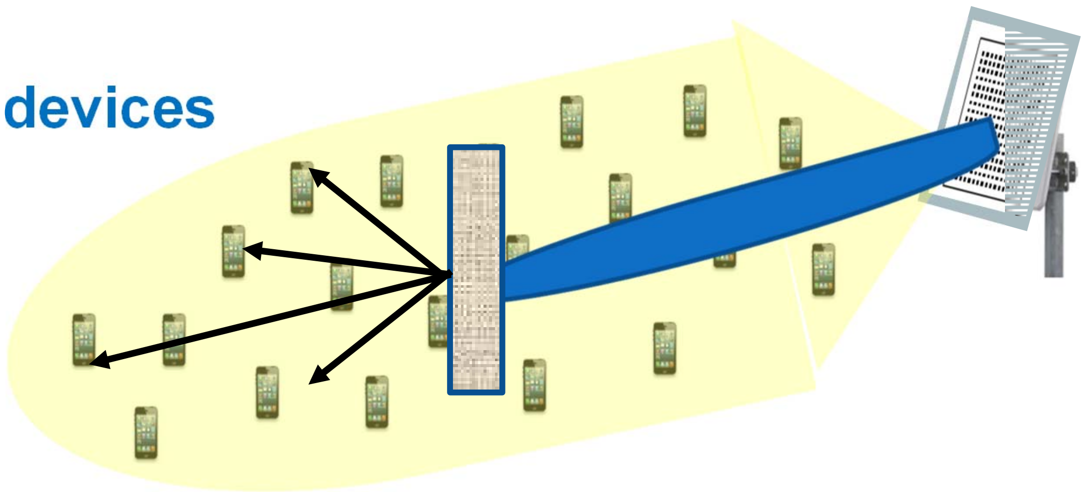




$$\hat{\mathbf{x}} = \mathrm{NN}(\mathbf{x}; \mathcal{W})$$



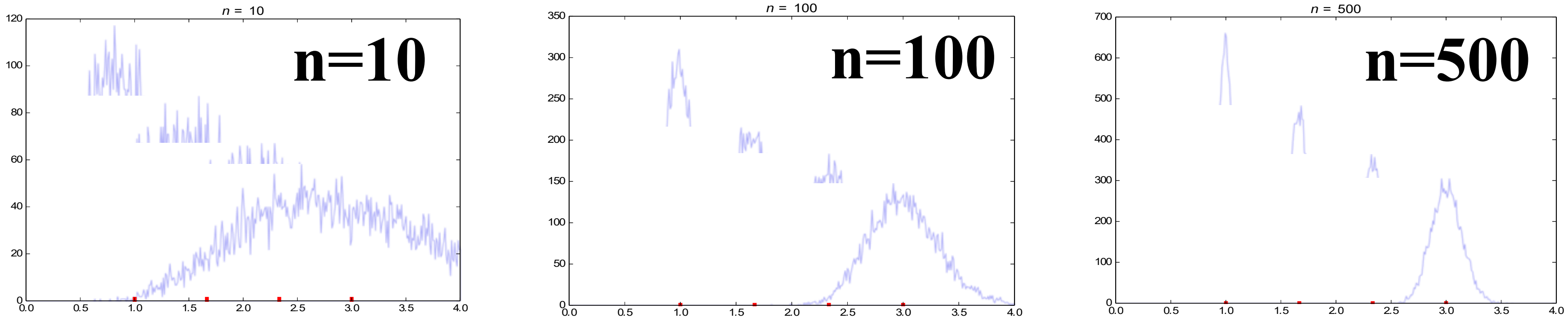
Massive MIMO



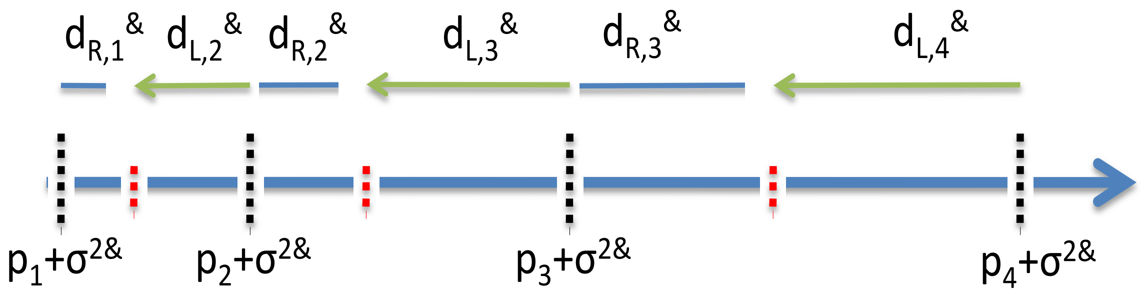
- Massive MIMO removes attenuation, fading, interference
- Bottlenecks: channel estimation, complexity
- Ideal beamforming disappears with shadowing
- Need multihop/mesh networks

Non-coherent massive MIMO

- Propose simple energy-based modulation
- No capacity loss for large arrays: $\lim_{n\to\infty} C_{nocsi} = \lim_{n\to\infty} C_{csi}$
  - Holds for single/multiple users (1 TX antenna, n RX antennas)



- Constellation optimization: unequal spacing



Joint with M. Chowdhery, A. Manlolakos

Blind MIMO Decoding via Vertex Hopping

Given samples in the form:

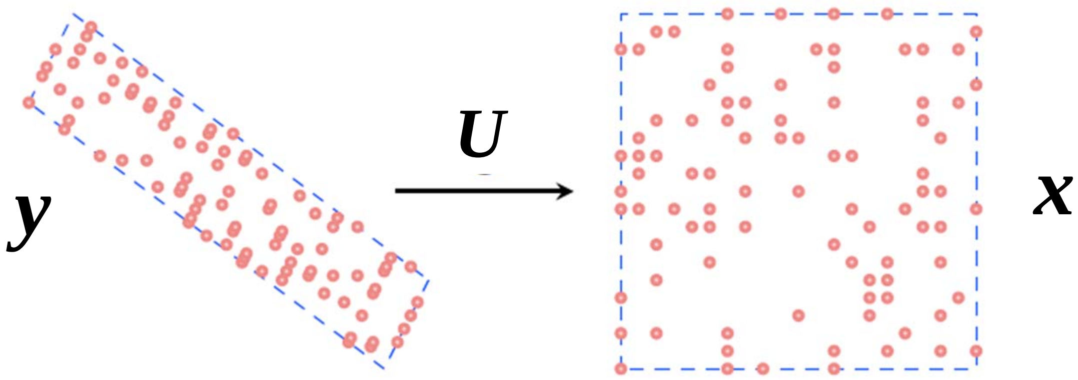
$$\boldsymbol{y} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{e}$$

- $\boldsymbol{A} \sim \mathcal{N}(0,1)^{n \times n}, \boldsymbol{e} \sim \mathcal{N}(0,\sigma^2)^{n \times n}$.
- x is drawn from an MPAM or BPSK constellation (source must be hypercubic).
- Rich scattering, small MIMO ($2 \leq n \leq 12$).

Blind MIMO Decoding
In a block-fading environment, estimate *A* and recover *x* given only k samples of *y*

Joint work with T. Dean

Fitting a Parallelepiped --- Algorithms



Gaussian noise will not greatly distort this shape

$$\underset{U}{\text{maximize}} \quad \log|\det \boldsymbol{U}| \qquad (*)$$

$$\text{subject to} \quad |\boldsymbol{U}\,\boldsymbol{y}_i|_\infty \leq 1 + c, i = 1, \ldots, k$$

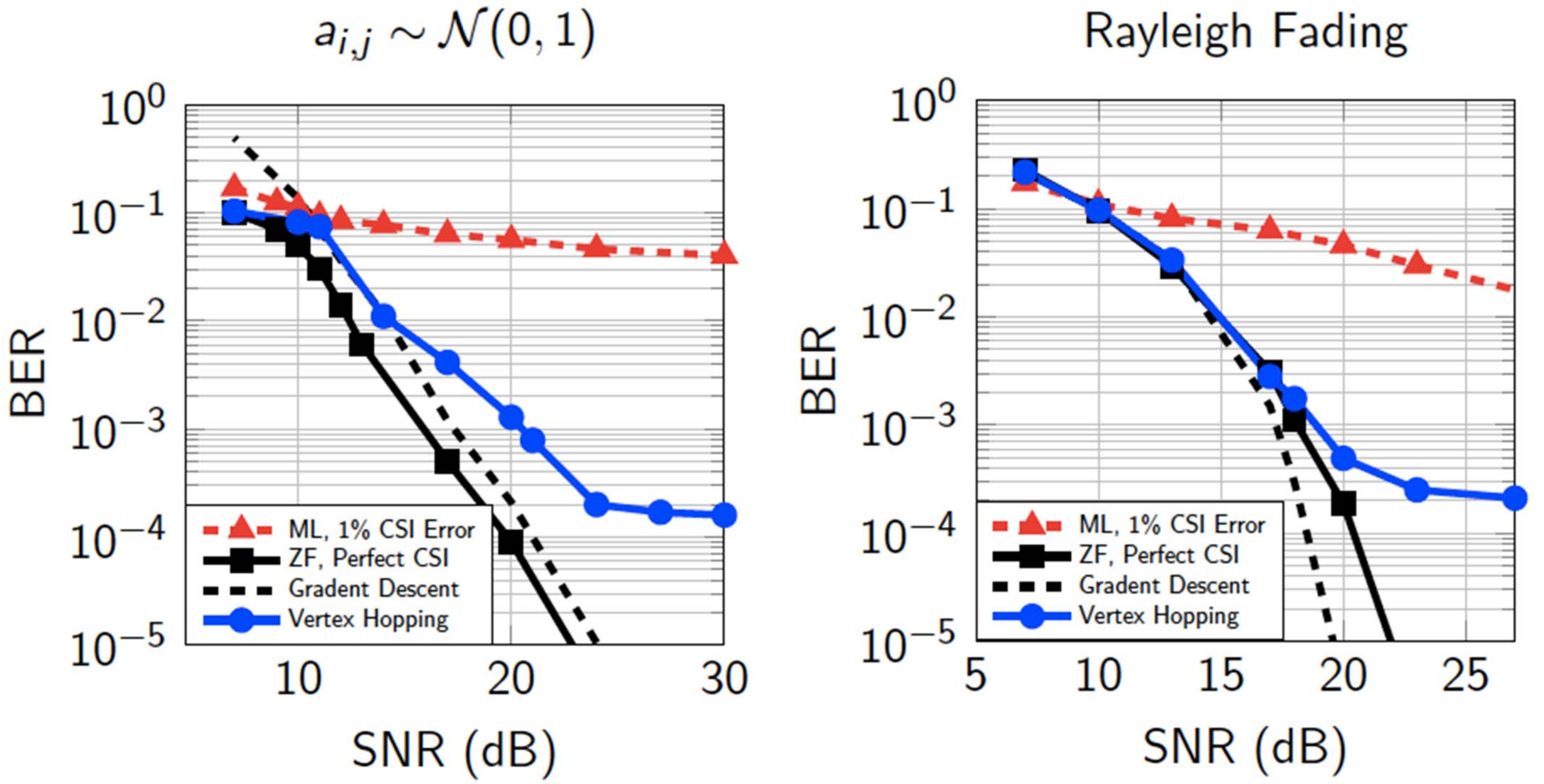
- $(*)$ is a non-convex optimization problem
- Constrained gradient descent works but is slow.
- The Vertex Hopping algorithm uses concepts from solving mixed-integer linear programming to solve $(*)$.

Runtime Performance

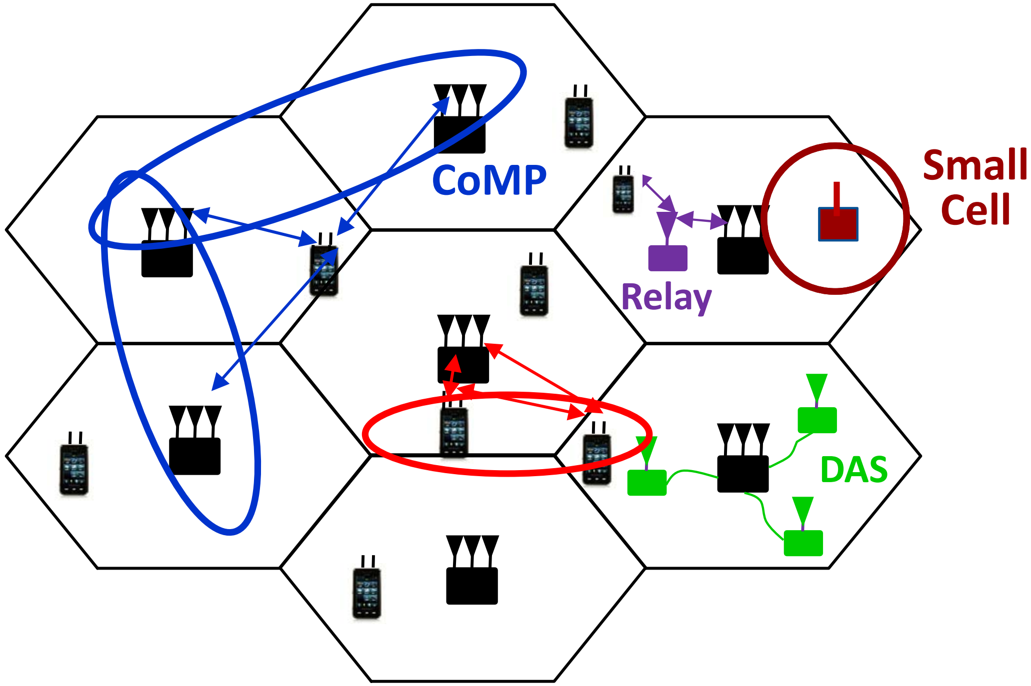
		Vertex Hopping*		Gradient Descent†	
n	k	Pr[success]	Time (s)	Pr[success]	Time (s)
2	8	1.0	1.83×10^{-5}	0.99	3.01×10^{-2}
3	13	1.0	6.46×10^{-5}	0.99	6.33×10^{-2}
4	18	1.0	1.74×10^{-4}	0.99	0.13
5	18	1.0	2.96×10^{-4}	0.97	0.30
6	22	1.0	8.52×10^{-4}	0.93	0.59
8	30	0.99	4.99×10^{-3}	0.80	3.5
10	45	0.99	5.36×10^{-2}	0	-
12	60	0.99	3.70×10^{-1}	0	-

***Implemented in Rust**
†MATLAB's `fmincon`

AWGN and Fading Performance



Rethinking Cellular System Design



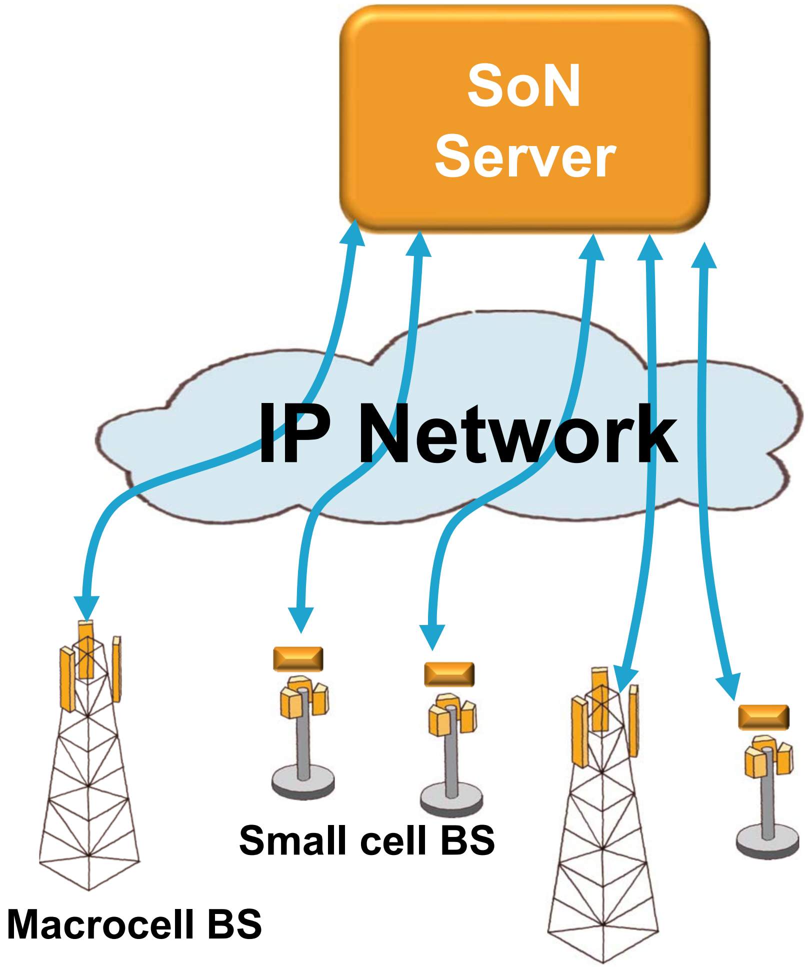
How should cellular systems be designed?

Will gains be big or incremental; in capacity, coverage or energy?

- Cellular systems reuse channels/timeslots in different cells
  - Traditional design assumes system is "interference-limited"
  - Capacity unknown; upper bound based on BC/MAC with pooled antennas
- No longer the case with recent technology advances:
  - MIMO, multiuser detection, cooperating BSs (CoMP) and relays
  - Raises interesting questions such as "what is a cell?"
- Dynamic self-organization (SoN) needed for deployment and optimization

Small cells are the solution to increasing cellular system capacity

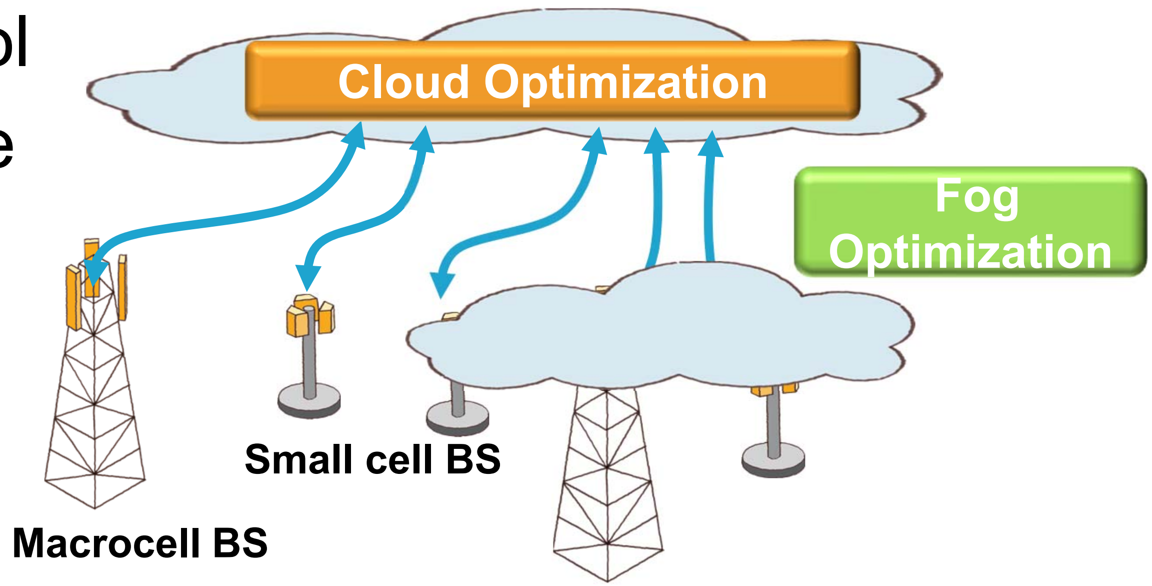
In theory, provide exponential capacity gain



- Future cellular networks will be hierarchical
- Large cells for coverage
- Small cells for capacity and power efficiency
- Small cells require self-optimization in the cloud

HetNet Optimization Challenge

- Algorithmic complexity
  - Frequency allocation alone is NP hard
  - Also have MIMO, power control, CST, hierarchical networks: *NP-really-hard*
  - Advanced optimization tools needed, including a combination of centralized (cloud) distributed, and locally centralized (fog) control
  - ML can also play a role

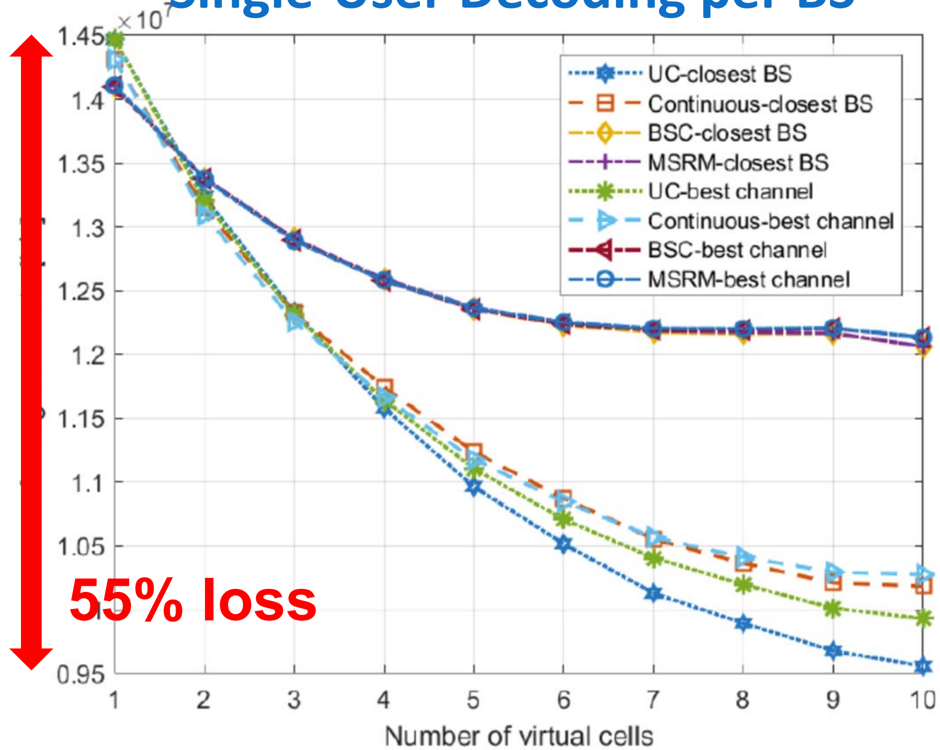


Next challenge: optimizing caching and edge computing

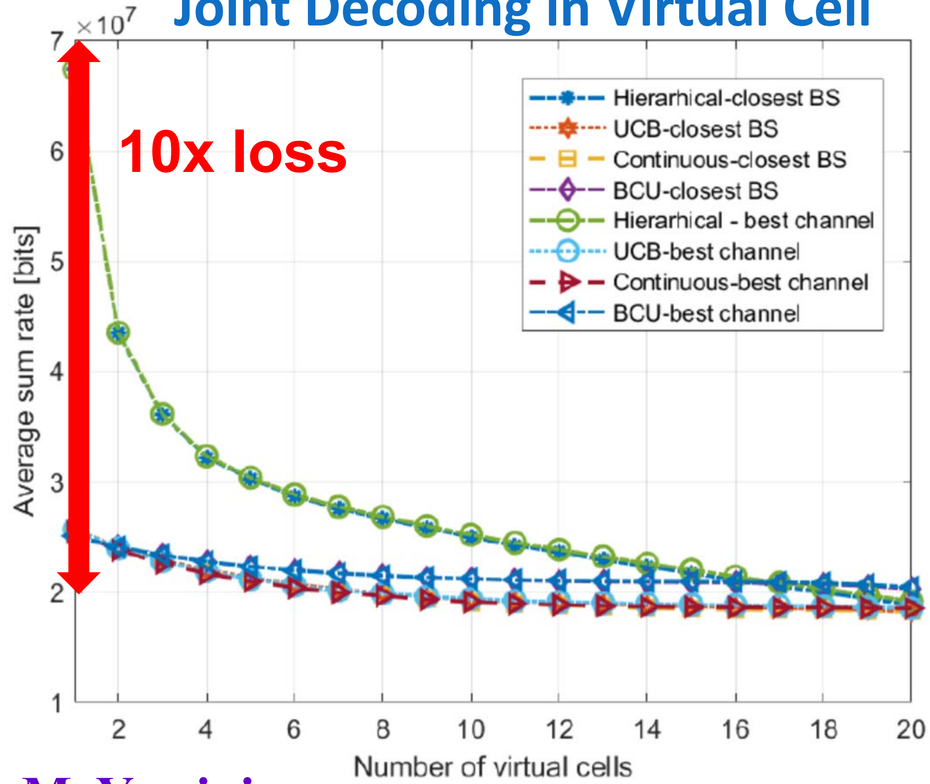
Fog-Optimization vs. Centralized

- Use clustering technique to cluster BSs, then optimize power allocation to maximize uplink sum rate
  - Consider multiple clustering techniques (not much difference)
  - Nonconvex approximation for optimization

Single-User Decoding per BS

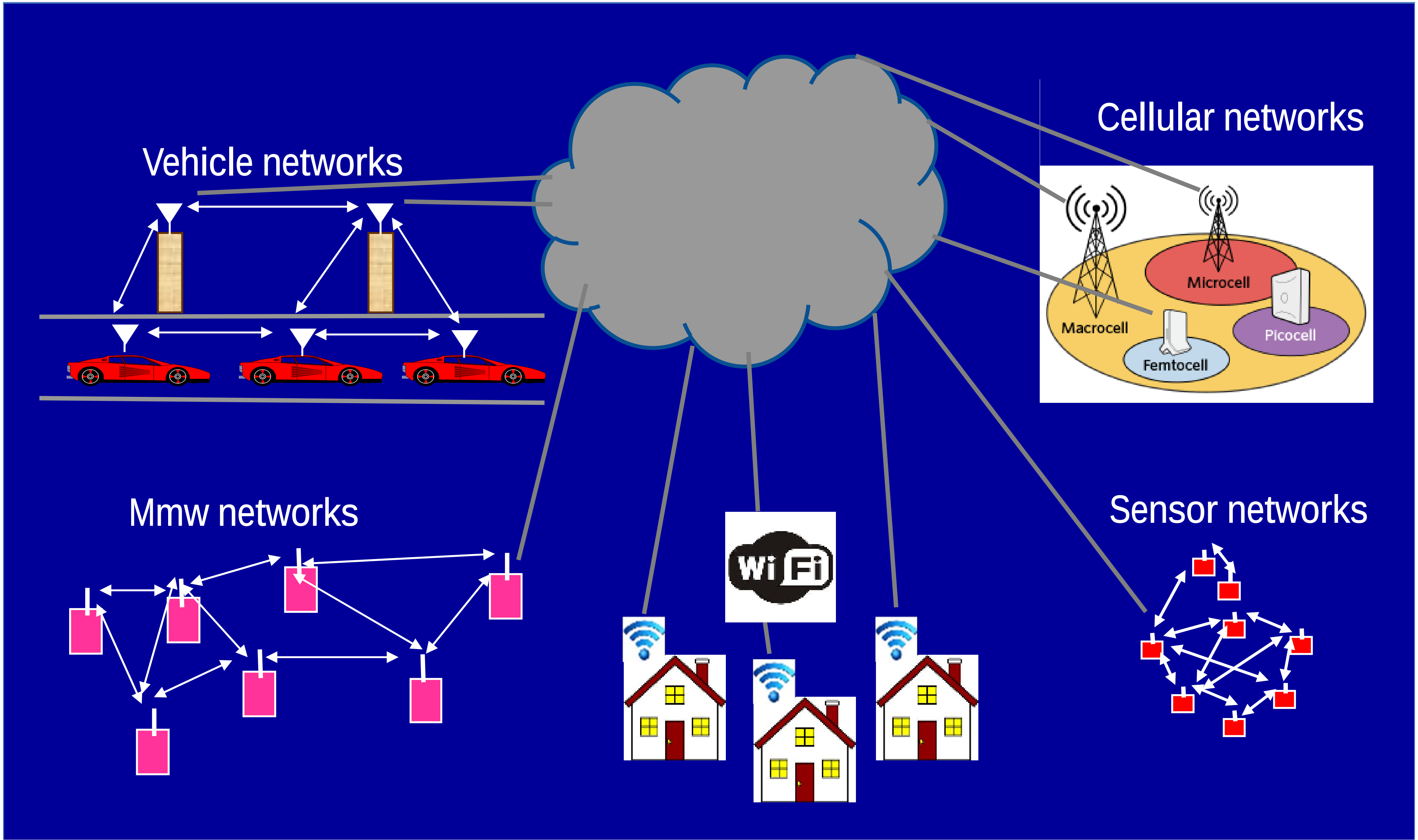


Joint Decoding in Virtual Cell

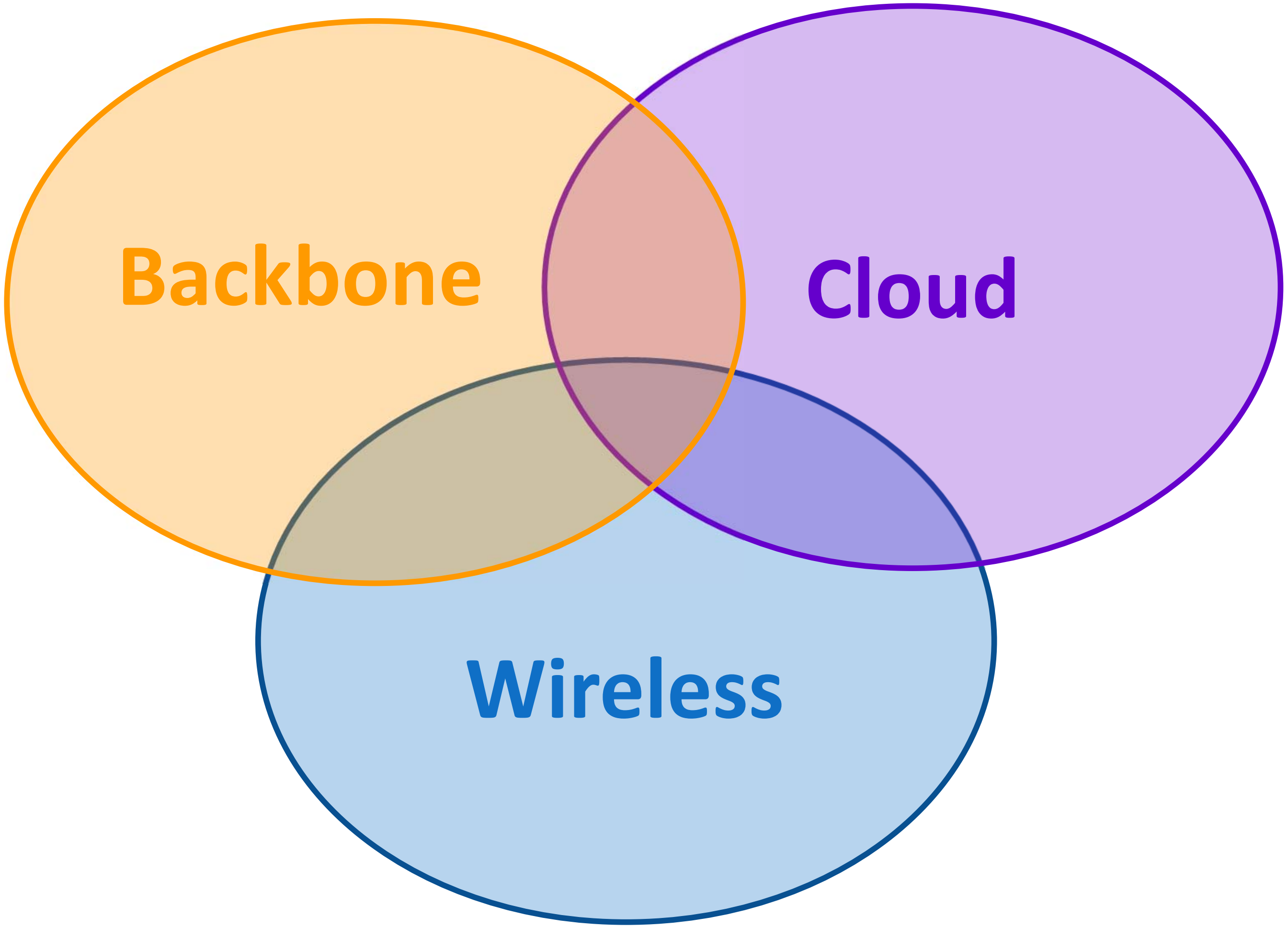


Joint work with M. Yemini

Cloud-Enabled Wireless Networks (includes "fog")

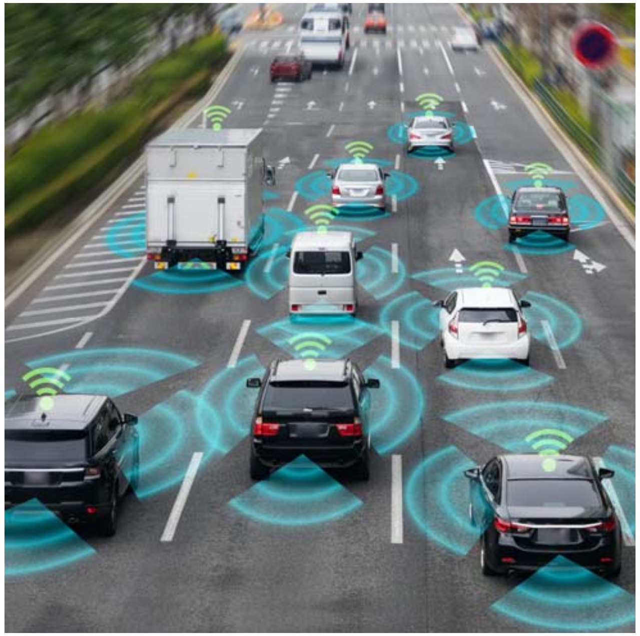


NextG Network Convergence

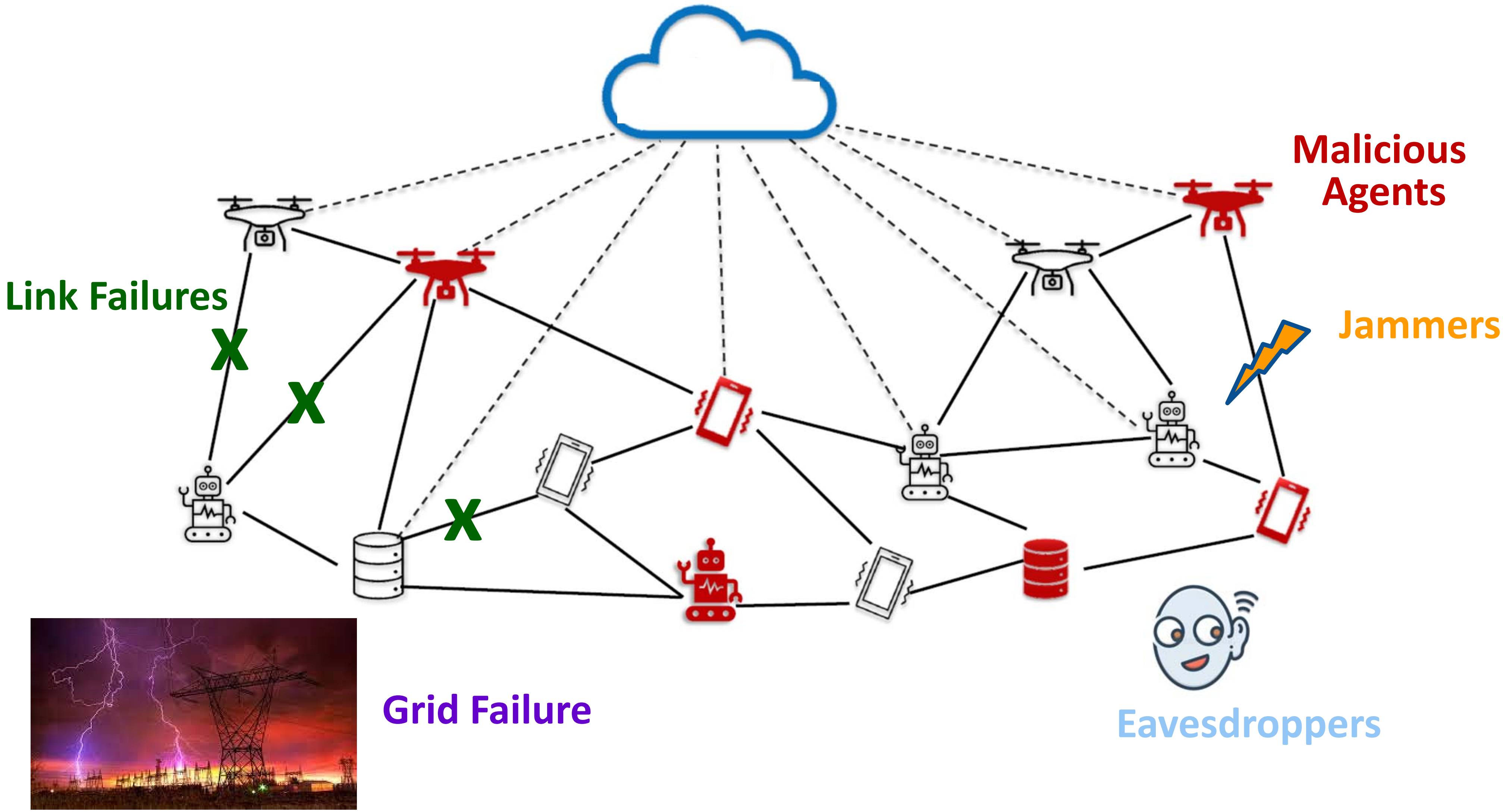


What design principles should drive this convergence?

This design is critical for NextG applications

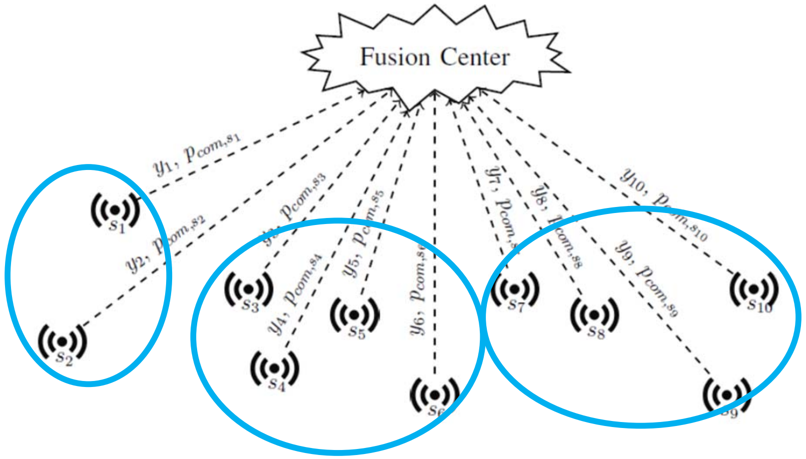


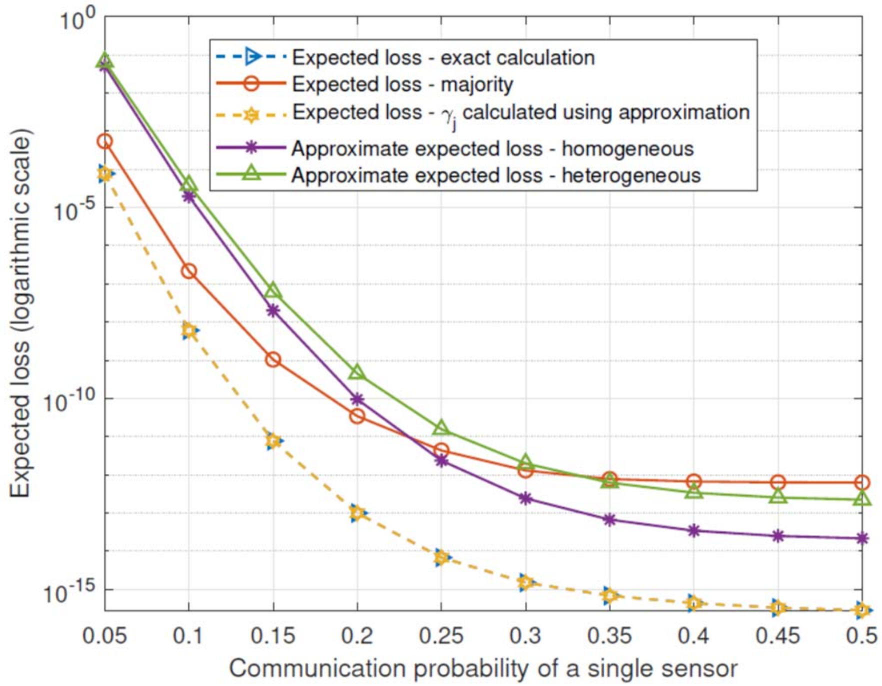
Collaboration over Wireless Networks: Security, Privacy, and Resilience



Centralized Detection with Flaky Links

- Sensors have intermittent connectivity to fusion center (FC)
- Sensors collaborate within predefined sensor clusters
  - Fuse their noisy sensor data to reach a common local estimate
  - Common estimate sent to FC
- FC fuses the received estimates for event detection
- Determine optimal decision rule with tractable complexity
- Excellent detection performance

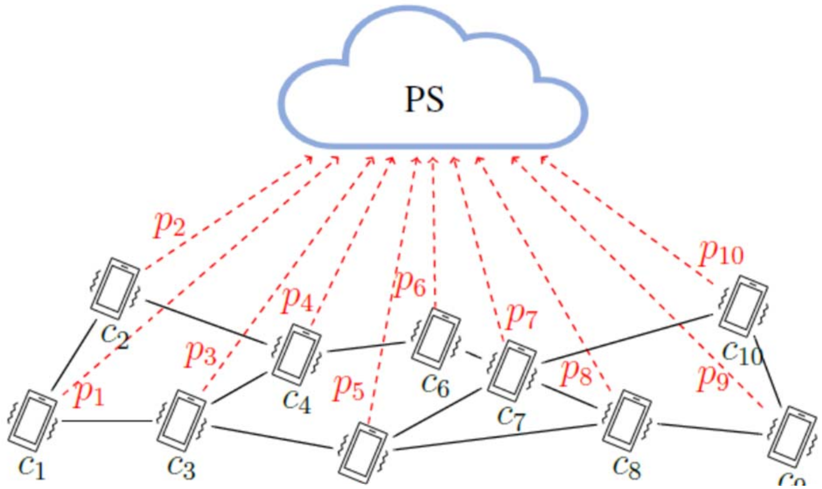


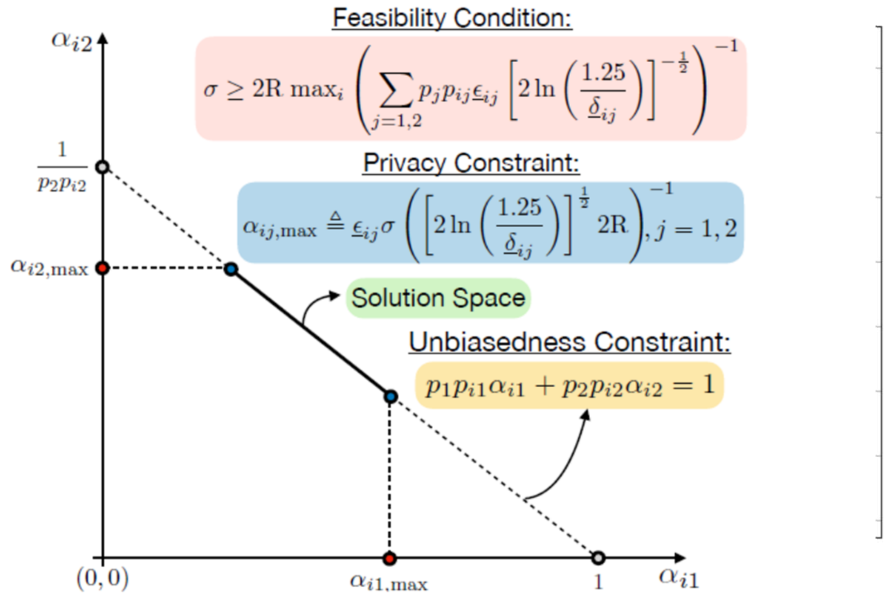


Joint work with Gil and Yemini

Federated Learning with Flaky Links

- Neighbors collaborate to send data to central parameter server
- Each client computes consensus estimate from neighbors
  - Weighted by connectivity
- Algorithm exhibits improved convergence and accuracy
- Can also introduce privacy constraints

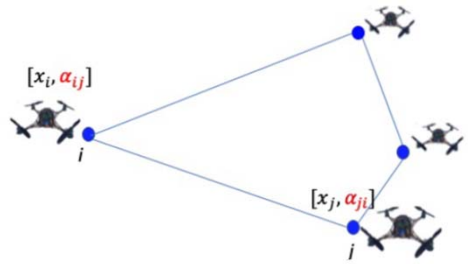


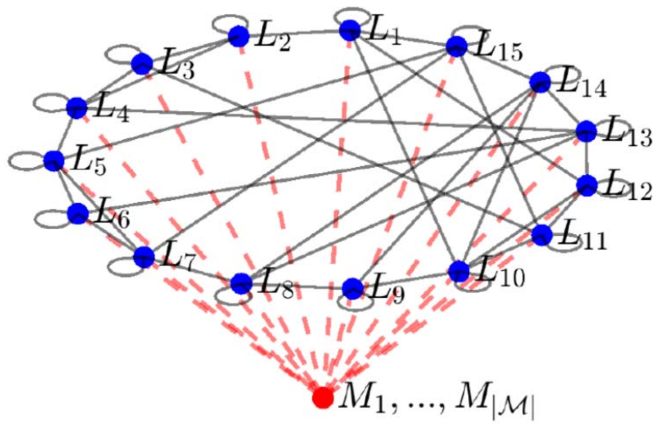


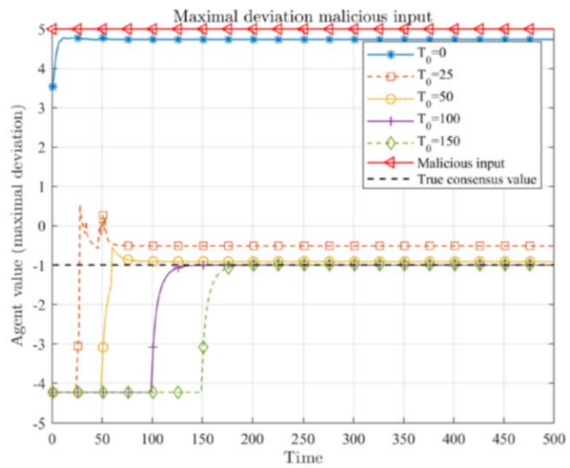
Joint work with Gunduz, Mohammed, Ozlatura, Saha, Yemini

Trust and Resilience in Distributed Consensus

- Consensus algorithms assume trusted agents
- We ask: how to achieve consensus when there are malicious agents
- Propose a consensus algorithm with untrusted agents, with almost sure convergence
  - Even when malicious agents constitute more than half of the network connectivity
- The true consensus value bounded with p→1.
- Correct classification of malicious and legitimate agents can be attained in finite time
- Expected convergence rate decays exponentially with trust







Joint work with Gil, Nedic, and Yemini

Challenges to NextG technology disruption

- Complexity of current networks
- Lack of significant research investment for a decade
- Standards process can stifle innovation
- NextG hardware and software proprietary and closed
- Research silos across wireless, backbone networks, cloud, electronics, and applications

New era for US technology innovation

2022 CHIPS and Science Act

Killer App for 6G?

Connecting the next billion

- Cellular architectures for long-range coverage
- Satellite systems
- Low-cost hardware and devices
- We have the technology today
  - A question of cost, commitment, policy, and politics

Summary

- The next wave in wireless technology is upon us
  - Will enable new applications that will change people's lives
- Future wireless networks must support high rates, extreme energy efficiency, and low latency
  - With robust security, privacy, and resilience
- Many challenges to creating the technical innovations and disruptions needed to achieve this vision
- Connecting the next billion is the killer app for 6G