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ICT Standards

TECH DEEP DIVE

TTDD 2024 CONFERENCE (7th EDITION)

REALIZING THE 6G VISION :
SOCIETAL NEEDS, USAGE SCENARIOS & TECHNOLOGIES

 **Date:** 16-19 July 2024

Session #2: Emerging Technology Trends

16 July 2024

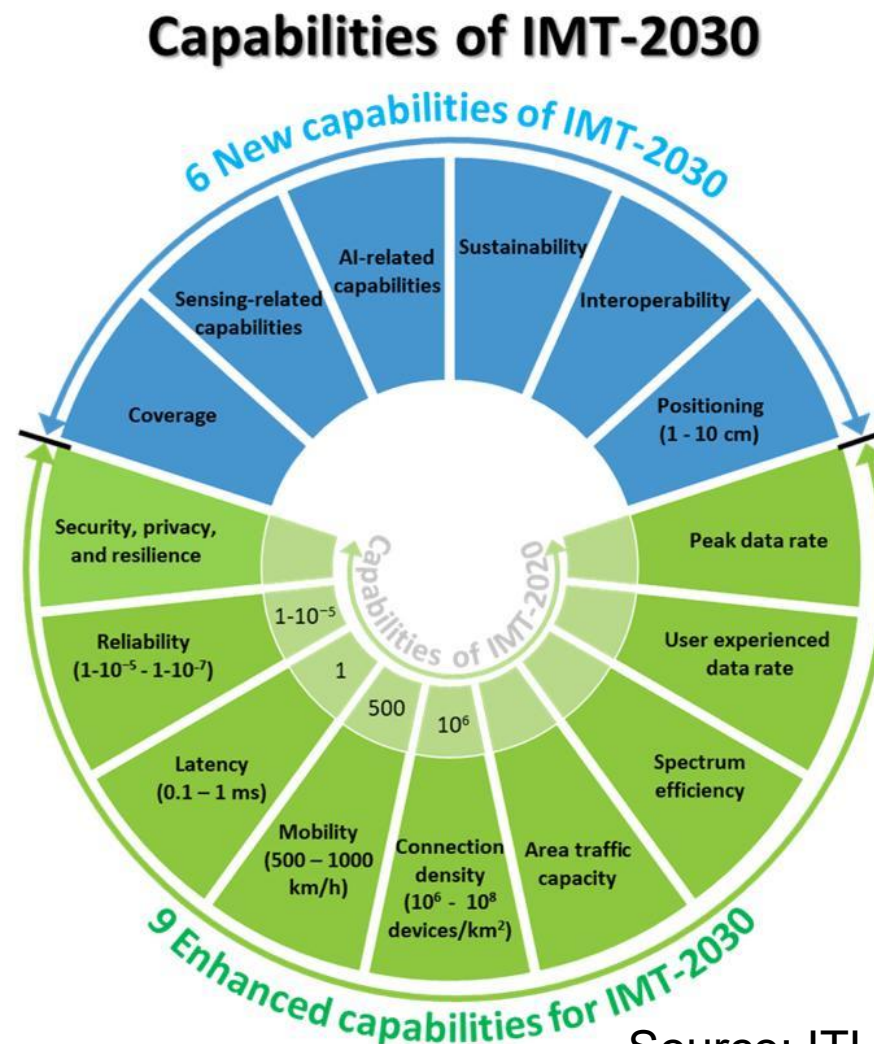
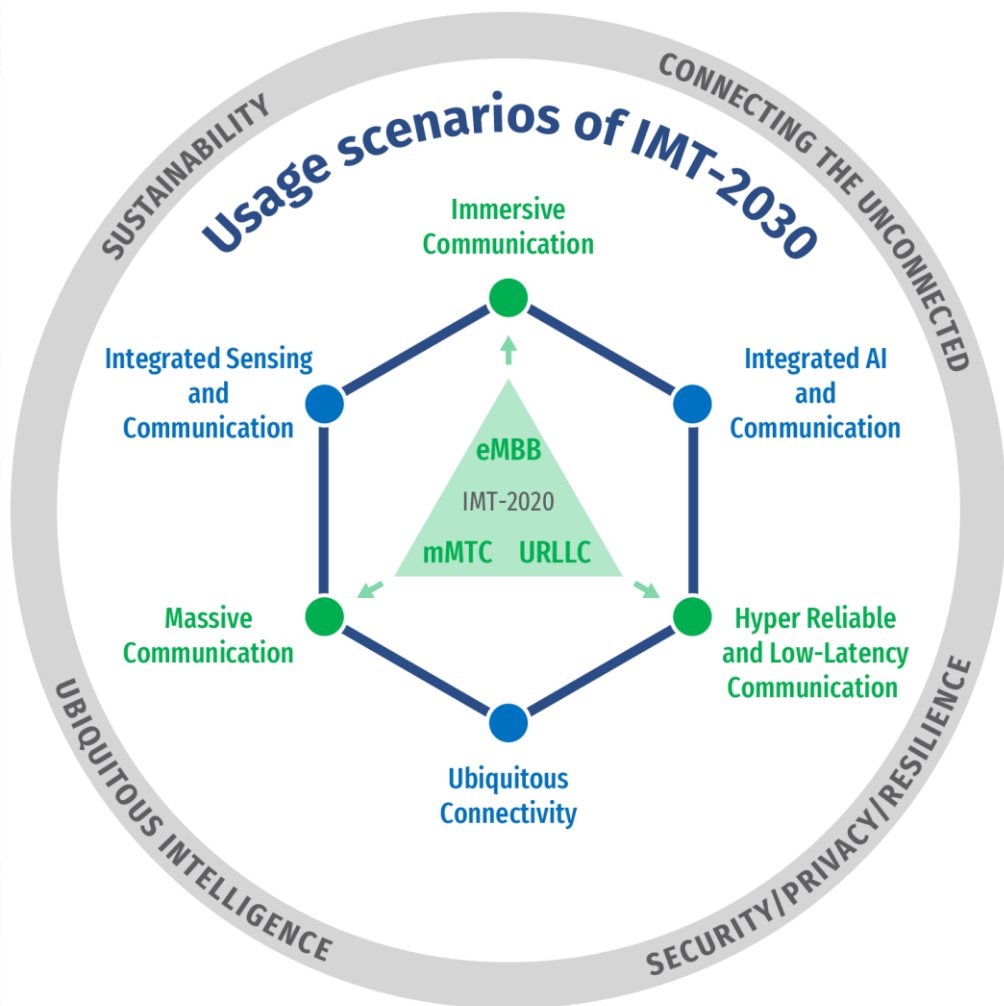
Beyond 5G communications: key technologies

by

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Mandatory First Slide

What is 6G?



Some Key Technologies

Outline of this presentation



Cell-free massive MIMO with dynamic TDD



Massive MIMO channel estimation and tracking



Low resolution ADCs



Energy-efficient mMTC via Grant-free Access



New waveforms



Intelligent Reflecting Surfaces

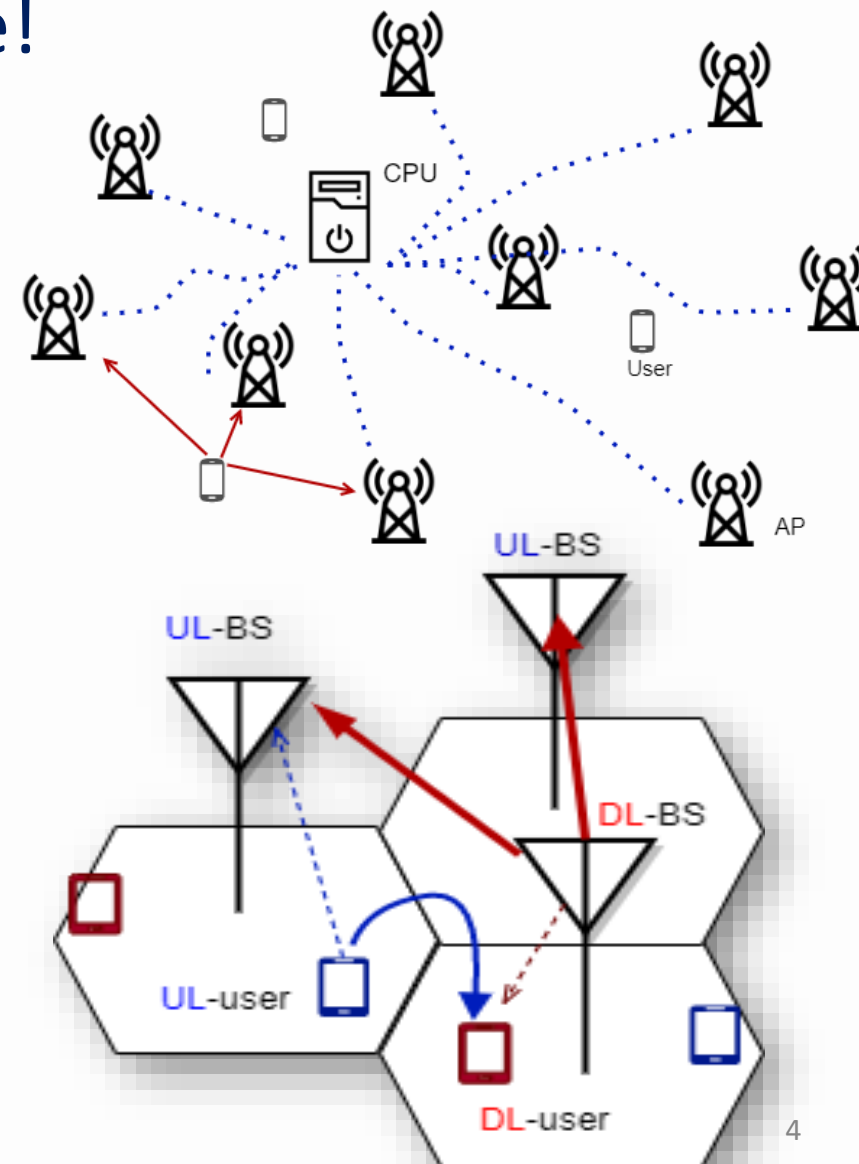


Other Topics

Cell-Free and Dynamic Time-Division Duplex

A happy marriage!

- All APs (BSs) process data to/from all UEs
- **Dynamic TDD:** each AP can independently choose to operate in UL/DL in each slot



C1	UL	UL	UL	UL	UL	DL	DL	DL
C2	DL	DL	DL	DL	UL	UL	UL	UL
C3	UL	UL	UL	UL	DL	DL	DL	DL

Two Questions

- Cell-free with half-duplex APs and dynamic TDD vs. cell-free or cellular with full duplex APs?
 - Cell free + dynamic TDD = virtual full duplex!
- Pilot design and allocation for cell-free systems?
 - All APs are required to estimate all users' channels

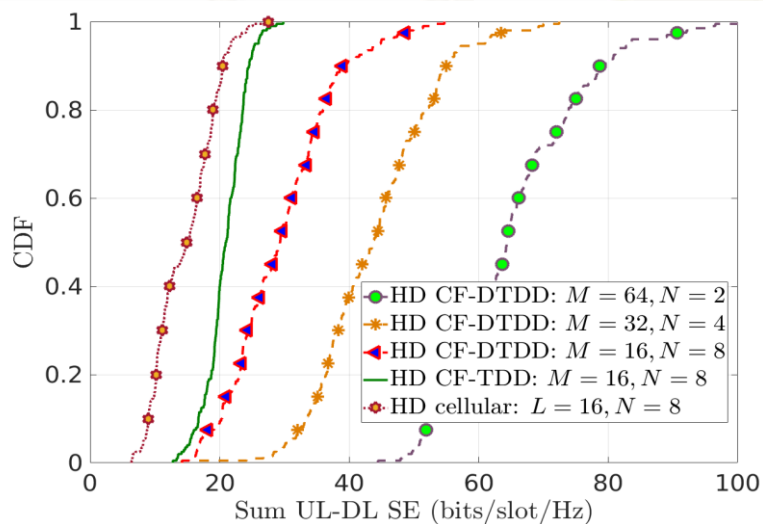
Key Findings

- HD-CF with many **distributed APs** and **fewer antennas/AP** is better than FD-massive MIMO cellular (& even FD CF!!)
- Overall, HD-CF has
 - Better **rate-region**
 - Better **resilience** to interference
 - Better **90%ile rate, better fairness**
- **“Cell-edge”** users’ performance improves
 - More uniform quality of service across the cell
- **Mutually unbiased orthogonal pilots** far outperform **orthogonal pilot reuse [TVT 2022]**

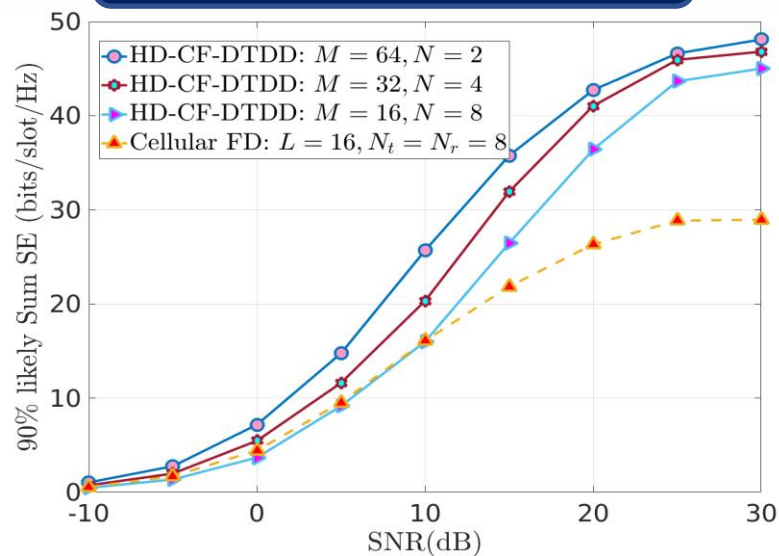
HD-CF + DTDD vs. FD-Cellular: TCOM 2022: <https://arxiv.org/abs/2110.09968>
 Cell-free under channel aging: <https://arxiv.org/abs/2209.02777>,
<https://arxiv.org/abs/2104.10404>

Simulation Results

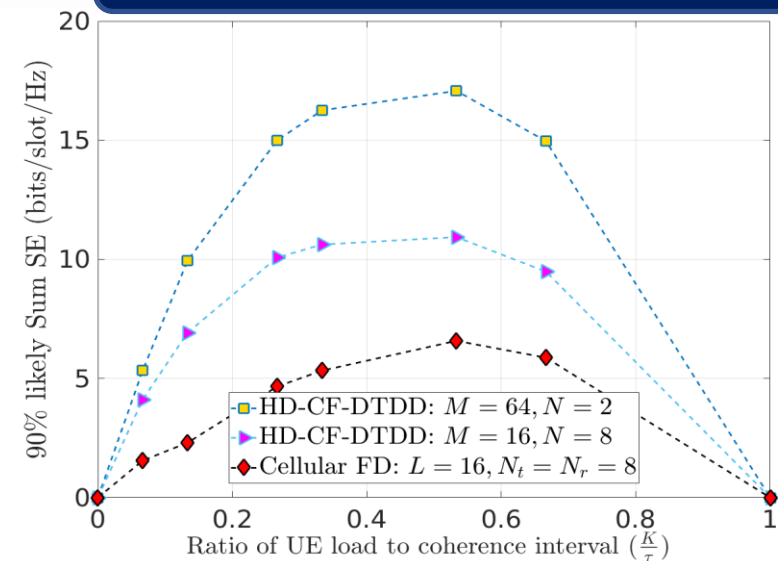
CF-DTDD >>> TDD CF & Cellular



CF-DTDD >> FD-cellular



CF-DTDD better at higher UE load



Massive MIMO Channel Estimation and Tracking

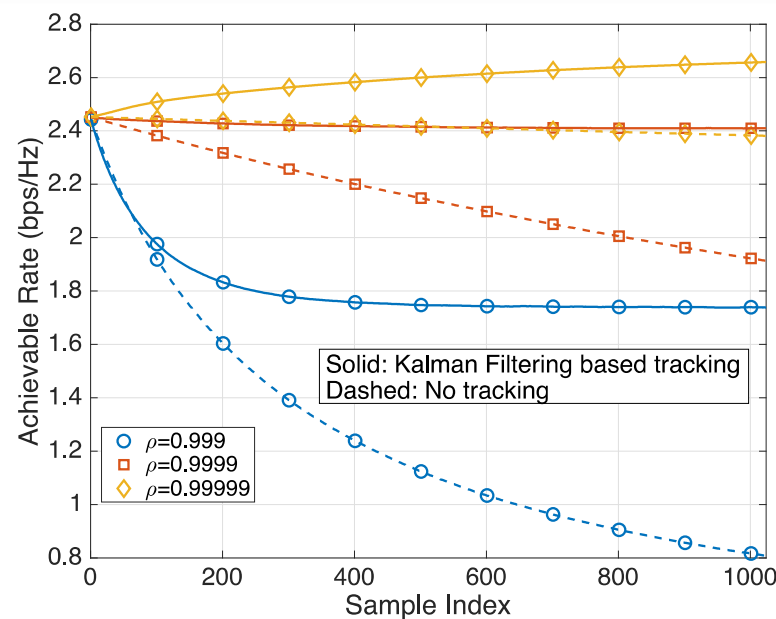
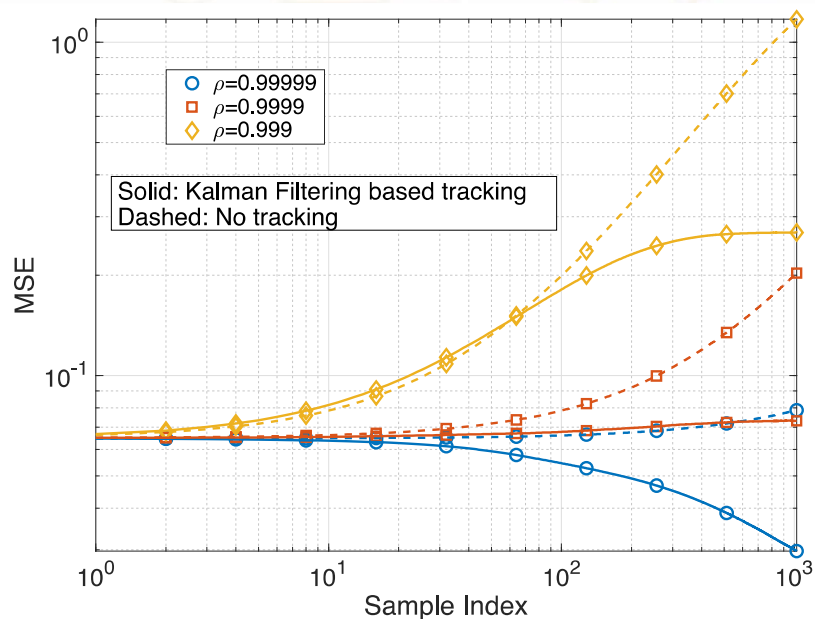
- Massive MIMO: A key technology for 5G & beyond
- Challenge: getting it to “work”
 - Channel aging
 - Lack of reciprocity/calibration imperfections
 - Pilot contamination
 - Intercarrier interference (in OFDM)
 - Intercell interference
 - Full duplex: self-interference

Goal

- Understand the effect of imperfections
- Develop techniques to mitigate them

Channel Tracking Helps!

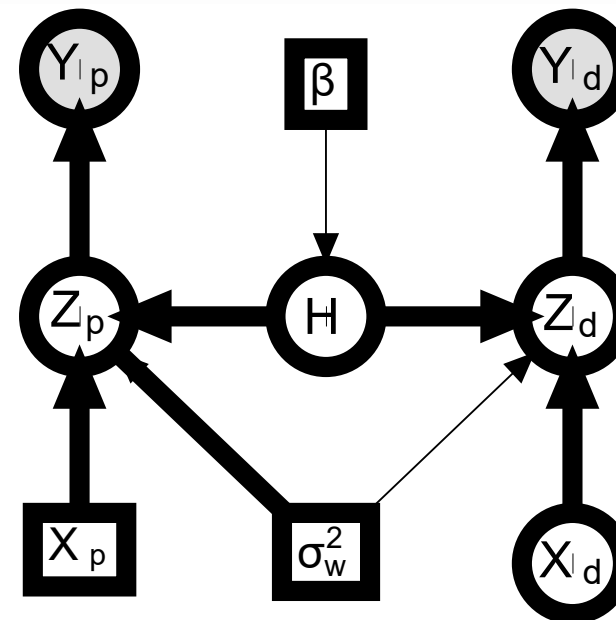
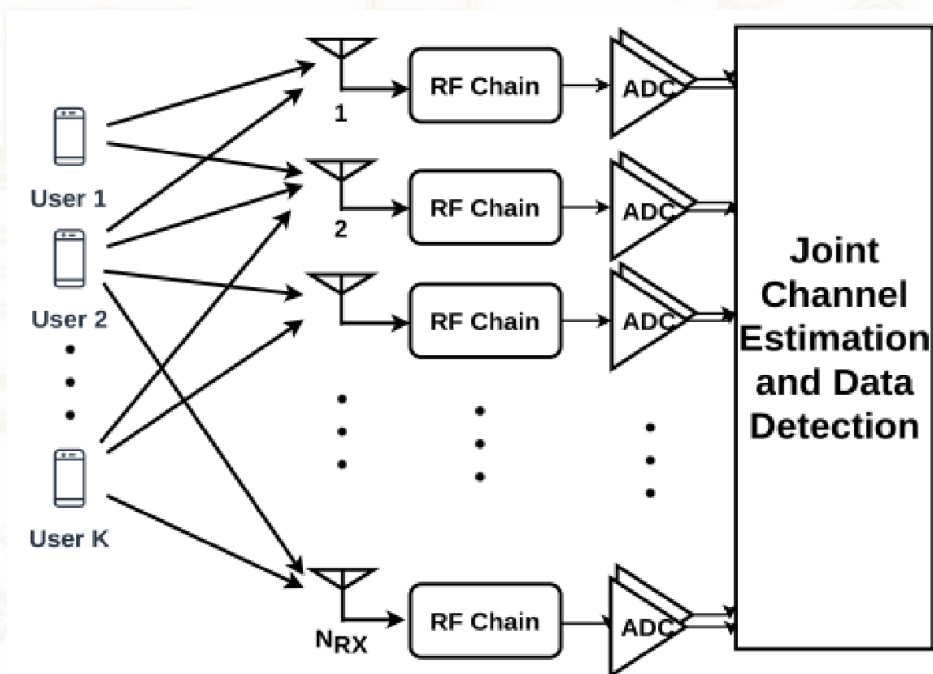
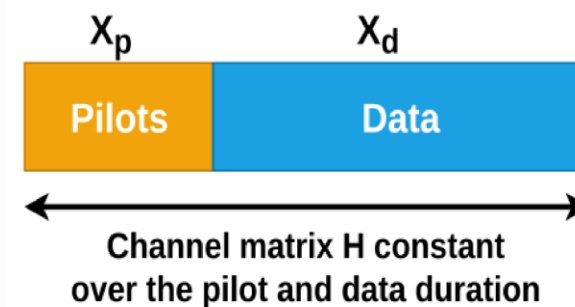
- Uplink massive MIMO with 256 antennas at the BS and 16 UEs/cell
- Carrier frequency 2 GHz, bandwidth 1 MHz
- UE velocity ranging from 10 to 270 kmph ($\rho = 0.99999$ to 0.999)
- Frame duration 1024 symbols



https://ece.iisc.ac.in/~cmurthy/Papers/Ribhu_adapt_MMSE_TSP_Jun2021.pdf, TSP 2021

Giga/Massive MIMO with Low Resolution ADCs

- Uplink massive MIMO system
 - Variational Bayesian inference, a powerful ML technique
 - Low resolution ADCs are energy efficient
 - New baseband algorithms are fast and guaranteed to converge

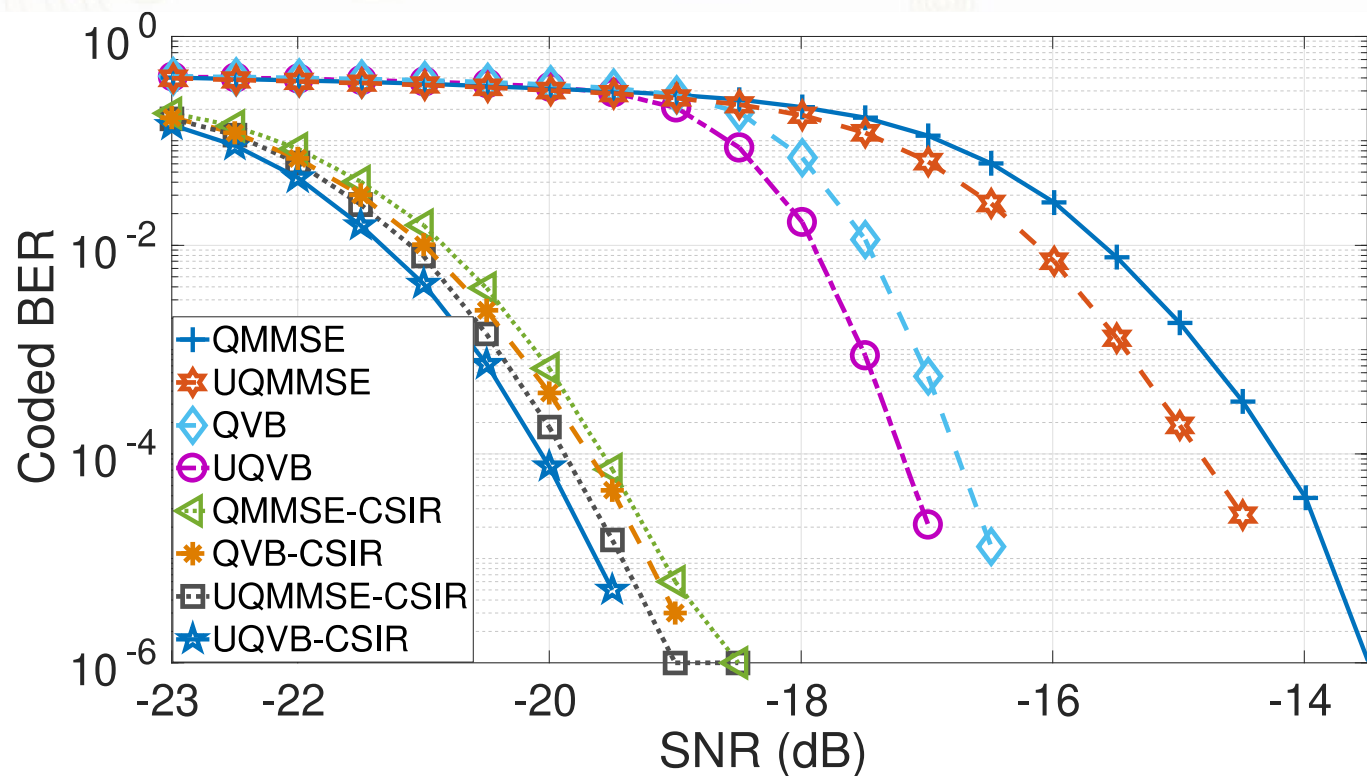


Advanced Receiver Algorithms

- Algorithms for **soft-symbol detection**
 - Unquantized observations (hi-res ADCs), perfect CSIR
 - Unquantized observations, statistical CSIR (known covariance)
 - Unquantized observations, no CSIR
 - Quantized observations (low-res ADCs), perfect CSIR
 - Quantized observations, statistical CSIR (known covariance)
 - Quantized observations, no CSIR
- **Combined** soft symbol detection and channel decoding
- Extension to **MIMO-OFDM** systems
 - Low-res ADCs destroy orthogonality of subcarriers!
 - Novel techniques needed: time-domain channel estimation

Sample Result

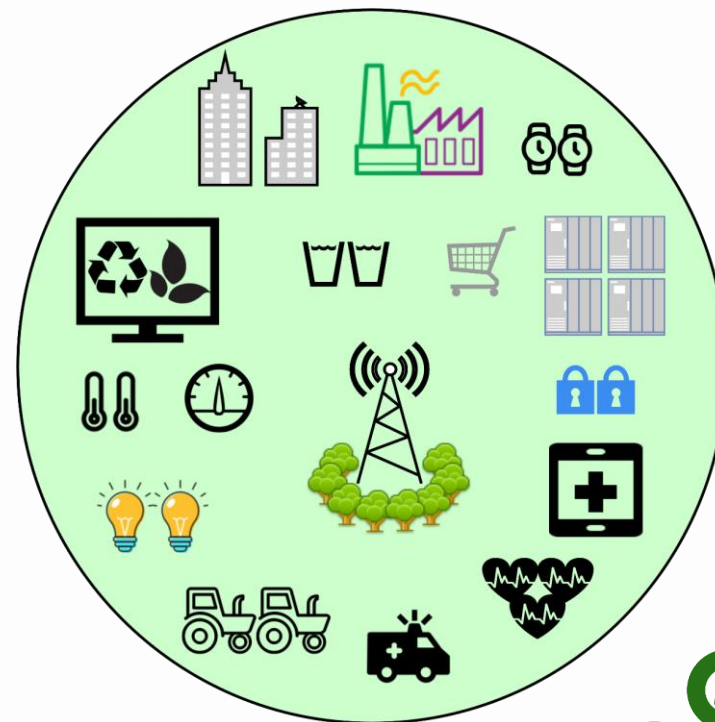
- BS with 200 antennas, 50 UEs, 50 training symbols, 450 data symbols, 3-bit quantization



https://ece.iisc.ac.in/~cmurthy/Papers/Main_QVB_MIMO_OFDM.pdf, TSP 2022
http://ece.iisc.ac.in/~cmurthy/Papers/Sai_VB_TCO_M_Feb2021.pdf, TSP 2021

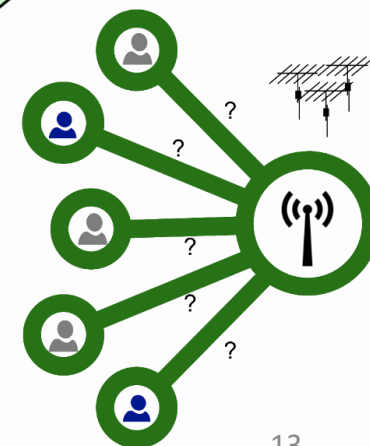
Massive Machine-Type Communications

- Use case: IoT
- Up to 10^6 devices/km²
- Sporadically send short packets
- Multiple access:
 - Grant-free: low overhead
 - Non-orthogonal: better spectral efficiency









Goal









- How to efficiently manage massive multiple access?
- User activity detection, channel estimation, and data decoding



Irregular Repetition Slotted Aloha

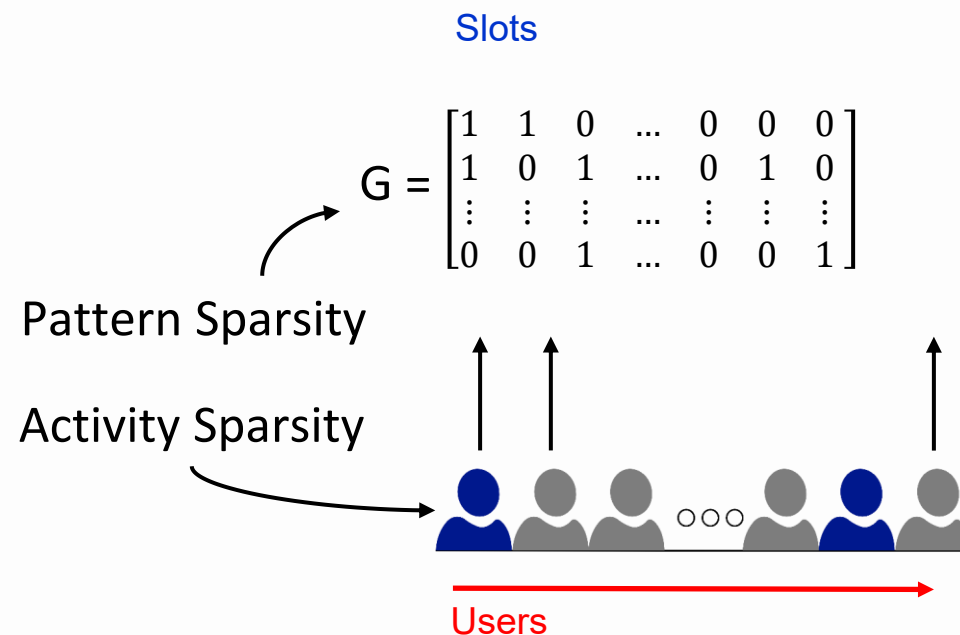
- Slotted Aloha, but with multiple copies txed
- Enabled by successive interference cancelation
- Packet “captures” further improve performance

	User 1	User 2	User 3	User 4
Slot 1				
Slot 2				
Slot 3				

	User 1	User 2	User 3	User 4
Slot 1				
Slot 2				
Slot 3				

Challenges: Irregular Repetition Slotted Aloha

- Synchronization
- User activity detection
- Channel estimation
 - Training signal design
- Multiple antennas at the BS
- Accounting for fading and path loss
- Optimizing the repetition distribution
- Performance analysis
 - Throughput
 - Energy efficiency
 - Fairness (or unfairness – prioritized access)
 - Age of information



Some Solutions

- A new **user activity detection** scheme based on sparse signal recovery adapted to the IRSA protocol
- Analysis of the **impact of channel estimation errors**
 - **Signal to interference plus noise ratio** accounting for user activity detection errors, multiple antennas, non-orthogonal training, fading and pathloss, etc
- **Throughput analysis** with fading and packet capture, with multiple antennas at the BS, via density evolution
- **Age of information-optimal design of IRSA**

S. Saha, V. B. Sukumaran and C. R. Murthy, "On the Minimum Average Age of Information in IRSA for Grant-free mMTC," IEEE JSAC 2021.

C. Srivatsa and C. R. Murthy, <https://arxiv.org/abs/2112.07242>, TSP 2022

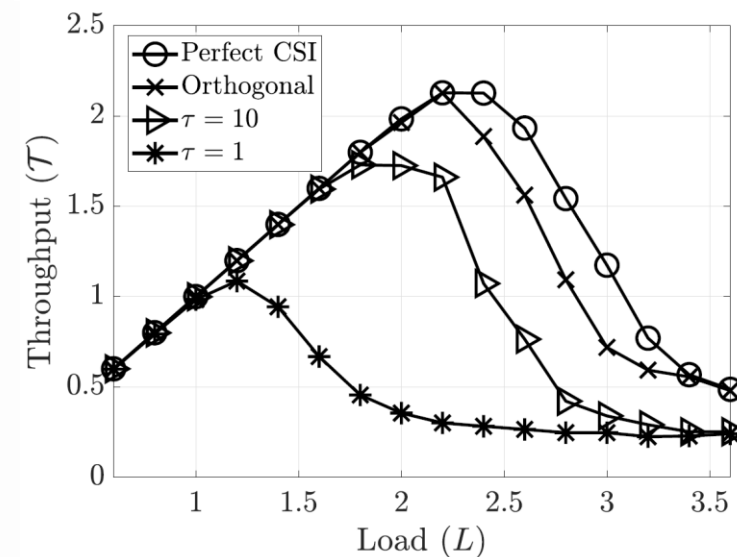
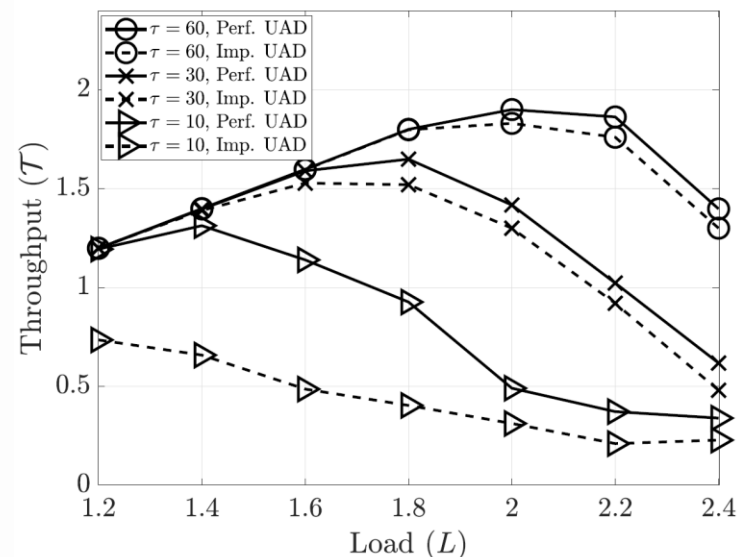
C. Srivatsa and C. R. Murthy, <https://arxiv.org/abs/2111.06140>, TSP 2022

Takeaways

- IRSA is a promising candidate for massive MTC
 - Grant-free: low overhead
 - Non-orthogonal: high spectral efficiency
- Our contributions
 - User activity detection
 - Effect of channel estimation
 - SINR-threshold based decoding
 - Pilot length
 - Number of antennas
- **Main message:** When params. are chosen “well”, can get much better than 1 packet/slot!

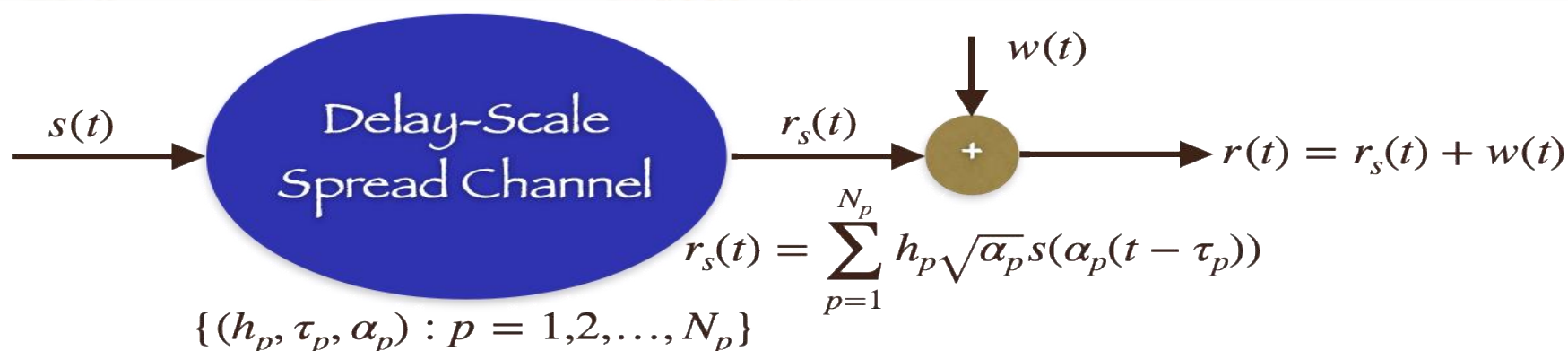
Longer presentation:

https://ece.iisc.ac.in/~cmurthy/QINF_Final_Presentation_Chirag_Ramesh_video.mp4



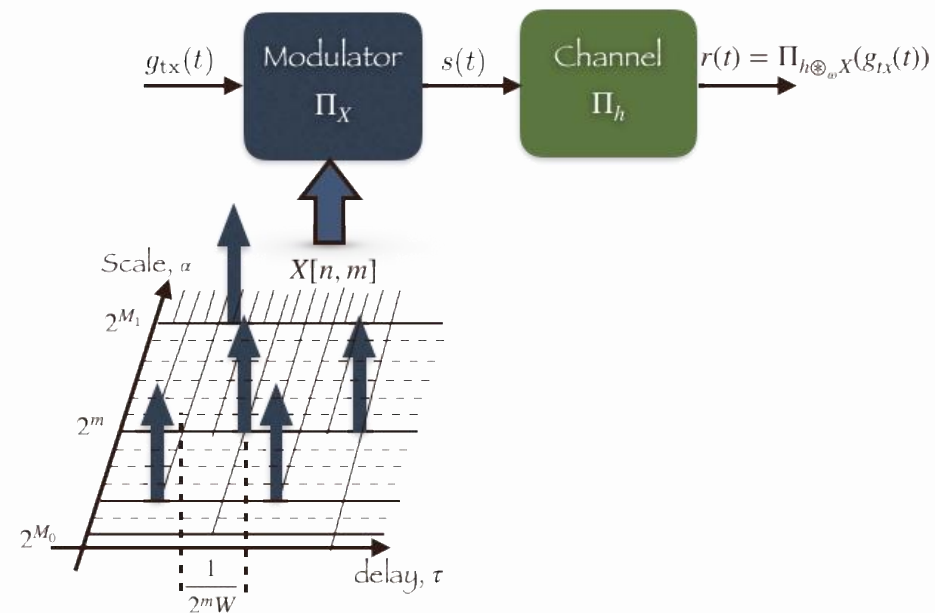
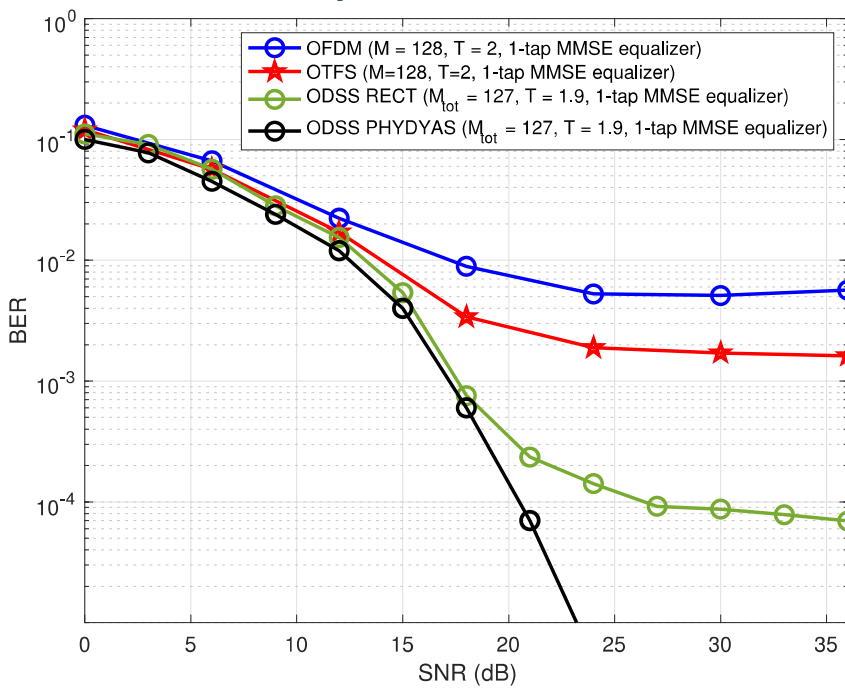
New Waveforms

- Broadband rural communications
 - Sub GHz center frequency: wide coverage
 - High bandwidth, high velocity support
- The effect of Doppler can be approximated as a frequency shift only if $B/f_c \ll 1$ and $v \ll \frac{c}{2BT}$
- Otherwise, delay-scale channel:



Orthogonal Delay Scale Space Modulation

- Uses the Mellin Transform
- Mount symbols in the delay-scale domain



$$X[n, m] = \frac{q^{-n/2}}{N} \sum_{k=0}^{N-1} \frac{\sum_{l=0}^{M(k)-1} x[k, l] e^{j2\pi(\frac{ml}{M(k)} - \frac{nk}{N})}}{M(k)}$$

$$s(t) = \sum_{n=0}^{N-1} \sum_{m=0}^{M(n)-1} X[n, m] q^{n/2} g_{tx} \left(q^n t - \frac{m}{q^n W} \right)$$

$$P = 20, \tau_{max} = 10ms, \alpha_{max} = 1.001$$

$$\tau_{max} \delta f_{max} = 0.2 < 0.25$$

https://ece.iisc.ac.in/~cmurthy/Papers/Journal_ODSS_Final_Arun_main.pdf, TSP 2022

IRS-Assisted Opportunistic User Scheduling

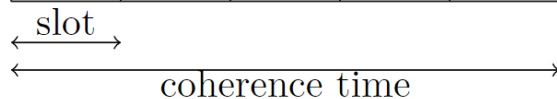
Channel model:

$$h_{k,q}(t) = \sqrt{\beta_{r,k}} \mathbf{h}_{2,k}^H \Theta_q(t) \mathbf{h}_1 + \sqrt{\beta_{d,k}} h_{d,k}$$

Randomly configure the **IRS phase angles** in every time slot, and schedule the user with **highest PF metric** for transmission

user K	\mathbf{h}_K	\mathbf{h}_K	\mathbf{h}_K	\mathbf{h}_K	\mathbf{h}_K
⋮	⋮	⋮	⋮	⋮	⋮
user 2	\mathbf{h}_2	\mathbf{h}_2	\mathbf{h}_2	\mathbf{h}_2	\mathbf{h}_2
user 1	\mathbf{h}_1	\mathbf{h}_1	\mathbf{h}_1	\mathbf{h}_1	\mathbf{h}_1

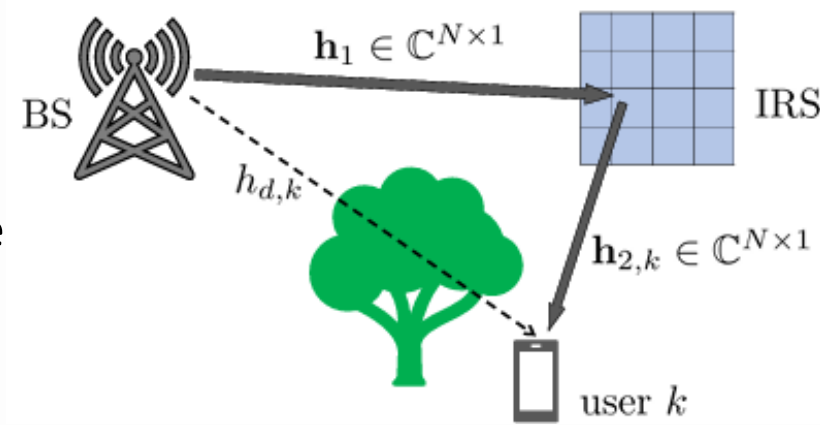
Θ_1	Θ_2	Θ_3	Θ_4	Θ_5
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$$k^* = \arg \max \frac{R_k(t)}{T_k(t)}$$

$$R_k(t) = \log_2 \left(1 + \frac{P|h_{k,q}(t)|^2}{\sigma^2} \right)$$

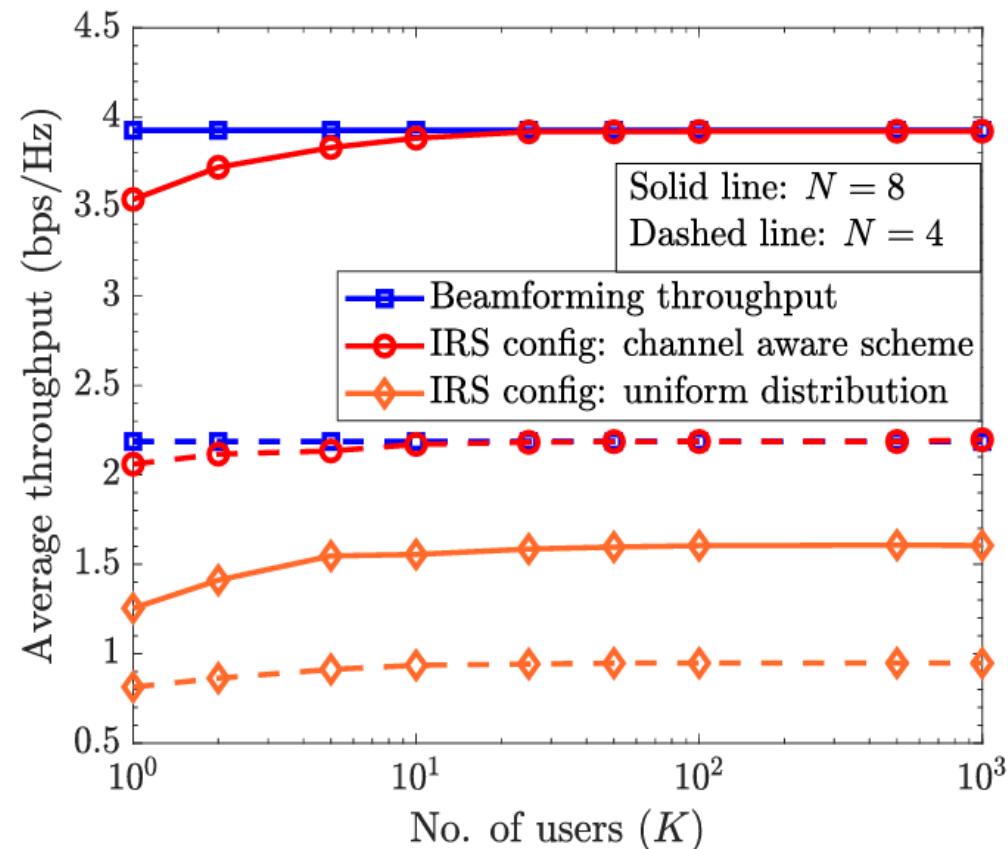
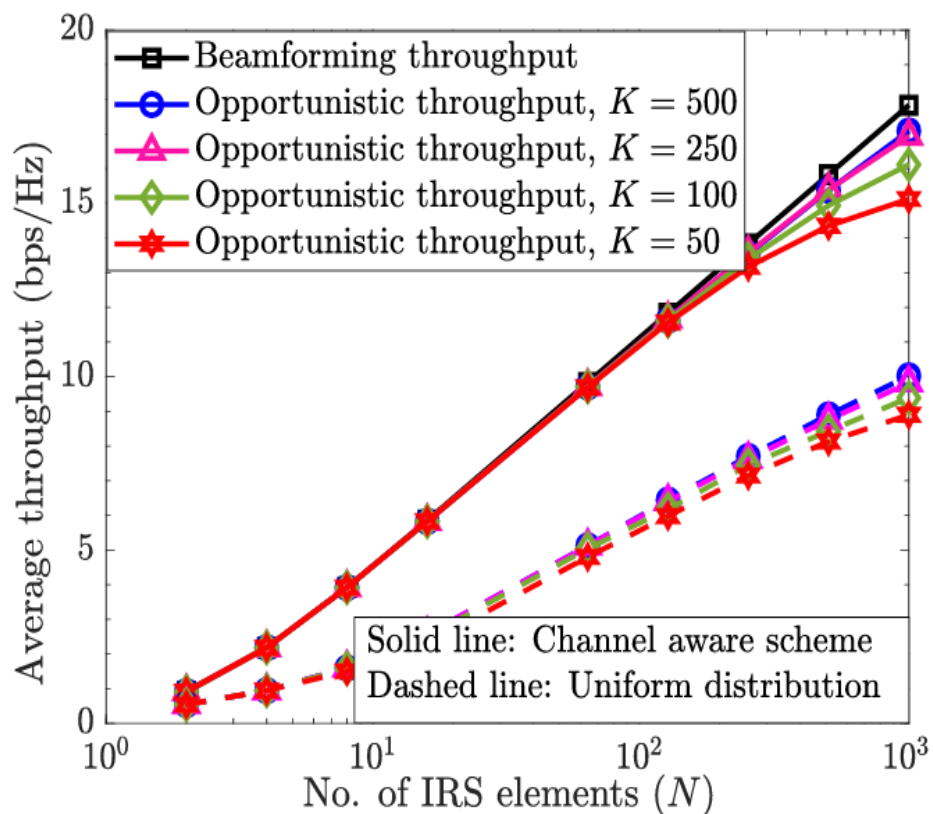
$$T_k(t+1) = \begin{cases} \left(1 - \frac{1}{t_c}\right) T_k(t) + \frac{1}{t_c} R_k(t), & k = k^* \\ \left(1 - \frac{1}{t_c}\right) T_k(t), & k \neq k^* \end{cases}$$



Randomly chosen IRS configuration will be close to the beamforming (BF) configuration for at least one of the users

* ArXiv: <https://arxiv.org/pdf/2203.06313>

Performance



Optimal Random Distribution:

$$\theta_i = \frac{2\pi(i-1)d}{\lambda} (\sin(\theta_A) + \sin(\phi)); \phi \sim \mathcal{U}[\phi_0, \phi_1]$$

Rate scaling law:

$$\lim_{K \rightarrow \infty} \left(R^{(K)} - \mathcal{O} \left(\log_2 \left(1 + \frac{\beta P}{\sigma^2} N^2 \ln K \right) \right) \right) = 0.$$

Other Topics

- Joint communications and sensing
- Upper mid-bands: channel modelling, giga-MIMO
- Quantum communications/learning
- Non-terrestrial (e.g., satellite) networks
- AI/ML based network orchestration
- And many more...

Thank You
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