Design and Analysis of Low Complexity Techniques for IRS-Aided Wireless Comm.

CNI seminar series

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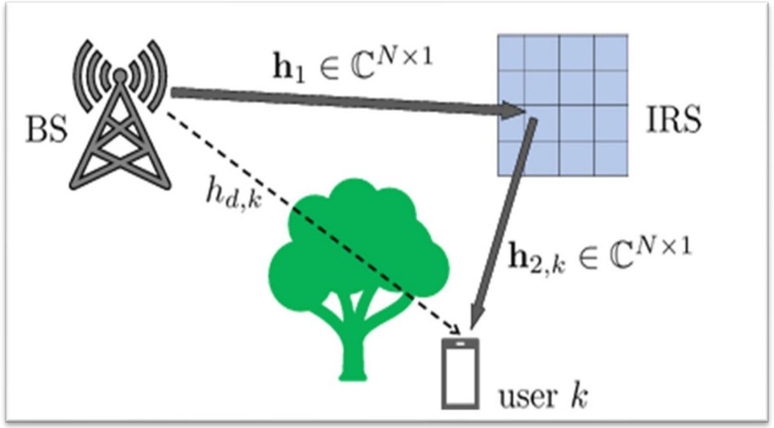
Intelligent Reflecting Surfaces (IRS)

- Also known as reconfigurable intelligent surfaces (RIS)
- Meta surfaces made up of passive elements
  - Reflect signals in specific directions
  - Alters the wireless channel as per our requirements
- <u>Perks:</u> Boosts SNR/SINR, energy efficiency, coverage, etc.



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

- A hot research topic for the last 5 years

Showing **1-25** of **10,463** results for **("All Metadata":Intelligent reflecting surfaces) OR ("All Metadata":Reconfigurable intelligent surfaces)** ×

- [ ] Conferences (4,797)
- [ ] Journals (4,692)
- [ ] Early Access Articles (483)
- [ ] Magazines (450)
- [ ] Books (41)

- Industry & standards: ETSI, TSDSI workshops, Qualcomm testbed, ZTE prototypes, etc.
  - https://www.etsi.org/technologies/reconfigurable-intelligent-surfaces

Three problems and solutions

Today's agenda

- IRS-aided opportunistic communications
  (Addresses the optimization of IRS phase)
- IRS-aided wireless systems with multiple mobile operators
  (Analyses the out-of-band performance)
- Wideband beamforming using IRSs
  (Addresses beam split effects with phased arrays)

IRS-Aided Opportunistic Communications

The benchmark rate using optimized IRS

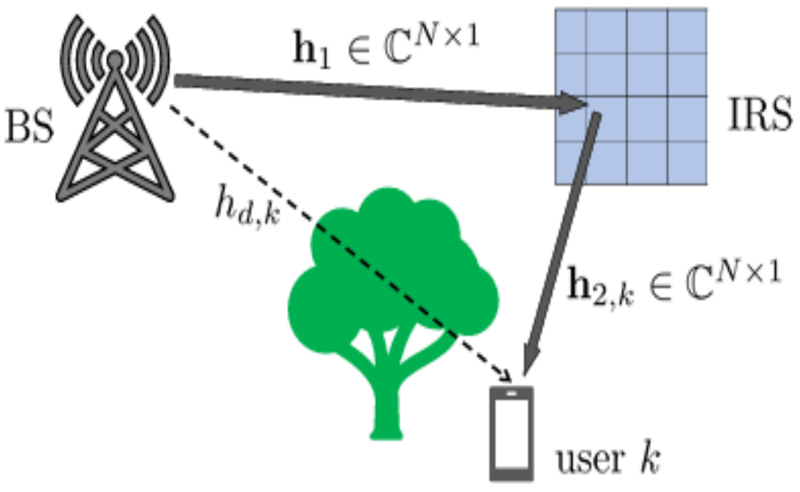
Theorem 1 (Performance of the optimized IRS - beamforming configuration)

The rate obtained by the user k when the IRS is optimized to user k is

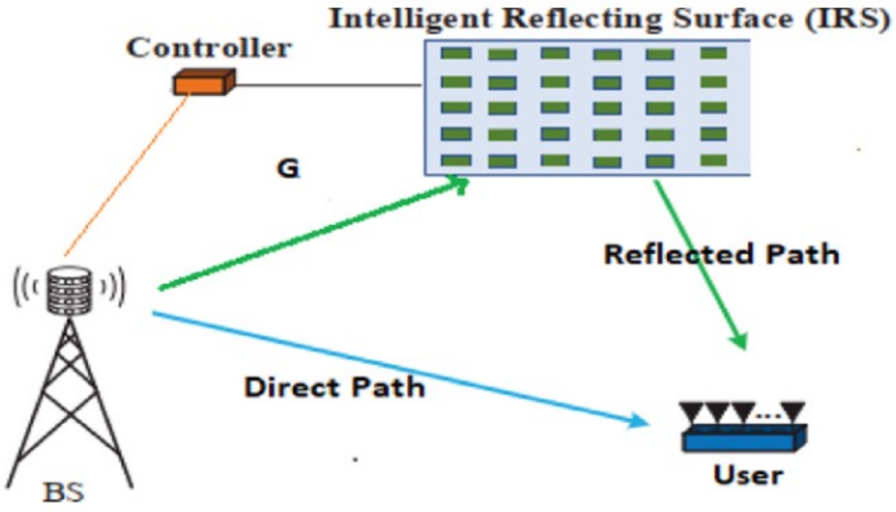
$$R_k^{BF} = \log_2\left(1 + \frac{P}{\sigma^2}\left|\sqrt{\beta_{r,k}}\sum_{n=1}^{N}|h_{1,n}||h_{2,k,n}| \times \exp(j\angle h_{d,k}) + \sqrt{\beta_{d,k}}h_{d,k}\right|^2\right).$$

It is achieved when (due to *Cauchy - Schwarz inequality*),

$$\theta_{n,k}^{BF} = \angle h_{d,k} - \angle(h_{1,n} + h_{2,k,n}), \qquad n = 1, \ldots, N.$$



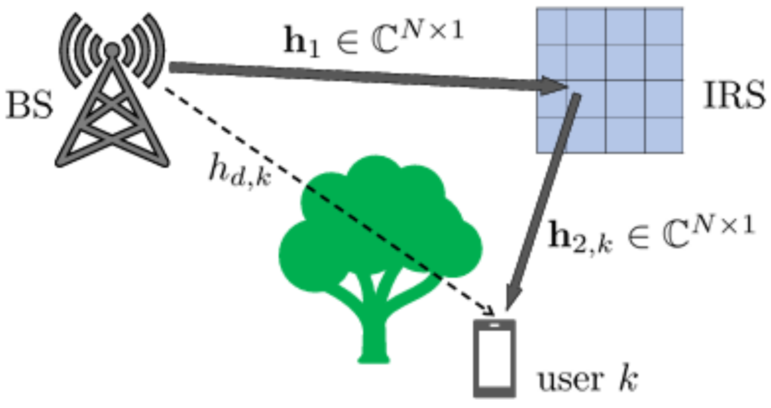
- Optimal SNR: $\mathcal{O}(N^2)$
- State-of-the-art: "Three-fold overhead"
  - Channel estimation – can be of complexity $\mathcal{O}(N)$
  - Phase optimization @ BS
  - Phase transportation – can be of complexity $\mathcal{O}(N)$
- Can we obtain optimal benefits without optimizing the IRS?



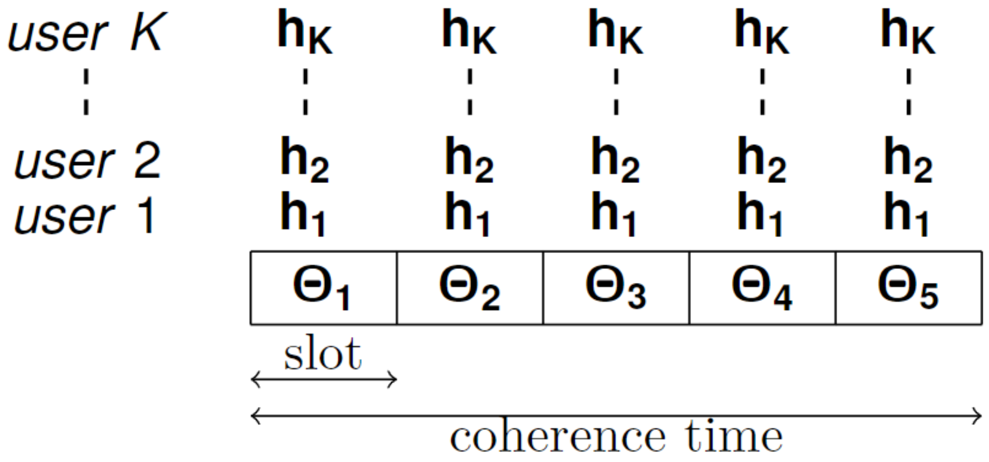
Source: Google Images

IRS assisted opportunistic comm. for narrowband channels

Channel model: $h_{k,q}(t) = \sqrt{\beta_{r,k}}\mathbf{h}_{2,k}^H \mathbf{\Theta}_q(t)\mathbf{h}_1 + \sqrt{\beta_{d,k}}h_{d,k}.$



Idea: Randomly configure the IRS phase angles in every time slot and schedule the UE with the highest PF metric for data txn.



$$k^* = \arg\max \frac{R_k(t)}{T_k(t)}$$

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

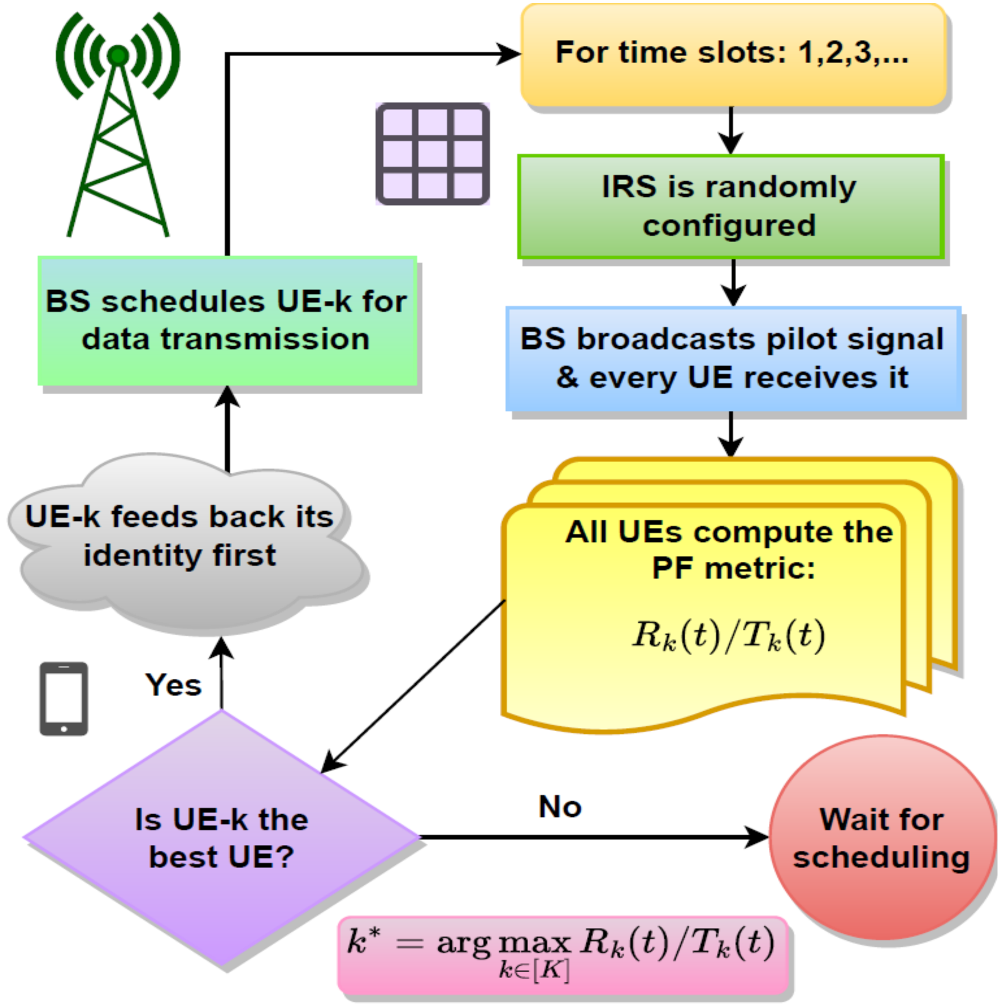
$$T_k(t+1) = \begin{cases} \left(1 - \frac{1}{t_c}\right) T_k(t) + \frac{1}{t_c} R_k(t), & k = k^* \\ \left(1 - \frac{1}{t_c}\right) T_k(t), & k \neq k^*. \end{cases}$$

Proportional fair (PF) scheduler

For large UEs, the random IRS config. is nearly in beamforming (BF) config. for at least one UE

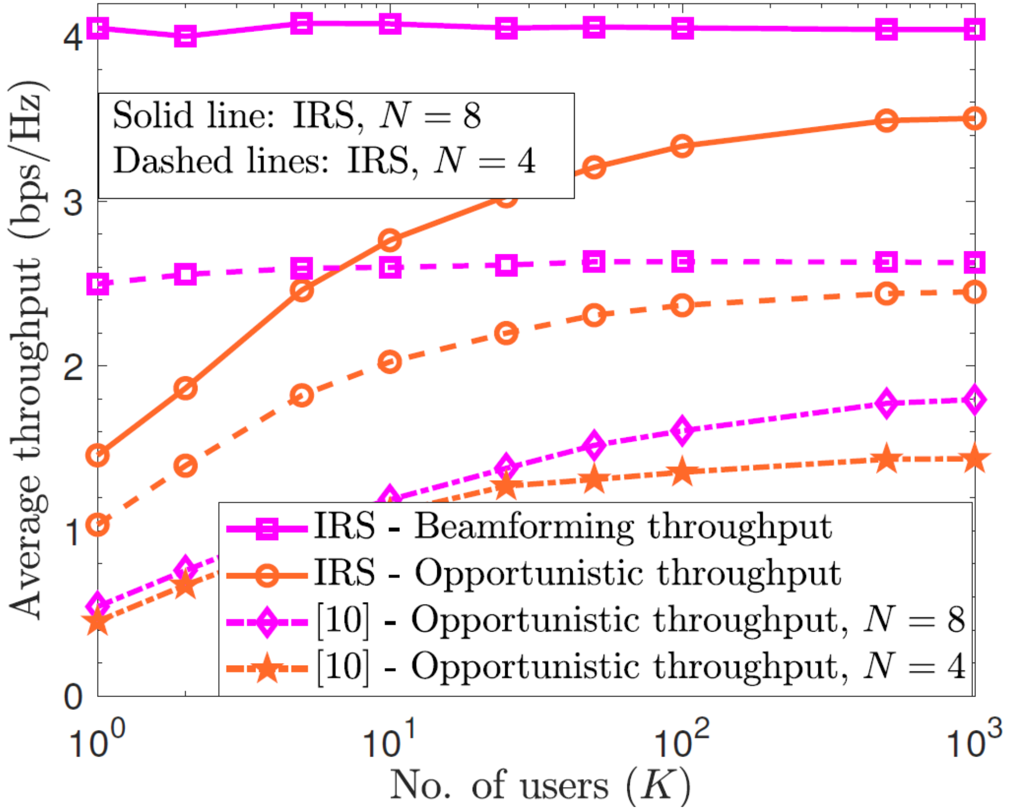
*L. Yashvanth and Chandra R. Murthy, "Performance Analysis of IRS Assisted Opportunistic Communications," IEEE Transactions on Signal Processing, vol. 71, pp. 2056-2070, Jun. 2023

Opportunistic comm. scheme with randomized IRS



Achieving the Benchmark:

$$\lim_{K\to\infty}\left(R^{(K)} - \frac{1}{K}\sum_{k=1}^{K} R_k^{BF}\right) = 0$$



*P. Viswanath, D. Tse, and R. Laroia, "**Opportunistic beamforming using dumb antennas**," in IEEE Transactions on Information Theory, June 2002

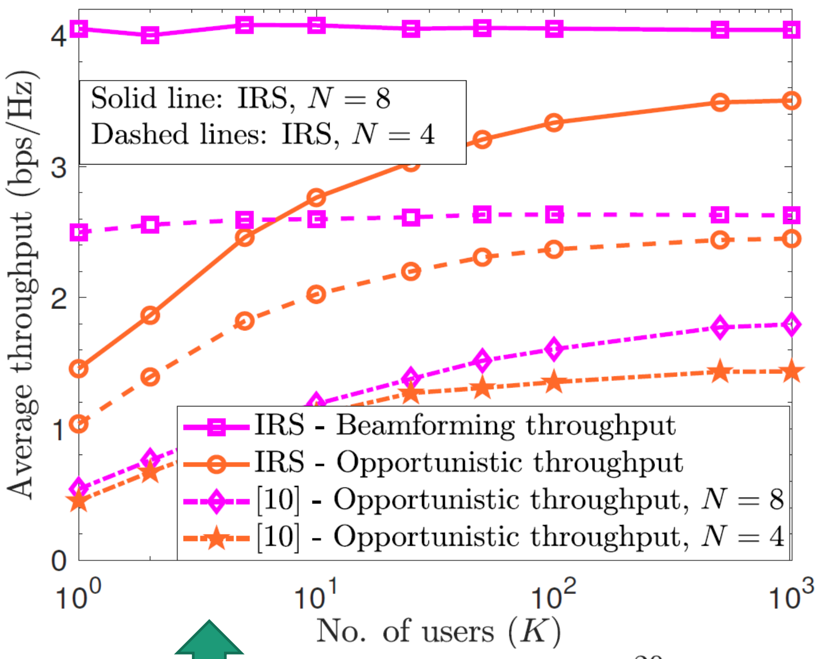
*V. Shah, N. B. Mehta, R. Yim, "**Optimal Timer Based Selection Schemes**" in IEEE Transactions on Communications, June 2010

Comparative analysis: i.i.d. versus LoS channels

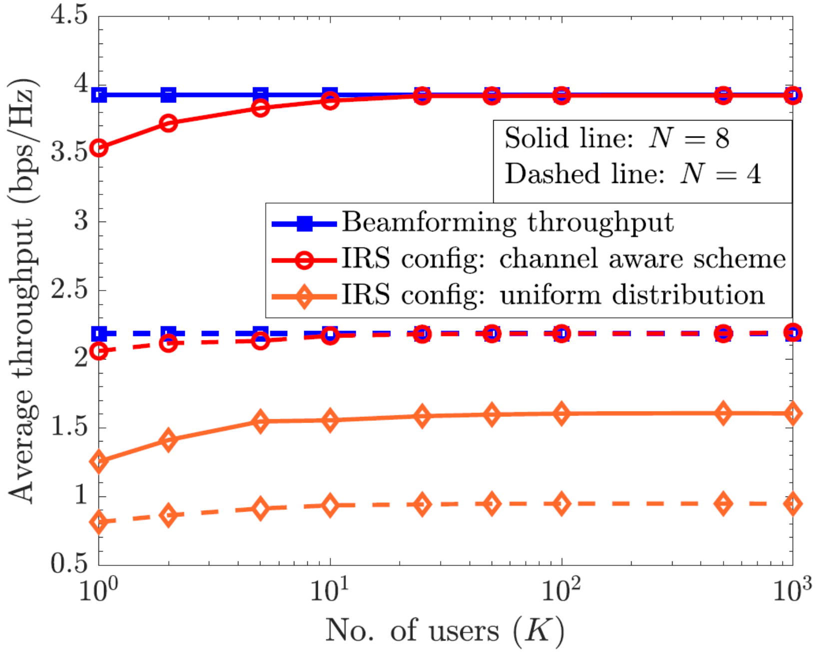
IRS aided multi-user diversity in i.i.d. channels	IRS Enhanced multi-user diversity in LoS channels
➢ Channel distribution: i.i.d. $\mathcal{CN}(\cdot)$	➢ Ch. model: LoS array response vector
➢ Optimal random sampling distribution: $\mathcal{U}[0, 2\pi)$	➢ Optimal random sampling distribution: $\theta_i = \left(2\pi(i-1)d\sin\phi\right)/\lambda$
➢ Convergence rate: $K \geq \left(-\log(1-P^{\epsilon}_{\text{succ}})\right)(\pi/\epsilon)^N$	➢ Convergence rate: $K \geq \left(-\log(1-P^{\epsilon}_{\text{succ}})\right)(\pi/\epsilon)$
➢ Rate-scaling law for fast-fading channels: $\lim_{K\to\infty}\left(R^{(K)} - \mathcal{O}\left(\log_2\left(1+\frac{\beta P}{\sigma^2}(N+1)\ln K\right)\right)\right) = 0$	➢ Rate-scaling law for fast-fading channel: $\lim_{K\to\infty}\left(R^{(K)} - \mathcal{O}\left(\log_2\left(1+\frac{\beta P}{\sigma^2}N^2\ln K\right)\right)\right) = 0$

*L. Yashvanth and Chandra R. Murthy, "**Comparative Study of IRS Assisted Opportunistic Communications over i.i.d. and LoS Channels**," Proc. IEEE ICASSP, Rhodes Island, Greece, June 2023

Numerical illustrations



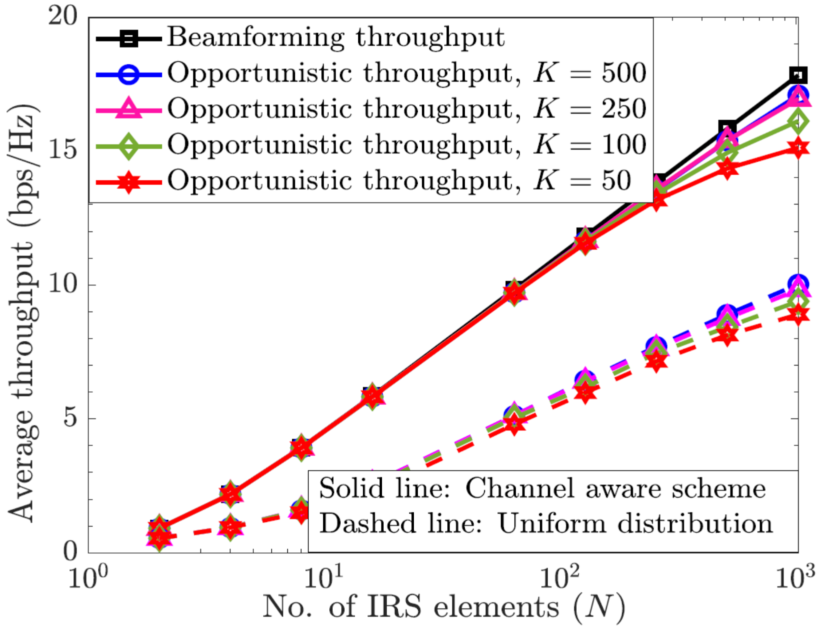
IRS assisted OC in i.i.d. channels.

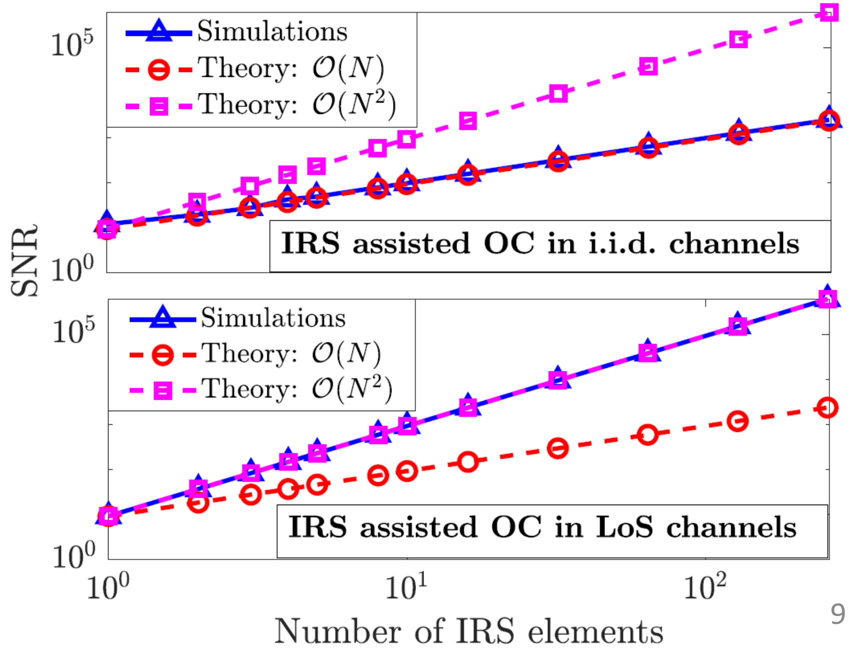


IRS assisted OC in LoS channels.

SNR scaling in i.i.d. & LoS ch.

IRS assisted OC in i.i.d. & LoS channels





Extensions and results

- Schemes to further reduce the exponential bottleneck in # IRS elements**:
  - Reflection diversity benefits
  - Spatial correlation aware opportunistic communications
- Extension to wideband channels**
  - SU-OFDM versus OFDMA
- Extension to multiple antenna channels$$
  - Random precoding versus fixed precoding

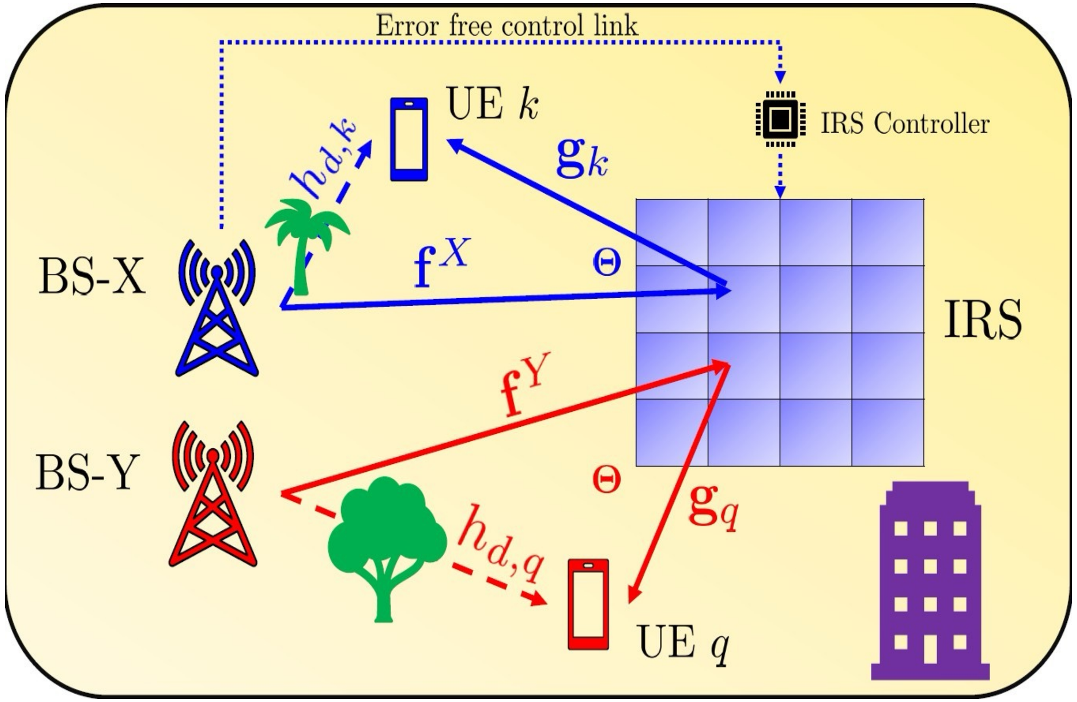
> - Convergence rate to optimal rate
> - Rate-scaling laws of the schemes

L. Yashvanth and Chandra R. Murthy, "Performance Analysis of IRS Assisted Opportunistic Communications**," IEEE Transactions on Signal Processing, vol. 71, pp. 2056-2070, June 2023

$$Q. -U. -A. Nadeem, A. Zappone, and A. Chaaban, "**Intelligent Reflecting Surface Enabled Random Rotations Scheme for the MISO Broadcast Channel**," in IEEE Transactions on Wireless Communications, August

IRS-Aided Wireless Systems with Multiple Mobile Operators

Problem description



- 2 operators, X & Y (e.g., Airtel & Jio)
- IRS does not have bandpass filters
- NO IRS can simultaneously beamform to UEs of BS - X & Y
- Operator X controls the IRS
  - Optimal IRS @ in-band UEs
  - Random IRS @ OOB UEs

Does an IRS Degrade Out-of-Band Performance?

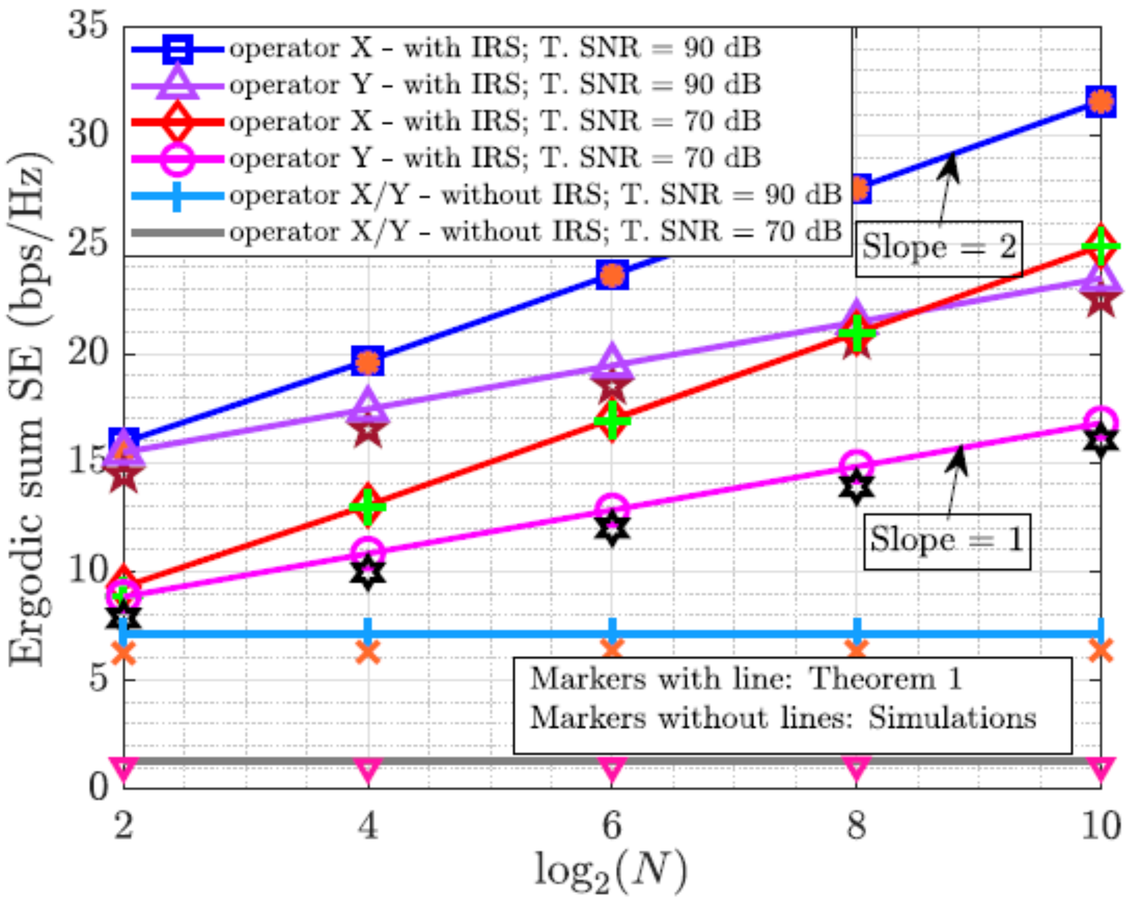
* L. Yashvanth and Chandra R. Murthy, "**On the Impact of an IRS on the Out-of-Band Performance in Sub-6 GHz and mmWave Frequencies**", Accepted, IEEE Transactions on Communications, May 2024

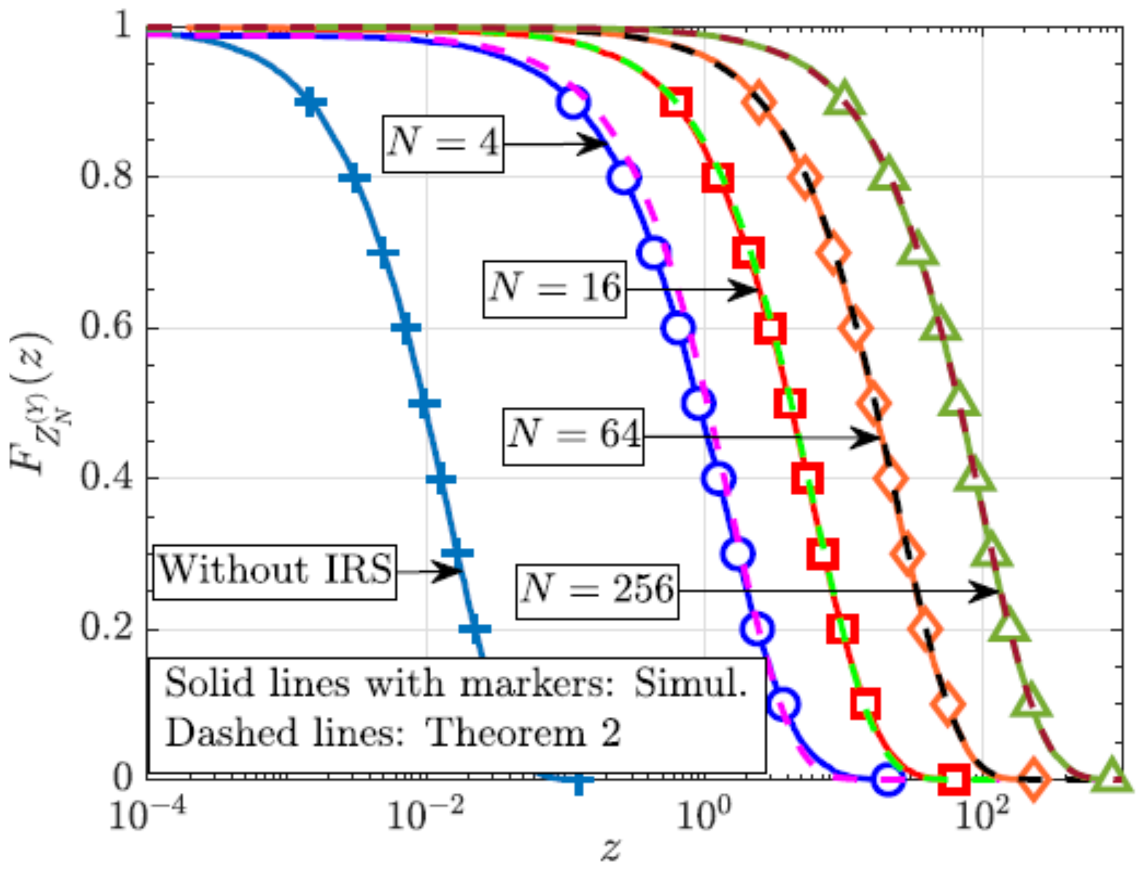
OOB Performance in Sub-6 GHz Bands

- FR-1 Bands in the 5G standards (410 MHz – 6 GHz, Rel. 15, 2018)
- Channels are rich-scattering with multiple paths
- E.g., Rayleigh channels
- Round-robin scheduling of UEs

L. Yashvanth and Chandra R. Murthy, "**Does an IRS Degrade Out-of-Band Performance?**," IEEE International Workshop on Signal Processing Advances in Wireless Communications (IEEE SPAWC), Shanghai, China, 2023.

OOB performance in sub-6 GHz frequencies





- SNR: N^2 @ in-band UEs/ N @ OOB UEs
  - Acts as a scatterer
  - Reception of multiple copies

$$Z_N^{(Y)} \triangleq \left| \sum_{n=1}^{N} f_n^J g_{q,n} + h_{d,q} \right|^2 + \left(-\mathbf{1}_{\{N \neq 0\}}\right) |h_{d,q}|^2$$

IRS does NOT degrade the OOB perf.

*L. Yashvanth and Chandra R. Murthy, "**Does an IRS Degrade Out-of-Band Performance?**", IEEE SPAWC 2023

OOB Performance in mmWave Bands

- FR-2 Bands in the 5G standards

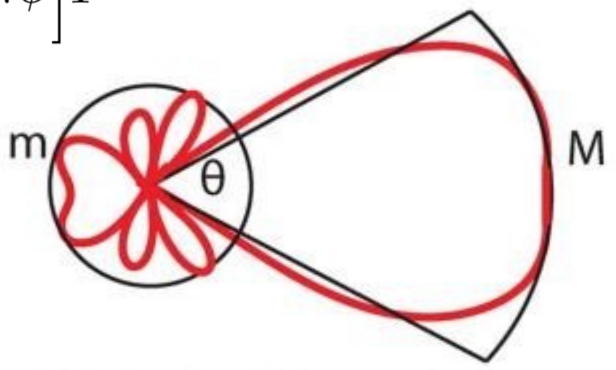
  (24.25 GHz – 52.6 GHz, Rel. 15, 2018)
- Sparse channels with few propagation paths
- Channels are highly directional!
- Round-robin scheduling of UEs

System model in mmWave frequency bands

- Directional Saleh – Valenzuela model:

$$\mathbf{f}^p = \sqrt{\frac{N}{L_{1,p}}} \sum_{i=1}^{L_{1,p}} \gamma_{i,p}^{(1)} \mathbf{a}_N^*(\phi_{i,p}); \quad \mathbf{g}_\ell = \sqrt{\frac{N}{L_{2,\ell}}} \sum_{j=1}^{L_{2,\ell}} \gamma_{j,\ell}^{(2)} z \mathbf{a}_N^*(\psi_{j,\ell}), \quad p \in \{X, Y\}$$

- Array steering vector: $\mathbf{a}_N(\phi) = \frac{1}{\sqrt{N}}[1, e^{-j\pi\phi}, \ldots, e^{-j(N-1)\pi\phi}]^T$



- Beam-resolution capability:
  - N-element ULA can form at most N resolvable beams
  - Resolvable beam book and angle book:

$$\mathcal{A} \triangleq \{\mathbf{a}_N(\phi), \phi \in \mathbf{\Phi}\}\,; \mathbf{\Phi} \triangleq \left\{ \left(-1 + \frac{2i}{N}\right) \middle| i = 0, \ldots, N-1 \right\}$$

  - Uniform distribution over beam book:

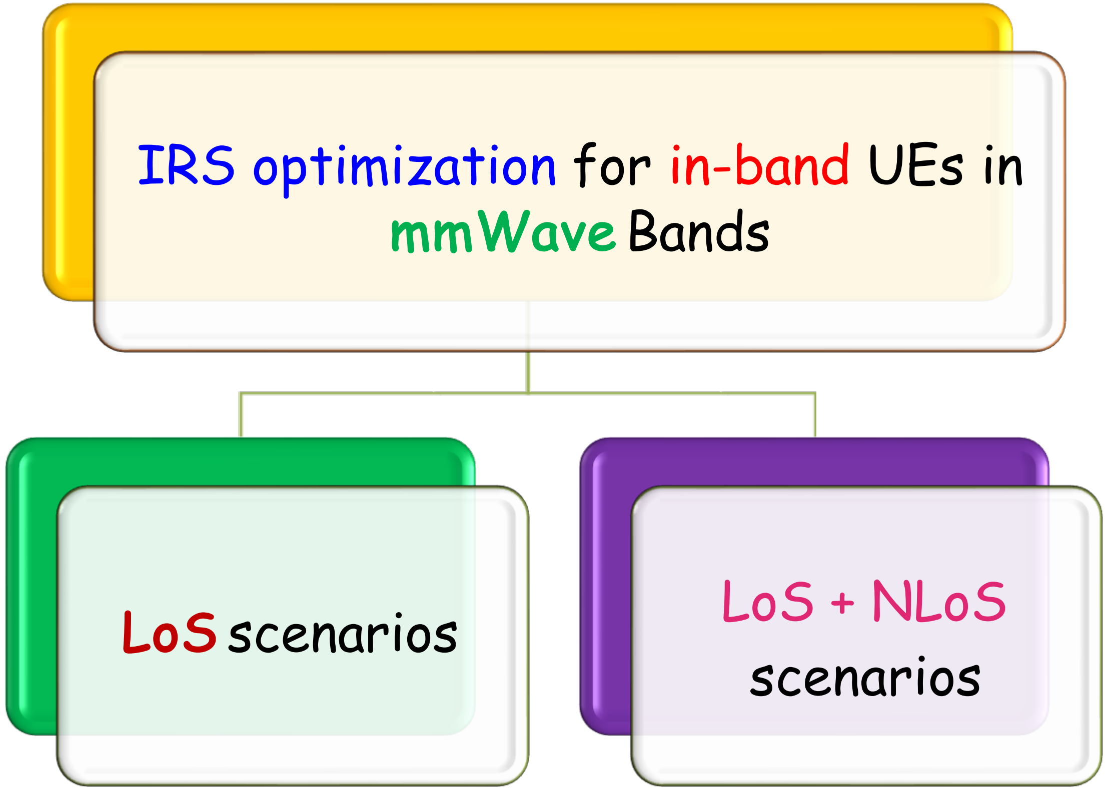
$$\mathcal{U}_{\mathcal{A}}(\phi) = \frac{1}{|\mathbf{\Phi}|} \mathbf{1}_{\{\phi \in \mathbf{\Phi}\}} = \frac{1}{N} \mathbf{1}_{\{\phi \in \mathbf{\Phi}\}}$$

Fig. The "Flat-top" beam pattern @ IRS

Categories of the study

LoS scenario

- IRS is aligned to the dominant cascaded path (virtual LoS)
- In-band UEs' channel approximated by the dominant path
- IRS vector is a phasor
- Signaling overhead does NOT SCALE with N



(L+)NLoS scenario

- IRS is jointly aligned to all cascaded paths
- No structure in the IRS vector
- Signaling overhead scales linearly with IRS elements

Channels for OOB UEs can have more than one spatial path

LoS scenarios

- Channel with dominant cascaded path: $$h_k = N\gamma^{(1)}_{1,X}\gamma^{(2)}_{1,k}\mathbf{a}^H_N(\psi_{1,k})\boldsymbol{\Theta}\mathbf{a}^*_N(\phi_{1,X}) + h_{d,k}$$
$$\overset{(a)}{=} N\left(\gamma^{(1)}_{1,X}\gamma^{(2)}_{1,k}\left(\mathbf{a}^H_N(\phi_{1,X})\odot\mathbf{a}^H_N(\psi_{1,k})\right)\right)\boldsymbol{\theta} + h_{d,k},$$
$$= N\gamma_{X,k}\dot{\mathbf{a}}^H_N(\omega^1_{X,k})\boldsymbol{\theta} + h_{d,k}$$

- Optimal IRS vector

$$\boldsymbol{\theta}^{\text{opt}} = \frac{h_{d,k}\gamma^*_{X,k}}{|h_{d,k}\gamma_{X,k}|} \times N\dot{\mathbf{a}}_N(\omega^1_{X,k})$$

- IRS has a uni-directional response

  @ in-band channel angle

- With probability $\frac{L}{N}$, OOB UE benefits!

- With probability $1-\frac{L}{N}$, OOB perf. same as without an IRS

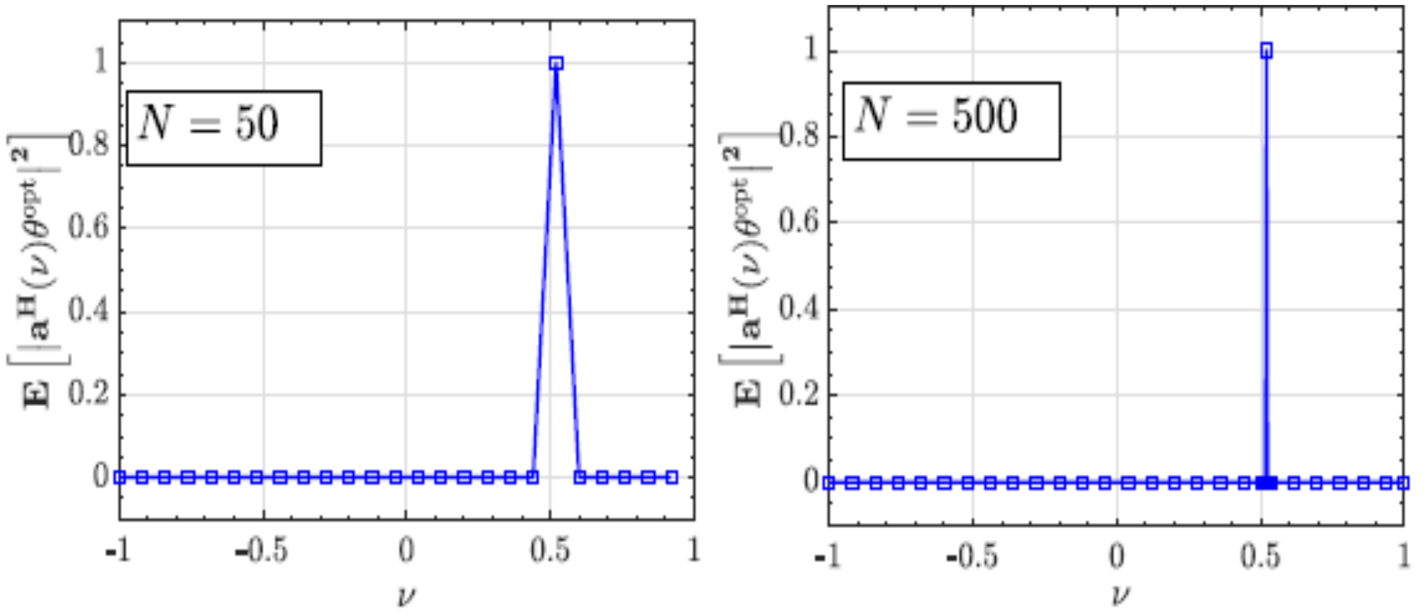


Fig. 3: Correlation response of the IRS vector and array steering vectors pointing at different spatial angles, ν, for (a) $N = 50$ and (b) $N = 500$. When $\nu = \omega^1_{X,k}$, the response attains its maximum value of 1.

Ergodic SE performance in LoS scenarios

The ergodic sum SEs of operator X & Y scale as

$$\bar{S}_1^{(X)} \approx \frac{1}{K}\sum_{k=1}^{K}\log_2\left(1+\left[N^2\beta_{r,k} + N\left(\frac{\pi^{3/2}}{4}\sqrt{\beta_{d,k}\beta_{r,k}}\right)+\beta_{d,k}\right]\frac{P}{\sigma^2}\right),$$

and

$$\bar{S}_1^{(Y)} \approx \frac{1}{Q}\sum_{q=1}^{Q}\left(\frac{\bar{L}}{N}\log_2\left(1+\left[\frac{N^2}{\bar{L}}\beta_{r,q}+\beta_{d,q}\right]\frac{P}{\sigma^2}\right)+\left(1-\frac{\bar{L}}{N}\right)\log_2\left(1+\beta_{d,q}\frac{P}{\sigma^2}\right)\right),$$

where $\bar{L} \triangleq \min\{L, N\}$, and $L \triangleq L_1 L_2$

- IRS does not degrade the OOB performance!
- It occasionally helps the OOB UEs
- Linear scaling of SNR with N is guaranteed if L >= N
- Sub-linear scaling of SNR with N if L < N.

The achievable OOB-SE in the presence of the IRS is at least the SE in the absence of the IRS

Numerical results for LoS scenarios

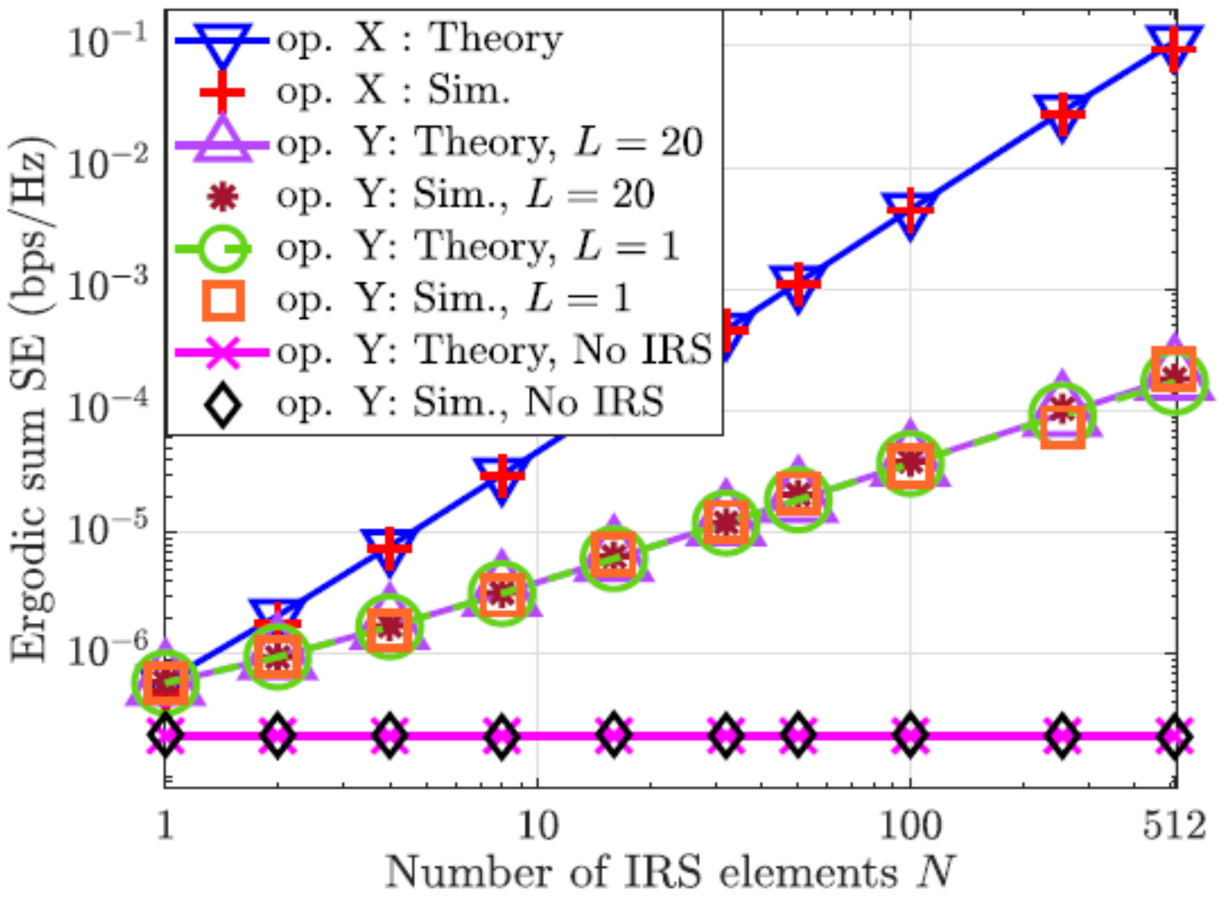


Fig. 6: Ergodic sum-SE vs. N in LoS scenarios at $\gamma = 70$ dB.

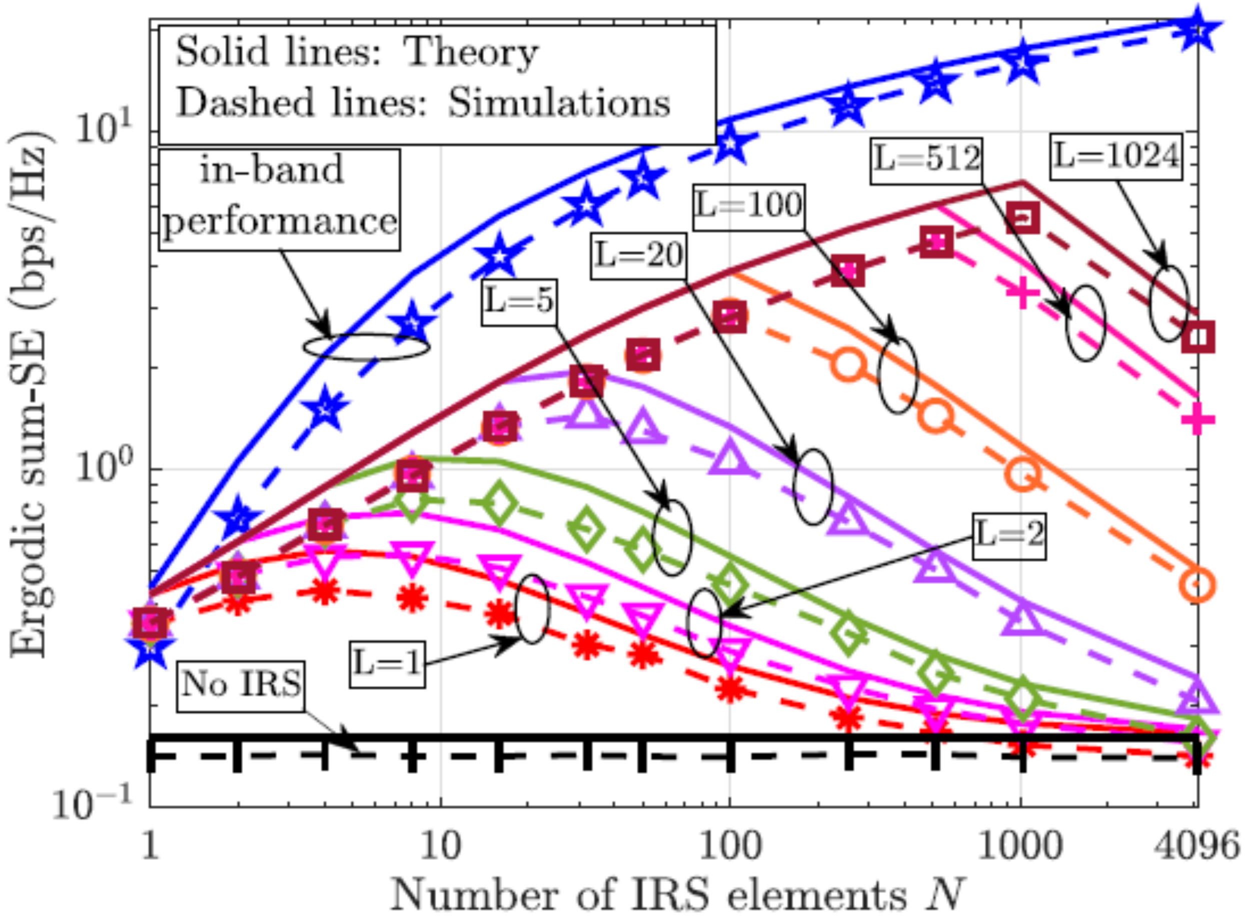


Fig. 7: Ergodic sum-SE vs. N in LoS scenarios at $\gamma = 130$ dB.

Performance with LoS + NLoS scenarios

- IRS is optimized to LoS and NLoS paths of the in-band UE's channel
- Channel: $h_k = h_{d,k} + \frac{N}{\sqrt{L}} \sum_{l=1}^{L} \gamma_{l,X}^{(1)} \gamma_{l,k}^{(2)} \dot{\mathbf{a}}_N^H(\omega_{X,k}^l)\boldsymbol{\theta}.$
- Optimal IRS configuration:

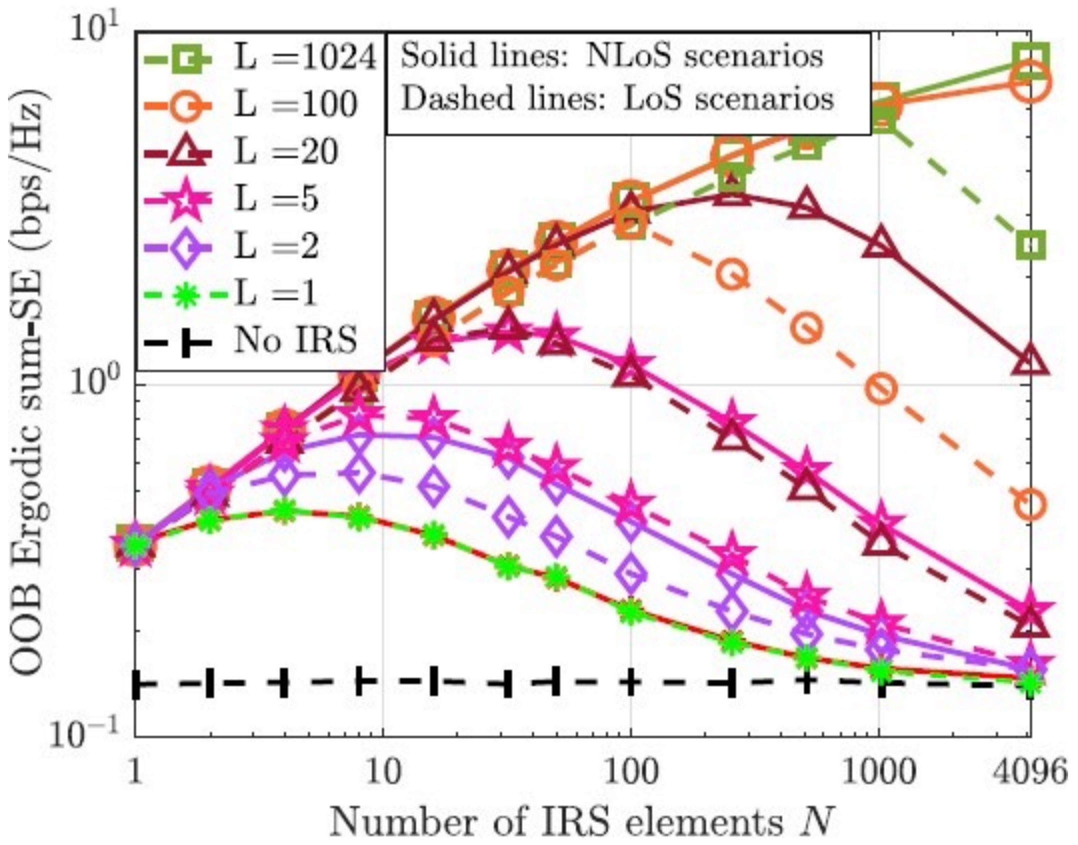
$$\boldsymbol{\theta}^{\text{opt}} = \frac{h_{d,k}}{|h_{d,k}|} \left(\sum_{l=1}^{L} \gamma_{l,X}^{(1)*} \gamma_{l,k}^{(2)*} \dot{\mathbf{a}}_N(\omega_{X,k}^l) \right) \odot \frac{1}{\left| \sum_{l=1}^{L} \gamma_{l,X}^{(1)} \gamma_{l,k}^{(2)} \dot{\mathbf{a}}_N(\omega_{X,k}^l) \right|},$$

- Directivity response:

Lemma 3. *The optimal IRS configuration*

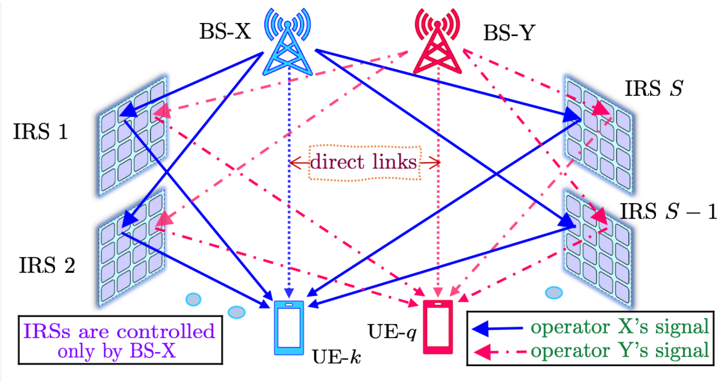
has the following spatial amplitude response:

$$\rho_{\phi,\theta} = \begin{cases} \Omega\left(\frac{N}{\sqrt{L}}\right) + o(N), \text{if } \phi \in \left\{\omega_{X,k}^1, \ldots, \omega_{X,k}^L\right\}, \\ o(N), \quad \text{if } \phi \in \Phi \setminus \left\{\omega_{X,k}^1, \ldots, \omega_{X,k}^L\right\}. \end{cases}$$

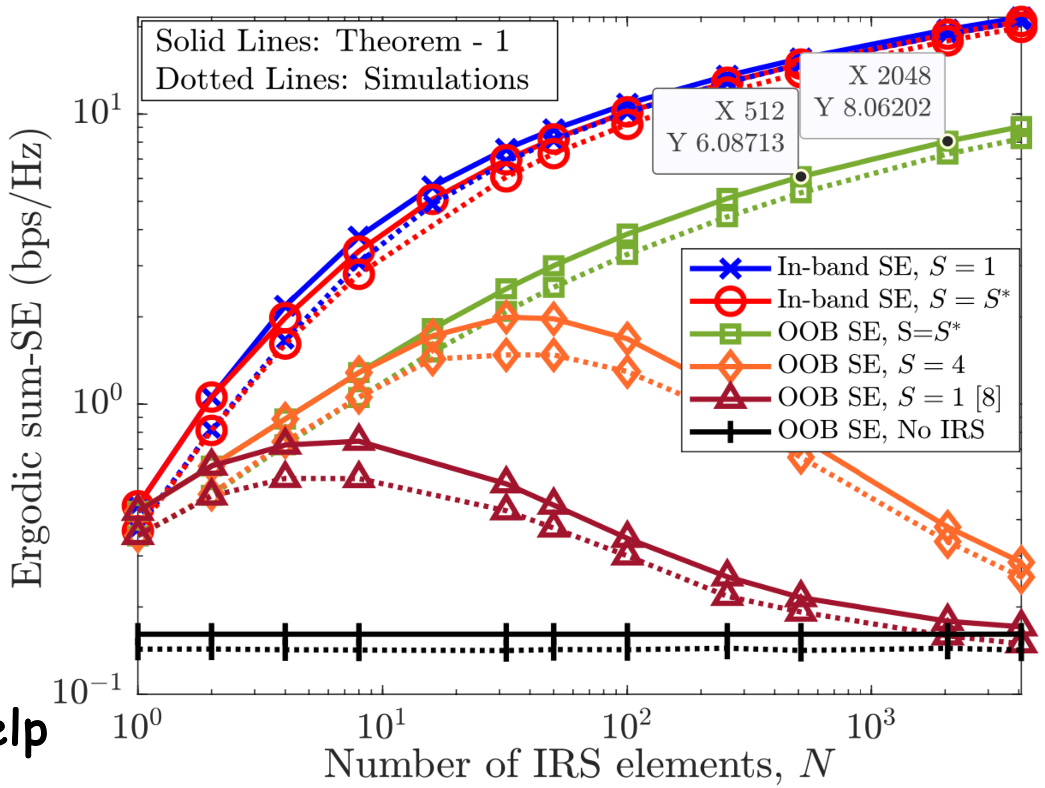


- OOB perf. is better compared to LOS
- Trade-off: more feedback @ MO-X

OOB performance with distributed IRSs



- Recall: a single IRS benefits the OOB UE with prob. $\frac{L}{N}$
  - L: # paths via the IRS; N: # IRS elements
- **Can we further boost OOB perf.? – increase # paths**
- Solution: Deploy S-distributed IRSs & $SM = N$
  - Probability of alignment increases $\frac{L}{N} \to \frac{L}{M} = S\frac{L}{N}$
- With sufficient IRSs, OOB SE scales as O(log(N))
- Distributed IRSs offer rich-scattering properties even in mmWave frequency bands! ☺

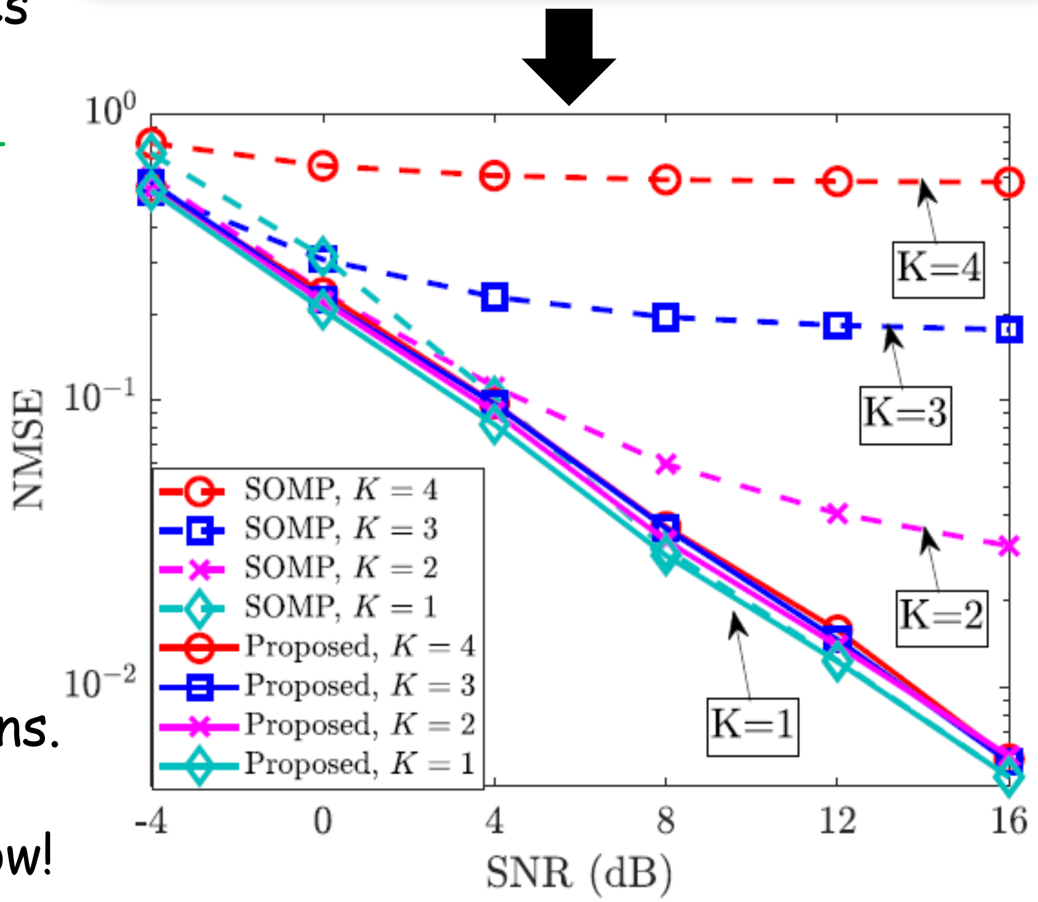


* L. Yashvanth & Chandra R. Murthy, "**Distributed IRSs Always Help Mobile Operators**," IEEE Wireless Commun. Letters, Nov. 2024

Can we reduce channel estim. overheads with dist. IRSs?

- SNR at OOB MO improves for **free** & **results are scalable!**
  - Provides more paths at OOB UEs: multiple signal copies
  - Distributed IRSs improve OOB perf. w/o affecting in-band performance
- We have also developed subspace exploiting low-complex techniques for channel estimation in distributed IRS scenarios using MUSIC and ESPRIT
  - Fixed overheads, outperforms compressed sensing solns.
  - How many pilots do we need? Answer in the paper below!

Our method is robust to # IRSs



* L. Yashvanth and Chandra R. Murthy, "**Cascaded Channel Estimation for Distributed IRS Aided mmWave Massive MIMO**," Proc. IEEE GLOBECOM, Rio de Janeiro, Brazil, December 2022

Wideband Beamforming using IRSs

System model in wideband mmWave scenarios

- **Setting:** N-element IRS in a point-point mmWave system with LoS propagation
- Baseband channel from BS to n^th IRS element with DoA ψ:

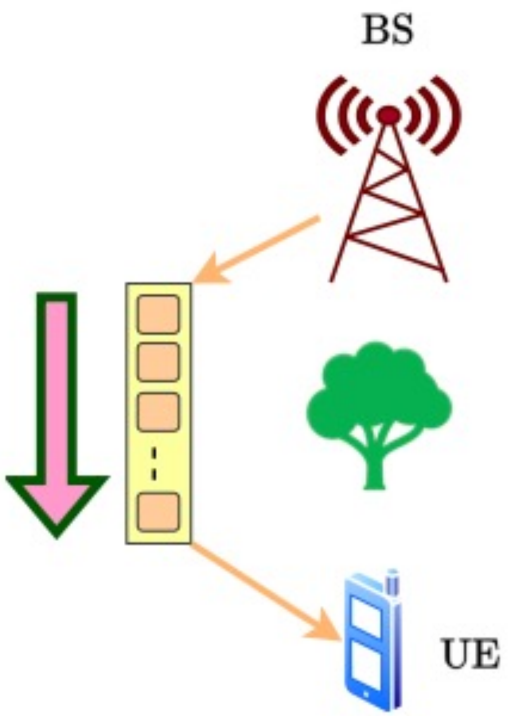
$$h_{1,n}(t) = \alpha\delta\left(t - \eta^{(1)} - (n-1)\frac{d}{c}\sin(\psi)\right) e^{-j2\pi f_c (n-1)\frac{d}{c}\sin(\psi)}$$

- Baseband channel from n^th IRS element to UE with DoD ω:

$$h_{2,n}(t) = \gamma\delta\left(t - \eta^{(2)} + (n-1)\frac{d}{c}\sin(\omega)\right) e^{-j2\pi f_c (n-1)\frac{d}{c}\sin(\omega)}$$

- Baseband channel from BS to UE with IRS configuration $\{\theta_n\}$:

$$\begin{aligned} h(t) &= \sum\nolimits_{n=1}^{N} \theta_n h_{2,n}(t) \circledast h_{1,n}(t) \\ &= \sum\nolimits_{n=1}^{N} \theta_n \alpha\gamma\delta\left(t - \eta - (n-1)\frac{d}{c}\left(\sin(\psi) - \sin(\omega)\right)\right) \times e^{-j2\pi f_c (n-1)\frac{d}{c}\sin(\phi)} \end{aligned}$$



Narrowband condition fails in large IRS scenarios

- The overall channel:

$$h(t) = \sum_{n=1}^{N} \theta_n \alpha \gamma \delta \left(t - \eta - (n-1)\frac{d}{c}\left(\sin(\psi) - \sin(\omega)\right) \right) e^{-j2\pi f_c (n-1) \frac{d}{c} \sin(\phi)}$$

- The bulk delay, η, can be compensated using a timing offset @ the receiver
- Delay spread: $\Delta\tau^{\mathrm{C}} = (N-1)\frac{d}{c}\left(\sin(\psi) - \sin(\omega)\right)$
- Narrowband condition: *Delay spread ≪ sampling time*: $\Delta\tau^{\mathrm{C}} \ll T_s = 1/W$
- **Some numbers with large IRSs**: $N = 1024, f_c = 30$ GHz, $W = 400$ MHz, $\sin(\psi) - \sin(\omega) = 1$:

  Delay spread: $\Delta\tau^{C} \approx 1.7\times10^{-8}$, sampling time: $T_s = 2.5\times10^{-9}$ **Narrowband condition fails!**

- Large arrays cause *spatial delay spread*, giving rise to the *spatial wideband effect (SWE)*

The curse of spatial wideband effect: The beam-split

- Spatial wideband effect in time domain $\Longrightarrow$ beam-split effect in frequency domain
- The frequency domain channel:

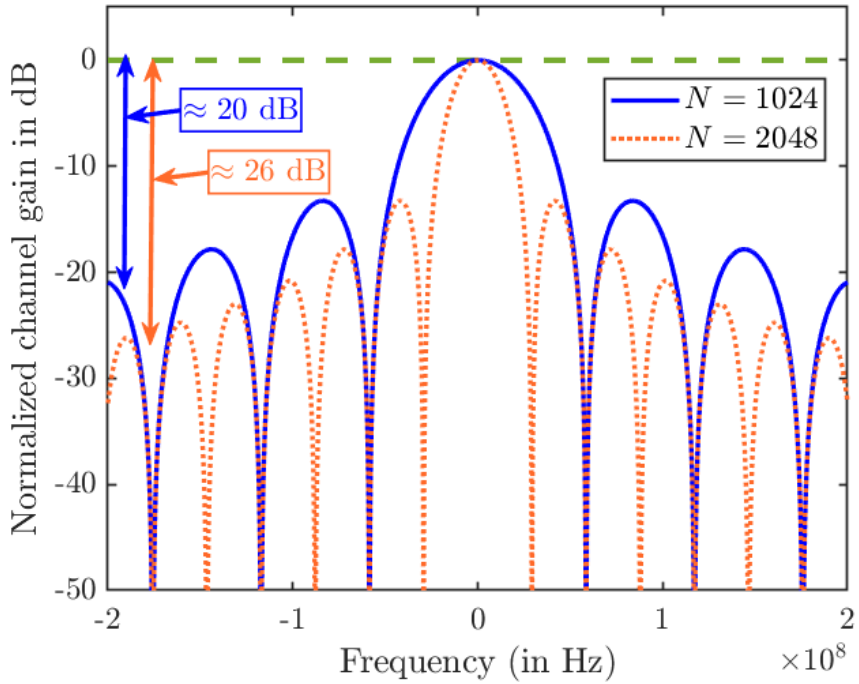
Frequency-dependent direction!

$$H(f) = \beta \sum_{n=1}^{N} \theta_n e^{-j\pi(n-1)\sin(\phi)\{1+\frac{f}{f_c}\}} = \sqrt{N}\beta\boldsymbol{\theta}^H \mathbf{a}_N\left(\sin_{(p)}^{-1}\{(1+(f/f_c))\sin(\phi)\}\right)$$

- Frequency-independent IRS phase shifters: cannot beamform to UE over full BW
- Say, IRS aligns to UE at $f=0$: $\boldsymbol{\theta} = \mathbf{a}_N(\phi)$
  - Channel response on sub-carrier k:

$$|H_C[k]|^2 = N^2|\beta|^2 \operatorname{sinc}^2\left(N\frac{f_k}{2f_c}\sin(\phi)\right)$$

    - ✓ From the previous. e.g., $N \leq 128$ to remain within HPBW
  - Array gain degrades on SCs with $f \neq 0$ – the beam split
  - Limits the allowed bandwidth or number of IRS elements

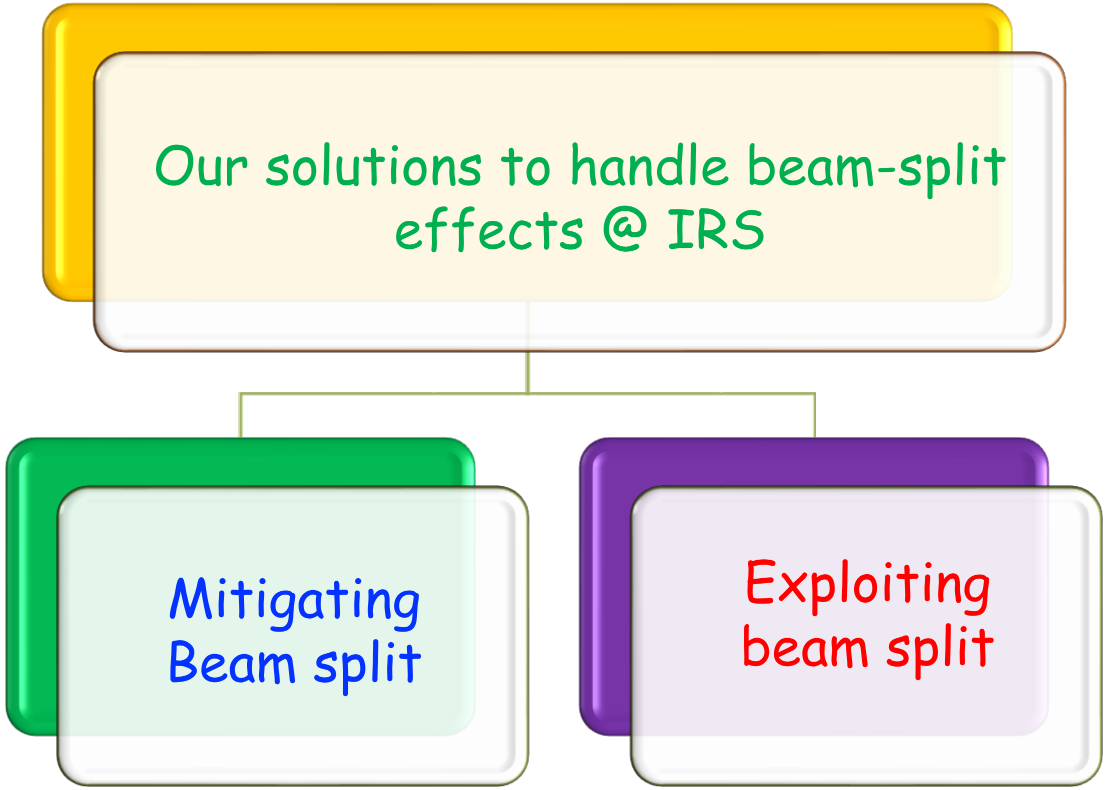


Problem: Handle beam split in wideband IRS systems

Existing approach: Use true-time delay (TTD) units instead of phase shifters

Mitigating beam split

- A given UE is scheduled on full BW
- Obtain full flat array gain at the given UE
- **Idea:** Multiple IRSs
  - Parallelizes SDS
- Angle diversity
- Spatial vs. Temporal characteristics

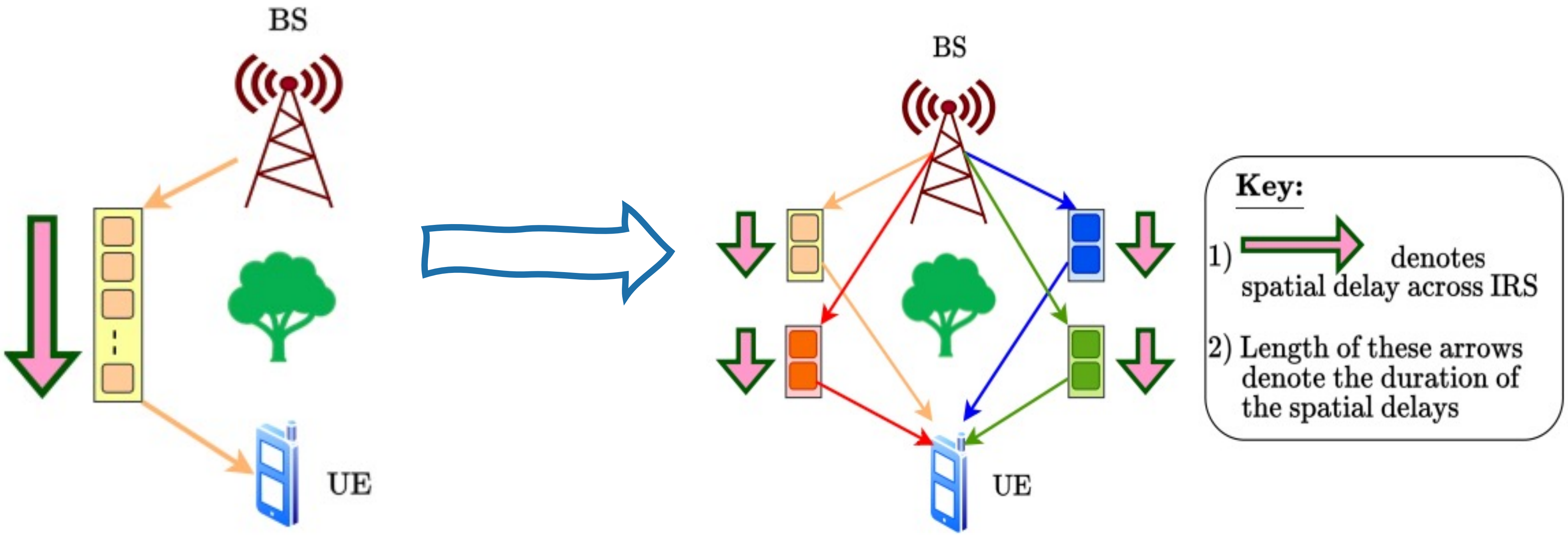


Exploiting beam split

- Multiplex UEs over BW
- Obtain full flat ch. Gain from N/W viewpoint
- **Idea:** OFDMA
  - Opportunistic Comm.
  - Diff. angles on diff. SCs for optimal gain
- Multi-user diversity

Mitigating beam-split via distributed IRSs

- **Idea**: *Parallelize* the *serial* spatial delays of centralized IRS via distributed IRSs!



- S IRSs and M elements with the same total IRS elements: $N = SM$
- New delay spread: $\Delta\tau^{\mathrm{D}} = \max_{s}\left\{(M-1)\frac{d}{c}(\sin(\psi_s) - \sin(\omega_s))\right\} \approx \frac{\Delta\tau^{\mathrm{C}}}{S}$
- The reduction in SWE also reduces the beam-split effect at the UEs

* "Distributed IRSs Mitigate Spatial Wideband & Beam-Split Effects," Under review at IEEE ICASSP, 2025

How many elements per IRS?

- The number of elements @ IRS depends on the tolerable beam split (or beam squint)
- Channel on the k^{th} sub-carrier:

$$H[k] = \sum_{s=1}^{S} \sqrt{M} \beta_s \boldsymbol{\theta}_s^H \mathbf{a}_M \left(\sin_{(p)}^{-1} \left\{ \left(1 + \frac{f_k}{f_c}\right) \sin(\phi_s) \right\} \right)$$

- Condition for ϵ-within beam squint:

$$|H[0]|^2 = |H[K]|^2 \geq (1-\epsilon)^2 |H[K/2]|^2$$

Theorem 1: The maximum M for which the channel gain at every IRS is at least $((1-\epsilon)N)^2$ on every sub-carrier is given by

$$M^* \triangleq \min\left\{ \max\left\{ \left\lfloor \frac{4\sqrt{6\epsilon}}{\pi} \frac{f_c}{W} \right\rfloor, 1 \right\}, N \right\}$$

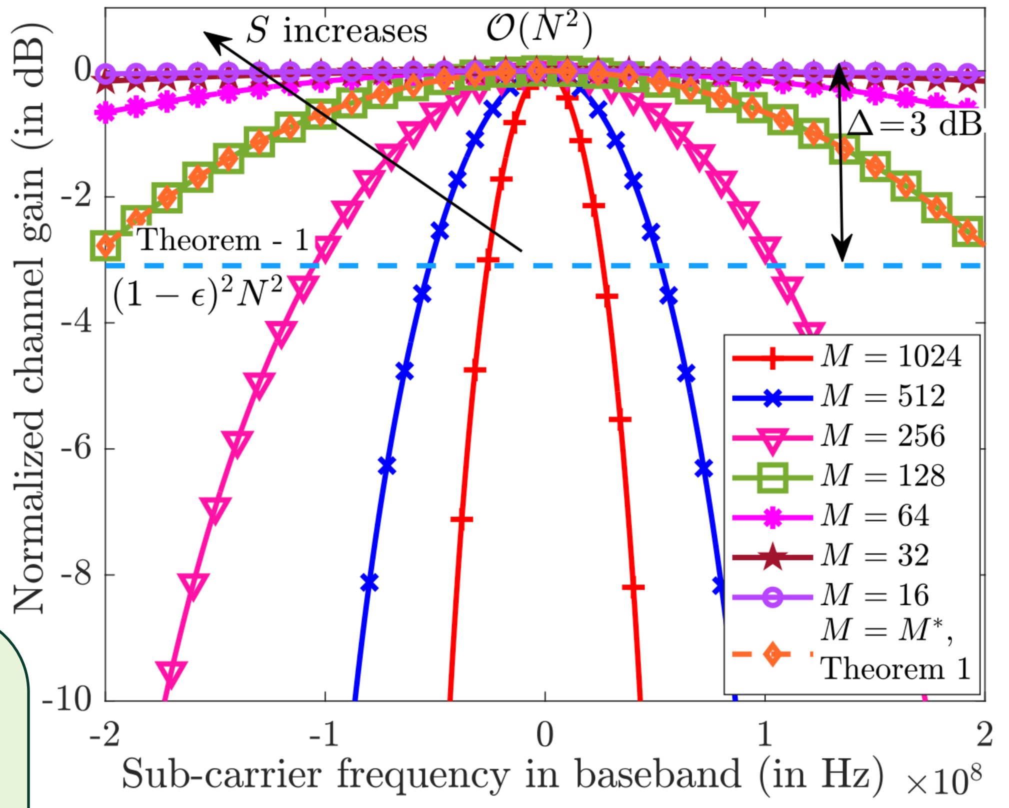


Fig: Theorem – 1 is marked for beam-squint within the HPBW

Setting: N = 1024, $M^* = 128$

Spatial vs. temporal characteristics of dist. IRSs

- Multiple IRSs can introduce temporal delay spread (TDS) via multiple paths!
- Our solution demonstrates the interplay between spatial & temporal characteristics

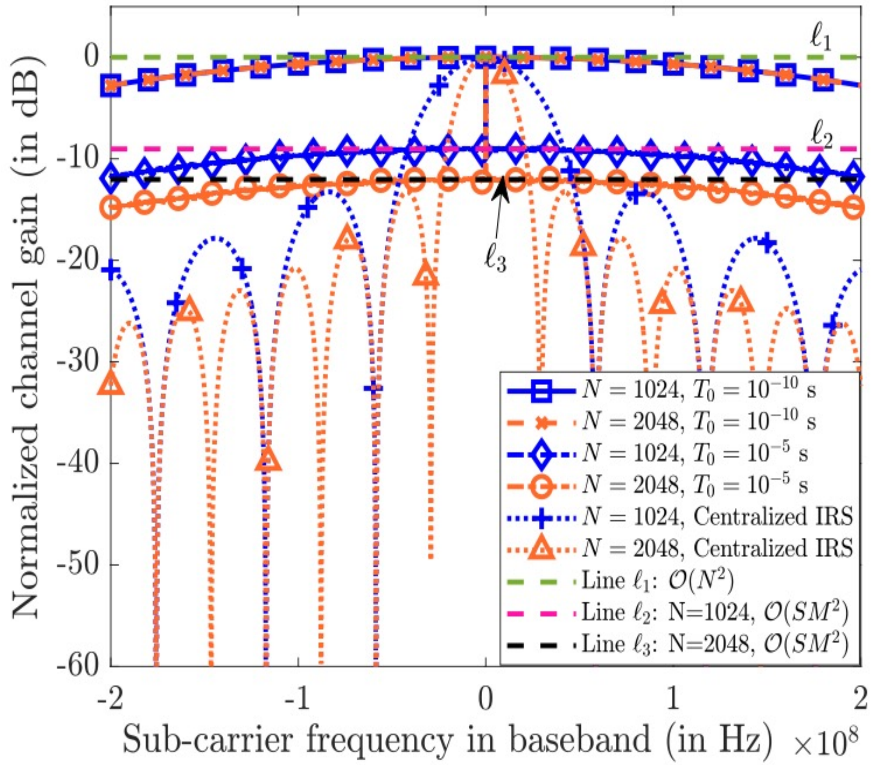
Theorem 2: The ergodic SEs of centralized vs. distributed IRS mmWave systems with K SCs:

$$\bar{R}_{\mathrm{C}} \approx \frac{1}{K+N_{\mathrm{CP}}^{\mathrm{C}}} \sum_{k=1}^{K} \log_2\left(1+\frac{p_k \sigma_{\mathrm{h}}^2}{\sigma^2} N^2 \operatorname{sinc}^2\left(N \frac{f_k}{2 f_c} \sin(\phi)\right)\right)$$

and

$$\bar{R}_{\mathrm{D}} \geq \mathrm{R}_{\min} \triangleq \frac{1}{K+N_{\mathrm{CP}}^{\mathrm{D}}} \sum_{k=1}^{K} \log_2\left(1+\frac{p_k \sigma_{\mathrm{h}}^2}{\sigma^2} M^2 (1-\epsilon)^2 \times \left[S^2 \operatorname{sinc}^2(f_k T_0) + S\left(1-\operatorname{sinc}^2(f_k T_0)\right)\right]\right)$$

$$\geq \mathrm{R}_{\min}^{\text{L-bound}} \triangleq \frac{1}{K+N_{\mathrm{CP}}^{\mathrm{D}}} \sum_{k=1}^{K} \log_2\left(1+\frac{p_k \sigma_{\mathrm{h}}^2}{\sigma^2} S M^2 (1-\epsilon)^2\right)$$



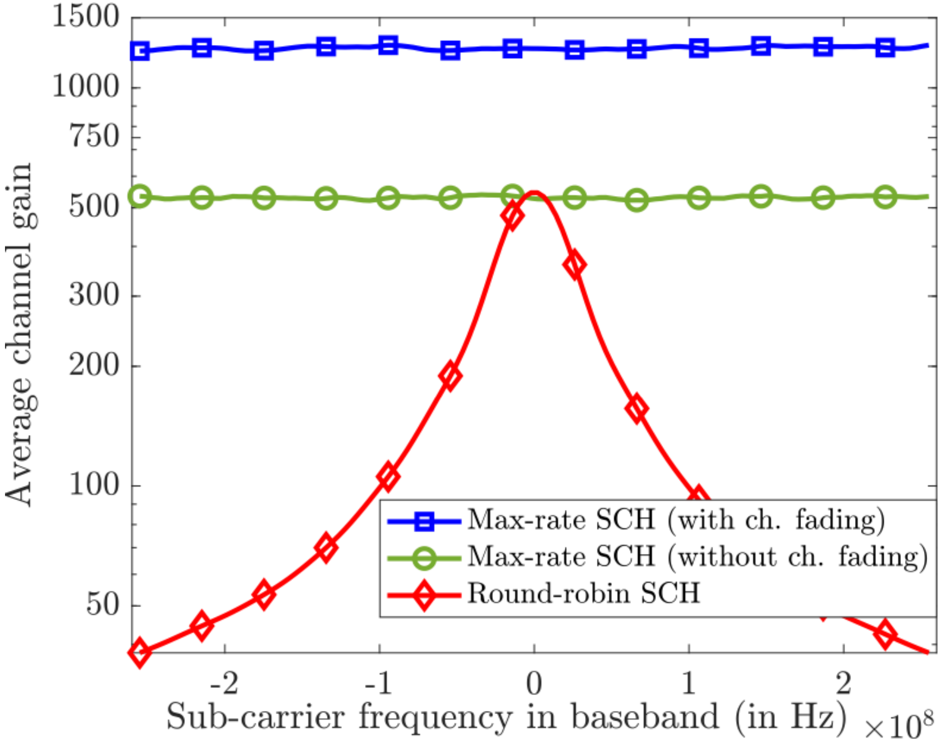
- Distributed IRSs mitigate B-SP effects even with large TDS with no deep channel nulls!

Exploiting beam-split effects via OFDMA

- **Idea**: IRS forms different angles over BW – opportunistic OFDMA of UEs
- Channel model aware randomized IRS phase sampling + Max-rate schedulers
- **Premise:** With large UEs, on every SC, at least one UE will be near-optimal
- The success probability of the scheme with M IRS elements, K UEs, and N subcarriers:

Theorem 1. *Let $\mathcal{A}_{k,n}^{\epsilon}$ denote the event that the array gain on SC-n at UE-k is at least $(1-\epsilon)M^2$ at some time t. Then, using a max-rate scheduler with randomized IRS configurations sampled as per* (14),

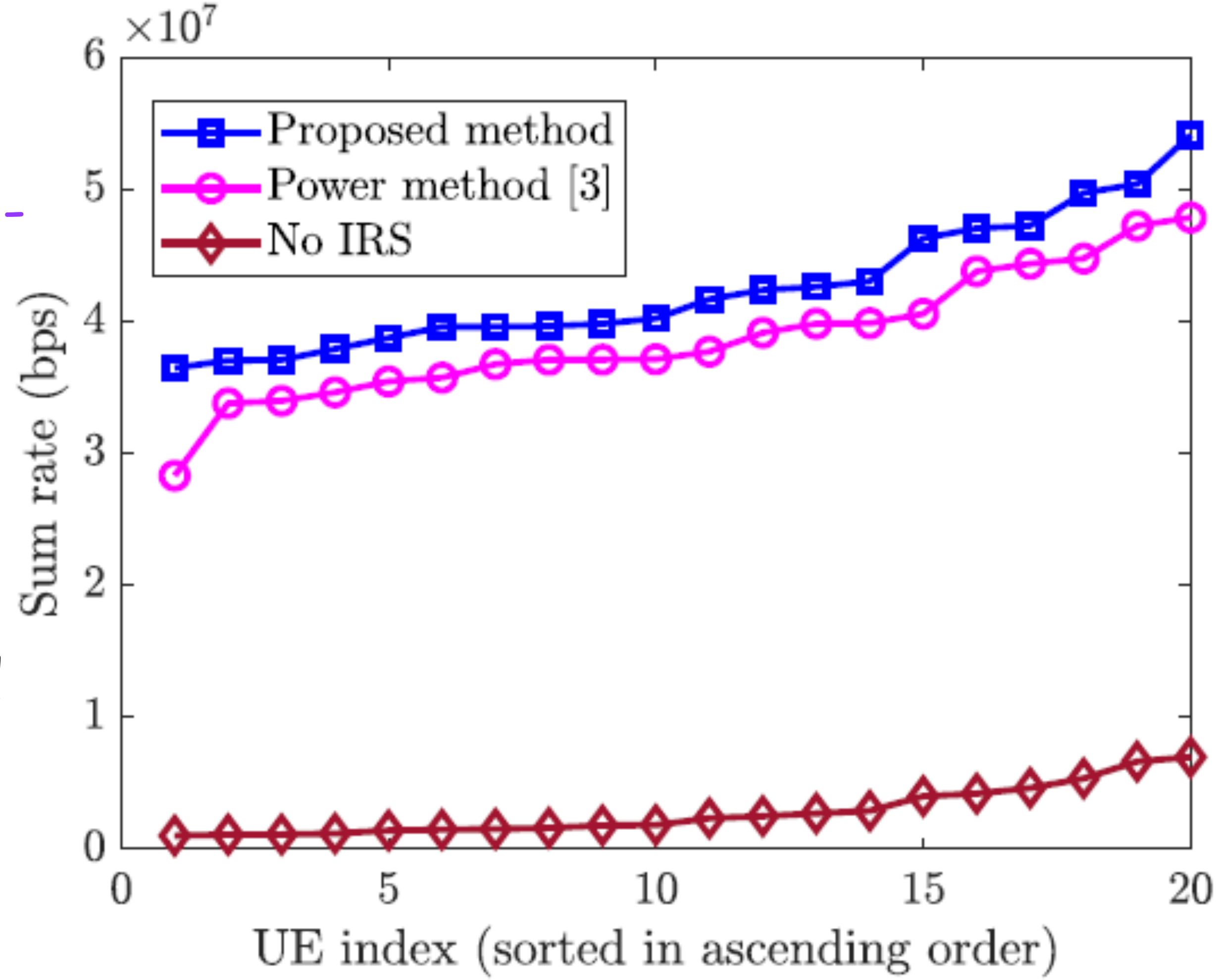
$$P_{succ}^{\epsilon} \triangleq \Pr\left(\bigcap_{n=1}^{N}\bigcup_{k=1}^{K}\mathcal{A}_{k,n}^{\epsilon}\right) \geq 1 - N\left(1 - \frac{\sqrt{3\epsilon}}{\pi M\left(1+\frac{W}{2f_c}\right)}\right)^{K}. \quad (15)$$



* "Exploiting Beam-Split in IRS-aided Systems via OFDMA", Under review at IEEE ICASSP, 2025

Wideband beamforming in Sub-6 GHz bands

- Beam-split is not prominent in sub-6 GHz frequency bands
- Frequency selectivity is caused due to multi-path effects at the UE
- Idea: Jointly optimal IRS phases to maximize the OFDM sum rate!
- Existing soln.: optimizes the Jensen's bound
- We directly optimize the sum rate via majorization-minimization, which has provable convergence guarantees



* L. Yashvanth, Chandra R. Murthy and D. Battu, "**Binary IRS Assisted OFDM Systems**," IEEE SPCOM, Jul. '22

Related unsolved problems (to my best knowledge)

- Opportunistic Communications with UE mobility:
  - Updating IRS sampling distribution using Bayesian approaches?
- Feedback overhead reduction exploiting the low-dimensional characteristics
- Channel estimation in IRS-aided multiple operator systems
- Beam-split aware opportunistic OFDMA with guaranteed QoS requirements
- Pre-distortion techniques to mitigate the B-SP effects
- Many more…

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