FlowForm: Scalable Passive Metasurface Network for mmWave Coverage Expansion

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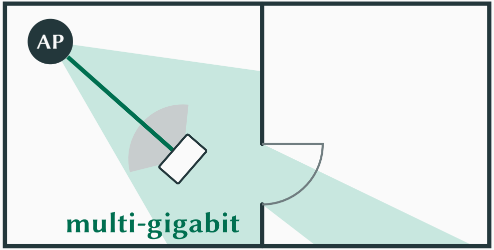
University of California San Diego

Spotty Coverage in mmWave Networks

- 60 GHz Wi-Fi gives **multi-gigabit** links.



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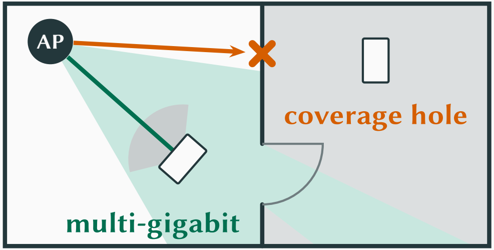

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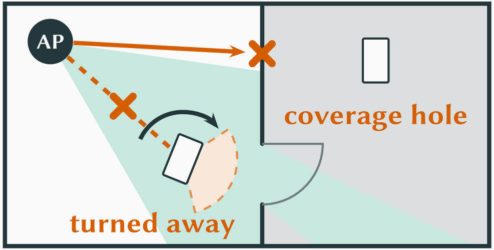

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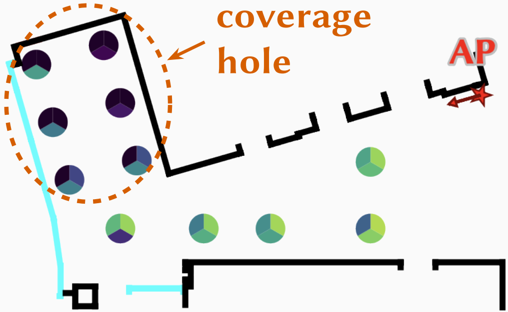
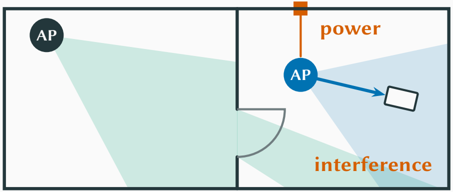


Measured RSS, one office floor (dark = weak).
Each point shows 3 device orientations.

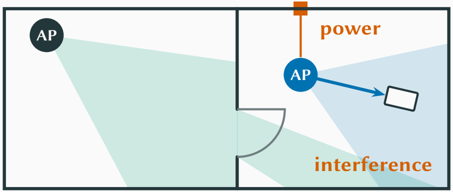
Coverage Expansion Alternatives



More APs

power + **backhaul**, **interference**

Coverage Expansion Alternatives



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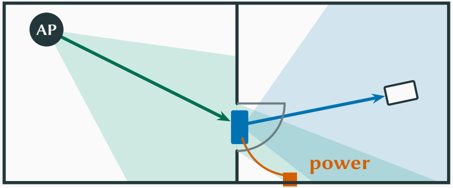

Active relays
power + **coordination** per hop

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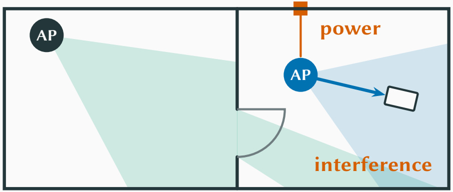

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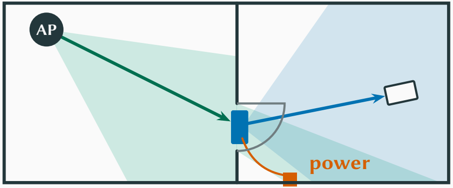

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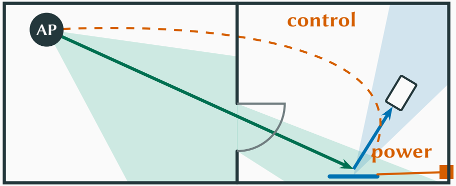

Active RIS
power, **control**, **CSI** — **$6k+**

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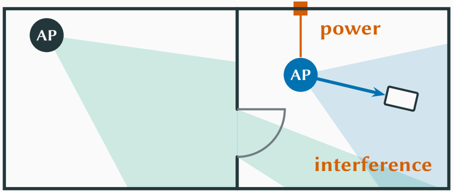

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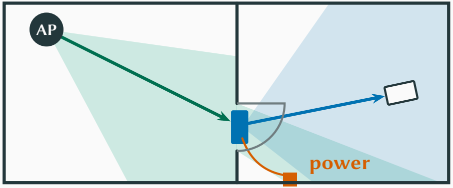

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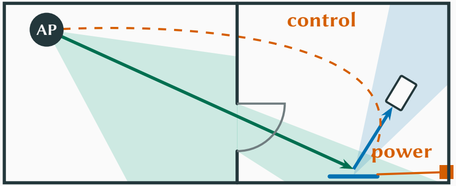

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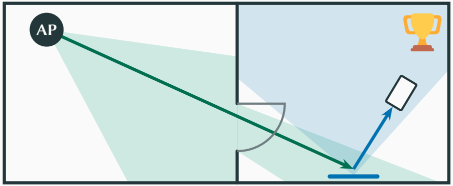
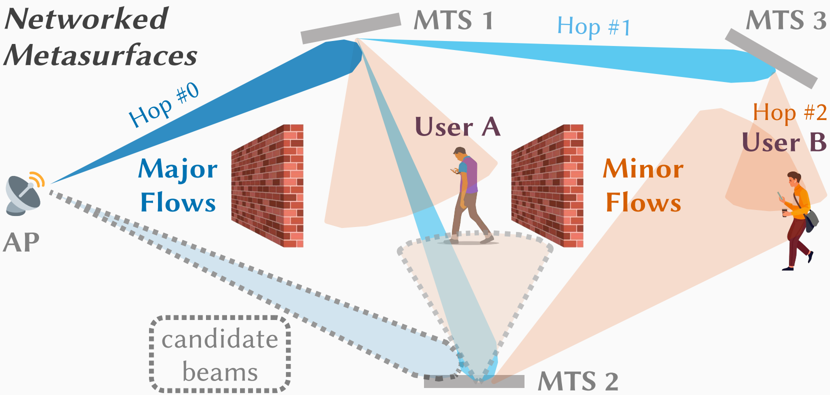


Passive metasurfaces

transparent operation — **$2**

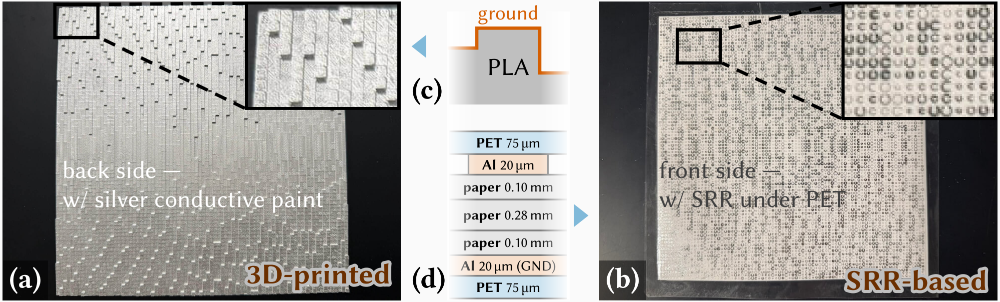
FlowForm: A Coordinated Passive Metasurface Network



Signals **hop** across surfaces, then **fan out** to users, combined over the air in the analog domain — with **no power, control channel, or runtime coordination**.

Fabrication of Passive Metasurface: \$2 or Less per Surface

Two low-cost fabrication processes: a 3D-printed dielectric with a conductive painted ground (**\$2**), or hot-stamped aluminium foil on paper (**\$0.5**).



20 cm × 20 cm, 80 × 80 **half-wavelength** unit cells.

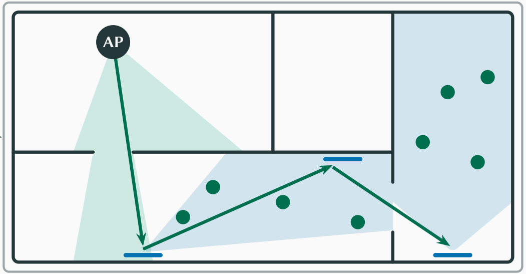
System Overview: Offline Optimization, Transparent Runtime

Input
floor plan, coverage targets, budget

Site-specific ray tracing
differentiable channel model

Major–minor topology
+ annealed passive routing

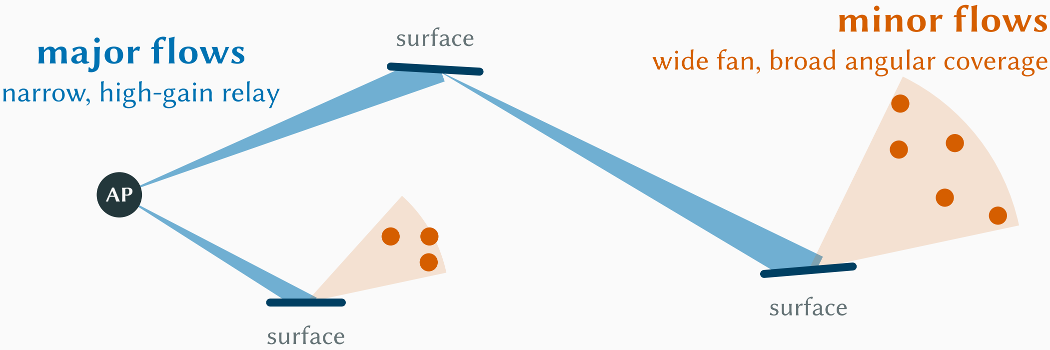
offline, once per site



Output: placement + beam patterns

All of it runs **once per site, offline**. At runtime the surfaces are ordinary reflectors — **no protocol change, no coordination**.

Major–Minor Flow Topology



Optimal solutions **naturally exhibit** the **major–minor** flow topology — it emerges from passive relaying and power splitting. *Proof in the paper.*

Major-Flow Near-Field Focusing

Major flows must reach far, yet passive surfaces never amplify — they only *redistribute* incident energy.

Loss adds instead of multiplying

With large enough surfaces,

$$(d_1 d_2 \cdots d_K)^2 \;\longrightarrow\; (d_1 + d_2 + \cdots + d_K)^2.$$

Mimics a **continuous LoS path**, plus **focusing gain** at every hop.

Scaling Passive Metasurface Network Deployment Optimization

Joint placement and configuration is a mixed discrete–continuous problem of exponential complexity.

1 Major–minor topology

Decouples relay from coverage: two tractable stages, not one joint search.

2 Beam pattern abstraction

Parametric beam arms replace 6400 element phases: 8–16 parameters.

3 Annealed passive routing

Routing weights specialize surfaces, then let them cooperate.

Complexity goes from **exponential to roughly linear** in the number of surfaces.

Handling Mobility and Multiple Users

FlowForm engineers **several strong paths** to every location, and the AP's standard sector sweep picks among them.

🚶 Mobility

Standard beam scanning switches to the next path.

👥 Multiple users

More paths unlock more spatial sharing.

FlowForm is ***transparent*** to mmWave nodes — **no protocol change, no control channel, no feedback**.

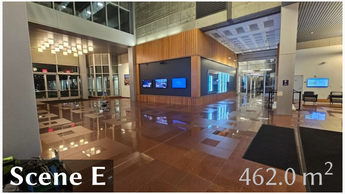
Deployment Across 5 Indoor Environments

Scene A 68.6 m^2

Scene B 133.0 m^2

Scene C 324.6 m^2

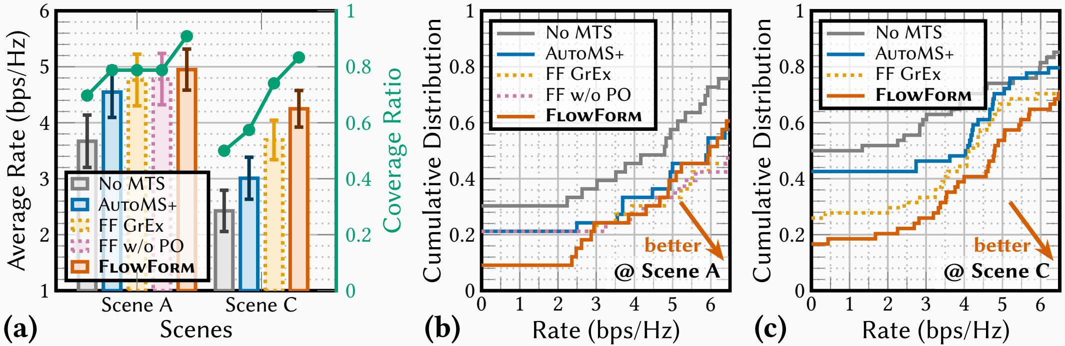
Scene D 382.9 m^2



Scene E 462.0 m^2

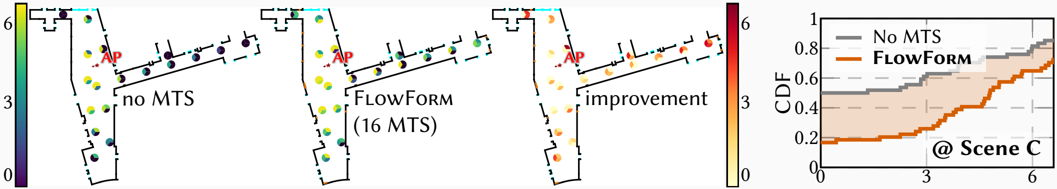
Hallways, and large corridors: 69 m^2 to 462 m^2.

Coverage Expansion vs. Baselines



- 16 surfaces (5 major + 11 minor): **+75% rate**, **+67% coverage**;
- **+41%** over AutoMS+, while being much more scalable;
- Largest gains at originally poorly covered locations, lifting the **lower tail** of the rate distribution.

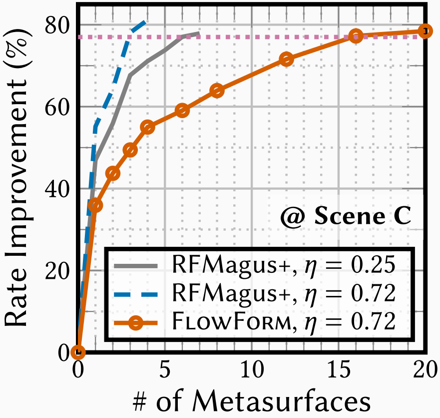
Measured Coverage Expansion



Measured physical rate at every user location in scene C with 16 surfaces — gains concentrate at the originally weak locations, shifting the rate distribution right across the floor.

See the paper for the other four scenes.

Comparison With Active RIS: ~200× Lower Cost



RFMagus+ is an *optimistic* RIS bound.

Passive surfaces avoid the high **insertion loss** that active RIS suffer in mmWave.

Only 2.7× more surfaces

16 passive surfaces match 6 active RIS at realistic 60 GHz efficiency.

~200× lower cost

- **$32** versus **$6k+**
- Without power, wiring, and control

Conclusion

1. **Passive surfaces can form a network** — **major** backbone, **minor** coverage, a structure that emerges from the physics.
2. **Scalable optimization** — beam abstraction and hierarchical design reduce complexity from exponential to roughly linear.
3. **Transparent operation** — unmodified 802.11ad/ay radios benefit without any protocol change.
4. **Validated in real deployments** — 5 environments, up to +94% rate and +114% coverage, at $2 a surface.

FlowForm project page
`https://flowform.wqzhao.org`

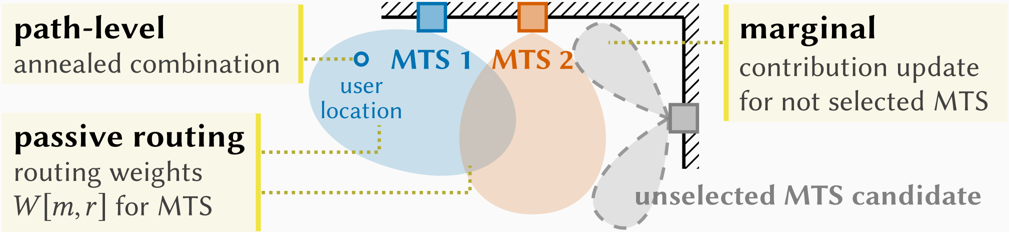
Thank you!

https://flowform.wqzhao.org

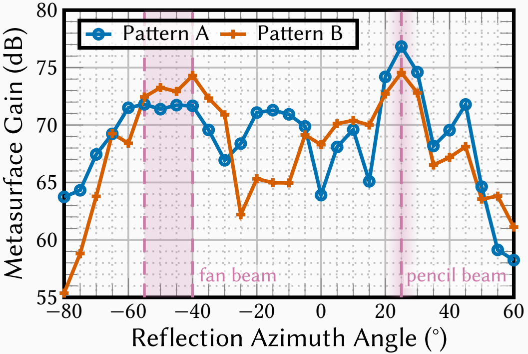
Backup: Annealed Passive Routing

Major flows are planned first; **APRO** then completes coverage.

- **Routing weights**: specialize surfaces by region;
- **Annealing**: a few strong paths per location, for robustness;
- **Marginal contribution**: the budget goes where coverage is missing.



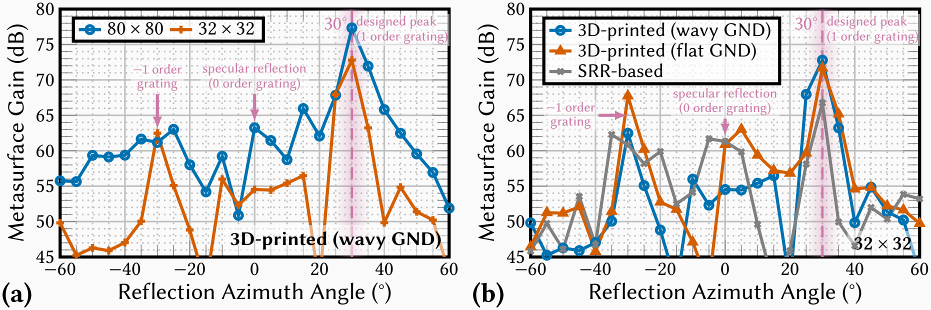
Backup: The Beam-Arm Abstraction Is Realizable



A fabricated 2-arm surface: one pencil beam for the major flow, one fan beam for the minor flow.

Pattern A puts 70% of the power in the fan, Pattern B 70% in the pencil; the measured patterns preserve the designed split.

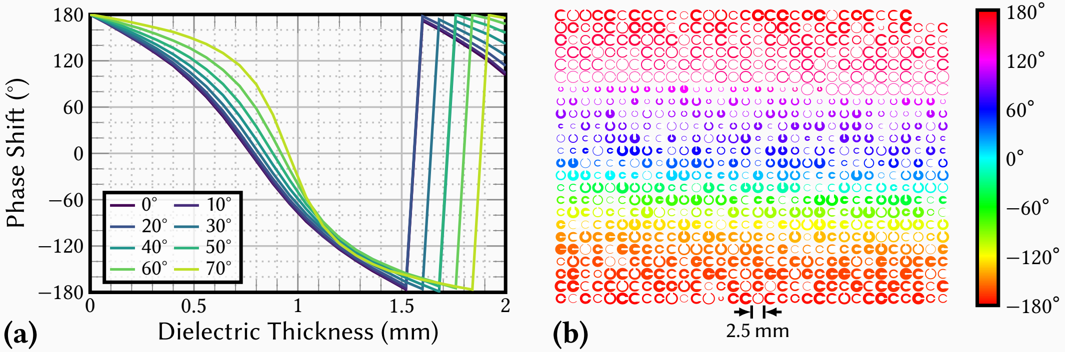
Backup: Measured Beam Patterns



Designed 30° steering. (a) Different sizes. (b) 3D-printed vs. SRR-based.

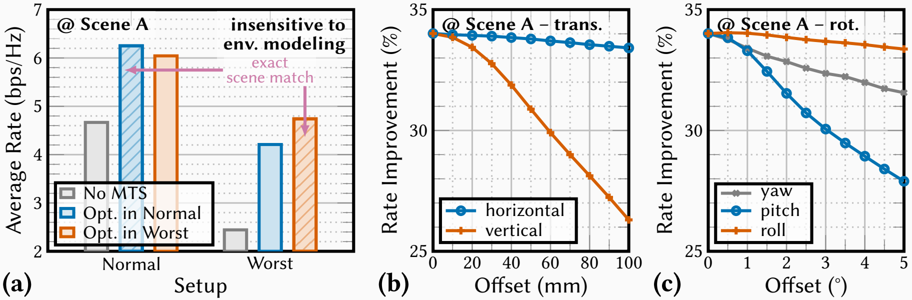
80×80 gains $\sim$5 dB over 32×32; steering error $< 3°$; $\sim$70 % of reflected power in the main lobe.

Backup: Unit-Cell Phase Profiles



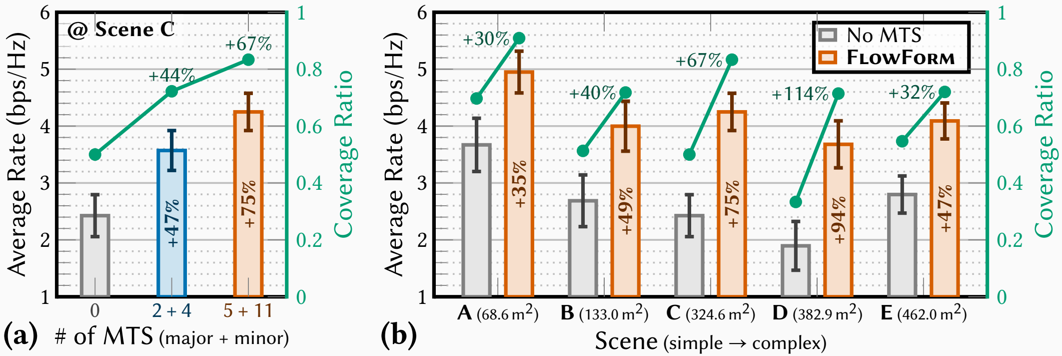
HFSS-simulated unit cells. (a) 3D-printed (wavy ground). (b) SRR-based.

Backup: Sensitivity to Modeling and Placement Errors



- Worst-case environment model (everything an absorber): only ~11 % degradation;
- ±10 cm horizontal offset costs < 1%; pitch is the sensitive axis;
- Wall construction tolerance is 0.5° — manual mounting is fine.

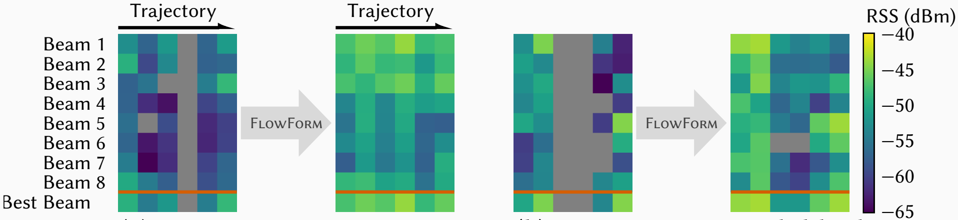
Backup: Scaling With Surface Count and Scene Complexity



- 6 surfaces (2 major + 4 minor) already yield +47% average rate;
- Up to **+94% average rate and +114% coverage expansion** (scene D), where multi-hop relaying shortens the effective propagation distance.

Backup: Robustness to Receiver Mobility and Orientation

Expanded coverage sustains **multiple strong beams** — as the user moves or rotates, the AP's existing beam scanning simply re-selects among them.



(a) User trajectory. **(b) User rotation with blockage.**

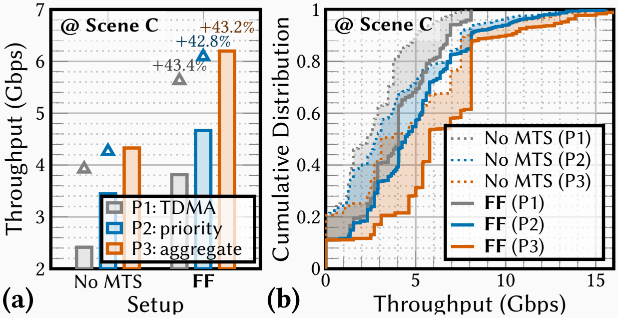
- RSS variation along a user trajectory: ~20 dB → ~5 dB;
- Beam scanning interval 100 ms → 250–300 ms — **reducing 60% of the beam scanning overhead**.

Backup: Multi-User Interference and Spatial Sharing

FlowForm follows the standard *spatial sharing* mechanism, with **more paths** to choose from — so links that would otherwise interfere can be routed apart and run concurrently.

Additional paths could introduce interference; the interference-aware design (SINR instead of SNR) prevents it — the **~43% spatial-sharing gain is preserved**.

Backup: Spatial Sharing Throughput

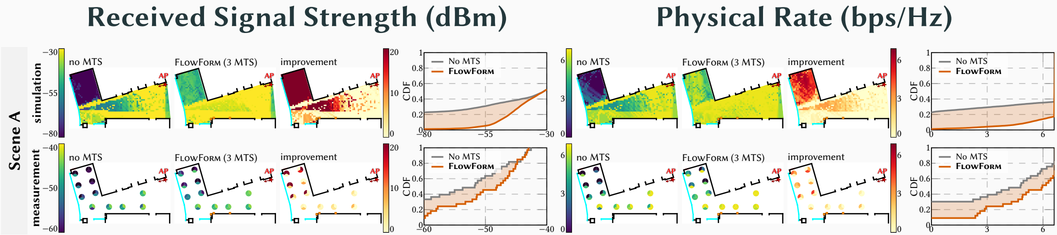


Two concurrent AP–receiver pairs in scene C, under three scheduling policies:

- **P1**: TDMA, no spatial sharing;
- **P2**: sharing, one AP prioritized;
- **P3**: maximum aggregate throughput.

P2 and P3 gain ~43 % over P1, both before and after deployment.

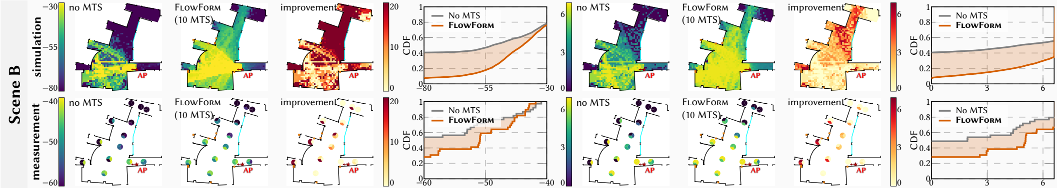
Backup: Coverage Expansion — Scene A



Small hallway, minimal obstacles, 68.6 m^2, 3 metasurfaces. Upper row simulation, lower row measurement; each shows no MTS, FlowForm, and the improvement.

Backup: Coverage Expansion — Scene B

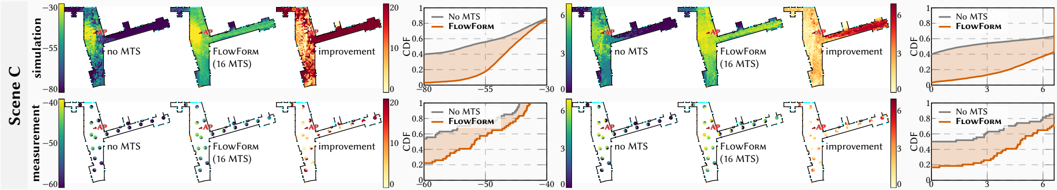
Received Signal Strength (dBm) **Physical Rate (bps/Hz)**



Office floor with furniture and partitions, 133.0 m^2, 10 metasurfaces. Upper row simulation, lower row measurement; each shows no MTS, FlowForm, and the improvement.

Backup: Coverage Expansion — Scene C

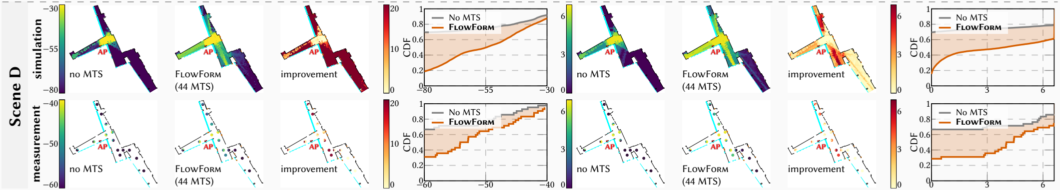
Received Signal Strength (dBm)   Physical Rate (bps/Hz)



Office floor with furniture and partitions, 324.6 m^2, 16 metasurfaces. Upper row simulation, lower row measurement; each shows no MTS, FlowForm, and the improvement.

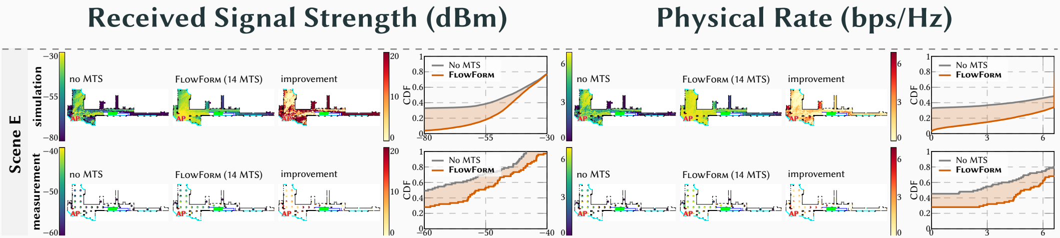
Backup: Coverage Expansion — Scene D

Received Signal Strength (dBm)   Physical Rate (bps/Hz)



Large corridor, severe blockage from columns, 382.9 m^2, 44 metasurfaces. Upper row simulation, lower row measurement; each shows no MTS, FlowForm, and the improvement.

Backup: Coverage Expansion — Scene E



Large corridor, severe blockage from walls, 462.0 m^2, 14 metasurfaces. Upper row simulation, lower row measurement; each shows no MTS, FlowForm, and the improvement.