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Sustainable Urban HAP Communications Through Geometry-Aware Fluid Antennas

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ABSTRACT

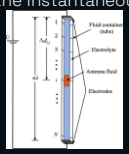
- **Problem:** Urban HAP links combine probabilistic LoS with sparse directional reflections, while conventional FAS analysis commonly assumes isotropic spatial correlation.
- **Approach:** We derive the FAS channel and covariance directly from HAP–user–building geometry.
- **Finding:** Geometry changes the usable spatial diversity, outage behavior, and the number of ports worth deploying.

MOTIVATION: WHY FAS FOR URBAN HAP LINKS?

- **HAPs:** provide wide-area connectivity from the stratosphere, but urban blockage can suppress the dominant LoS path and sharply degrade link reliability.
- **FAS:** creates spatial adaptability within a compact aperture by selecting a favorable receive position according to the instantaneous channel.

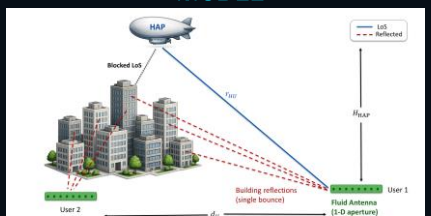
FAS selects favorable port according to:

$$n^* = \arg\max_{1\le n\le N} |h_n|^2$$



- **HAP + FAS:** turns this adaptability into a blockage-resilience mechanism, exploiting favorable spatial locations when a fixed antenna is most vulnerable.

URBAN HAP–FAS SYSTEM MODEL



LoS-available and LoS-blocked HAP–FAS propagation

The received field combines a probabilistically visible direct HAP path with reflections from visible building facades. Buildings are modeled stochastically through their locations, dimensions, heights, and orientations.

PHYSICAL PROPAGATION INSIGHT

- **LoS visible:** the deterministic component dominates; port powers are strongly correlated and selection gain is limited.
- **LoS blocked:** the reflected field governs the link; spatial variations become more consequential for port selection.
- **Implication:** FAS gain is limited under dominant LoS and becomes more significant under blockage, when reflections create stronger spatial variations across the aperture.

GEOMETRY-AWARE SPATIAL CHANNEL MODEL

LoS component: The direct component is determined by HAP–user geometry.

$$\mathbf{h}_{\mathrm{L}} = \frac{\sqrt{C_{\mathrm{L}}}}{r_{\mathrm{HU}}} e^{-jkr_{\mathrm{HU}}} \mathbf{a}_{\mathrm{L}}.$$

NLoS component: The reflected component is the superposition of visible facade contributions with geometry-dependent power, phase, and arrival direction.

$$\mathbf{h}_{\mathrm{R}} = \sum_{i\in\Phi_{\mathrm{R}}} \sqrt{P_{\mathrm{R},i}}\, e^{-jk(r_{\mathrm{HR},i}+r_{\mathrm{RU},i})}$$

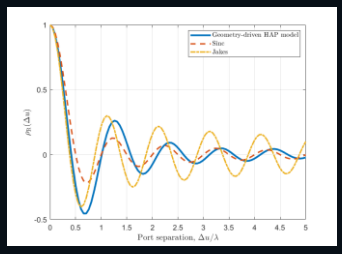
Full channel:

$$\mathbf{h} = I_{\mathrm{L}}\mathbf{h}_{\mathrm{L}} + \mathbf{h}_{\mathrm{R}}, \quad I_{\mathrm{L}} \sim \mathrm{Bernoulli}(p_{\mathrm{L}})$$

- Buildings follow a Poisson Boolean process
- Reflection follow the Lambertian scattering model

Unlike sinc/Jakes benchmarks, correlation is not imposed a priori: it emerges from the physical propagation environment.

SPATIAL CORRELATION: WHY GEOMETRY MATTERS



- **Zero crossings:** The geometry-derived correlation exhibits different zero crossings
- **Lobe structure:** The correlation magnitude and lobe locations differ.

Conventional isotropic models can therefore misrepresent the diversity available within a finite FAS aperture since they do not reproduce the geometry-driven correlation structure and assume isotropic scattering.

DESIGN CONSEQUENCE

CONVENTIONAL MODELS

Fixed sinc/Jakes correlation can overestimate useful spatial diversity, suggesting gains from ports that the actual HAP–urban channel does not support.

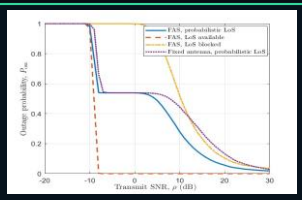
GEOMETRY-AWARE MODEL

The proposed model reveals the diversity actually available across the aperture from the underlying propagation geometry.

FAS DIMENSIONING

This identifies the number and spacing of ports needed to capture that diversity; avoiding unnecessary oversampling and hardware complexity.

NUMERICAL RESULTS



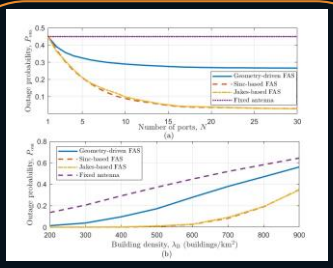
FAS REDUCES THE SNR NEEDED FOR RELIABILITY

FAS consistently outperforms a fixed antenna by selecting the strongest instantaneous port.

$$P_{\mathrm{out}} = p_{\mathrm{L}}P_{\mathrm{out|L}} + (1-p_{\mathrm{L}})P_{\mathrm{out|B}}.$$

The outage reflects the occurrence of two propagation states: lower outage when the dominant LoS component is available and higher outage when blockage leaves only the reflected field.

FAS is most beneficial under blockage, where reflected-field spatial variations provide greater selection gain.



MORE PORTS ≠ MORE USEFUL DIVERSITY

Outage initially decreases strongly with N, then saturates once the diversity supported within the apertude is captured.

Sinc/Jakes saturate at larger N and can therefore over-dimension the FAS.

URBAN DENSITY EXPOSES THE MODELING MISMATCH

Increasing building density raises outage as blockage increases and viable reflected paths change; FAS retains an advantage over a fixed antenna.

Sinc/Jakes underpredict outage by attributing excessive diversity to the reflected field.

SUSTAINABILITY IMPLICATIONS

- **Lower energy demand:** port selection reduces the transmit SNR required to meet a target reliability.
- **Right-sized hardware:** geometry-aware diversity avoids ports that add negligible reliability gain.
- **Lower overhead:** fewer unnecessary ports can reduce probing, switching, control, and processing requirements.

KEY RESULT: Geometry-aware correlation enables propagation-matched FAS dimensioning instead of over-dimensioning based on conventional sinc/Jakes assumptions.

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