Eliminating Channel Feedback in Next-Generation Cellular Networks

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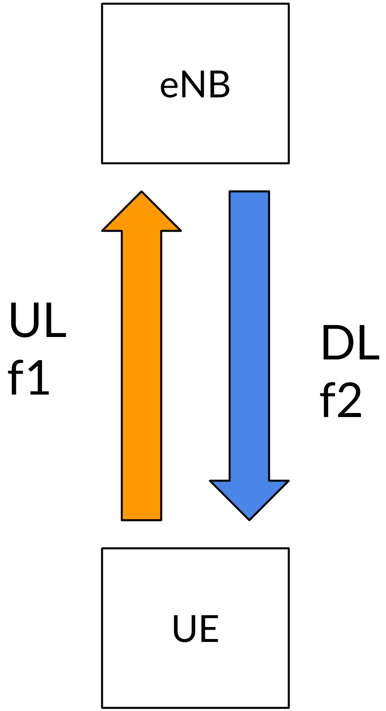
Background

Channel feedback is essential for applications like MIMO beamforming, nulling, etc.

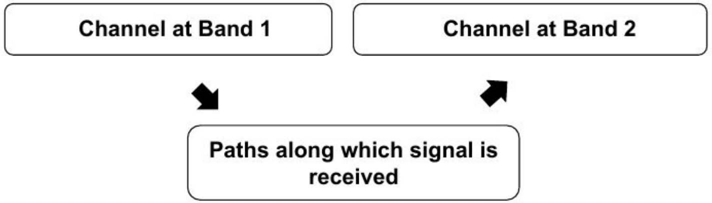
However, the feedback overhead is excessive: "*about 4.6 Mb/s of signaling per user in a 20 MHz 4×2 network*"

This paper focuses on a simple, yet fundamental question: "Can a node infer the wireless channels on one frequency band by observing the channels on a different frequency band?"

Contributions



A model that given f1 signals and its channel, outputs channel at f2.



Actualize and evaluate on real system.

Relevant Works

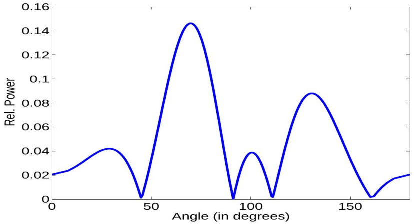
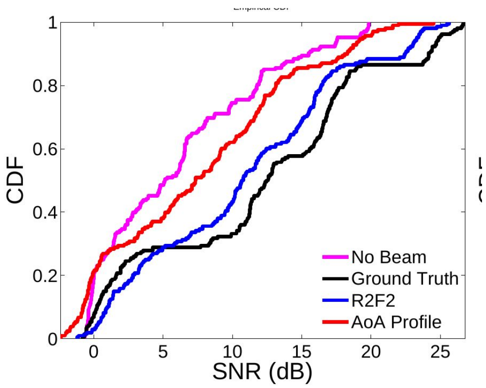


Figure 2: **Power Profile:** The power profile represents the relative power of the signal coming along different spatial directions.



Previous works on FDD channel estimation:

- Based on long-term stats, not suitable for fast variation
- Based on AoA, frequency dependent
- Does not account for hardware artifacts (real system)

Other systems like WiFi:

- Estimate one channel from other coarsely (i.e., just amplitude response)

R2F2 Model (background)

An abstract path:

d: path length; λ: wavelength;
Φ: constant phase shift

$$h = ae^{-j2\pi\frac{d}{\lambda}+j\phi} \quad (1)$$

Multi abstract path:

$$h = \sum_{n}^{N} a_n e^{-j2\pi\frac{d_n}{\lambda}+j\phi_n}, \quad (2)$$

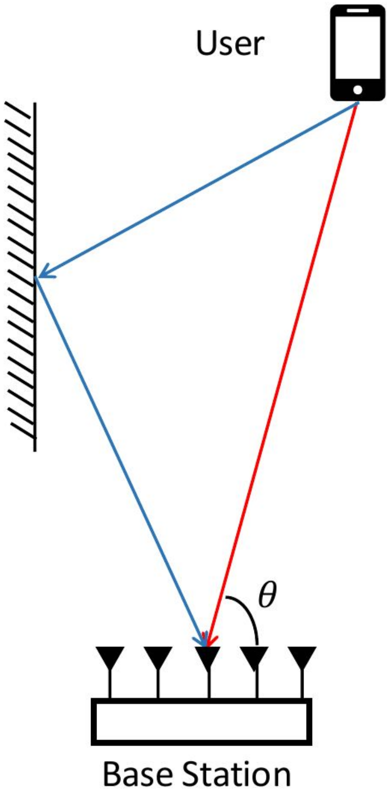
Multi path received by an antenna:

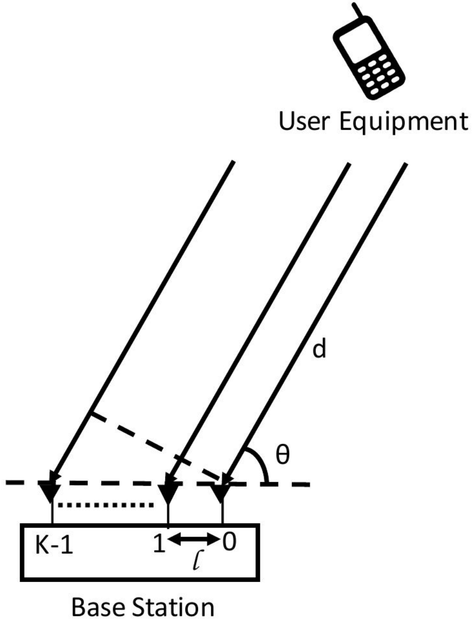
$$h_i = \sum_{n}^{N} \left(a_n e^{-j2\pi\frac{d_n}{\lambda}+j\phi_n}\right) \boxed{e^{-j2\pi\frac{il\cos\theta_n}{\lambda}}}, \quad (3)$$

Antenna geometry

l: antenna spacing
i: antenna index
Θ: AoA

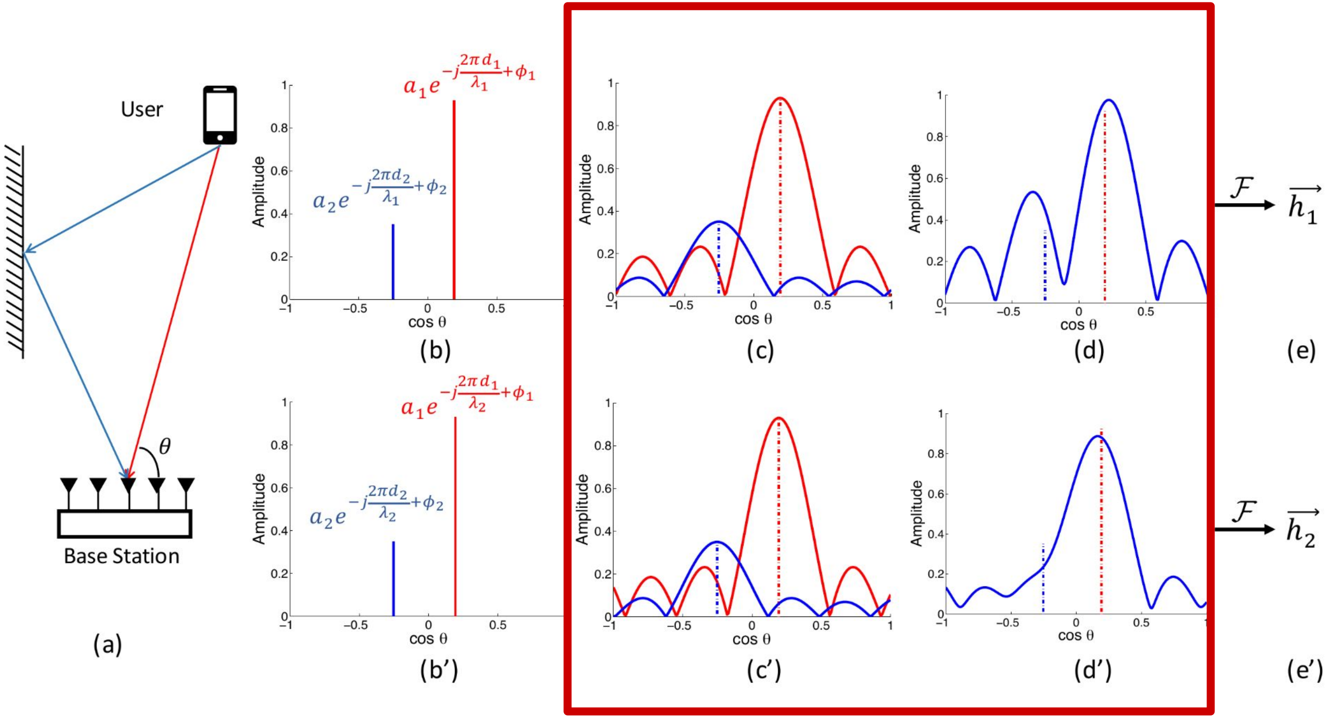
R2F2 Model (background)





R2F2 Model (practical)

Know (e) from rx signal, derive (a) (i.e., backward), so we can obtain (e’) (i.e., forward) for another freq.



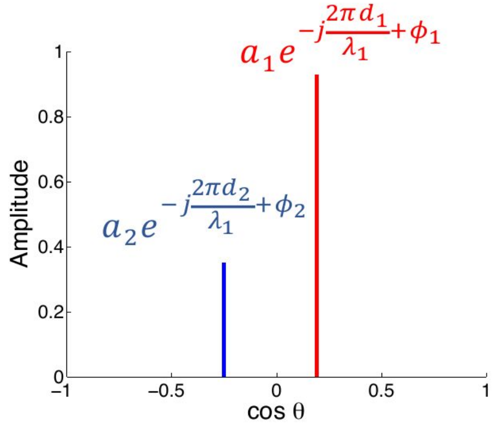
What are (c) and (d): windowing effect due to imperfect sampling

R2F2 Model: path to channel

We have path model (a):

$$(a_n, \phi_n, \theta_n, d_n)$$

AoA →

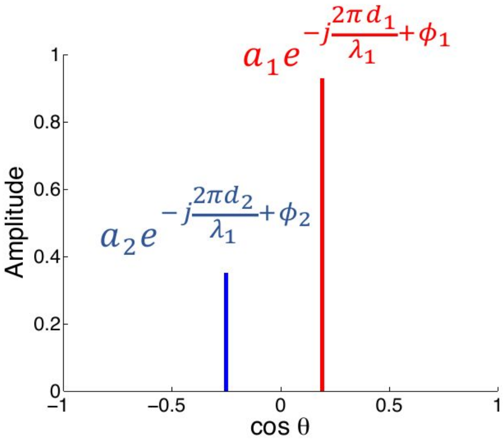


(b)

: $\psi = \cos\theta.$

$$P_1^n(\psi) = a_n e^{-j\frac{2\pi d_n}{\lambda_1}+j\phi_n}\delta(\psi - \psi_n), \qquad (4)$$

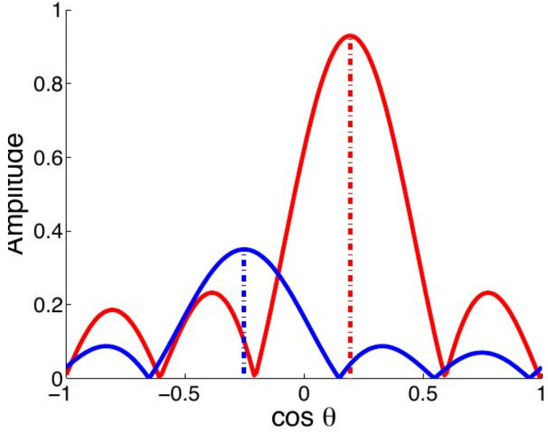
R2F2 Model: path to channel



(b)

Windowing

Artifact given imperfect
spatial sampling

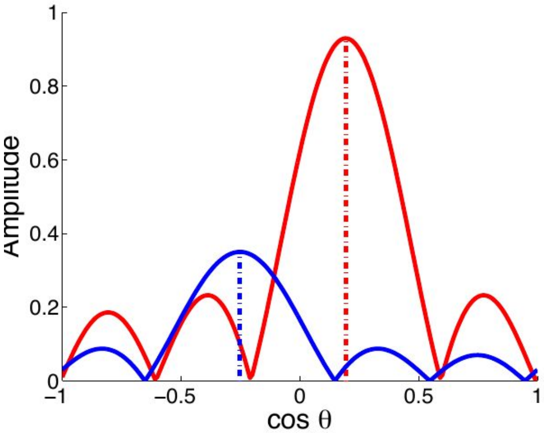


$$P_2^n(\psi) = \{a_n e^{-j\frac{2\pi d_n}{\lambda_1}+j\phi_n}\delta(\psi - \psi_n)\} * \frac{L}{\lambda_1} sinc\left(\frac{L\psi}{\lambda_1}\right) \quad (5)$$

$L\ (=\ Kl)$

L: ant array length;
K: ant num

R2F2 Model: path to channel

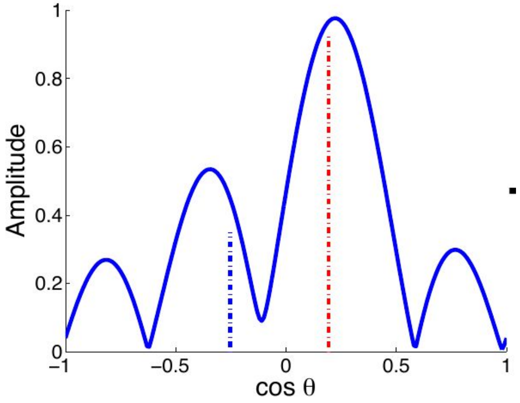


superposition

$$P_3(\psi) = \sum_{n=0}^{N-1} P_2^n(\psi).$$

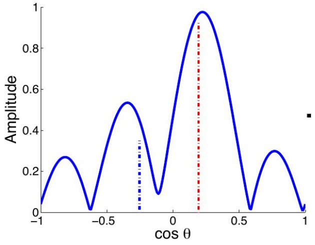
$$P_3(\psi) = \sum_{n=0}^{N-1} \{a_n e^{-j\frac{2\pi d_n}{\lambda_1}+j\phi_n} \delta(\psi - \psi_n)\} * \frac{L}{\lambda_1} sinc\left(\frac{L\psi}{\lambda_1}\right) \quad (7)$$

$$= \sum_{n=0}^{N-1} a_n e^{-j\frac{2\pi d_n}{\lambda_1}+j\phi_n} \times \frac{L}{\lambda_1} sinc\left(\frac{L(\psi - \psi_n)}{\lambda_1}\right) \quad (8)$$



(d)

R2F2 Model: path to channel



(d)

$$\xrightarrow{\mathcal{F}} \overrightarrow{h_1}$$

K * 1

To summarize:

$$\vec{h}_1 = \mathbf{F}\mathbf{S}\vec{a}'_1 \qquad (9)$$

N * 1

K *K

$$\mathbf{F}_{ij'} = e^{-j\frac{2\pi i l j' \psi'}{\lambda_1}}$$

K *N (path num)

$$\mathbf{S}_{ij} = \frac{L}{\lambda_1} sinc\left(\frac{L(i\psi' - \psi_j)}{\lambda_1}\right)$$

$$a_i e^{-j\frac{2\pi d_i}{\lambda_1} + j\phi_i}$$

From Channel to Path

IFT is simply $\mathbf{F}^{-1}\vec{h_1}$

Then goal is to find/guess AoA and amp and phase response of each path

$$O(\{a'_{1,n}, \psi_n\}_{n=0}^{N-1}) = ||\mathbf{F}^{-1}\vec{h_1} - \mathbf{S}\vec{a}'_1||^2 \qquad (10)$$

Note phase response not considered yet $a'_{1,n} = a_n e^{-j\frac{2\pi d_n}{\lambda_1} + j\phi_n}$

Use multiple OFDM waves to form equations and add constraints

From Channel to Path

arrow (Pi) = $\mathbf{F}^{-1}\vec{h}_i,$

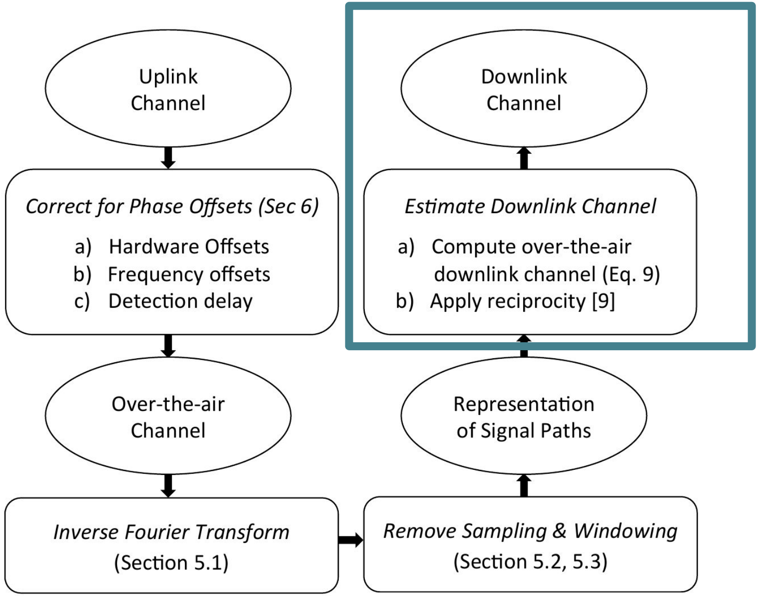
$$\vec{\mathcal{P}} = \begin{pmatrix} \vec{P}_1 \\ \vec{P}_2 \\ . \\ . \\ \vec{P}_K \end{pmatrix} \quad \mathcal{S} = \begin{pmatrix} \mathbf{S}_1\mathbf{D}_1 \\ \mathbf{S}_2\mathbf{D}_2 \\ . \\ . \\ \mathbf{S}_K\mathbf{D}_K \end{pmatrix}$$

N * N diagonal matrix where only kk has the observed final phase shift

$$O(\{\psi_n, d_n, a_n\}_{n=0}^{N-1}) = ||\vec{\mathcal{P}} - \mathcal{S}\vec{a}||^2 \qquad (13)$$

Compute, iteratively add guessed candidate path based on sinc peaks, and if conditions reach, all the guessed paths are considered

Apply to LTE system



Apply reciprocity

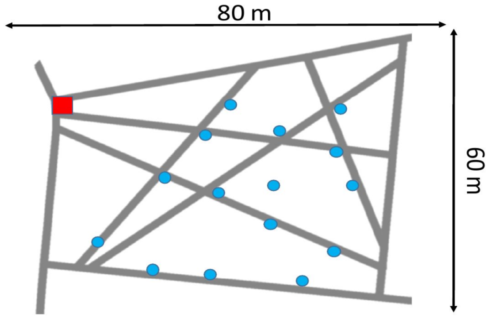
Compensate for hardware artifacts:

- Frequency offset
- Frame detection delay
- Hardware delay

Use periodic SRS for uplink ground-truth data

System Setup

(a)



(b)

Basestation:

- five-antenna Ettus USRP N210
- MIMO mode
- 1024 subcarriers; 10MHz
- 640MHz to 690MHz

UE:

- One antenna USRP
- UL and DL separated by 30MHz by default

Microbenchmark

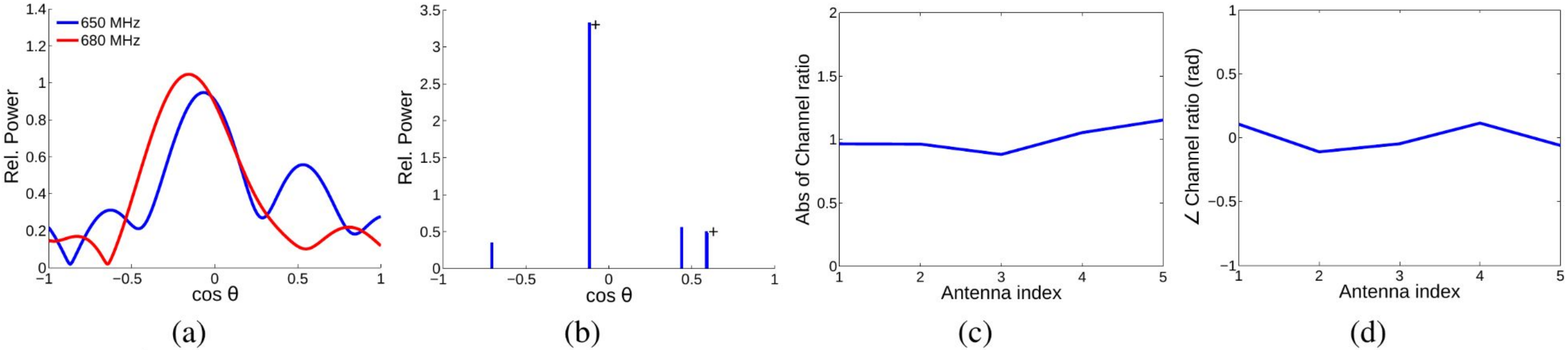


Figure 7: **Microbenchmark:** R2-F2 measures wireless channels on the uplink at 650 MHz and predicts the downlink channels on 680 MHz. The directional power profile for the uplink channel in a particular measurement is shown in (a). We also plot the downlink profile, obtained using ground truth measurements for reference. As explained in §4, these profiles appear very different. The paths inferred by R2-F2 are plotted in (b). A '+' sign next to a path indicates presence of two paths being plotted as one due to the plotting resolution. R2-F2 uses these paths to predict channels on 680 MHz. The absolute value of the ratio of the estimated channels to the ground truth channels is plotted in (c), while (d) plots the phase of this ratio.

Evaluation: Beamforming

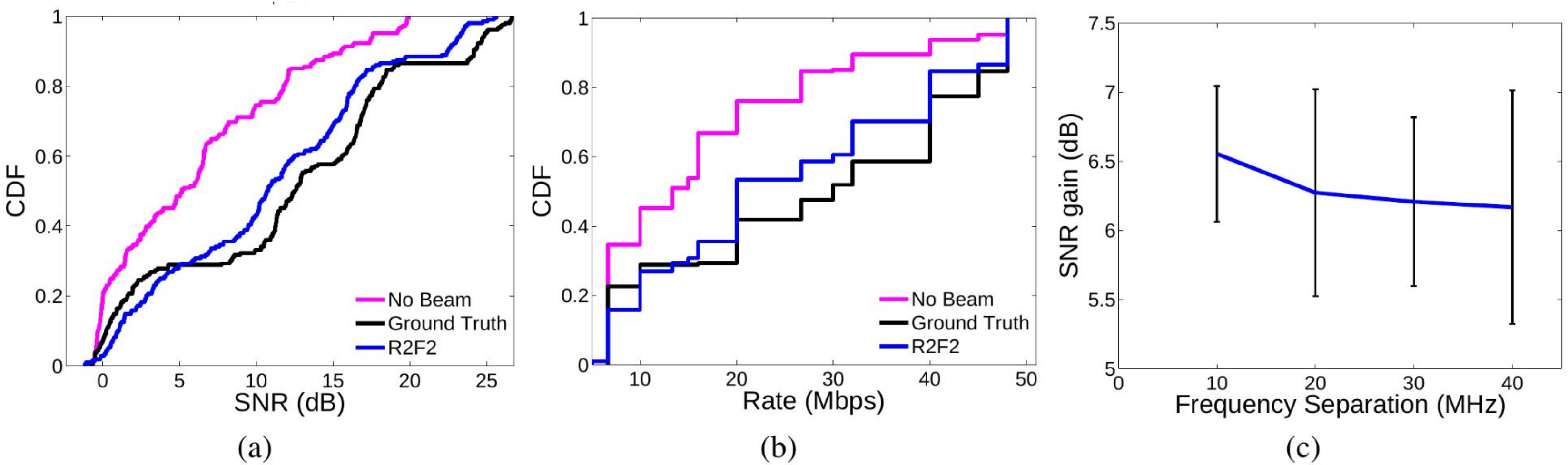


Figure 8: **Beamforming:** We use the channels estimated by R2-F2 to achieve beamforming towards the client. Figure (a) depicts the CDF of the SNR at the client without beamforming, using beamforming with the channels predicted by R2-F2 and using beamforming with the true channels measured at the client. R2-F2 achieves ~6 dB SNR gain over no beamforming, which is just 0.7 dB less than beamforming with ideal channels. Figure (b) depicts the datarates achieved by the different schemes. R2-F2 enables a median gain of 1.7x in datarate for clients in our testbed. Figure (c) depicts the median gain in SNR due to beamforming using channels estimated by R2-F2 as a function of frequency separation.

Interference nulling

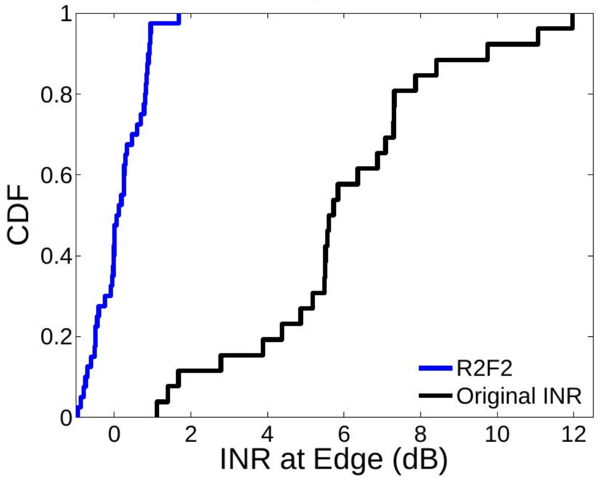
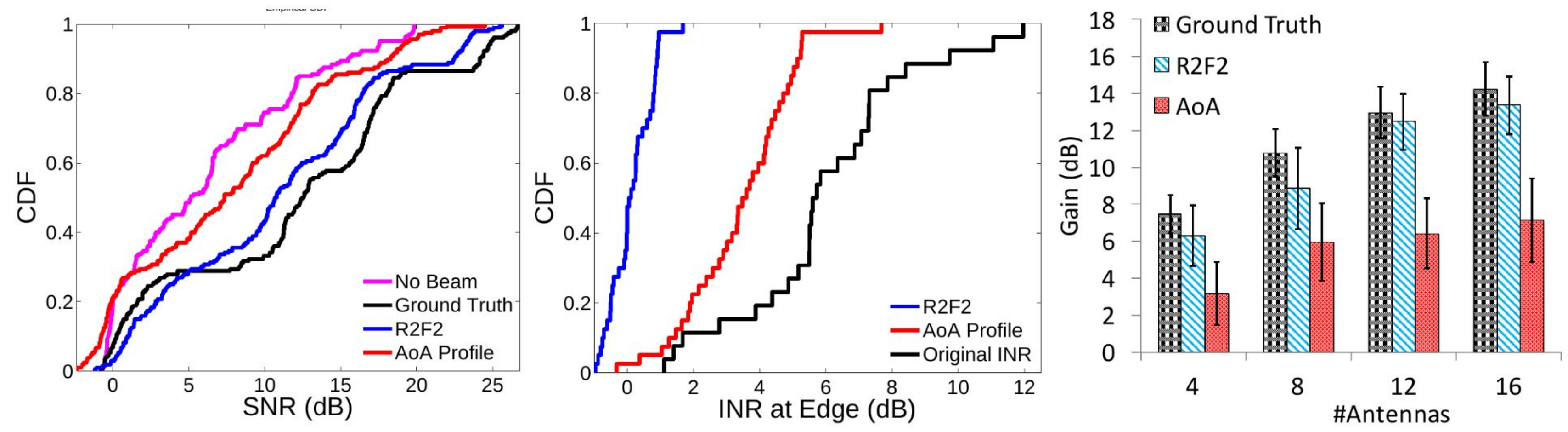


Figure 9: **Nulling interference at Edge Clients:** R2-F2 can reduce inter-cell interference by enabling the base station to null it's signal to the clients at the cell edge. R2-F2 reduces the interference at the edge from a median of 5.5 dB to 0.2 dB and the 90th percentile from 9 dB to 0.9 dB.

Compare with AoA



(a) (b) (c)

Figure 10: **Comparison with AoA Power Profile:** (a) AoA profile based channel estimation increases the median SNR of the testbed by 2.8 dB (as opposed to 6.3 dB for R2-F2). (b) Interference at the edge clients can be brought down from a median of 5.5 dB to 3.5 dB. However, R2-F2 outperforms this approach by nulling to 0.2 dB (median). (c) Simulation results show that with increase in number of antennas, the gain achieved by R2-F2 closely follows the ideal beamforming gain.

Opinion

- Beautiful and computationally light model
- Educational
- Might not work well if large frequency gap