Wireless Backhaul (*and Access*) at Millimeter Wave Frequencies

David J. Love
Associate Professor
School of Electrical and Computer Engineering
Purdue University
djlove@ecn.purdue.edu

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Need for Small Cells

- Many dire predictions for throughput demand
- Solution higher frequency reuse (Cooper’s law)
- Move users physically closer to an assumed high rate link
- Backhaul arguably the key challenge!
- Will backhaul end up being the bottleneck?
Backhaul in the News

- 2009 - AT&T iPhone troubles:
  “The executive says some Apple staffers fumed last year when AT&T told them of its plans to hype cell tower upgrades without investing in backhaul capacity” – Businessweek, Aug. 23, 2009 (http://www.businessweek.com/technology/content/aug2009/tc20090823_412749.htm)

- Touted backhaul upgrades (e.g., Verizon fiber and wireless, AT&T enhanced backhaul)

- 2011 - Alternative backhaul industry against failed AT&T-T-Mobile deal

- 2012 - Study saying backhaul demand scales 10x by 2016
Flavors of Backhaul

- Wired backhaul still very common (60%-70% copper in US, 40% wired globally)
- Wireless backhaul growing
- Must avoid “usable spectrum” (< 3GHz)
- Future backhaul possibilities
  - Copper/Fiber
  - In-band backhaul
  - 5-38GHz wireless
  - mmWave wireless
  - 100-400 GHz wireless
  - Free space optics

Source: Fibertower SEC filing
Possible Architecture

- Networks of small cells (pico) connected by millimeter wave backhaul (~50 meter links)
- User could access with 4G+ or mmwave radios
- Likely Requirements
  1) Must be easy to install
  2) At least one node per network sees macro (beamforming) or can collaborate (distributed beamforming [Madhow])
  3) Has a backup! (e.g., in-band backhaul)
  4) Nodes could use self-organizing topology [Singh et al]
Two Challenges

- **Challenge 1) Aligning the beam**
  - Narrow beam = Hard to align!
  - Limited resources for alignment

- **Challenge 2) Deployment and mounting**
  - Pole mounting
  - Wind
Challenge 1: Sounding and Beam Alignment

- Beamforming at Tx and Rx is critical!

\[ y[k] = z^*Hf_{\text{f}}s[k] + n[k] \]

- Receiver does not have access to each element output

- Observes noisy \( z^*Hf \) not \( Hf \)

- Must sound channel using training sequence to figure out where beams must point
Initial Beam Alignment

- Figure out how to point beam with little initial side info
  - New user, new installation, blockage, etc
  - Assume training sequence

- Must solve
  \[
  \max g(z, f) = |z^*Hf|^2 \quad \text{using observations}
  \]
  \[
  z^*[\ell]Hf[\ell] + n[\ell], \quad \ell = 1, 2, \ldots, L
  \]

- Interesting prior work for indoor millimeter wave (e.g., [Wang et al, Tsang et al])

- Alignment time may be highly constrained in some situations (i.e., \(L\) small)

- Can take \(L\) noisy subspace samples (possibly adaptively) with
  \[
  L \ll MrMt \quad \text{and usually} \quad L = O(Mr + Mt)
  \]
Understanding Beam Alignment

- Possibly many antennas

\[ H \in \mathbb{C}^{M_r \times M_t} \]

- Very few dominant paths (usually rank one)

\[ \frac{\text{rank}(H)}{\min(M_r, M_t)} \approx 0 \]

- Often

\[ z \in \mathcal{A}_r = \{z_1, \ldots, z_{N_r}\}, \quad f \in \mathcal{A}_t = \{f_1, \ldots, f_{N_t}\} \]

- Focus on case when finite beam directions used
Problems to Solve

1) Alignment Given Observations

Given sounding pairs \( \{(z[\ell], f[\ell])\}_{\ell=1}^{L} \) and samples \( \{y[\ell]\}_{\ell=1}^{L} \), how do we choose \((z, f)\) to maximize SNR?

2) Sounding Problem

How do we select sounding beamformer/combiner pair \((z[\ell], f[\ell])\) ?

- Random (non-adaptive) sounding
- Adaptive sounding
Beam alignment typically works by probing the channel with possible pairs \( \{(z, f), z \in A_r, f \in A_t\} \).

**Hard alignment**: Best alignment chosen simply as max receive power pair

\[
(z, f) = \arg \max (z^*[\ell] H f[\ell] + n[\ell])^2
\]

\( (z[\ell], f[\ell]) \)

Has a particularly appealing interpretation with array manifold
Beam Alignment is Related to….

- Problem actually one of rank one approximation
  \[
  \argmax_{z,f} |z^*Hf|^2 = \argmin_{z,f} \min_{\lambda} \|H - \lambda zf^*\|_F
  \]

- Must approximate using i) very few subspace samples and ii) low rank assumption

  \textbf{Matrix Completion}

- Much work in this area (e.g., [Candes, Tao],[Candes,Plan], [Keshavan,Montanari,Oh])

\textit{Matrix completion idea:} Randomly sample entries of a very large dimension rank $r$ matrix. Find rank at most $r$ matrix to minimize some distortion relative to this data
Example of Matrix Completion

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- Samples drawn uniformly
- Often important to “spread” samples out
- Use algorithm that creates low rank approximation (e.g., OPTSPACE)
Beam Alignment + Matrix Completion?

- Possibly have subspace side info of channel
  - Array manifold \( A(\theta) \)

- Reconstruction limited to \( z \in A_r, f \in A_t \)

- Can be viewed as direction matrix completion

\[
G = \begin{bmatrix}
  z_1^* \\
  \vdots \\
  z_{N_r}^*
\end{bmatrix} H \begin{bmatrix}
  f_1 \\
  \vdots \\
  f_{N_t}
\end{bmatrix} \quad \text{Find largest entry of } G
\]

- **Soft alignment**: Minimize subspace distance from observed points

\[
\begin{align*}
\argmin_{z,f} \min_{\lambda} & \sum_{\ell=1}^{L} |y[\ell] - \lambda z^*[\ell]z^*f[f][\ell]|^2 \\
= & \argmax_{z,f} \frac{|\sum_{\ell=1}^{L} y^*[\ell]z^*[\ell]z^*f[f][\ell]|}{|z^*[1]z^*f[f][1]|^2 + \cdots + |z^*[L]z^*f[f][L]|^2}
\end{align*}
\]
Topic 2) Adaptive Sounding

- Reciprocity or feedback allows adaptive sounding!

- Can choose pair \((z[\ell], f[\ell])\) prior to sounding

\[
z^*[\ell]Hf[\ell] + n[\ell], \quad \ell = 1, 2, \ldots, L
\]

- Questions:
  - How can Tx help Rx align?
  - How can Rx help Tx align?
  - What role does noise play?
Adaptive Sounding Approach

- Suppose channel rank one and $H = h_1 h_2^*$

- If Tx uses a near optimal beamformer, $|h_2^* f[\ell]|$ large
  *Higher SNR Rx observations*

- If Rx uses a near optimal combiner, $|z^*[\ell]h_1|$ large
  *Higher SNR Tx observations*

- Ping-pong alignment
  - Tx sounds its best known direction, Rx aligns
  - Tx sounds various directions, Rx points in best known direction
Hard Decision Alignment

- Works very well with LOS array manifold concepts
- Use progressively narrower beams
- Motivates sub-codebooks
- Important points:
  1) Each path in tree is a direction for further search
  2) Different path sub-codebooks must “overlap”
- Continue to probe area of strongest return
Matrix completion obviously difficult for many matrices.

Incoherence measure [Candès]: Let SVD be $\mathbf{H} = \sum_{k \leq r} \sigma_k \mathbf{u}_k \mathbf{v}_k^*$ we require $\mu$ as small as possible with

$$
\|\mathbf{u}_k\|_\infty \leq \sqrt{\mu/M_r}, \quad \|\mathbf{v}_k\|_\infty \leq \sqrt{\mu/M_t}
$$

Intuitively, want singular vectors to be equal gain because we sample with vectors of form $[0 \ldots 0 1 0 \ldots 0]^T$. 

Reconstructs to all zero matrix!
Understanding Incoherence

- Matrix completion assumes “peaky” subspace sampling
  \[ A_{\text{peaky}} = \{ e_1, \ldots, e_M \} \]
  columns of identity matrix

- Incoherence stipulates that singular vecs are not too distant from vectors in \( A_{\text{peaky}} \)

- Channel Sounding: Singular vectors in array manifold
  Omnidirectional Sounding!

- By-product: Would allow access in crowded user scenarios! (but is it legal????)
Alignment Comparison w/ SNR

- LOS 32x32
- ULA
- AoD and AoA uniform in [-60°, 60°]
- Adaptive soft alignment gives ~1dB improvement
- Random alignment comes at >5db penalty!

Sounding SNR (db)

Beamforming Gain (db)

4096 samples

48 samples
Comparison with WiGig Alignment

- Beamforming Gain
  - TX, RX use ULA ($M_T = M_R = 32$) multi-level codebook with
    - $K = 3$ (three level)
    - $N_B = 4$ (branch expansion)
    - $N_k = 8$ (extended search branches)

  - Carrier frequency : 60 GHz
  - Bandwidth : 400 MHz
  - Rician fading channel with K-factor = 13 dB
    - Modeled with 4 multipaths
Challenge 2: Understanding Pole Movement

- In pole-to-pole backhaul, is beam movement a big problem?
- Pole mounting (Civil engineers!!! AASHTO)
- Sources of movement
  - Ground movement
  - Wind excitation
- Movement types
  - Ground and rotational movement assumed negligible
  - Wind = Gusts + Steady wind
- Do we ever need to adjust beam? What time scale?

Source: American Association of State Highway and Transportation Officials (AASHTO)
Wind Induced Movement

- Cause 1: Mean and Gust-based movement
- Cause 2: Flow of wind over lamppost
  - Vortex shedding
  - Low pressure zones cause movement perpendicular to wind direction
  - Cause constant vibration

Vortex shedding

Constant pole sway

Wind movement

Low pressure zones
Models of Movement

Wind assumed well modeled by a stationary Gaussian process + velocity dependent mean [Davenport]

Davenport filter shapes spectrum (low-pass)

Aero admittance maps velocity perturbation to force
(Recall: Drag force proportional to squared velocity)

\[(\overline{W} + w(t))^2 \approx \overline{W}^2 + 2\overline{W}w(t)\]

Mechanical transfer gives response to force

\[|H_m(\omega)|^2 = \frac{1}{(\omega_n^2 - \omega^2) + (2\zeta\omega_n\omega)^2}\]

Natural frequency
Structural damping ratio
Beam Outage

- Outage Probability

Wind–induced beam outage, moderate turbulence (0.1 intensity)

Percentage of time in outage, $P_{\text{out}}$

mean wind speed, $v$ (m/s)
Role of Tolerable SNR Loss

- Received beam gain faded under $SNR_{\text{loss}}$
  - Antenna Array - $M = 256$ ULA at transmitter / receiver
  - Mean wind-velocity: $\bar{v} = 30 \ [m/s]$ (extreme gust)
Dealing With Wind

- Insight 1: Time scale is slow (order of seconds)
  - Tracking problem will require relatively small feedback overhead
  - Problem will be exacerbated at higher and higher frequencies

- Insight 2: Movement will be easy to track and relatively predictable
  - Simple monopulse tracking
  - Prediction

- Insight 3: Civil engineers can help in designing devices (e.g., damping movement, helping us pick mountings, etc)
mmWave Beamforming Summary

- Economic and technical issues motivate smaller cells
- Backhaul challenges are tremendous
- There is no magic bullet for backhaul!
- Beam alignment critical
- Environmental factors influence beam alignment