(RF) Media-based Modulation

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Basic Idea:
Think of Smoked Signalling

--- Message is formed outside TX antenna.
--- Message is encoded into pseudorandom channel states.
Media-based Wireless

- Keep the source shining and change the transmission medium to embed data.
Example

- Have two beams of gain **0.5 and 1.5** and have to use only one of them
  - Do not know which beam has higher gain.
- Want to form a 4 points 1-D constellation

**Option 1:** Select one beam at random and use a 4 PAM constellation

50% chance of constellation of having a constellation with \( d_{\text{min}} = \frac{1}{\sqrt{2}} \)

Energy spent: \( \frac{5}{4} \)
Example

- Have two beams of gain 0.5 and 1.5 and have to use only one of them. Do not know which beam has higher gain.
- Want to form a 4 points 1-D constellation

Option 2: Select one bits of information to select one of the beams, and modulate a BPSK

\[ d_{\text{min}} = \sqrt{2} \]

Energy spent: \( \frac{1}{4} \) times

10 Times Energy Saving
How to Change the Channel State?

14 RF Mirrors $\Rightarrow$ $2^{14}$ channel states $\Rightarrow$ Modulate 14 bits
Examples of Antenna Patterns
Propagation Environments

Indoor Model
(residential with dry-walls)

Outdoor Model
(down-town Ottawa)
Examples of Resulting Constellations (without symmetrization)
Examples of Resulting Constellations (with symmetrization)
Some Remarks

• Rich scattering environment:
  – Slightest perturbation in the environment causes independent outcomes.

• Should not be confused with RF beam-forming using parasitic elements.
  – RF beam-forming aims at focusing energy.
  – Media-based relies on additive information over receive antennas to increase rate, and on randomness of constellation to combat slow fading.
What about line of sight
Media-based vs. (legacy) Source-based

• Main idea:
  – Embed the information in the variation of the RF channel external to the antenna.

• Benefits vs. (legacy) source-based wireless:
  • Additive information over multiple receive antennas (similar to MIMO) with the advantages of:
    – Using a single transmit antenna
    – Independence of noise over receive antennas
  • Inherent diversity over a static channel (constellation diversity) using single or multiple antenna(s)
    – Diversity improves with the number of constellation points
    – Unlike MIMO, diversity does not require sacrificing the rate
    – It essentially converts the Raleigh fading channel into an AWGN channel with the same average receive energy and with a minor loss in capacity.
Media-based: Rate

\( m: \text{Data} \)

\( m \leftrightarrow \vec{h}(m) \)

\( m = 1, \ldots, L \)

\( E | h_k(m) |^2 = 1 \)

\( \vec{y} = \vec{h}(m) + \vec{z} \)

\( E( z_k^2 ) = 2 \)

\( h(m), m = 1, \ldots, L : K\text{-D constellation (iid Gaussian elements)} \)

\( I(\vec{y};m) = I(\vec{y};\vec{h}(m)) = H(\vec{y}) \quad H(\vec{z}) = H(\vec{y}) \quad K \log_2(2e^2) \)
Gain due to Inherent Diversity:
Typicality of Random Constellation

Carrier of Energy $E$

$m$: Data

$m \leftrightarrow \tilde{h}(m) \quad m = 1, \ldots, L$

$m \rightarrow \tilde{N}_q \quad \tilde{Z} \quad \text{AWGN: } |z_k|^2 = 1$

$\tilde{y} = \tilde{h}(m) + \tilde{N}_q \sim \text{Gaussian}$

$I = H(\tilde{y}) - H(\tilde{N}_q + \tilde{z} | \tilde{h}) \geq K \left[ \frac{1}{2} \log(2\pi e \sigma^2_Y) - E_{\tilde{c}} \left\{ \frac{1}{2} \log 2\pi e (\sigma^2_N + \sigma^2_{Nq\tilde{h}}) \right\} \right]

\geq K \left[ \frac{1}{2} \log(2\pi e \sigma^2_Y) - \int_{\tilde{c} \in \mathbb{R}^Q} f_G(\tilde{c}) \frac{1}{2} \log 2\pi e (\sigma^2_N + \sigma^2_{Nq\tilde{h}}) d\tilde{h} \right]

\sigma^2_{Nq\tilde{h}} \leq \frac{L}{K} \int_{\tilde{x} \in \mathbb{R}^2} f_G(\tilde{x}) \|\tilde{x} - \tilde{h}\|^2 e^{-(L-1)P(\tilde{x},\tilde{h})} d\tilde{x}.$
Main Computational Tool

\[ I \geq K \left[ \frac{1}{2} \log(2\pi e \sigma_Y^2) - E_C \{ \frac{1}{2} \log 2\pi e (\sigma_N^2 + \sigma_{Nq\vec{h}}^2) \} \right] \]

\[ \geq K \left[ \frac{1}{2} \log(2\pi e \sigma_Y^2) - \int_{\mathcal{H}^Q} f_G(\vec{h}) \frac{1}{2} \log 2\pi e (\sigma_N^2 + \sigma_{Nq\vec{h}}^2) d\vec{h} \right] \]

\[ \sigma_{Nq\vec{h}}^2 \leq \frac{L}{K} \int_{\mathcal{H}^2} f_G(\vec{x}) \| \vec{x} - \vec{h} \|^2 e^{-(L-1)p(\vec{x},\vec{h})} d\vec{x} \]

\[ \approx \frac{2\Gamma(2/K + 1)}{K} \left( \frac{\Gamma(K/2 + 1)}{L} \right)^{\frac{2}{K}} e^{\frac{c^2}{Q}} = Ae^{\frac{c^2}{K}} \left( \frac{1}{L} \right)^{2/K} \]

where, \[ A = \frac{2\Gamma(2/K + 1)(\Gamma(K/2 + 1))^{\frac{2}{K}}}{K} \]

As a result, \[ \sigma_{Nq\vec{h}}^2 \approx \left( \frac{1}{L} \right)^{2/K} \rightarrow 0, \text{ as } L \rightarrow \infty \]
Main Conclusion of \[ \sigma^2_{N_{\rho} \bar{y}} \approx \left( \frac{1}{L} \right)^{2/K} \rightarrow 0, \text{ as } L \rightarrow \infty \]

- Consider a slow Raleigh fading channel for which statistical average of the fading gain per receive antenna is one.
  - Using a single TX and \( Q \) RX antennas over such channel, mutual information averaged over different realizations of a constellation with \( L \) points approaches the capacity of \( 2Q \) parallel AWGN channels, each with unit energy, as \( L \rightarrow \infty \).
Accuracy of the Computational Tool and its Simplified Version in Non-asymptotic Situations

$L=256, Q=1$ (SISO)
Main Benefit: Inherent Diversity in A Single Constellation

- Conventional methods suffer from deep fades in slow fading.
- This problem disappears as “Good and Bad” channel realizations contribute to forming the constellation.

![Graph showing mutual information vs. SNR for different TX energy levels and P(outage) values.](image)
Comparisons for the Average Rate

Approximate Gain vs. Static Rayleigh Fading (gain due to Inherent Diversity):
RX=20dB, P(outage)=0.1, TX=30dB, Gain=10dB
RX=20dB, P(outage)=0.01, TX=40dB, Gain=20dB
RX=20dB, P(outage)=0.001, TX=50dB, Gain=30dB

M=256, Q=2

Mutual Information vs. SNR

256 QAM at SNR 20dB
256 QAM at SNR 15dB
Media-based vs. Source-based

$K \times K$ MIMO

$K$ complex Dimensions

Total signal energy: $KE$
Basis: **Non-orthogonal**
Complex Dimensions/sec/Hz: $K$

Better Performance

$E/K$

Basis: **Orthogonal**
Complex Dimension/sec/Hz: $K$

Data

$E$

ISIT 2014
Media-based vs. Legacy Systems: Effective Dimensionality

$1 > 2 > \ldots > K$ : Eigenvalues of a $K \times K$ Wishart random matrix

$E(slope) = K$

$slope = \frac{1}{1}$

$E(\frac{1}{1}) < 4$

$slope = \frac{1}{1} + \frac{2}{2}$

$slope = \frac{1}{1} + \frac{2}{2} + \frac{3}{3}$

$slope = 1$

$slope = \frac{1}{1} + \frac{2}{2} + \frac{3}{3} + \ldots + \frac{k}{k}$

$E(\frac{1}{1} + \frac{2}{2} + \frac{3}{3} + \ldots + \frac{k}{k}) = K$

Legacy SISO
Rate = $\log(1+E)$
Selection Gain

- Select a subset of points, which, subject to uniform probabilities, maximize the mutual information.
- In practice, using the subset of points with highest energy, which maximizes the slope the rate at zero SNR, performs very well.
Media-based vs. Legacy Systems: Slope of Rate vs. SNR (dB) at SNR=0

- Legacy SISO: Slope = 1
- Legacy $K \times K$ MIMO: Maximum eigenvalue of a $K \times K$ Wishart matrix (upper limited by 4)
- $I \times K$ Media-based: $K$

<table>
<thead>
<tr>
<th></th>
<th>$L=1, K=2$</th>
<th>$L=1, K=4$</th>
<th>$L=1, K=8$</th>
<th>$L=1, K=\infty$</th>
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<tbody>
<tr>
<td>$K \times K$ MIMO</td>
<td>1.75</td>
<td>2.45</td>
<td>2.96</td>
<td>4</td>
</tr>
<tr>
<td>$I \times K$ Media-based</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>Infinity</td>
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- *Selection Gain* further increases the slope of media-based to: $\max \left\| c_i \right\|, i = 1, \ldots, L$
  - e.g. average slope scales as $\log(L)$ for SISO case.
Comparison with Ergodic Capacity

![Comparison with Ergodic Capacity Graphs](image-url)
Comparison with Outage Capacity
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