Energy Detection in ISI Channels Using Large-Scale Receiver Arrays

Lishuai Jing and Elisabeth De Carvalho

APNet Section, Dept. of Electronic Systems
Aalborg University, Aalborg, Denmark

March 24, 2016.

Outline

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Motivation: Systems with a Large Number of Antennas

Non-coherent Detection in Wideband Systems with Massive Receiver Arrays

Conclusions

Prospective of Systems with a Large Number of Antennas

Enablers for next generation communication systems:

Massive MIMO: Base stations/ Back-hauls have the capacity to nest a large number of antennas.

In mmWave frequencies, small size terminals can host a large number of antennas.

Why Hosting More Antennas?

Drastic improvement of system capacity and reliability becomes possible.

- More antennas, more DoF and multiplexing gain.

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Simple linear processing techniques lead to close-to-optimal performance.

- Uplink: when $M \gg K$, MF, ZF, MMSE nearly optimal.
- Downlink: simple precoders, e.g. MRT, ZF, MMSE, are promising.

Key assumption: **Perfect** or **nearly-perfect** channel state information (CSI) is required.

Channel Estimation Challenges

Downlink training becomes not "economical":

To provide optimal performance, orthogonal training is required:

- No. of downlink pilots scales with the number of BS antenna M: A large portion of time-frequency resource is needed.

No. of unknown channel coefficients scales with M:

- Resources demanded to feedback the CSI from user terminal to base station escalates.

Uplink Training Solution: TDD operation exploiting channel reciprocity.

- Training resources scale with K instead of M.

However,

- Channel reciprocity does not always hold: hardware constraints and fast fading channels.
- Large channel estimation error in medium and low SNR scenarios.
- Pilot contamination.

Our Proposal: Low Complexity Non-coherent Energy Detection

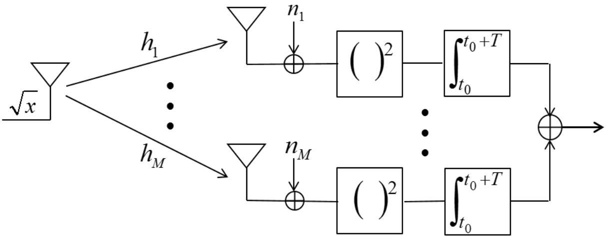

Figure: Single stream transmission with a large-scale receiver array.

Advantages:

- Low hardware complexity: No phase shifter and amplifiers at RF chains.
- Noise hardening: Deterministic noise.
- Central limit theorem: Gaussian approximations for related variables.
- Simple decoding method: Detection based on the statistics of the channel energy instead of instantaneous CSI.
- No capacity loss compared to coherent detection when M is large.

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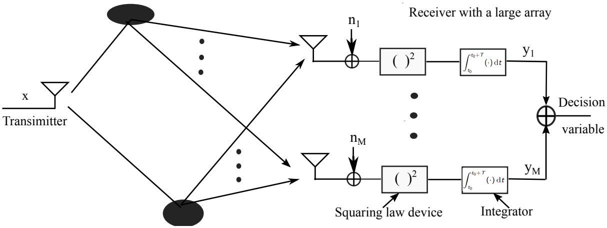
Non-coherent Energy Detection in Wideband (mmWave) Systems



Consider additive white Gaussian noise, the received signal at time j reads

$$\mathbf{y}(j) = \sum_{l=0}^{L-1} \mathbf{h}_l x(j-l) + \mathbf{n}(j), \tag{1}$$

- lth path channel coeff.: $\mathbf{h}_l = [h_{1,l}, \ldots, h_{M,l}]^T$.

Objective: Detect unknown data $x(j)$ based on

$$z(j) = \frac{||\mathbf{y}(j)||_2^2}{M}. \tag{2}$$

Asymptotical Analysis

The output of the ED is written as:

$$z(j) = \frac{1}{M}||\mathbf{h}_0||_2^2|x(j)|^2 + \underbrace{\frac{1}{M}\sum_{l=1}^{L-1}||\mathbf{h}_l||_2^2|x(j-l)|^2}_{\mathrm{ISI}_1} + \underbrace{\frac{1}{M}\sum_{l\neq l'}x^*(j-l)x(j-l')\mathbf{h}_l^H\mathbf{h}_{l'}}_{\mathrm{ISI}_2} + \underbrace{\frac{2}{M}\Re\left(\sum_{l=0}^{L-1}\mathbf{h}_l^H\mathbf{n}x(j-l)\right)}_{\mathrm{ISI}_3} + \frac{1}{M}\mathbf{n}^H(j)\mathbf{n}(j). \tag{3}$$

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Employing uncorrelated scattering assumption, asymptotically, we obtain

$$\frac{\mathbf{h}_l^H\mathbf{h}_{l'}}{M} \xrightarrow{M\to+\infty} \sigma_{h,l}^2\delta_{l,l'}, \quad \frac{\mathbf{h}_l^H\mathbf{n}(j)}{M} \xrightarrow{M\to+\infty} 0, \quad \frac{\mathbf{n}^H(j)\mathbf{n}(j)}{M} \xrightarrow{M\to+\infty} \sigma_n^2.$$

Thus,

$$z(j) \xrightarrow{M\to+\infty} \sum_{l=0}^{L-1}\sigma_{h,l}^2|x(j-l)|^2 + \sigma_n^2. \tag{4}$$

Asymptotical Analysis

A standard equalization problem is obtained:

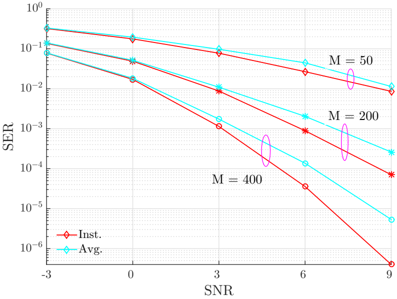
$$z(j) \xrightarrow{M \to +\infty} \sum_{l=0}^{L-1} \sigma_{h,l}^2 |x(j-l)|^2 + \sigma_n^2. \tag{5}$$

- Noise contribution becomes deterministic.
- Instantaneous CSI becomes irrelevant: only average channel energy of each tap is required (long term statistics).
- Simple equalization techniques may work well.

Proposed solution: Employing Zero Forcing equalizer and use average channel energy to compute its coefficients.

Performance Evaluation

Uncoded system: channel with exponential power decay PDP and $L = 4$.



- ZF produces a SER performance scales with the number of antennas and SNR.
- Promising results at low and medium SNR regimes.
- More antennas leads to significantly lower SER.
- Reach extension is granted with equipping more antennas.

Performance Evaluation

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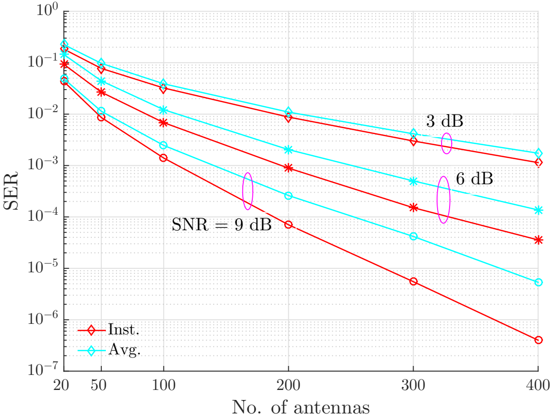

- As SNR increases, the performance gap widens a bit due to the noise enhancement when applying the ZF equalizer.

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Conclusions: Coherent or Non-coherent Detection

Coherent detection is optimal, but channel estimation is the bottleneck.

With a large number of receiver antennas, **non-coherent detection performs close-to-optimal:**

- Second order statistics of the channel coefficients are required instead of instantaneous CSI.
    - Long term and more robust statistics can be estimated over a longer horizon.
    - A simplified channel estimation problem and robust to mobility.
- Noise hardening: reach extension is guaranteed and noise may not be the limiting factor for system performance.
- Low complexity hardware: no phase shifters and gain controller at each RF chain.
- Low complexity decoding algorithms thanks to the law of large numbers and central limit theorem.