(RF) Media-based Modulation

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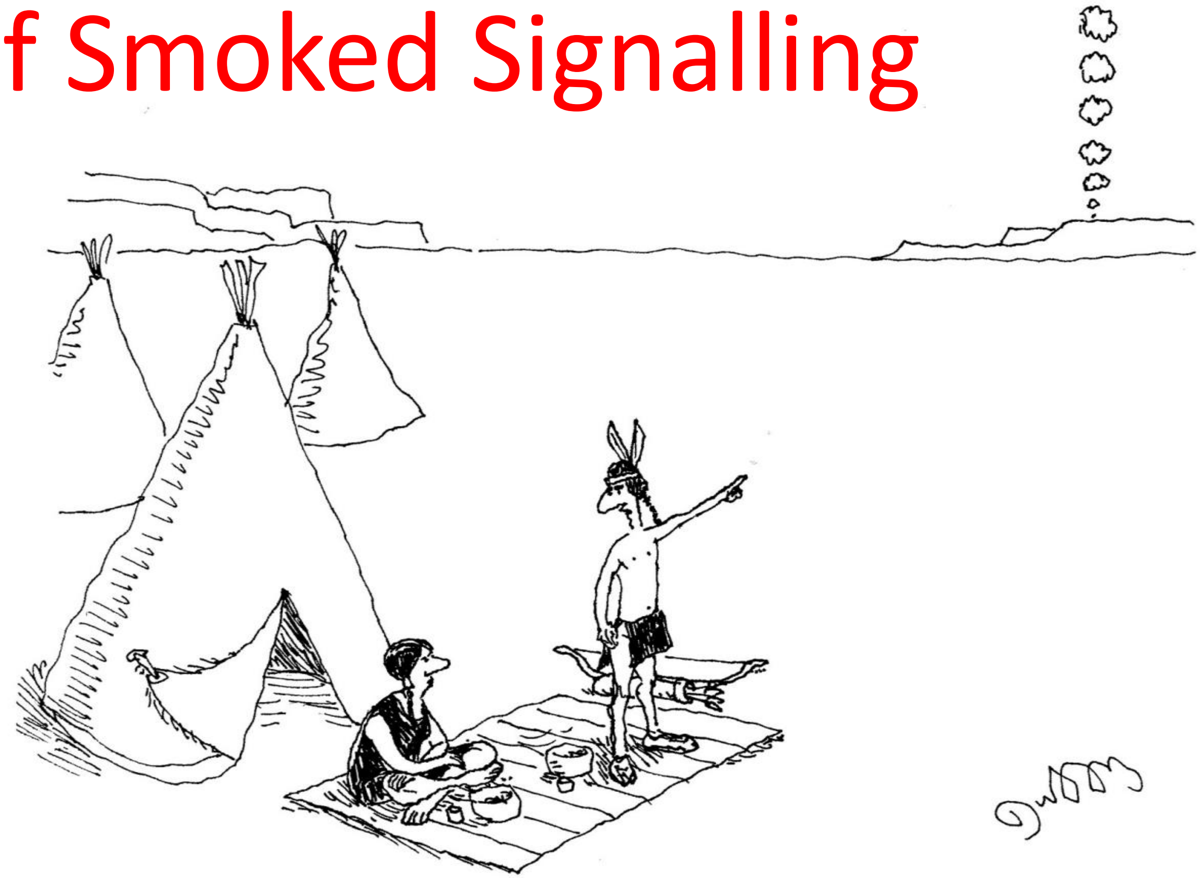
Basic Idea:

Think of Smoked Signalling

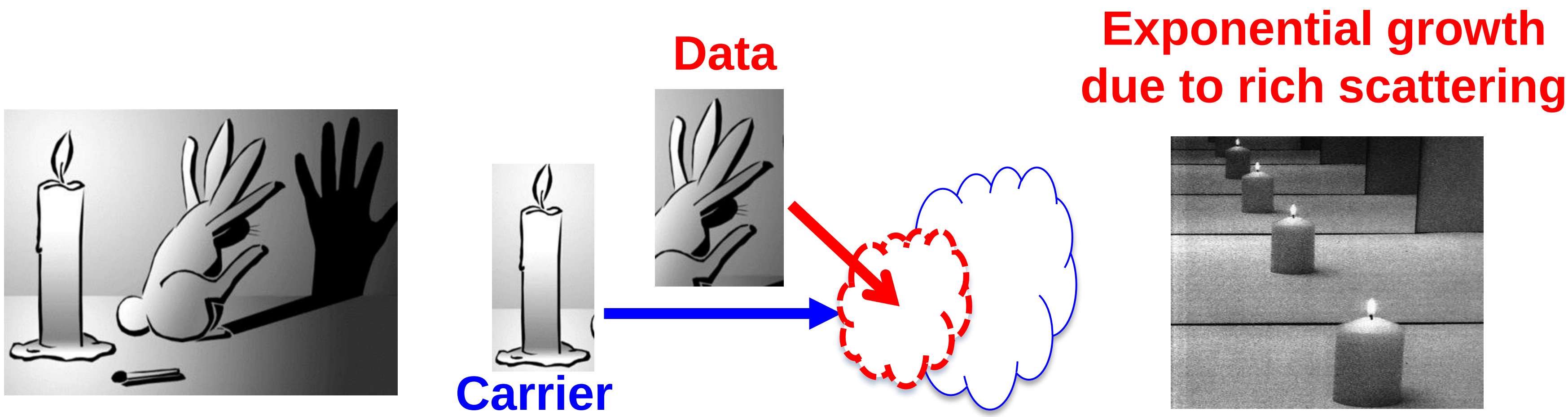


"SORRY, BUT I REALLY NEED TO TAKE THIS."

--- 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.

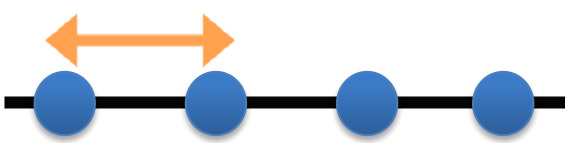
Example

- 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

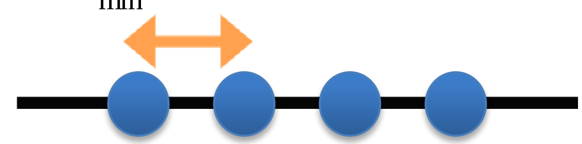
Option 1: *Select one beam at random and use a 4 PAM constellation*

50% chance of constellation of having a constellation with $d_{\min} = 1/\sqrt{2}$

$d_{\min} = 1$



$d_{\min} = 1/\sqrt{2}$



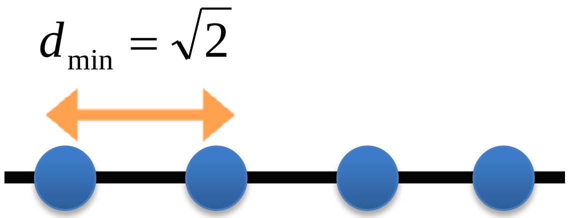
Energy spent: 5/4

$$d_{\min} = 1/\sqrt{2}$$

Example

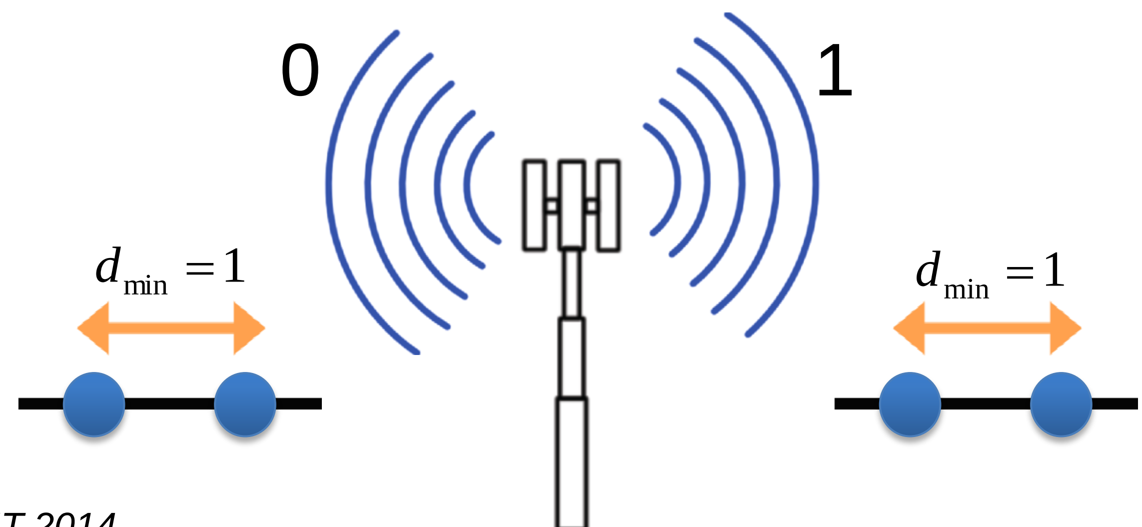
- Have two beams of gain **0.5 and 1.5** and **have to use only one of them**
  -Do not know which beam has higher gain.
- Want to form a 4 points 1-D constellation

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



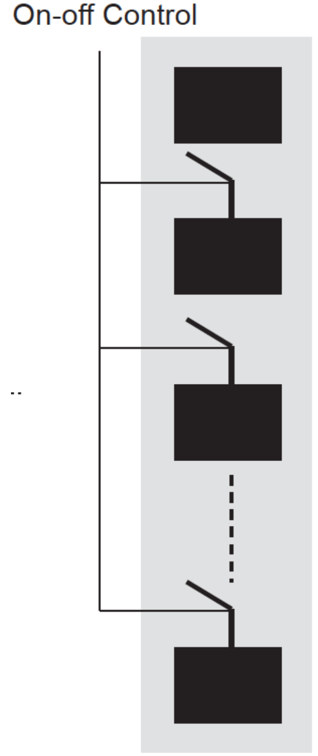
Energy spent:1/4

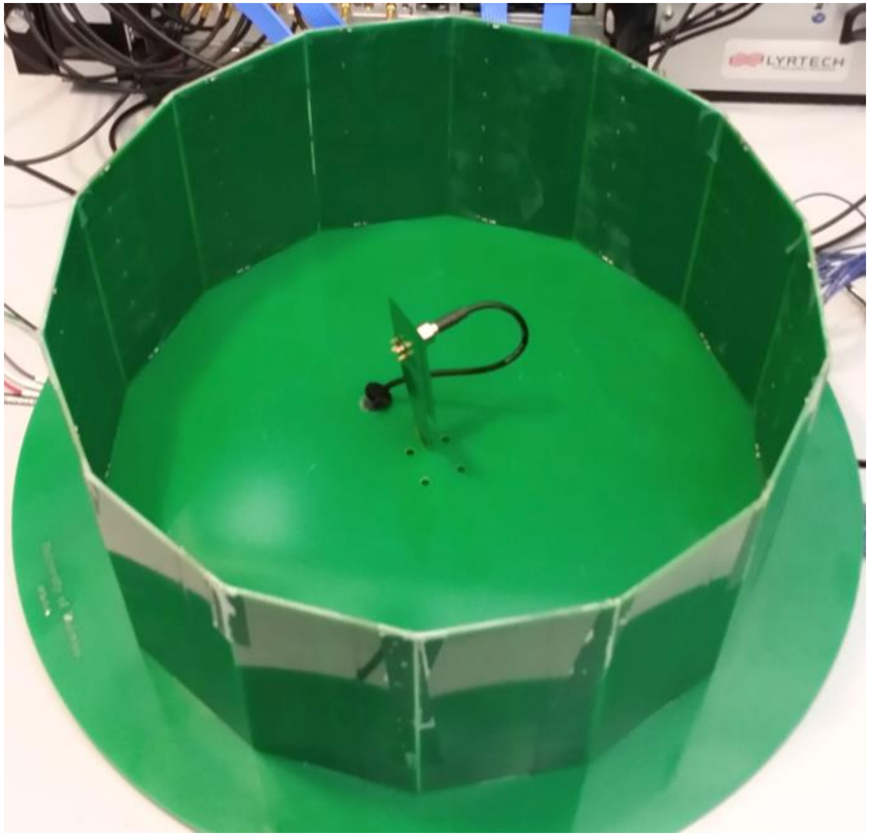
$$d_{\min} = \sqrt{2}$$



10 Times Energy Saving

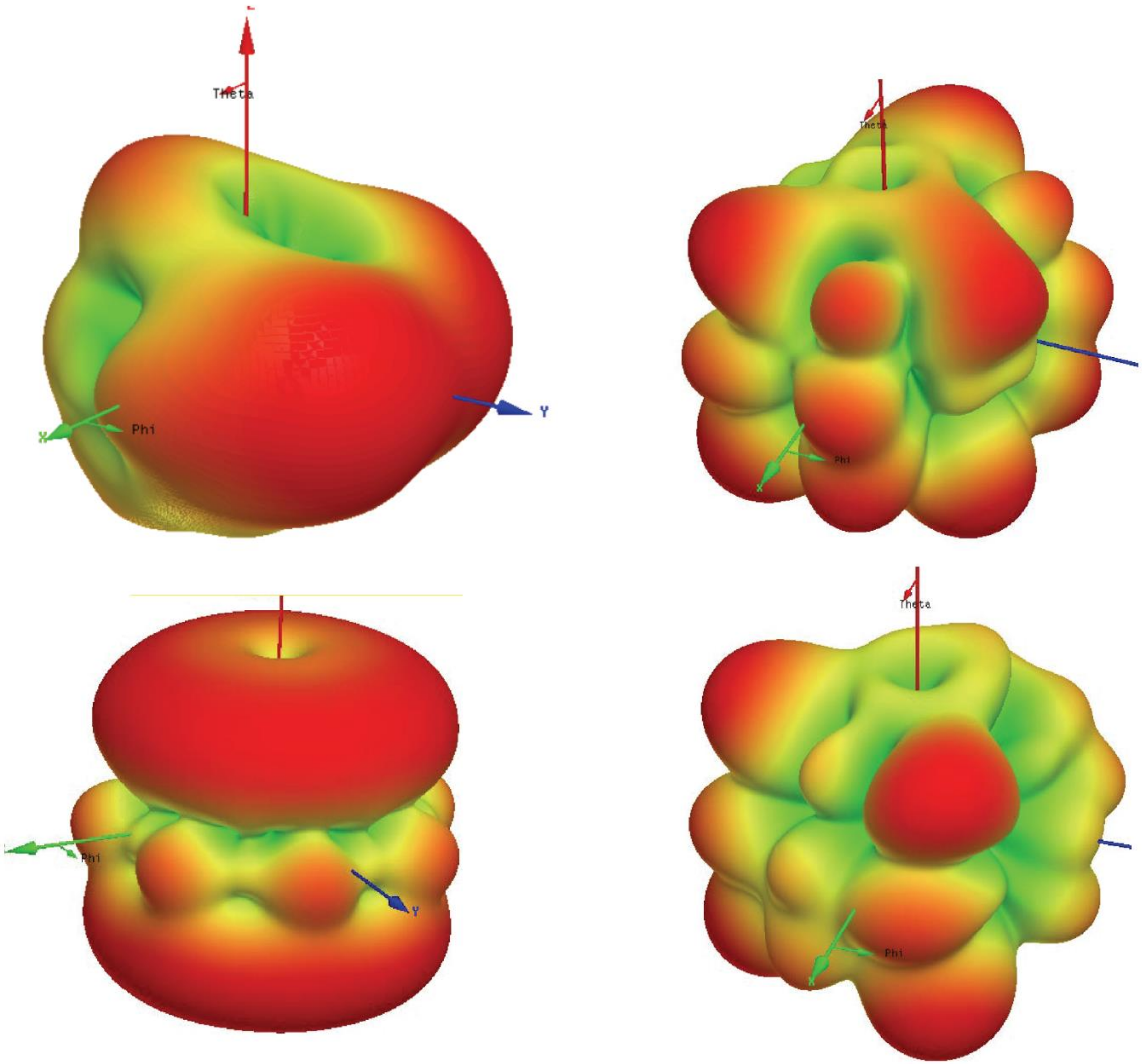
How to Change the Channel State?



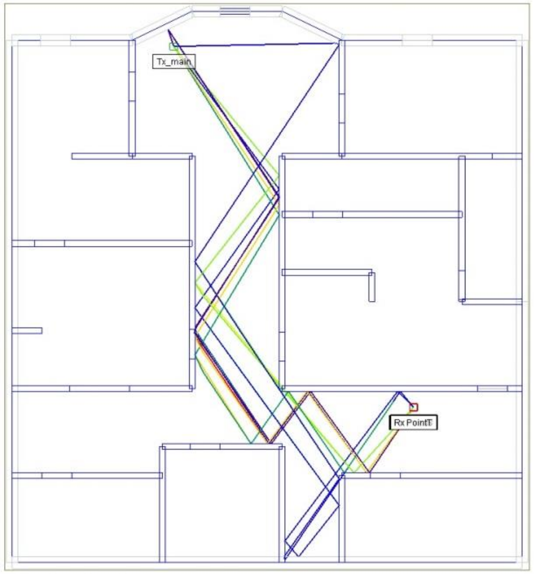


14 RF Mirrors ➔ 2^{14} channel states ➔ Modulate 14 bits

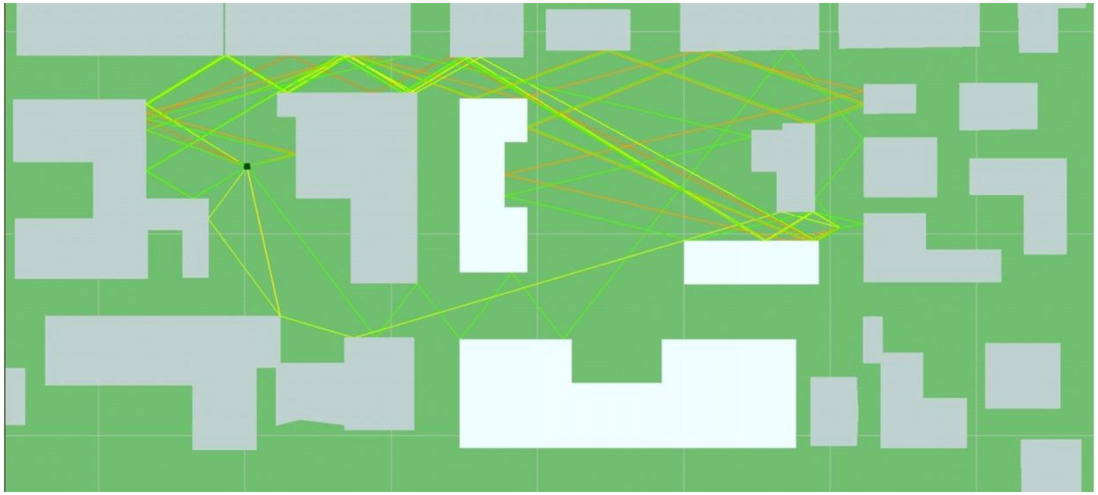
Examples of Antenna Patterns



Propagation Environments

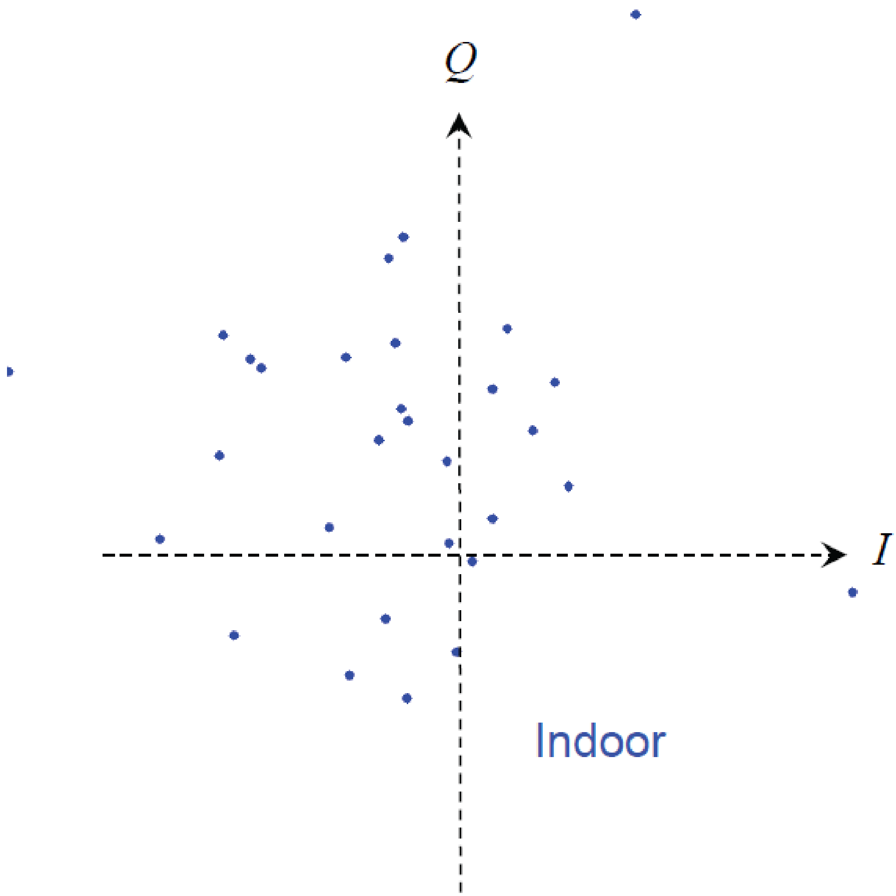


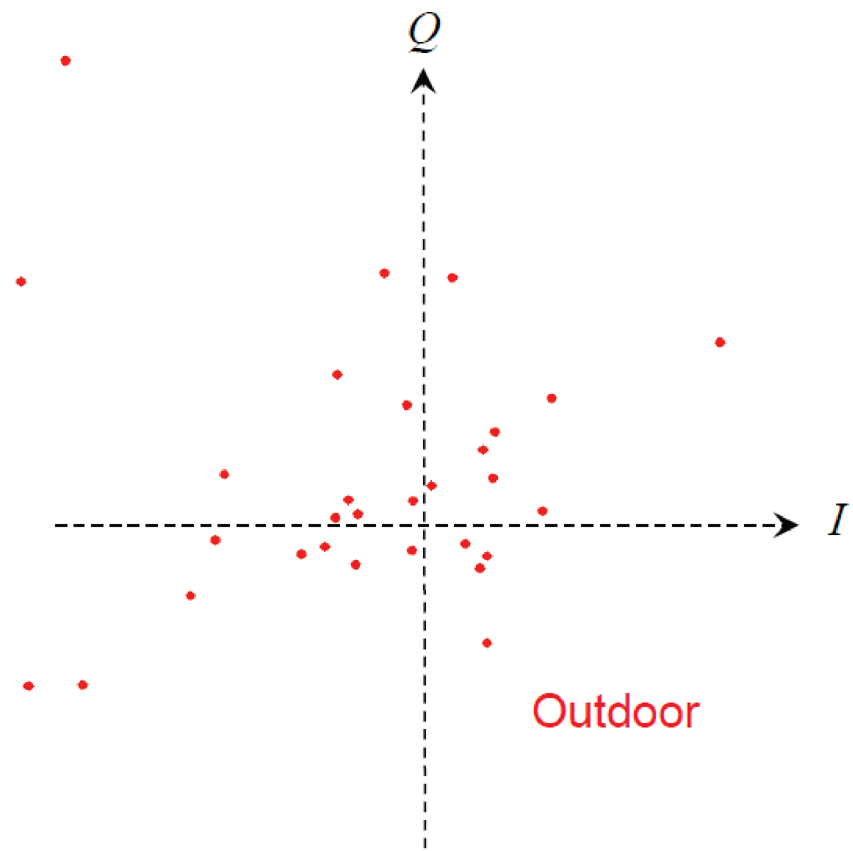
Indoor Model
(residential with dry-walls)



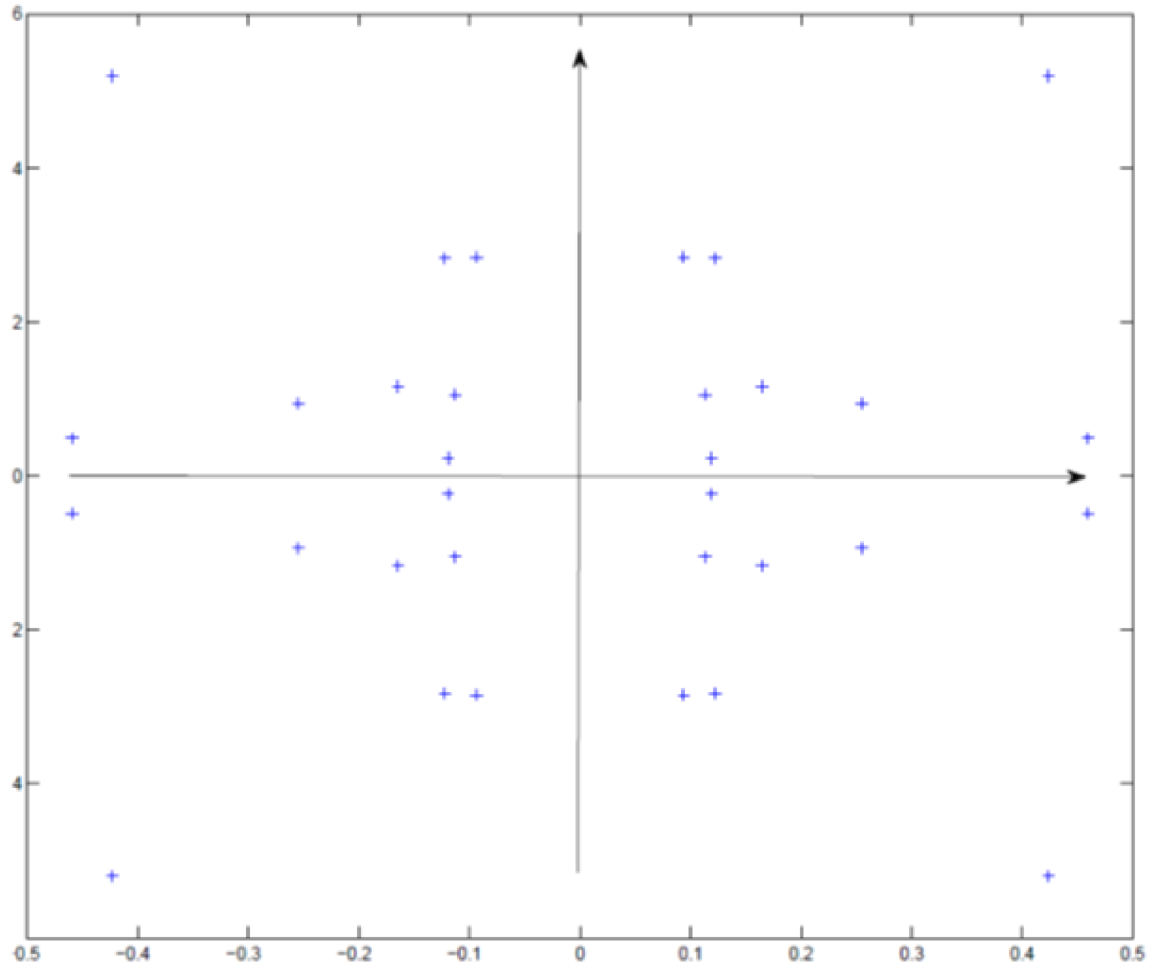
Outdoor Model
(down-town Ottawa)

Examples of Resulting Constellations (without symmetrization)





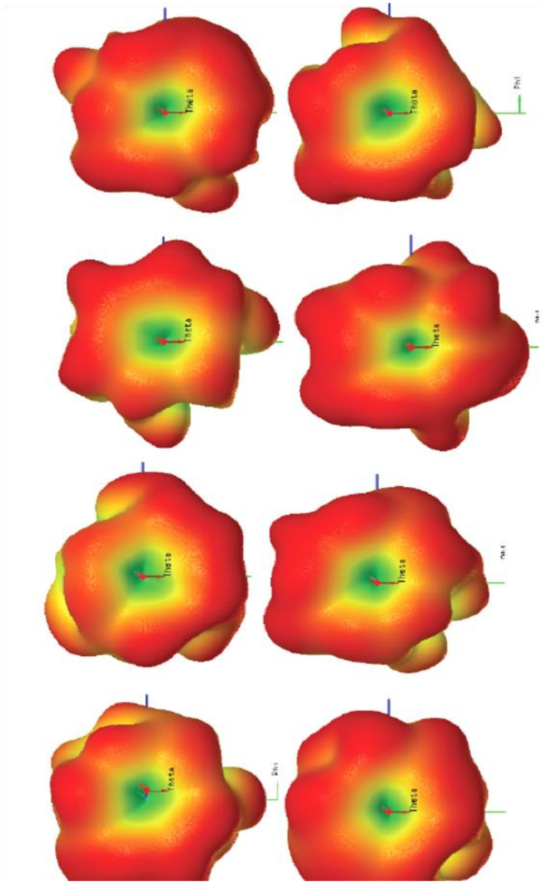
Examples of Resulting Constellations (with symmetrization)

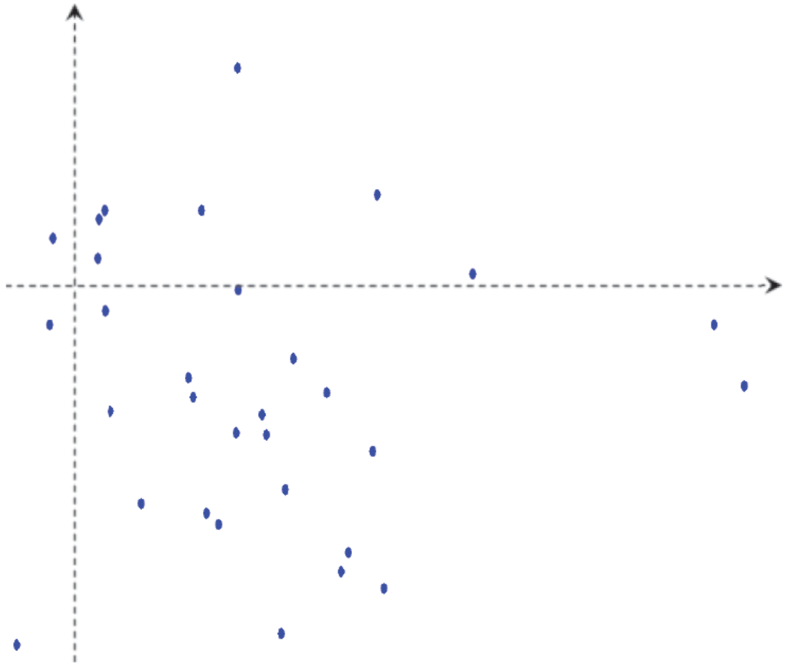


Some Remarks

- 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

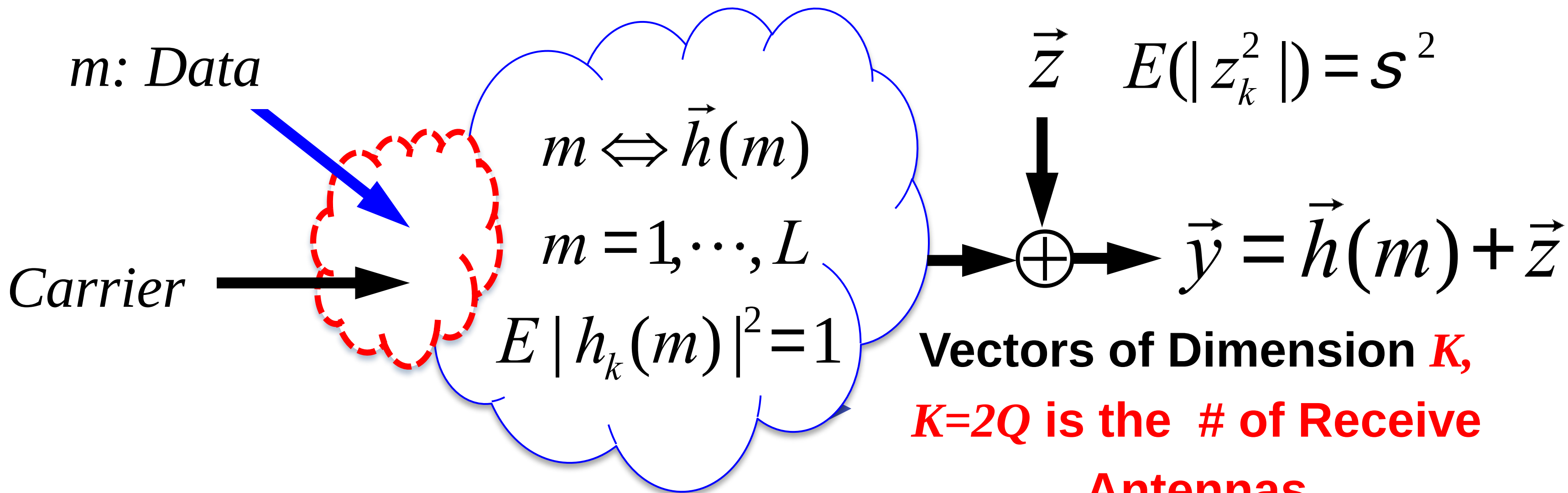




Media-based vs. (legacy) Source-based

- 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 coverts the Raleigh fading channel into an AWGN channel with the same average receive energy and with a minor loss in capacity.

Media-based: Rate

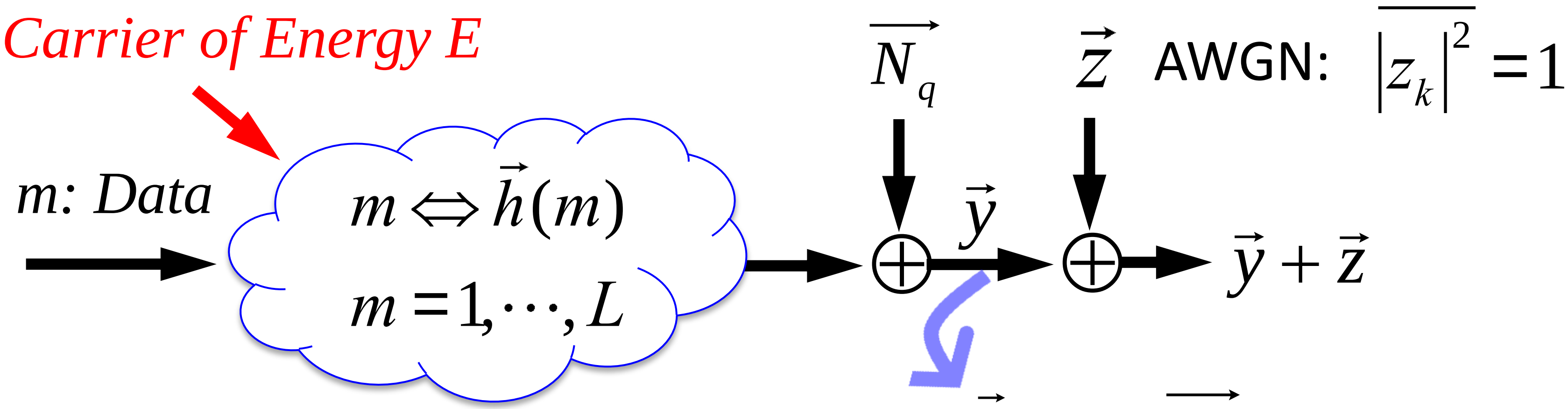


$$I(\vec{y};m) = I(\vec{y};\vec{h}(m)) = H(\vec{y}) - H(\vec{z}) = H(\vec{y}) - K\log_2(2\pi e\sigma^2)$$

$\vec{h}(m), m = 1, \cdots, L$: *K*-D constellation (iid Gaussian elements)

Gain due to Inherent Diversity:

Typicality of Random Constellation



$$\vec{y} = \vec{h}(m) + \overrightarrow{N_q} \sim Gaussian$$

$$I = H(\vec{y}) - H(\overrightarrow{N_q} + \vec{z} | \vec{h}) \geq K[\frac{1}{2}\log(2\pi e \sigma_Y^2) - E_{\vec{C}}\{\frac{1}{2}\log 2\pi e(\sigma_N^2 + \sigma^2{}_{N_q|\vec{h}})\}]$$

$$\geq K[\frac{1}{2}\log(2\pi e \sigma_Y^2) - \int_{\vec{c}\in\Re^Q} f_G(\vec{c})\frac{1}{2}\log 2\pi e(\sigma_N^2 + \sigma^2{}_{N_q|\vec{h}})d\vec{h}]$$

$$\sigma^2{}_{N_q|\vec{h}} \leq \frac{L}{K}\int_{\vec{x}\in\Re^2} f_G(\vec{x})\left\|\vec{x} - \vec{h}\right\|^2 e^{-(L-1)P(\vec{x},\vec{h})} d\vec{x}.$$

Main Computational Tool

$$I \geq K[\frac{1}{2}\log(2\pi e\sigma_Y^2) - E_{\vec{C}}\{\frac{1}{2}\log 2\pi e(\sigma_N^2 + \sigma^2{}_{N_q|\vec{h}})\}]$$

$$\geq K[\frac{1}{2}\log(2\pi e\sigma_Y^2) - \int_{\vec{c}\in\Re^Q} f_G(\vec{h})\frac{1}{2}\log 2\pi e(\sigma_N^2 + \sigma^2{}_{N_q|\vec{h}})d\vec{h}]$$

$$\sigma^2{}_{N_q|\vec{h}} \leq \frac{L}{K}\int_{\vec{x}\in\Re^2} f_G(\vec{x})\left\|\vec{x}-\vec{h}\right\|^2 e^{-(L-1)P(\vec{x},\vec{h})}d\vec{x}$$

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

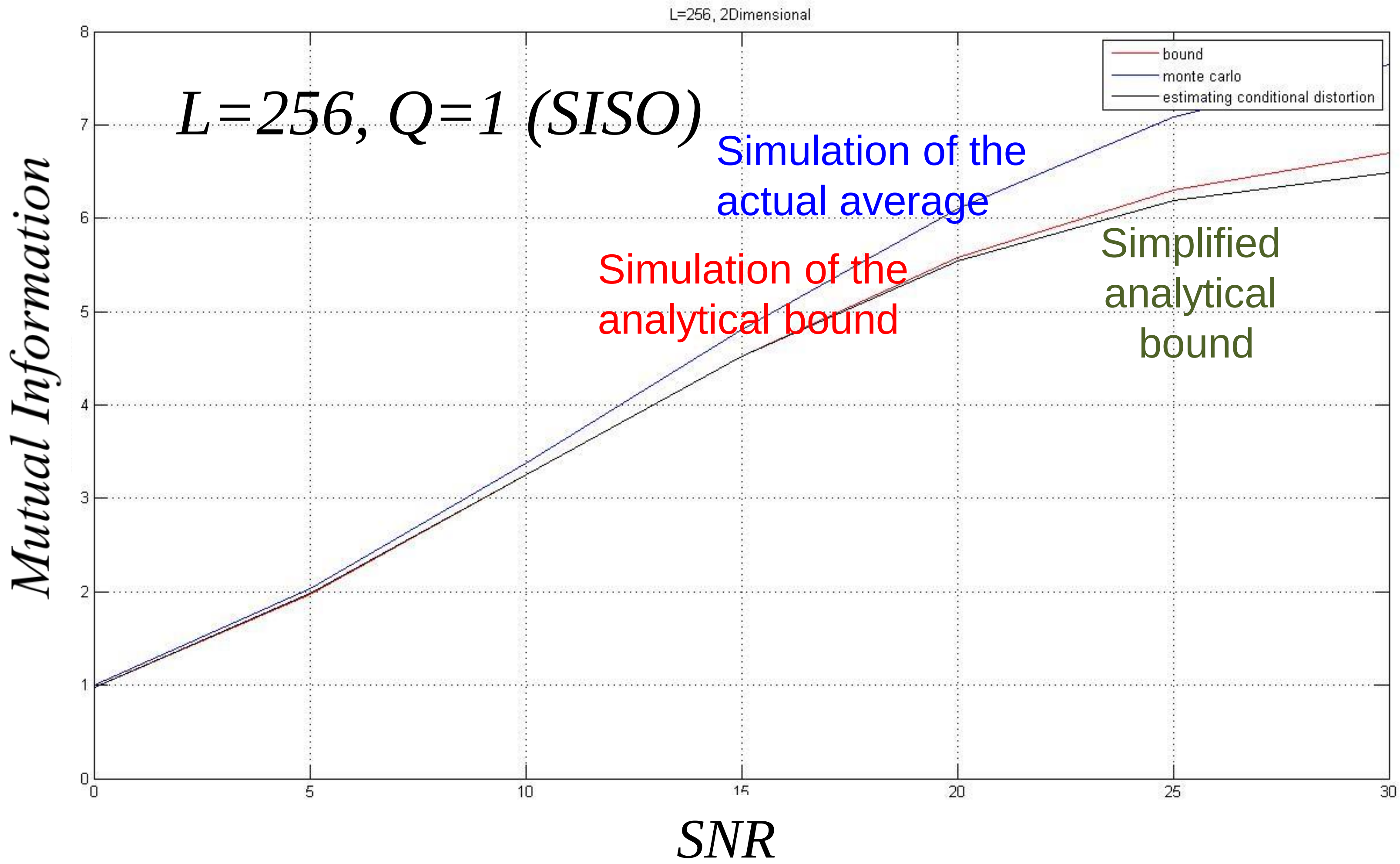
$$where,\quad A = \frac{2\Gamma(2/K+1)\left(\Gamma(K/2+1)\right)^{\frac{2}{K}}}{K}$$

$$As\ a\ result,\quad \sigma^2{}_{N_q|\vec{h}} \cong \left(\frac{1}{L}\right)^{2/K} \rightarrow 0,\ as\ L\rightarrow\infty$$

Main Conclusion of $\sigma^2_{N_q|\vec{h}} \cong \left(\frac{1}{L}\right)^{2/K} \to 0, \; as \;\; L \to \infty$

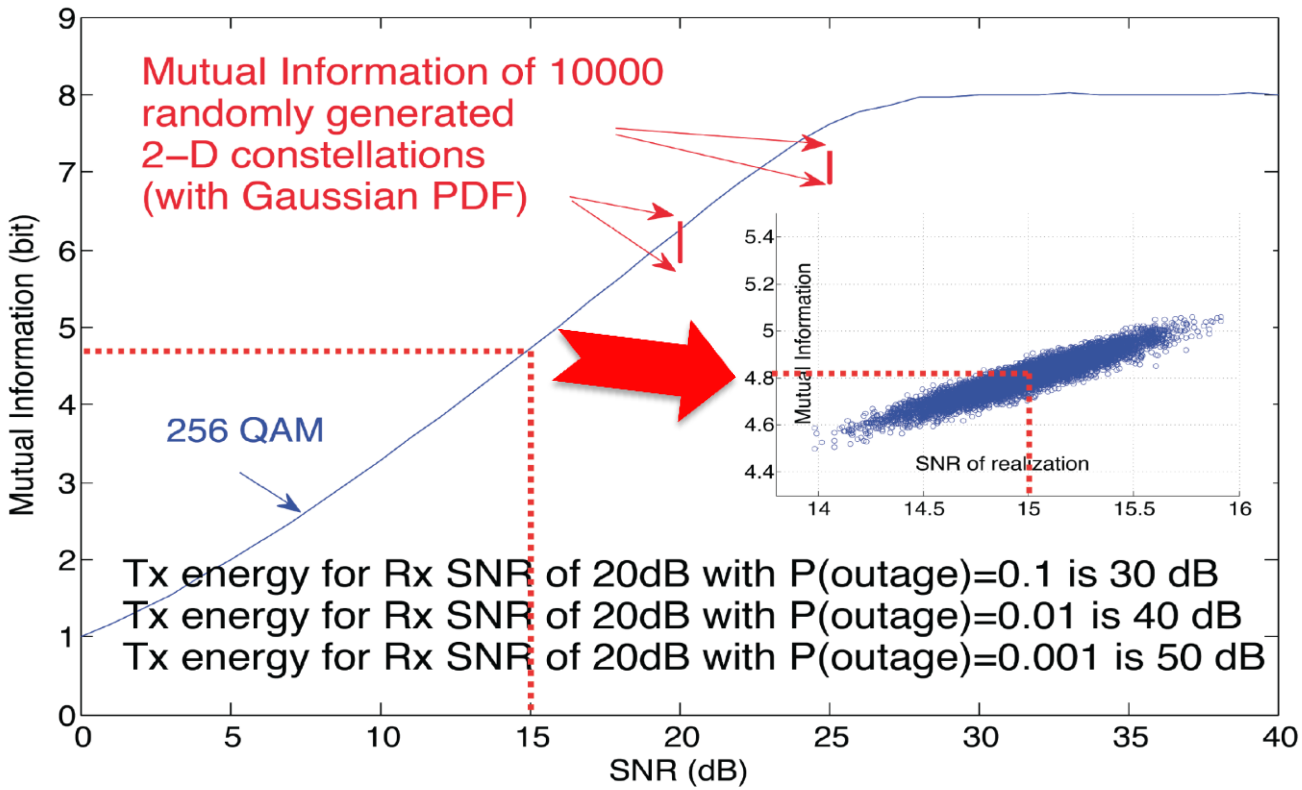
- Consider a slow Raleigh fading channel for which statistical average of the fading gain per receive antenna is one.
  - Using a single TX and Q RX antennas over such channel, mutual information averaged over different realizations of a constellation with L points approaches the capacity of $2Q$ parallel AWGN channels, each with unit energy, as $L \to \infty$.

Accuracy of the Computational Tool and its Simplified Version in Non-asymptotic Situations

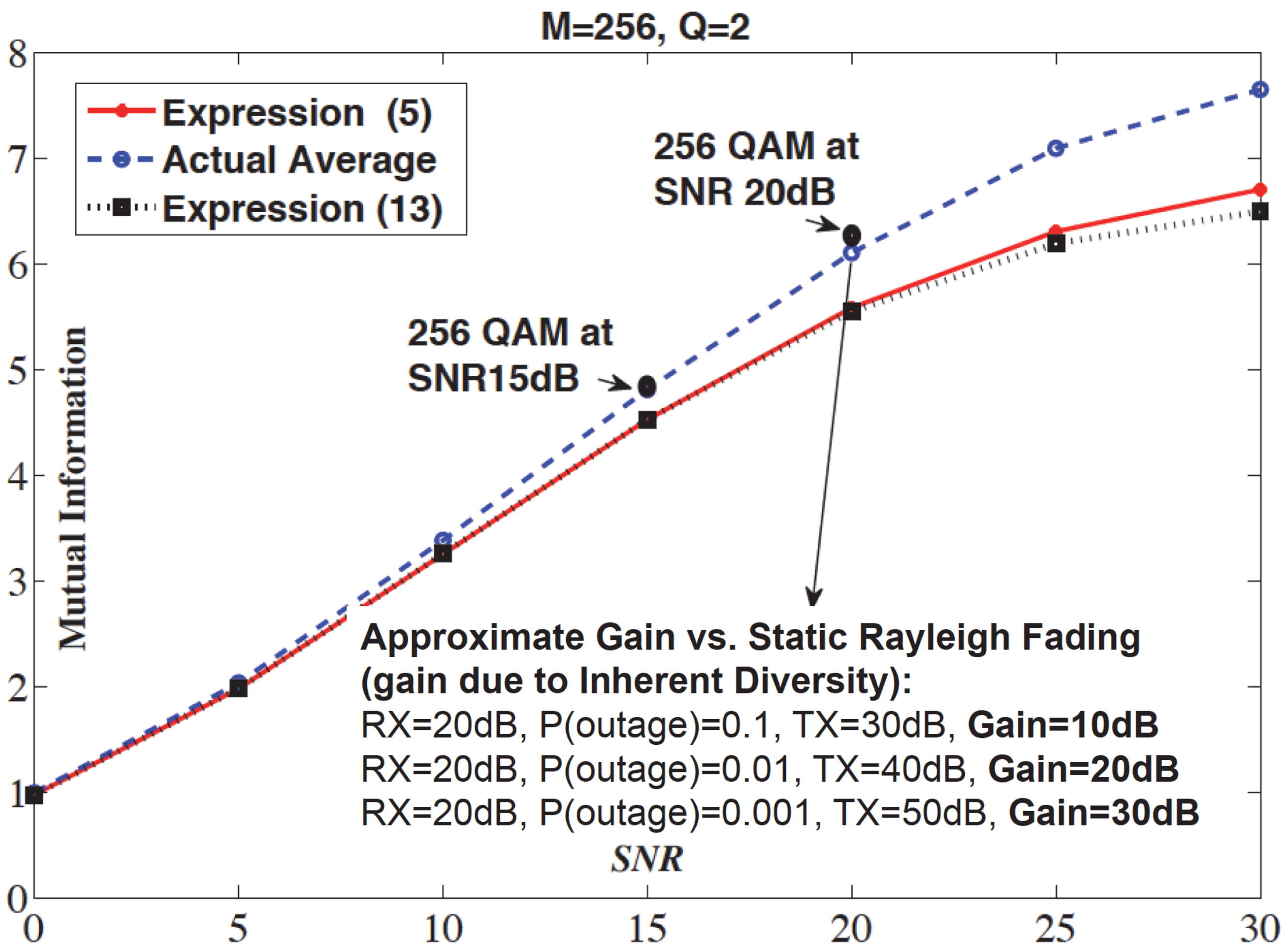


Main Benefit: Inherent Diversity in A Single Constellation

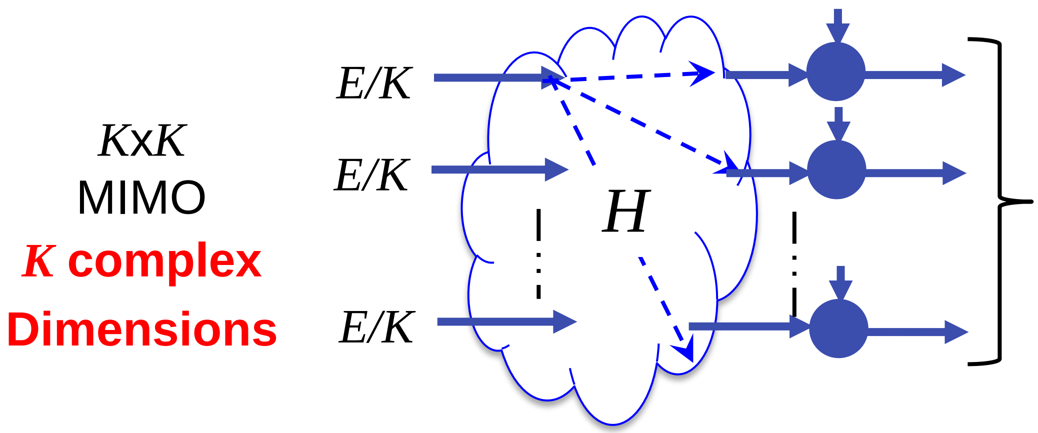
- Conventional methods suffer from deep fades in slow fading.
- This problem disappears as “Good and Bad” channel realizations contribute to forming the constellation.



Comparisons for the Average Rate

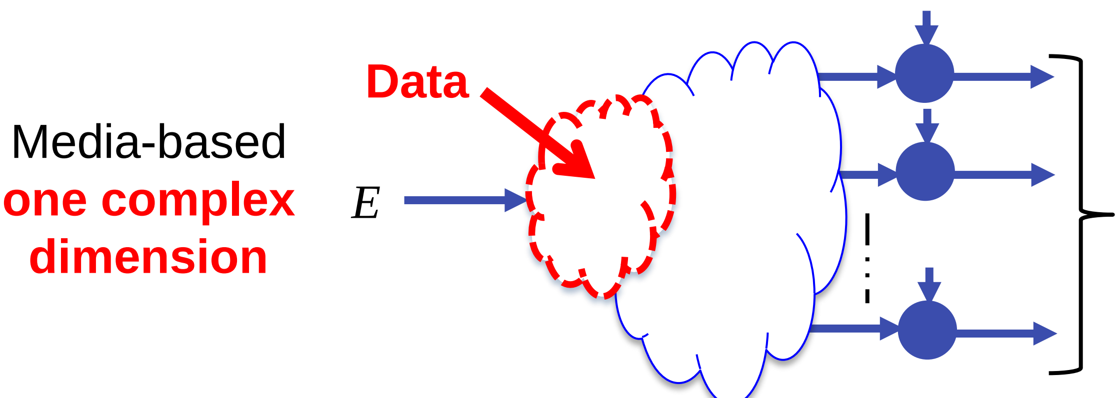


Media-based vs. Source-based



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

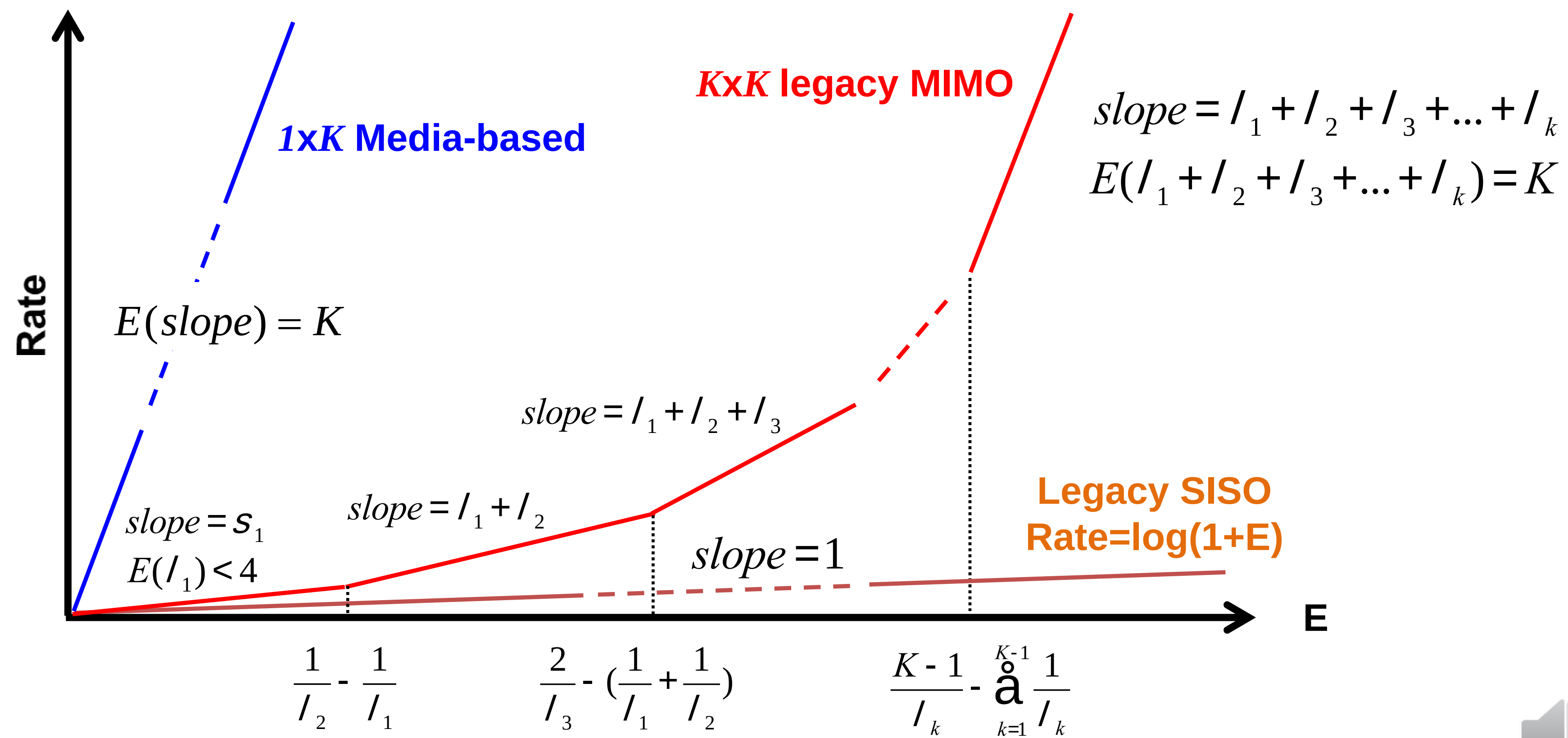
Better Performance



Total signal energy: *KE*
Basis: **Orthogonal**
Complex Dimension/sec/Hz: *K*

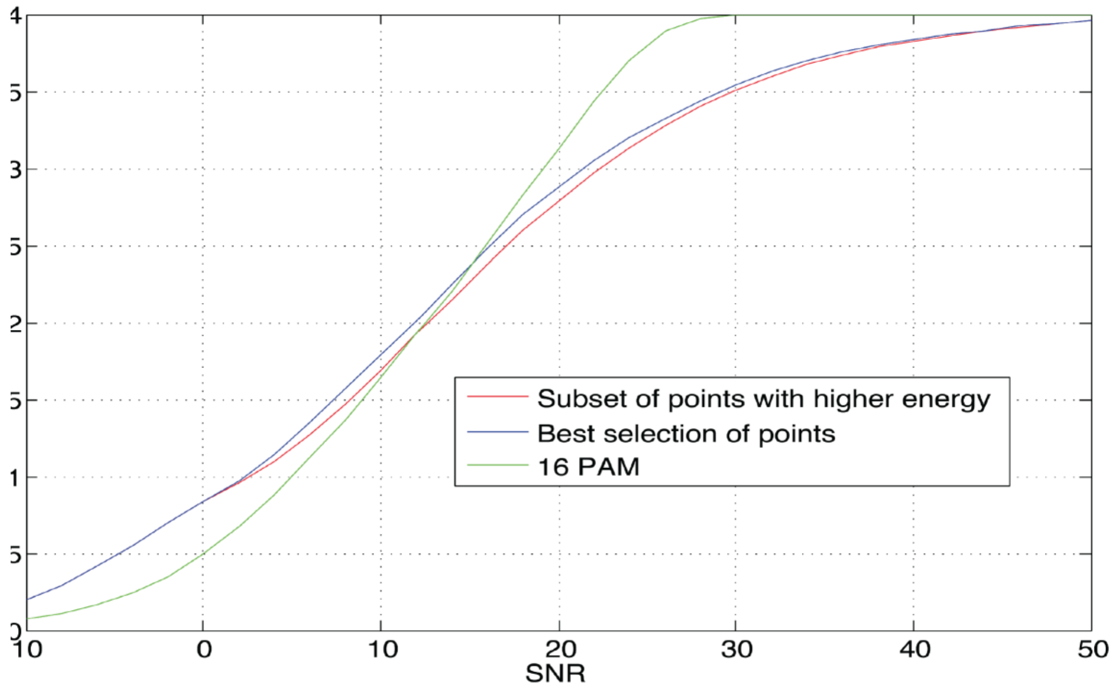
Media-based vs. Legacy Systems: Effective Dimensionality

$\lambda_1 > \lambda_2 > \ldots > \lambda_K$: Eigenvalues of a KxK Wishart random matrix



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.



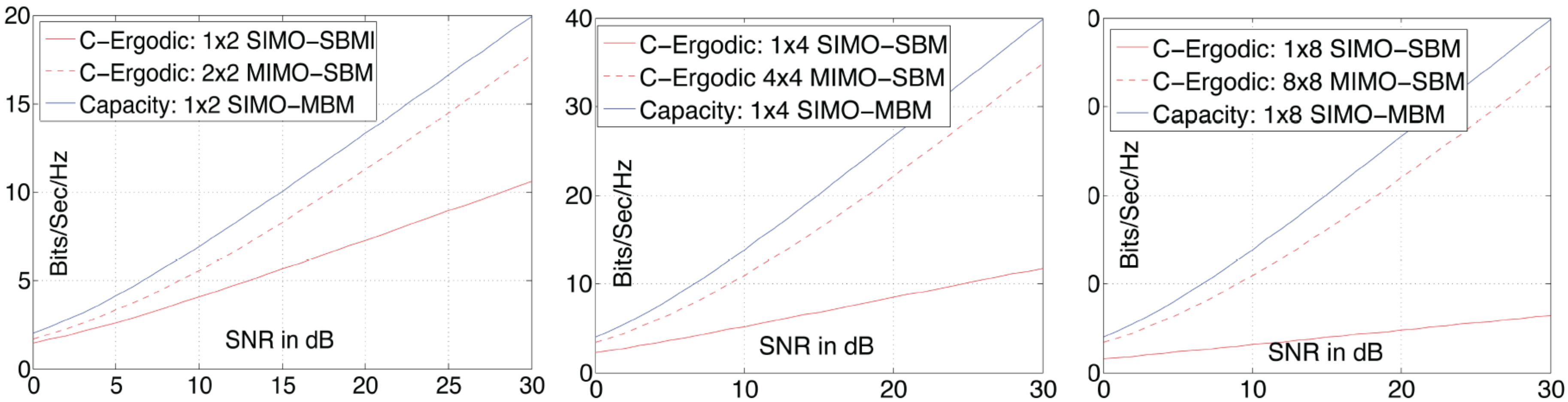
Media-based vs. Legacy Systems: Slope of Rate vs. SNR (dB) at SNR=0

- Legacy SISO: Slope=1
- Legacy *K*x*K* MIMO: **Maximum eigenvalue of a *K*x*K* Wishart matrix (upper limited by 4)**
- *1*x*K* Media-based: *K*

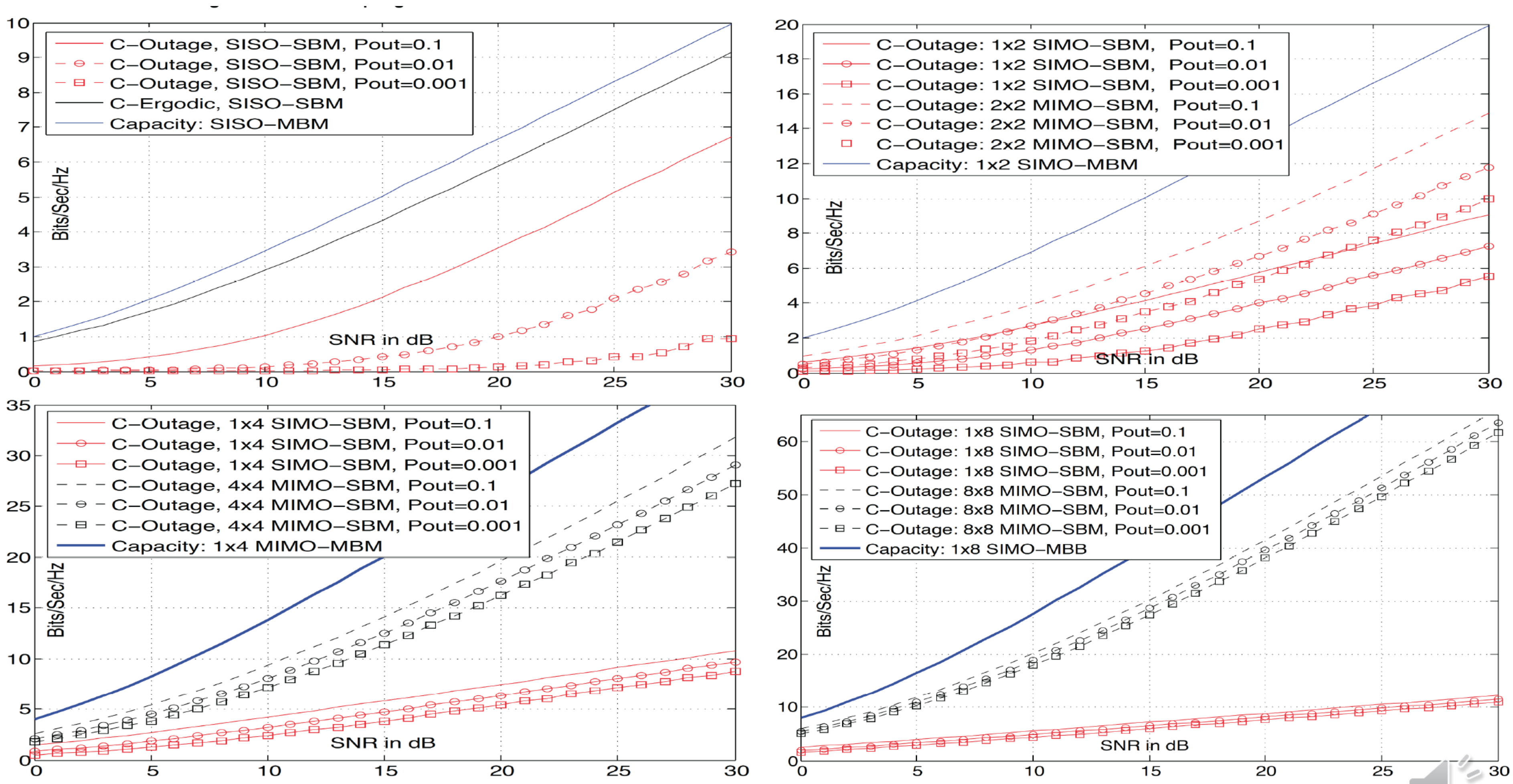
	L=1, K=2	*L=1, K=4*	*L=1, K=8*	*L=1, K=infinity*
*K*x*K* MIMO	1.75	2.45	2.96	4
*1*x*K* Media-based	2	4	8	Infinity

- *Selection Gain* further increases the slope of media-based to: $\max \left\| \vec{c}_i \right\|, \ i = 1, \cdots, L.$
  - **e.g. average slope scales as** $\log(L)$ for SISO case.

Comparison with Ergodic Capacity



Comparison with Outage Capacity



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