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# Beyond MIMO: Media-based Wireless


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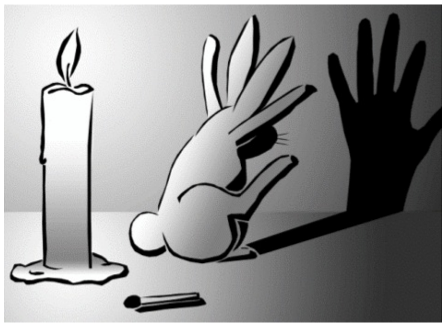
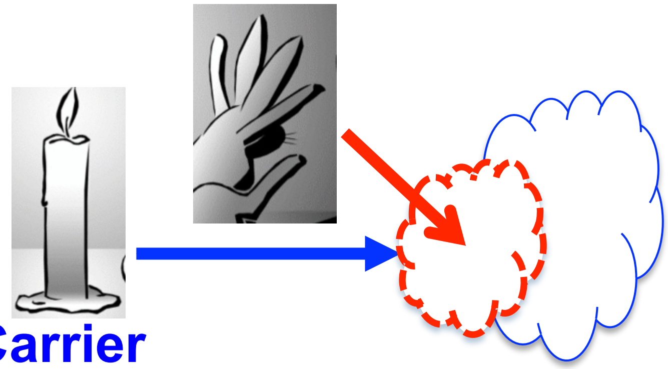
# A New Paradigm in Wireless: Media-based vs. (legacy) Source-based

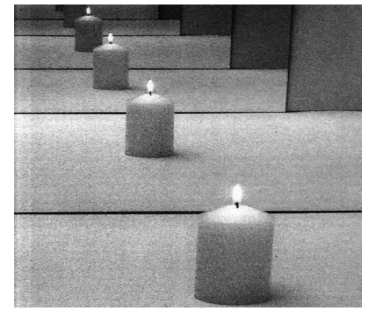
- Main idea:
  – Embed the information in the variation of the RF channel external to the antenna.
- Benefits vs. (legacy) source-based wireless:
    - Additive information over multiple receive antennas (similar to MIMO) with the advantages of:
      – Using a single transmit antenna
      – Independence of noise over receive antennas
    - Inherent diversity over a static channel (constellation diversity) using single or multiple antenna(s)
      – Diversity order improves with the number of constellation points
      – Unlike MIMO, diversity does not necessitates 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.
    - Harvesting transmit energy using multiple receive antennas

# Media-based Wireless





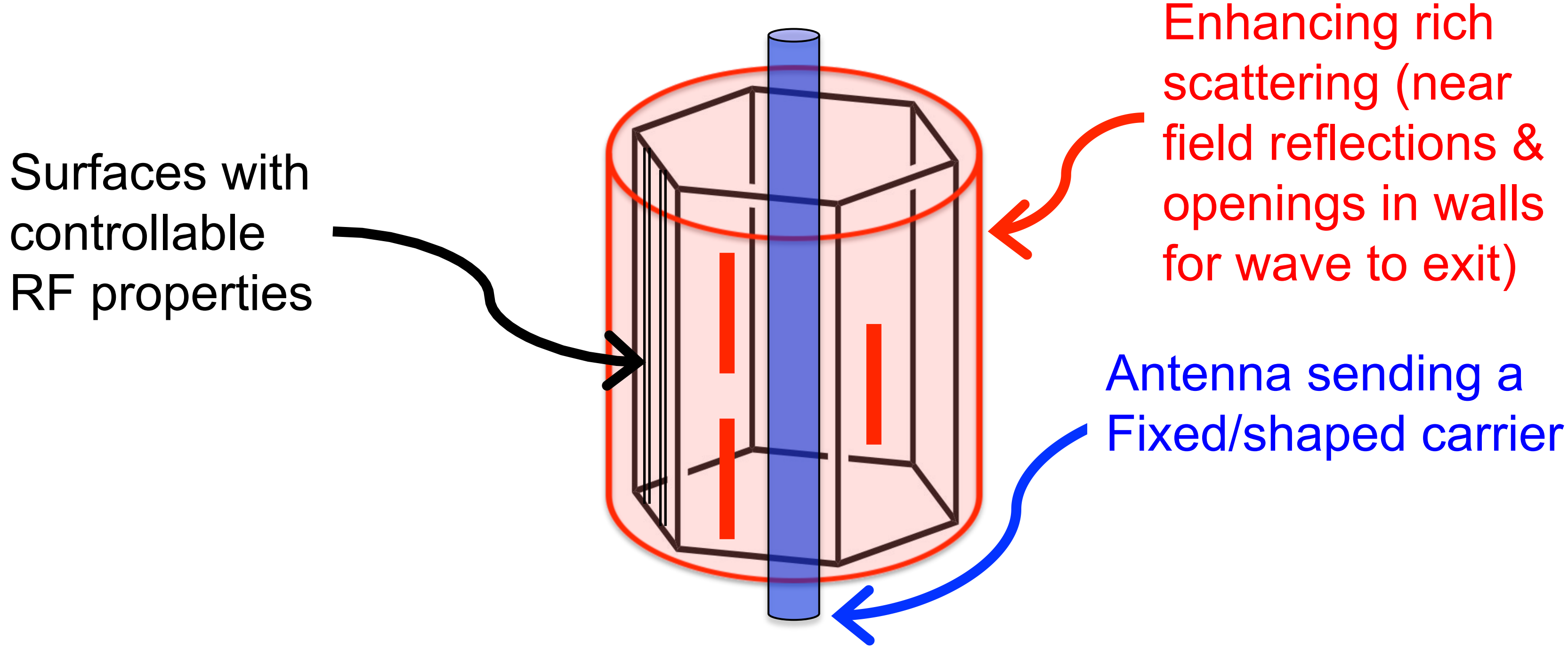

Exponential growth due to rich scattering



- Keep the source shining and change the media
- Enjoy rich variations with small changes in media
- Rich scattering environment: slightest perturbation in the environment causes independent outcomes.
- Variations of phase is critical and can be exploited with stable TX/RX synchronization using **two-way link** (continually sending back pilot from RX to TX).

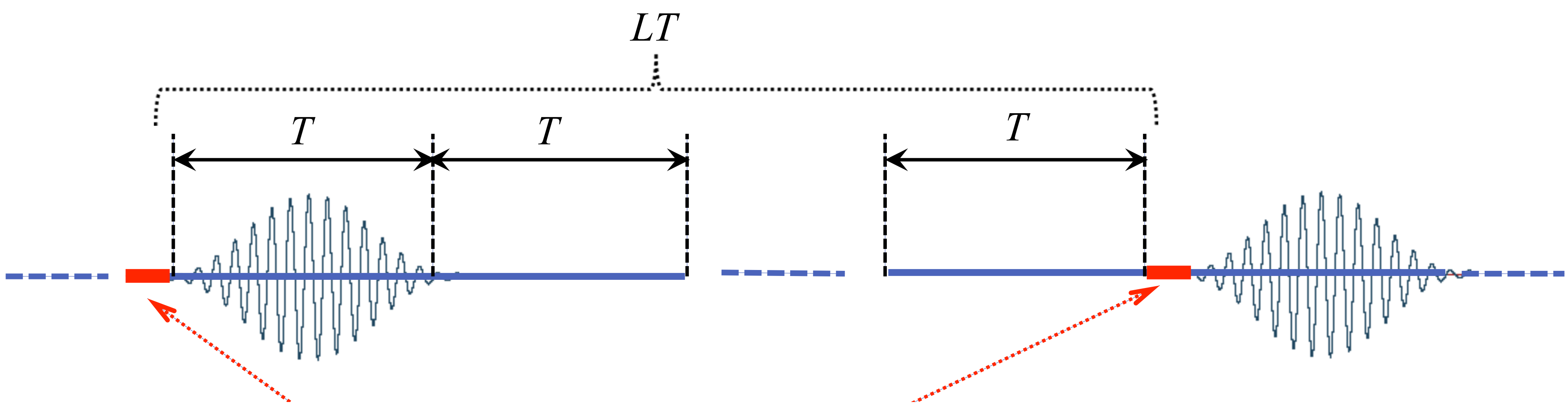
# How to Change the RF Channel?

## Just An Example




- Separately control some of RF properties, i.e. $\mu, \varepsilon, \sigma$ of each surface, e.g., on-off partial mirrors, according to the input data (**media-based**) or randomly (**security**).
- More details at: www.cst.uwaterloo.ca/2way

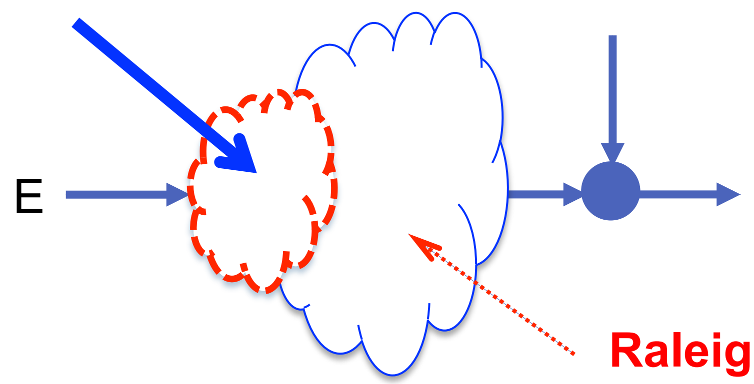
# Media-based: Signaling Scheme




**At these times, coded (FEC) bits are used to select one of possible channel states.**

**Coded Data**

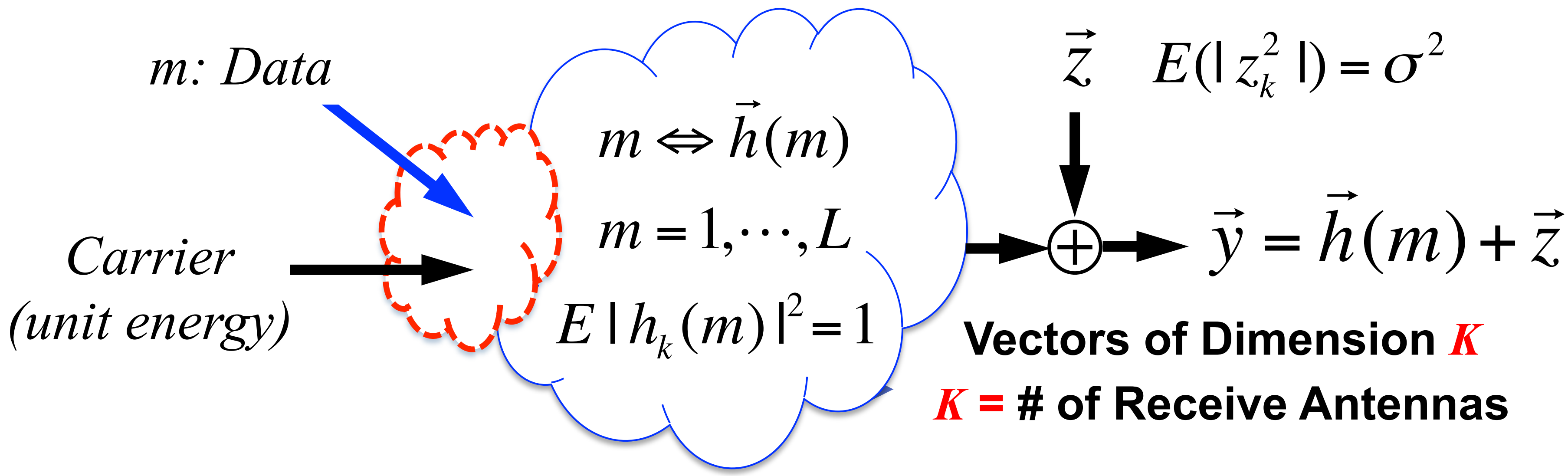
Media-based
**one complex dimension**




Total signal energy: LE
Basis: Orthogonal
Complex Dimensions: L

**Raleigh channel of impulse response of length L.**

# Media-based: Rate



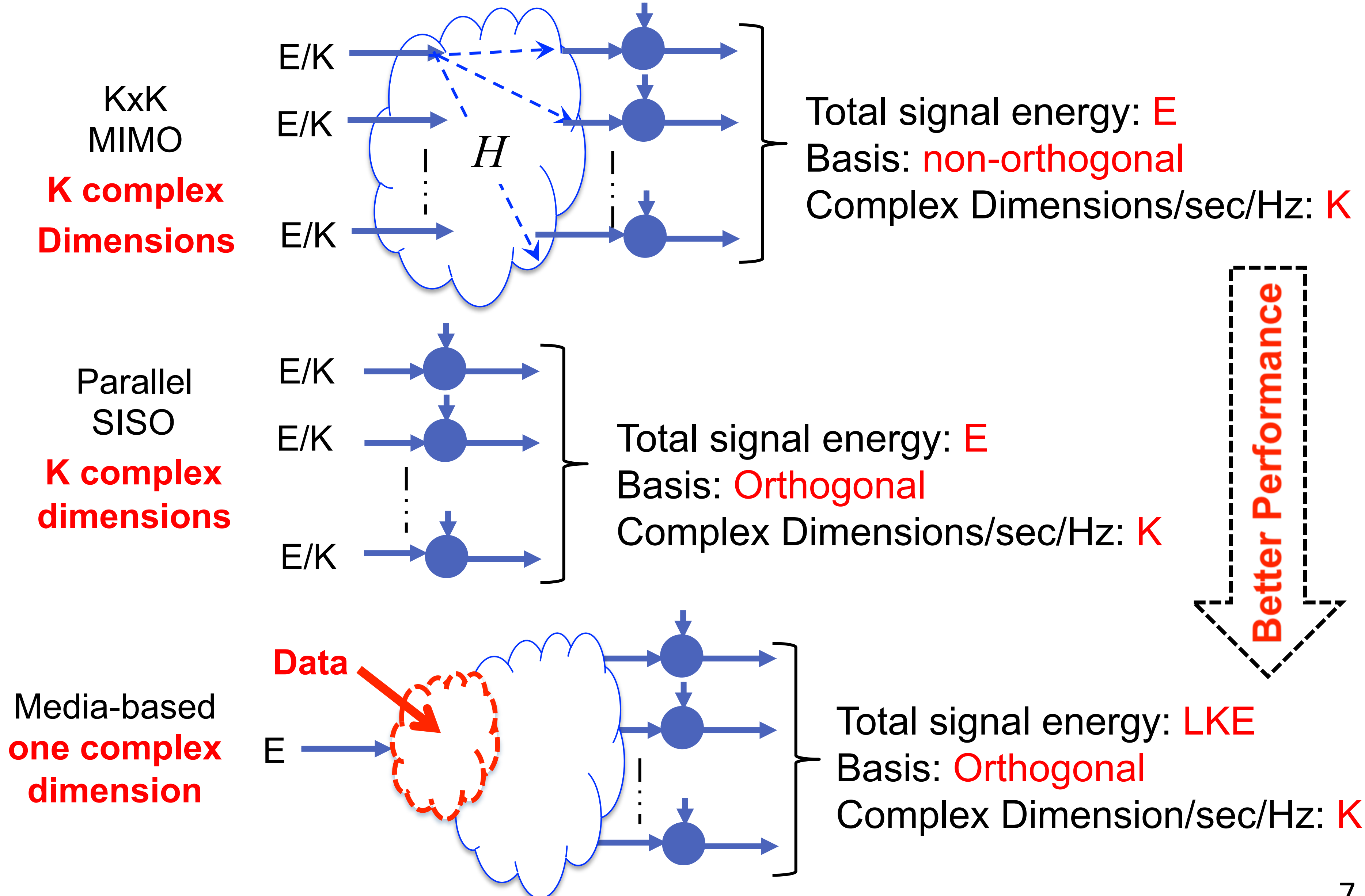

$$I(\vec{y};m) = I(\vec{y};\vec{h}(m)) = H(\vec{y}) - H(\vec{z}) = H(\vec{y}) - K\log_2(2\pi e\sigma^2)$$

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

$$H(\vec{y}) \approx \frac{1}{L}\sum_i |h_i|^2 \times \log_2(1 + 2\pi e\sigma^2)$$

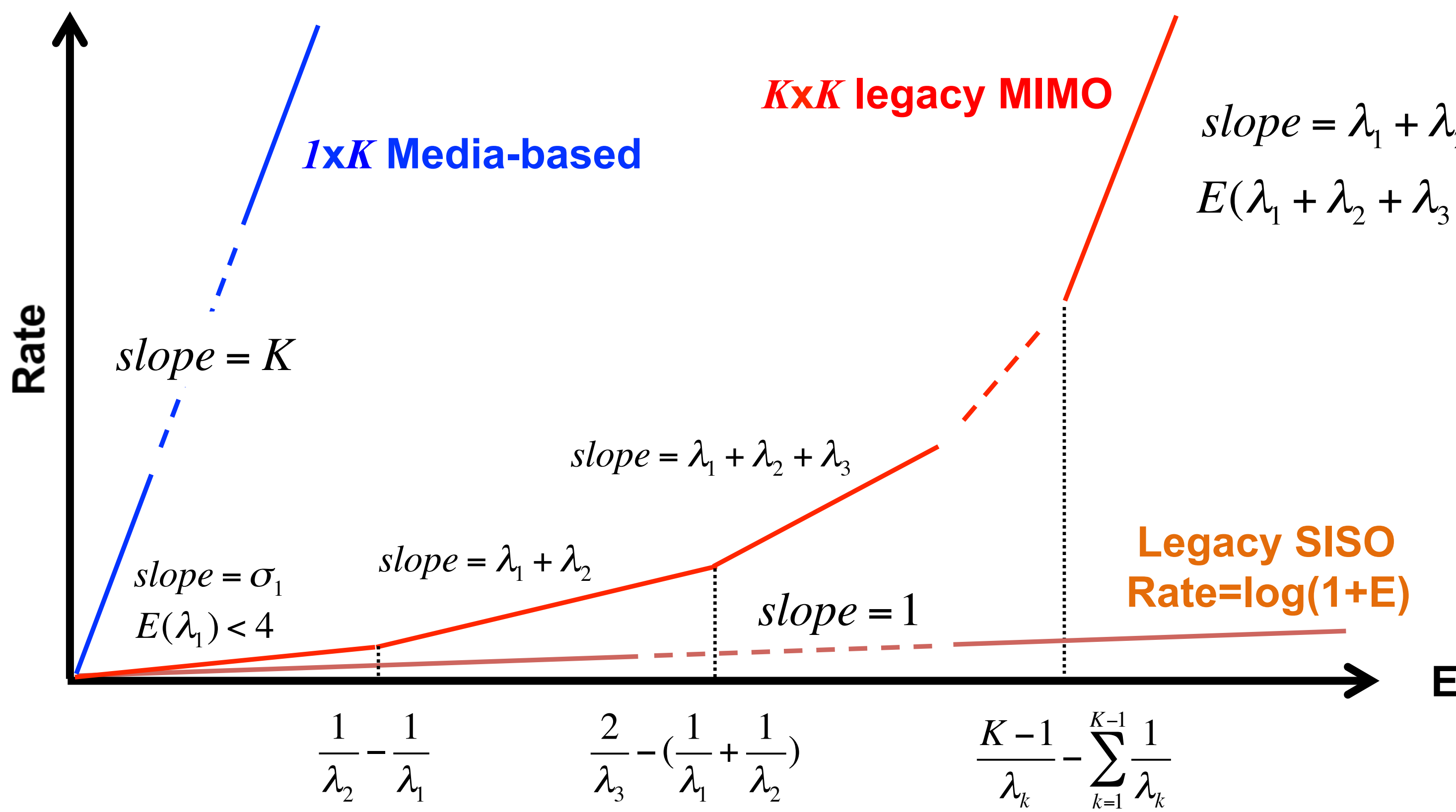
For low SNR, i.e., prior to saturation to $\log_2(L)$

# Media-based vs. Source-based



# Media-based vs. Legacy Systems: Effective Dimensionality

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



# Asymptotic Gain (for E→∞) in Rate and Energy

$$\begin{cases} C_{MIMO}(E) = K\log_2\left(\frac{E}{K}+\frac{1}{K}\sum\frac{1}{\lambda_k}\right) + \sum\log_2(\lambda_k) \\ C_{Media-based}(E) = K\log_2(1+LE) \end{cases}$$

$$E\to\infty \begin{cases} \overline{C_{MIMO}(E)} \approx K\log_2\left(\frac{E}{K}\right) + \overline{\sum\log_2(\lambda_k)} = K\log_2(E) + \overline{\sum\log_2\left(\frac{\lambda_k}{K}\right)} \\ C_{Media-based}(E) \approx K\log_2(LE) \end{cases}$$

$$\Delta E(L,K) \cong \frac{10}{K\times\log_2(10)}\overline{\sum\log_2\left(\frac{\lambda_k}{KL}\right)} \qquad \Delta R(L,K) \cong \overline{-\sum\log_2\left(\frac{\lambda_k}{KL}\right)}$$

# Asymptotic Gain (for E→∞) in Energy & Rate

$$\Delta E(L,K) \cong \frac{10}{K \times \log_2(10)} \overline{\sum \log_2(\frac{\lambda_k}{KL})}, \qquad \Delta R(L,K) \cong \overline{-\sum \log_2(\frac{\lambda_k}{KL})}$$

| $K$ | $L$ | $KL$ | $\Delta R$ | $\Delta E$ |
|---|---|---|---|---|
| **1** | **2** | **2** | **4.2 bits** | **6.4 dB** |
| **2** | **1** | **2** | **4.2 bits** | **9.4 dB** |
| **1** | **4** | **4** | **13.0 bits** | **9.8 dB** |
| **4** | **1** | **4** | **13.0 bits** | **15.8 dB** |
| **1** | **8** | **8** | **34.8 bits** | **13.1 dB** |
| **8** | **1** | **8** | **34.8 bits** | **22.1 dB** |
| **1** | **16** | **16** | **86.4 bits** | **16.2 dB** |
| **16** | **1** | **16** | **86.4 bits** | **28.2 dB** |

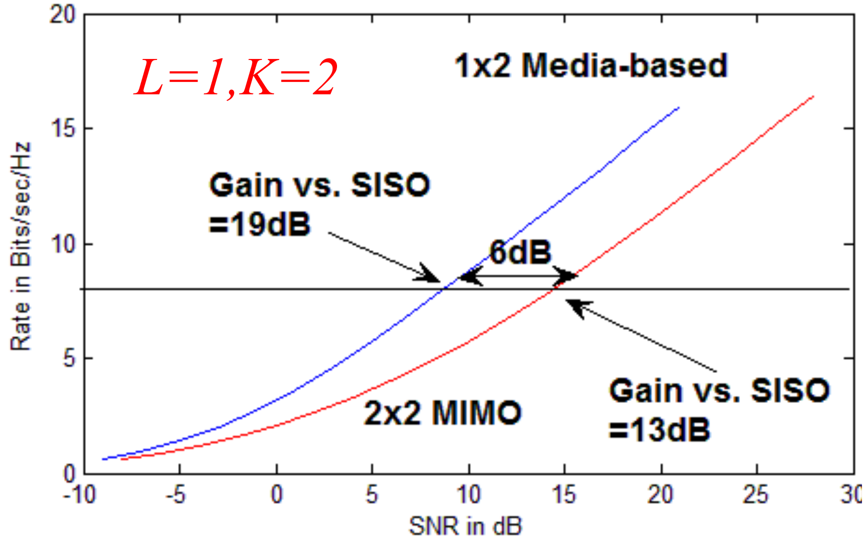
# Media-based vs. Legacy Systems: Slope of Rate vs. SNR (dB) at SNR=0

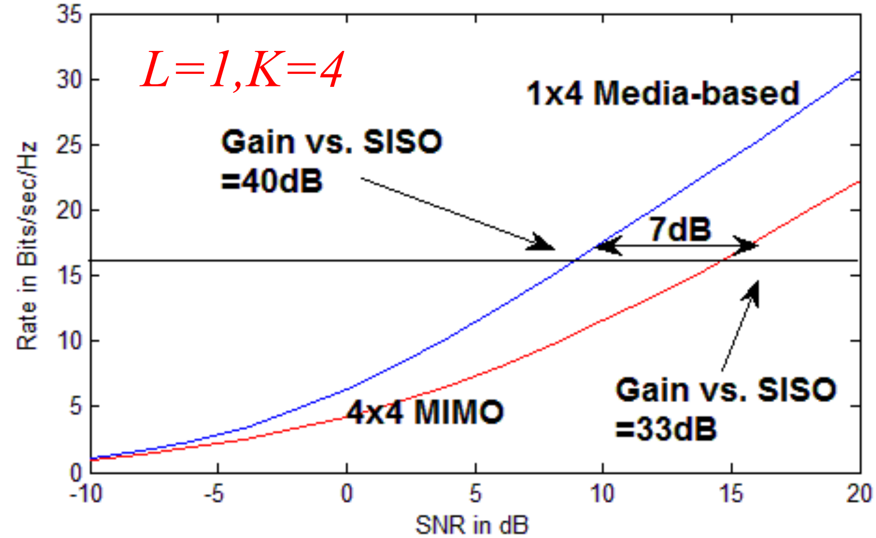
- Legacy SISO: Slope=**1**
- Legacy KxK MIMO: **Maximum eigenvalue of a KxK Wishart matrix (upper limited by 4)**
- 1xK Media-based: **LK**

| | L=1, K=2 | L=1, K=4 | L=1, K=8 | L=1, K=infinity |
|---|---|---|---|---|
| KxK MIMO | 1.75 | 2.45 | 2.96 | 4 |
| 1xK Media-based | 2 | 4 | 8 | Infinity |

# Media-based vs. Legacy MIMO

**2 or 4 antenna with a rate of 4 bits/s/Hz/antenna is typical in current systems**



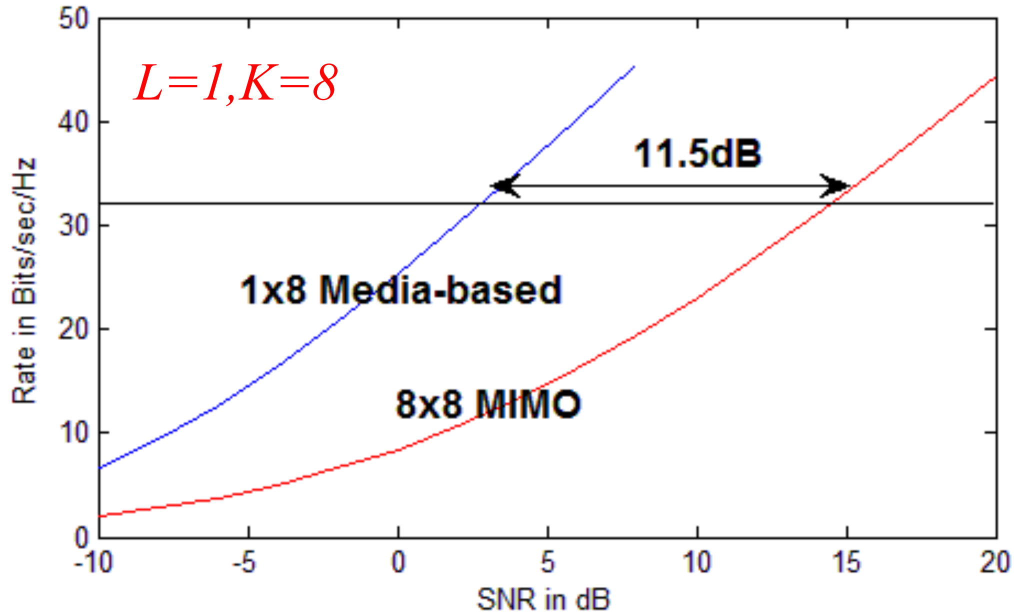




Relative Gain of Media-based will be much higher for $L>1$, typically $L>>1$

- MIMO works well only at high SNR values, but in some applications, e.g., optical transmission where MIMO is formed over different polarizations, or very lower power wireless, it is important to use spatial degrees of freedom offered by multiple antennas to save energy.

# Media-based vs. Legacy MIMO

8 antenna systems with a rate of 4 bits/s/Hz/antenna




Relative Gain of Media-based will be much higher for $L>1$, usually $L>>1$.

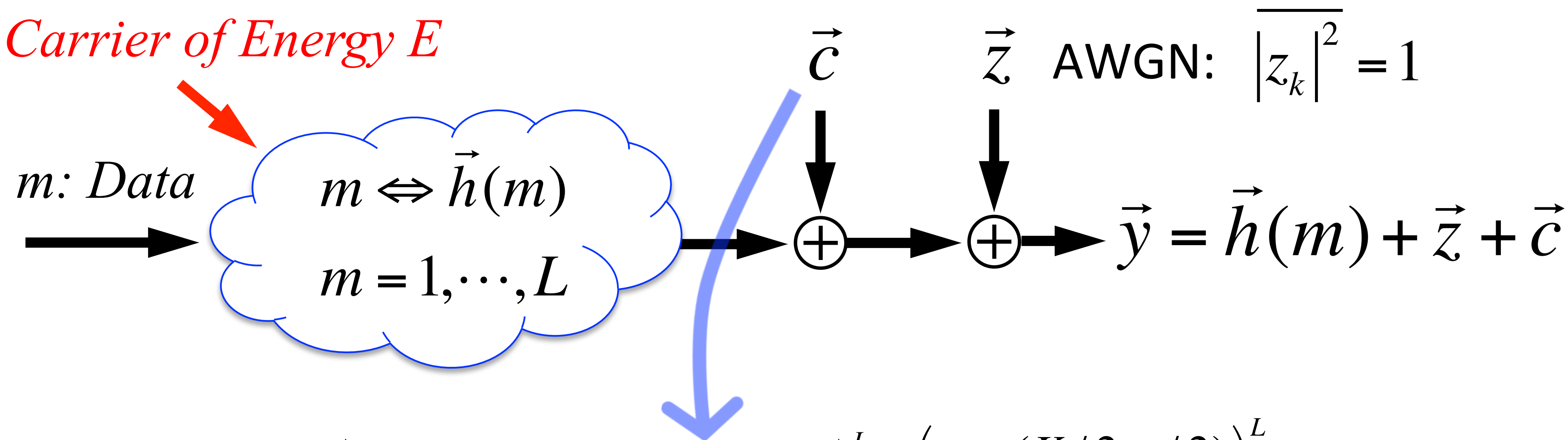
- 1xK media-based is significantly simpler than KxK MIMO.
- **At low SNR**, unlike MIMO, media-based is optimum.
- **At high SNR**, energy saving of media-based vs. MIMO is significant and increases with the number of antennas.

# Some Remarks

- Power spectrum for media-based:
  - Linear time-varying (LTV) while legacy systems are linear time-invariant (LTI).
  - LTV can cause frequency expansion.
  - Received Power Spectrum: Average of channels' spectrums times input spectrum
  - Input spectrum is shaped to limit the bandwidth.
- Equalization:
  - Channels with an impulse response of length $L$ provides $L$ extra dimensions per receive antenna (inserting time gaps between subsequent transmissions).

# Gain due to Inherent Diversity:

## Typicality of Random Constellation




$$P\left(\|\vec{c}\|^2 > x\right) = \left(1 - \int_0^{x/2} t^{K/2-1} e^{-t} dt / \Gamma(K/2)\right)^L = \left(1 - \frac{\gamma(K/2, x/2)}{\Gamma(K/2)}\right)^L$$

$$\overline{\|\vec{c}\|^2} = 2\int_0^{\infty} e^{-Ly} \left( \sum_{i=0}^{K/2-1} \frac{y^i}{\Gamma(i+1)} \right)^L dy = 2\int_0^{\infty} e^{-Ly} \sum_{j=0}^{L(K/2-1)} A_j y^j \, dy = 2 \sum_{j=0}^{L(K/2-1)} A_j \frac{\Gamma(j+1)}{L^{j+1}}$$

$$\overline{\|\vec{c}\|^2} \approx \frac{1}{L} \qquad and \qquad L \to \infty, L >> Q \Rightarrow \overline{\|\vec{c}\|^2} \to 0$$

# Modeling Discrete Constellation= Additional Additive Noise Variance of Additional Noise Power

$$\overline{\|\vec{c}\|^4} = \int_0^\infty \left(1 - \frac{\gamma(K/2, \sqrt{x}/2)}{\Gamma(K/2)}\right)^L dx = \int_0^\infty \left(1 - \left(\frac{\sqrt{x}}{2}\right)^{K/2} e^{-\sqrt{x}/2} \sum_{i=0}^{\infty} \frac{(\sqrt{x}/2)^i}{\Gamma(K/2+i+1)}\right)^L dx$$

$$= 8\int_0^\infty y e^{-Ly} \left(\sum_{i=0}^{K/2-1} \frac{y^i}{\Gamma(i+1)}\right)^L dy = 8\int_0^\infty e^{-Ly} \sum_{j=0}^{L(K/2-1)} A_j y^{j+1}\, dy = 8 \sum_{j=0}^{L(K/2-1)} A_j \frac{\Gamma(j+2)}{L^{j+2}}$$

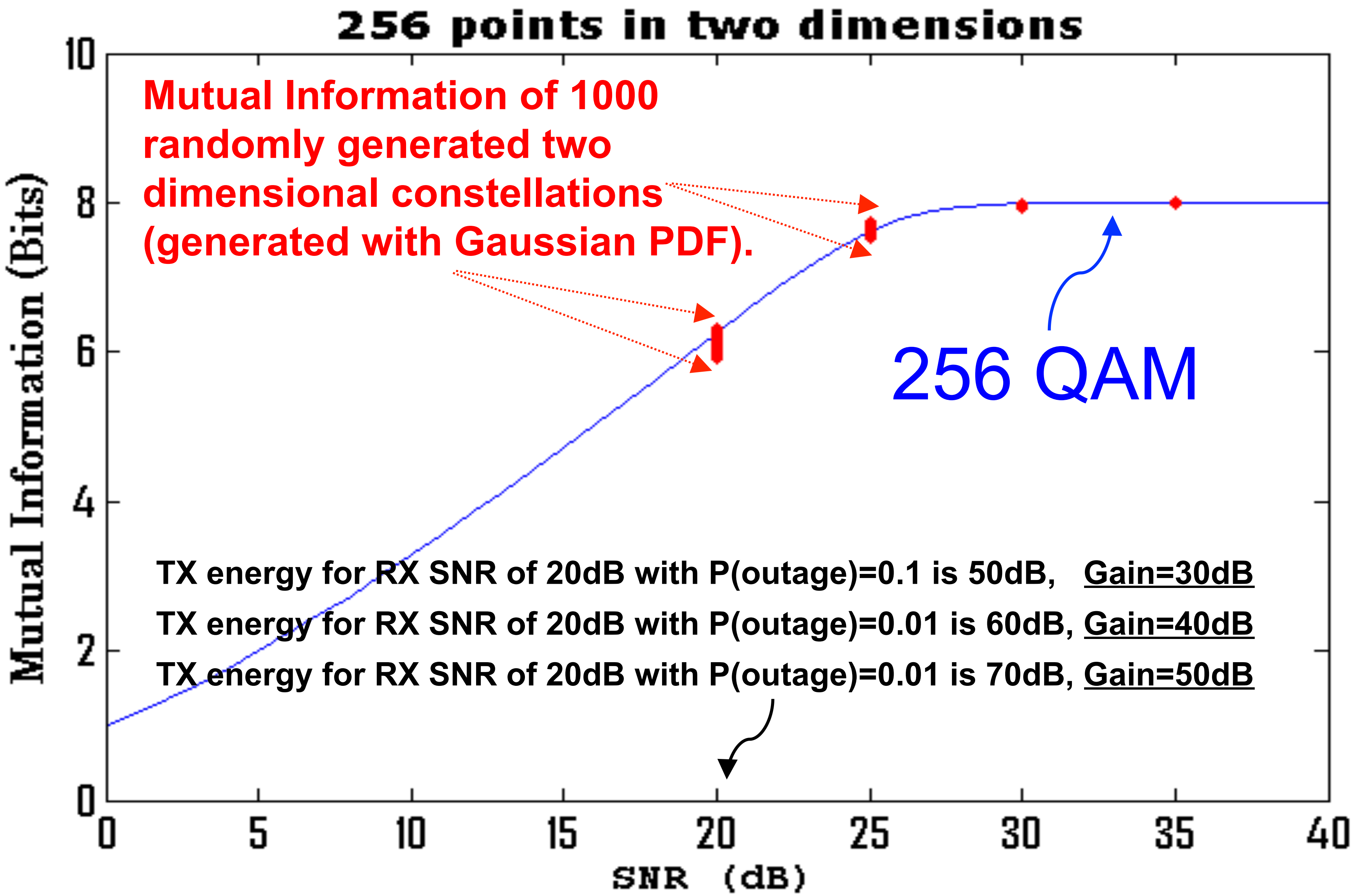
$$\overline{\|\vec{c}\|^4} - \left(\overline{\|\vec{c}\|^2}\right)^2 \approx 8 \sum_{j=0}^{L(K/2-1)} A_j \frac{\Gamma(j+2)}{L^{j+2}} - \left(2 \sum_{j=0}^{L(K/2-1)} A_j \frac{\Gamma(j+1)}{L^{j+1}}\right)^2$$

Two dimensional space: $Q = 1 \Rightarrow \overline{\|\vec{c}\|^2} = \frac{2}{L}$ *and* $\sqrt{\mathrm{var}\left(\|\vec{c}\|^2\right)} = \frac{2}{L}$

# Example for Behavior of Mean and Standard Deviation of Additional Noise

| Constellation with L=256 points | | | |
| --- | --- | --- | --- |
| | **2 dimensions (Q=1)** | **4 dimensions (Q=2)** | **8 dimensions (Q=4)** |
| **Mean** | 0.0078 | 0.1619 | 0.9140 |
| **Standard Deviation** | 0.0078 | 0.0870 | 0.1363 |

# Inherent Diversity Gains



# SISO Case Revisited

- TX block is a train of $K$ consecutive base TX signals, followed by $L$-$1$ zeros prior to the next TX block.
- Channel in changed in each of $K$ time slots among $2^r$ possibilities, resulting in a linear system with a random impulse response.
  - Time shift in input results in the same time shift in the response.
  - Oversample RX signal (sum of time-shifted responses) by $L$.
    - $KL$ samples are full rank, yielding $LK^2/(L+K-1)$ dimensions per unit time.
    - Extra dimensions are correlated, degrading the performance.
    - Noise is correlated, improving the performance.
    - Iterative or Trellis decoding can be used for detection.
  - Source code-book is composed of a discrete set of shells (circular shells) with uniform phase.

More discussion on Media-based, including discussions on embedding information in both source and channel are at: www.cst.uwaterloo.ca

# Realizing (external to antenna) RF Perturbation

- Objective: Create several random, selectable, options for propagation path
  - Simpler than traditional beam-forming
    - No need for tuning/control, having specific patterns, or concentration of energy

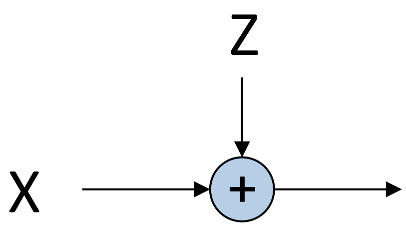
# Candidates for RF Channel Perturbation

- Photonic microwave
  - Changing waveguide property by surface plasma generated through light source
    - Uses several photo masks for plasma grating
  - Creating surface plasma in an external to antenna parasitic object
    - Uses light intensity to change plasma depth
- Electrically tunable impendence surface
  - Leaky wave antenna (based on a waveguide with tunable surface leakage)
  - Electrically changeable impedance surface as an external to antenna parasitic element
- Changing the permeability of ferrite under the effect of a magnetic field (e.g., via a current-carrying coil)
- Changing the permittivity of ferroelectric material under the effect of an electric field (e.g., via a bias voltage)
- Using meta-material as an external to antenna parasitic object with changeable refraction index

# Security Applications:
# One-time Pad (Vernam Cipher)

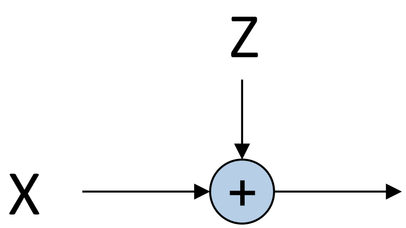
# Unbreakable Security: Vernam Cipher, One-time Pad

- Vernam Cipher, One-time Pad: Bit-wise XOR of a (non-reusable) mask with the message




$Y=X+Z \pmod 2$, $X,Y,Z$ are binary, $I(X;Y)=0$

- Generalization:




$Y=X+Z \pmod{2\pi}$, $X,Y,Z$ are angle, $I(X;Y)=0$

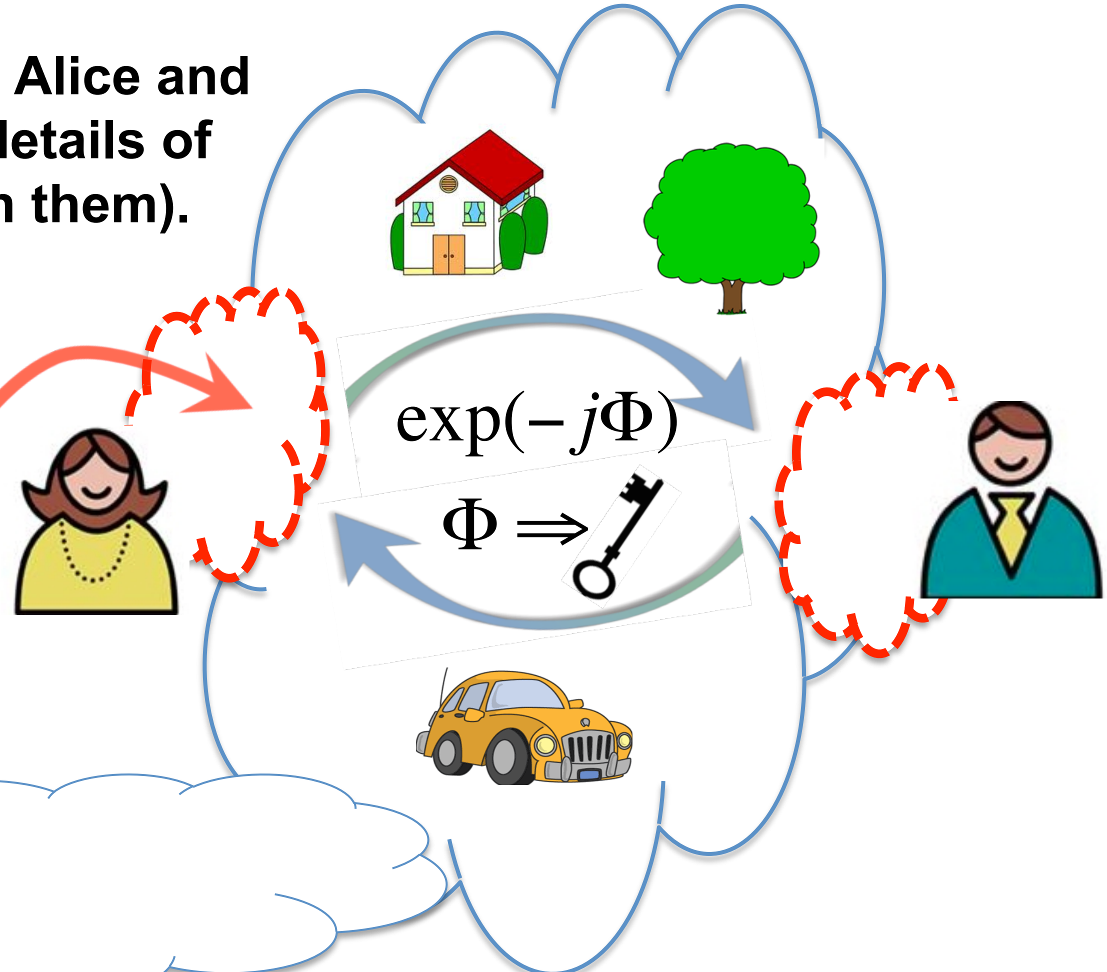
  – Happens naturally in wireless transmission
    - Each random phase can completely mask one PSK symbol.

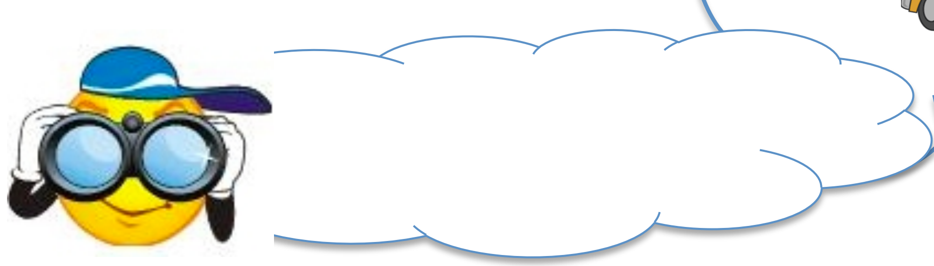
# Exploiting Channel Randomness to Share a Common Phase (Key)

**Closed loop gain is unique to Alice and Bob (determined by the fine details of the propagation path between them).**

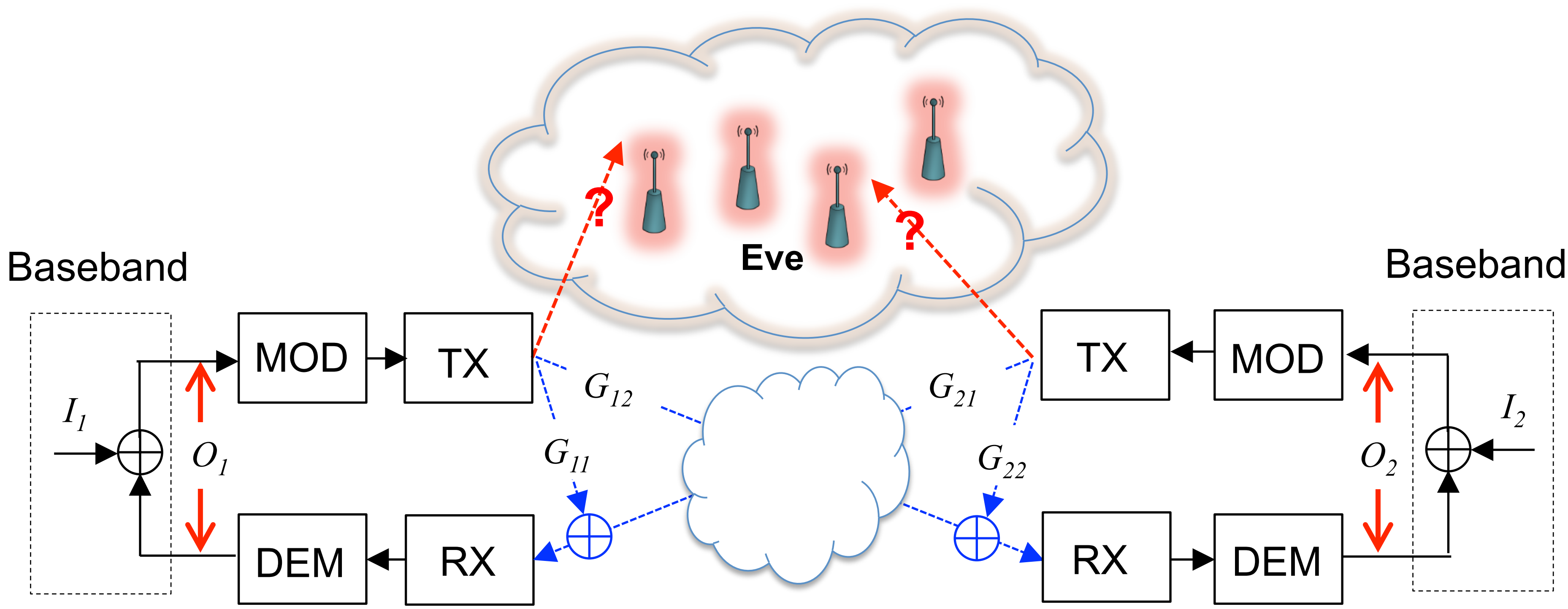
$$G = A\exp(-j\Phi)$$

**After extracting $\phi$ , RF environment around Alice and/or Bob is perturbed and a new phase value is extracted.**



# Key Generation: A Simpler Approach




$$\left.\frac{O_1}{I_2}\right|_{I_1=0} = \frac{G_{21}}{1-G_{12}G_{21}} \equiv \alpha \qquad \left.\frac{O_1}{I_1}\right|_{I_2=0} = \left.\frac{O_2}{I_2}\right|_{I_1=0} = \frac{1}{1-G_{12}G_{21}} \equiv \gamma \qquad \left.\frac{O_2}{I_1}\right|_{I_2=0} = \frac{G_{12}}{1-G_{12}G_{21}} \equiv \beta$$

# Exploiting Channel Randomness to Share a Common Phase (Key)

- **Key Point:** Each TX antenna should be used only once for each channel perturbation.
- Challenges:
  - Synchronizing the two parties to agree on phase.
  - Providing a new common random phase for each PSK symbol.
  - Two-way wireless solves both these challenges.
- Errors in common phase values are corrected by the overall channel code.
- Hardware implementation shows that the common phase values can be measured with very high precision.

# Exploiting Channel Randomness to Share a Common Phase (Key)

- Two algorithms are provided for key generation.
  - Please see www.cst.uwaterloo.ca/2way for details.

More discussion on security, including discussions on causing confusion using legitimate jamming,  embedding information in both source and channel are at:

www.cst.uwaterloo.ca

# Thank You!

# Questions/Comments?

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