Interference Exploitation via Symbol-Level Precoding for Physical layer security

Thang K. Nguyen

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Symbol level precoding

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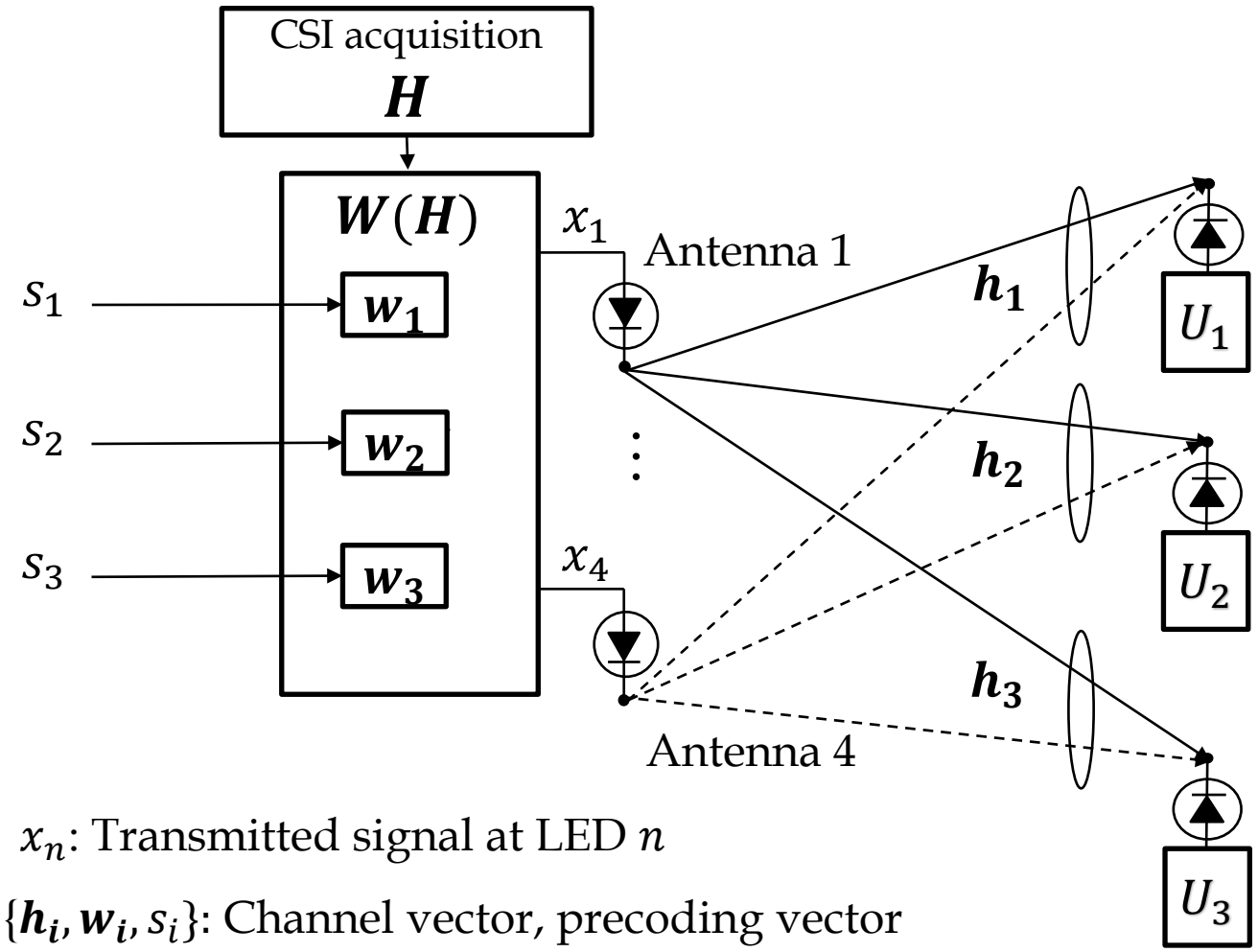
Conventional precoding

- Linearly encoding s_i by a vector $\boldsymbol{w_i}$ to reduce the effect of **multi-user interference (MUI)** in the multi-user transmission



x_n: Transmitted signal at LED n

$\{\boldsymbol{h_i}, \boldsymbol{w_i}, s_i\}$: Channel vector, precoding vector & data signal for i-th user

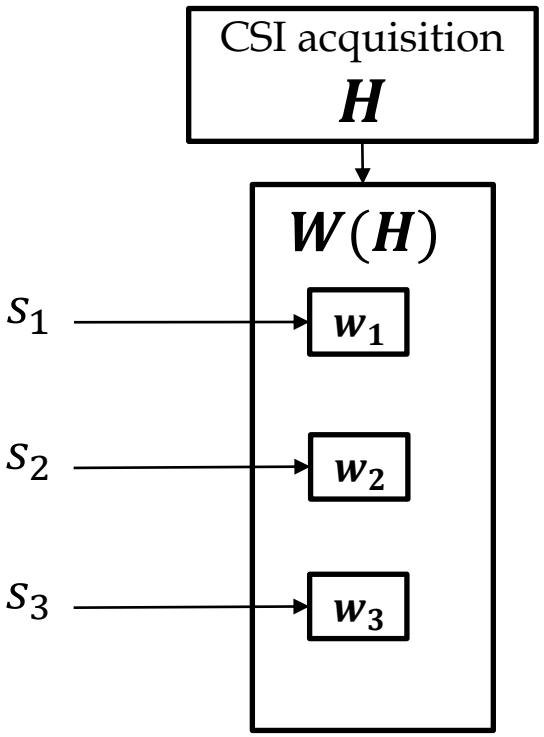
- Received signal at the i-th user

$$y_i = \boldsymbol{h_i w_i} s_i + \boldsymbol{h_i} \sum_{j=1, j\neq i}^{K} \boldsymbol{w_j} s_j + n_i$$

Target signal **MUI** Noise

- By generate precoding vector $\boldsymbol{w}$ based on the channel state information (CSI), MUI can be **mitigated or fully eliminated**

Conventional precoding



- Received signal at the i-th user

$$y_i = \boldsymbol{h_i w_i} s_i + \boldsymbol{h_i} \sum_{j=1, j\neq i}^{K} \boldsymbol{w_j} s_j + n_i$$

Target signal — MUI — Noise

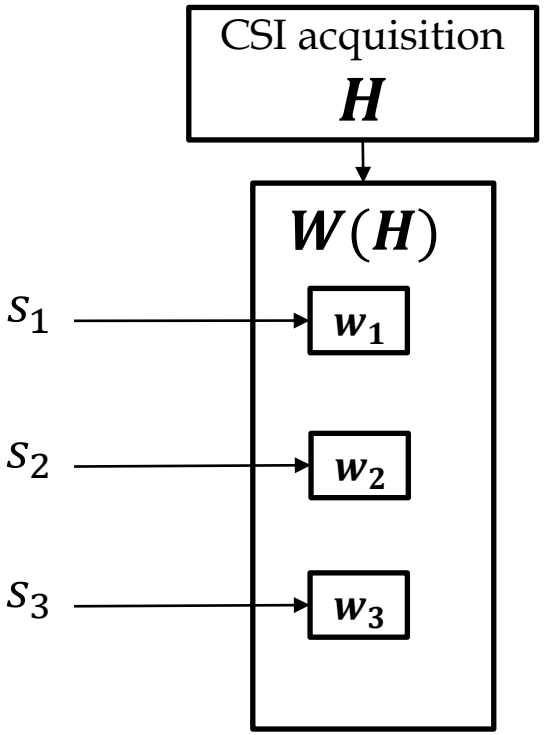
- The idea of conventional precoding is encoding the users' symbol in the way to reduce the **MUI** ($\boldsymbol{h_i} \sum_{j=1, j\neq i}^{K} \boldsymbol{w_j} s_j$)
- The encoding process of conventional precoding does not depend on the **users' symbols** (s_i), the precoding matrix is a function of only **channel gain matrix**: $\boldsymbol{W(H)}$

- Conventional precoding treats all the interference as **harmful** and try to eliminate it
- The **average** received SNR at the i-th user can be given as

$$\gamma_i = \frac{|\boldsymbol{h_i w_i}|^2}{|\boldsymbol{h_i} \sum_{j=1, j\neq i}^{K} \boldsymbol{w_j}|^2 + \sigma_i^2}$$

* Assuming that $E(|s_i|^2) = 1 \; \forall i$

Conventional precoding



Disadvantage

- The achievable rate is limited and do not improve with the increase in the number of antennas
- The effectiveness decreases with number of users due to treating all interference as harmful
- The performance is highly dependent on the correlation of users' channel vectors
- Less power efficient since it focuses on minimizing the effect of interference, which requires higher transmission power

➡ Conventional precoding is not suitable for high density networks with a large number of users

Symbol level precoding

- The conventional precoding is designed based on the CSI only and therefore operates on a block level.
- Only the power of the interference can be controlled, which leads to the statistical view that **the effect of interference is similar to noise and is harmful**

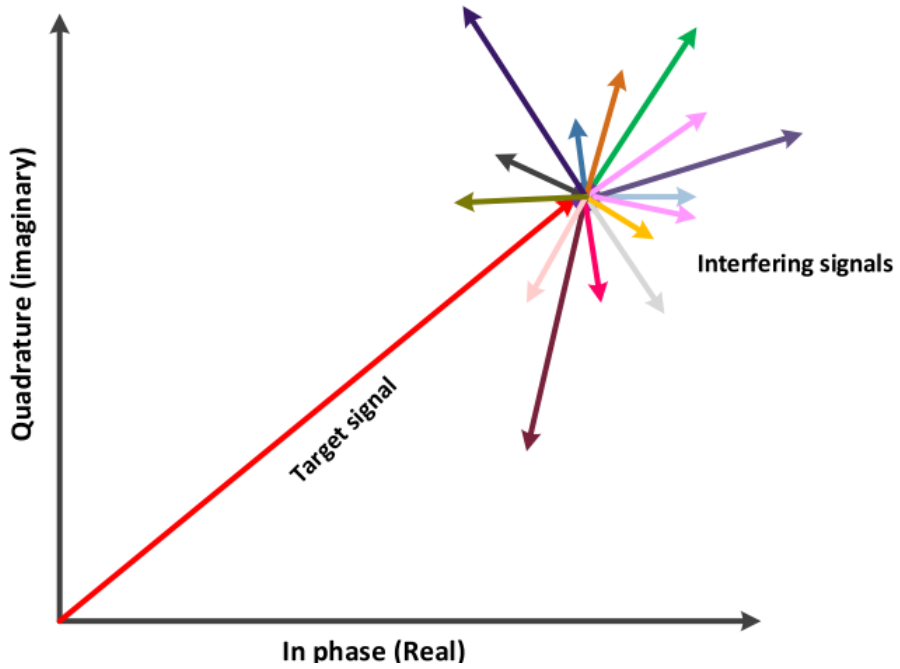
What is Interference ?

Is Interference All Harmful ?

$$y_i = \boldsymbol{h_i w_i} s_i + \boldsymbol{h_i} \sum_{j=1, j\neq i}^{K} \boldsymbol{w_j} s_j + n_i$$

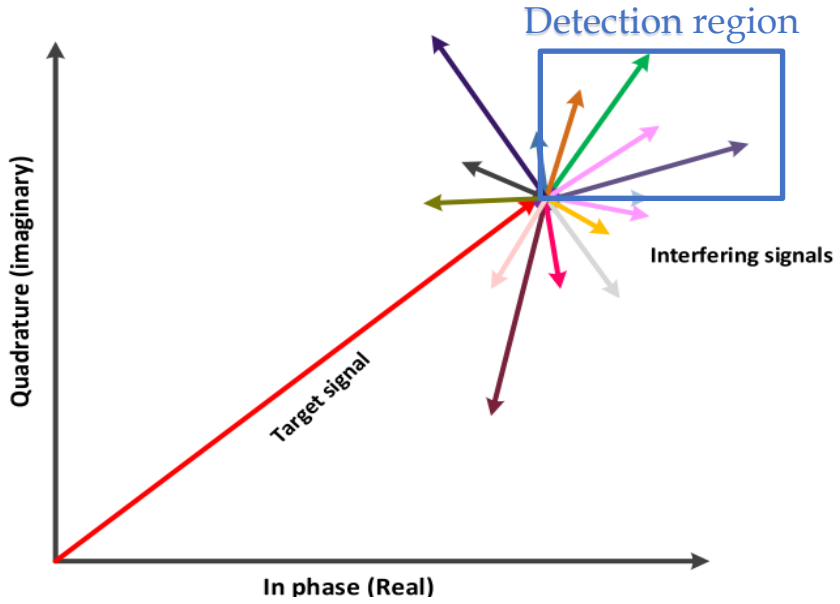
Target signal **MUI** Noise

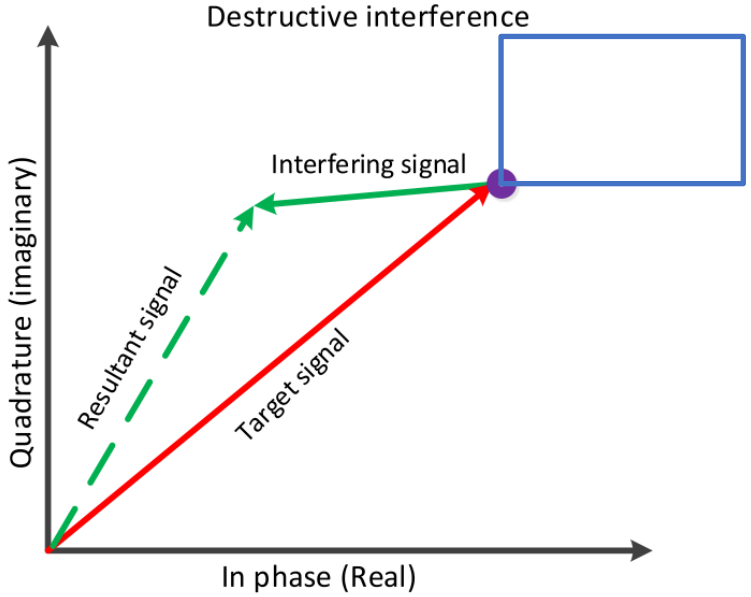
- Interference is a random deviation which can move the desired target signal in any direction
- The existence of interference is based on the observation that the transmit signals for different users are superimposed in multi-user transmissions

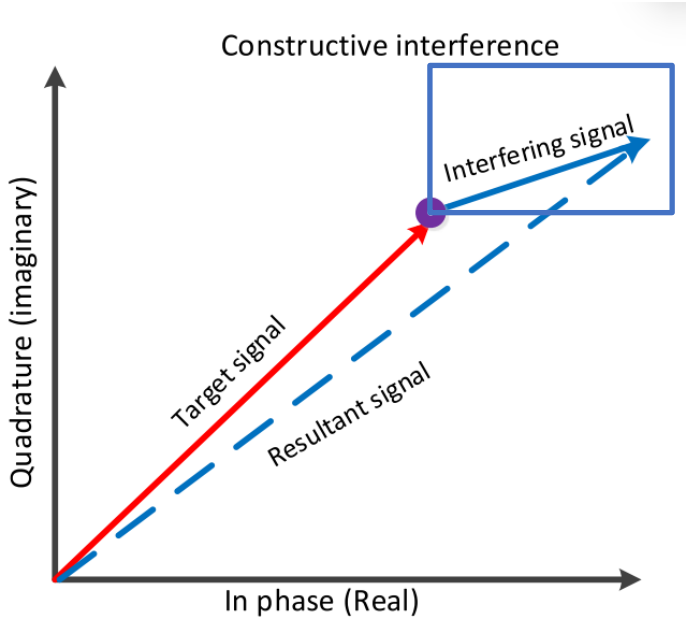


Symbol level precoding

- Interference is a random deviation which can move the desired target signal **in any direction**
  - It can move the desired target signal **into further the correct detection region** ⟶ Constructive interference
  - Or it can move the desired target signal **outside the correct detection region** ⟶ Destructive interference







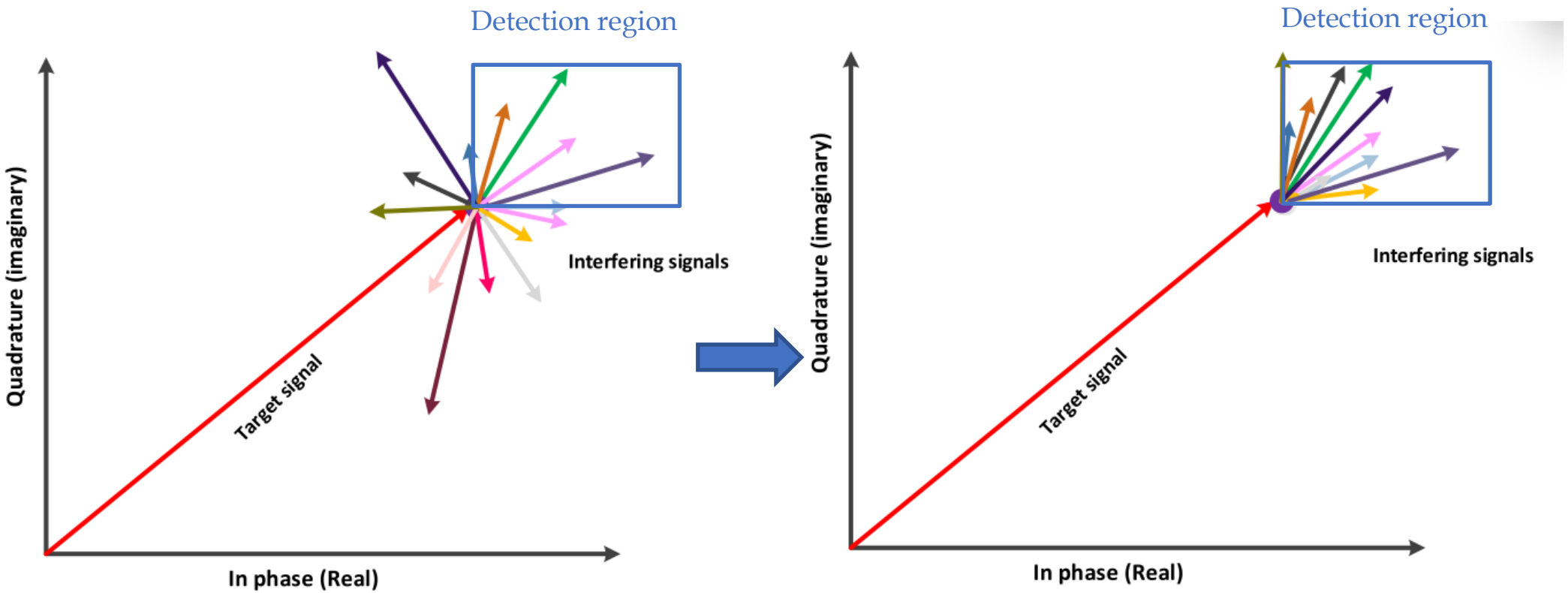
Is Interferences All Harmful ?

- Not all interference is harmful
- Interference can be exploited to enhance the target signal

Symbol level precoding

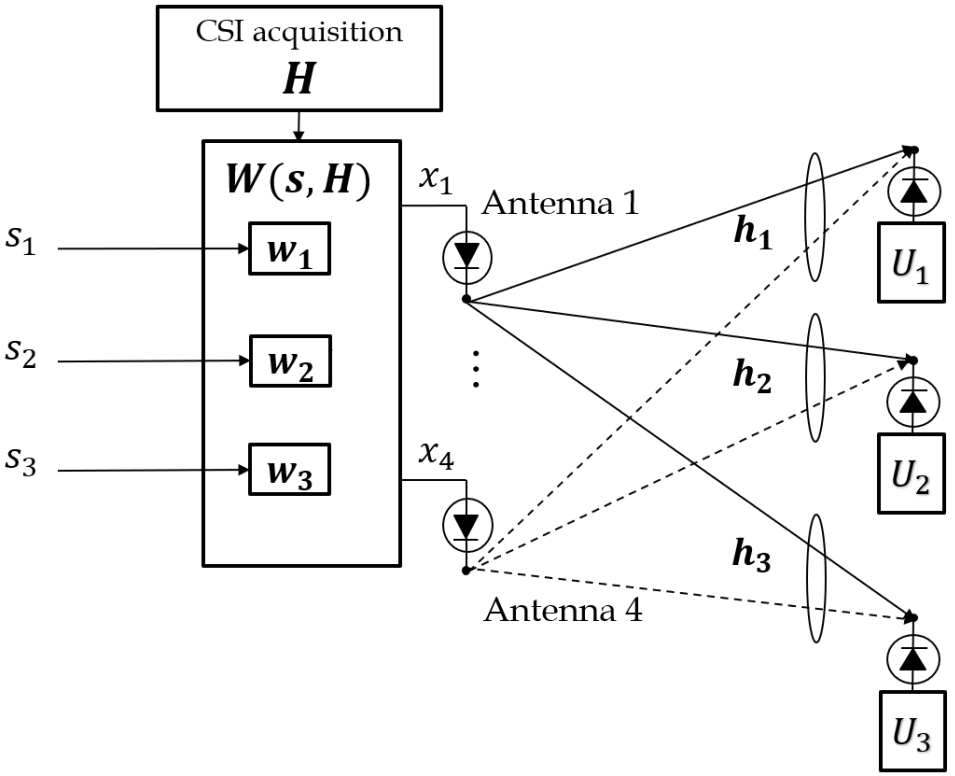
- Interference can be exploited to enhance the target signal
- If the interference can be controlled **symbol-by-symbol**, the interfering signal can be rotated to be in the correct detection region

➡ **Symbol level precoding** is an approach to exploit the interference effectively



Symbol level precoding

- Symbol-level precoding is designed based on the **known CSI (CI)** at the BS and **the information of the data symbols (DI)**
- Multi-user interference (MUI) is able to be predicted prior to transmission.
- With both **CI** and **DI**, the precoding matrix can be designed **symbol-by-symbol** to **make the interference constructively** to the target signal



The precoding matrix $\boldsymbol{W}$ is a function of both channel matrix $\boldsymbol{H}$ and data symbols $\boldsymbol{s}$

The **instantaneous** received SNR of the i-th user is given as

Target signal Constructive interference

$$\gamma'_i = \frac{|\boldsymbol{h_i w_i s_i}|^2 + |\boldsymbol{h_i} \sum_{j=1, j\neq i}^{K} \boldsymbol{w_j s_j}|^2}{n_i}$$

Symbol level precoding

Features	Conventional precoding	Symbol level precoding
Interference	Minimize interference	Exploit interference
Operation level	Transmission block	Transmission symbol
Prior requirements	Only CSI	CSI and data symbols
System performance (BER, achievable rate)	Only good at high power	Effective in all conditions
Power efficiency	Less efficient	More efficient
Complexity	Low complexity	High complexity

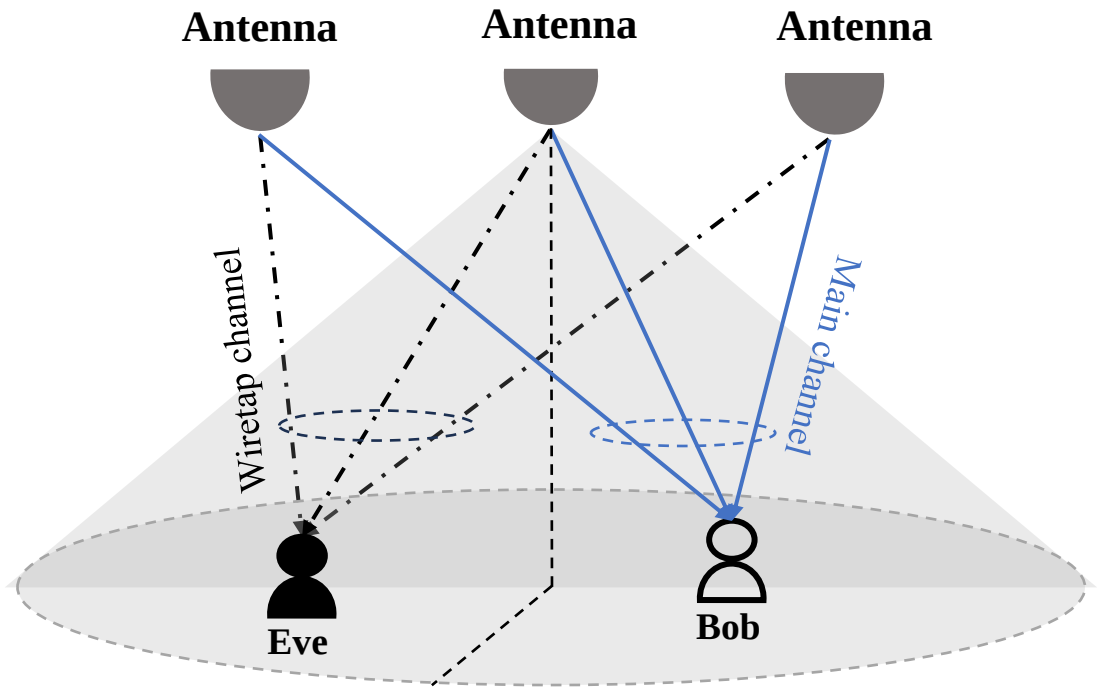
Symbol-level precoding offers a better system performance and power efficiency, but at the cost of increased complexity and dependence on both CSI and data symbol knowledge

SLP for physical layer security

- Physical layer security
- SLP for physical layer security

Physical layer security

- Ensuring information confidentiality at the physical layer
  - Exploiting the physical properties of the wireless channels (fading, interference,…) to protect the confidentiality of the transmitted messages
  - If Eve's channel has higher noise or distortion (degraded channel) compared to Bob's, then secure communication is achievable. Alice can transmit at a certain rate (called the secrecy rate) so that Bob can decode the message correctly, but Eve cannot.

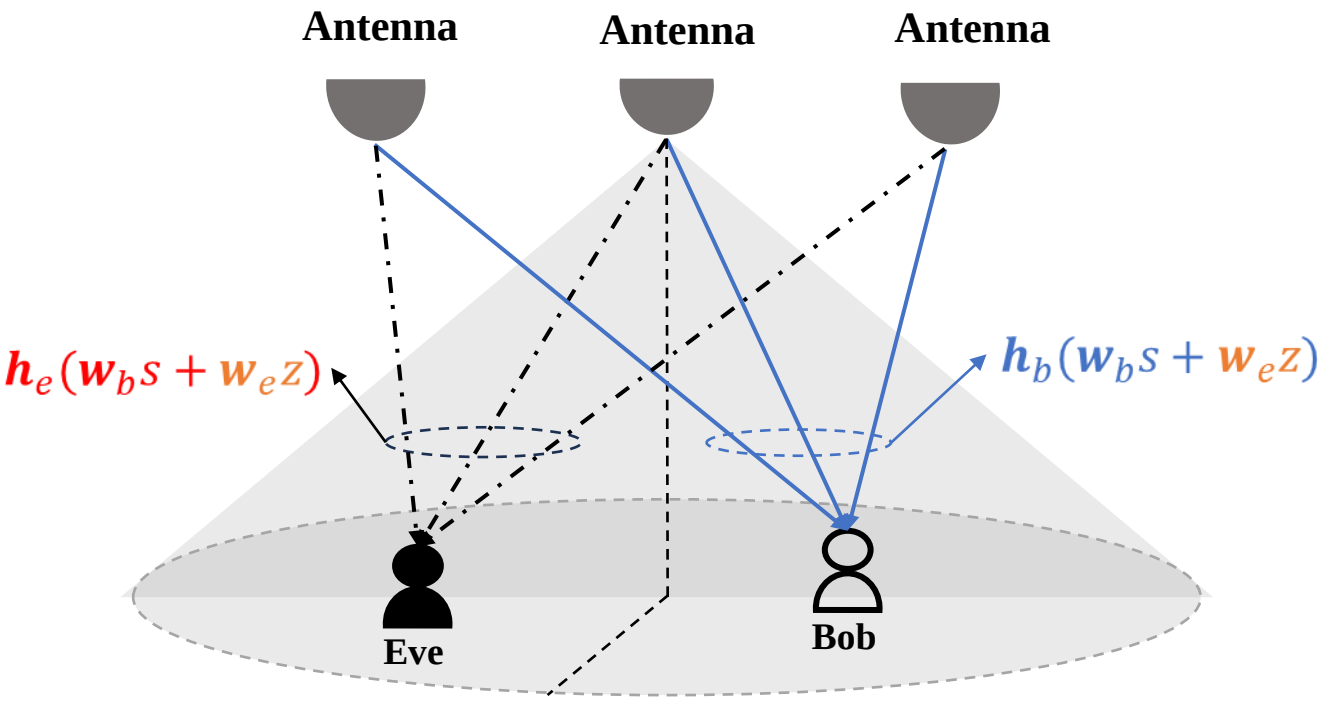


Objective of PLS:

Maximizing Bob's SNR while minimizing Eve's SNR

Physical layer security

- Artificial Noise (AN) aid conventional precoding technique
  - Artificial Noise: the AN is created by the transmitters in the way that it **degrades the Eve's channel as much as possible** while **interfering the Bob's channel as little as possible**
  - Conventional precoding: precoding exploits the available spatial dimensions to **improve Bob's channel** while **controlling the quality of Eve's channel**

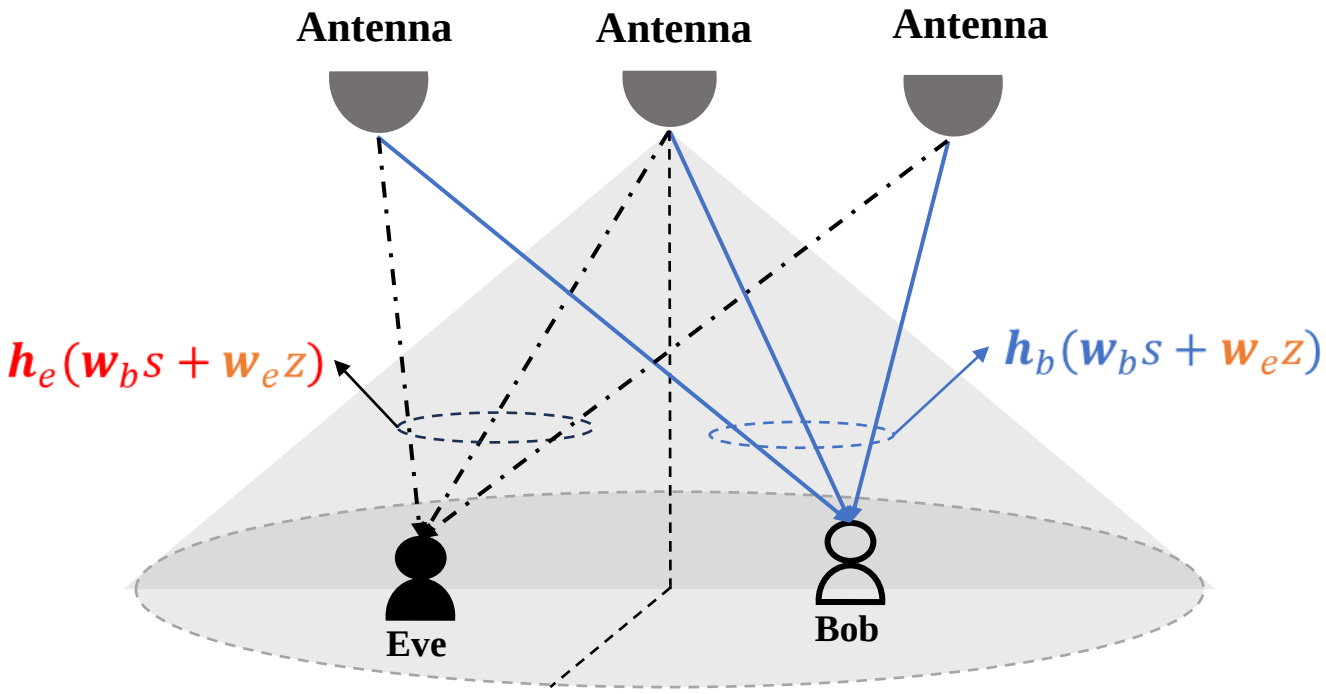


$\{h_b, h_e\}$: Bob's channel and Eve's channel

$\{w_b, w_e, s, z\}$: Data precoding, AN precoding, data symbol and AN symbol

Physical layer security

- Artificial Noise (AN) aid conventional precoding technique
  - The conventional precoding technique **treats the AN signal as harmful** for the Bob' channel and hence mitigates it.



$\{h_b, h_e\}$: Bob's channel and Eve's channel

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❖ Received signal at Bob

$$y_b = h_b w_b s + h_b w_e z + n_b$$

Target signal | AN | Noise

❖ Average received SNR of Bob

$$\gamma_b = \frac{|h_b w_b|^2}{|h_b w_e|^2 + \sigma_b^2}$$

➡ High required power to guarantee the Bob's SNR while **the AN power is wasted**

SLP for physical layer security

- Artificial Noise (AN) aid symbol level precoding (SLP) technique
  - Instead of treating AN as harmful, SLP exploits AN signal ($\boldsymbol{h_b w_e z}$) **constructively for Bob's channel** by redesign AN precoding vector $\boldsymbol{w_e}$ based on knowledge of $\boldsymbol{h_b}$ and z
  - If Eve's CSI ($\boldsymbol{h_e}$) also available at the transmitters, the AN signal can be further designed to be **destructive to Eve's channel**.

❖ Received signal at Bob

$$y_b = \boldsymbol{h_b w_b} s + \boldsymbol{h_b w_e} z + n_b$$

Target signal — AN — Noise

❖ Received signal at Eve

$$y_e = \boldsymbol{h_e w_b} s + \boldsymbol{h_e w_e} z + n_e$$

Eavesdropper signal — AN — Noise

❖ The instantaneous received SNR of Bob

$$\gamma_b = \frac{|\boldsymbol{h_b w_b} s + \boldsymbol{h_b w_e} z|^2}{\sigma_b^2}$$

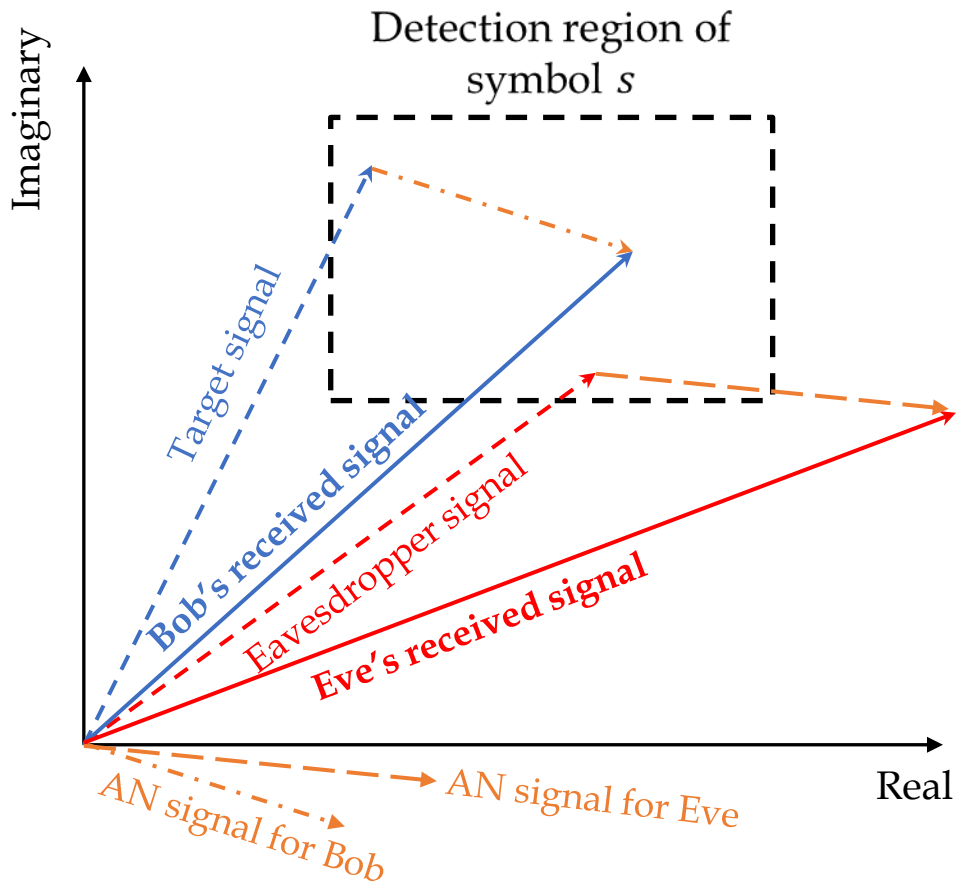
❖ The instantaneous received SNR of Eve

$$\gamma_e = \frac{|\boldsymbol{h_e w_b} s|^2}{|\boldsymbol{h_e w_e} z|^2 + \sigma_e^2}$$

+

SLP for physical layer security

- Instead of treating AN as harmful, SLP exploits AN signal ($\boldsymbol{h_b w_e z}$) **constructively for Bob's channel** by redesign AN precoding vector $\boldsymbol{w_e}$ based on knowledge of $\boldsymbol{h_b}$ and z
- If Eve's CSI ($\boldsymbol{h_e}$) also available at the transmitters, the AN signal can be further designed to be **destructive to Eve's channel**.



- ❖ AN signal pushes the Bob's received signal **deeper the detection region**
- ❖ AN signal pushes the Eve's received signal **away from the detection region**

- ❖ AN aid SLP technique makes correct detection easier for Bob and more challenging for Eve
- ❖ Improve Bob' SNR and reduce Eve's SNR
- ❖ Need lower power to guarantee the required Bob's SNR

SLP for physical layer security

- Power minimization problem with SNR constraints for Bob and Eve

$$\mathbb{P}\mathbf{1}: \underset{\mathbf{w}_b,\mathbf{w}_e}{\text{minimize}} \ \left|\left|\mathbf{w}_b s+\mathbf{w}_e z\right|\right|^2$$

→ Transmission power

$$\text{subject to} \quad \begin{aligned} R(\mathbf{h}_b\mathbf{w}_b s+\mathbf{h}_b\mathbf{w}_e z) &\trianglelefteq R(s), \\ I(\mathbf{h}_b\mathbf{w}_b s+\mathbf{h}_b\mathbf{w}_e z) &\trianglelefteq I(s), \\ R(\mathbf{h}_e\mathbf{w}_b s+\mathbf{h}_e\mathbf{w}_e z) &\not\trianglelefteq R(s), \\ I(\mathbf{h}_e\mathbf{w}_b s+\mathbf{h}_e\mathbf{w}_e z) &\not\trianglelefteq I(s), \end{aligned}$$

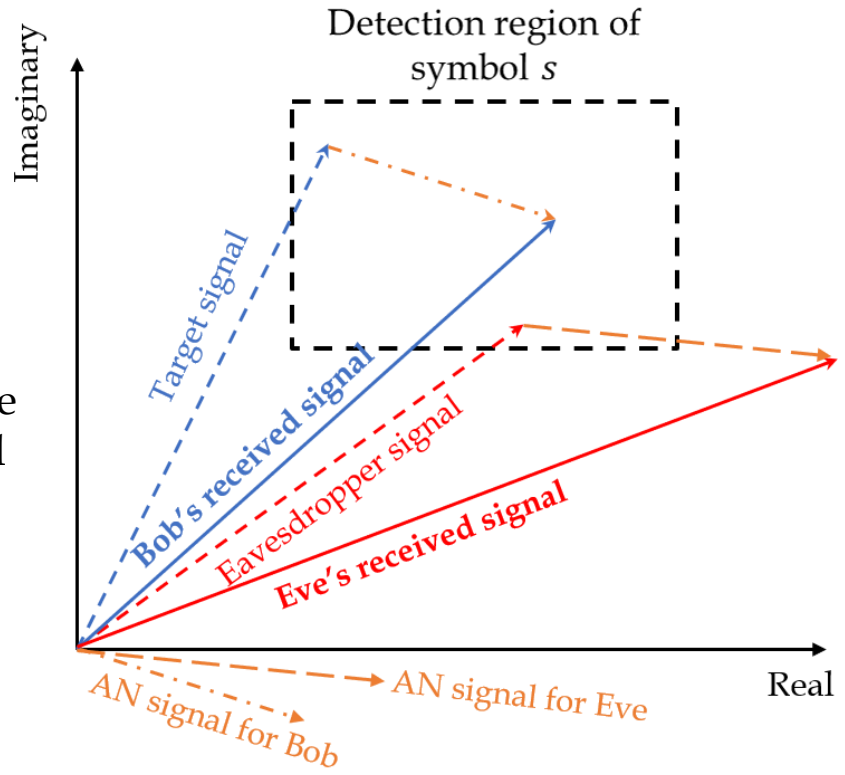
→ Constructive/Destructive constraints for AN signal

Bob's SNR constraint:

$$\frac{\left|\mathbf{h}_b\mathbf{w}_b s+\mathbf{h}_b\mathbf{w}_e z\right|^2}{\sigma_b^2} \geq \Gamma_b,$$

Eve's SNR constraint:

$$\frac{\left|\mathbf{h}_e\mathbf{w}_b s\right|^2}{\left|\mathbf{h}_e\mathbf{w}_e z\right|^2+\sigma_e^2} \leq \Gamma_e.$$



with $\trianglelefteq$ denotes the correct detection region

Thank you for listening!

Q & A