Physical Layer Security for Wireless Networks

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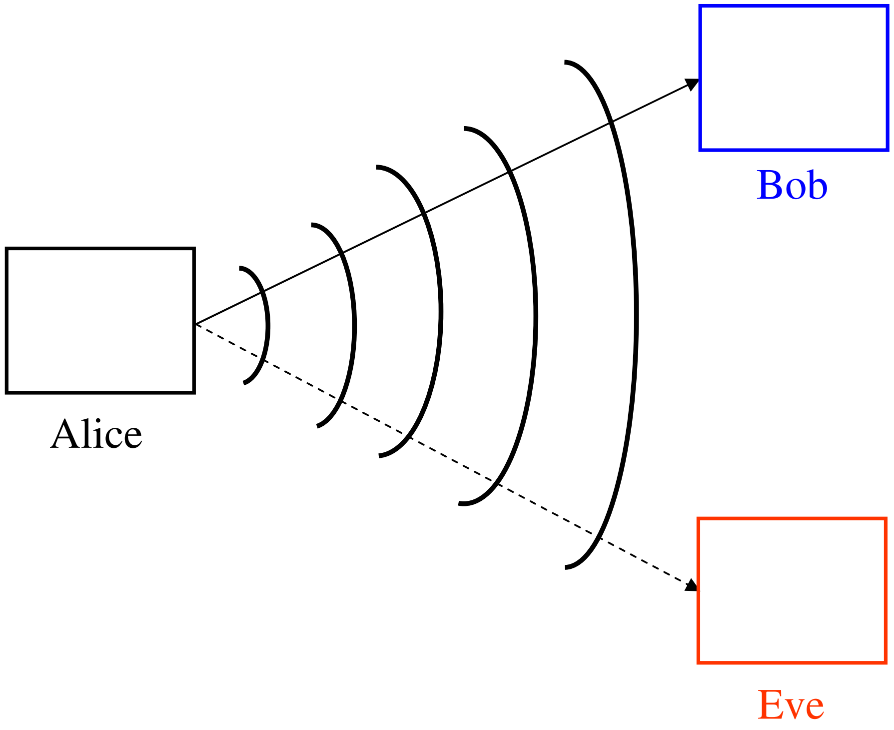
Security in Wireless Systems

- Inherent openness in wireless communications channel: eavesdropping and **jamming** attacks

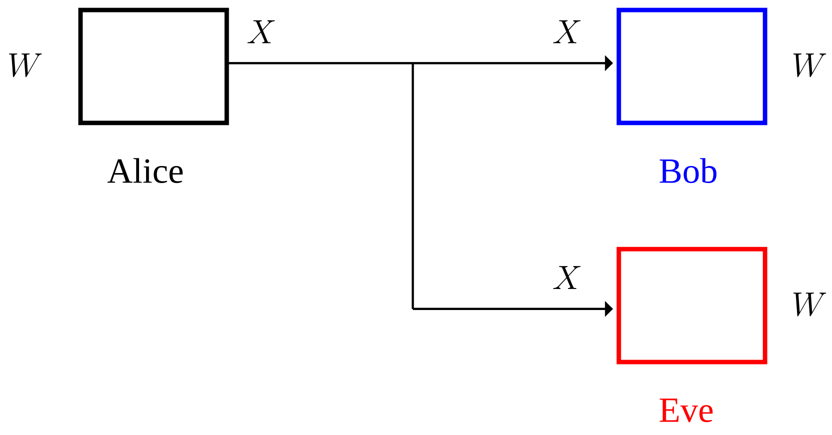


Countering Security Threats in Wireless Systems

- Cryptography
  - at higher layers of the protocol stack
  - based on the assumption of **limited computational power** at Eve
  - vulnerable to large-scale implementation of quantum computers
- Techniques like frequency hopping, CDMA
  - at the physical layer
  - based on the assumption of **limited knowledge** at Eve
  - vulnerable to rogue or captured node events
- Physical layer security
  - at the physical layer
  - no assumption on Eve's computational power
  - no assumption on Eve's available information
  - **unbreakable, provable,** and **quantifiable** (in bits/sec/hertz)
  - implementable by signal processing, communications, and coding techniques

Beginnings of Security Research: Shannon 1949

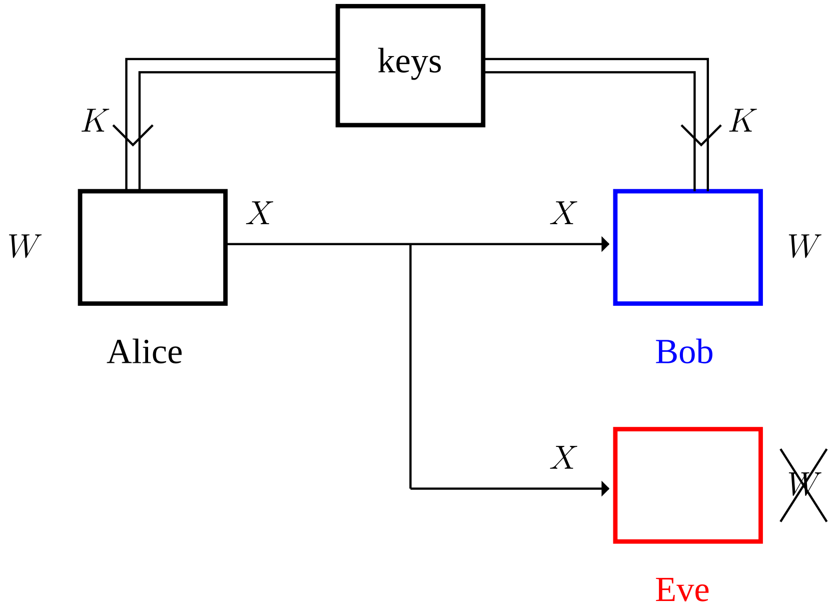
- Noiseless bit pipes to Bob and Eve.



- Eve gets whatever Bob gets.
- Secure communications is not possible.

Shannon's 1949 Security Paper

- Noiseless bit pipes to Bob and Eve.

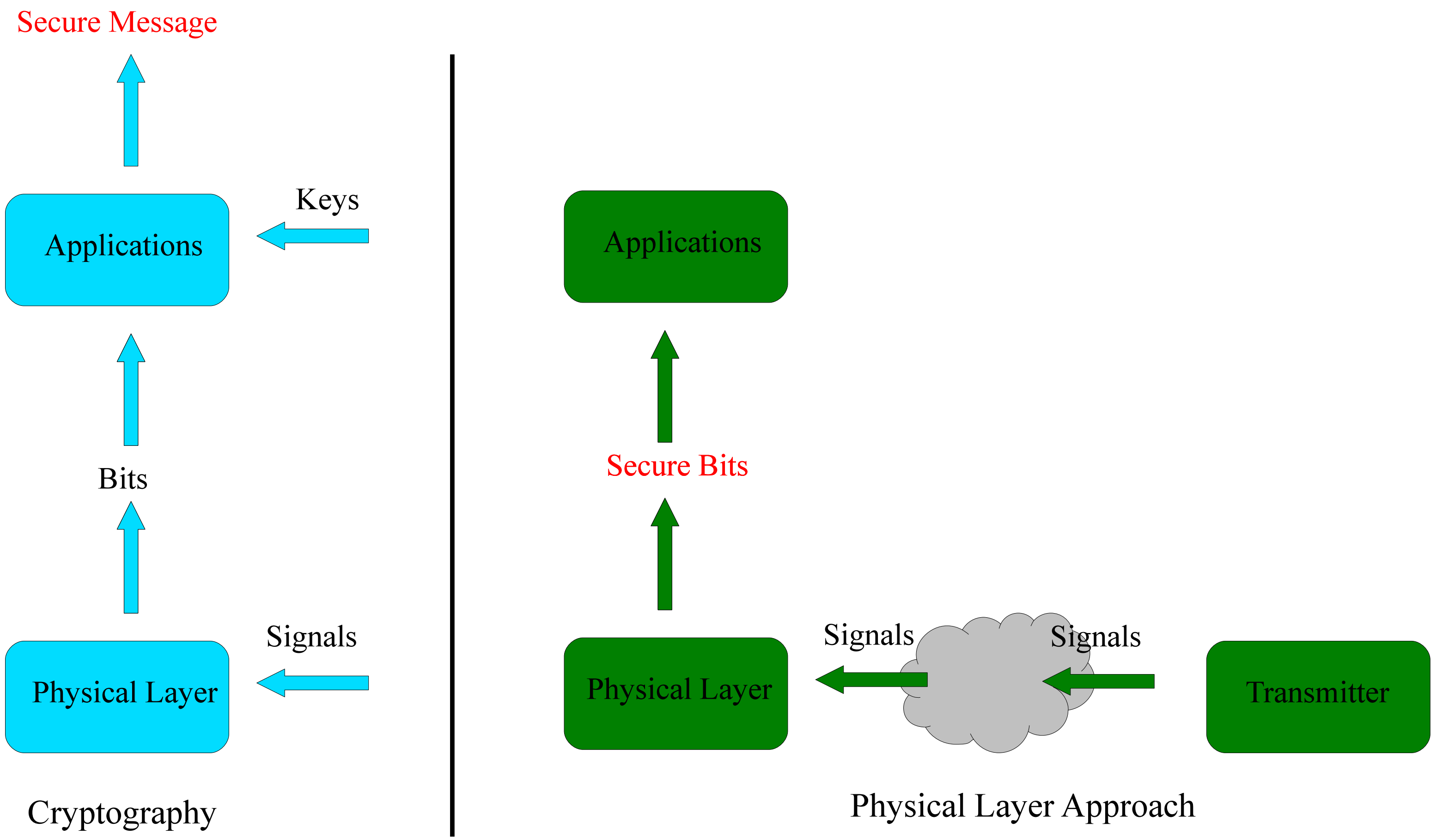


- **One-time pad:** $X = W \oplus K$
- If K is uniform, then X is independent of W. If we know K, then $W = X \oplus K$.
- **For perfect secrecy, length of K (key rate) must be as large as length of W (message rate).**

Beginnings of Cryptography

- Private key cryptography
  - Based on one-time pad
  - There are separate secure communication links for key exchange
  - Encryption and decryption are done using these keys
- Public key cryptography
  - Encryption is based on publicly known key (or method)
  - Decryption can be performed only by the desired destination
  - Security based on computational advantage
  - **Security against computationally limited adversaries**
  - Certain operations are easy in one direction, difficult in the other direction
    - Multiplication is easy, factoring is difficult (RSA)
    - Exponentiation is easy, discrete logarithm is difficult (Diffie-Hellman)

Cryptography versus Physical Layer Security



Secure Message

Applications

Keys

Bits

Physical Layer

Signals

Cryptography

Applications

Secure Bits

Physical Layer

Signals

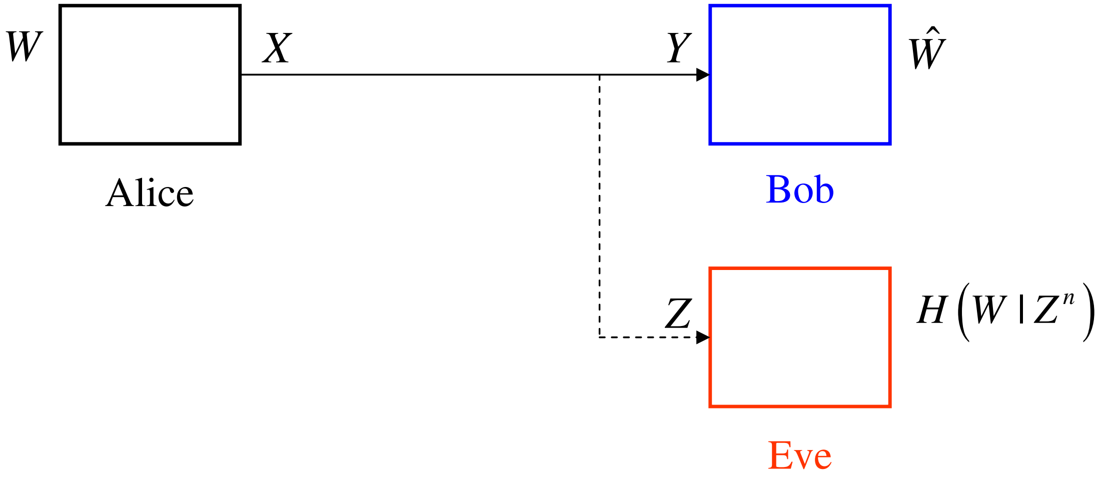
Signals

Transmitter

Physical Layer Approach

Wyner's Wiretap Channel

- Wyner introduced the **wiretap** channel in 1975.
- Major departure from Shannon's model: noisy channels.
- Eve's channel is **degraded** with respect to Bob's channel: $X \rightarrow Y \rightarrow Z$



- Secrecy is measured by equivocation, R_e, at Eve, i.e., the **confusion** at Eve:

$$R_e = \lim_{n \to \infty} \frac{1}{n} H(W|Z^n)$$

Notions of Perfect Secrecy

- Perfect secrecy is achieved if $R_e = R$
- This is perfect weak secrecy:

$$\lim_{n\to\infty} \frac{1}{n} I(W;Z^n) = 0$$

- Also, there is perfect strong secrecy:

$$\lim_{n\to\infty} I(W;Z^n) = 0$$

- All capacity results obtained for weak secrecy have been extended for strong secrecy.
- However, there is still no proof of equivalence or strict containment.

Capacity-Equivocation Region

- Wyner characterized the optimal (R, R_e) region:

$$R \leq I(X;Y)$$
$$R_e \leq I(X;Y) - I(X;Z)$$

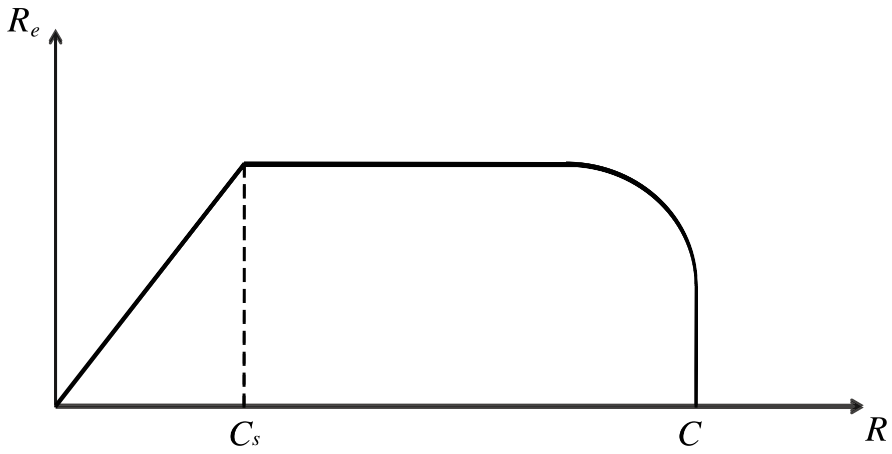
- Main idea is to split the message W into two coordinates, secret and public: (W_s, W_p).
- W_s needs to be transmitted in perfect secrecy.
- W_p has two roles:
  - Carries some information on which there is no secrecy constraint
  - Provides protection for W_s by creating confusion for the eavesdropper

A Typical Capacity-Equivocation Region

- Wyner characterized the optimal (R, R_e) region:

$$R \leq I(X;Y)$$
$$R_e \leq I(X;Y) - I(X;Z)$$

- A typical (R, R_e) region:



- There might be a tradeoff between rate and its equivocation:
  - Capacity and secrecy capacity might not be simultaneously achievable

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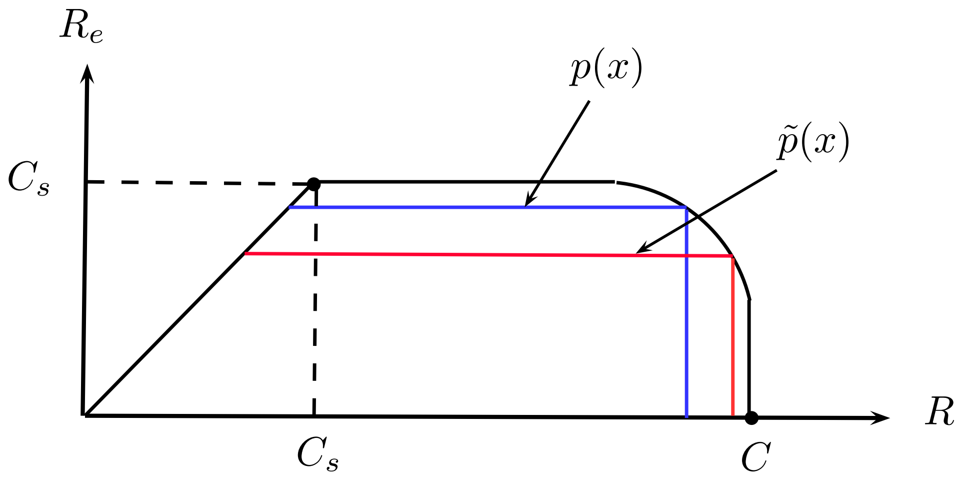


- There might be a tradeoff between rate and its equivocation:
  - Capacity and secrecy capacity might not be simultaneously achievable

Secrecy Capacity

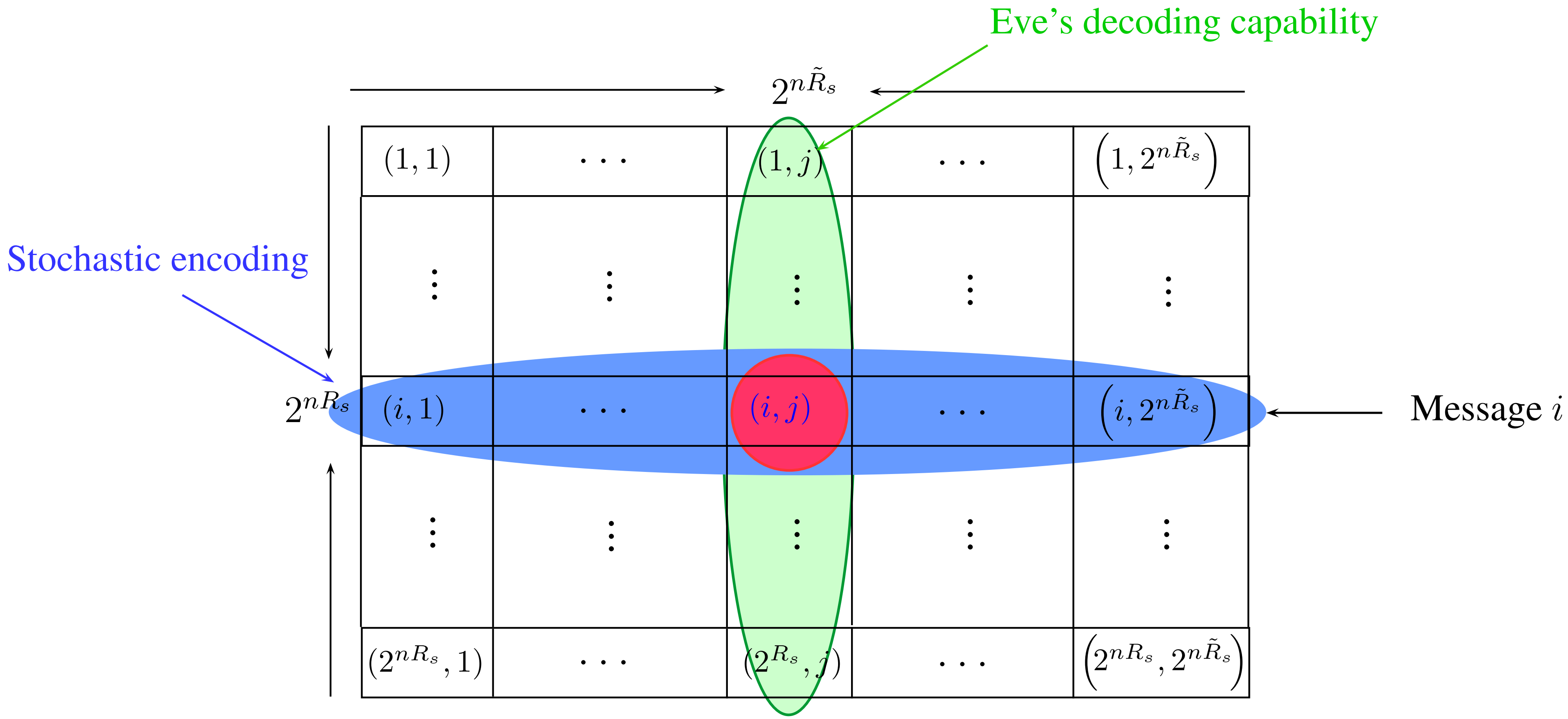
- Perfect secrecy when $R = R_e$.
- The maximum perfect secrecy rate is the secrecy capacity:

$$C_s = \max_{X \to Y \to Z} I(X;Y) - I(X;Z)$$

- Main idea is to replace W_p with dummy indices, $\tilde{W}_s$, which carry no information.
- In particular, each W_s is mapped to **many** codewords:
  - **Stochastic encoding (a.k.a. random binning)**
- To send message W_s securely, we send $X^n(W_s, \tilde{W}_s)$ where $\tilde{W}_s$ is random.
- This one-to-many mapping aims to confuse the eavesdropper

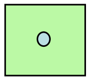
Main Tool: Stochastic Encoding

- Each message W_s is associated with many codewords: $X^n(W_s, \tilde{W}_s)$.

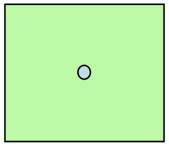


Stochastic Encoding: 64-QAM Example

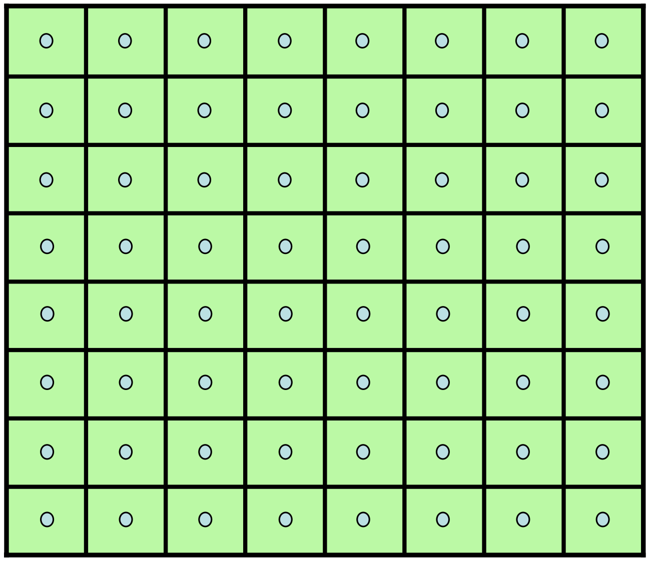
Bob’s Noise



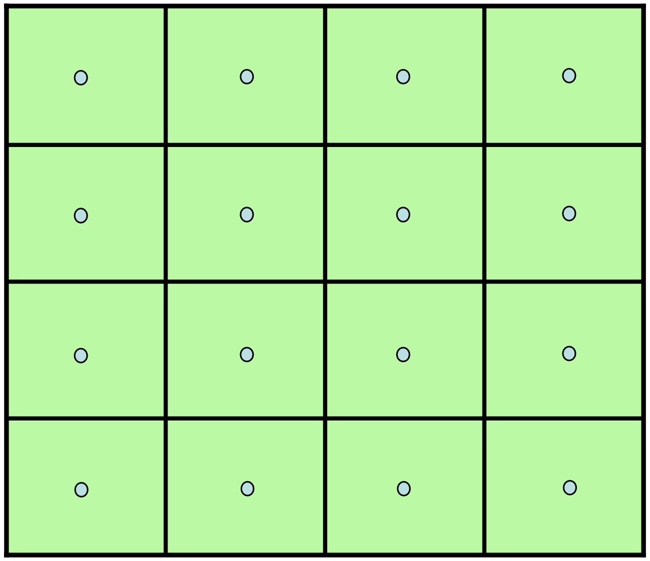
Eve’s Noise



Bob’s Constellation



Eve’s Constellation



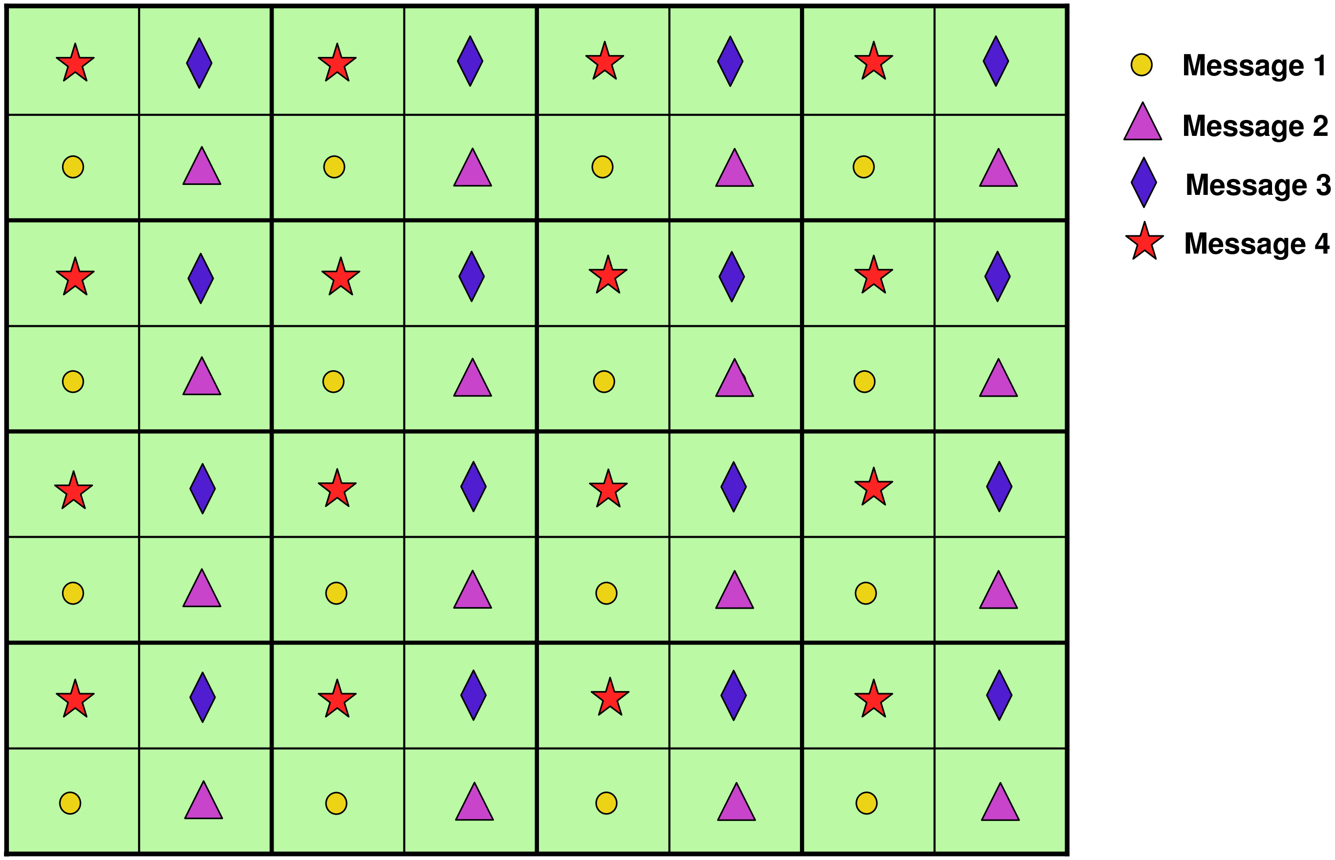
$$C_B = \log_2 64 = 6 \text{ b/s}$$

$$C_E = \log_2 16 = 4 \text{ b/s}$$

$$C_s = C_B - C_E = 2 \text{ b/s}$$

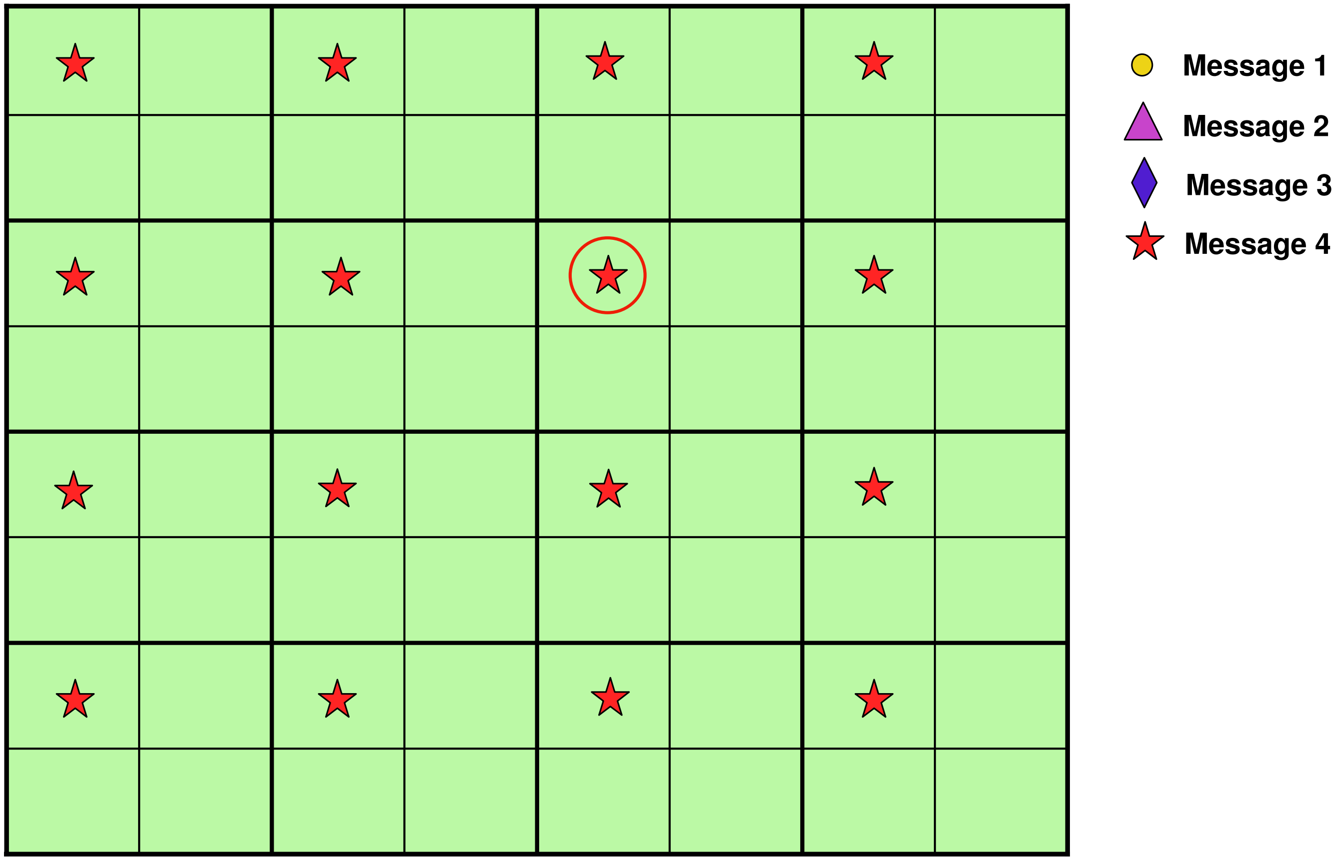
Stochastic Encoding: 64-QAM Example

Divide Bob’s constellation into 4 subsets.



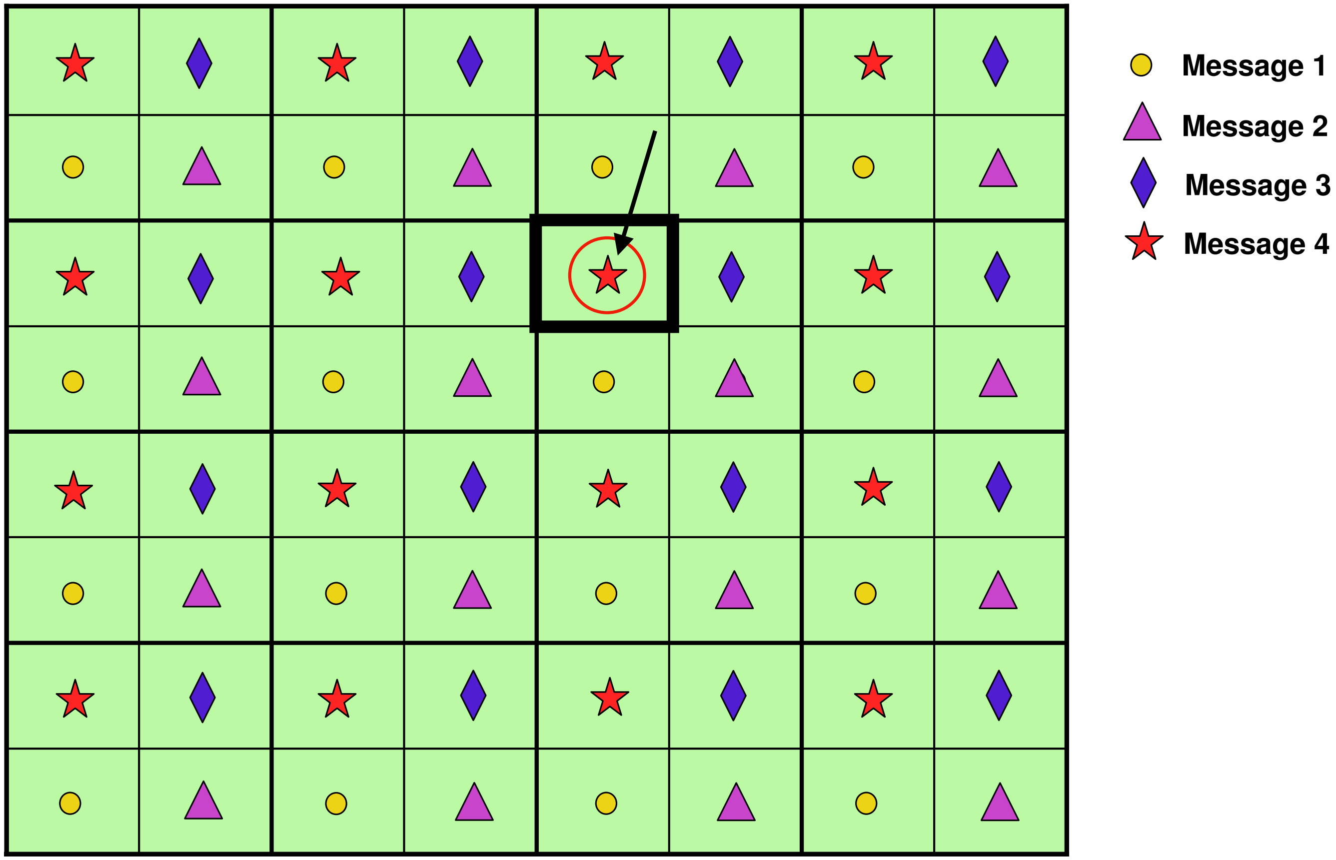
Stochastic Encoding: 64-QAM Example

All red stars denote the same message. Pick one randomly.



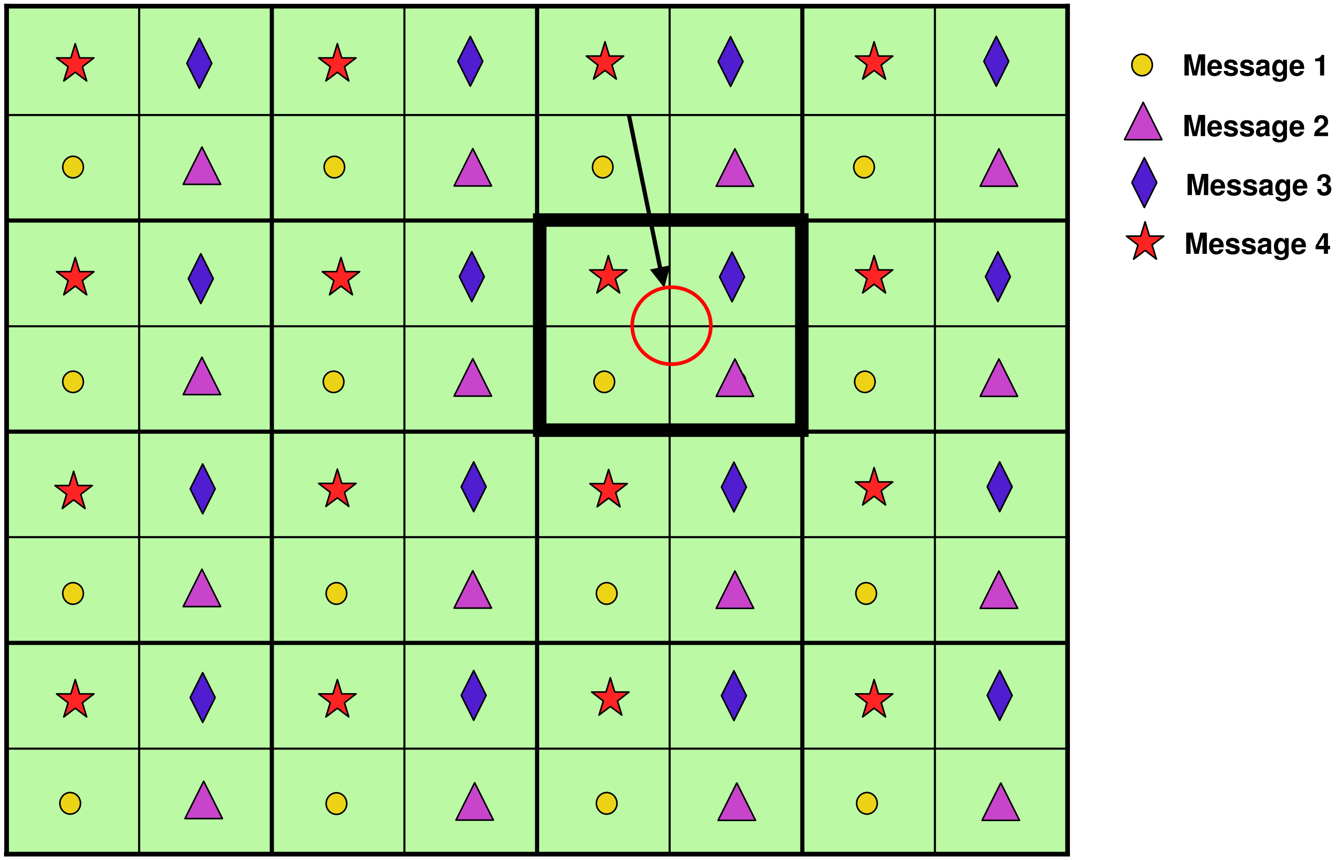
Stochastic Encoding: 64-QAM Example

Bob can decode the message reliably.



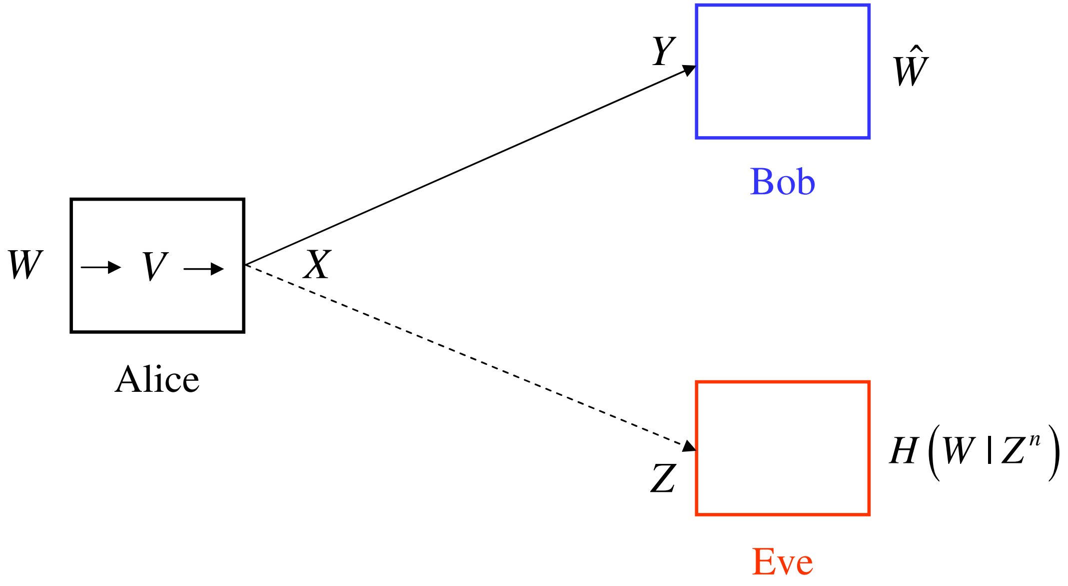
Stochastic Encoding: 64-QAM Example

For Eve, all 4 messages look equally likely.



General Wiretap Channel

- Csiszar and Korner considered the general wiretap channel in 1978.
- Eve’s signal is not necessarily a degraded version of Bob’s signal.



General Capacity-Equivocation Region

- General (R, R_e) region:

$$R \leq I(V;Y)$$
$$R_e \leq I(V;Y|U) - I(V;Z|U)$$

  for some (U,V) such that $U \to V \to X \to Y,Z$.

- Two new ingredients in the achievable scheme
  - V: channel prefixing
  - U: rate splitting

General Capacity-Equivocation Region

- Contrast with the degraded case

$$R \leq I(V;Y) \qquad\qquad R \leq I(X;Y)$$

$$R_e \leq I(V;Y|U) - I(V;Z|U) \qquad\qquad R_e \leq I(X;Y) - I(X;Z)$$

for some (U,V) such that $U \to V \to X \to Y,Z$.

- Two new ingredients in the achievable scheme
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  - U: rate splitting

General Secrecy Capacity

- Contrast with the degraded case

$$R \leq I(V;Y) \qquad\qquad R \leq I(X;Y)$$

$$R_e \leq I(V;Y|U) - I(V;Z|U) \qquad\qquad R_e \leq I(X;Y) - I(X;Z)$$

  for some (U,V) such that $U \to V \to X \to Y,Z$.

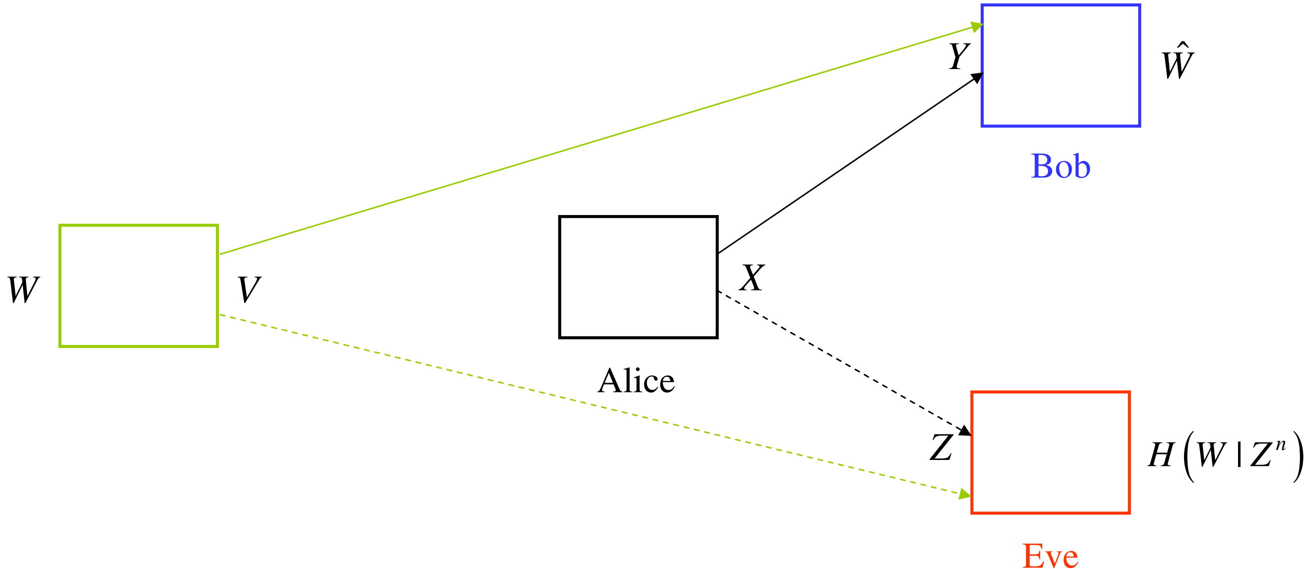
- Two new ingredients in the achievable scheme
  - V: channel prefixing
  - U: rate splitting
- General secrecy capacity expression:

$$C_s = \max_{V \to X \to YZ} I(V;Y) - I(V;Z)$$

  i.e., rate splitting is not needed.

Main Tool: Channel Prefixing

- A virtual channel from V to X.
- Additional stochastic mapping from the message to the channel input: $W \to V \to X$.
- Real channel: $X \to Y$ and $X \to Z$. Constructed channel: $V \to Y$ and $V \to Z$.



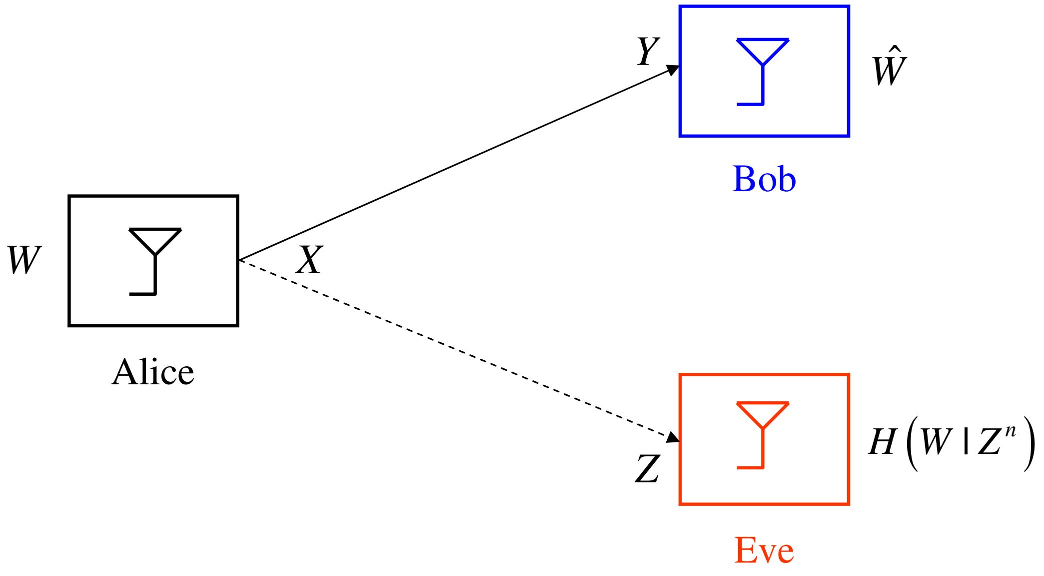
- With channel prefixing: $V \to X \to Y, Z$.
- From DPI, both mutual informations decrease, but the difference may increase.
- The secrecy capacity:

$$C_s = \max_{V \to X \to YZ} I(V;Y) - I(V;Z)$$

Gaussian Wiretap Channel

- Leung-Yang-Cheong and Hellman considered the Gaussian wire-tap channel in 1978.

$$Y = X + N_1 \qquad \text{and} \qquad Z = X + N_2$$



- **Degraded:** No channel prefixing is necessary and Gaussian signalling is optimal.
- The secrecy capacity:

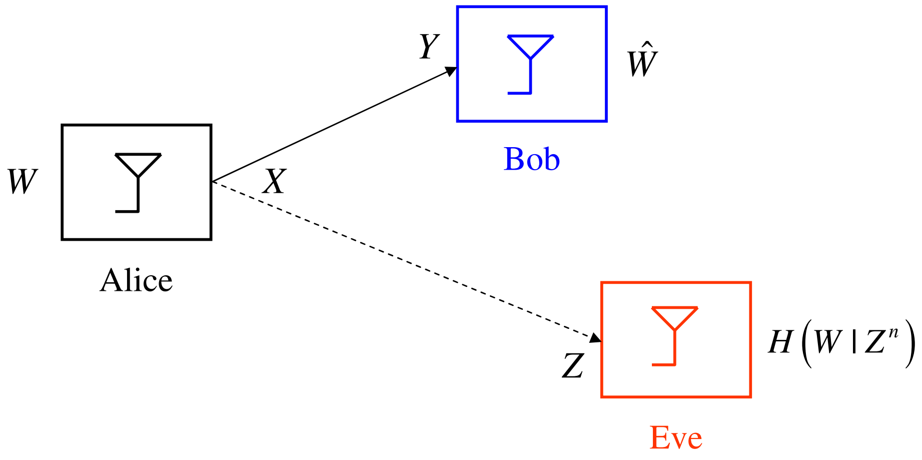
$$C_s = \max_{X \to Y \to Z} I(X;Y) - I(X;Z) = [C_B - C_E]^+$$

i.e., the difference of two capacities.

Caveat: Need Channel Advantage

The secrecy capacity: $C_s = [C_B - C_E]^+$

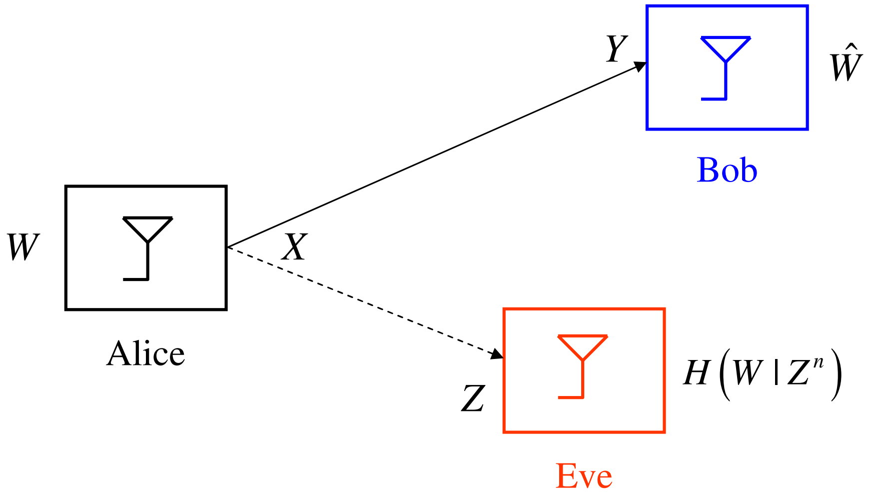
Bob's channel is better



positive secrecy

$$C_s = C_B - C_E$$

Eve's channel is better



no secrecy

$$C_s = 0$$

Two Recurring Themes

- Creating advantage for the legitimate users:
  - computational advantage (cryptography)
  - knowledge advantage (spread spectrum)
  - channel advantage (physical layer security)

- Exhausting capabilities of the illegitimate entities:
  - exhausting computational power (cryptography)
  - exhausting searching power (spread spectrum)
  - exhausting decoding capability (physical layer security)

Outlook at the End of 1970s and Transition into 2000s

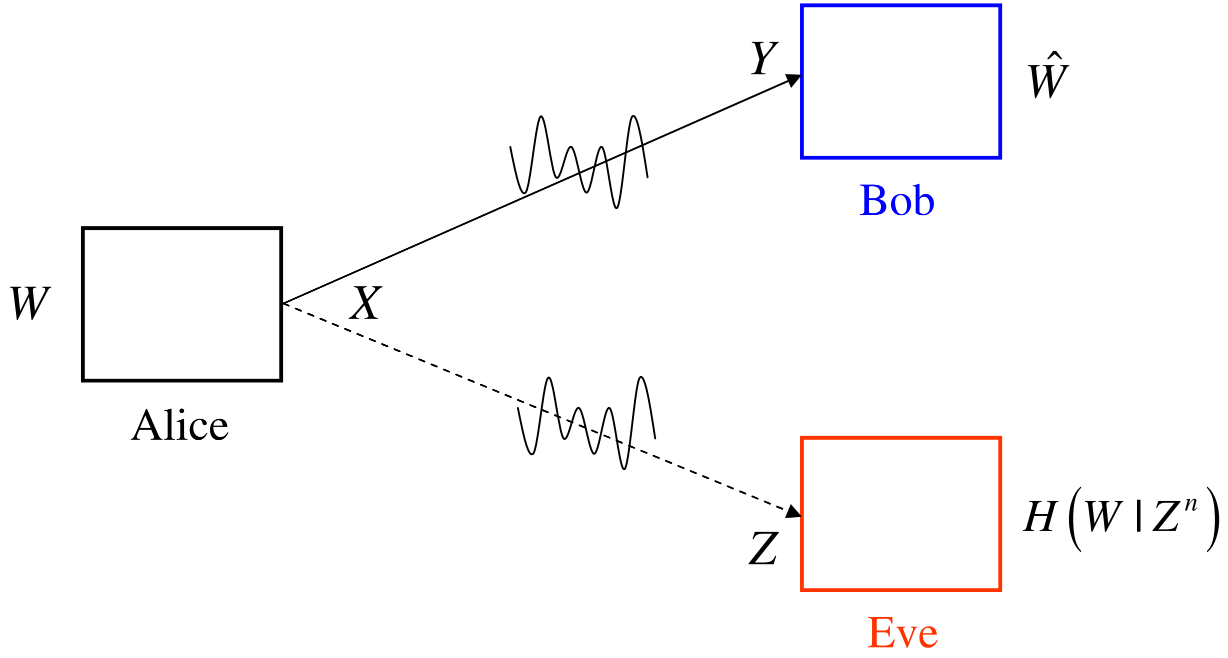
- Information theoretic secrecy is extremely powerful:
  - no limitation on Eve’s computational power
  - no limitation on Eve’s available information
  - yet, we are able to provide secrecy to the legitimate user
  - **unbreakable, provable,** and **quantifiable** (in bits/sec/hertz) secrecy
- We seem to be at the mercy of the nature:
  - if Bob’s channel is stronger, positive perfect secrecy rate
  - if Eve’s channel is stronger, no secrecy
- We need channel advantage. Can we create channel advantage?
- Wireless channel provides many options:
  - time, frequency, multi-user diversity via fading
  - cooperation via overheard signals
  - multi-dimensional signalling via multiple antennas
  - signal alignment

Fading Wiretap Channel

- In the Gaussian wiretap channel, secrecy is not possible if

$$C_B \leq C_E$$

- Fading provides time-diversity: Can it be used to obtain/improve secrecy?

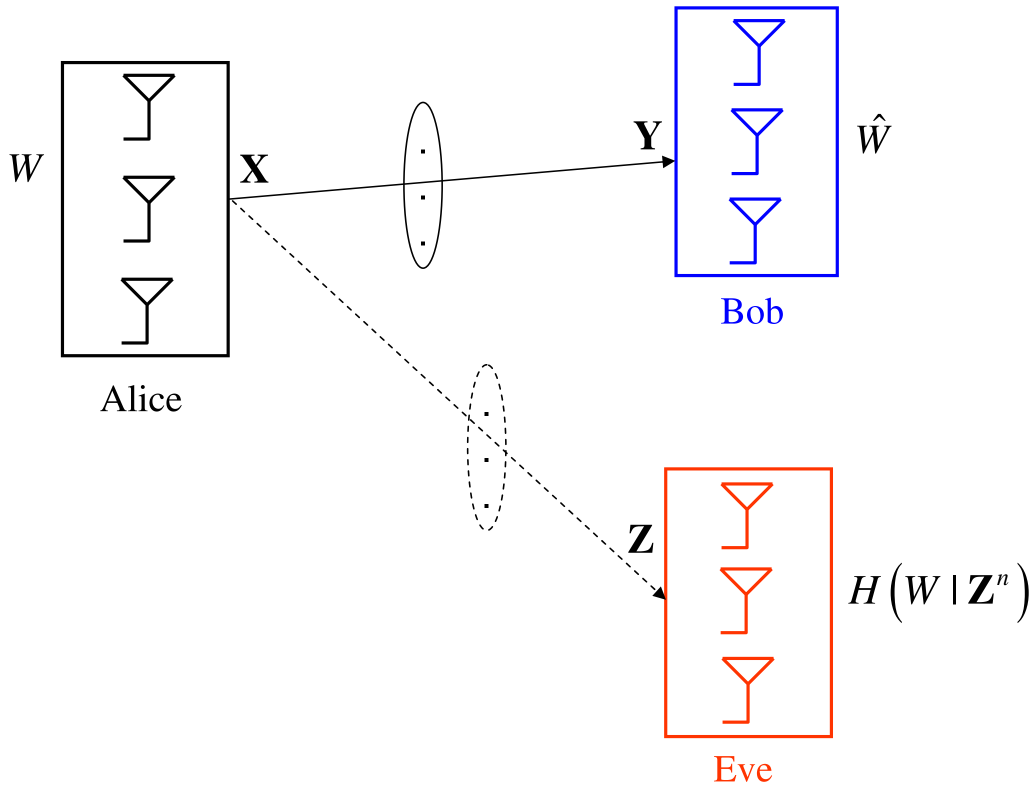


MIMO Wiretap Channel

- In SISO Gaussian wiretap channel, secrecy is not possible if

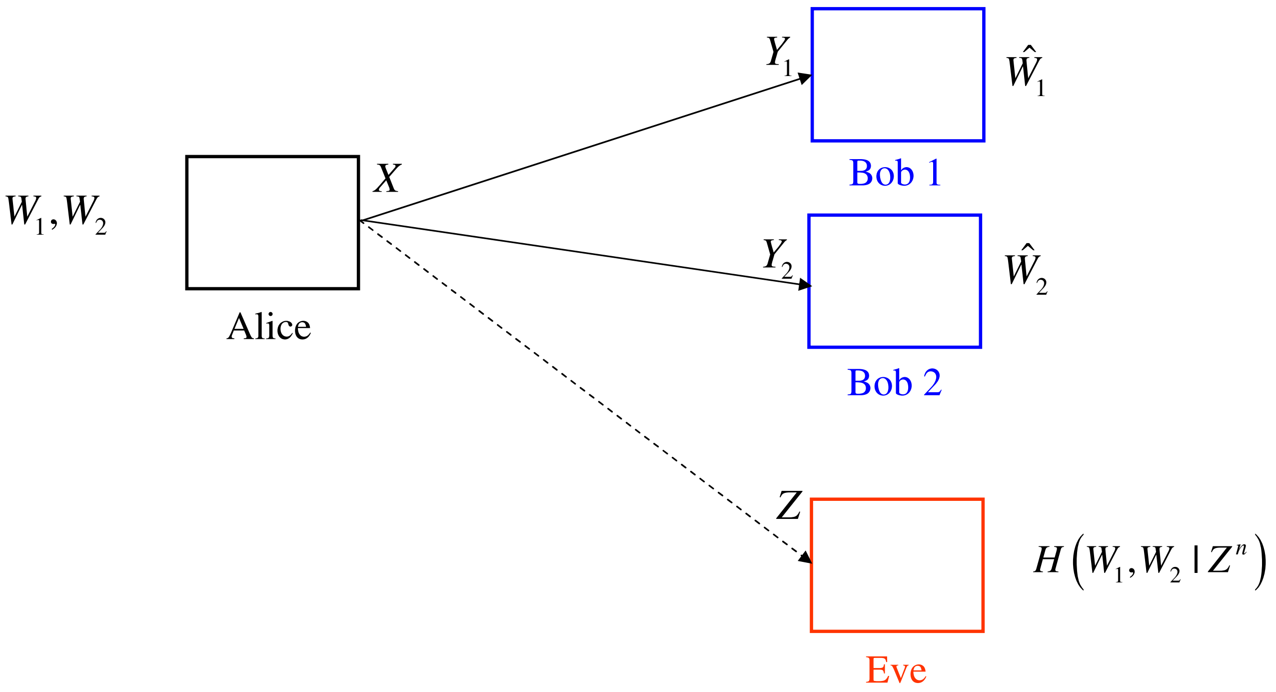
$$C_B \leq C_E$$

- Multiple antennas improve reliability and rates. How about secrecy?



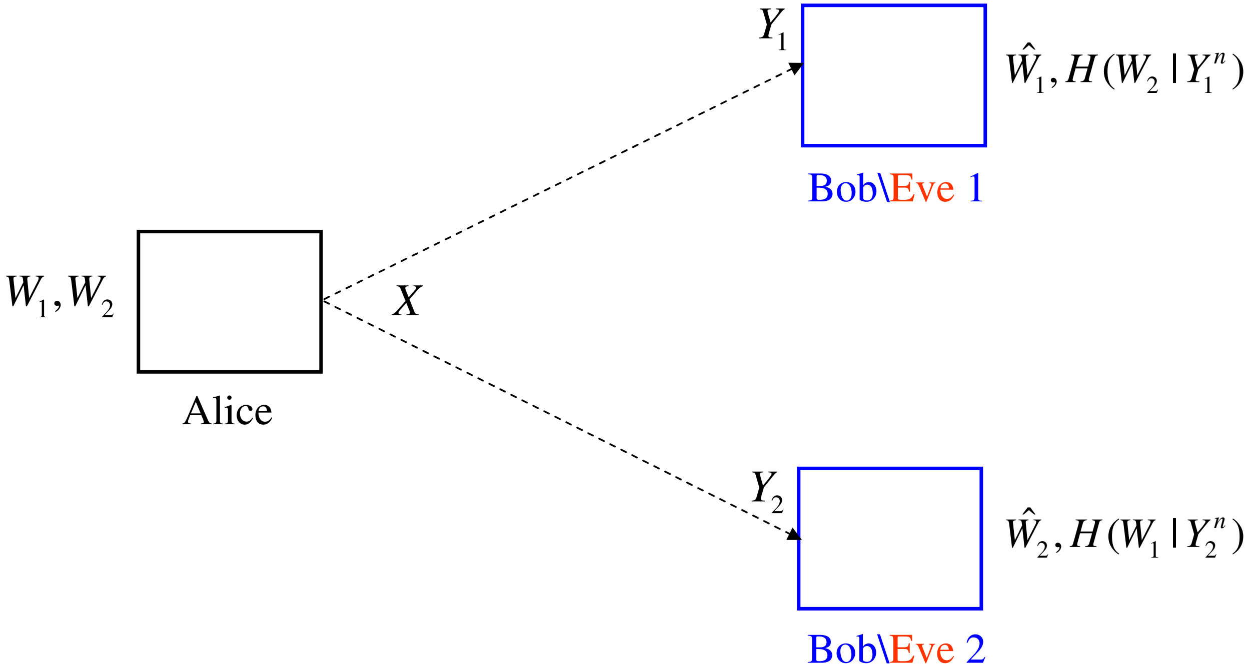
Broadcast (Downlink) Channel

- In cellular communications: base station to end-users channel can be eavesdropped.
- This channel can be modelled as a broadcast channel with an external eavesdropper.



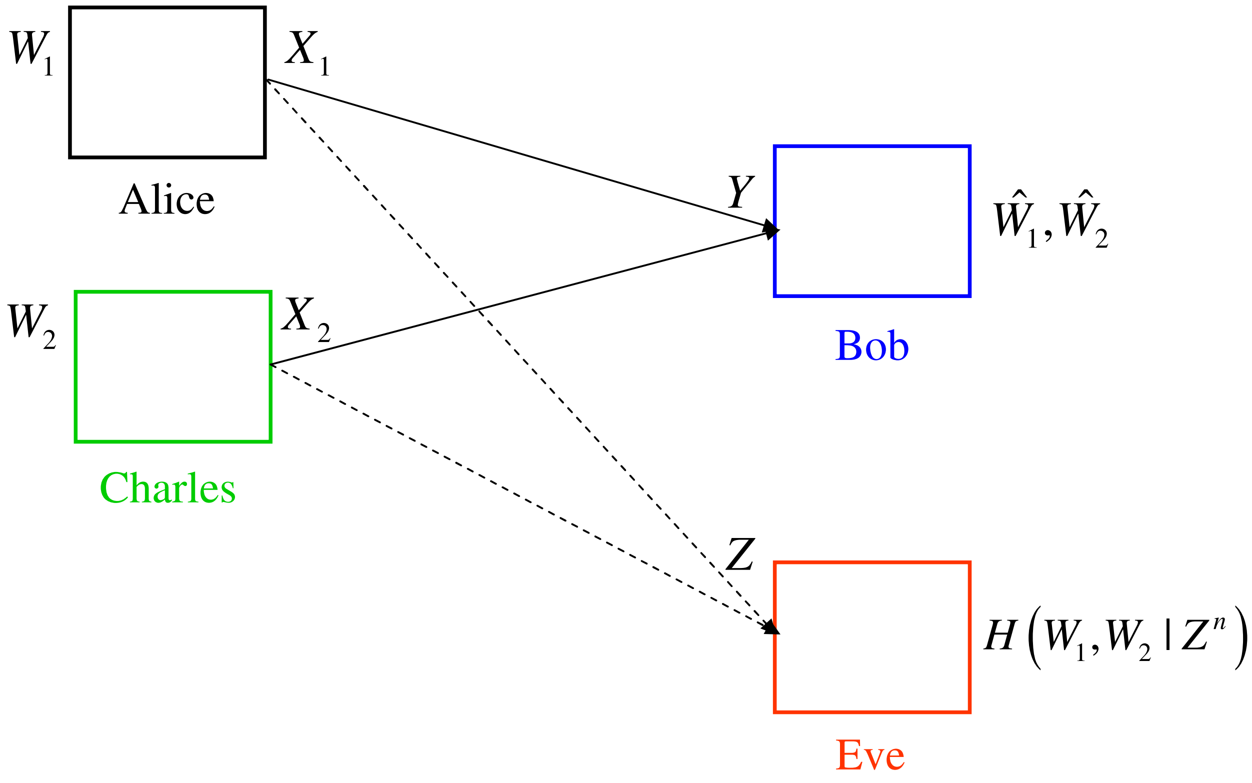
Internal Security within a System

- Legitimate users may have different security clearances.
- Some legitimate users may have paid for some content, some may not have.
- Broadcast channel with two confidential messages.



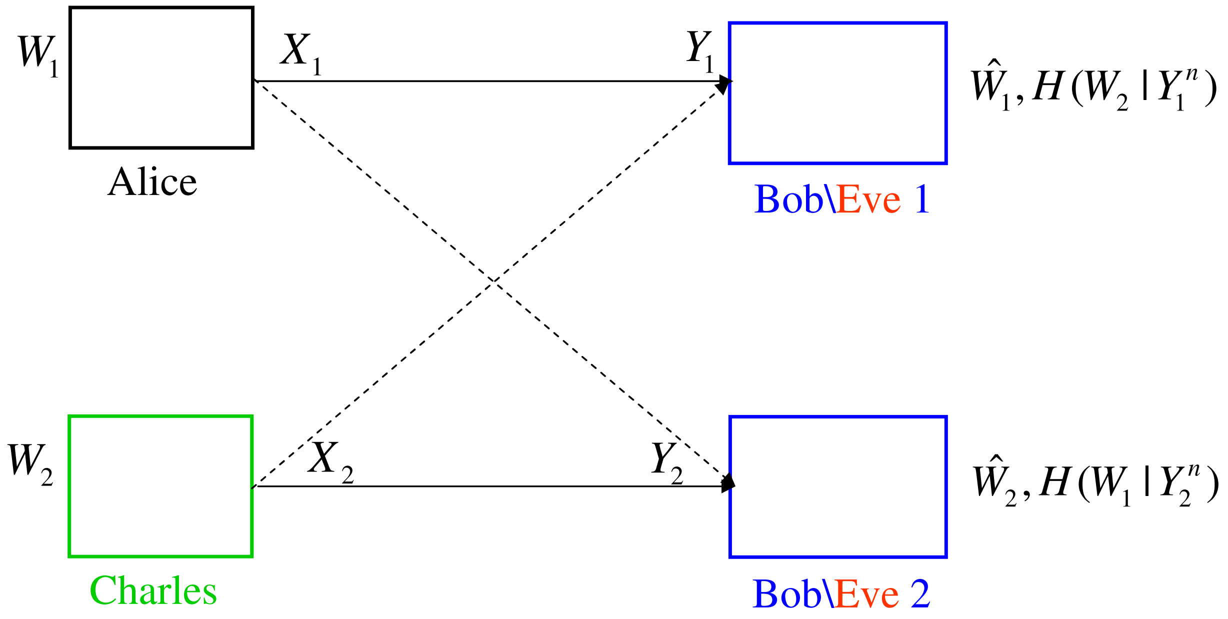
Multiple Access (Uplink) Channel

- Alice and Charles want to have secure communication with Bob in the presence of Eve.
- Simultaneous multi-message secrecy. Opportunities for **deaf cooperation.**



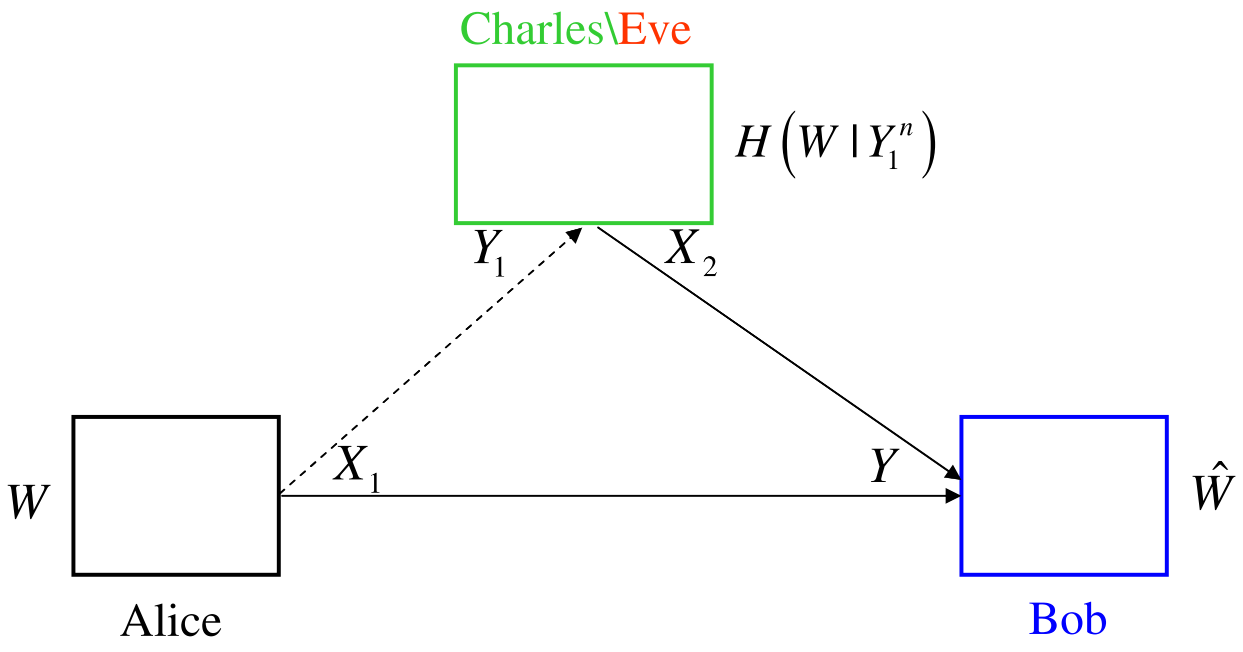
Interference Channel with Confidential Messages

- Interference results in performance degradation, requires sophisticated transceiver design.
- From a secrecy point of view, interference (overheard signal) results in loss of confidentiality.



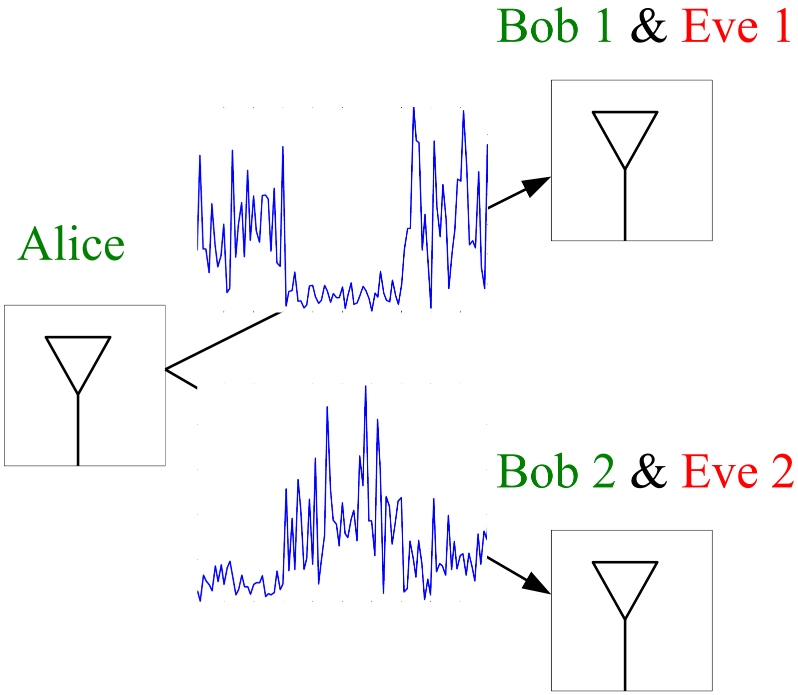
Cooperative Channels

- **Overheard information** at communicating parties:
  - Forms the basis for cooperation; results in loss of confidentiality
- How do cooperation and secrecy interact?
- Can Charles help without learning the messages going to Bob?



Fading Broadcast Channel with Confidential Messages

- Both users want secrecy against each other.
- In a non-fading setting, only one user can have a positive secure rate.
- With full CSIT and CSIR: Gaussian signalling with power control is optimal.



Bob 1 & Eve 1

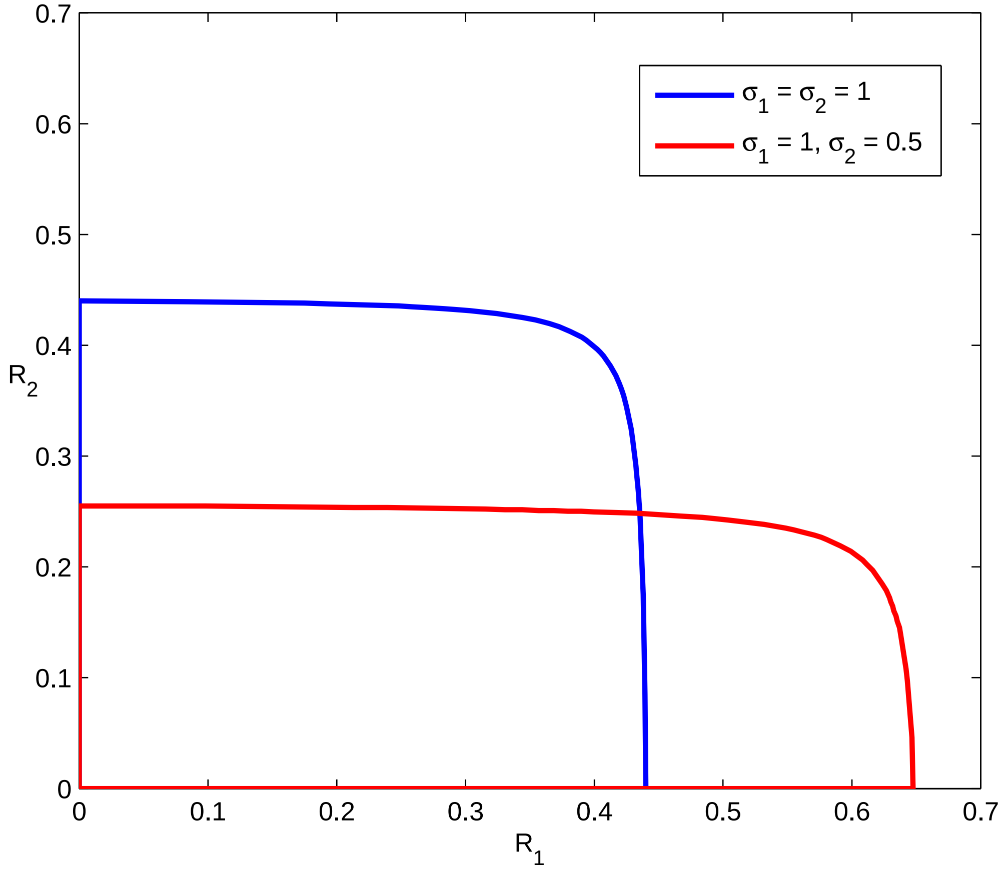
Alice

Bob 2 & Eve 2

- Ekrem et. al., Ergodic Secrecy Capacity Region of the Fading Broadcast Channel, ICC 2009.

The Secrecy Capacity Region

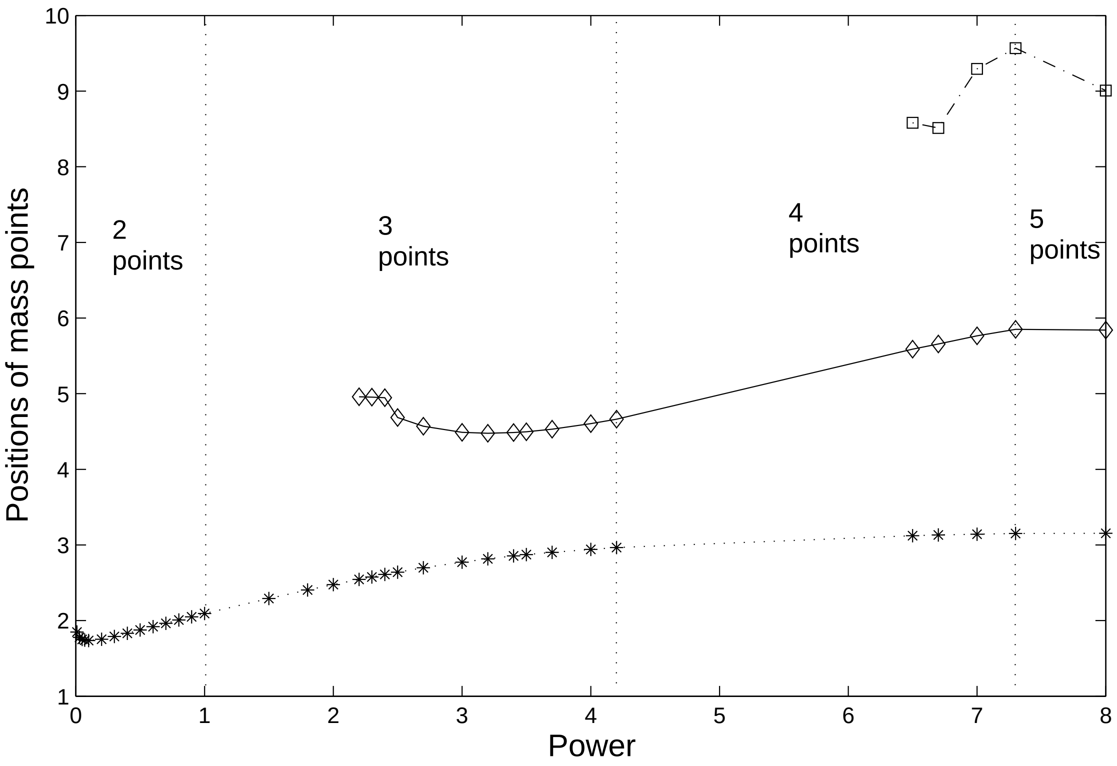
- (Squared) channel gains are exponential random variables with means σ_1, σ_2, respectively.



- Fading (channel variation over time) is beneficial for secrecy.
- Both users can have positive secrecy rates in fading (even if they have the same average quality). **This is not possible without fading.**

Fading Wiretap Channel without CSI

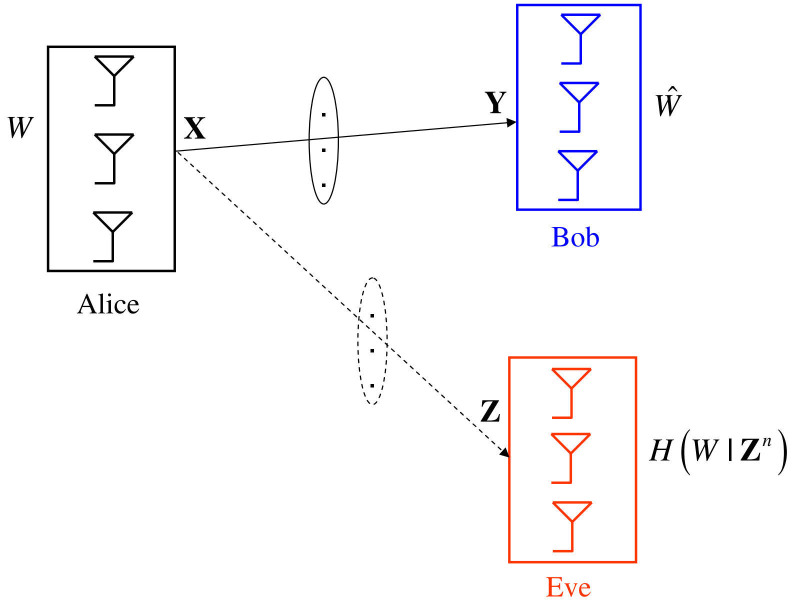
- Fast fading channel: no CSI anywhere.
- Discrete signalling is optimal.



- Mukherjee et. al., Fading Wiretap Channel with No CSI Anywhere, ISIT 2013.

Gaussian MIMO Wiretap Channel

- Multiple antennas improve reliability and rates. They improve secrecy as well.



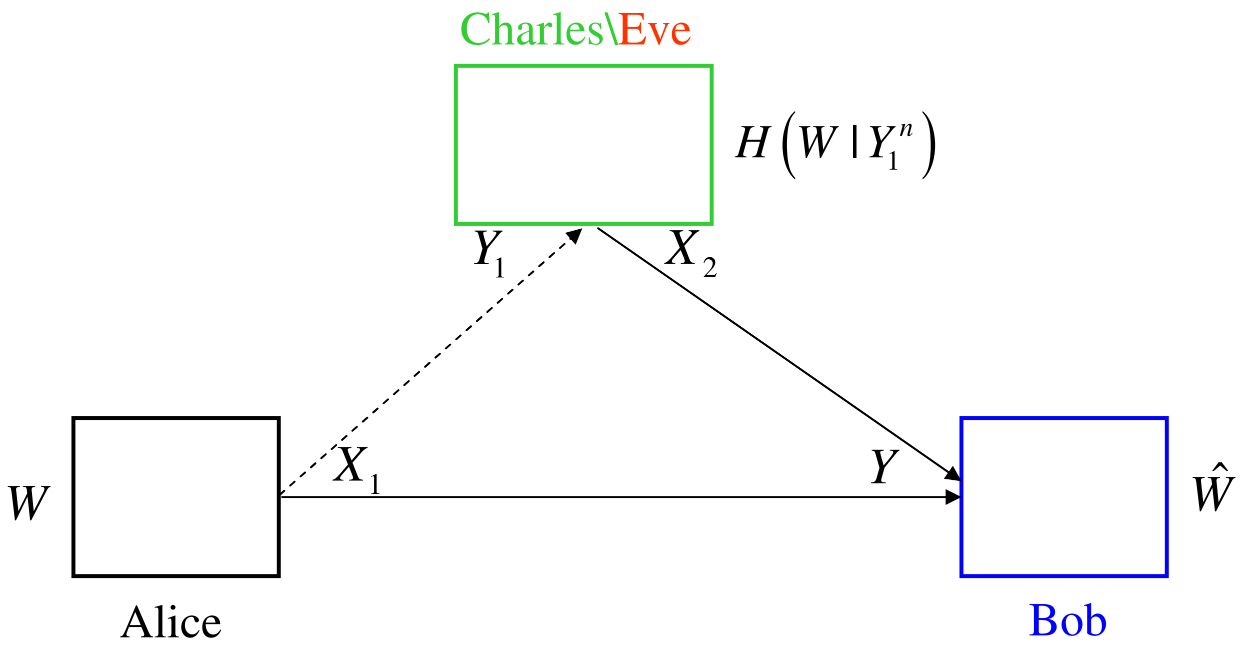
- No channel prefixing is necessary and Gaussian signalling is optimal. The secrecy capacity:

$$C_s = \max_{\mathbf{K}:\mathrm{tr}(\mathbf{K})\leq P} \frac{1}{2}\log\left|\mathbf{H}_M\mathbf{K}\mathbf{H}_M^\top + \mathbf{I}\right| - \frac{1}{2}\log\left|\mathbf{H}_E\mathbf{K}\mathbf{H}_E^\top + \mathbf{I}\right|$$

- As opposed to the SISO case, $C_S \neq C_B - C_E$. **Tradeoff** between the rate and its equivocation.
- Shafiee et. al., Towards the Secrecy Capacity of the Gaussian MIMO Wire-tap Channel: The 2-2-1 Channel, IEEE Trans. on Information Theory, 2009.

Cooperative Channels and Secrecy

- How do cooperation and secrecy interact?
- Is there a trade-off or a synergy?



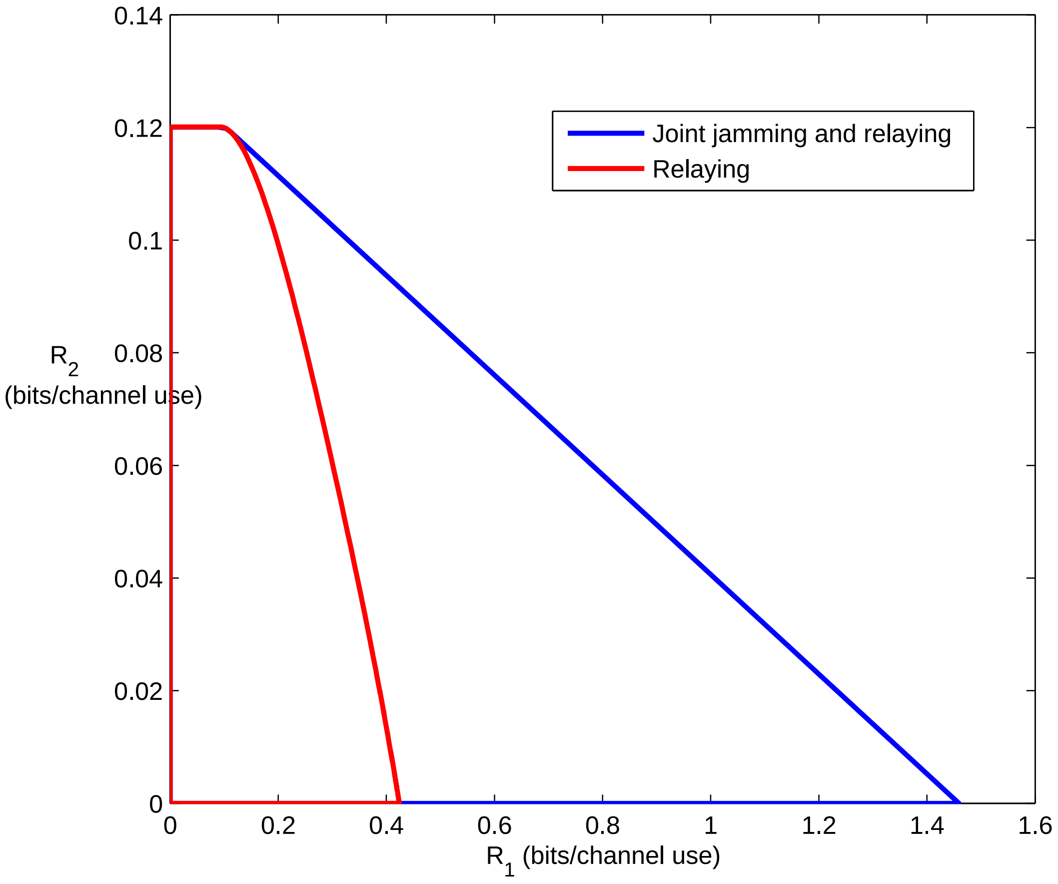
- Ekrem et. al., Secrecy in Cooperative Relay Broadcast Channels, IEEE Trans. on Information Theory, 2011.

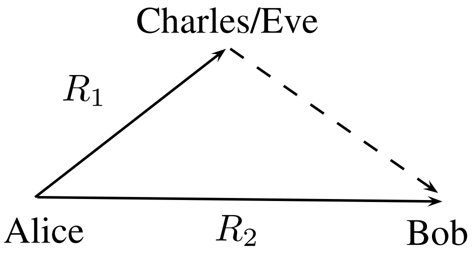
Interactions of Cooperation and Secrecy

- Existing cooperation strategies:
  - Decode-and-forward (DAF)
  - Compress-and-forward (CAF)
- Decode-and-forward:
  - Relay decodes (learns) the message.
  - No secrecy is possible.
- Compress-and-forward:
  - Relay does not need to decode the message.
  - Can it be useful for secrecy?
- Achievable secrecy rate when relay uses CAF:

$$I(X_1;Y_1,\hat{Y}_1|X_2)-I(X_1;Y_2|X_2)=\underbrace{I(X_1;Y_1|X_2)-I(X_1;Y_2|X_2)}_{\text{secrecy rate of the wiretap channel}}+\underbrace{I(X_1;\hat{Y}_1|X_2,Y_1)}_{\text{additional term due to CAF}}$$

Gaussian Relay Broadcast Channel (Charles is Stronger)





- Bob cannot have any positive secrecy rate without cooperation.
- Cooperation is beneficial for secrecy if CAF based relaying (cooperation) is employed.
- Charles can further improve his own secrecy by joint relaying and jamming.

Secure Degrees of Freedom: Motivation

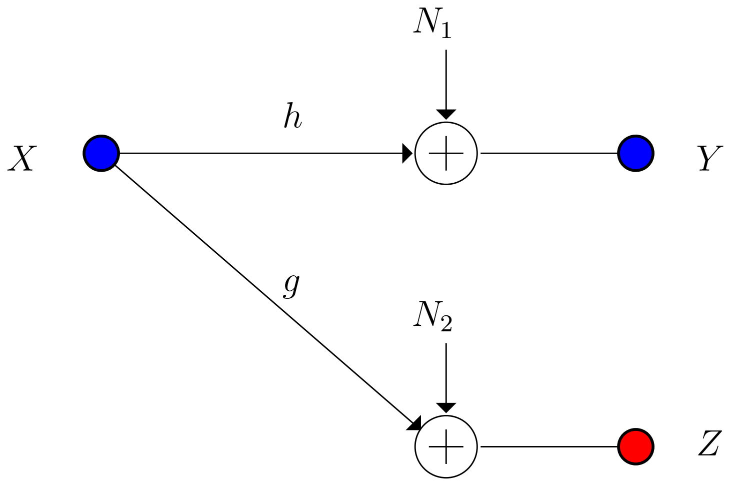
- For most multi-user wiretap channels, secrecy capacity is unknown.
- Partial characterization in the high power, P, regime.
- Secure degrees of freedom (d.o.f.) is defined as:

$$D_s \overset{\triangle}{=} \lim_{P \to \infty} \frac{C_s}{\frac{1}{2} \log P}$$

- Rest of this talk:
  - Secrecy penalty paid in d.o.f
  - Role of a helper for security
  - D.o.f. optimal **deaf** cooperation
  - Secure d.o.f. of some multi-user channels

Canonical Gaussian Wiretap Channel

- Canonical Gaussian wiretap channel with power P,



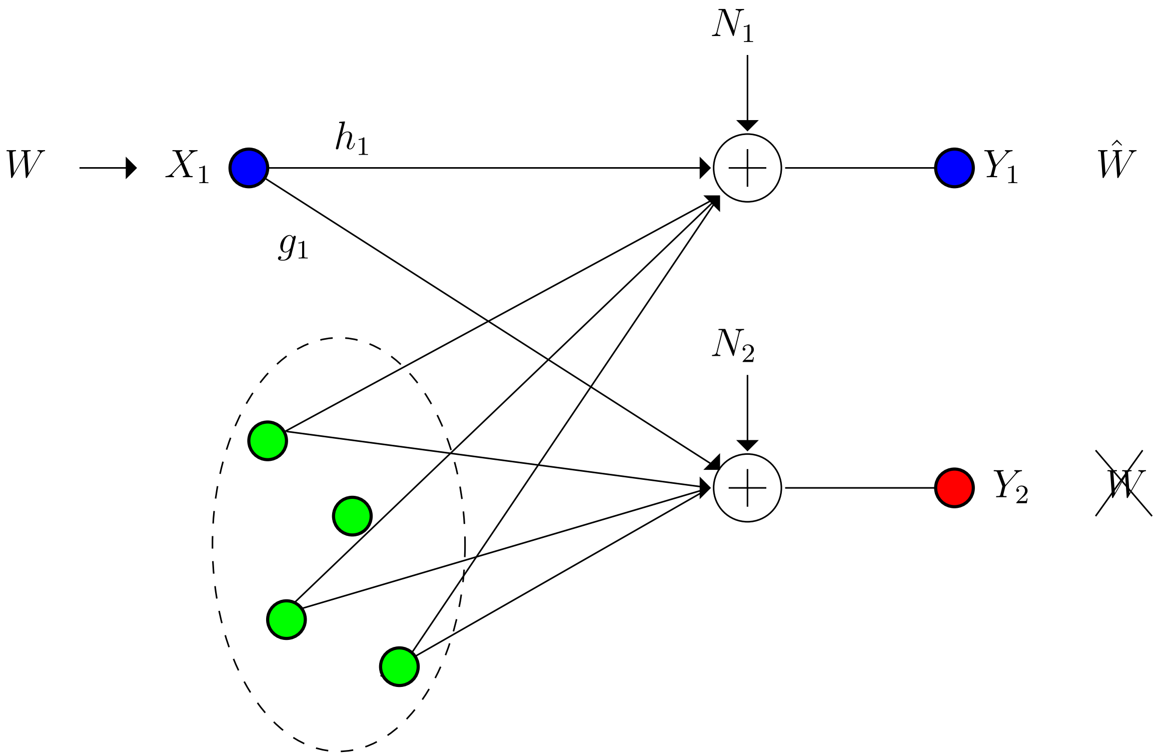
- The secrecy capacity is known exactly:

$$C_s = \frac{1}{2}\log\left(1+h^2P\right) - \frac{1}{2}\log\left(1+g^2P\right)$$

- In this case, C_s does not scale with $\log P$, and $D_s = 0$.
- Severe penalty for secrecy. D.o.f. goes from 1 to 0 due to secrecy.

Cooperative Jamming

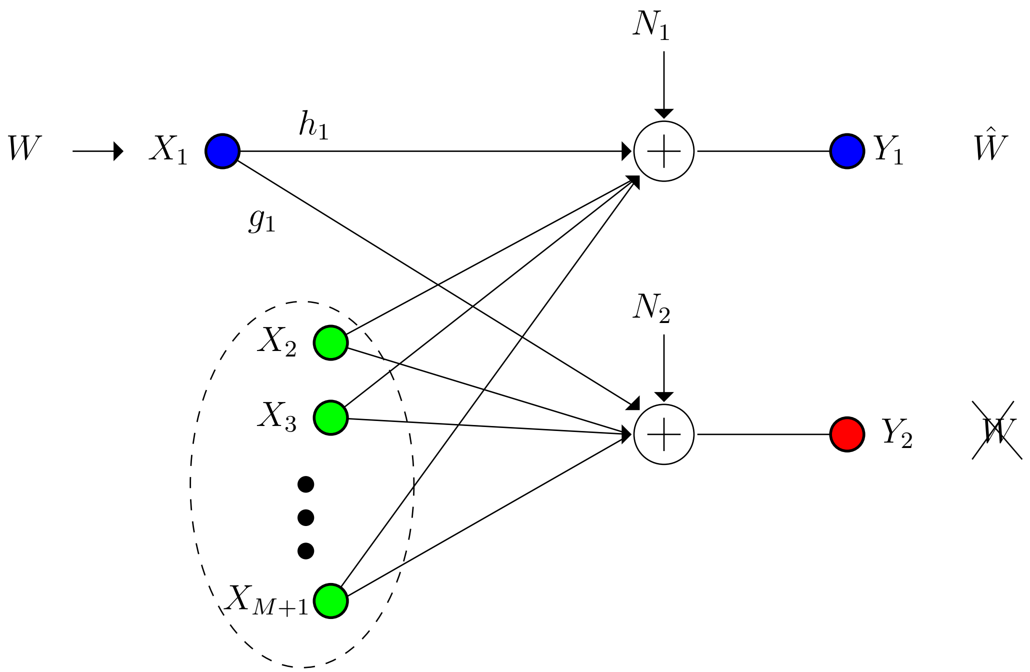
- Cooperative jamming from helpers improves secure rates [Tekin, Yener, 2008].



- Secure d.o.f. with i.i.d. Gaussian cooperative jamming is still zero.
- Positive secure d.o.f. by using nested lattice codes [He, Yener, 2009].
- **Question**: What is the **exact** secure d.o.f.?

Gaussian Wiretap Channel with M Helpers

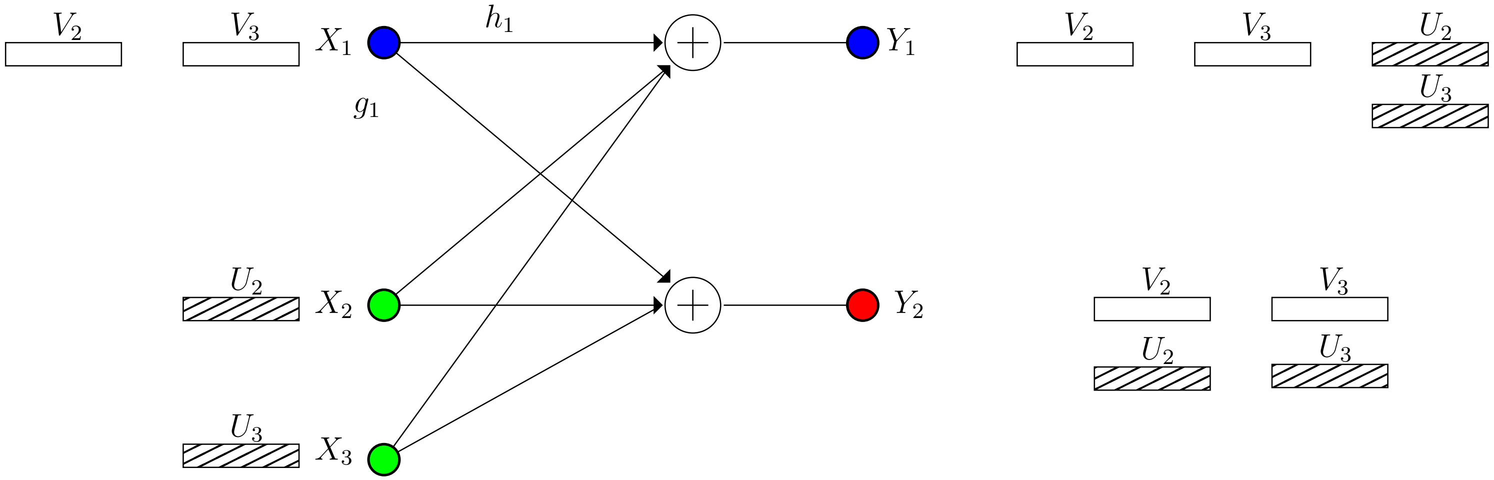
- The exact secure d.o.f. with M helpers is $\frac{M}{M+1}$.
- Even though they are independent, more helpers is better.



- Tools: Real interference alignment and structured coding.
- Xie et. al., Secure Degrees of Freedom of the Gaussian Wiretap Channel with Helpers, Allerton Conference, 2012.

Secure Signal Alignment with M Helpers

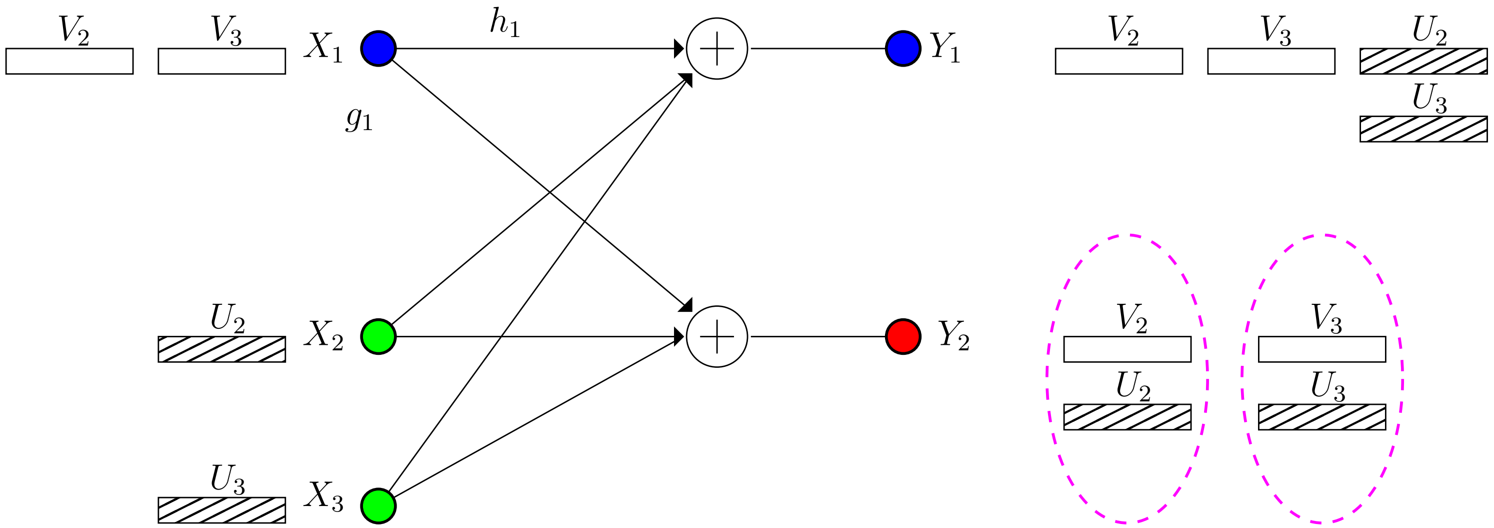
- Alignment for the $M = 2$ case:



- The transmitter sends M independent sub-messages.
- M helpers send an independent cooperative jamming signal each.
- Each cooperative jamming signal is aligned with one sub-message at the eavesdropper.
- All cooperative jamming signals are aligned together at the legitimate receiver.

Eavesdropper CSI?

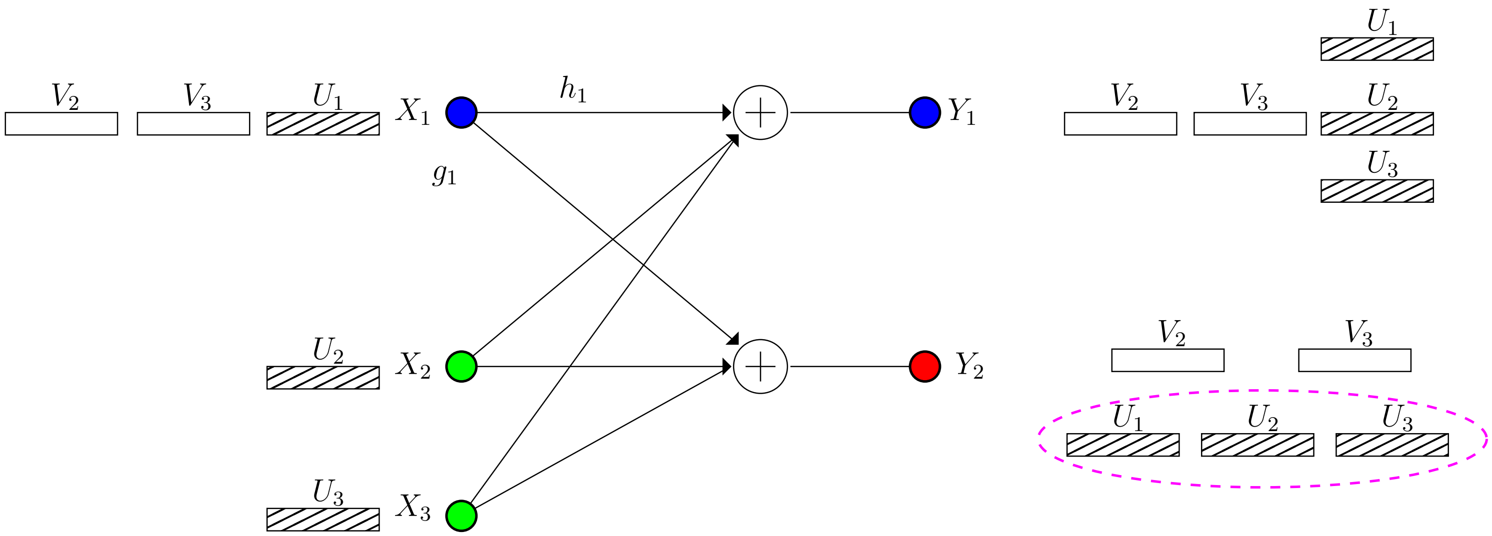
- The previous achievable scheme required **perfect knowledge** of eavesdropper CSI.



- Generally, it is **difficult or impossible** to obtain the eavesdropper's CSI.
- **Question**: What is the **exact** secure d.o.f. **without** eavesdropper CSI?
- **The exact secure d.o.f. is <u>still</u>** $\frac{M}{M+1}$.
- Xie et. al., Secure Degrees of Freedom of the Gaussian Wiretap Channel with Helpers and No Eavesdropper CSI: Blind Cooperative Jamming, CISS 2013.

Secure Signal Alignment with M Helpers without Eavesdropper CSI

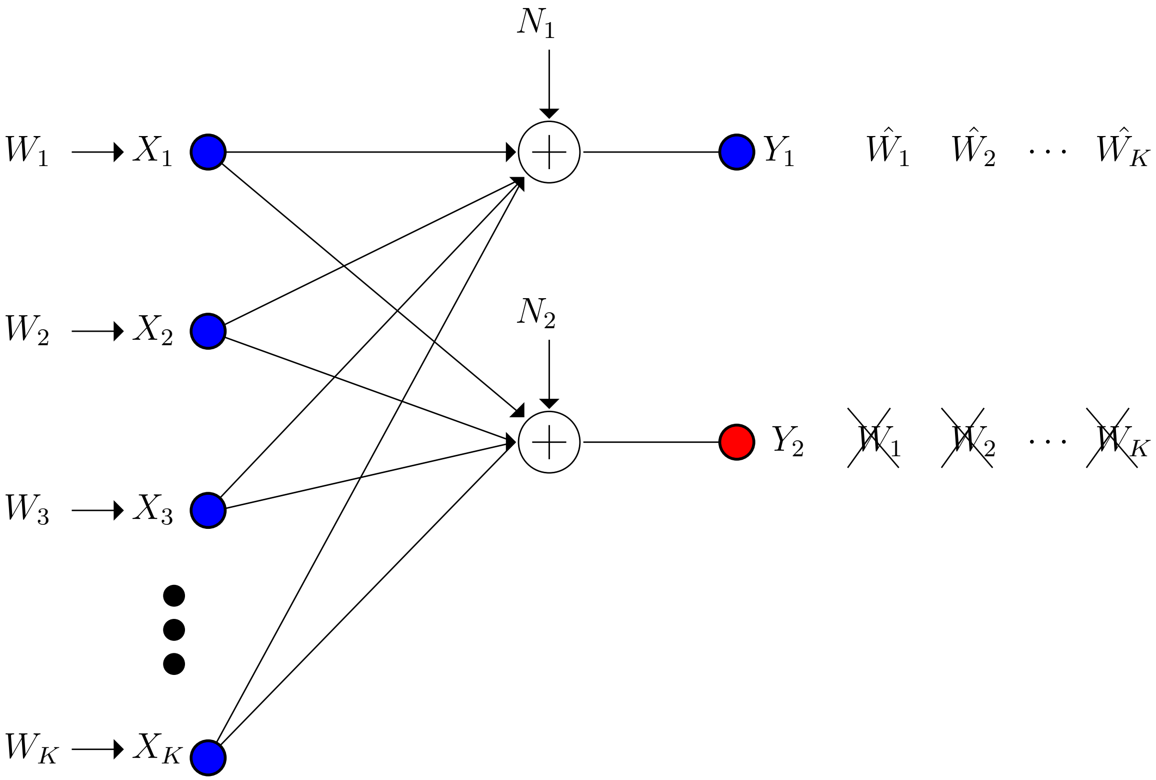
- Alignment for $M = 2$ helpers without eavesdropper CSI:



- The transmitter sends M independent sub-messages and also a cooperative jamming signal.
- M helpers send an independent cooperative jamming signal each.
- All $M + 1$ cooperative jamming signals are blue aligned together at the legitimate receiver.
- All cooperative jamming signals span the entire space at the eavesdropper.

Multiple Access Wiretap Channel

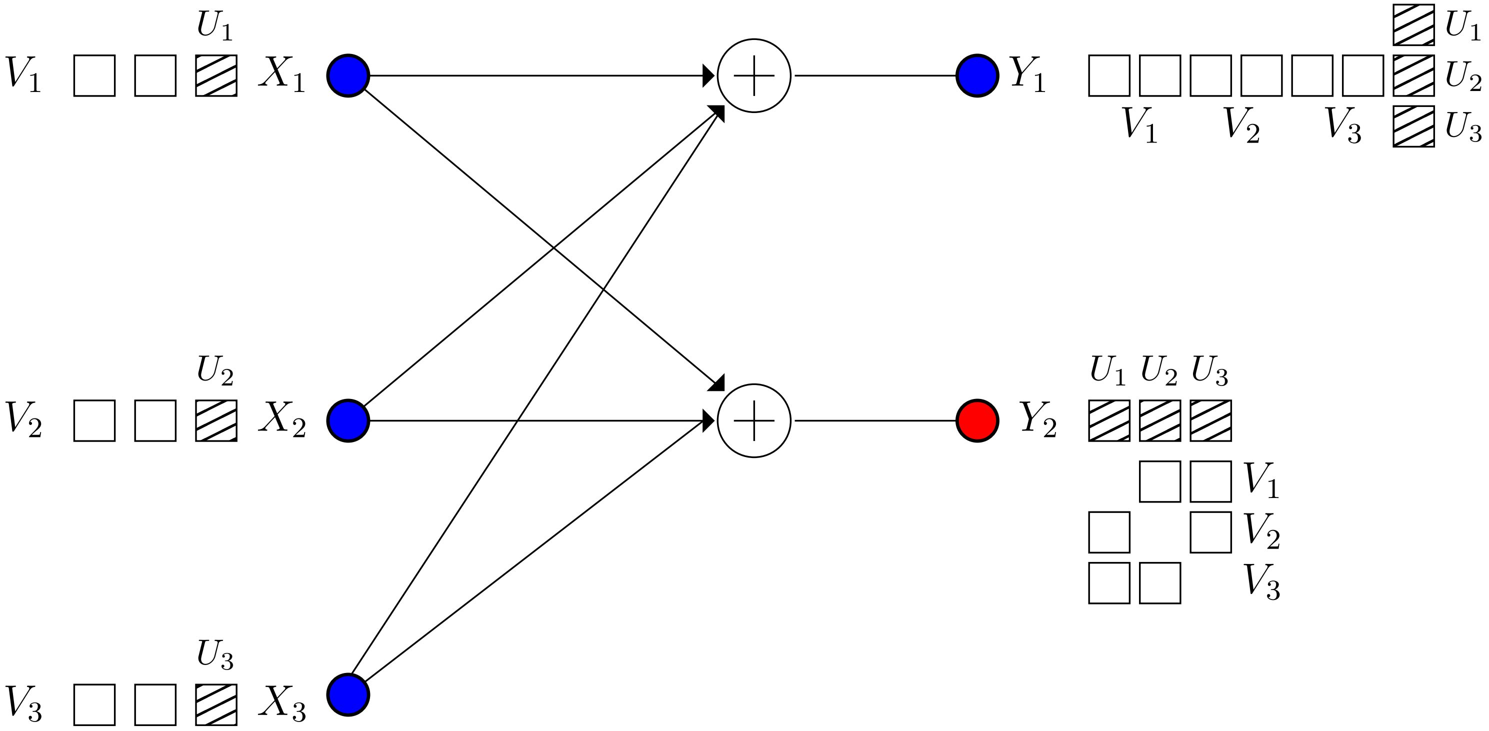
- Each user has its own message to be kept secret from the external eavesdropper.



- The exact sum secure d.o.f. is $\frac{K(K-1)}{K(K-1)+1}$.
- Xie et. al., Secure Degrees of Freedom of the Gaussian Multiple Access Wiretap Channel, ISIT 2013.

Secure Signal Alignment for the Multiple Access Channel

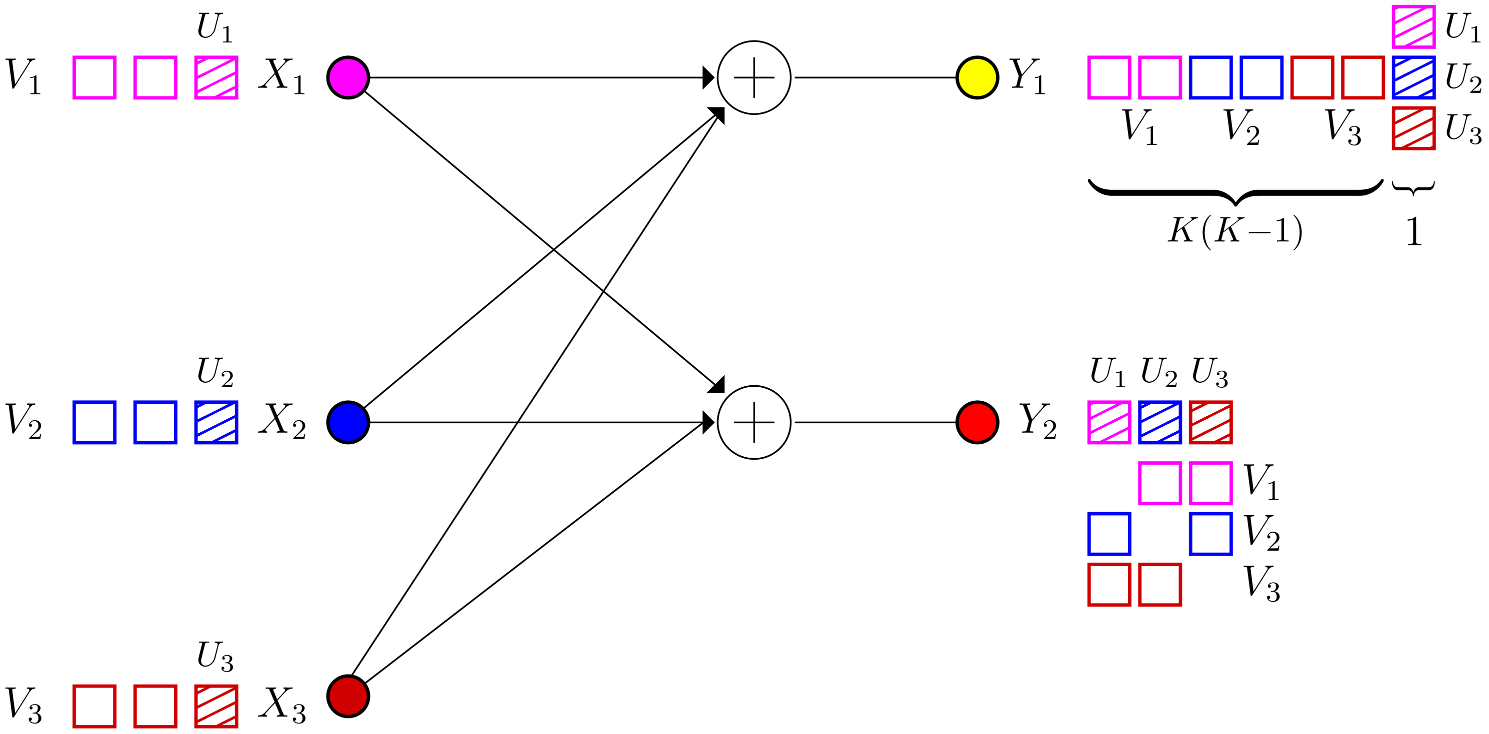
- Alignment for the $K = 3$ case:



- Each transmitter divides its own message into $K-1$ sub-messages.
- The total K jamming signals from the K users span the whole space at the eavesdropper.
- The jamming signals are aligned in the same dimension at the legitimate receiver.

Secure Signal Alignment for the Multiple Access Channel

- Alignment for the $K = 3$ case:



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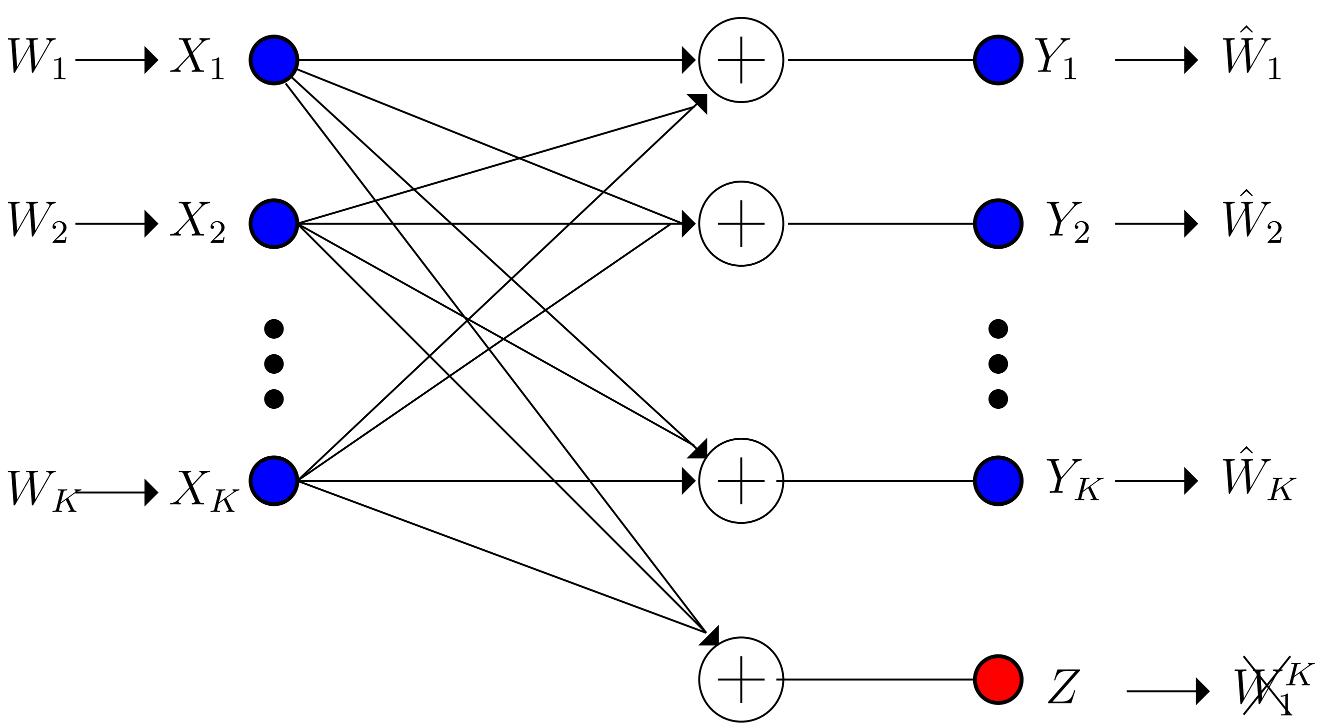
Interference Channel with an External Eavesdropper

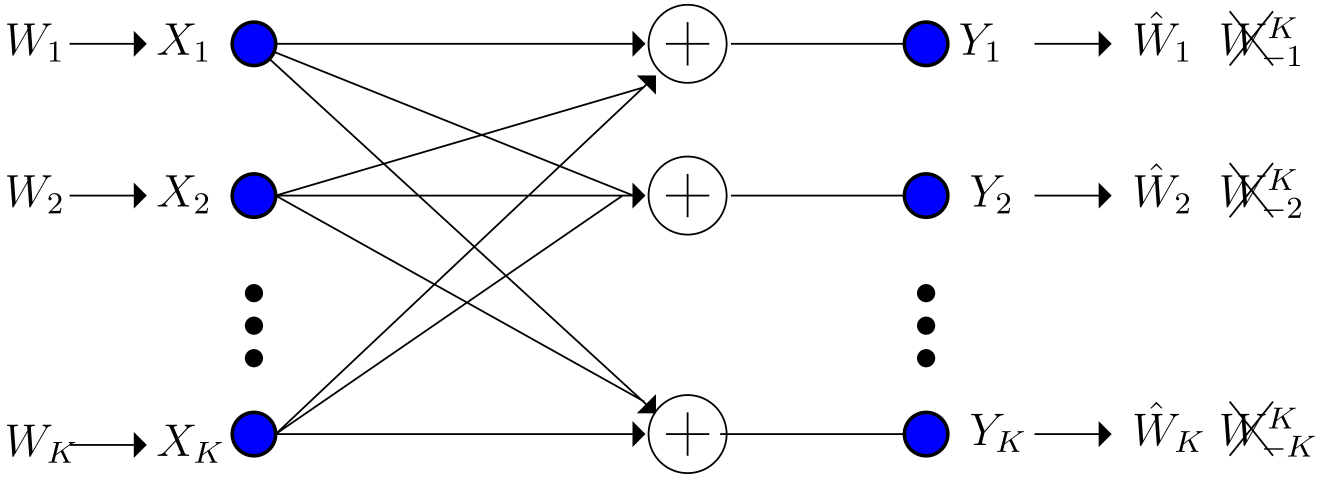
- External eavesdropper model (IC-EE).



- Secure all messages against the external eavesdropper.

Interference Channel with Confidential Messages

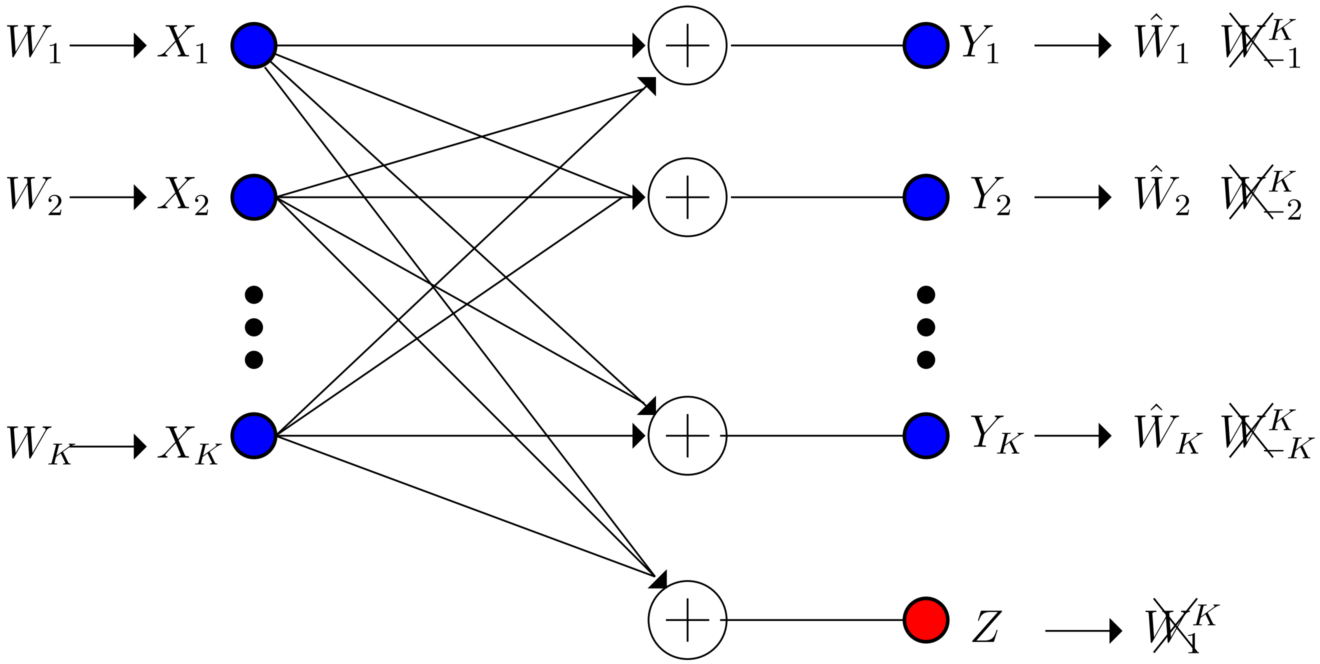
- Confidential message model (IC-CM).



- Secure all messages against all unintended receivers.

Unified Model: Internal and External Security

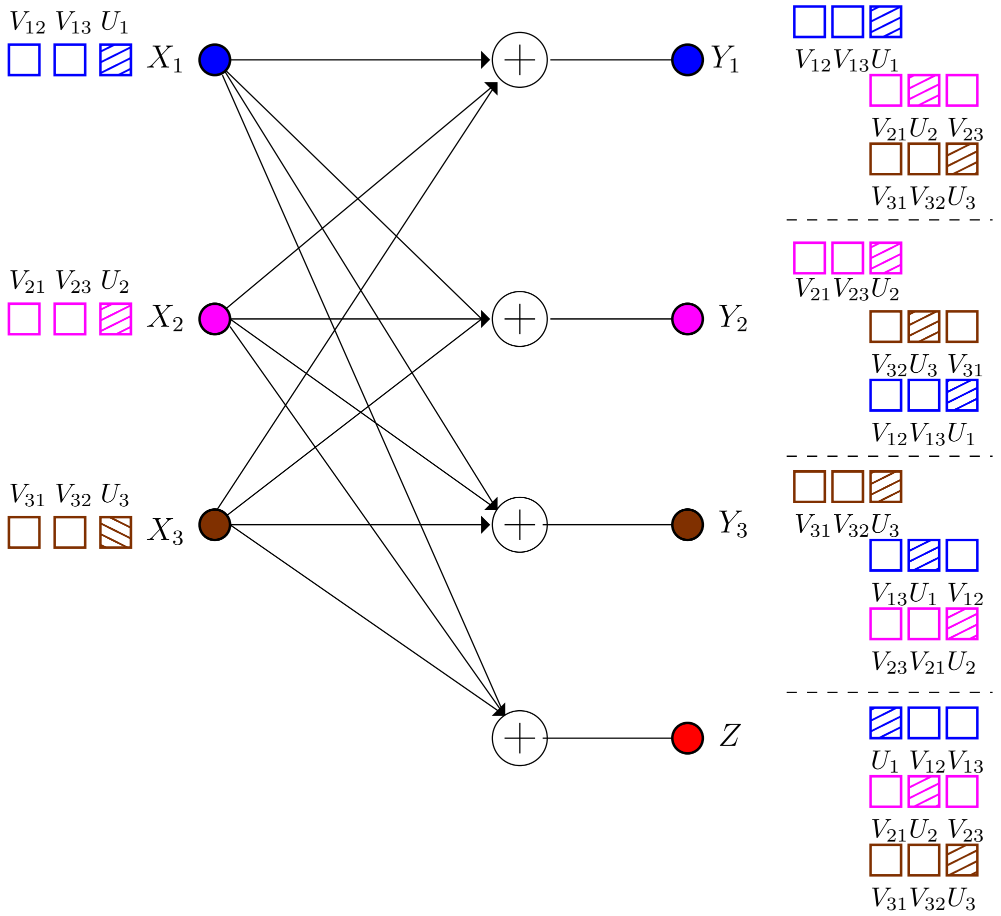
- Interference channel with confidential messages and one external eavesdropper (IC-CM-EE):



- Secure all messages against the internal unintended receivers and the external eavesdropper.

Secure Signal Alignment for the Unified K-User IC-CM-EE

- The **exact** sum secure dof is $\frac{K(K-1)}{2K-1}$.
- Added challenge: simultaneous alignment at multiple receivers.



- Xie et. al., Unified Secure DoF Analysis of K-User Gaussian Interference Channels, ISIT 2013.

Going Back to where We have Started

- Cryptography
  - at higher layers of the protocol stack
  - based on the assumption of **limited computational power** at Eve
  - vulnerable to large-scale implementation of quantum computers
- Techniques like frequency hopping, CDMA
  - at the physical layer
  - based on the assumption of **limited knowledge** at Eve
  - vulnerable to rogue or captured node events
- Physical layer security
  - at the physical layer
  - no assumption on Eve's computational power
  - no assumption on Eve's available information
  - **unbreakable, provable,** and **quantifiable** (in bits/sec/hertz)
  - implementable by signal processing, communications, and coding techniques

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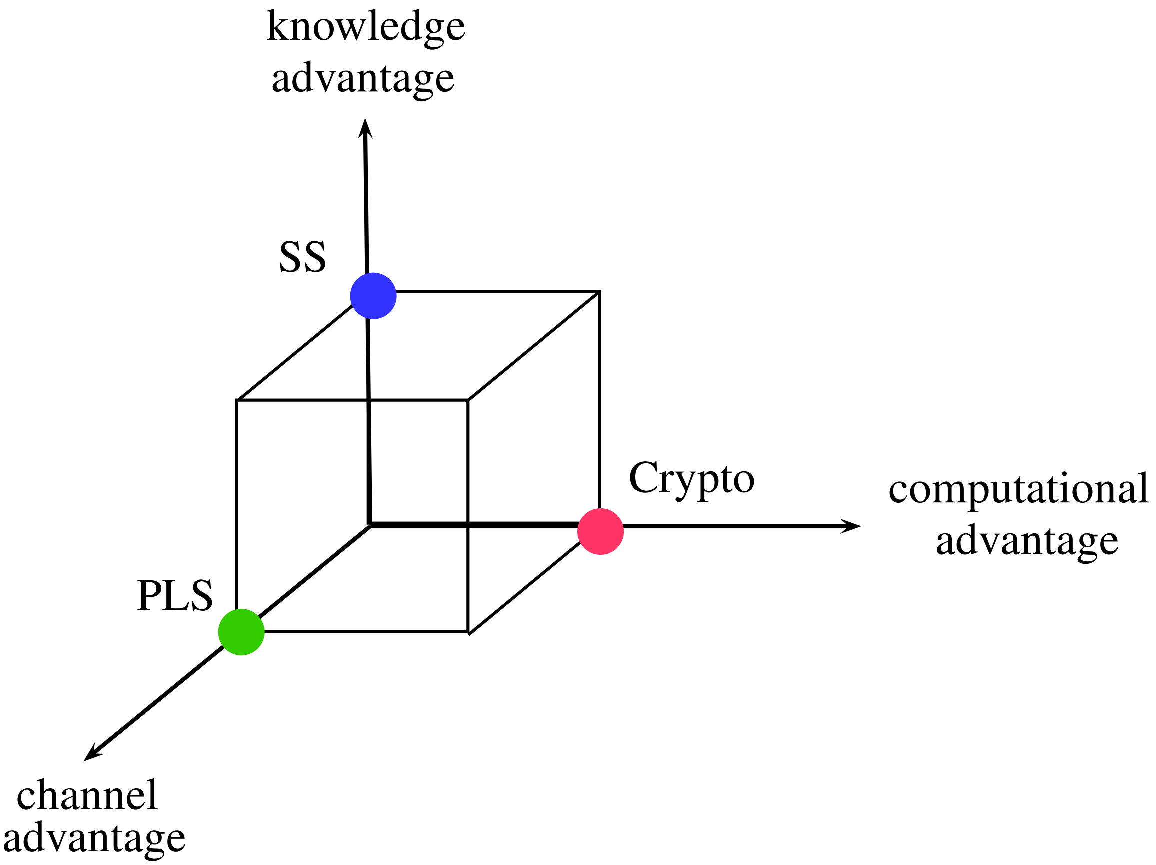
Two Recurring Themes

- Creating advantage for the legitimate users:
    - computational advantage (cryptography)
    - knowledge advantage (spread spectrum)
    - channel advantage (physical layer security)

- Exhausting capabilities of the illegitimate entities:
    - exhausting computational power (cryptography)
    - exhausting searching power (spread spectrum)
    - exhausting decoding capability (physical layer security)

Three Dimensions of Advantage

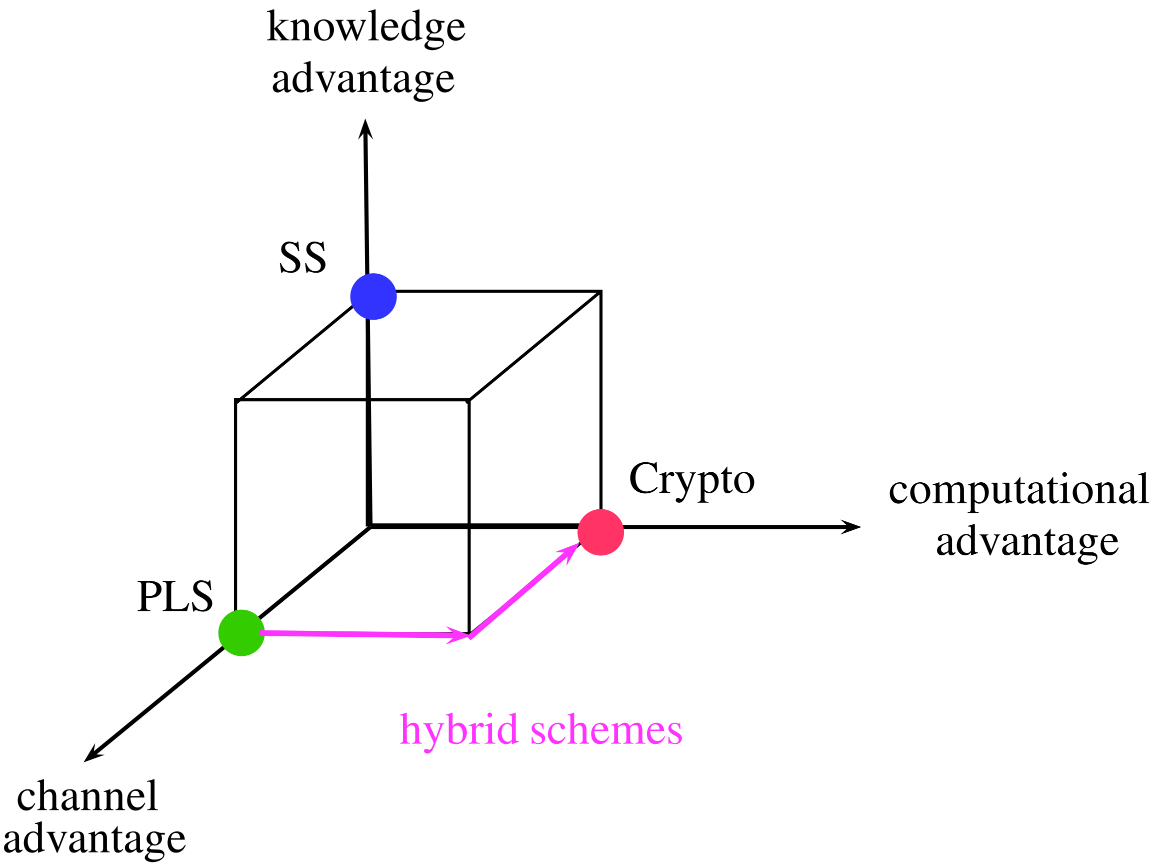
- **Three <u>known</u> dimensions of advantage:** knowledge, computational, channel advantage.



- Each method uses **only one possible dimension** of advantage.

Hybrid Schemes

- Hybrid schemes: move to another dimension when an advantage is lost.



- Still a **single dimension** is used.

Hybrid Schemes

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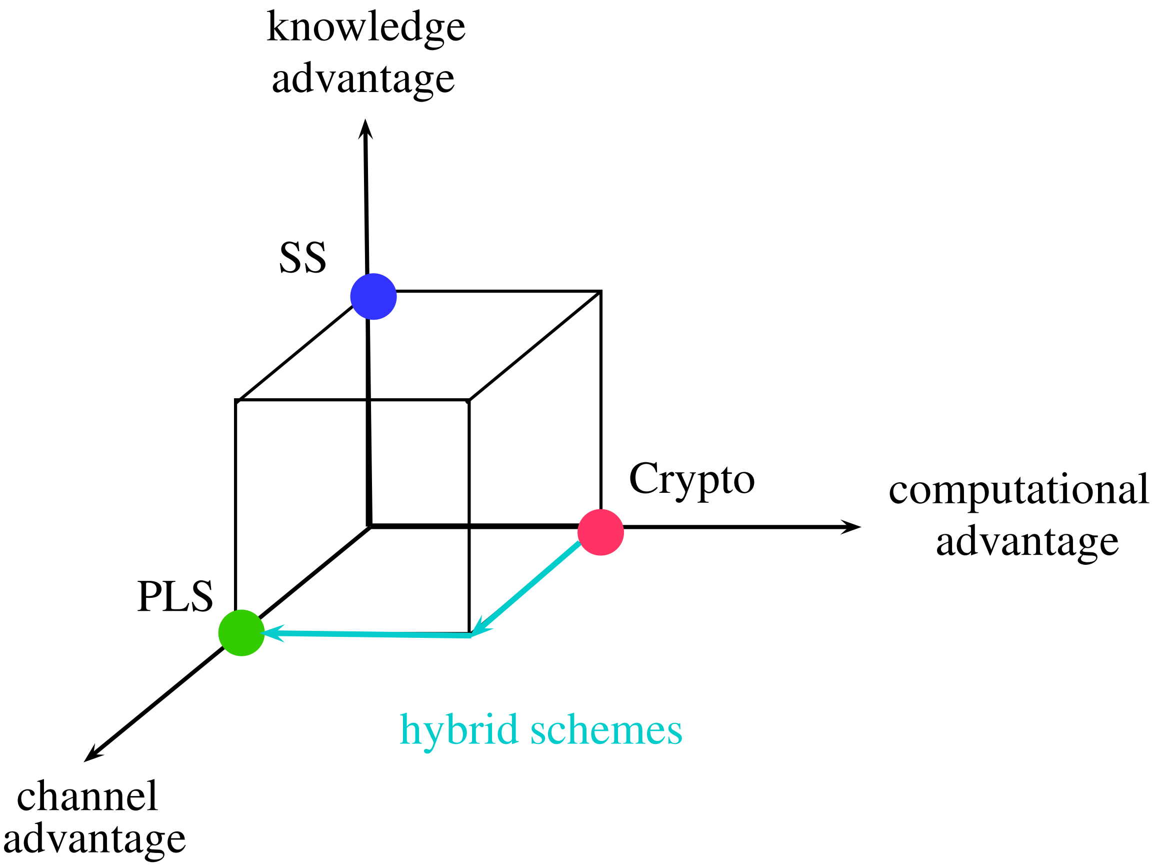
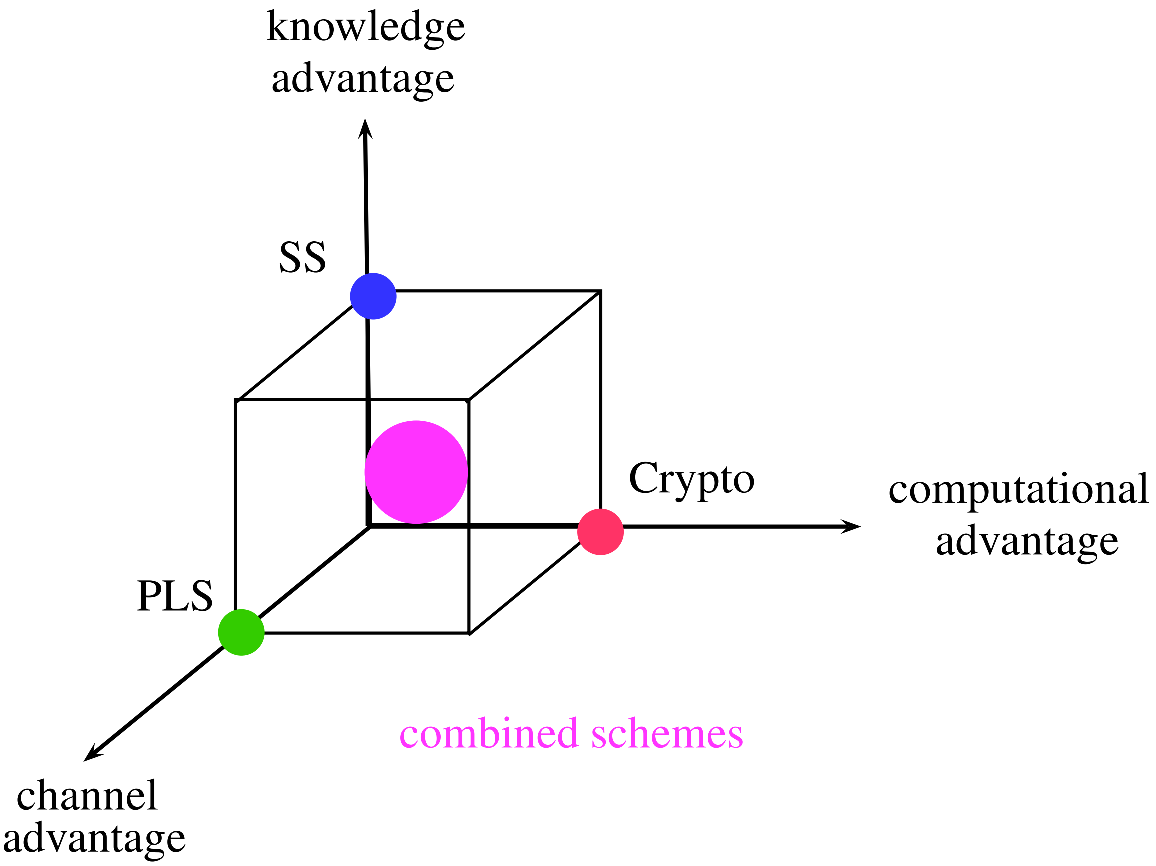


- Still a **single dimension** is used.

Combined Schemes

- Combine and utilize multiple dimensions of advantage



- Multi-dimensional, multi-faceted, **cross-layer** security.

Conclusions

- Wireless communication is susceptible to eavesdropping and **jamming** attacks.
- Wireless medium also offers ways to neutralize the loss of confidentiality:
  - time, frequency, multi-user diversity via fading
  - cooperation via overheard signals
  - multi-dimensional signalling via multiple antennas
  - secure signal alignment
- Information theory directs us to methods that can be used to achieve:
  - **unbreakable, provable,** and **quantifiable** (in bits/sec/hertz) security
  - irrespective of the adversary's computation power or inside knowledge
- Resulting schemes implementable by signal processing, communications and coding tech.
- Many open problems...