Secure MIMO Interference Channel with Confidential Messages and Delayed CSIT

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Outline

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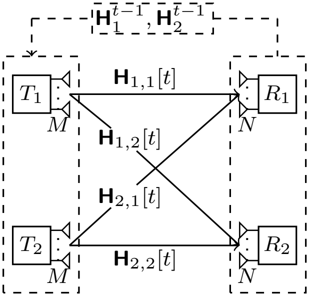
MIMO Interference Channel with Delayed Channel State Information at Transmitter (CSIT)



- Each transmitter has M antennas and each receiver has N antennas.
- The CSI matrices from the transmitter $i, i = 1, 2$ to the receiver $j, j = 1, 2$ at time slot t is denoted by $\mathbf{H}_{i,j}[t]$.
- The collection of delayed CSI matrices, i.e., $\mathbf{H}_{i,j}^{t-1}, i, j = 1, 2$, is fed back to all transmitters at time slot t.

Secure Degrees-of-Freedom (SDoF)

- Transmitter 1 sends confidential message W_1 to receiver 1 without information leakage to receiver 2.
- Transmitter 2 sends confidential message W_2 to receiver 2 without information leakage to receiver 1.
- SDoF is a first-order approximation of secure channel capacity.
- Mathematically, the sum-SDoF is defined as follows:

$$\text{Sum-SDoF} = \sup \lim_{n \to \infty} \frac{\log |W_1| + \log |W_2|}{n \log(\text{SNR})} \tag{1}$$

  where n denotes the number of channel uses.
- Physically, the sum-SDoF represents the maximal number of secure independent channels that a network can support.

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Related Works & The Problem

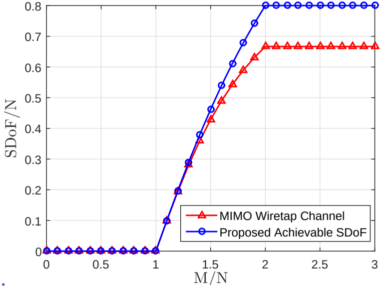
- **With perfect CSIT**, sum-SDoF of MIMO interference channel has been obtained by [Banawan and Ulukus, 2015, Banawan and Ulukus, 2019].
- **With delayed CSIT**
  - SDoF region of two-user MIMO broadcast channel [Yang et al., 2013].
  - SDoF region of K-user MISO broadcast channel [Yang and Kobayashi, 2015].
  - Sum-SDoF of multi-user wiretap channel [Awan et al., 2016, Tandon et al., 2014, Yang and Kobayashi, 2015]
  - Sum-SDoF of $2 \times 2 \times 2$ SISO interference channel [Wang et al., 2014]
- **Problem**: For MIMO interference channel with delayed CSIT, the sum-SDoF has not been thoroughly studied.

Contributions

- For the first time, an achievable sum-SDoF was derived in this paper, which is a lower bound of sum-SDoF and given by

$$\text{Sum-SDoF} \geq \begin{cases} 0, & M/N \leq 1 \\ \dfrac{2MN(M-N)}{M^2+N^2}, & 1 < M/N \leq 2 \\ 4N/5, & 2 < M/N \end{cases} \quad (2)$$

- The proposed achievable sum-SDoF can be 20% greater than that of MIMO wiretap channel with delayed CSIT.



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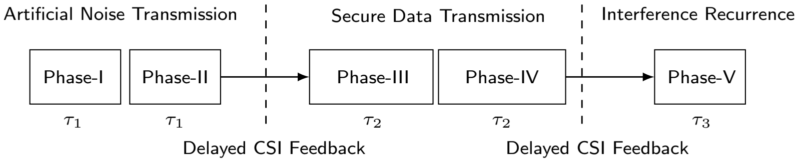
Sketch of The Proposed Design

- If $M \leq N$, we claim that the achievable sum-SDoF is 0. Because, the artificial noise sent by the single transmitter can be immediately decoded, thus the security cannot be guaranteed.
- If $N < M$, we then design a multi-phase transmission scheme, which will be introduced later on. The sketch is given by



Proposed Scheme for $N < M$ Case

- **Definition 1**: We define the effective CSI matrices from Phase-I to Phase-V as follows:

$$\underline{\mathbf{H}}^{\mathsf{I}}_{i,j} \triangleq \text{blkdiag}\{\mathbf{H}^{\mathsf{I}}_{i,j}(1), \cdots, \mathbf{H}^{\mathsf{I}}_{i,j}(\tau_1)\}$$
$$\underline{\mathbf{H}}^{\mathsf{II}}_{i,j} \triangleq \text{blkdiag}\{\mathbf{H}^{\mathsf{II}}_{i,j}(\tau_1+1), \cdots, \mathbf{H}^{\mathsf{II}}_{i,j}(2\tau_1)\}$$
$$\underline{\mathbf{H}}^{\mathsf{III}}_{i,j} \triangleq \text{blkdiag}\{\mathbf{H}^{\mathsf{III}}_{i,j}(2\tau_1+1), \cdots, \mathbf{H}^{\mathsf{III}}_{i,j}(2\tau_1+\tau_2)\}$$
$$\underline{\mathbf{H}}^{\mathsf{IV}}_{i,j} \triangleq \text{blkdiag}\{\mathbf{H}^{\mathsf{IV}}_{i,j}(2\tau_1+\tau_2+1), \cdots, \mathbf{H}^{\mathsf{IV}}_{i,j}(2\tau_1+2\tau_2)\}$$
$$\underline{\mathbf{H}}^{\mathsf{V}}_{i,j} \triangleq \text{blkdiag}\{\mathbf{H}^{\mathsf{V}}_{i,j}(2\tau_1+2\tau_2+1), \cdots, \mathbf{H}^{\mathsf{V}}_{i,j}(2\tau_1+2\tau_2+\tau_3)\}$$

  where $i, j = 1, 2$.
- **Definition 2**: We also set the full-rank randomized matrices, which are pre-stored at all transmitters and receivers, as follows:

$$\mathbf{\Phi}_1 \in \mathbb{C}^{\min\{M,2N\}\tau_2 \times N\tau_1}, \qquad \mathbf{\Phi}_2 \in \mathbb{C}^{\min\{M,2N\}\tau_2 \times N\tau_1}$$
$$\mathbf{B}_1 \in \mathbb{C}^{N\tau_3 \times N\tau_2}, \qquad \mathbf{B}_2 \in \mathbb{C}^{N\tau_3 \times N\tau_2}$$

Proposed Scheme for $N < M$ Case

- *Phase-I (Artificial Noise Transmission from Transmitter 1)*: Transmitter 1 sends artificial noise $\mathbf{u}_1 \in \mathbb{C}^{\min\{M,2N\}\tau_1}$, while transmitter 2 keeps silent. The received signals are given by

$$\mathbf{y}_1^{\mathsf{I}} = \underline{\mathbf{H}}_{1,1}^{\mathsf{I}} \mathbf{u}_1 \quad (3a)$$

$$\mathbf{y}_2^{\mathsf{I}} = \underline{\mathbf{H}}_{1,2}^{\mathsf{I}} \mathbf{u}_1 \quad (3b)$$

- *Phase-I (Artificial Noise Transmission from Transmitter 2)*: Transmitter 2 sends artificial noise $\mathbf{u}_2 \in \mathbb{C}^{\min\{M,2N\}\tau_2}$, while transmitter 1 keeps silent. The received signals are given by

$$\mathbf{y}_1^{\mathsf{II}} = \underline{\mathbf{H}}_{1,1}^{\mathsf{II}} \mathbf{u}_2 \quad (4a)$$

$$\mathbf{y}_2^{\mathsf{II}} = \underline{\mathbf{H}}_{1,2}^{\mathsf{II}} \mathbf{u}_2 \quad (4b)$$

Proposed Scheme for $N < M$ Case

- *Phase-III (Secure Data Transmission for Receiver 1)*:
  The secure transmit signal at transmitter 1 is designed as follows:

$$\mathbf{x}_1^{\mathsf{III}} = \mathbf{s}_1 + \mathbf{\Phi}_1 \mathbf{y}_1^{\mathsf{I}} \in \mathbb{C}^{\min\{M,2N\}\tau_2} \tag{5}$$

  At the same time, transmitter 2 keeps silent. The received signals:

$$\mathbf{y}_1^{\mathsf{III}} = \underline{\mathbf{H}}_{1,1}^{\mathsf{III}} \left(\mathbf{s}_1 + \mathbf{\Phi}_1 \mathbf{y}_1^{\mathsf{I}}\right) \tag{6a}$$

$$\mathbf{y}_2^{\mathsf{III}} = \underline{\mathbf{H}}_{1,2}^{\mathsf{III}} \left(\mathbf{s}_1 + \mathbf{\Phi}_1 \mathbf{y}_1^{\mathsf{I}}\right) \tag{6b}$$

- *Phase-IV (Secure Data Transmission for Receiver 2)*:
  The secure transmit signal at transmitter 2 is designed as follows:

$$\mathbf{x}_2^{\mathsf{IV}} = \mathbf{s}_2 + \mathbf{\Phi}_2 \mathbf{y}_2^{\mathsf{II}} \in \mathbb{C}^{\min\{M,2N\}\tau_3} \tag{7}$$

  At the same time, transmitter 1 keeps silent. The received signals:

$$\mathbf{y}_1^{\mathsf{IV}} = \underline{\mathbf{H}}_{1,1}^{\mathsf{IV}} \left(\mathbf{s}_2 + \mathbf{\Phi}_2 \mathbf{y}_2^{\mathsf{II}}\right) \tag{8a}$$

$$\mathbf{y}_2^{\mathsf{IV}} = \underline{\mathbf{H}}_{1,2}^{\mathsf{IV}} \left(\mathbf{s}_2 + \mathbf{\Phi}_2 \mathbf{y}_2^{\mathsf{II}}\right) \tag{8b}$$

Proposed Scheme for $N < M$ Case

- *Phase-V (Interference Recurrence for Equation Switching)*: The transmit signals are designed to facilitate the switch of equations in Phases-III and Phase-IV, which are given by

$$\mathbf{x}_1^{\mathsf{V}} = \mathbf{B}_1 \mathbf{y}_2^{\mathsf{III}} \tag{9a}$$

$$\mathbf{x}_2^{\mathsf{V}} = \mathbf{B}_2 \mathbf{y}_1^{\mathsf{IV}} \tag{9b}$$

  Therefore, the received signals are given by

$$\mathbf{y}_1^{\mathsf{V}} = \underline{\mathbf{H}}_{1,1}^{\mathsf{V}} \mathbf{B}_1 \mathbf{y}_2^{\mathsf{III}} + \underline{\mathbf{H}}_{2,1}^{\mathsf{V}} \mathbf{B}_2 \mathbf{y}_1^{\mathsf{IV}} \tag{10a}$$

$$\mathbf{y}_2^{\mathsf{V}} = \underline{\mathbf{H}}_{1,2}^{\mathsf{V}} \mathbf{B}_1 \mathbf{y}_2^{\mathsf{III}} + \underline{\mathbf{H}}_{2,2}^{\mathsf{V}} \mathbf{B}_2 \mathbf{y}_1^{\mathsf{IV}} \tag{10b}$$

- **Decoding Condition**: To ensure all transmitted symbols can be decoded, τ_2 and τ_3 should satisfy

$$N\tau_3 = \min\{M - N, N\}\tau_2 \tag{C1}$$

- **Security Condition**: To ensure zero information leakage to the other receiver, τ_1 and τ_2 should satisfy

$$N(\tau_1 + \tau_2) = \min\{M, 2N\}\tau_1 \tag{C2}$$

Analysis of Decoding and Security Conditions

- For the decoding condition $(C1)$, it can be re-written w.r.t. τ_3/τ_2 as follows:

Table: Re-writing of Decoding Condition $(C1)$

$N < M < 2N$	$M \geq 2N$
$\tau_3/\tau_2 = (M-N)/N$	$\tau_3/\tau_2 = 1$

- For the security condition $(C2)$, it can be re-written w.r.t. τ_2/τ_1 as follows:

Table: Re-writing of Security Condition $(C2)$

$N < M < 2N$	$M \geq 2N$
$\tau_2/\tau_1 = (M-N)/N$	$\tau_2/\tau_1 = 1$

- We can see that both τ_3/τ_2 and τ_2/τ_1 are not more than 1.

Proposed Scheme for $N < M$ Case

- **Proposed Achievable Sum-SDoF Maximization Problem**:

$$\max_{\tau_1,\tau_2,\tau_3 \in \mathbb{Z}_+} \quad \frac{2\min\{M,2N\}\tau_2}{2\tau_1 + 2\tau_2 + \tau_3} \qquad \text{s.t.} \quad \text{C1, C2} \tag{11}$$

  Problem re-formulation:

$$\max_{\tau_1/\tau_2,\ \tau_3/\tau_2} \quad \frac{2\min\{M,2N\}}{2\tau_1/\tau_2 + 2 + \tau_3/\tau_2} \qquad \text{s.t.} \quad f_1(\tau_1/\tau_2) = 0, f_2(\tau_3/\tau_2) = 0 \tag{12}$$

  where C1 $\Longleftrightarrow f_1(\tau_1/\tau_2) = 0,$ C2 $\Longleftrightarrow f_2(\tau_3/\tau_2) = 0.$

- **Optimal Solution**: Re-writing condition (C1) and condition (C2) yields the optimal solutions. For example, we can select

$$\begin{cases} \tau_1^* = N^2 \\ \tau_2^* = \min\{M-N, N\}N \\ \tau_3^* = (\min\{M-N, N\})^2 \end{cases} \tag{13}$$

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Conclusion & Future Work

- **Conclusion**: An achievable sum-SDoF for secure MIMO interference channel with confidential messages and delayed CSIT was proposed in this paper. This is the first attempt to the best of our knowledge.
- **Future Work**: To figure out the exact sum-SDoF, an upper bound is needed, which motivates future work.

Outline

Preliminary

Related Works & Contributions

The Proposed Scheme

Conclusion & Future Work

References

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