Robust Artificial-Noise Aided Transmit Design for Multi-User MISO Systems with Integrated Services

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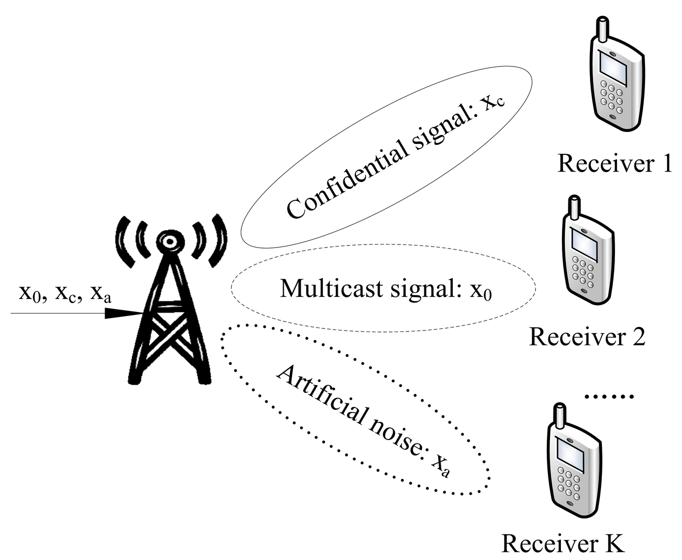
Background

- Physical-layer (PHY) security and multicasting
  - PHY security can overcome the inherent difficulties of cryptographic methods.
  - PHY-multicasting transmits common messages in a way that all receivers can decode them.
  - Traditionally they are independently investigated.
- PHY service integration
  - merging multiple services into one integral service for one-time transmission.
  - enable coexisting services to share the same resources, thereby significantly increasing the spectral efficiency.
- Motivation
  - Many works focused on PHY service integration only from the viewpoint of information theory.
    - ✓ DMBC (Csiszar et al. '78)
    - ✓ MIMO (Ly et al. '10)
    - ✓ Bidirectional relay (Wyrembelski et al. '12)
    - ✓ Compound BC with uncertainties (Wyrembelski et al. '12)
  - How to derive certain transmit design to achieve the boundary points of the secrecy rate region?

System Model

- A multi-antenna transmitter serves K receivers, and each receiver has a single antenna.
- All receivers have ordered the multicast service and receiver 1 further ordered the confidential service.



- The received signal at receiver k

$$y_k = \mathbf{h}_k \mathbf{x} + z_k$$

$\mathbf{h}_k$-*k*th receiver's channel response z_k-AWGN

- Transmitted components

$$\mathbf{x} = \mathbf{x}_0 + \mathbf{x}_c + \mathbf{x}_a$$

$\mathbf{x}_0$-multicast message, $\mathbf{x}_0 \sim CN(\mathbf{0},\mathbf{Q}_0)$

$\mathbf{x}_c$-confidential message, $\mathbf{x}_c \sim CN(\mathbf{0},\mathbf{Q}_c)$

$\mathbf{x}_a$-artificial noise, $\mathbf{x}_a \sim CN(\mathbf{0},\mathbf{Q}_a)$

- Deterministically bounded CSI error model

$$\mathbf{h}_k = \tilde{\mathbf{h}}_k + \mathbf{e}_k, \|\mathbf{e}_k\|_F^2 \le \varepsilon_k^2$$

Robust Scheme

- Worst-case secrecy rate region

Under the above described deterministically bounded CSI error model, an achievable worst-case secrecy rate region is determined by [Ly et al. '10]

$$R_c \le \min_{k\in\mathcal{K}_e} \log \frac{\min_{\mathbf{h}_1\in B_1} 1+(1+\mathbf{h}_1\mathbf{Q}_a\mathbf{h}_1^H)^{-1}\mathbf{h}_1\mathbf{Q}_c\mathbf{h}_1^H}{\max_{\mathbf{h}_k\in B_k} 1+(1+\mathbf{h}_k\mathbf{Q}_a\mathbf{h}_k^H)^{-1}\mathbf{h}_k\mathbf{Q}_c\mathbf{h}_k^H}$$

$$R_0 \le \min_{\substack{k\in\mathcal{K}\\ \mathbf{h}_k\in B_k}} \log\left(1+\frac{\mathbf{h}_k\mathbf{Q}_0\mathbf{h}_k^H}{1+\mathbf{h}_k(\mathbf{Q}_c+\mathbf{Q}_a)\mathbf{h}_k^H}\right)$$

where $B_k = \{\mathbf{h}_k | \mathbf{h}_k = \tilde{\mathbf{h}}_k + \mathbf{e}_k\}, \mathcal{K} = \{1,2,...,K\}, \mathcal{K}_e = \mathcal{K}/\{1\}$

- Problem Formulation

$$g^*(\tau) = \max_{\mathbf{Q}_0,\mathbf{Q}_a,\mathbf{Q}_c} \log \frac{\min_{\mathbf{h}_1\in B_1} 1+(1+\mathbf{h}_1\mathbf{Q}_a\mathbf{h}_1^H)^{-1}\mathbf{h}_1\mathbf{Q}_c\mathbf{h}_1^H}{\max_{k\in\mathcal{K}_e,\mathbf{h}_k\in B_k} 1+(1+\mathbf{h}_k\mathbf{Q}_a\mathbf{h}_k^H)^{-1}\mathbf{h}_k\mathbf{Q}_c\mathbf{h}_k^H}$$

$$\begin{aligned} s.t.\quad & \min_{\substack{k\in\mathcal{K}\\ \mathbf{h}_k\in B_k}} \left\{\log\frac{1+\mathbf{h}_k(\mathbf{Q}_c+\mathbf{Q}_a+\mathbf{Q}_0)\mathbf{h}_k^H}{1+\mathbf{h}_k(\mathbf{Q}_c+\mathbf{Q}_a)\mathbf{h}_k^H}\right\} \ge \tau, \\ & \mathrm{Tr}(\mathbf{Q}_0+\mathbf{Q}_a+\mathbf{Q}_c) \le P, \\ & \mathbf{Q}_0 \succeq \mathbf{0}, \mathbf{Q}_a \succeq \mathbf{0}, \mathbf{Q}_c \succeq \mathbf{0}, \end{aligned} \quad \textbf{(1)}$$

Demand for QoMS

This optimization problem also provides us a way to determine the boundary points of the secrecy rate region, by traversing all possible τ's.

Further simplify (1) by introducing a slack variable β

$$g^*(\tau) = \max_{\mathbf{Q}_0,\mathbf{Q}_a,\mathbf{Q}_c,\beta} \min_{\mathbf{h}_1\in B_1} \log\left(\frac{1+\mathbf{h}_1(\mathbf{Q}_c+\mathbf{Q}_a)\mathbf{h}_1^H}{\beta(1+\mathbf{h}_1\mathbf{Q}_a\mathbf{h}_1^H)}\right)$$

$$\begin{aligned} s.t.\quad & (\beta-1)(1+\mathbf{h}_k\mathbf{Q}_a\mathbf{h}_k^H)-\mathbf{h}_k\mathbf{Q}_c\mathbf{h}_k^H \ge 0, \forall \mathbf{h}_k \in B_k, k\in\mathcal{K}_e, \quad \textbf{(2)} \\ & \mathbf{h}_k\mathbf{Q}_0\mathbf{h}_k^H - \tau'\mathbf{h}_k\mathbf{Q}_a\mathbf{h}_k^H - \tau'\mathbf{h}_k\mathbf{Q}_c\mathbf{h}_k^H - \tau' \ge 0, \forall \mathbf{h}_k\in B_k, k\in\mathcal{K}, \\ & \mathrm{Tr}(\mathbf{Q}_0+\mathbf{Q}_a+\mathbf{Q}_c) \le P, \\ & \mathbf{Q}_0 \succeq \mathbf{0}, \mathbf{Q}_a \succeq \mathbf{0}, \mathbf{Q}_c \succeq \mathbf{0}, \end{aligned}$$

$$\tau' \triangleq 2^\tau - 1$$

Since this problem is non-convex and challenging to solve directly. To deal with it, we recast it into a two-stage optimization problem.

- Problem Re-Formulation

The outer-stage part is with regard to (w.r.t.) β

$$\gamma^*(\tau') = \max_{\beta} \eta(\tau',\beta)$$

$$s.t.\quad 1 \le \beta \le 1 + P\min_{\mathbf{h}_1\in B_1}\|\mathbf{h}_1\|^2$$

where $\log\gamma^*(\tau')=g^*(\tau')$. The inner-stage part calculates $\eta(\tau',\beta)$ for a fixed β

$$\eta(\tau',\beta) = \max_{\mathbf{Q}_0,\mathbf{Q}_a,\mathbf{Q}_c} \min_{\mathbf{h}_1\in B_1} \frac{1+\mathbf{h}_1(\mathbf{Q}_c+\mathbf{Q}_a)\mathbf{h}_1^H}{\beta(1+\mathbf{h}_1\mathbf{Q}_a\mathbf{h}_1^H)}$$

$$\begin{aligned} s.t.\quad & (\beta-1)(1+\mathbf{h}_k\mathbf{Q}_a\mathbf{h}_k^H)-\mathbf{h}_k\mathbf{Q}_c\mathbf{h}_k^H \ge 0, \forall \mathbf{h}_k \in B_k, k\in\mathcal{K}_e, \quad \textbf{(3)} \\ & \mathbf{h}_k\mathbf{Q}_0\mathbf{h}_k^H - \tau'\mathbf{h}_k\mathbf{Q}_a\mathbf{h}_k^H - \tau'\mathbf{h}_k\mathbf{Q}_c\mathbf{h}_k^H - \tau' \ge 0, \forall \mathbf{h}_k\in B_k, k\in\mathcal{K}, \\ & \mathrm{Tr}(\mathbf{Q}_0+\mathbf{Q}_a+\mathbf{Q}_c) \le P, \\ & \mathbf{Q}_0 \succeq \mathbf{0}, \mathbf{Q}_a \succeq \mathbf{0}, \mathbf{Q}_c \succeq \mathbf{0}. \end{aligned}$$

❑ The inner-stage optimization

➢ By resorting to the *S-procedure* [1], we can recast the above optimization as follows

$$\eta(\tau',\beta)=\max_{\substack{\mathbf{Q}_0,\mathbf{Q}_a,\mathbf{Q}_c,\\ \{t_k\}_{k\in\mathcal{K}_e},\{\delta_k\}_{k\in\mathcal{K}}}}\ \min_{\mathbf{h}_1\in B_1}\frac{1+\mathbf{h}_1(\mathbf{Q}_c+\mathbf{Q}_a)\mathbf{h}_1^H}{\beta(1+\mathbf{h}_1\mathbf{Q}_a\mathbf{h}_1^H)}$$

$$\begin{aligned} s.t.\ & \mathbf{T}_k(\beta,\mathbf{Q}_c,\mathbf{Q}_a,t_k)\succeq\mathbf{0}, t_k\geq 0,\forall k\in\mathcal{K}_e,\\ & \mathbf{S}_k(\tau',\mathbf{Q}_c,\mathbf{Q}_a,\mathbf{Q}_0,\delta_k)\succeq\mathbf{0},\delta_k\geq 0,\forall k\in\mathcal{K},\\ & \mathrm{Tr}(\mathbf{Q}_0+\mathbf{Q}_a+\mathbf{Q}_c)\leq P,\\ & \mathbf{Q}_0\succeq\mathbf{0},\mathbf{Q}_a\succeq\mathbf{0},\mathbf{Q}_c\succeq\mathbf{0}. \end{aligned} \quad \textbf{(4)}$$

where

$$\mathbf{T}_k(\beta,\mathbf{Q}_c,\mathbf{Q}_a,t_k)=\begin{bmatrix} t_k\mathbf{I}+(\beta-1)\mathbf{Q}_a-\mathbf{Q}_c & ((\beta-1)\mathbf{Q}_a-\mathbf{Q}_c)\tilde{\mathbf{h}}_k^H \\ \tilde{\mathbf{h}}_k((\beta-1)\mathbf{Q}_a-\mathbf{Q}_c) & \tilde{\mathbf{h}}_k((\beta-1)\mathbf{Q}_a-\mathbf{Q}_c)\tilde{\mathbf{h}}_k^H-t_k\varepsilon_k^2+\beta-1 \end{bmatrix}$$

$$\mathbf{S}_k(\tau',\mathbf{Q}_c,\mathbf{Q}_a,\mathbf{Q}_0,\delta_k)=\begin{bmatrix} \delta_k\mathbf{I}+\mathbf{Q}_0-\tau'(\mathbf{Q}_a+\mathbf{Q}_c) & (\mathbf{Q}_0-\tau'(\mathbf{Q}_a+\mathbf{Q}_c))\tilde{\mathbf{h}}_k^H \\ \tilde{\mathbf{h}}_k(\mathbf{Q}_0-\tau'(\mathbf{Q}_a+\mathbf{Q}_c)) & -\delta_k\varepsilon_k^2-\tau'+\tilde{\mathbf{h}}_k(\mathbf{Q}_0-\tau'(\mathbf{Q}_a+\mathbf{Q}_c))\tilde{\mathbf{h}}_k^H \end{bmatrix}$$

– *S-procedure*

Let $\varphi_k(\mathbf{x})=\mathbf{x}^H\mathbf{A}_k\mathbf{x}+2\Re\{\mathbf{b}_k^H\mathbf{x}\}+c_k$, where $\mathbf{A}_k\in\mathbb{H}^n$ $\mathbf{b}_k\in\mathbb{C}^n$, $c_k\in\mathbb{R}$. The implication $\varphi_1(\mathbf{x})\leq 0\Rightarrow\varphi_2(\mathbf{x})\leq 0$ holds if and only if there exists a $\mu\ \geq\ 0$ such that

$$\mu\begin{bmatrix}\mathbf{A}_1 & \mathbf{b}_1\\ \mathbf{b}_1^H & c_1\end{bmatrix}-\begin{bmatrix}\mathbf{A}_2 & \mathbf{b}_2\\ \mathbf{b}_2^H & c_2\end{bmatrix}\succeq\mathbf{0}$$

The remaining difficulty in solving (4) lies in its objective function, especially the uncertainty therein.

[1] S. Boyd and L. Vandenberghe, Convex optimization. Cambridge university press, 2009..

➢ Identification of the quasi-concavity of (4)

Property 1: Let us define

$$f(\mathbf{Q}_c,\mathbf{Q}_a)=\min_{\mathbf{h}_1\in B_1}\frac{1+\mathbf{h}_1(\mathbf{Q}_c+\mathbf{Q}_a)\mathbf{h}_1^H}{\beta(1+\mathbf{h}_1\mathbf{Q}_a\mathbf{h}_1^H)}$$

Then $f(\mathbf{Q}_c,\mathbf{Q}_a)$ is a quasi-concave function on the problem domain of (4), and hence the maximization problem (4) is a quasi-concave problem.

Proof: We just need to verify the convexity of the α-superlevel set of $f(\mathbf{Q}_c,\mathbf{Q}_a)$.

$$S_\alpha=\{f(\mathbf{Q}_c,\mathbf{Q}_a)|\mathbf{Q}_a\succeq\mathbf{0},\mathbf{Q}_c\succeq\mathbf{0},f(\mathbf{Q}_c,\mathbf{Q}_a)\geq\alpha\}$$

By using the *S-procedure* again, one can easily obtain

$$f(\mathbf{Q}_c,\mathbf{Q}_a)\geq\alpha\Leftrightarrow\mathbf{X}(\beta,\mathbf{Q}_c,\mathbf{Q}_a,\rho)\succeq\mathbf{0}$$

where

$$\mathbf{X}(\beta,\mathbf{Q}_c,\mathbf{Q}_a,\rho)=\begin{bmatrix} \rho\mathbf{I}+(1-\alpha\beta)\mathbf{Q}_a+\mathbf{Q}_c & ((1-\alpha\beta)\mathbf{Q}_a+\mathbf{Q}_c)\tilde{\mathbf{h}}_k^H \\ \tilde{\mathbf{h}}_k((1-\alpha\beta)\mathbf{Q}_a+\mathbf{Q}_c) & \tilde{\mathbf{h}}_k((1-\alpha\beta)\mathbf{Q}_a+\mathbf{Q}_c)\tilde{\mathbf{h}}_k^H-\rho\varepsilon_1^2-\alpha\beta+1 \end{bmatrix}$$

The proof is completed . ■

Consequently, the optimization problem (4) can be efficiently solved by combining a bisection search [1] with a convex optimization solver, e.g., CVX.

Numerical Results

➢ N_t=2, K=5

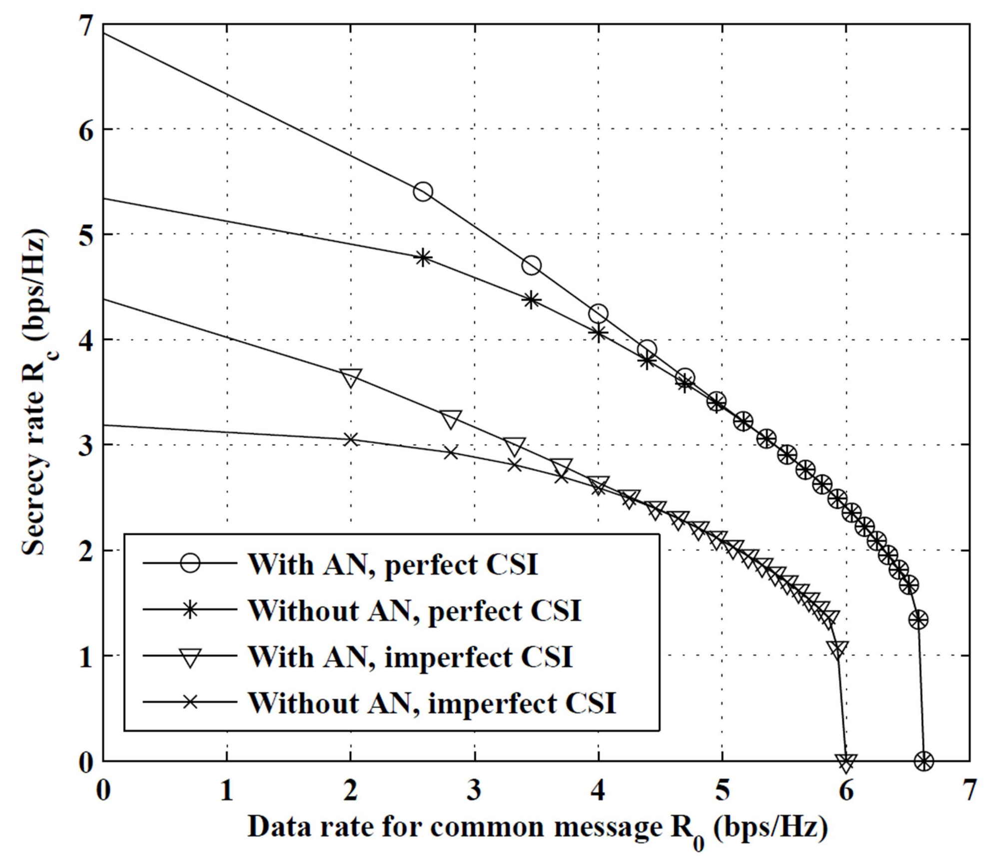
➢ Channel responses

$$\tilde{\mathbf{h}}_1=[2,0.4],\tilde{\mathbf{h}}_k=[0.9-0.1k,0.5+0.1k],k\in\mathcal{K}_e$$

➢ P=20dB

➢ ε_k=0.2 for all k

❑ Worst-case secrecy rate regions

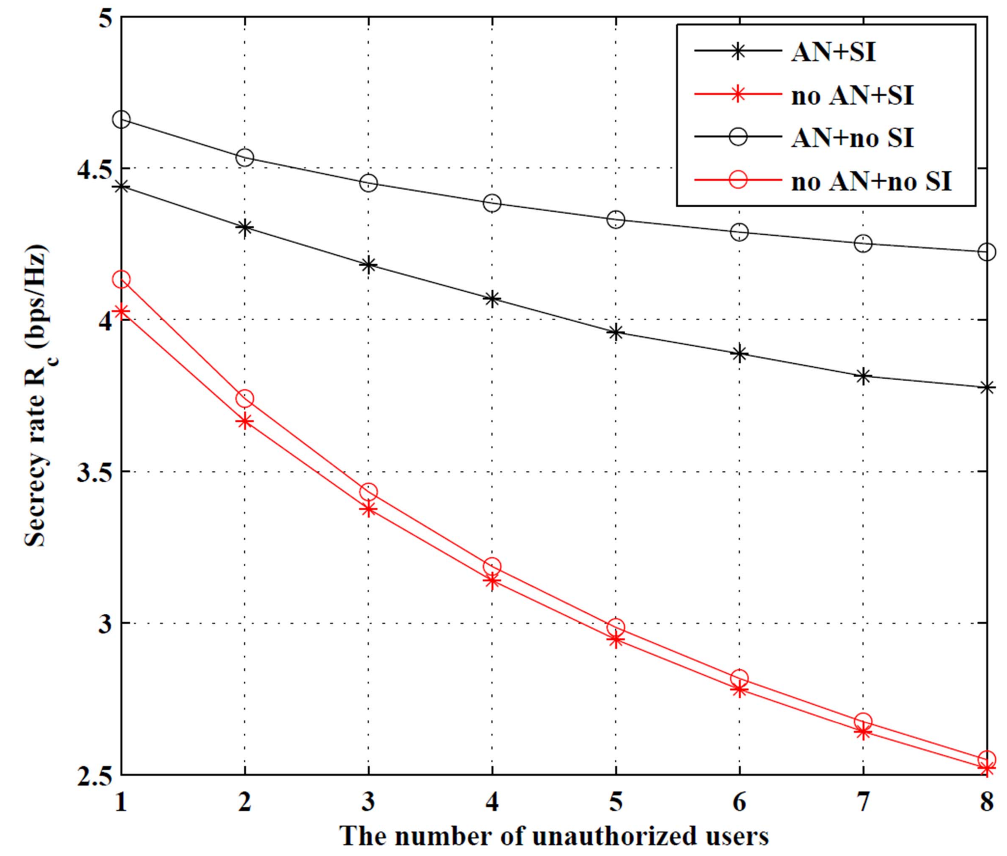


➢ The existence of channel uncertainty dramatically diminishes the achievable secrecy rate region

➢ AN indeed enhances the security performance without compromising the QoMS.

➢ The gap tends to be reduced, which implies that AN is prohibitive at high QoMS region.

❑ Secrecy rate versus #unauthorized receivers



➢ The worst secrecy rates drops with the number of unauthorized receivers.

➢ Incorporating service integration restrains the maximum worst-case secrecy rates

Concluding Remarks

❑ Considered the optimal robust AN-aided transmit design for multiuser MISO broadcast channel with confidential service and multicast service .

❑By resorting to a two-stage reformulation, the problem can be handled by solving a sequence of fractional SDPs.

❑AN can effectively fortify the transmission security, but high demand for QoMS will confine its use in turn.