Spectrum-Efficient Cognitive MIMO Relaying: A Practical Design Perspective

Soutenance
Zakaria EL MOUTAOUAKKIL

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12th of October 2018

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By

Zakaria EL MOUTAOUAKKIL

Supervised by **Pr. Samir Saoudi** (IMT Atlantique, France),
Dr. Kamel Tourki (Huawei Technologies, France), and
Pr. Halim Yanikomeroglu (Carleton University, Canada)

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Outline

Major Trends Posed on Current Wireless Networks

- **Unprecedented Increase in Mobile Users and Devices** (expected to exceed 8 billion by 2020).
- **Massive Connectivity ⇒ Significant Increase in Mobile Data Traffic.**
- **Scarcity of the Spectrum Medium.**
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Beyond 5G Requirements Impacting on the Physical Layer

- **High Big Data Rates** (e.g. up to 10 Gb/s) with **High User Densities**.
- **Ubiquitous Coverage with Ultra-Reliable Communications.**
- **Efficient Usage of the Spectrum and Energy Resources**.
- **Moderate Cost**.

Goal ⇒ enabling the 4A paradigm
“any rate, anytime, anywhere, affordable”

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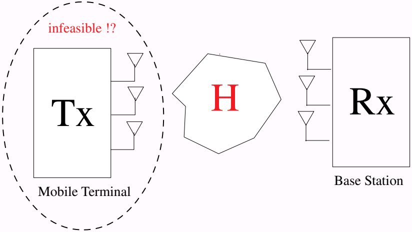
Technology Solution $\Rightarrow$ **Cognitive (Virtual) MIMO Relaying**

Cognitive Spectrum Policies

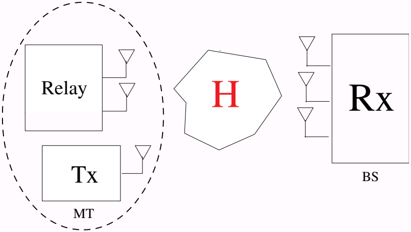
SInce its first introduction by Mitola in 1995, cognitive radio has been evolving as three spectrum rules named as:

1. **Spectrum Interweave:** Unlicensed users detect the unused spectrum holes in the licensed users spectrum and make use of them.
2. **Spectrum Overlay:** Unlicensed users engage in improving the licensed users transmission quality in return of the occupied spectrum. A win-win approach.
3. **Spectrum Underlay (Sharing):** Unlicensed users access the licensed spectrum while not causing harmful degradation to the primary system users QoS.

From MIMO to Virtual MIMO



3 × 3 MIMO System



3 × 3 Virtual MIMO System

- In cellular Networks, it is not feasible to deploy several antennas; 2 or 3 are envisaged at our smartphones at least for the time being !!

Solution

- Virtual MIMO has been proposed.

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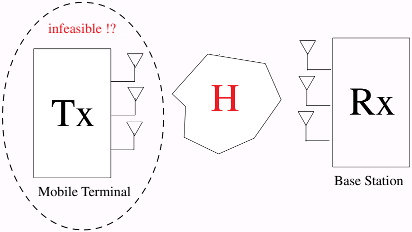

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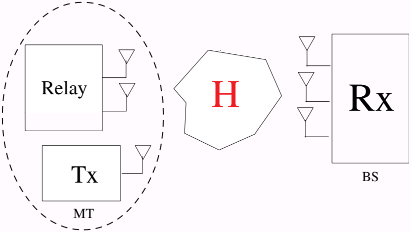

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Relaying Modes and Protocols

- **Half-Duplex MIMO Relaying**
    - Pros: Does not suffer from residual interference, and can easily be implemented.
    - Cons: Transmission rate is halved in orthogonal AF or DF relaying.
- **Full-Duplex MIMO Relaying**
    - Pros: Relays operate at full rate.
    - Cons: Suffers from residual interference, complex, and costly to implement especially in our smartphones.

Important Remarks

1. In half-duplex MIMO **non-orthogonal** AF (NAF) relaying, the transmission rate is not halved.
2. **Incremental** half-duplex MIMO **DF** relaying is spectrum efficient as it represents a generalization of the ARQ protocol.

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Problematic 1

In underlay half-duplex MIMO-ISI **non-orthogonal** AF (NAF) relaying, MIMO virtualization of our two-hop relay-aided transmission is primordial. While this is feasible over frequency-flat fading channels, the issue arises for coded transmission over frequency-selective fading channels.

⇒ **Solution Ideas:**

- **Sub-block splitting** at the transmitter and **signal-level** combining at the receiver.
- Turbo Receiver Design and Transmit Power Optimization.

Problematic 2

In underlay **incremental** half-duplex MIMO **DF** relaying, transmit-antenna selection (TAS) has only been applied from an SNR maximization point of view. Therefore, not optimal in the SINR sense.

⇒ **Solution Ideas:**

- **Interference-aware** TAS/MRC is efficiently applied in underlay incremental half-duplex MIMO DF relay systems to combat the mutual interference between the primary and secondary systems.

System and Communication Models

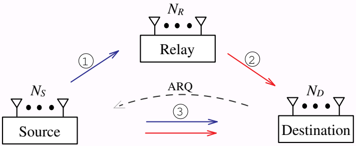
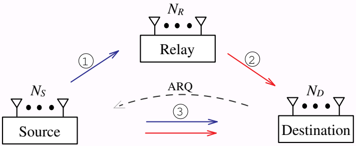


Fig1: Cognitive MIMO NAF Relay System Model.

- Channel 1, channel 2, and channel 3 are regarded at as a frequency-selective fading MIMO channels having L_{SR}, L_{RD}, and L_{SD} independent paths, respectively.
- Each path is characterized by its quasi-static flat fading MIMO channel matrix $\mathbf{H}_l^{AB} \in \mathbb{C}^{N_A \times N_B}$, for $l \in \{0, \ldots, L_{AB} - 1\}$ where $A \in \{S, R\}$ and $B \in \{R, D\}$.
- Relaying works under the framework of half-duplex amplify-and-forward protocol.
- The transmission between the source and the destination is block-oriented and coded.

System and Communication Models



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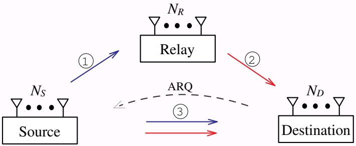

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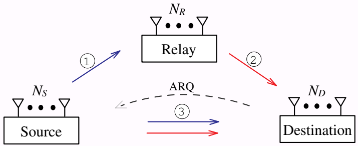

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Brief Description of the Concept

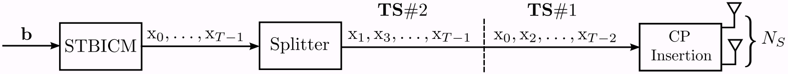

Fig2: Source node transmitter scheme for a single-carrier CP-aided transmission scheme.

Solution: Sub-Block Splitting at the Source Node is Key 1

- To proceed, the source node generates according to an STBICM encoder the symbol packet

$$\mathbf{x} \triangleq [\mathrm{x}_0, \ldots, \mathrm{x}_{T-1}] \in \mathbb{C}^{N_S \times T} \Rightarrow [\mathrm{z}_1 \mathrm{z}_2] \tag{1}$$

- It is then splitted into two equally sized $N_S \times \frac{T}{2}$ sub-packets $\mathbf{z}_1$ and $\mathbf{z}_2$ constructed as

$$\mathcal{S}_2 : \begin{cases} \mathrm{z}_{1,t} = \mathrm{x}_{2t} & , \quad 0 \leq t \leq \frac{T}{2} - 1 \\ \mathrm{z}_{2,t} = \mathrm{x}_{2t+1} & , \quad 0 \leq t \leq \frac{T}{2} - 1 \end{cases}. \tag{2}$$

- The splitting order of $\mathcal{S}_2$ is two yet can be generalized to an Mth order under the condition that the integer M is a divisor of T. $\mathbf{z}_1$ and $\mathbf{z}_2$ are transmitted during the first and the second hops, respectively.

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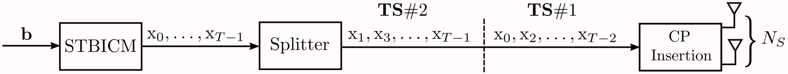

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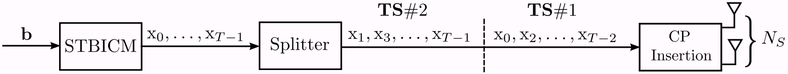

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First-Hop Received Signals

During the 1^{st} hop transmission:

$$\begin{aligned}\mathbf{y}_{R,t} &= \sqrt{P_{S,1}}\sum_{l=0}^{L_{SR}-1}\mathbf{H}_l^{SR}\mathbf{z}_{1,(t-l)\bmod\frac{T}{2}}+\mathbf{n}_{R,t} &(3)\\ \mathbf{y}_{D,t}^{1} &= \sqrt{P_{S,1}}\sum_{l=0}^{L_{SD}-1}\mathbf{H}_l^{SD}\mathbf{z}_{1,(t-l)\bmod\frac{T}{2}}+\mathbf{n}_{D,t}^{1} &(4)\end{aligned}$$

- $P_{S,1}$ and $P_{S,2}$ are the transmit powers of the source node during the first and second hops, respectively.
- $\mathbf{n}_{B,t}\sim\mathcal{N}(\mathbf{0}_{N_B\times 1},N_0\mathbf{I}_{N_B})$ for $B\in\{R,D\}$.
- A cyclic prefix (CP) portion of length $L_{cp}=\max\{L_{SD},L_{SR}+L_{RD}-1\}$ is appended to $\mathbf{z}_1$ and $\mathbf{z}_2$ upon their transmission.

AF function at the Relay node:

$$\begin{cases}\tilde{\mathbf{y}}_{R,t}^{(k)}=\gamma P_R\mathbf{y}_{R,t}^{(k)}, \quad t=0,\ldots,\frac{T}{2}-1\\ \gamma=1/\sqrt{N_S P_{S,1}+N_0}\end{cases} \qquad (5)$$

Second-Hop Received Signals

During the 2^{nd} TS of ARQ round k:

$$\mathbf{y}^2_{D,t} = \sum_{l=0}^{L_{max}-1} \widetilde{\mathbf{H}}_l \mathbf{z}_{(t-l) \bmod \frac{T}{2}} + \widetilde{\mathbf{n}}^2_{D,t} \tag{6}$$

where

$$\begin{cases} \mathbf{z}_t & \triangleq \begin{bmatrix} \mathbf{z}_{1,t} \\ \mathbf{z}_{2,t} \end{bmatrix} \in \mathcal{X}^{2N_S}, \\ L_{max} & \triangleq \max(L_{SD}, L_{SRD}), \;\text{ and }\; L_{SRD} = L_{SR} + L_{RD} - 1, \end{cases} \tag{7}$$

$$\widetilde{\mathbf{H}}_l = \left[\gamma\sqrt{P_{S,1}P_R}\mathbf{H}_l^{SRD} \quad \sqrt{P_{S,2}}\mathbf{H}_l^{SD} \right], \tag{8}$$

$$\widetilde{\mathbf{n}}^2_{D,t} = \gamma\sqrt{P_R} \sum_{l=0}^{L_{RD}-1} \mathbf{H}_l^{RD} \mathbf{n}_{R,(t-l) \bmod \frac{T}{2}} + \mathbf{n}^2_{D,t}. \tag{9}$$

Virtualized MIMO NAF Relaying System

Solution: Signal-level Combining at the Destination Node is Key 2

- Thanks to Cholesky decomposition, the covariance matrix of $\tilde{\mathbf{n}}^2_{D,t}$ can be expressed as $\Theta_{\tilde{\mathbf{n}}^2_{D,t}} = N_0\mathrm{L}\mathrm{L}^H$.
- By the end of the second-hop transmission, the destination node builds up (jointly) the augmented size signal vector resulting from the reception during both relaying hops as

$$\mathbf{y}^{equ}_{D,t}\left\{\begin{bmatrix}\mathbf{y}^1_{D,t}\\ \tilde{\mathbf{y}}^2_{D,t}\end{bmatrix}\right. = \sum_{l=0}^{L_{max}-1}\mathbf{H}^{equ}_l\mathbf{z}_{(t-l)\bmod\frac{T}{2}} + \mathbf{n}^{equ}_{D,t}, \qquad (10)$$

in which the the virtual MIMO channel matrix $\mathbf{H}^{equ}_l$ has carefully been introduced as

$$\mathbf{H}^{equ}_l = \begin{bmatrix}\sqrt{P_{S,1}}\mathbf{H}^{SD}_l, & \mathbf{0}_{N_D\times N_S}\\ \gamma\sqrt{P_{S,1}P_R}\mathrm{L}^{-1}\mathbf{H}^{SRD}_l & \sqrt{P_{S,2}}\mathrm{L}^{-1}\mathbf{H}^{SD}_l\end{bmatrix}\in\mathbb{C}^{2N_S\times 2N_D}. \qquad (11)$$

- One transmission hop ⇒ additional set of N_S transmit and N_D receive antennas at node S and Node D, respectively.

Frequency Domain Turbo Receiver Design

Consequence: Our Virtual MIMO-ISI Channel can be Turbo-Equalized in the Frequency Domain

- Applying the DFT to both sides of

$$\underline{\mathbf{y}}^{equ} = \underset{0\leq t\leq T/2-1}{\mathbf{vect}}(\mathbf{y}_{D,t}^{equ})$$

yields an augmented size block-circulant channel matrix that can be block-diagonalized in the Fourier basis as

$$\underline{\mathbf{y}}_f^{equ} \quad = \quad \underline{\underline{\Delta}}\mathbf{x}_f + \underline{\mathbf{n}}_f^{equ}. \tag{12}$$

$$\boxed{\textsf{\textbf{Unconditional MMSE} Filter} \Rightarrow \underline{\widetilde{\mathbf{x}}}_f = \mathbf{\Phi}\underline{\mathbf{y}}_f^{equ} - \mathbf{\Psi}\underline{\overline{\mathbf{x}}}_f}$$

- The forward filter $\mathbf{\Phi} = \mathrm{diag}\left\{\mathbf{\Phi}_0, \cdots, \mathbf{\Phi}_{T/2-1}\right\}$, and the backward filter $\mathbf{\Psi} = \mathrm{diag}\left\{\Psi_0, \cdots, \Psi_{T/2-1}\right\}$ are respectively expressed, for $t = 0, \cdots, T/2-1$, as

$$\begin{cases} \mathbf{\Phi}_t^k = \frac{1}{N_0}\underline{\underline{\Delta}}_t^{\mathrm{H}}\left\{\mathbf{I}_{2N_D} + \underline{\underline{\Delta}}_t\mathbf{C}_t^{-1}\underline{\underline{\Delta}}_t^{\mathrm{H}}\right\} \\ \mathbf{C}_t^{-1} = N_0\widetilde{\mathbf{\Theta}}_{\underline{\overline{\mathbf{x}}}}^{-1} + \underline{\underline{\Delta}}_t^{\mathrm{H}}\underline{\underline{\Delta}}_t \\ \Psi_t^k = \mathbf{\Phi}_t\underline{\underline{\Delta}}_t - \frac{2}{T}\sum_{i=0}^{T/2-1}\mathbf{\Phi}_t\underline{\underline{\Delta}}_t \end{cases}.$$

Building Blocks of the Proposed Turbo Receiver

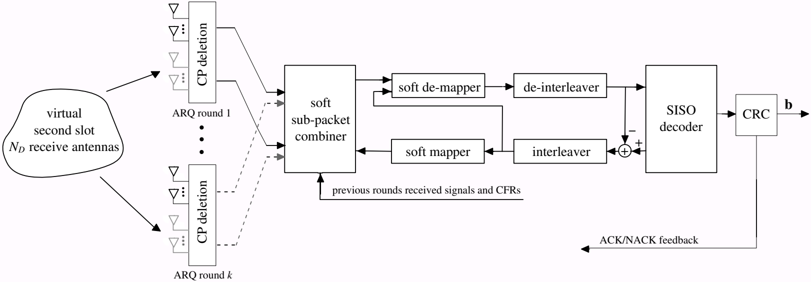


Fig 3: Building blocks of the proposed frequency domain turbo receiver.

Achievable Mutual Information

The achievable mutual information by our virtualized MIMO NAF Relaying system under the Gaussian channel inputs assumption can be expressed as

$$\mathcal{I} = \frac{1}{T} \sum_{i=0}^{T/2-1} \log_2 \left(\det \left(\mathbf{I}_{2N_D} + \frac{1}{N_0} \triangle_i^H \triangle_i \right) \right), \tag{13}$$

where the matrix product $\triangle_i^H \triangle_i$ for each frequency bin $i \in \{0, \cdots, T/2-1\}$ can be factorized as

$$\frac{1}{N_0} \triangle_i^H \triangle_i = \mathcal{Q} \Lambda_i^H \mathcal{R} \Lambda_i. \tag{14}$$

In (14), the matrices $\mathcal{Q}$, $\mathcal{R}$ and Λ_i are given by

$$\mathcal{Q} = \begin{bmatrix} P_{S,1} & 0 \\ 0 & P_{S,2} \end{bmatrix} \otimes \mathbf{I}_{n_{st}} \in \mathbb{C}^{2N_S \times 2N_S}, \tag{15}$$

$$\mathcal{R} = \begin{bmatrix} \Theta^{-1}_{\tilde{\mathbf{n}}^2_{D,t}} & \mathbf{0} \\ \mathbf{0} & \Theta^{-1}_{\tilde{\mathbf{n}}^2_{D,t}} \end{bmatrix} \in \mathbb{C}^{2N_D \times 2N_D}, \tag{16}$$

$$\Lambda_i = \begin{bmatrix} \Lambda_{ai} & 0 \\ \gamma\sqrt{P_{sre}}\Lambda_{bi} & \Lambda_{ai} \end{bmatrix} \in \mathbb{C}^{2N_D \times 2N_D}. \tag{17}$$

Problem Formulation

Our main objective in allocating the secondary system transmit powers $P_{S,1}$, $P_{S,2}$ and P_R is to maximize (13) under the spectrum sharing interference constraints in (4) and (5) or (6). Therefore, we formulate our problem as

$$\max_{\{P_{S,1},P_{S,2},P_R\}} \mathcal{I}, \tag{18}$$

$$\text{subject to C1 or C2.} \tag{19}$$

$$C1 : \begin{cases} P_{S,1} & \leq \min\left(\frac{Q}{n_{st}\lambda^{st\to pr}}, \bar{P}\right), \\ N_S\lambda^{SP}P_{S,2} + N_R\lambda^{RP}P_R & \leq Q, \\ P_{S,2} & \leq \bar{P}, \\ P_R & \leq \bar{P}. \end{cases} \Rightarrow \text{Sub-Optimal NAF,}$$

$$C2 : \begin{cases} N_S\lambda^{SP}\left(P_{S,1}+P_{S,2}\right) + N_R\lambda^{RP}P_R & \leq 2Q, \\ P_{S,1} & \leq \bar{P}, \\ P_{S,2} & \leq \bar{P}, \\ P_R & \leq \bar{P}, \end{cases} \Rightarrow \text{Optimal NAF.}$$

Achievable Rate: Scenario 1

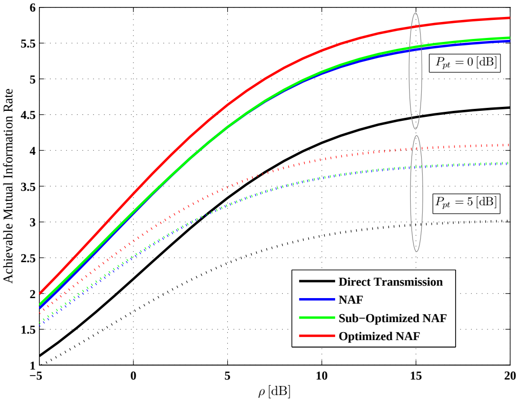
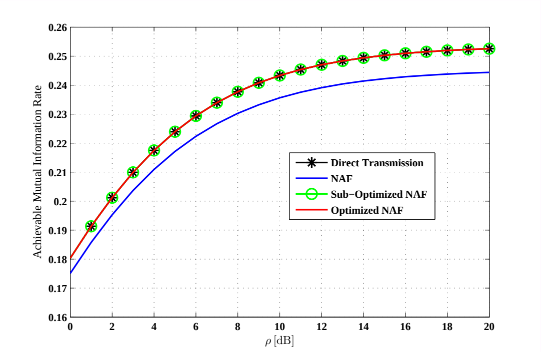


Fig 4: Outage probability versus $\rho = N_S/N_0$ for $l_{SR} = 0.3$, $N_S = N_R = N_D = 2$, $L_{SR} = L_{RD} = L_{SD} = 3$, $\bar{P} = 0\text{dB}$, and $Q = 5\text{dB}$.

Achievable Rate: Scenario 2



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Motivation for TAS/MRC

- In its simplest form, only the RF chain causing less interference on the primary system and enabling greater secondary system performance is selected at the secondary transmitter.
- Simple and less expensive yet realizes a good tradeoff among performance, cost and complexity.
- A promising technology candidate for beyond 5G massive-oriented MIMO systems.
- MRC is a receive combining technique powerful against fading.

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TAS/MRC Strategies for Cognitive MIMO Systems

The received combined SINR at S-Rx can be expressed as

$$\gamma_k^{s\to s} = \frac{P_s \left\|\boldsymbol{h}_k^{1,s\to s}\right\|^2}{P_p \frac{\left|\boldsymbol{h}_k^{1,s\to s^H} \boldsymbol{h}_1^{1,p\to s}\right|^2}{\left\|\boldsymbol{h}_k^{1,s\to s}\right\|^2} + N_0}.$$

- According to an **SNR**-driven TAS/MRC strategy, we have

$$\dot{s}_1 = \arg \max_{k\in\{1,\ldots,s_t\}} \left\{\left\|\boldsymbol{h}_k^{1,s\to s}\right\|^2\right\}.$$

- According to an **SINR**-driven TAS/MRC strategy, we have

$$\ddot{s}_1 \quad = \arg \quad \max_{k\in\{1,\ldots,s_t\}} \{\gamma_k^{s\to s}\}.$$

CDF of $\gamma_{\dot{s}_1}^{s\rightarrow s}$

If the secondary transmitter selects its transmit antenna according to an SINR-driven TAS, the CDF of t $\gamma_{\dot{s}_1}^{s\rightarrow s}$ is given by

$$F_{\gamma_{\dot{s}_1}^{s\rightarrow s}}(\gamma) = \mathcal{P}\left(\frac{P_s X_{\dot{s}_1}^1}{P_p Z_{\dot{s}_1}^1 + N_0} < \gamma\right),$$

where

$$X_{\dot{s}_1}^1 \quad = \quad \left\|\boldsymbol{h}_{\dot{s}_1}^{1,s\rightarrow s}\right\|^2$$

and

$$Z_{\dot{s}_1}^1 = \frac{\left|\boldsymbol{h}_{\dot{s}_1}^{1,s\rightarrow s^H}\boldsymbol{h}_1^{1,p\rightarrow s}\right|^2}{\left\|\boldsymbol{h}_{\dot{s}_1}^{1,s\rightarrow s}\right\|^2}.$$

- A. Shah and A. M. Haimovich, “Performance analysis of maximal ratio combining and comparison with optimum combining for mobile radio communications with cochannel interference,” *IEEE Trans. on Vehicular Technology*, vol. 49, no. 4, pp. 1454-1463, July 2000.
- M. Kang, M.-S. Alouini, “A comparative study on the performance of MIMO MRC systems with and without cochannel interference,” *IEEE Trans. Commun.*, vol. 52, no. 8, pp. 1417-1425, Aug. 2004.

CDF of $\gamma_{\ddot{s}_1}^{s\to s}$

If antenna $\ddot{s}_1$ at S-Tx is rather selected according to an SINR-driven TAS, the CDF of $\gamma_{\ddot{s}_1}^{s\to s}$ is given by

$$F_{\gamma_{\ddot{s}_1}^{s\to s}}(\gamma) = \mathcal{P}\left(\frac{P_s X_{\ddot{s}_1}^1}{P_p Z_{\ddot{s}_1}^1 + N_0} < \gamma\right), \tag{20}$$

where the variables $X_{\ddot{s}_1}^1 = \left\|\boldsymbol{h}_{\ddot{s}_1}^{1,s\to s}\right\|^2$ and $Z_{\ddot{s}_1}^1 = \left|\boldsymbol{h}_{\ddot{s}_1}^{1,s\to s^H}\boldsymbol{h}_1^{1,p\to s}\right|^2 / \left\|\boldsymbol{h}_{\ddot{s}_1}^{1,s\to s}\right\|^2$ are constructed such as

$$\underbrace{\frac{P_s X_{\ddot{s}_1}^1}{P_p Z_{\ddot{s}_1}^1 + N_0}}_{\gamma_{\ddot{s}_1}^{s\to s}} = \underbrace{\max_{k\in\{1,\ldots,s_t\}}\left\{\frac{P_s X_k^1}{P_p Z_k^1 + N_0}\right\}}_{\gamma_k^{s\to s}}. \tag{21}$$

- Zakaria El-Moutaouakkil, Kamel Tourki, Halim Yanikomeroglu, and Samir Saoudi, "TAS Strategies for Incremental Cognitive MIMO Relaying: New Results and Accurate Comparison," IEEE Access, vol. 6, pp. 23480-23499, 2018.

CDF of $\gamma_{\ddot{s}_1}^{s\rightarrow s}$

The CDF of the received SINR $\gamma_{\ddot{s}_1}^{s\rightarrow s}$ after MRC is given by

$$F_{\gamma_{\ddot{s}_1}^{s\rightarrow s}}(\gamma) = \mathcal{P}\left(\frac{P_s X_{\ddot{s}_1}^1}{P_p Z_{\ddot{s}_1}^1 + N_0} < \gamma\right), \tag{22}$$

where

$$\underbrace{\frac{P_s X_{\ddot{s}_1}^1}{P_p Z_{\ddot{s}_1}^1 + N_0}}_{\gamma_{\ddot{s}_1}^{s\rightarrow s}} = \max_{k\in\{1,\ldots,s_t\}} \underbrace{\left\{\frac{P_s X_k^1}{P_p Z_k^1 + N_0}\right\}}_{\gamma_k^{s\rightarrow s}}. \tag{23}$$

In the papers below, assuming equality instead of the following approximation is not consistent,

$$F_{\gamma_{\ddot{s}_1}^{s\rightarrow s}}(\gamma) \approx F_{\gamma_k^{s\rightarrow s}}(\gamma)^{s_t}. \tag{24}$$

- R. M. Radaydeh, and M. S. Alouini, “On the performance of arbitrary transmit selection for threshold-based receive MRC with and without co-channel interference,” *IEEE Trans. on Communications*, vol. 59, no. 11, pp. 3177-3191, November 2011.

Exact and Asymptotic Outage Analysis

- First-Hop Outage Probability for both TAS/MRC Strategies under investigation:

$$\begin{cases} op^1_{s,snr} = F_{\gamma^{s\to s}_{\dot{s}_1}}\left(\Phi_s\right) & ;\ (a) \\ op^1_{s,sinr} = F_{\gamma^{s\to s}_{\ddot{s}_1}}\left(\Phi_s\right) & ;\ (b) \end{cases}. \tag{25}$$

- Asymptotic Outage Probability for both TAS/MRC Strategies under investigation:

$$\begin{cases} opA^1_{s,snr} & = \frac{\Gamma(s_r s_t+1)}{\Gamma(s_r+1)^{s_t}}\left(\frac{\Phi_s\lambda_{ps}}{\eta\lambda_{ss}}\right)^{s_r s_t} \\ opA^1_{s,snr} & = \frac{\sqrt{\pi}^{s_t}\,2^{-2s_t\left(s_r-\frac{1}{2}\right)}\Gamma(s_r s_t+s_r)}{\Gamma(s_r)\Gamma\left(s_r+\frac{1}{2}\right)^{s_t}}\left(\frac{\Phi_s\lambda_{ps}}{\eta\lambda_{ss}}\right)^{s_r s_t} \end{cases}. \tag{26}$$

Diversity and Coding Gains

- Using the concept of generalized diversity gain, the achievable diversity gains (d^1_{snr} and d^1_{sinr}) and coding gains (c^1_{snr} and c^1_{sinr}) by the SNR and SINR-driven TAS strategies can be deduced by rewriting (26) as

$$\begin{cases} opA^1_{s,snr} = \left(c^1_{snr}/\lambda_{ps}\right)^{-d^1_{snr}}, \\ \qquad \Longrightarrow \begin{cases} d^1_{snr} = \lim_{\lambda_{ps}\to 0} \frac{\log opA^1_{s,snr}}{\log \lambda_{ps}} = s_r s_t \\ c^1_{snr} = \frac{\Gamma(s_r+1)^{\frac{1}{s_r}}}{\Gamma(s_r s_t+1)^{\frac{1}{s_r s_t}}} \frac{\eta\lambda_{ss}}{\Phi_s} \end{cases} \\ opA^1_{s,sinr} = \left(c^1_{sinr}/\lambda_{ps}\right)^{-d^1_{sinr}}, \\ \qquad \Longrightarrow \begin{cases} d^1_{sinr} = \lim_{\lambda_{ps}\to 0} \frac{\log opA^1_{s,sinr}}{\log \lambda_{ps}} = s_r s_t \\ c^1_{sinr} = \frac{\Gamma(s_r)^{\frac{1}{s_r s_t}}\Gamma\left(s_r+\frac{1}{2}\right)^{\frac{1}{s_r}}}{\pi^{\frac{1}{2s_r}} 2^{\left(\frac{1}{s_r}-2\right)} \Gamma(s_r s_t+s_r)^{\frac{1}{s_r s_t}}} \frac{\eta\lambda_{ss}}{\Phi_s} \end{cases} \end{cases} . \qquad (27)$$

Insights and Remarks

The derived asymptotic closed-form expressions in (26) reveal two important conclusions:

- Even if the primary system tolerates a high amount of interference, i.e., $Q_i \to +\infty$ as a result of $P_p/N_0 \to +\infty$, the secondary system outage performance still saturates at outage floors because the primary system pumps a high amount of co-channel interference in return, and
- The coefficient η is not inversely proportional to λ_{sp}, i.e., η does not go beyond 1 for $\lambda_{sp} \to 0$ because of the minimum operator inherited from the underlay interference constraint put on P_s. Therefore, λ_{ps} plays a more crucial role in decreasing $opA^1_{s,snr}$ and $opA^1_{s,sinr}$ in (26) than λ_{sp}.

End-to-End (Second-Hop) Outage Performance

Using the total probability law, the end-to-end transmission outage probability of the proposed incremental cognitive MIMO DF relaying system is given by

$$op_s^2 = \underbrace{\mathcal{P}\left(\gamma_k^{s\rightarrow s} < \Phi_s; \gamma_{k,k'}^{s,s\rightarrow s} < \Phi_s\right)}_{A_3} \underbrace{\mathcal{P}\left(\gamma_k^{s\rightarrow r} < \Phi_s\right)}_{A_1} + \underbrace{\mathcal{P}\left(\gamma_k^{s\rightarrow s} < \Phi_s; \gamma_{k,k'}^{s,r\rightarrow s} < \Phi_s\right)}_{A_2} \underbrace{\mathcal{P}\left(\gamma_k^{s\rightarrow r} \geq \Phi_s\right)}_{1-A_1}, \tag{28}$$

where k and k' are selected depending on the TAS/MRC strategy being adopted during both relaying hops.

Diversity and Coding Gains

Following the approach used to derive the asymptotic expressions of the direct-transmission outage probability, we have

$$d_{sinr}^2 = d_{snr}^2 = s_r \left(s_t + r_e \right). \tag{29}$$

As for the achievable coding gains c_{snr}^2 and c_{sinr}^2, they can accurately be evaluated using numerical integration with the same observation in the direct (first-hop) that is $c_{sinr}^2 > c_{snr}^2$.

Concluding Remarks

Finally, we deduce from the asymptotic outage analysis of the end-to-end transmission of our incremental cognitive MIMO DF relay system the following remarks:

- Both TAS strategies under investigation achieve the same generalized diversity gain yet the SINR-driven TAS strategy has the advantage of achieving a better coding gain than the SNR-driven TAS strategy.
- Incremental cognitive MIMO DF relaying plays an important role in the enhancement of the achievable system diversity gain. In particular, s_t and r_e play interchangeable roles. This implies that whenever S-Tx can not support multiple antennas, Re is a good substitute in guaranteeing the same diversity gain.
- Since the second-order statistic λ_{ps} of the channel between P-Tx and S-Rx has a crucial impact on the overall system outage performance, it is highly recommended to adopt scheduling algorithms where S-Rx is selected on the basis of low λ_{ps} values.

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Direct-Transmission Outage Performance

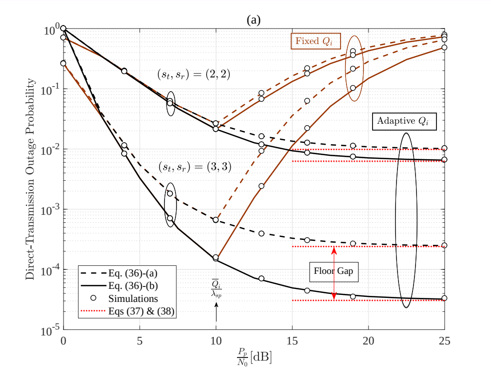

Fig 6: Comparison of the derived end-to-end outage probability for both TAS strategies under different MIMO relay system configurations while the parameters $\lambda_{ss} = 1$, $\lambda_{sr} = \lambda_{rs} = 0.4$, $\lambda_{sp} = \lambda_{ps} = 0.1$, $\lambda_{pr} = 0.6$, $\lambda_{rp} = 0.5$, $\Phi_s = 2^2 - 1$, $\varepsilon_p = 0.01$ and $Q_{th} = -0.1\,\text{dB}$ are being fixed as exemplary parameters.

Received SINR PDFs

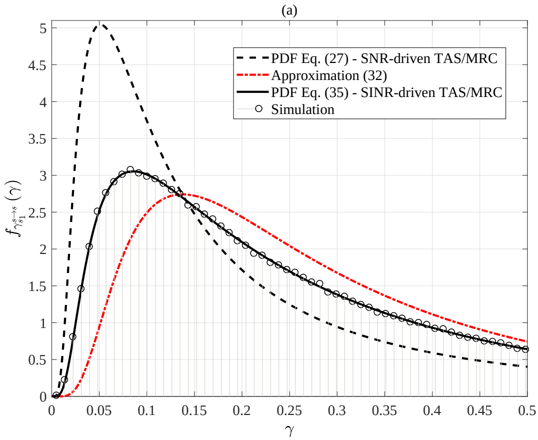

Fig 7: The figure is generated for $\lambda_{ss} = \lambda_{sp} = \lambda_{ps} = 1$, $P_p/N_0 = 10\,\mathrm{dB}$, $Q_i = -5\,\mathrm{dB}$ $s_t = 5$ and $s_r = 2$.

Received SINR PDFs

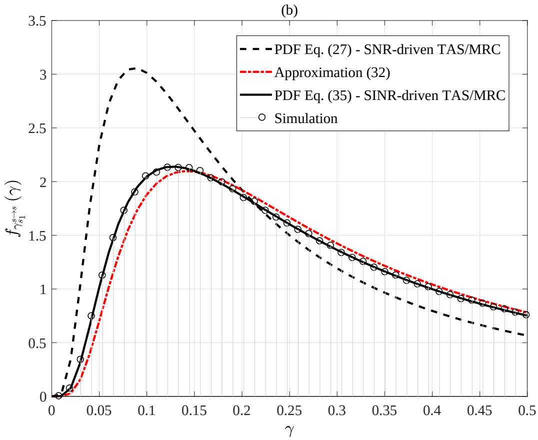

Fig 8: The figure is generated for $\lambda_{ss} = \lambda_{sp} = \lambda_{ps} = 1$, $P_p/N_0 = 10\,\text{dB}$, $Q_i = -5\,\text{dB}$ $s_t = 2$ and $s_r = 5$.

End-to-End Transmission Outage Performance

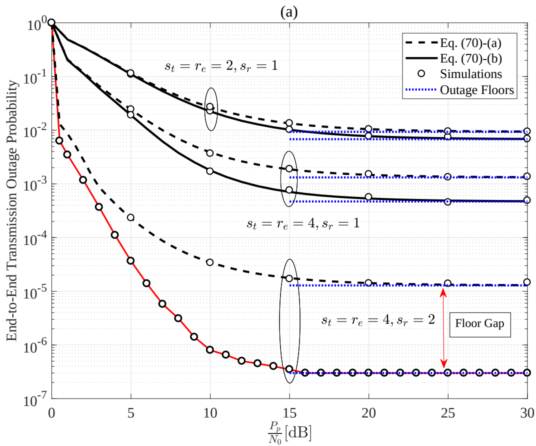

Fig 9: The figure is generated for $\lambda_{ss} = 1$, $\lambda_{sr} = \lambda_{rs} = 0.4$, $\lambda_{sp} = \lambda_{ps} = 0.1$, $\lambda_{pr} = 0.6$, $\lambda_{rp} = 0.5$, $\Phi_s = 2^2 - 1$, $\varepsilon_p = 0.01$ and $Q_{th} = -0.1$ dB

Published Works (1 journal and 5 conference papers)

- Zakaria El-Moutaouakkil, Kamel Tourki, Halim Yanikomeroglu, and Samir Saoudi, “TAS Strategies for Incremental Cognitive MIMO Relaying: New Results and Accurate Comparison,” IEEE Access, vol. 6, pp. 23480-23499, 2018.
- Zakaria El-Moutaouakkil, Kamel Tourki, Samir Saoudi, “Exact Outage Analysis of SIMO Relay-aided Underlay Communications with Limited Feedback,” in Proc., 76th Semi-Annual Vehicular Technology Conference VTC Spring, Nanjing, China, May 2016.
- Zakaria El-Moutaouakkil, Kamel Tourki, Samir Saoudi, “Spectrally-efficient SIMO relay-aided underlay communications: An exact outage analysis,” in Proc., IEEE International Conference on Communications ICC, Sydney, Australia, June 2014.
- Zakaria El-Moutaouakkil, Kamel Tourki, Khalid Qaraqe, Samir Saoudi, “Exact Outage Analysis for Relayaided Underlay Cognitive Radio Communications,” in Proc., 76th Semi-Annual Vehicular Technology Conference VTC Fall, Québec City, Canada, September 2012.
- Zakaria El-Moutaouakkil, Tarik Ait-Idir, Samir Saoudi, Halim Yanikomeroglu, and Mounir Ghogho, “Turbo Receiver Design for MIMO Relay ARQ Transmissions,” in Proc., 55th Annual IEEE Global Communications Conference GLOBECOM, California, USA, December 2012.
- Zakaria El-Moutaouakkil, Tarik Ait-Idir, Halim Yanikomeroglu, and Samir Saoudi, “Relay ARQ Strategies for Single Carrier MIMO Broadband Amplify-and-Forward Cooperative Transmission,” in Proc., 21th Annual IEEE Symposium on Personal Indoor and Mobile Radio Communications PIMRC, Istanbul, Turkey, September 2010.

Perspectives & Ongoing Research Works (2 journal papers)

Turbo reception (parallelized) can be further be optimized when the power allocation strategy in cognitive MIMO NAF relaying takes into account the statistics of the MMSE frequency-domain filter.

- Zakaria El-Moutaouakkil, Kamel Tourki, Halim Yanikomeroglu, and Samir Saoudi, “Energy-Efficient MIMO Non-Orthogonal AF Relaying in Broadband Spectrum Sharing,” to be submitted to an IEEE transactions paper.

Interference-aware TAS/MRC can be envisaged in massive MIMO systems to mitigate co-channel interference in a more sophisticated way.

- Zakaria El-Moutaouakkil, Kamel Tourki, Halim Yanikomeroglu, and Samir Saoudi, “Optimal TAS for Cognitive MIMO Systems,” to be submitted to an IEEE transactions paper.

Future Research Directions

- **MIMO non-orthogonal AF Relaying can smoothly be applied in non-orthogonal Multiple Access (NOMA) systems as a means to improve the Uplink transmission performance under an optimized transmit power allocation strategy.**
- **Turbo concept parallelization is becoming more and more a necessity due to low-latency 5G and Beyond requirements.**
- **The proposed optimal TAS/MRC for cognitive MIMO Systems gives insights to the rewarding gains it can achieve in transmit maximum ratio combining (TMRC) in the presence of co-channel interference.**

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Conclusion

Thank you very much
to my thesis supervisors and thesis committee.