Single Front-end MIMO Architecture with Parasitic Antenna Elements

Araki-Sakaguchi Laboratory

Mitsuteru YOSHIDA

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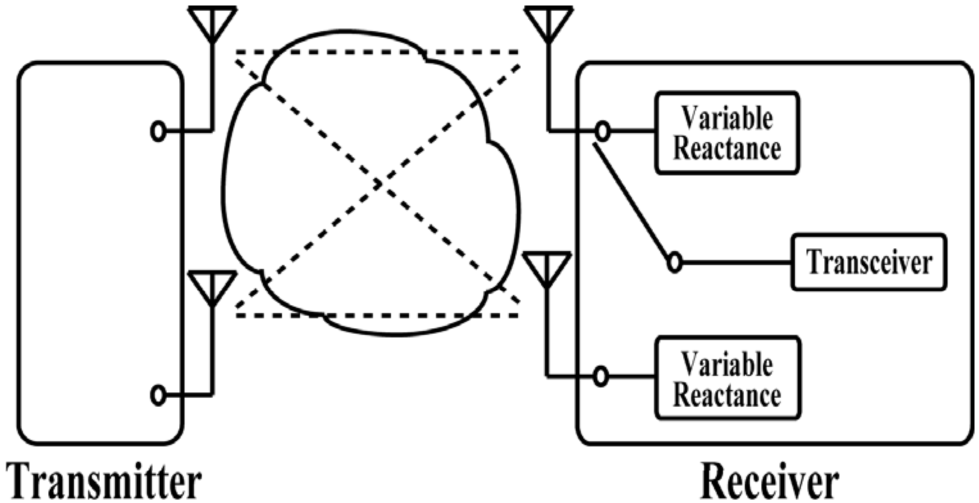
ε **Abbreviation**

- SF : Single Front-end, PAE : Parasitic Antenna Element
- T : Transmitter, P : PAE, R : Receiver

Background

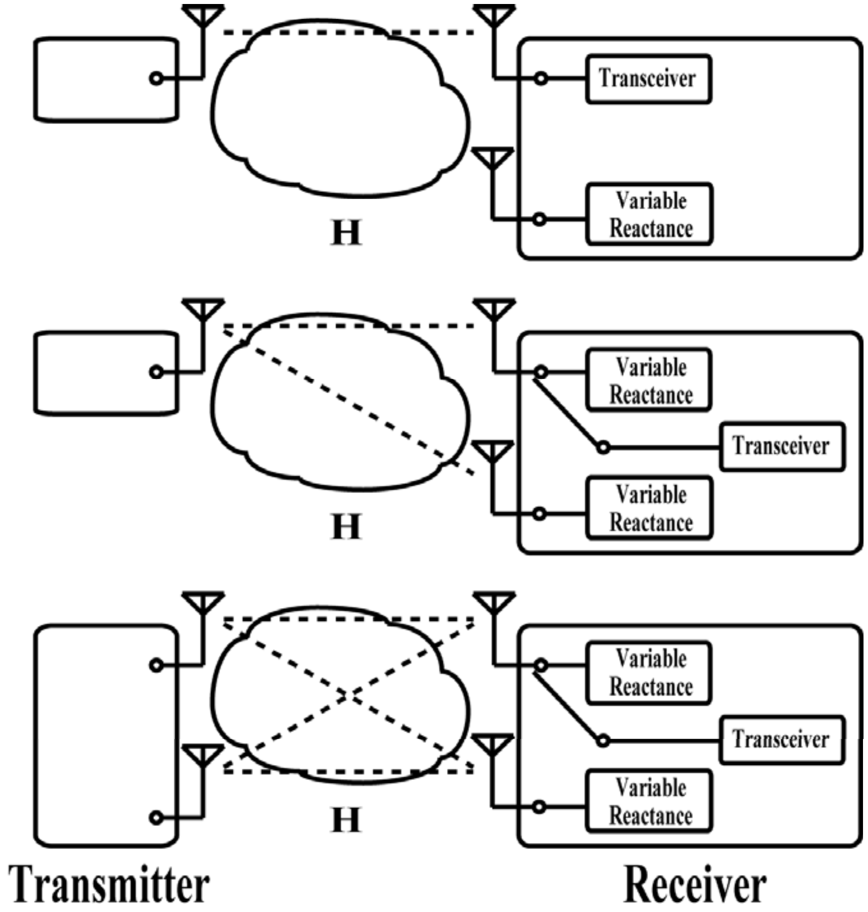
- **MIMO system requires …**
  - Low spatial correlation in limited space (e.g. mobile terminal)
  - Transceivers for each branch

- **Novel architecture is needed**
  - Mutual coupling effect
    - Adaptive beamforming (e.g. ESPAR)
  - Single RF Front-end
    - Spatiotemporal conversion
    - Multiplexing



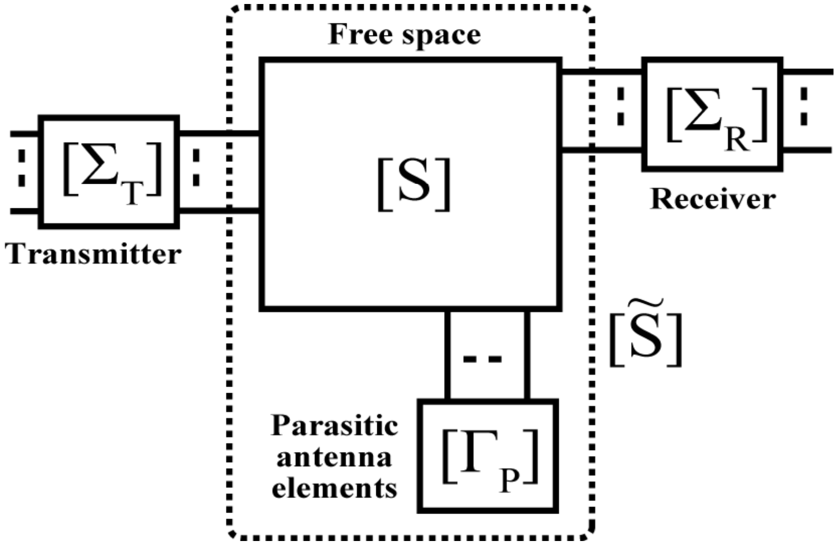
SF-MIMO w/ PAE

- **Analytical study**
  - Effect of PAE
    - Conventional : Empirical study
  - Effect of Single Front-end
    - Switching causes SNR penalty
  - MIMO performance
    - Eigenvalue analysis



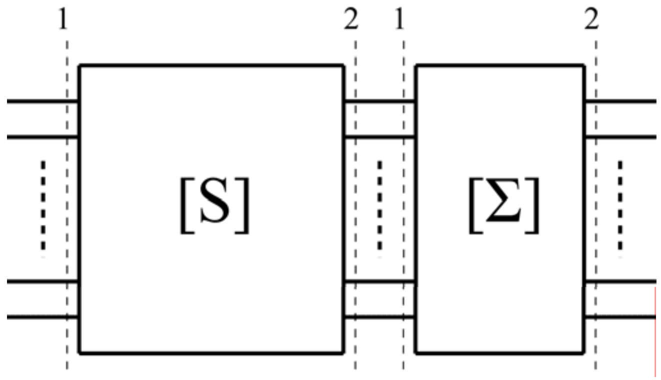
SF-MIMO w/ PAE

- **Concept of design for MIMO transceivers**
  - Free space
    - Stochastic : undesignable
  - Free space + PAE
    - Quasi stochastic : designable



- **Two designable parameters**
  - Receiver
    - Matching problem
  - Parasitic antenna elements
    - Operating problem

Matching problem



- **Capacity maximization**
  - Two independent problems

$$\mathop{\mathrm{argmax}}_{\mathbf{H},\mathbf{R}} \log\det\left(\mathbf{I}+\mathbf{H}\mathbf{R}\mathbf{H}^{\mathrm{H}}\right)=\mathop{\mathrm{argmax}}_{\mathbf{H},\mathbf{C}} \log\det\left(\mathbf{I}+\mathbf{C}\mathbf{H}^{\mathrm{H}}\mathbf{H}\mathbf{C}^{\mathrm{H}}\right)$$

$$\left(\because \mathbf{R}=\mathbf{C}^{\mathrm{H}}\mathbf{C} \Leftrightarrow \mathbf{R}:\text{Positive definite}\right)$$

$$\mathbf{H}^{\mathrm{H}}\mathbf{H} \le \tilde{\mathbf{H}}^{\mathrm{H}}\tilde{\mathbf{H}} \Rightarrow \mathbf{C}\mathbf{H}^{\mathrm{H}}\mathbf{H}\mathbf{C}^{\mathrm{H}} \le \mathbf{C}\tilde{\mathbf{H}}^{\mathrm{H}}\tilde{\mathbf{H}}\mathbf{C}^{\mathrm{H}} \Rightarrow \log\det\left(\mathbf{I}+\mathbf{C}\mathbf{H}^{\mathrm{H}}\mathbf{H}\mathbf{C}^{\mathrm{H}}\right) \le \log\det\left(\mathbf{I}+\mathbf{C}\tilde{\mathbf{H}}^{\mathrm{H}}\tilde{\mathbf{H}}\mathbf{C}^{\mathrm{H}}\right)$$

  - Lossless condition

$$\boldsymbol{\Sigma}^{\mathrm{H}}\boldsymbol{\Sigma}=\mathbf{I} \Rightarrow \boldsymbol{\Sigma}_{11}^{\mathrm{H}}\boldsymbol{\Sigma}_{11}+\boldsymbol{\Sigma}_{21}^{\mathrm{H}}\boldsymbol{\Sigma}_{21}=\mathbf{I}$$

  - Hermitian matching $\boldsymbol{\Sigma}_{11}=\mathbf{S}_{22}^{\mathrm{H}}$

$$\mathbf{H}(\boldsymbol{\Sigma})=\boldsymbol{\Sigma}_{21}\left(\mathbf{I}-\mathbf{S}_{22}\boldsymbol{\Sigma}_{11}\right)^{-1}\mathbf{S}_{21}$$

$$\mathbf{H}^{\mathrm{H}}\mathbf{H}\left(\mathbf{S}_{22}^{\mathrm{H}}\right)-\mathbf{H}^{\mathrm{H}}\mathbf{H}\left(\boldsymbol{\Sigma}_{11}\right)=\mathbf{S}_{21}^{\mathrm{H}}\left(\mathbf{I}-\mathbf{S}_{22}\mathbf{S}_{22}^{\mathrm{H}}\right)^{-1}\mathbf{S}_{21}-\mathbf{S}_{21}^{\mathrm{H}}\left(\mathbf{I}-\mathbf{S}_{22}\boldsymbol{\Sigma}_{11}\right)^{-1^{\mathrm{H}}}\boldsymbol{\Sigma}_{21}^{\mathrm{H}}\boldsymbol{\Sigma}_{21}\left(\mathbf{I}-\mathbf{S}_{22}\boldsymbol{\Sigma}_{11}\right)^{-1}\mathbf{S}_{21}$$

$$=\mathbf{S}_{21}^{\mathrm{H}}\left(\mathbf{I}-\mathbf{S}_{22}\boldsymbol{\Sigma}_{11}\right)^{-1^{\mathrm{H}}}\left(\boldsymbol{\Sigma}_{11}-\mathbf{S}_{22}^{\mathrm{H}}\right)^{\mathrm{H}}\left(\mathbf{I}-\mathbf{S}_{22}^{\mathrm{H}}\mathbf{S}_{22}\right)^{-1}\left(\boldsymbol{\Sigma}_{11}-\mathbf{S}_{22}^{\mathrm{H}}\right)\left(\mathbf{I}-\mathbf{S}_{22}\boldsymbol{\Sigma}_{11}\right)^{-1}\mathbf{S}_{21} \ge 0 \left(\because \mathbf{S}_{22}^{\mathrm{H}}\mathbf{S}_{22} \le \mathbf{I}\right)$$

$$\therefore \mathbf{S}_{21}^{\mathrm{H}}\left(\mathbf{I}-\mathbf{S}_{22}\mathbf{S}_{22}^{\mathrm{H}}\right)^{-1}\mathbf{S}_{21} \ge \mathbf{S}_{21}^{\mathrm{H}}\left(\mathbf{I}-\mathbf{S}_{22}\boldsymbol{\Sigma}_{11}\right)^{-1^{\mathrm{H}}}\left(\mathbf{I}-\boldsymbol{\Sigma}_{11}^{\mathrm{H}}\boldsymbol{\Sigma}_{11}\right)\left(\mathbf{I}-\mathbf{S}_{22}\boldsymbol{\Sigma}_{11}\right)^{-1}\mathbf{S}_{21}$$

Matching problem (cont.)

- **Parasitic antenna elements system model**
  - Effective free space

$$\mathbf{S} \to \widetilde{\mathbf{S}} = \begin{bmatrix} \widetilde{\mathbf{S}}_{\mathrm{TT}} & \widetilde{\mathbf{S}}_{\mathrm{TR}} \\ \widetilde{\mathbf{S}}_{\mathrm{RT}} & \widetilde{\mathbf{S}}_{\mathrm{RR}} \end{bmatrix} = \begin{bmatrix} \mathbf{S}_{\mathrm{TT}} + \mathbf{S}_{\mathrm{TP}}\left(\mathbf{\Gamma}_{\mathrm{P}}^{-1} - \mathbf{S}_{\mathrm{PP}}\right)^{-1}\mathbf{S}_{\mathrm{PT}} & \mathbf{S}_{\mathrm{TR}} + \mathbf{S}_{\mathrm{TP}}\left(\mathbf{\Gamma}_{\mathrm{P}}^{-1} - \mathbf{S}_{\mathrm{PP}}\right)^{-1}\mathbf{S}_{\mathrm{PR}} \\ \mathbf{S}_{\mathrm{RT}} + \mathbf{S}_{\mathrm{RP}}\left(\mathbf{\Gamma}_{\mathrm{P}}^{-1} - \mathbf{S}_{\mathrm{PP}}\right)^{-1}\mathbf{S}_{\mathrm{PT}} & \mathbf{S}_{\mathrm{RR}} + \mathbf{S}_{\mathrm{RP}}\left(\mathbf{\Gamma}_{\mathrm{P}}^{-1} - \mathbf{S}_{\mathrm{PP}}\right)^{-1}\mathbf{S}_{\mathrm{PR}} \end{bmatrix}$$

  - Hermitian matching

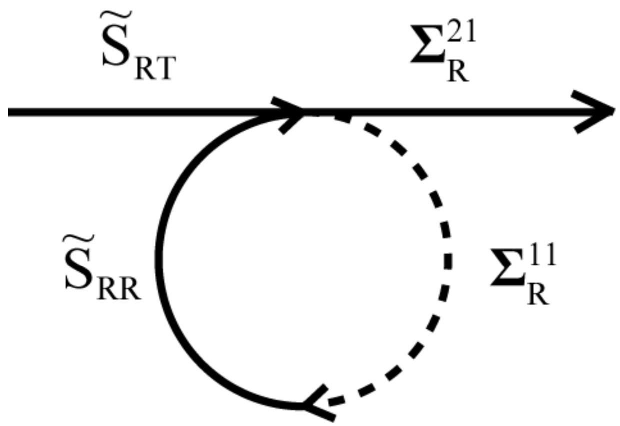
$$\mathbf{\Sigma}_{\mathrm{R}}^{11} = \widetilde{\mathbf{S}}_{\mathrm{RR}}^{\mathrm{H}}$$

  - Effective channel

$$\widetilde{\mathbf{H}} = \mathbf{\Sigma}_{\mathrm{R}}^{21}\left(\mathbf{I} - \widetilde{\mathbf{S}}_{\mathrm{RR}}\widetilde{\mathbf{S}}_{\mathrm{RR}}^{\mathrm{H}}\right)^{-1}\widetilde{\mathbf{S}}_{\mathrm{RT}}$$

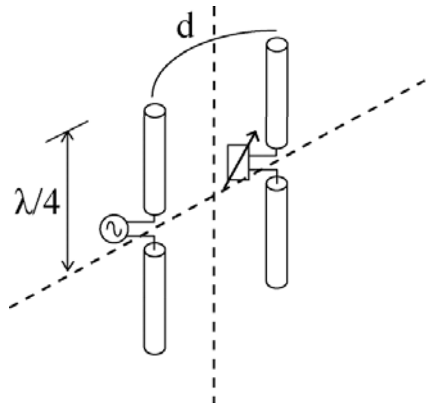
  - Capacity : Equal power allocation

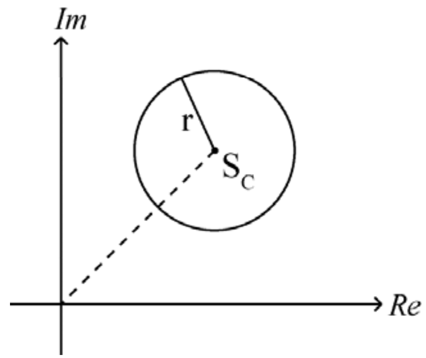
$$C = B\log\left|\mathbf{I} + \gamma\widetilde{\mathbf{S}}_{\mathrm{RT}}^{\mathrm{H}}\left(\mathbf{I} - \widetilde{\mathbf{S}}_{\mathrm{RR}}\widetilde{\mathbf{S}}_{\mathrm{RR}}^{\mathrm{H}}\right)^{-1}\widetilde{\mathbf{S}}_{\mathrm{RT}}\right|$$



Operating problem

- **(T,R,P)=(1,1,1)**
  - Mobius transform





$$\arg\max_{|\Gamma_P|\le 1} \log\left(1+\gamma\frac{|\widetilde{S}_{RT}|^2}{1-|\widetilde{S}_{RR}|^2}\right) = \arg\max_{|\Gamma_P|\le 1} \frac{|\widetilde{S}_{RT}|^2}{1-|\widetilde{S}_{RR}|^2}$$

$$= \arg\max_{|\Gamma_P|=1} \left|\frac{A\Gamma_P + B}{C\Gamma_P + D}\right| \left(\because 1+|S_{PP}|^2-|S_{RR}|^2-|\Delta|^2 \ge 0 \text{ where } \Delta = \det\begin{bmatrix} S_{RR} & S_{RP} \\ S_{PR} & S_{PP}\end{bmatrix}\right)$$

  - Γ_P is uniquely determined

- **Performance analysis**
  - No matching (All pass) model $\widetilde{\mathbf{S}}_{RT}^{H}\left(\mathbf{I}-\widetilde{\mathbf{S}}_{RR}\widetilde{\mathbf{S}}_{RR}^{H}\right)^{-1}\widetilde{\mathbf{S}}_{RT} \to \widetilde{\mathbf{S}}_{RT}^{H}\widetilde{\mathbf{S}}_{RT}$

$$\mathbf{\Sigma}_R^{11} = \mathbf{O}, \mathbf{\Sigma}_R^{21} = \mathbf{I}$$

Performance analysis

- **Applying Equal Gain Combining (EGC) analysis**

$$\left|\tilde{S}_{\mathrm{RT}}\right|_{\max} = \left| S_{\mathrm{RT}} + \frac{S_{\mathrm{RP}} S_{\mathrm{PP}}^{*} S_{\mathrm{PT}}}{1-\left|S_{\mathrm{PP}}\right|^{2}} \right| + \frac{\left|S_{\mathrm{RP}} S_{\mathrm{PT}}\right|}{1-\left|S_{\mathrm{PP}}\right|^{2}} \equiv X + Y \equiv Z$$

$$\begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} s + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \Rightarrow \mathbf{r}' = \begin{bmatrix} \dfrac{h_1^{*}}{|h_1|} & \dfrac{h_2^{*}}{|h_2|} \end{bmatrix} \mathbf{r} = \left(|h_1| + |h_2|\right) s + \mathbf{n}'$$

  - X,Y : pseudo branch

$$\gamma_{\mathrm{X}} \equiv E\left[X^2\right], \gamma_{\mathrm{Y}} \equiv E\left[Y^2\right], \rho^2 \equiv \frac{\operatorname{cov}\left(X^2, Y^2\right)}{\sqrt{\operatorname{var}\left(X^2\right)\operatorname{var}\left(Y^2\right)}}$$

$$P_{\mathrm{e}} = \frac{1}{2} - \frac{1-\rho^2}{2} \sum_{n=0}^{\infty} \binom{2n}{n} \left(\frac{\rho}{2}\right)^{2n} \sum_{k=0}^{n} \binom{n}{k} (-1)^k \frac{2n+1}{2k+1} \cdots$$

$$\cdots \times \left\{ \left(\frac{\gamma_{\mathrm{X}}}{2\left(1-\rho^2\right)^{-1} + \gamma_{\mathrm{X}} + \gamma_{\mathrm{Y}}} \right)^{k+\frac{1}{2}} {}_2F_1\left(-n-\frac{1}{2}, k+\frac{1}{2}; \frac{1}{2}; \frac{\gamma_{\mathrm{Y}}}{2\left(1-\rho^2\right)^{-1} + \gamma_{\mathrm{X}} + \gamma_{\mathrm{Y}}} \right) + \left(\frac{\gamma_{\mathrm{Y}}}{2\left(1-\rho^2\right)^{-1} + \gamma_{\mathrm{X}} + \gamma_{\mathrm{Y}}} \right)^{k+\frac{1}{2}} {}_2F_1\left(-n-\frac{1}{2}, k+\frac{1}{2}; \frac{1}{2}; \frac{\gamma_{\mathrm{X}}}{2\left(1-\rho^2\right)^{-1} + \gamma_{\mathrm{X}} + \gamma_{\mathrm{Y}}} \right) \right\}$$

- **Performance of EGC is quite close to that of MRC**
  - Exhibiting less than 1dB of power penalty

- **Noise is added only from 1 branch**

Simulation results

- **Configuration**
  - S_{RT},S_{PT} : Propagation channel (stochastic)
    - Correlated complex gaussian RVs (CN(0,σ^2))
    - Envelope correlation coefficient by Jakes' model

$$\rho = J_0\left(\frac{2\pi d}{\lambda}\right)$$

    - Power correlation coefficient

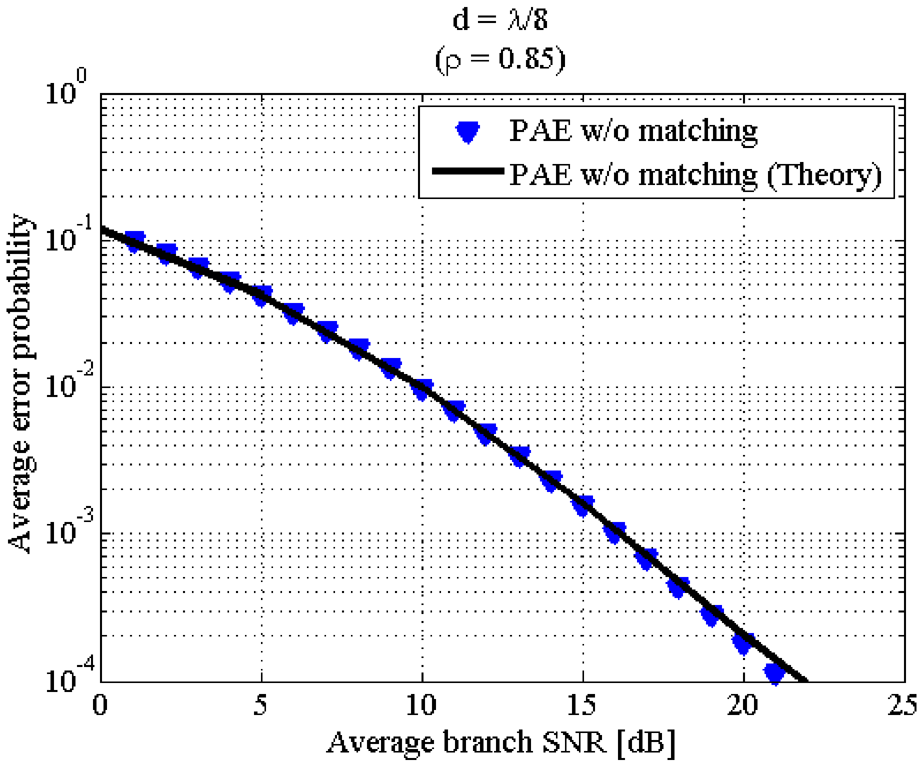
$$\frac{\mathrm{cov}\left(\left|S_{\mathrm{RT}}\right|^2,\left|S_{\mathrm{PT}}\right|^2\right)}{\sqrt{\mathrm{var}\left(\left|S_{\mathrm{RT}}\right|^2\right)\mathrm{var}\left(\left|S_{\mathrm{PT}}\right|^2\right)}} = \rho^2$$

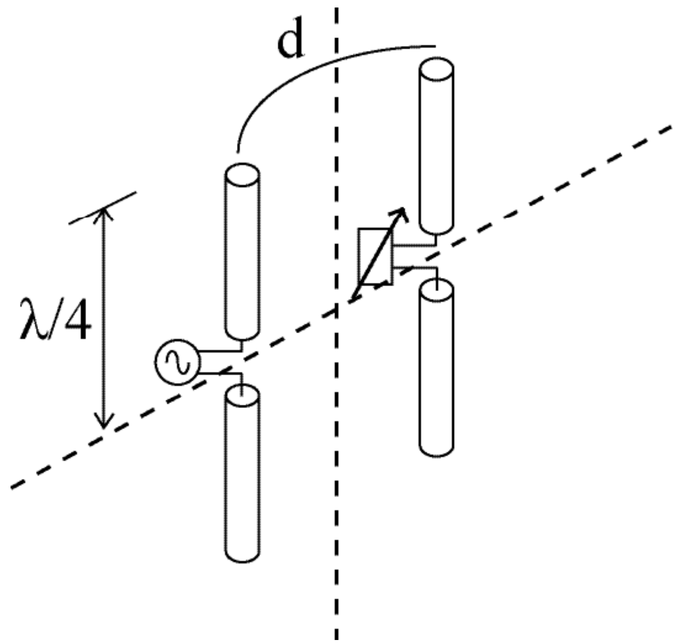
  - S_{RR},S_{PP},S_{PR},S_{RP} : Antenna parameters (deterministic)
    - Calculated by HFSS

Simulation results (cont.)

- **Average error probability vs SNR**

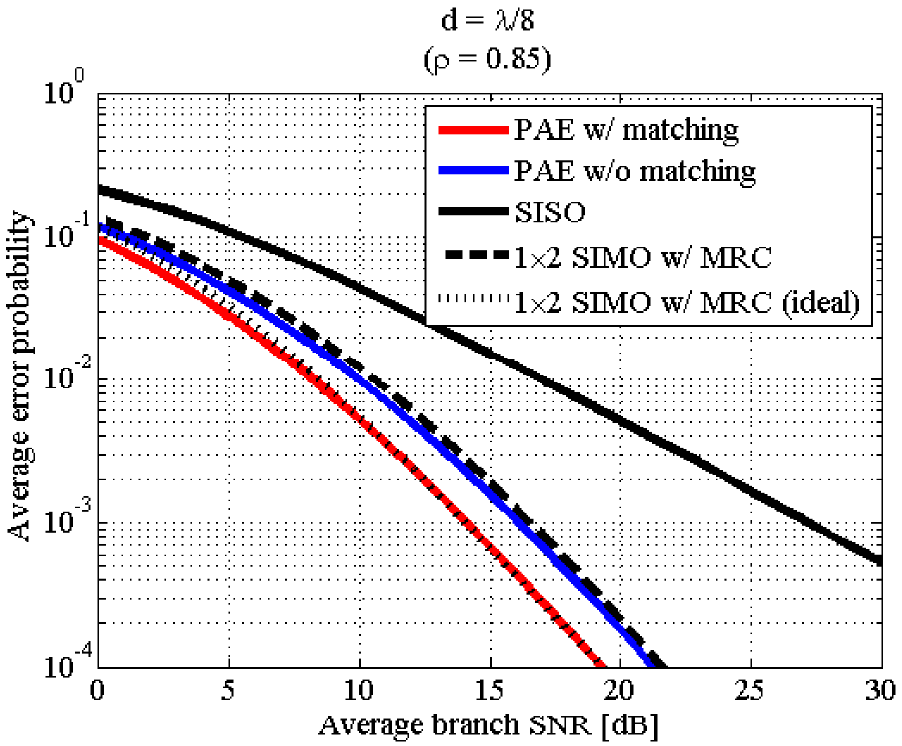
$$\begin{bmatrix} S_{\mathrm{RR}} & S_{\mathrm{RP}} \\ S_{\mathrm{PR}} & S_{\mathrm{PP}} \end{bmatrix} = \begin{bmatrix} 4.9\times10^{-1} + j3.6\times10^{-1} & 1.1\times10^{-1} - j3.9\times10^{-1} \\ 1.1\times10^{-1} - j3.9\times10^{-1} & 5.0\times10^{-1} + j3.6\times10^{-1} \end{bmatrix}$$

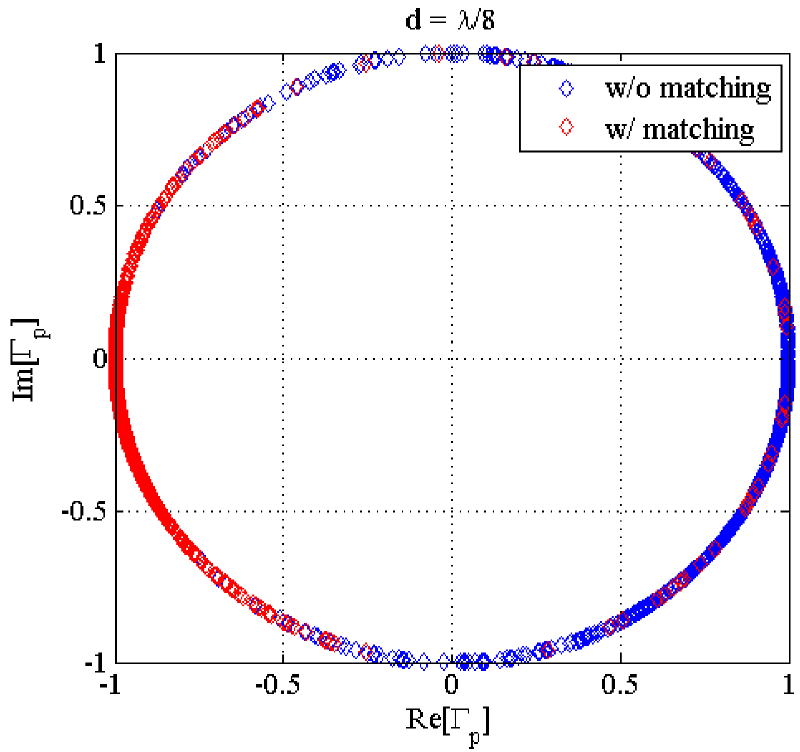




Simulation results (cont.)

- **Average error probability vs SNR**
- **Distribution of Γ_P**

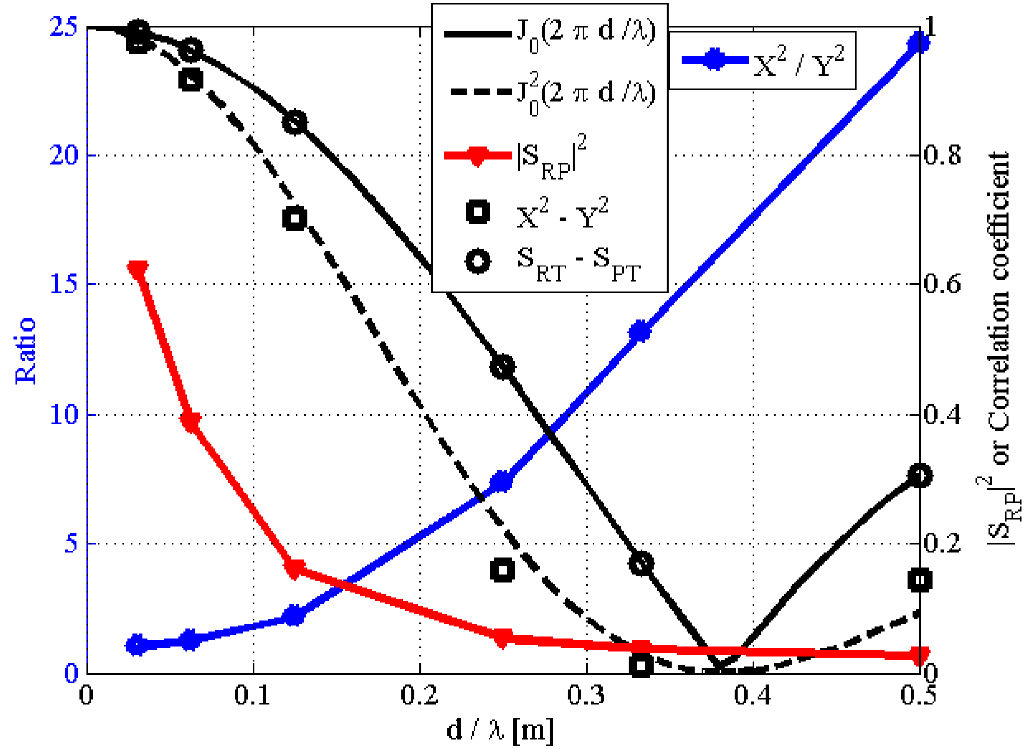




Simulation results (cont.)

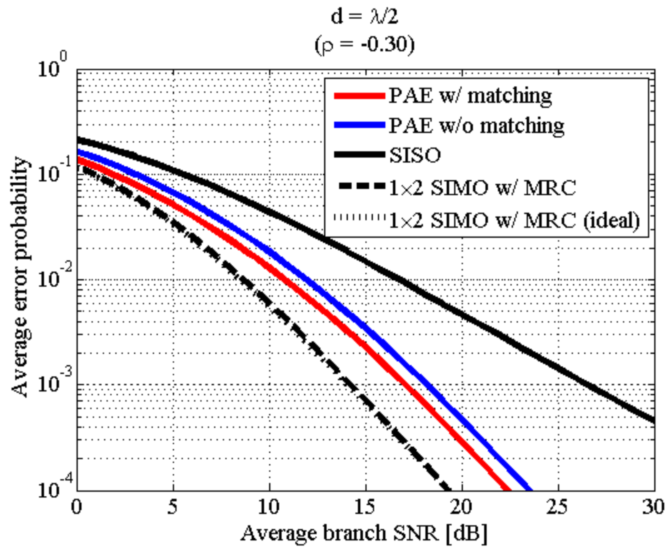
- **Effect of distance between antenna elements**
  - Mutual coupling (S_{RP})
  - Correlation coefficient
  - $E[X^2/Y^2]$

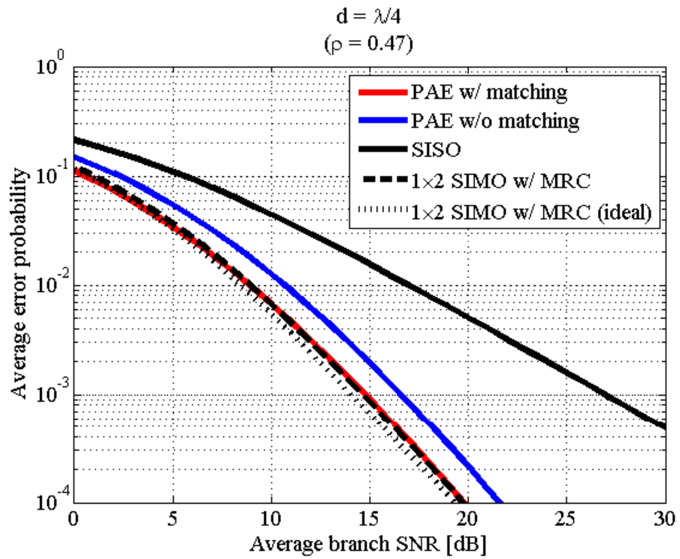
$$\left|\tilde{S}_{RT}\right|_{max} = \left|S_{RT} + \frac{S_{RP}S_{PP}^{*}S_{PT}}{1-\left|S_{PP}\right|^2}\right| + \frac{\left|S_{RP}S_{PT}\right|}{1-\left|S_{PP}\right|^2} \equiv X + Y \equiv Z$$

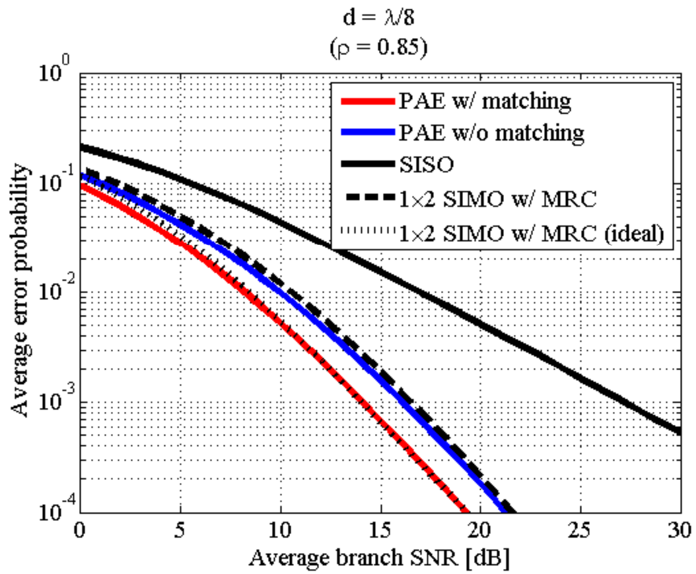


Simulation results (cont.)

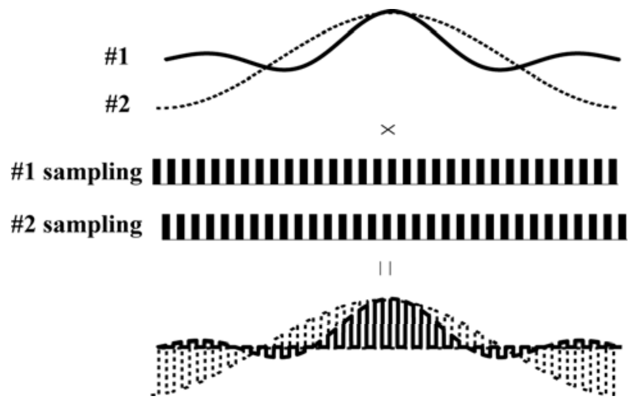
- **Optimum distance**
  - Distance gets closer, performance becomes better





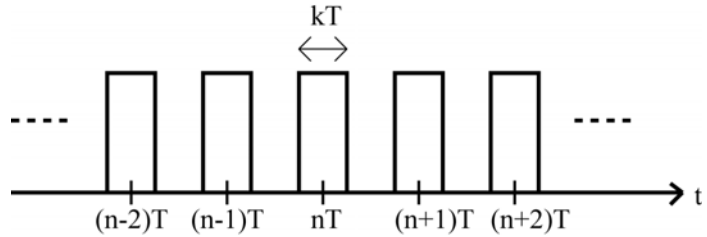


Single Front-end



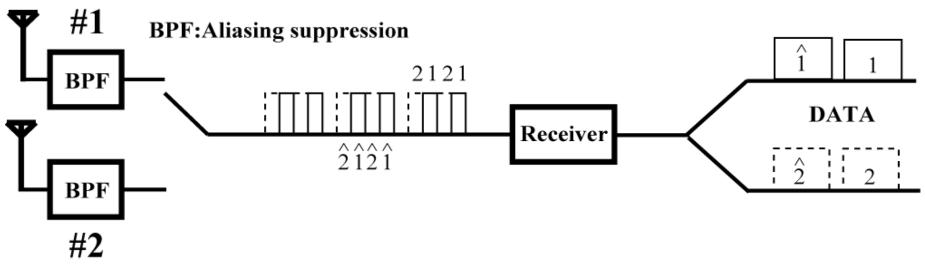
- **Spatiotemporal conversion**
  - PSD of switched signal

$$\tilde{R}(f) = k^2 \sum_n \frac{\sin^2 nk\pi}{(nk\pi)^2} R\left(f - \frac{n}{T} \right) \text{ where } k \in [0,1]$$

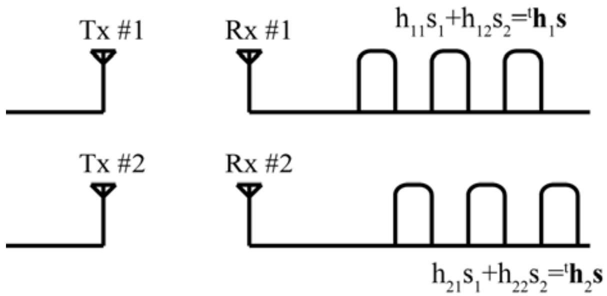


  - PSD of white noise (e.g. 3dB penalty where k=1/2)

$$\tilde{N}(f) = k^2 \sum_n \frac{\sin^2 nk\pi}{(nk\pi)^2} N_0 = kN_0$$



  - Equivalent channel



$$\mathbf{H} = \begin{bmatrix} {}^t\mathbf{h}_1 \\ {}^t\mathbf{h}_2 \end{bmatrix} \rightarrow \tilde{\mathbf{H}} = \begin{bmatrix} {}^t\tilde{\mathbf{h}}_1 \\ {}^t\tilde{\mathbf{h}}_2 \end{bmatrix} \Rightarrow \sqrt{k} \begin{bmatrix} {}^t\tilde{\mathbf{h}}_1 \\ {}^t\tilde{\mathbf{h}}_2 \end{bmatrix}$$

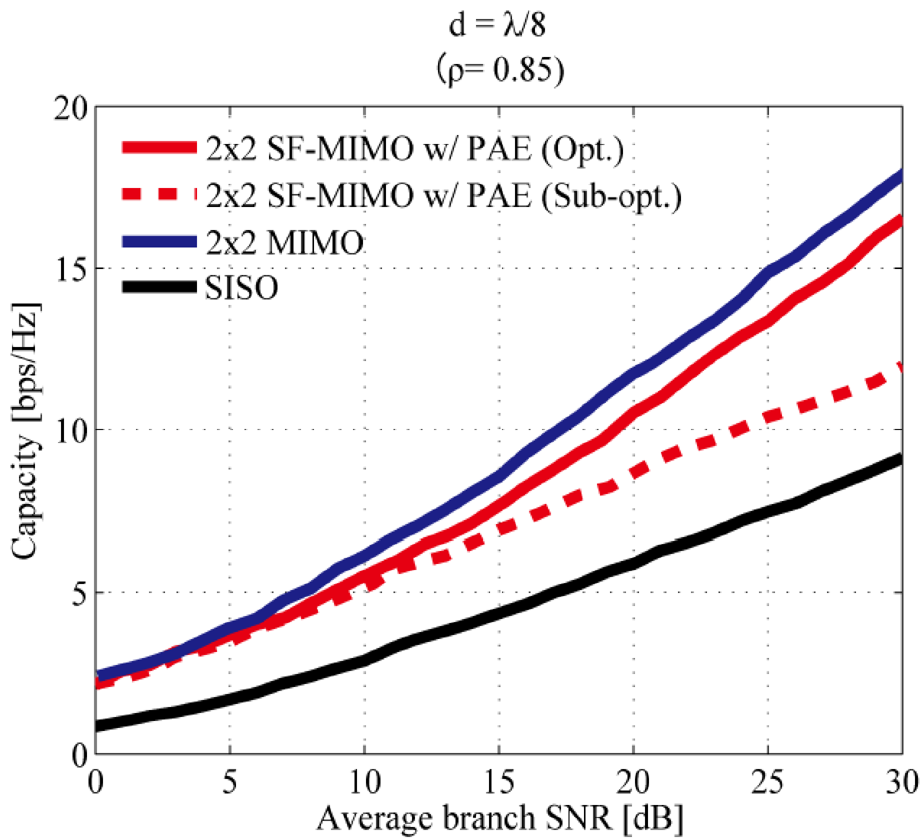
Simulation results

- **Capacity**
  - Optimum

$$\underset{\mathbf{\Gamma}_{\mathrm{P}}}{\arg\max} \log\det\left(\mathbf{I} + \gamma\tilde{\mathbf{H}}\tilde{\mathbf{H}}^{\mathrm{H}}\right)$$

  - Sub-optimum at low SNR

$$\underset{\mathbf{\Gamma}_{\mathrm{P}}}{\arg\max} \left\|\tilde{\mathbf{H}}\right\|_F^2$$



- **The performance of single front-end MIMO w/ PAE is close to that of conventional 2x2 MIMO**

Summary

- **SF-MIMO w/ PAE is proposed**
  - Performance of PAE is evaluated analytically
  - Switching operation can realize MIMO by single RF front-end
- **Feasibility of adaptive matching circuit**

<u>Thank you for your kind attention</u>