RF Energy Harvesting for Future Communications

TAN HANH - VO NGUYEN QUOC BAO

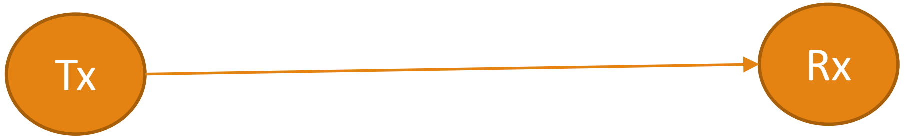
POSTS AND TELECOMMUNICATIONS INSTITUTE OF TECHNOLOGY, VIETNAM

Outline

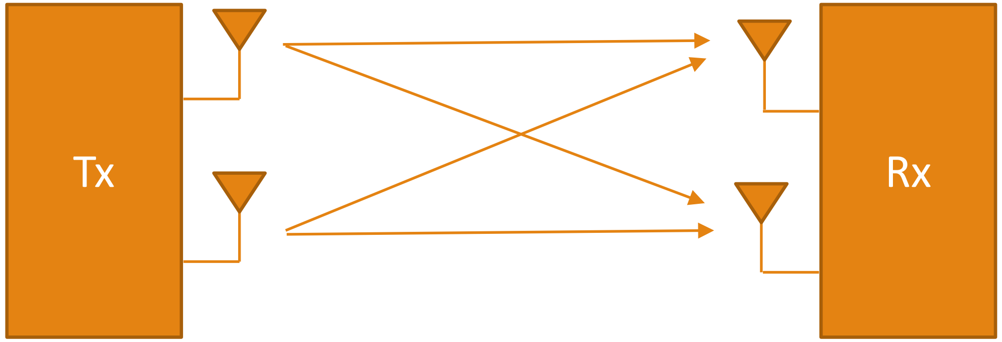
- Introduction
- System Model
  - Model #1
  - Model #2
- Conclusion

INTRODUCTION

Direct Transmission



MIMO



- Outage Probability

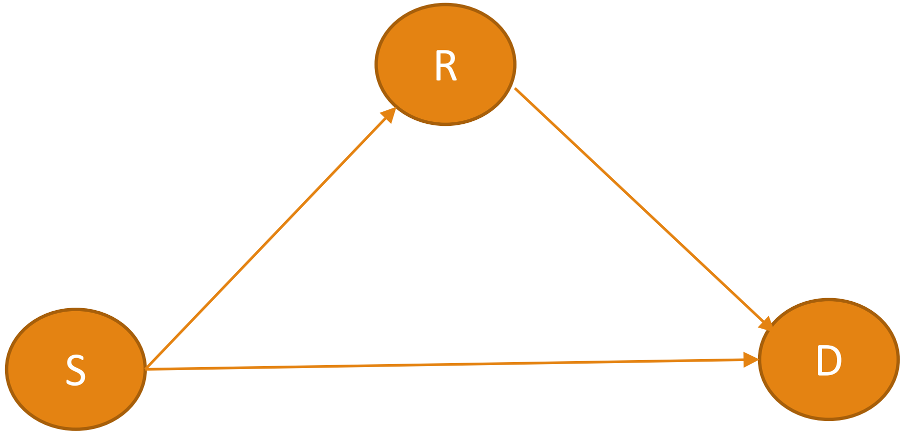
$$\begin{aligned}\text{OP} &= \Pr\left[\log_2(1+\gamma) < R\right] \\ &= \Pr(\gamma < \gamma_{\text{th}} = 2^R - 1) \\ &= 1 - \exp\left(-\frac{\gamma_{\text{th}}}{\bar{\gamma}}\right)\end{aligned}$$

High SNR

$$\text{OP} \approx \frac{\gamma_{\text{th}}}{\bar{\gamma}}$$

- MIMO technology
  - Advantage: Improving spatial diversity gain
  - Disadvantage: Having constraint on space

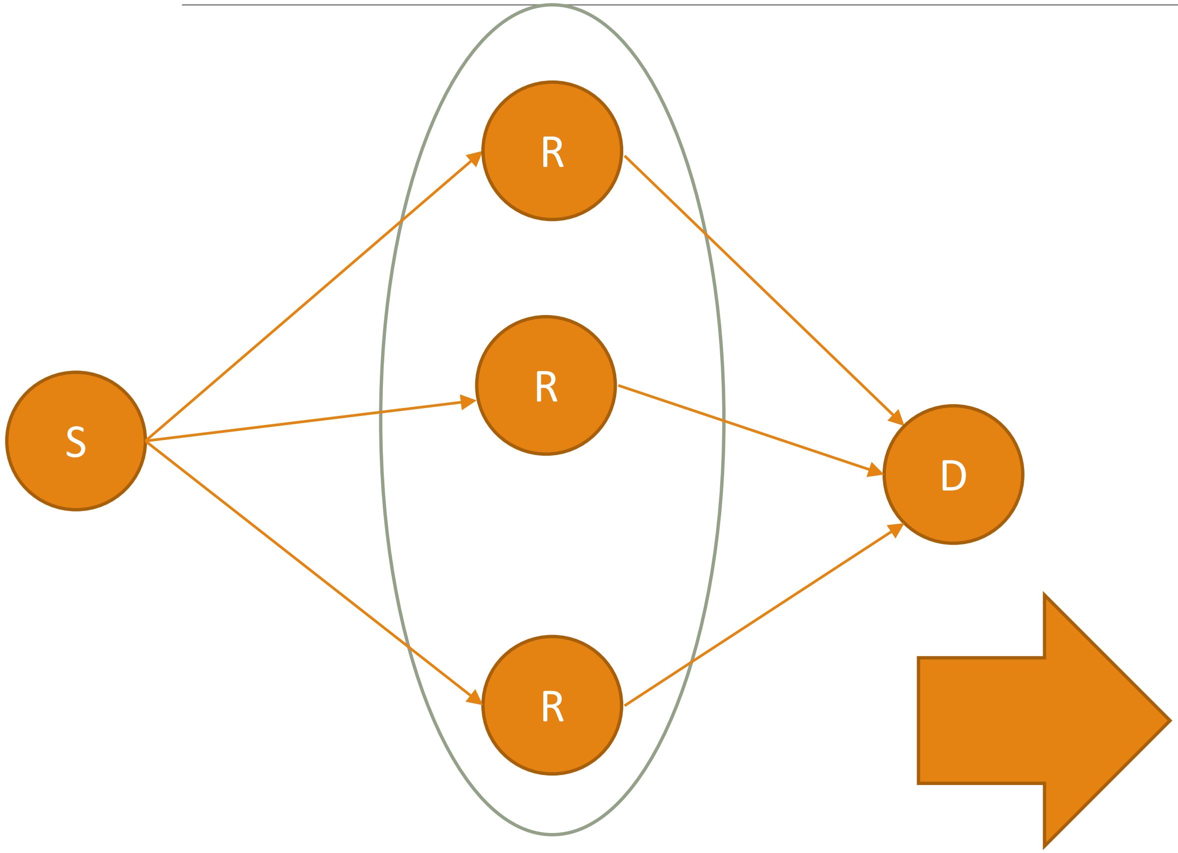
INTRODUCTION



- Cooperative Communications
  - At Relay
    - Amplify-and-Forward
    - Decode-and-Forward
  - At Destination
    - Maximal ratio Combining
    - Selection Combining

Full spatial diversity gain: TWO

INTRODUCTION

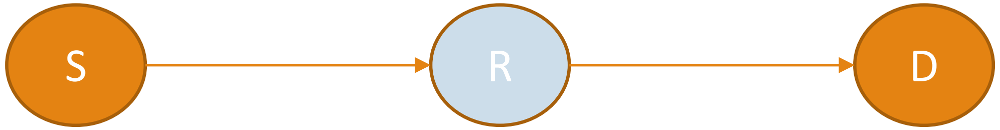


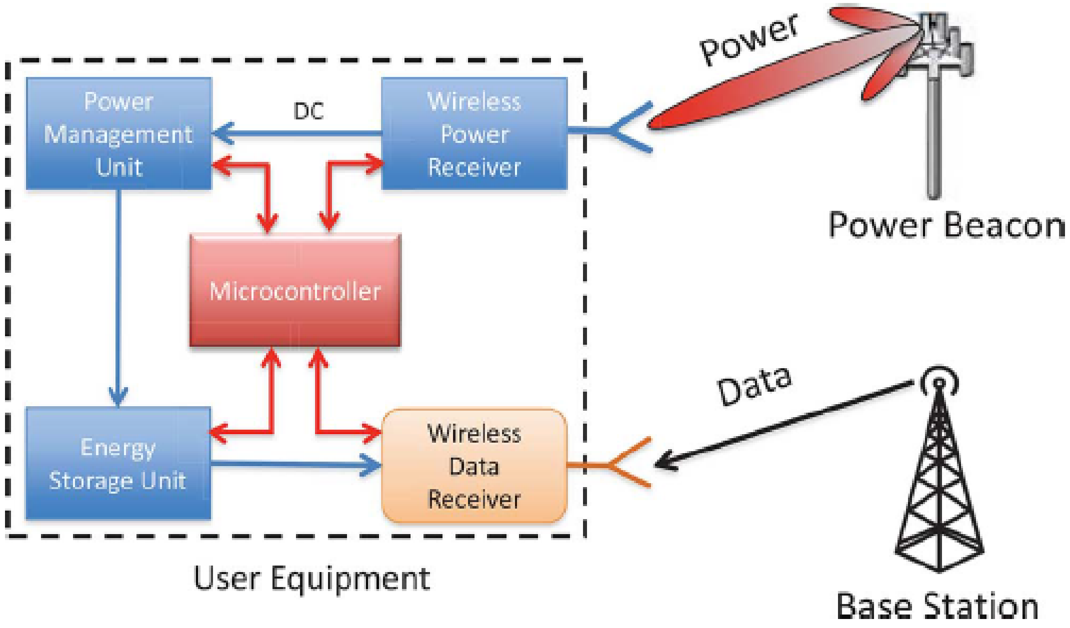
- Relay selection
  - Full Relay Selection
    - Diversity gain = number of relays
  - Partial Relay Selection
    - Diversity gain = 1 (2 if direct transmission is available)

- Relays availability
- Fairness on selecting relays, i.e., energy issue

Model #1

Energy Harvesting (Wireless Powered Transfer) relay

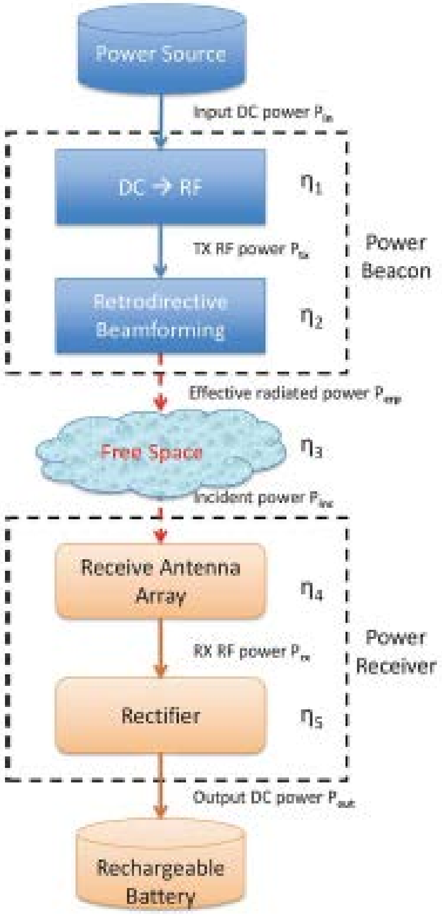




X. Minghua and S. Aissa, "On the Efficiency of Far-Field Wireless Power Transfer," *IEEE Transactions on Signal Processing*, vol. 63, pp. 2835-2847, 2015.

- Transmit and receive its own data: battery energy
- Receive and forward data for other nodes: harvested energy

Model #1



Time switching receiver mechanism

Phase 1	Phase 2	Phase 3
αT	$\frac{(1-\alpha)T}{2}$	$\frac{(1-\alpha)T}{2}$

❑Harvesting energy and sending signals

- The first phase: The relay harvests energy from the source signal
- The second phase: The source broadcasts its signal
- The third phase: The relay forwards the source signal to the destination

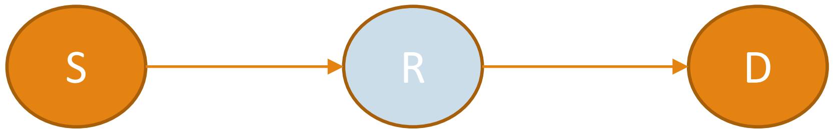
Model #1

- The harvested energy of R during energy harvesting time αT

$$E_R = \varepsilon \alpha P_s \left| h_1 \right|^2 T$$

- The transmit power of the relay

$$P_2 = \frac{E_R}{(1-\alpha)T/2} = \frac{2\varepsilon \alpha P_1 \left| h_1 \right|^2}{1-\alpha}$$



- The instantaneous signal-to-noise ratio (SNR) of the first hop and second hop

$$\gamma_1 = \frac{P_1 \left| h_{1,k^*} \right|^2}{N_0} \qquad \gamma_2 = \frac{P_2 \left| h_2 \right|^2}{N_0} = \frac{2\varepsilon \alpha P_1 \left| h_{1,k^*} \right|^2 \left| h_2 \right|^2}{(1-\alpha) N_0}$$

Correlated

$$\gamma_\Sigma = \min(\gamma_1, \gamma_2) = \min\left(\frac{P_1 \left| h_{1,k^*} \right|^2}{N_0}, \frac{2\varepsilon \alpha P_1 \left| h_{1,k^*} \right|^2 \left| h_2 \right|^2}{(1-\alpha) N_0} \right)$$

Model #1

- The System Outage Probability

$$\text{OP}=\Pr\left[\frac{(1-\alpha)}{2}\log_2(1+\gamma_\Sigma)<\text{R}\right]$$

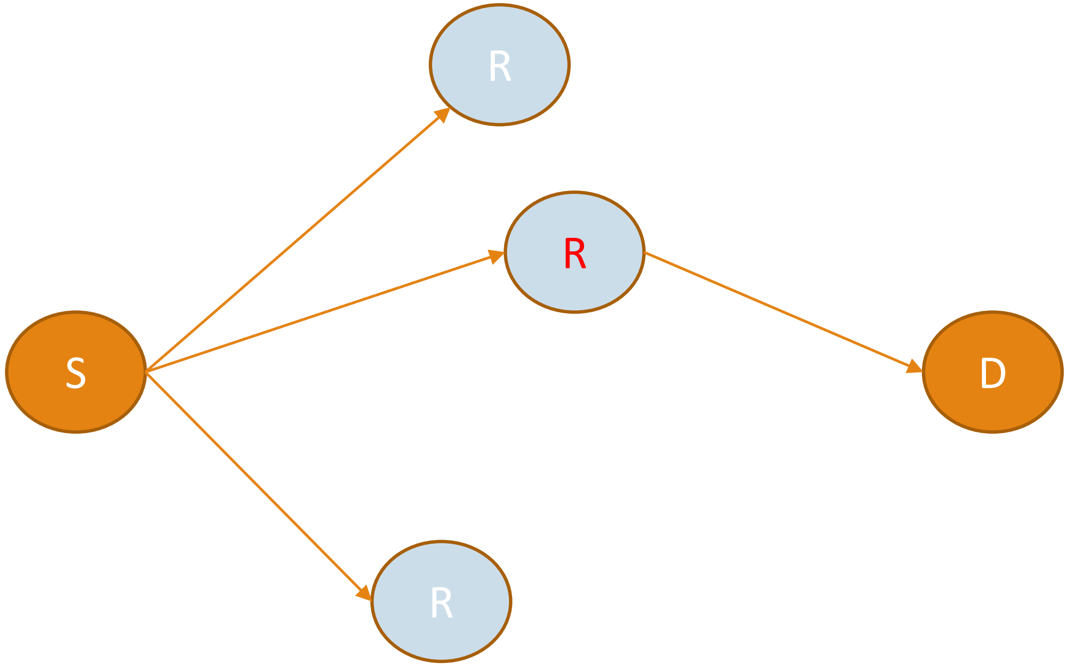
$$=\Pr\left(\min\left(\frac{P_1|h_1|^2}{N_0},\frac{2\varepsilon\alpha P_1|h_1|^2|h_2|^2}{(1-\alpha)N_0}\right)<\gamma_{th}\right)$$

$$\frac{\gamma_{th}N_0}{P_1}\to 0$$

$$\text{OP}\approx 1-\frac{k}{\lambda_1}\int_0^\infty e^{-\left(\frac{k}{\lambda_1}x+\frac{b/\lambda_2}{x}\right)}dx$$

$$\text{OP}\approx 1-\sqrt{\frac{\gamma_{th}(1-\alpha)N_0\lambda_1}{2\varepsilon\alpha P_1\lambda_2}}\,\text{BesselK}\left[1,2\sqrt{\frac{\gamma_{th}(1-\alpha)N_0}{2\varepsilon\alpha P_1\lambda_1\lambda_2}}\right]$$

Model #1



- The harvested energy of R_k during energy harvesting time αT

$$E_k = \varepsilon \alpha P_s \left|h_{1,k}\right|^2 T$$

- The selected relays is chosen as

$$k^* = \arg\max_{k=1,\ldots,\mathrm{N}} E_k$$

- The system outage probability

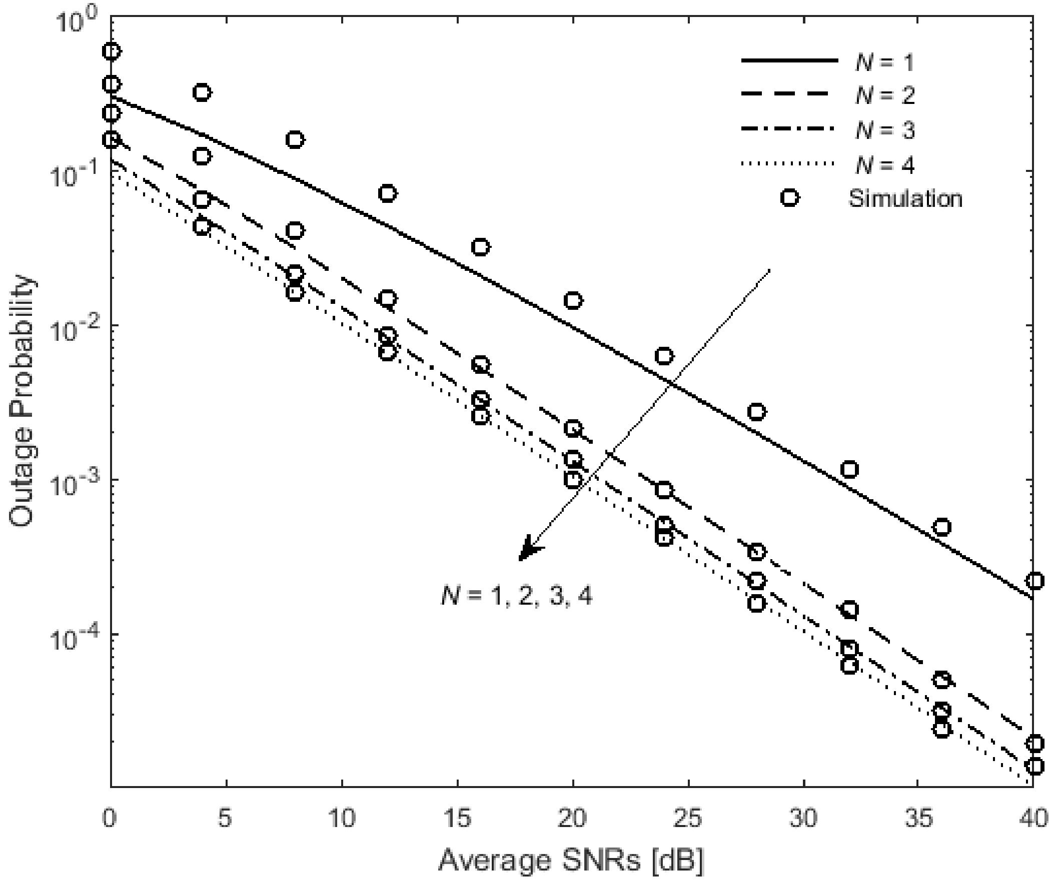
The relay having the highest harvested energy among N available relays will be the forwarder of the next hop

$$\mathrm{OP} = 1 - \sum_{k=1}^{N} (-1)^{k-1} \binom{N}{k} \frac{2k}{\lambda_1} \sqrt{\frac{\gamma_{th}(1-\alpha)N_0\lambda_1}{2\varepsilon\alpha P_1 k \lambda_2}}\, \mathrm{BesselK}\left[1, 2\sqrt{\frac{k\gamma_{th}(1-\alpha)N_0}{2\varepsilon\alpha P_1 \lambda_1 \lambda_2}}\right]$$

Model #1

Settings	Value
Target transmission rate [bits/sec/Hz]	1
Energy harvesting efficiency	0.75
Path loss exponent	3
S-R distance	0.5

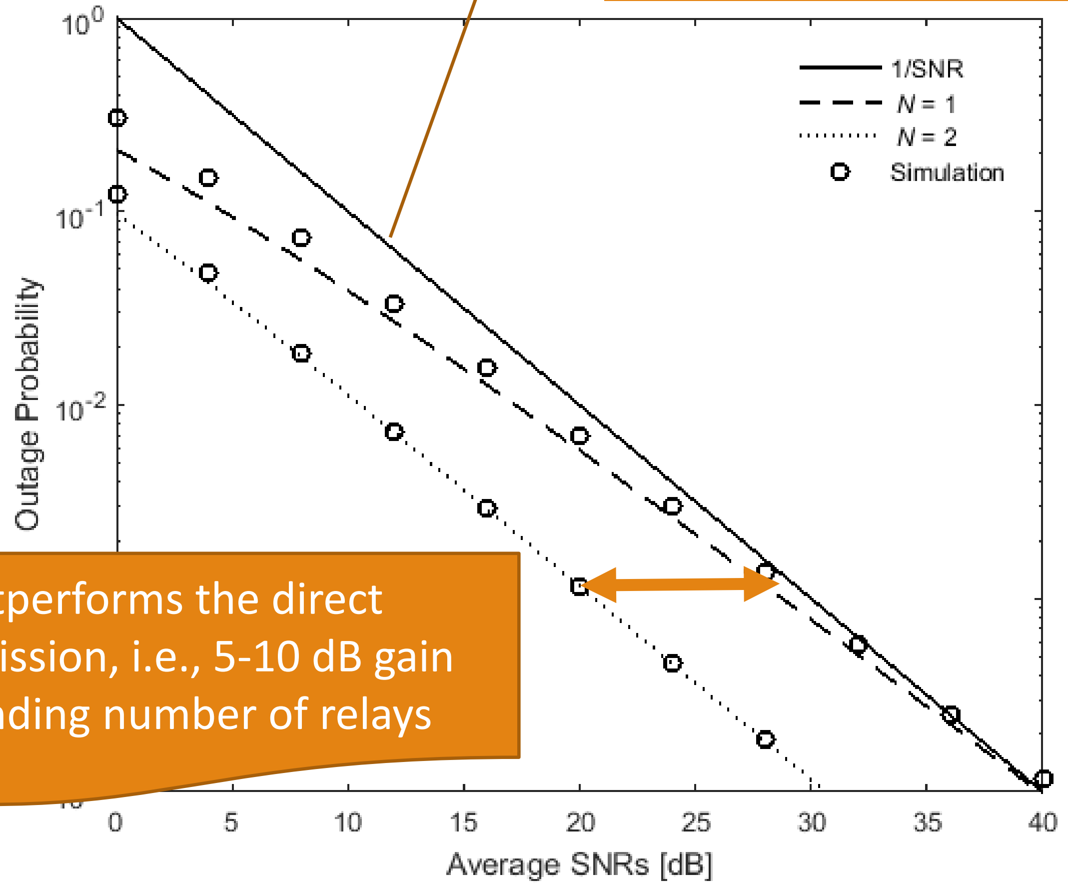
- Increasing number of energy harvesting relays improves the system performance
- The coding gain seems still to be increases since the number of relays increases
- At high SNRs, the approximation results match well with the simulation results.



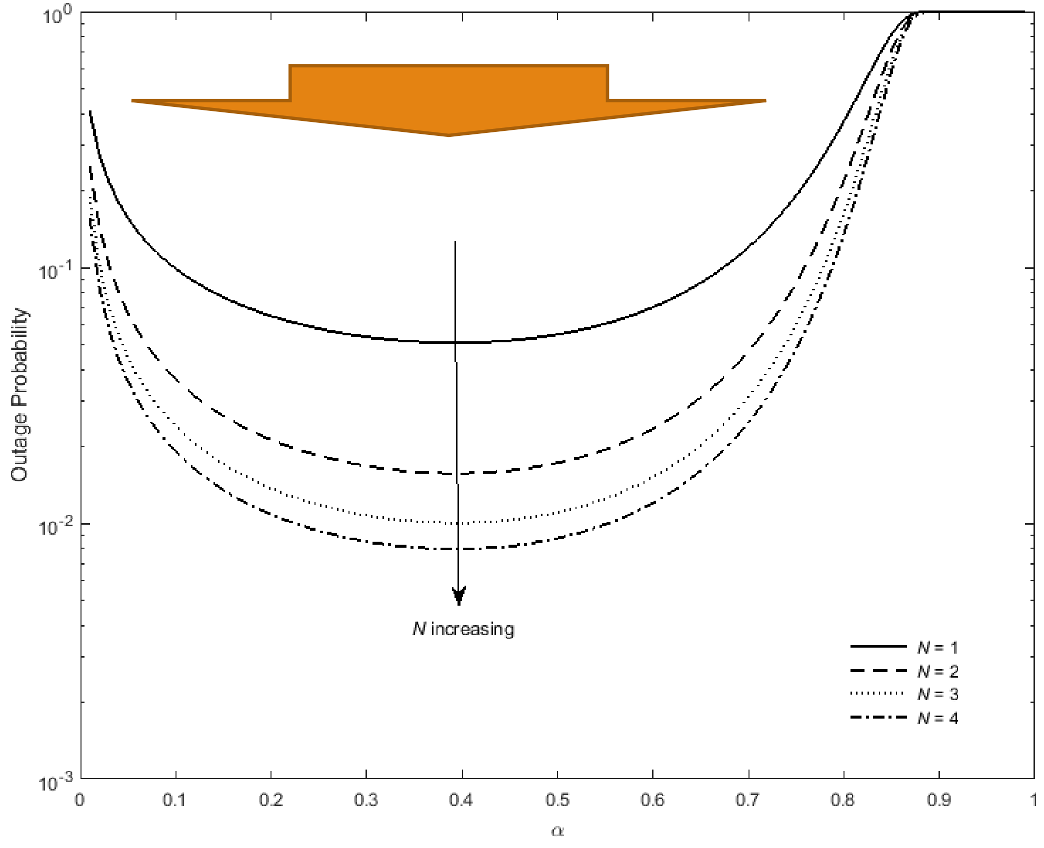
Model #1

Direct Transmission

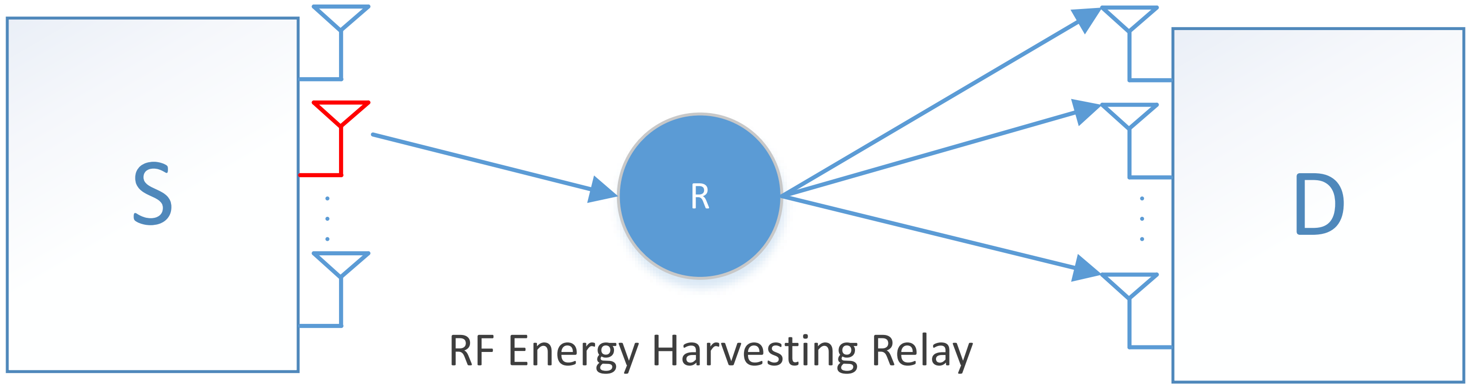
- OP approaches 1 since α > 0.9
- OP reaches the minimum value since α ~ 0.39
- The minimum OP will depend on *d* and *R*



Outperforms the direct transmission, i.e., 5-10 dB gain depending number of relays



Model #2



Source: Transmit Antenna Selection

Destination: Maximal Ratio Combining

$$\gamma_{\Sigma} = \min(\gamma_1, \gamma_2) = \min\left(\frac{P_S}{N_0} \max_{i=1,\ldots,N_S} \left|h_{1,i}\right|^2, \frac{2\eta\alpha P_S{}^2}{(1-\alpha)N_0} \max_{i=1,\ldots,N_S} \left|h_{1,i}\right| \sum_{j=1}^{N_D} \left|h_{2,j}\right|^2 \right)$$

Model #2

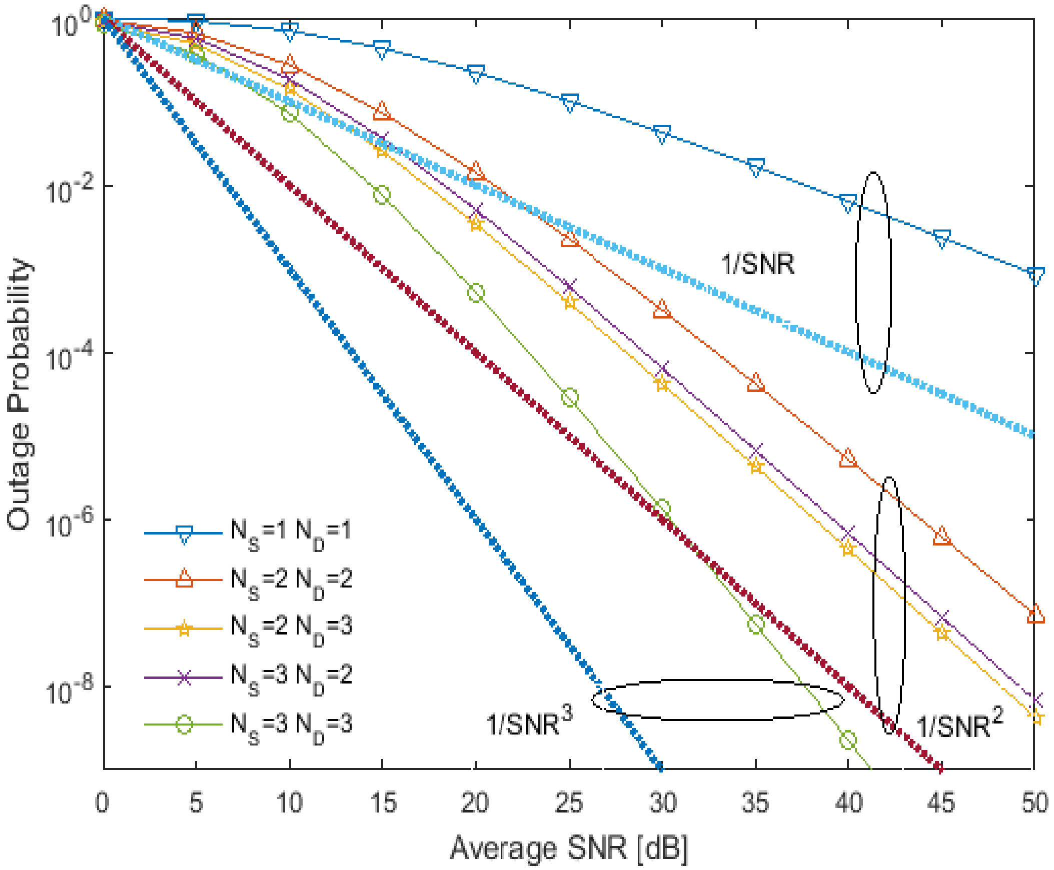
Denote N_t as the number of truncated terms in the series, we can approximate

$$e^{x}=\sum_{k=0}^{\infty}\frac{x^{k}}{k!} \quad\Rightarrow\quad e^{-\frac{b/\lambda_2}{x}}=\sum_{k=0}^{\infty}\frac{(-1)^{k}}{k!}\left(\frac{b/\lambda_2}{x}\right)^{k}$$

$$\mathrm{OP}\approx 1-\sum_{i=1}^{N_S}\sum_{j=0}^{N_D-1}\sum_{k=0}^{N_t}\frac{(-1)^{i+k-1}}{j!k!}\binom{N_S}{i}\frac{i}{\lambda_1}\left(\frac{\gamma_{th}}{\frac{2\varepsilon\alpha P_S\lambda_2}{(1-\alpha)N_0}}\right)^{k+j}$$

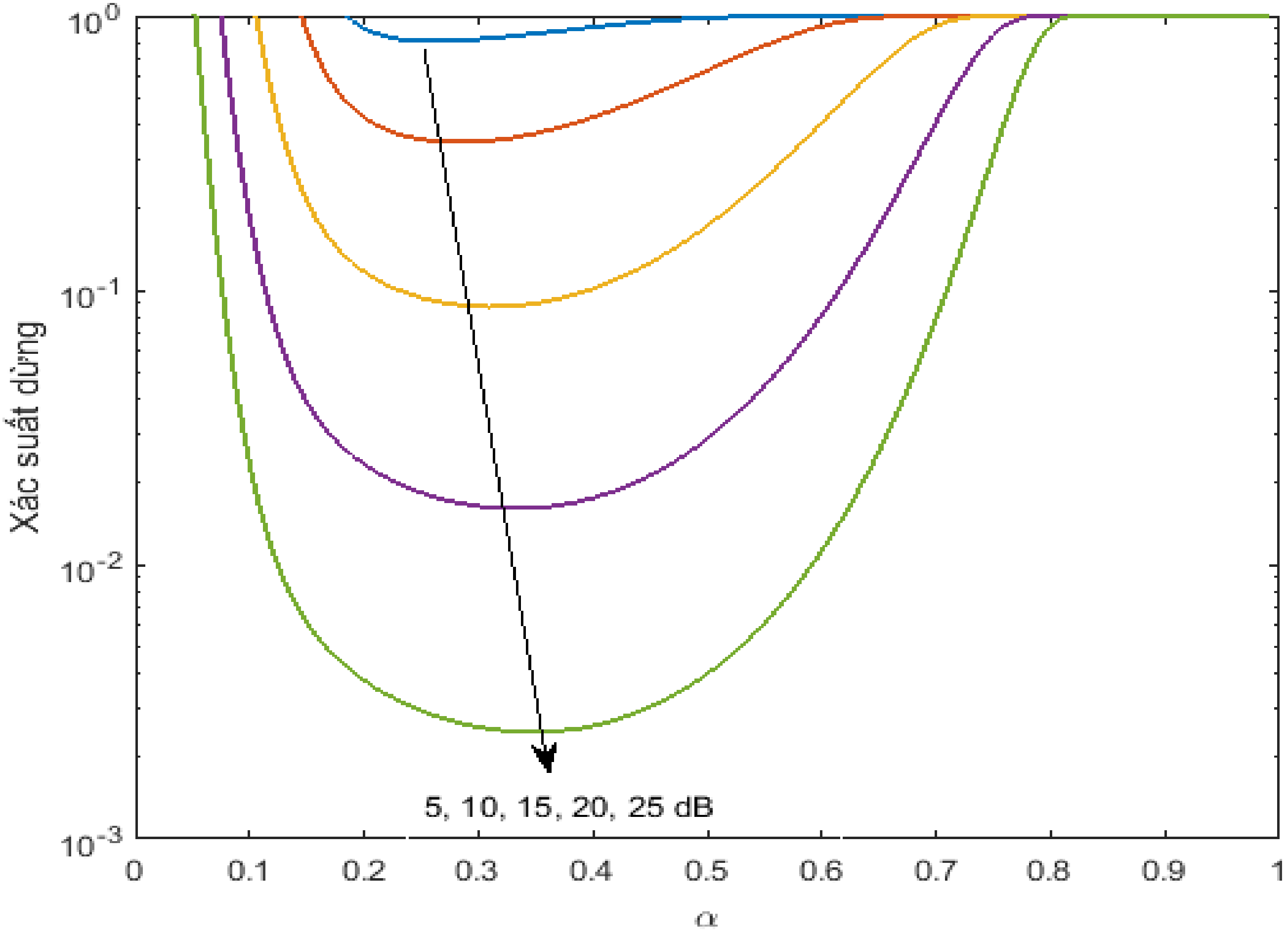
$$\times\left[\frac{(-1)^{j+k}}{(j+k-1)!}\left(\frac{i}{\lambda_1}\right)^{j+k-1}\mathrm{Ei}\left(-\frac{i}{\lambda_1}\frac{\gamma_{th}}{\frac{P_S}{N_0}}\right)+\frac{e^{-\frac{i}{\lambda_1}\frac{\gamma_{th}}{\frac{P_S}{N_0}}}}{\left(\frac{\gamma_{th}}{\frac{P_S}{N_0}}\right)^{j+k-1}}\sum_{\ell=0}^{j+k-2}\frac{(-1)^{\ell}\left(\frac{i}{\lambda_1}\right)^{\ell}\left(\frac{\gamma_{th}}{\frac{P_S}{N_0}}\right)^{\ell}}{(j+k-1)(j+k-2)\ldots(j+k-1-\ell)}\right]$$

Model #2



The system achieves full diversity

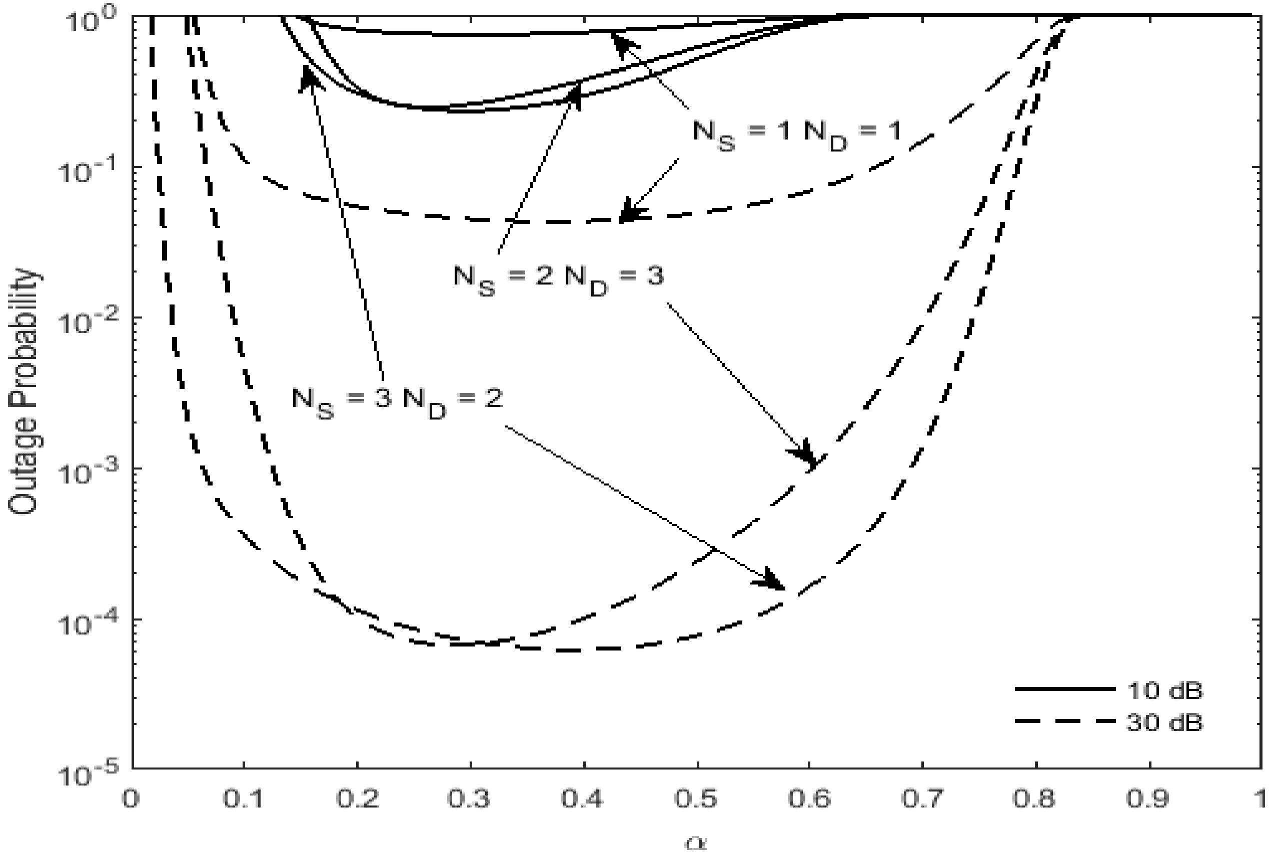
Model #2



Increasing of average SNRs will increase the optimum value of α

Model #2

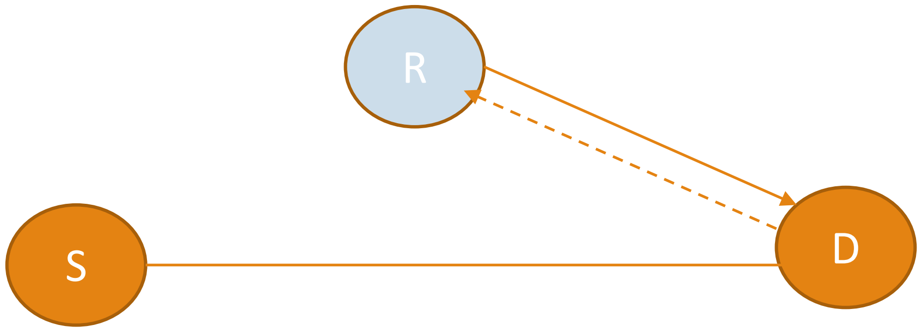
α is a complex function of number of transmit antenna and receive antenna as well as average SNR



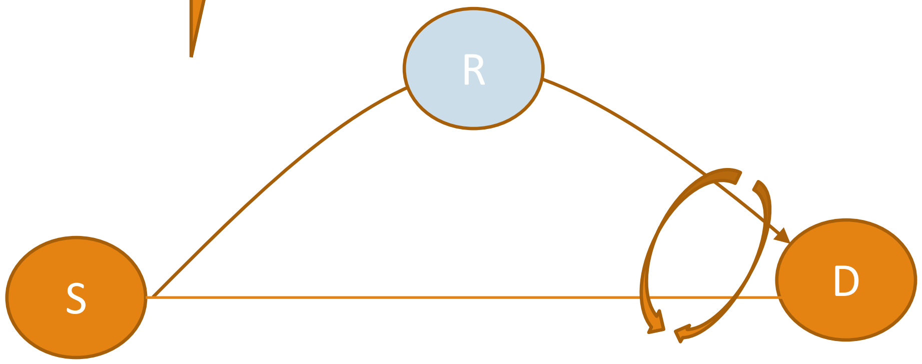
Conclusion

- ❑ Cooperative communication using relays:
  - to extend coverage of wireless networks
  - to improve the network performance
- ❑ Energy harvesting
  - to prolong network lifetime.
  - to solve the fairness in relay selection

To be candidate for next generation wireless networks.



EH based Incremental relaying networks



EH based Distributed Switch-and-Stay Combining Networks

Thank you for your attention