RF Energy Harvesting for Future Communications

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Outline

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

Direct Transmission

MIMO

- Outage Probability
  \[
  \Pr[\log_2(1 + \gamma) < R] = \Pr(\gamma < \gamma_{th} = 2^R - 1) = 1 - \exp\left(-\frac{\gamma_{th}}{\bar{\gamma}}\right)
  \]

- 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

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

Model #1

Time switching receiver mechanism

<table>
<thead>
<tr>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha T$</td>
<td>$\frac{(1-\alpha)T}{2}$</td>
<td>$\frac{(1-\alpha)T}{2}$</td>
</tr>
</tbody>
</table>

- 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 \( \alpha T \)
  \[ E_R = \varepsilon \alpha P_s |h_1|^2 T \]

- The transmit power of the relay
  \[ P_2 = \frac{E_R}{(1 - \alpha)T/2} = \frac{2\varepsilon \alpha P_1 |h_1|^2}{1 - \alpha} \]

- The instantaneous signal-to-noise ratio (SNR) of the first hop and second hop
  \[ 
  \gamma_1 = \frac{P_1 |h_{1,k}|^2}{N_0} \\
  \gamma_2 = \frac{P_2 |h_2|^2}{N_0} = \frac{2\varepsilon \alpha P_1 |h_{1,k}|^2 |h_2|^2}{(1 - \alpha)N_0} 
  \]

\[ \gamma_2 = \min(\gamma_1, \gamma_2) = \min \left( \frac{P_1 |h_{1,k}|^2}{N_0}, \frac{2\varepsilon \alpha P_1 |h_{1,k}|^2 |h_2|^2}{(1 - \alpha)N_0} \right) \]
Model #1

The System Outage Probability

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

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

\[ \approx 1 - \int_0^\infty e^{-\left( \frac{k}{\lambda_1} + \frac{h_1^2}{\lambda_2} \right)} \, dx \]

\[ \approx 1 - \sqrt{\frac{\gamma_{th} (1 - \alpha) N_0 \lambda_1}{2 \varepsilon \alpha P_1 \lambda_2}} \text{BesselK} \left[ 1, 2 \sqrt{\frac{\gamma_{th} (1 - \alpha) N_0}{2 \varepsilon \alpha P_1 \lambda_1 \lambda_2}} \right] \]
The relay having the highest harvested energy among $N$ available relays will be the forwarder of the next hop.

The harvested energy of $R_k$ during energy harvesting time $\alpha T$

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

The selected relays is chosen as

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

The system outage probability

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

- 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.

<table>
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<tr>
<th>Settings</th>
<th>Value</th>
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<tbody>
<tr>
<td>Target transmission rate [bits/sec/Hz]</td>
<td>1</td>
</tr>
<tr>
<td>Energy harvesting efficiency</td>
<td>0.75</td>
</tr>
<tr>
<td>Path loss exponent</td>
<td>3</td>
</tr>
<tr>
<td>S-R distance</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Model #1

- OP approaches 1 since $\alpha > 0.9$
- OP reaches the minimum value since $\alpha \sim 0.39$
- The minimum OP will depend on $d$ and $R$

Outperforms the direct transmission, i.e., 5-10 dB gain depending on the number of relays.
Model #2

Source: Transmit Antenna Selection

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

Destination: Maximal Ratio Combining
Model #2

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

$$e^x = \sum_{k=0}^{\infty} \frac{x^k}{k!}$$

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

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

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

The system achieves full diversity
Increasing of average SNRs will increase the optimum value of $\alpha$. 

Model #2
Model #2

$\alpha$ 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

EH based Incremental relaying networks

EH based Distributed Switch-and-Stay Combining Networks

To be candidate for next generation wireless networks.
Thank you for your attention