On the Feasibility of *Full-Duplex Relaying* Powered by *Wireless Energy Transfer*

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System Model

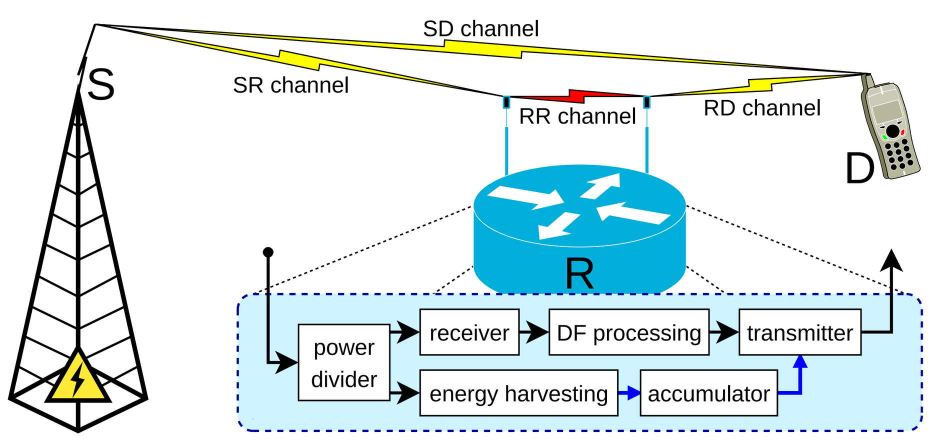

Fig. 1. Two-hop full-duplex relay link powered by wireless energy transfer.

Energy Harvesting and Usage in the Relay

When a portion $\alpha \in [0,1]$ of the original received RF signal is used for power-splitting-based energy harvesting, the harvested energy per second at the relay node is given by

$$p_{\mathrm{H}} = \eta\alpha\left(p_{\mathrm{S}}|h_{\mathrm{SR}}|^2 + p_{\mathrm{R}}|h_{\mathrm{RR}}|^2 + \tilde{\sigma}_{\mathrm{R}}^2\right),$$

where η represents conversion and utilization efficiency.

When the relay consumes a portion $\beta \in [0,1]$ of the harvested energy, its transmission power can be solved as

$$p_{\mathrm{R}} = \beta\, p_{\mathrm{H}} = \frac{\alpha\beta\eta\left(p_{\mathrm{S}}|h_{\mathrm{SR}}|^2 + \tilde{\sigma}_{\mathrm{R}}^2\right)}{1 - \alpha\beta\eta\,|h_{\mathrm{RR}}|^2}.$$

- We cannot directly presume that the optimal setting p_{R}^* would be the maximum one (i.e., $\beta^* = 1$).
- In fact, $p_{\mathrm{R}}^* < p_{\mathrm{H}}$ is often the case when power p_{H} can be drawn from a battery or any external source instead of energy harvesting.

Signal-to-Interference-and-Noise Ratios

The effective end-to-end link SINR of the system is given by

$$\Gamma_{\mathrm{SRD}} = \min\{\Gamma_{\mathrm{SR}}, \Gamma_{\mathrm{RD}}\},$$
$$\Gamma = \Gamma(p_{\mathrm{S}}, \alpha, \beta) = \max\{\Gamma_{\mathrm{SRD}}, \Gamma_{\mathrm{SD}}\},$$

where

- SINR at the relay receiver:
$$\Gamma_{\mathrm{SR}} = \frac{p_{\mathrm{S}}\gamma_{\mathrm{SR}}}{p_{\mathrm{R}}\gamma_{\mathrm{RR}} + \frac{1}{1-\alpha}}.$$
- SINR at the destination receiver, Γ_{RD}, depends on the way how it processes the superposition of direct and relayed signals:

a) $\Gamma_{\mathrm{RD}} \geq \Gamma_{\mathrm{RD}}^{\mathrm{lb}} = \dfrac{p_{\mathrm{R}}\gamma_{\mathrm{RD}}}{p_{\mathrm{S}}\gamma_{\mathrm{SD}} + 1}$,

b) $\Gamma_{\mathrm{RD}} \leq \Gamma_{\mathrm{RD}}^{\mathrm{ub}} = p_{\mathrm{R}}\gamma_{\mathrm{RD}} + p_{\mathrm{S}}\gamma_{\mathrm{SD}}$,

c) $\Gamma_{\mathrm{RD}} \to \Gamma_{\mathrm{RD}}^{\mathrm{ref}} = \Gamma_{\mathrm{RD}}^{\mathrm{lb}}\big|_{\gamma_{\mathrm{SD}}=0} = \Gamma_{\mathrm{RD}}^{\mathrm{ub}}\big|_{\gamma_{\mathrm{SD}}=0}$,

d) $\Gamma_{\mathrm{SD}} = \dfrac{p_{\mathrm{S}}\gamma_{\mathrm{SD}}}{p_{\mathrm{R}}\gamma_{\mathrm{RD}} + 1}$.

We set $p_{\mathrm{S}} = 1$ in the analysis because $p_{\mathrm{S}}^* = 1$ trivially.

Research Problem

- How much can actually be gained by taking advantage of 'self-energy recycling' [12] in the full-duplex relay link?
- Is complicated coherent combining for direct and relayed transmissions much better than simple selective relaying?
- When full-duplex relaying that is powered by wireless energy transfer can outperform plain direct transmission?
- Can the system gain anything by reducing source transmission power instead of constantly using its maximum?
- What is the interplay between optimizing receive-side energy harvesting and transmission power consumption?

Optimize the achievable transmission rate from the source to the destination, namely $R = \log_2(1+\Gamma)$ [bit/s/Hz]:

$$\Gamma^* = \max_{p_{\mathrm{S}},\alpha,\beta} \Gamma(p_{\mathrm{S}}, \alpha, \beta) \text{ subject to } \begin{cases} 0 \leq p_{\mathrm{S}} \leq 1, \\ 0 \leq \alpha \leq 1, \\ 0 \leq \beta \leq 1, \end{cases}$$

where

p_{S} – transmission power in the source node
α – power splitting factor for energy harvesting
β – power consumption portion in the relay

Analytical Results

Result 1: *One may reduce the exact expression of* p_{R} *to*

$$p_{\mathrm{R}} \simeq \alpha\beta\eta\left(p_{\mathrm{S}}|h_{\mathrm{SR}}|^2 + \tilde{\sigma}_{\mathrm{R}}^2\right)$$

that is a very tight lower bound in practical scenarios.

Result 2: *Given any constant* α *such that* $0 \leq \alpha \leq 1$,

$$\beta^* = \arg\max_{0\leq\beta\leq1} \Gamma(p_{\mathrm{S}}^*, \alpha, \beta) = \min\left\{1, \sqrt{a^2+b} - a\right\}$$

where

$$a = \frac{1}{2}\begin{cases} \dfrac{\gamma_{\mathrm{RD}}/(1-\alpha)}{(\alpha\,\gamma_{\mathrm{SR}}\,\eta\sigma_{\mathrm{R}}^2)\gamma_{\mathrm{RR}}\gamma_{\mathrm{RD}}}, & \Gamma_{\mathrm{RD}} \to \Gamma_{\mathrm{RD}}^{\mathrm{lb}}, \\ \dfrac{\gamma_{\mathrm{RD}}/(1-\alpha) + \gamma_{\mathrm{RR}}\gamma_{\mathrm{SD}}}{(\alpha\,\gamma_{\mathrm{SR}}\,\eta\sigma_{\mathrm{R}}^2)\gamma_{\mathrm{RR}}\gamma_{\mathrm{RD}}}, & \Gamma_{\mathrm{RD}} \to \Gamma_{\mathrm{RD}}^{\mathrm{ub}}, \end{cases}$$

$$b = \begin{cases} \dfrac{\gamma_{\mathrm{SR}}(\gamma_{\mathrm{SD}}+1)}{(\alpha\,\gamma_{\mathrm{SR}}\,\eta\sigma_{\mathrm{R}}^2)^2\gamma_{\mathrm{RR}}\gamma_{\mathrm{RD}}}, & \Gamma_{\mathrm{RD}} \to \Gamma_{\mathrm{RD}}^{\mathrm{lb}}, \\ \dfrac{\gamma_{\mathrm{SR}} - \gamma_{\mathrm{SD}}/(1-\alpha)}{(\alpha\,\gamma_{\mathrm{SR}}\,\eta\sigma_{\mathrm{R}}^2)^2\gamma_{\mathrm{RR}}\gamma_{\mathrm{RD}}}, & \Gamma_{\mathrm{RD}} \to \Gamma_{\mathrm{RD}}^{\mathrm{ub}}, \end{cases}$$

provided that $(1-\alpha)\gamma_{\mathrm{SR}} > \gamma_{\mathrm{SD}}$.

Result 3: *When* $\gamma_{\mathrm{RR}} = 0$,

$$\alpha^* = \begin{cases} \dfrac{\gamma_{\mathrm{SD}}+1}{\beta\,\gamma_{\mathrm{RD}}\,\eta\sigma_{\mathrm{R}}^2 + \gamma_{\mathrm{SD}} + 1}, & \Gamma_{\mathrm{RD}} \to \Gamma_{\mathrm{RD}}^{\mathrm{lb}}, \\ \dfrac{\gamma_{\mathrm{SR}} - \gamma_{\mathrm{SD}}}{\gamma_{\mathrm{SR}}(\beta\,\gamma_{\mathrm{RD}}\,\eta\sigma_{\mathrm{R}}^2 + 1)}, & \Gamma_{\mathrm{RD}} \to \Gamma_{\mathrm{RD}}^{\mathrm{ub}}, \end{cases}$$

provided that $\gamma_{\mathrm{SR}} > \gamma_{\mathrm{SD}}$.

Result 4: *We have* $\beta^* = 1$ *when* $\alpha = \alpha^*$.

Result 5: *When* $\gamma_{\mathrm{RR}} = 0$ *and* $\Gamma_{\mathrm{RD}} \to \Gamma_{\mathrm{RD}}^{\mathrm{lb}}$, $\Gamma_{\mathrm{SRD}}^* > \gamma_{\mathrm{SD}}$ *if*

$$\gamma_{\mathrm{SD}} < \chi_{\mathrm{SD}} = \sqrt{c^2 + d} - c,$$

where $c = \frac{1}{2}(\beta\,\gamma_{\mathrm{RD}}\,\eta\sigma_{\mathrm{R}}^2 + 1)$ *and* $d = \beta\,\gamma_{\mathrm{SR}}\gamma_{\mathrm{RD}}\,\eta\sigma_{\mathrm{R}}^2$. *When* $\Gamma_{\mathrm{RD}} \to \Gamma_{\mathrm{RD}}^{\mathrm{ub}}$, $\Gamma_{\mathrm{SRD}}^* \geq \gamma_{\mathrm{SD}}$ *for all* $\gamma_{\mathrm{SD}} \leq \gamma_{\mathrm{SR}}$.

Numerical Results

Self-energy Recycling

The extra power gained from 'self-energy recycling':

$$\Delta p_{\mathrm{R}} = \frac{p_{\mathrm{R}} - p_{\mathrm{R}}|_{h_{\mathrm{RR}}=0}}{p_{\mathrm{R}}|_{h_{\mathrm{RR}}=0}} = \frac{\alpha\beta\eta\,|h_{\mathrm{RR}}|^2}{1 - \alpha\beta\eta\,|h_{\mathrm{RR}}|^2}.$$

- Recycling allows the relay to use at best only 1% higher power than without it when the attenuation in the self-interference channel is as poor as 20 dB.
- Despite efficient analog cancellation, successful information decoding requires much better physical isolation to begin with such that the gain is vanishing.

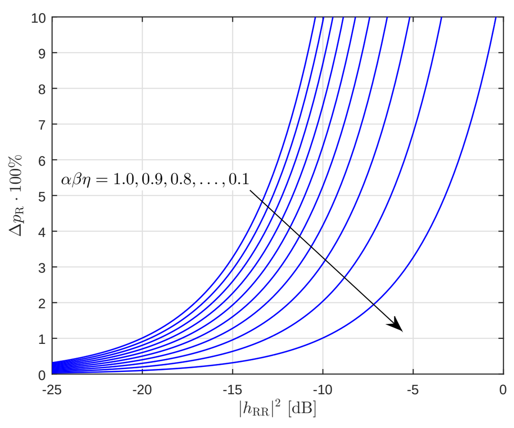

Fig. 2. The amount of extra transmission power gained from 'self-energy recycling' in terms of physical isolation in the self-interference channel.

Optimal Energy Harvesting and Usage

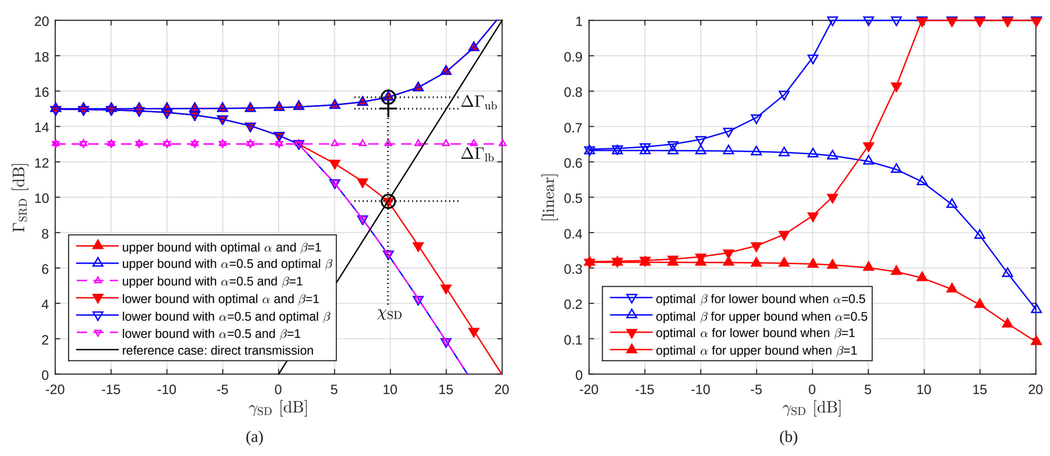

Fig. 3. (a) Effective end-to-end link SINRs with (b) the corresponding optimal parameter settings α^* and β^* in terms of the strength of the direct link when $p_{\mathrm{S}} = 1$, $\gamma_{\mathrm{SR}} = \gamma_{\mathrm{RR}} = 55$ dB, $\gamma_{\mathrm{RD}} = 30$ dB, and $\eta\sigma_{\mathrm{R}}^2 = -65$ dBm.

SINR Gain or Loss from Direct Link

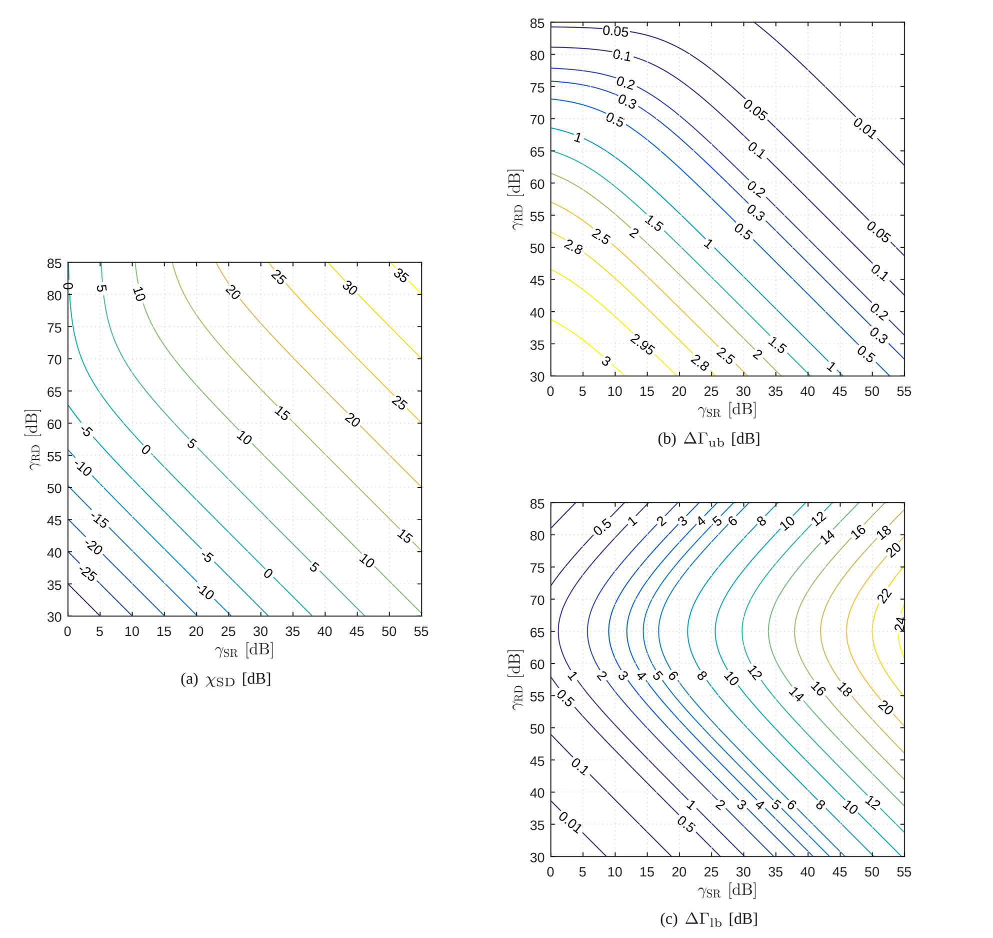

Fig. 4. (a) The cross-over point between relaying and direct transmission and the corresponding (b) SINR gain achieved by coherently combining the signals from the source and the destination or (c) SINR loss caused by the direct link if it is treated as mere interference when $\gamma_{\mathrm{RR}} = 0$ and $\eta\sigma_{\mathrm{R}}^2 = -65$ dBm.

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