Spring 2022 – Cooperative Communication and Networking

Intelligent Reflecting Surface vs. Decode-and-Forward: How Large Surfaces are Needed to Beat Relaying? (Redo)

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Abstract

此期末報告愈重現 2020 年 2 月發表於 *IEEE Wireless Communications Letters* 的文章，"Intelligent Reflecting Surface Versus Decode-and-Forward: How Large Surfaces are Needed to Beat Relaying?[1]" 該論文目前累積被引用次數有 367 次。文中假設在智能反射板(Reconfigurable Intelligence Surface, RIS)能做到完美相位偏移(ideal phase-shifting)且在平坦衰減通道(frequency-flat fading channels)的條件下，RIS 需要多少個被動反射元件(discrete element)才能達到跟傳統的 Decode-and-Forward (DF) relaying 一樣的效果，此處的效果定義為最小化總傳輸功率(transmit power)及最大化能源效率(energy efficiency)。從模擬結果觀察到，只有在要求非常高鏈路頻譜效率(bit/s/Hz)或有極大反射面積的情況下，RIS 才有辦法勝過 DF relaying。

[1] E. Björnson, Ö. Özdogan and E. G. Larsson, "Intelligent Reflecting Surface Versus Decode-and-Forward: How Large Surfaces are Needed to Beat Relaying?," in IEEE Wireless Communications Letters, vol. 9, no. 2, pp. 244-248, Feb. 2020.

1. Introduction

智能反射板(Reconfigurable Intelligence Surface, 簡稱 RIS)，是一種能將平面波(plane wave)反射成一個波束(beam)的平面[2]，RIS 由多個被動元件(discrete components)組成，透過即時調整(real-time reconfigure)相位(phase)的方式將波變成波束並反射到指定的方向，每個元件大小約是次波長(sub-wavelength)[3] [4]，理想上只需要被動反射元件即可，但實際上在調整相位偏移時還是需要用到一些功率放大器等主動元件(active components)。

為什麼拿 RIS 跟 relay 比較? 因為 IRS 的使用時機跟 half-duplex relay 類似[5]，二者最主要的不同之處在於，relay 是主動處理訊號並放大重傳訊號，而 RIS 是被動地將訊號反射形成波束。此外之前有類似研究是拿 AF relaying 跟 RIS 做能源效率上的比較[6]，該研究結果呈現 RIS 完勝 AF relaying，但我們知道 DF relaying 在可達訊息率(achievable rate)比較上亦完勝 AF relaying，所以在 relay 跟 RIS 的比較上，DF relaying 應該是個更好的基準[7]。
為什麼大小很重要? 因為 RIS 所受到的路徑損耗(pathloss)，是受整體大小影響，而不是受元件個數或個別元件大小影響[8]，RIS 越大所受 pathloss 也越大，所以本文假設每個 RIS 元件都跟 relay 的天線一樣大。

為了呈現盡可能公平地比較結果，會先找出最佳傳輸功率(optimal transmit powers)、RIS 最佳元件個數(optimal number of elements)、並假設有完美相位偏移(ideal phase-shifting)及考慮有利 RIS 的平坦衰減通道(frequency-flat fading channels)設定。

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[2] J. Huang, Reflectarray Antenna. Hoboken, NJ, USA: Wiley, 2005.
[3] D. Headland et al., “Terahertz reflectarrays and nonuniform meta-surfaces,” IEEE J. Sel. Topics Quantum Electron., vol. 23, no. 4, Jul./Aug. 2017, Art. no. 8500918.
[4] Sub-wavelength structure, a structure unit which is smaller than wavelength and thus induces some specific properties that can’t be explained by classic electromagnetic theorem.
[5] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, “Cooperative diversity in wireless networks: Efficient protocols and outage behavior,” IEEE Trans. Inf. Theory, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.
[6] C. Huang, A. Zappone, G. C. Alexandropoulos, M. Debbah, and C. Yuen, “Reconfigurable intelligent surfaces for energy efficiency in wireless communication,” IEEE Trans. Wireless Commun., vol. 18, no. 8, pp. 4157–4170, Aug. 2019.
[7] G. Farhadi and N. C. Beaulieu, “On the ergodic capacity of multi-hop wireless relaying systems,” IEEE Trans. Wireless Commun., vol. 8, no. 5, pp. 2286–2291, May 2009.
[8] O. Özdogan, E. Björnson, and E. G. Larsson, “Intelligent reflecting surfaces: Physics, propagation, and pathloss modeling,” CoRR, 2019.

2. System Model

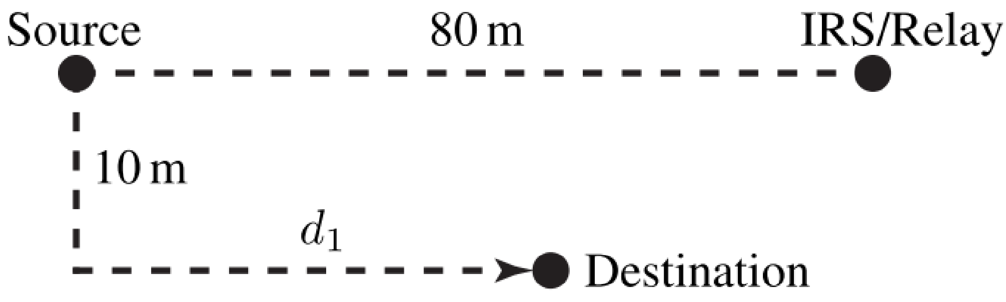


Fig. 3. The simulation setup where d_1 is a variable.

本文考慮單天線發訊(single-antenna source)跟單天線收訊(single-antenna destination)間的情況。假設的確定性通道(deterministic flat-fading channels)以 $h_{sd} \in \mathbb{C}$ 表示。所以接收端收到的訊號即為 $y = h_{sd}\sqrt{p} \cdot s + n$, p是傳輸功率(transmit power)，s是愈傳輸的單位功率訊號(unit-power information signal)，$n \sim \mathcal{N}_{\mathbb{C}}(0, \sigma^2)$是雜訊(complex Gaussian noise)。為了表示簡潔起見把天線增益包含在通道內就不另外標示，則此單輸入單輸出(single-input single-output, SISO)的通道容量(channel capacity)可以表示為

$$R_{\mathrm{SISO}} = \log_2\left(1 + \frac{p|h_{\mathrm{sd}}|^2}{\sigma^2}\right)$$

由 RIS 輔助傳輸的訊號為 $y = (h_{sd} + h_{sr}^T \cdot \Theta \cdot h_{rd})\sqrt{p} \cdot s + n$, 此處$p, s, n$的假設都跟 SISO 一樣，從 source 到 RIS 的通道以 $h_{sd} \in \mathbb{C}^N$ 表示，$[h_{sd}]_n$ 表示第 n 個元件所經通道，從 RIS 到 destination 的通道以 $h_{rd} \in \mathbb{C}^N$ 表示，RIS 由對角矩陣 $\Theta = \alpha \cdot diag(e^{j\theta_1}, \dots, e^{j\theta_N})$ 表示，α ∈ (0, 1] 是反射係數的固定振幅，$\theta_1, \dots, \theta_N$ 是可被 RIS 調整的相位變數，本文假設傳輸中 RIS 可以做到完美相位偏移。則 RIS 輔助傳輸的通道容量可以表示為

$$\begin{aligned} R_{\mathrm{IRS}}(N) &= \max_{\theta_1,\dots,\theta_N} \log_2\left(1 + \frac{p|h_{\mathrm{sd}} + \mathbf{h}_{\mathrm{sr}}^{\mathrm{T}}\boldsymbol{\Theta}\mathbf{h}_{\mathrm{rd}}|^2}{\sigma^2}\right) \\ &= \log_2\left(1 + \frac{p(|h_{\mathrm{sd}}| + \alpha\sum_{n=1}^{N} |[\mathbf{h}_{\mathrm{sr}}]_n\, [\mathbf{h}_{\mathrm{rd}}]_n|)^2}{\sigma^2}\right) \end{aligned}$$

由 DF relay 輔助傳輸的訊號分二個階段，第一個階段，source 傳送訊號給 destination 及 relay，此時 destination 收到的訊號為 $y_{1d} = h_{sd}\sqrt{p_1} \cdot s + n_{1d}$，而 relay 收到的訊號為 $y_{1r} = h_{sr}\sqrt{p_1} \cdot s + n_{1r}$，第二個階段 relay 傳送訊號給 destination，此時 destination 收到的訊號為 $y_{2d} = h_{rd}\sqrt{p_2} \cdot s + n_{2d}$，$h_{sd}, h_{rd} \in \mathbb{C}$ 分別是 source 及 relay 到 destination 所經通道，$n_{1d}, n_{1r}, n_{2d} \sim \mathcal{N}_{\mathbb{C}}(0, \sigma^2)$是所受雜訊。透過 Max Ratio Combining (MRC)合併二個階段收到的訊號，可得 DF relay 輔助傳輸的通道容量為

$$R_{\mathrm{DF}} = \frac{1}{2}\log_2\left(1 + \min\left(\frac{p_1|h_{\mathrm{sr}}|^2}{\sigma^2}, \frac{p_1|h_{\mathrm{sd}}|^2}{\sigma^2} + \frac{p_2|h_{\mathrm{rd}}|^2}{\sigma^2}\right)\right)$$

3. Analytical Performance Comparison

先考慮從理論角度比較三種狀況下的 achievable rates (或稱 spectral efficiencies)，觀察上面的式子會發現，achievable rate 只跟 channel amplitude 有關、跟各自的 phase 無關。

為簡化表示式，把振幅 $|h_{sd}|$ 以 $\sqrt{\beta_{sd}}$ 表示，$|h_{sr}|$ 以 $\sqrt{\beta_{sr}}$ 表示，$|h_{rd}|$ 以 $\sqrt{\beta_{rd}}$ 表示，$\frac{1}{N}\sum_{n=1}^{N} |[h_{sd}]_n\,[h_{rd}]_n|$ 以 $\sqrt{\beta_{IRS}}$ 表示，所以 SISO, RIS, DF 的通道容量變成如下表示式，

$$R_{\mathrm{SISO}} = \log_2\left(1 + \frac{p\beta_{\mathrm{sd}}}{\sigma^2}\right)$$

$$R_{\mathrm{IRS}}(N) = \log_2\left(1 + \frac{p(\sqrt{\beta_{\mathrm{sd}}} + N\alpha\sqrt{\beta_{\mathrm{IRS}}})^2}{\sigma^2}\right)$$

$$R_{\mathrm{DF}} = \frac{1}{2}\log_2\left(1 + \min\left(\frac{p_1\beta_{\mathrm{sr}}}{\sigma^2}, \frac{p_1\beta_{\mathrm{sd}}}{\sigma^2} + \frac{p_2\beta_{\mathrm{rd}}}{\sigma^2}\right)\right)$$

A. Optimal achievable rate

首先是 DF relaying 的最佳傳輸功率配置，當傳輸功率 $p_1 = 2p\beta_{rd} \,/\, \beta_{sr} + \beta_{rd} - \beta_{sd}$，$p_2 = 2p(\beta_{sr} - \beta_{sd}) \,/\, \beta_{sr} + \beta_{rd} - \beta_{sd}$ 且 $\beta_{sd} \le \beta_{sr}$ 的時候，可達到最大通道容量如下，

$$R_{\mathrm{DF}} = \frac{1}{2}\log_2\left(1 + \frac{2p\beta_{\mathrm{rd}}\beta_{\mathrm{sr}}}{(\beta_{\mathrm{sr}} + \beta_{\mathrm{rd}} - \beta_{\mathrm{sd}})\sigma^2}\right)$$

再來是 RIS 的最佳元件個數配置，當 $\beta_{sd} > \beta_{sr}$ 的時候，任意 $\mathrm{N} \geq 1$ 都會是最佳解，當 $\beta_{sd} \leq \beta_{sr}$，且 N 滿足下列不等式的時候，可以得到最大通道容量，

$$N > \frac{\sqrt{\left(\sqrt{1 + \frac{2p\beta_{\mathrm{rd}}\beta_{\mathrm{sr}}}{(\beta_{\mathrm{sr}}+\beta_{\mathrm{rd}}-\beta_{\mathrm{sd}})\sigma^2}} - 1\right)\frac{\sigma^2}{p}} - \sqrt{\beta_{\mathrm{sd}}}}{\alpha\sqrt{\beta_{\mathrm{IRS}}}}$$

B. Minimize Tx Power and Total Tx Power Under Rate Constraints

考慮 SISO, RIS, DF relaying 都達到相同 data rate $\bar{R}$，所需傳輸功率關係式分別如下，

$$p_{\mathrm{SISO}} = \left(2^{\bar{R}} - 1\right)\frac{\sigma^2}{\beta_{\mathrm{sd}}}$$

$$p_{\mathrm{IRS}}(N) = \left(2^{\bar{R}} - 1\right)\frac{\sigma^2}{(\sqrt{\beta_{\mathrm{sd}}} + N\alpha\sqrt{\beta_{\mathrm{IRS}}})^2}$$

$$p_{\mathrm{DF}} = \begin{cases} \left(2^{2\bar{R}} - 1\right)\frac{\sigma^2}{\beta_{\mathrm{sd}}} & \text{if } \beta_{\mathrm{sd}} > \beta_{\mathrm{sr}} \\ \left(2^{2\bar{R}} - 1\right)\frac{(\beta_{\mathrm{sr}}+\beta_{\mathrm{rd}}-\beta_{\mathrm{sd}})\sigma^2}{2\beta_{\mathrm{rd}}\beta_{\mathrm{sr}}} & \text{if } \beta_{\mathrm{sd}} \leq \beta_{\mathrm{sr}} \end{cases}$$

有了所需傳輸功率可以推得各自的總功率如下，

$$P_{\mathrm{total}}^{\mathrm{SISO}} = p_{\mathrm{SISO}}/\nu + P_{\mathrm{s}} + P_{\mathrm{d}}$$

$$P_{\mathrm{total}}^{\mathrm{IRS}}(N) = \frac{p_{\mathrm{IRS}}(N)}{\nu} + P_{\mathrm{s}} + P_{\mathrm{d}} + NP_{\mathrm{e}}$$

$$P_{\mathrm{total}}^{\mathrm{DF}} = \frac{p_{\mathrm{DF}}}{\nu} + \frac{1}{2}P_{\mathrm{s}} + P_{\mathrm{d}} + P_{\mathrm{r}}$$

其中 $\nu \in (0,1]$ 是功率放大器的轉換效率，P_s 跟 P_d 是傳送跟接收端的功率消耗，P_e 是 RIS 個別元件功率消耗。給定 data rate $\bar{R}$ 時，最低總功率 $P_{total}^{IRS}(N)$可由下列等式求得，

$$N^{\text{opt}} = \sqrt[3]{\frac{\left(2^{\bar{R}}-1\right)\sigma^2}{\alpha^2 \beta_{\text{IRS}} P_{\text{e}}}} - \frac{1}{\alpha}\sqrt{\frac{\beta_{\text{sd}}}{\beta_{\text{IRS}}}}$$

4. Numerical Performance Comparison

數值模擬的部分，本文採用 3GPP Urban Micro (UMi)的通道增益(channel gain)模型[9]，考慮的載波頻率為 3 GHz，頻寬為 10MHz，雜訊係數為 10dB，相關參數及公式如下，

Table B.1.2.1-1 Summary table of the primary module path loss models

Scenario		Path loss [dB] Note: f_c is given in GHz and distance in meters!	Shadow fading std [dB]	Applicability range, antenna height default values
Indoor Hotspot (InH)	LOS	$PL = 16.9\log_{10}(d) + 32.8 + 20\log_{10}(f_c)$	$\sigma = 3$	3 m < d < 100 m h_{BS}=3-6 m h_{UT}=1-2.5 m
	NLOS	$PL = 43.3\log_{10}(d) + 11.5 + 20\log_{10}(f_c)$	$\sigma = 4$	10 m < d < 150 m h_{BS}= 3-6 m h_{UT}= 1-2.5 m
Urban Micro (UMi)	LOS	$PL = 22.0\log_{10}(d) + 28.0 + 20\log_{10}(f_c)$	$\sigma = 3$	10 m < d_1 < d'_{BP} [1)]
		$PL = 40\log_{10}(d_1) + 7.8 - 18\log_{10}(h'_{BS}) - 18\log_{10}(h'_{UT}) + 2\log_{10}(f_c)$	$\sigma = 3$	d'_{BP} < d_1 < 5000 m [1)] h_{BS}= 10 m [1)], h_{UT}= 1.5 m [1)]

$$\beta(d)\,[\text{dB}] = G_{\text{t}} + G_{\text{r}} + \begin{cases} -37.5 - 22\log_{10}(d/1\,\text{m}) & \text{if LOS} \\ -35.1 - 36.7\log_{10}(d/1\,\text{m}) & \text{if NLOS} \end{cases}$$

下面的圖 2，圖 4(a)，圖 4(b)，圖 5 皆為重現的模擬結果，

[9] Further Advancements for E-UTRA Physical Layer Aspects (Release 9), 3GPP Standard TS 36.814, Mar. 2010.

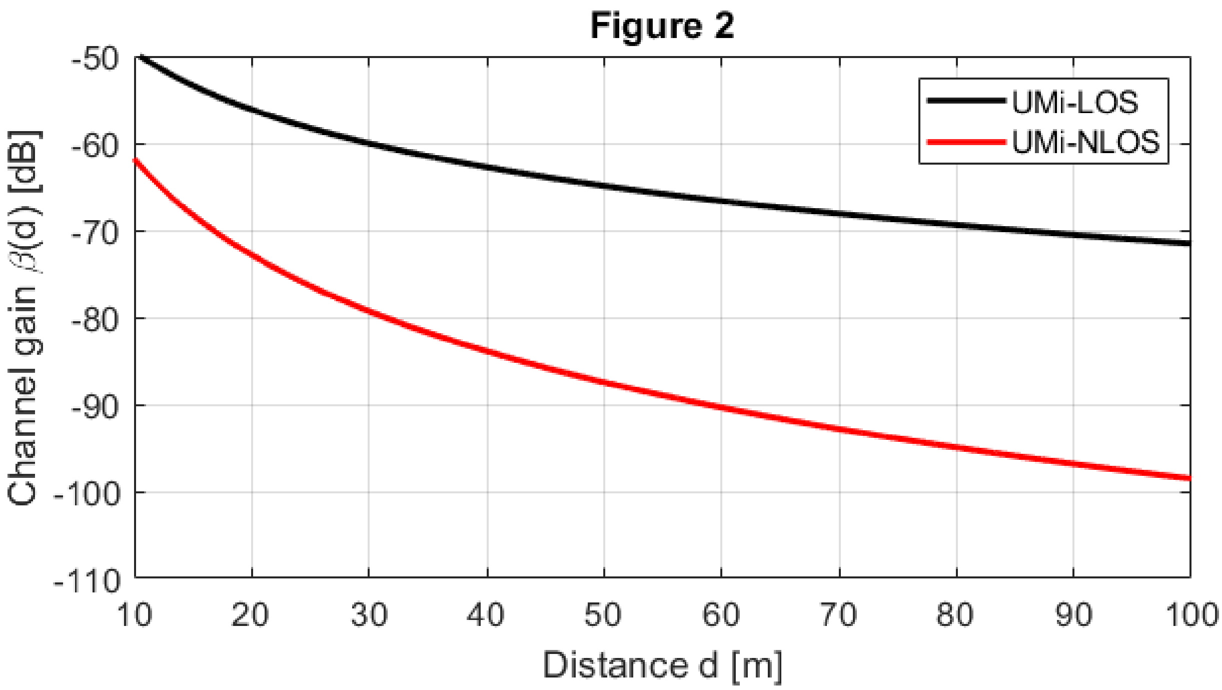


圖 2 說明一個看起來很小的數字如−60 dB，其實是超級大的通道增益，正常的數值會落在−70 到−110 dB 之間。由於 3GPP Urban Micro model 是考慮 10 到 500 公尺的狀況，所以距離 10 公尺以下沒有值存在。

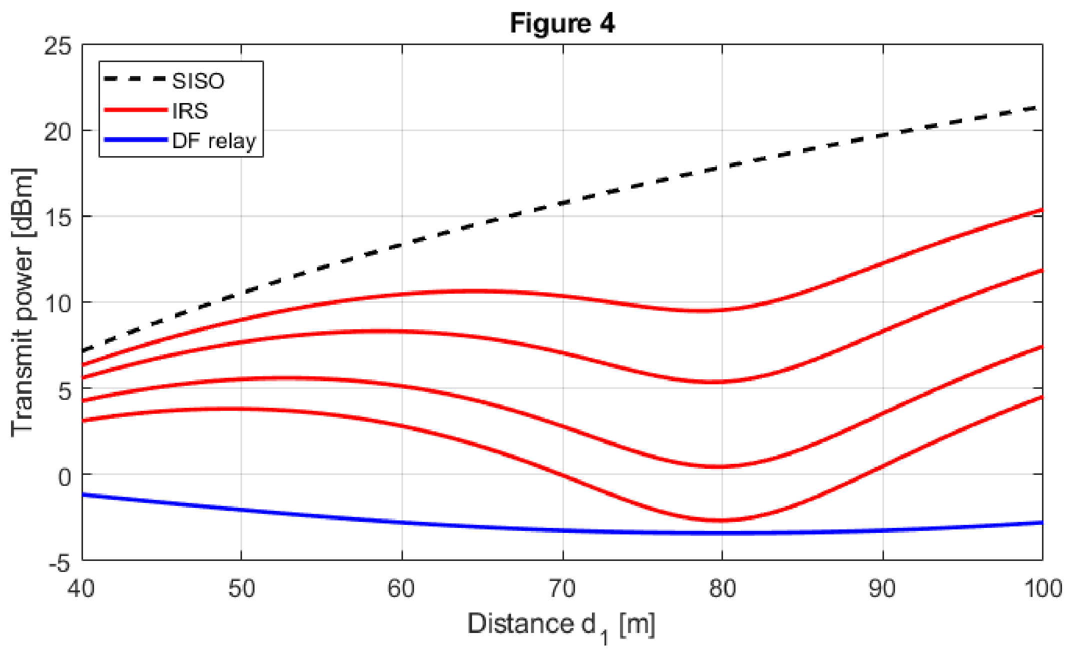


圖 4(a)如上，考慮當 $\bar{R} = 4\ bit/s/Hz$，$\alpha = 1$ 的時候，所需傳輸功率對距離的關係圖，紅色實線由上而下分別是 N = 25, 50, 100, 150，可以發現在此設定下，最佳傳輸距離為 80 公尺，此時 RIS 需要 N = 164 才能勝過 DF relaying，也就是比 DF relay 的 164 倍大的情況。

下圖可以看出當 RIS 有 164 個元件 (N=164) 時，才能在 $\bar{R}=4$ 跟 DF 有相同效果。

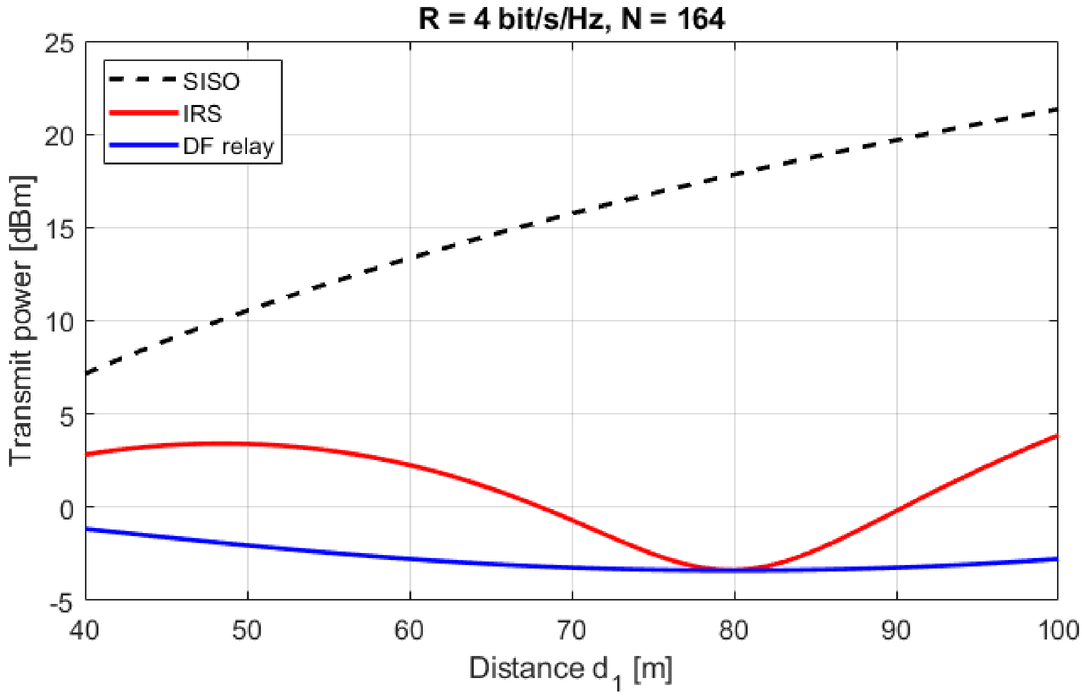
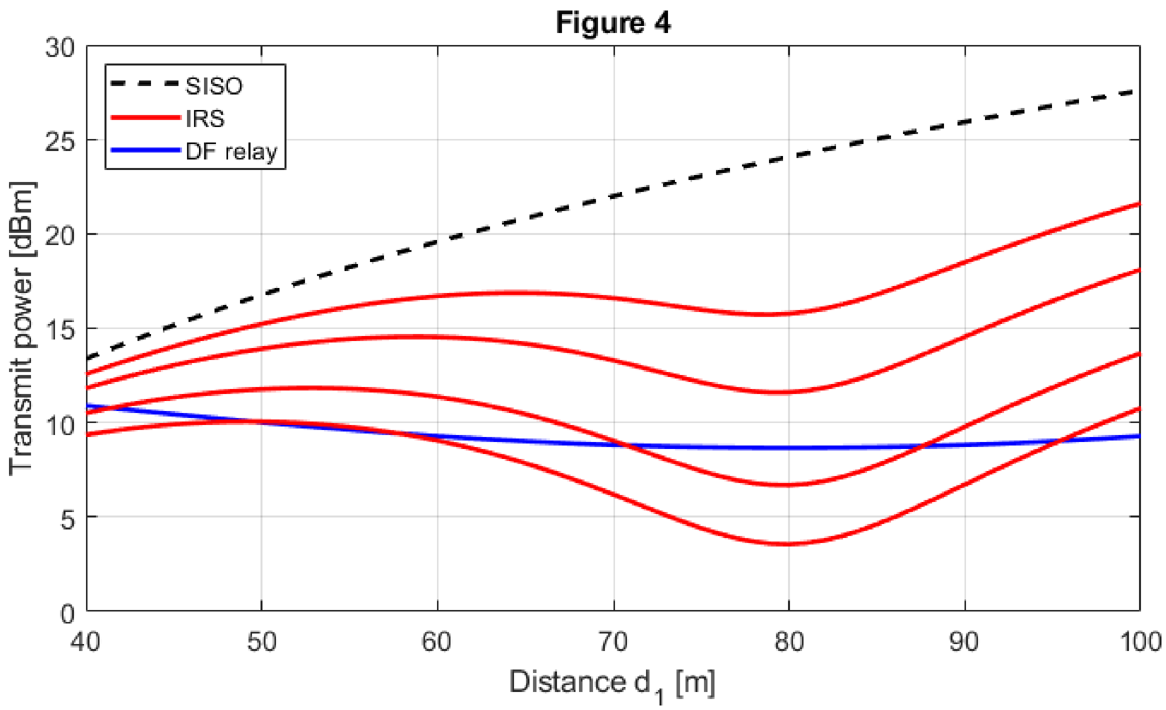
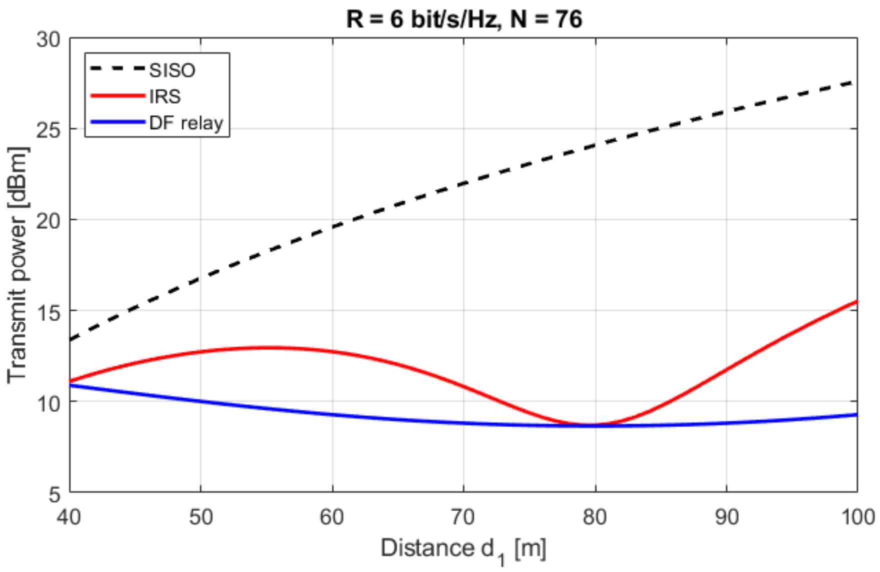


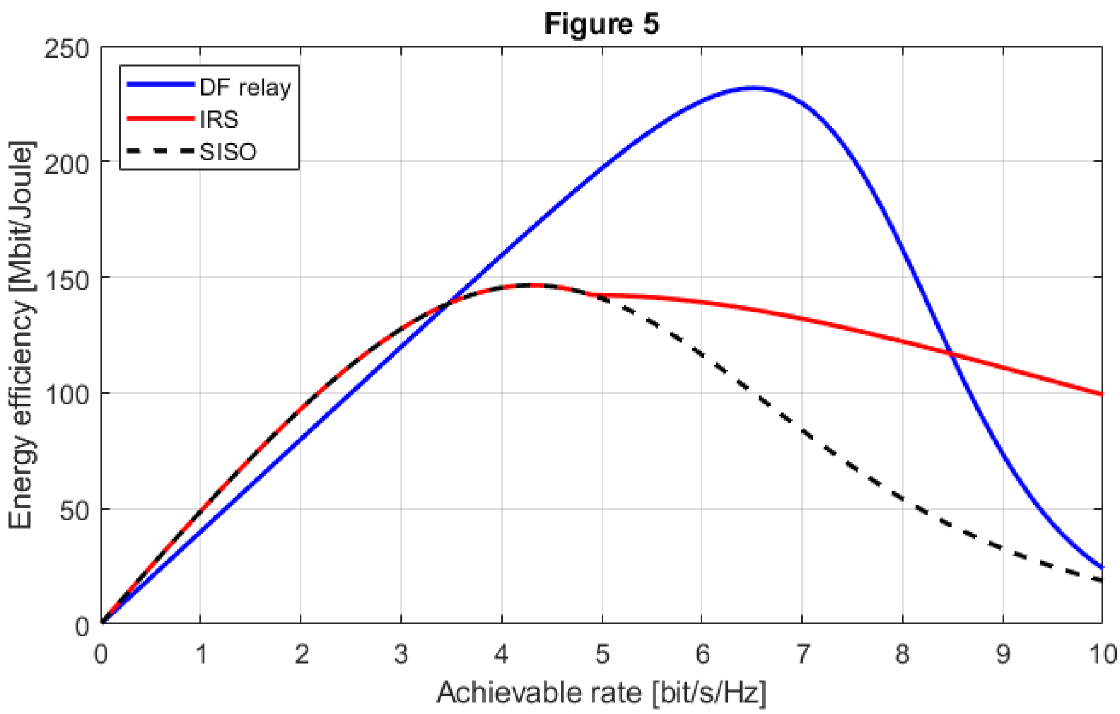
圖 4(b)如下，考慮當 $\bar{R}=6\ bit/s/Hz$，$\alpha=1$ 的時候，所需傳輸功率對距離的關係圖，紅色實線由上而下一樣分別是 N = 25, 50, 100, 150，可以發現在此設定下，最佳傳輸距離一樣為 80 公尺，此時 RIS 需要 N = 76 才能勝過 DF relaying，也就是比 DF relay 的 76 倍大的情況。



下圖可以看出當 RIS 有 76 個元件 (N=76) 時，才能在 $\bar{R} = 6$ 跟 DF 有相同效果。



最後是比較能源效率於圖 5 如下，能源效率定義為 $\mathrm{EE} = \mathrm{B} \cdot \bar{R} \,/\, P_{total}$，考慮 $\nu = 0.5,\ P_s = P_d = P_r = 100\ mW$ ，$P_e = 5\ mW$ 和 $d_1 = 70\ m$ 的情況[10]，SISO 在 $\bar{R} = 0{\sim}3.47$ 時有最好的能源效率，DF relaying 在 $\bar{R} = 3.47{\sim}8.48$ 時有最好的能源效率，當 $\bar{R} < 4.9$ 時，RIS 所需元件個數 $\mathrm{N} < 0$ 不存在，RIS 只有在 $\bar{R} > 8.48$ 時有最好的能源效率。



[10] C. Huang, A. Zappone, G. C. Alexandropoulos, M. Debbah, and C. Yuen, “Reconfigurable intelligent surfaces for energy efficiency in wireless communication,” IEEE Trans. Wireless Commun., vol. 18, no. 8, pp. 4157–4170, Aug. 2019.

為了對 achievable rate 有一個更具體的理解，下表整理常見無線通訊場景的 max rates，

Services / Spec	Max. link spectral efficiency (bit/s/Hz)
Wi-Fi 6 / IEEE 802.11ax	7.5
Digital cable TV / DVB-C 256-QAM	6.33
Wi-Fi 5 / IEEE 802.11ac	5.42
Fixed WiMAX / IEEE 802.16d	4.8
4G cellular / LTE-Advanced	3.75

從表格中可以看出，其實目前常見的無線通訊應用場域都鮮少有 $\bar{R} > 8.48$ 的情況。

5. Conclusion and Discussion

本文比較 RIS 跟 classic repetition-coded DF relaying 的效能表現，考慮 ideal phase-shifting 及 frequency-flat channels 的條件下，RIS 需要幾百個元件才能有足夠競爭力。此外本文選用的是最一般的 DF relay scheme，若是考慮其他更強的 DF Protocol 還達到更高的 achievable rate[11]，使得 DF relaying 更具競爭力。

Reference

[1] E. Björnson, Ö. Özdogan and E. G. Larsson, "Intelligent Reflecting Surface Versus Decode-and-Forward: How Large Surfaces are Needed to Beat Relaying?," in *IEEE Wireless Communications Letters*, vol. 9, no. 2, pp. 244-248, Feb. 2020.

[2] J. Huang, Reflectarray Antenna. Hoboken, NJ, USA: Wiley, 2005.

[3] D. Headland et al., “Terahertz reflectarrays and nonuniform meta-surfaces,” *IEEE J. Sel. Topics Quantum Electron.*, vol. 23, no. 4, Jul./Aug. 2017, Art. no. 8500918.

[11] M. N. Khormuji and E. G. Larsson, “Cooperative transmission based on decode-and-forward relaying with partial repetition coding,” IEEE Trans. Wireless Commun., vol. 8, no. 4, pp. 1716–1725, Apr. 2009.

[4] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[5] C. Huang, A. Zappone, G. C. Alexandropoulos, M. Debbah, and C. Yuen, "Reconfigurable intelligent surfaces for energy efficiency in wireless communication," *IEEE Trans. Wireless Commun.*, vol. 18, no. 8, pp. 4157–4170, Aug. 2019.

[6] G. Farhadi and N. C. Beaulieu, "On the ergodic capacity of multi-hop wireless relaying systems," *IEEE Trans. Wireless Commun.*, vol. 8, no. 5, pp. 2286–2291, May 2009.

[7] O. Özdogan, E. Björnson, and E. G. Larsson, "Intelligent reflecting surfaces: Physics, propagation, and pathloss modeling," *CoRR*, 2019.

[8] *Further Advancements for E-UTRA Physical Layer Aspects (Release 9)*, 3GPP Standard TS 36.814, Mar. 2010.

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[10] M. N. Khormuji and E. G. Larsson, "Cooperative transmission based on decode-and-forward relaying with partial repetition coding," *IEEE Trans. Wireless Commun.*, vol. 8, no. 4, pp. 1716–1725, Apr. 2009.

Appendix

A. 論文的模擬結果

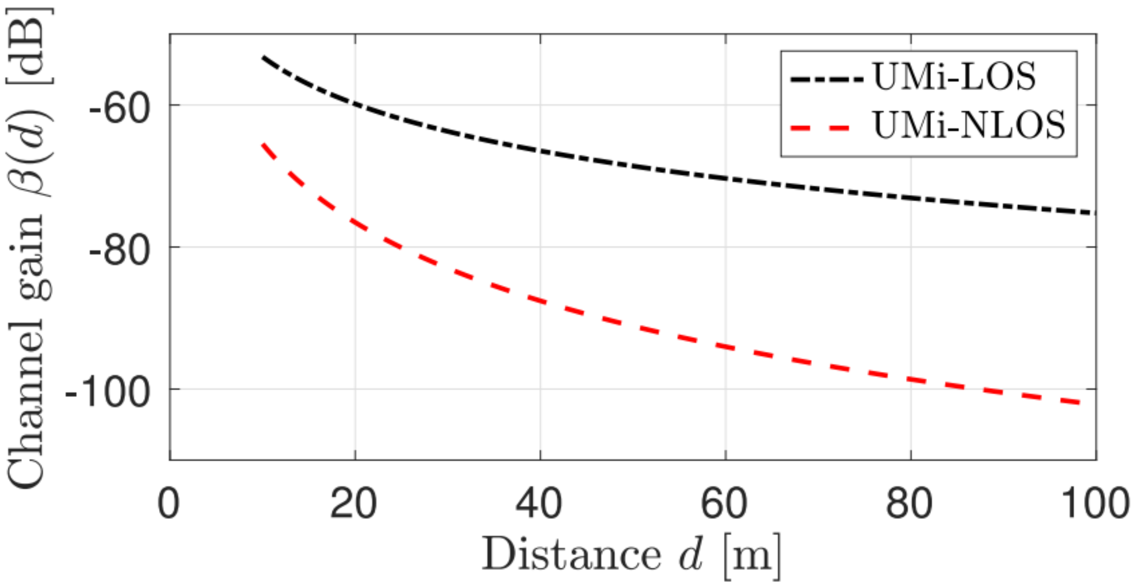
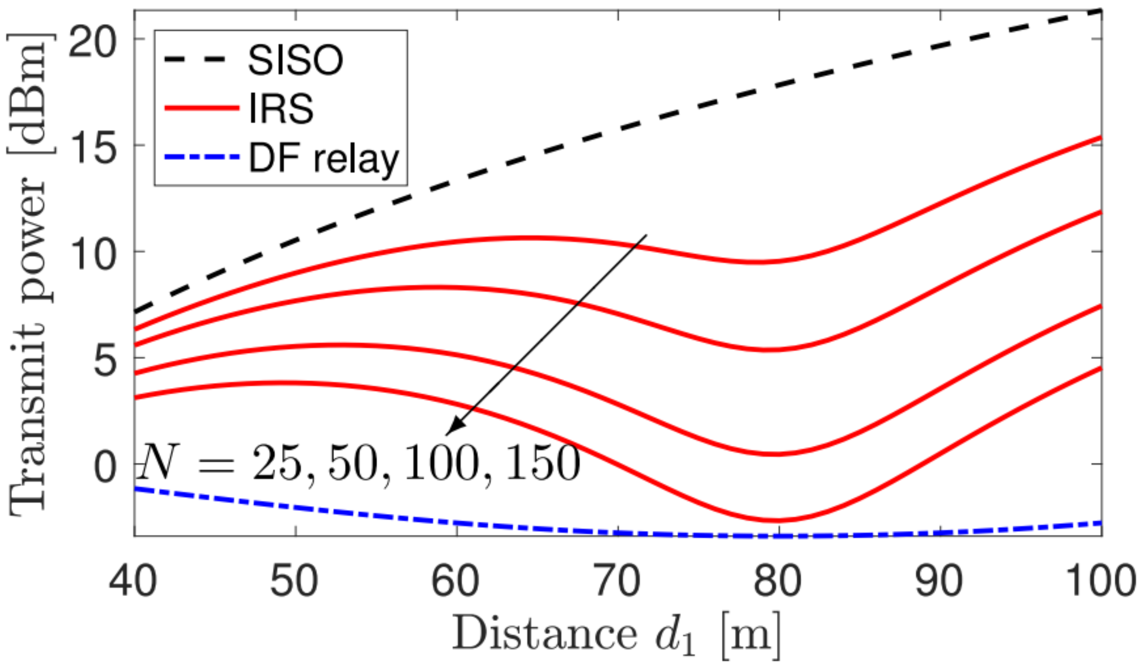
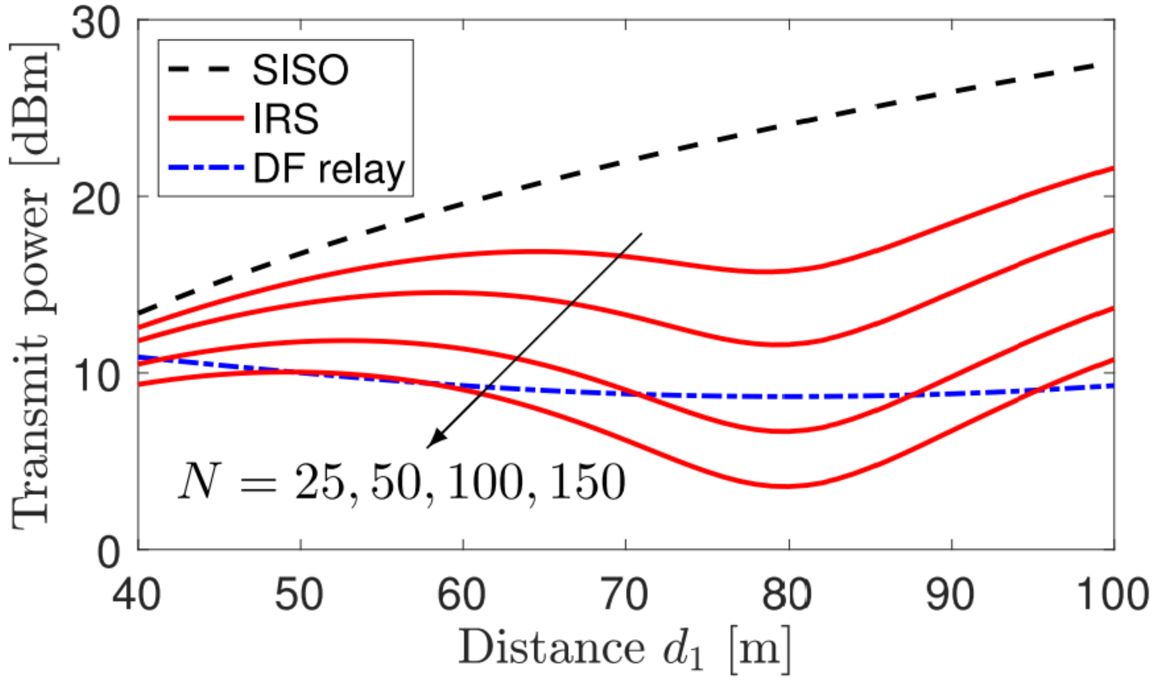


Fig. 2. Typical channel gains as a function of the distance, when including the antenna gains $G_\mathrm{t} = G_\mathrm{r} = 5\,\mathrm{dBi}$.



(a) $\bar{R} = 4\,\mathrm{bit/s/Hz}$.



(b) $\bar{R} = 6$ bit/s/Hz.

Fig. 4. The transmit power needed to achieve the rate $\bar{R}$ in the scenario shown in Fig. 3, as a function of the distance d_1.

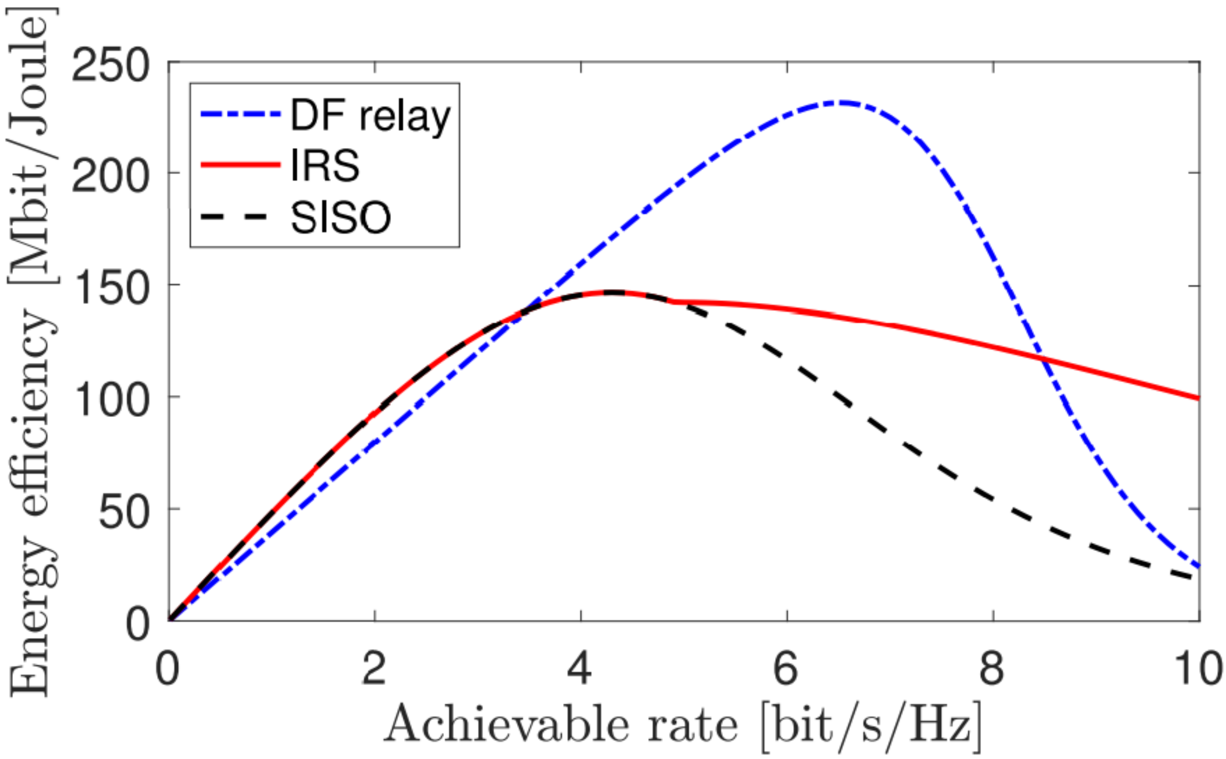


Fig. 5. The energy efficiency as a function of the rate $\bar{R}$.

B. 程式碼

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%
% Figure 2 - Typical channel gains as a function of the distance, when
%            including the antenna gains Gt = Gr = 5 dBi.
% ref. E. Björnson, Ö. Özdogan and E. G. Larsson, "Intelligent Reflecting Surface
%      Versus Decode-and-Forward: How Large Surfaces are Needed to Beat Relaying?,"
%      in IEEE Wireless Communications Letters, vol.9, no.2, pp.244-248, Feb.2020
%
% close all;
clear;
clc;
%
% set parameter values
%
% carrier frequency f_c = 3GHz
%
fc = 3;
%
% distances in meter
%
d = 10:0.1:100;
%
% define the antenna gains at the transmitter and receiver
%
Gt = 5; % Tx antenna Gain in dBi
Gr = 5; % Rx antenna Gain in dBi
%
% compute channel gains based on the 3GPP Urban Micro
% Note that the antenna gains are included.
%
beta_3GPP_LOS  = db2pow(Gt + Gr - 28.0 - 20 * log10(fc) - 22.0 * log10(d));
beta_3GPP_NLOS = db2pow(Gt + Gr - 22.7 - 26 * log10(fc) - 36.7 * log10(d));
%
% plot simulation results
%
figure;
hold on; box on; grid on;
%

plot(d, 10 * log10(beta_3GPP_LOS), 'k', 'LineWidth', 2);
plot(d, 10 * log10(beta_3GPP_NLOS), 'r', 'LineWidth', 2);
%
title('Figure 2');
xlabel('Distance d [m]');
ylabel('Channel gain \beta(d) [dB]');
%
legend({'UMi-LOS', 'UMi-NLOS'});
set(gca, 'fontsize', 13);
xlim([10 100]);
ylim([-110 -50]);
%
%
```

```
%
% Figure 4 - The transmit power needed to achieve the rate R¯ in the scenario
%            shown in Fig. 3, as a function of the distance d1
% ref. E. Björnson, Ö. Özdogan and E. G. Larsson, "Intelligent Reflecting Surface
%      Versus Decode-and-Forward: How Large Surfaces are Needed to Beat Relaying?,"
%      in IEEE Wireless Communications Letters, vol.9, no.2, pp.244-248, Feb.2020
%
% close all;
clear;
clc;
%
% set simulation parameters
%
% carrier frequency f_c = 3GHz
%
fc = 3;
%
% bandwidth B = 10 MHz
%
B = 10e6;
%
% noise figure in dB
%
noiseFiguredB = 10;
%
% compute the noise power in dBm, σ^2
%
sigma2dBm = -174 + 10*log10(B) + noiseFiguredB;
sigma2 = db2pow(sigma2dBm);
%
% define the channel gain functions based on the 3GPP Urban Micro (UMi)
%
% pathloss_3GPP_LOS  = @(x) db2pow(-28.0 - 20*log10(fc) - 22.0*log10(x));
% pathloss_3GPP_NLOS = @(x) db2pow(-22.7 - 26*log10(fc) - 36.7*log10(x));
%
% define the antenna gains at the source, Relay/IRS, and destination.
% the numbers are in linear scale
%
Gs = db2pow(5); % antenna gains at the source
Gr = db2pow(5); % antenna gains at the relay/IRS
Gd = db2pow(0); % antenna gains at the destination
%
% set the amplitude reflection coefficient
%
alpha = 1;
%
% define the range of different number of reflection elements in the IRS
%
N = [25 50 100 150];
%
% set the range of rate values
```

```matlab
%
Rbar = [4 6];
%
% define distances in simulation setup
%
d_SR = 80; % distance between the source and IRS/relay
dv = 10;   % minimum distance between destination and the IRS/relay
%
% define the range of d1 values in the simulation setup
%
d1range = 40:100;
%
% prepare to save simulation results
%
powerFractionRelay = zeros(length(d1range), length(Rbar));
Nmin = zeros(length(Rbar), 1);
%
% go through all rate values, which is 4 and 6 bit/s/Hz
%
for i = 1:length(Rbar)
    %
    % prepare to save transmit powers
    %
    P_IRS  = zeros(length(d1range), length(N));
    P_DF   = zeros(length(d1range), 1);
    P_SISO = zeros(length(d1range), 1);
    %
    % compute required SINR values
    %
    SINR = 2^(Rbar(i)) - 1;       % SISO and IRS
    SINR_DF = 2^(2*Rbar(i)) - 1; % DF relaying
    %
    % go through all values of d1
    %
    for k = 1:length(d1range)
        %
        % extract value of d1
        % extract value of d1
        %
        d1 = d1range(k);
        %
        % compute distance between the source and destination
        %
        d_SD = sqrt(d1^2 + dv^2);
        %
        % compute distance between the IRS/relay and destination
        %
        d_RD = sqrt((d1 - d_SR)^2 + dv^2);
        %
        % compute the channel gains using the 3GPP models and antenna gains
        %
```

```
        betaSR = pathloss_3GPP_LOS(d_SR, fc) * Gs * Gr;  % β_sr
        betaRD = pathloss_3GPP_LOS(d_RD, fc) * Gr * Gd;  % β_rd
        betaSD = pathloss_3GPP_NLOS(d_SD, fc) * Gs * Gd; % β_sd
        betaIRS = betaSR * betaRD;  % β_IRS = β_sr * β_rd
        %
        % compute the transmit power in mW in the SISO case, using Eq.(11)
        %
        % p_SISO = (2^R¯ - 1) * σ^2 / β_sd;
        P_SISO(k) = SINR * sigma2 / betaSD;
        %
        % compute the transmit power in mW in the IRS case, using Eq.(12)
        %
        % p_IRS(N) = (2^R¯ - 1) * σ^2 / (√β_sd + N*α*√β_IRS)^2;
        P_IRS(k, :) = SINR * sigma2 ./ (sqrt(betaSD) + N * alpha * sqrt(betaIRS)).^2;
        %
        % compute the transmit power in mW in the DF relaying case, using Eq.(14)
        %
        if betaSR >= betaSD
            % SINR_DF = 2^(2*R¯) - 1;
            bSum = betaSR + betaRD - betaSD;
            P_DF(k) = SINR_DF * sigma2 * bSum / (2 * betaRD * betaSR);
            powerFractionRelay(k, i) = 2 * (betaSR - betaSD) / bSum;
        else
            P_DF(k) = SINR_DF * sigma2 / betaSD;
            powerFractionRelay(k, i) = 0;
        end
        %
        % compute the number of reflecting elements needed to get a lower
        % transmit power with the IRS than with DF relaying, using Eq.(15)
        %
        if d1 == d_SR
            % ρ = p / σ^2, β_IRS = β_sr * β_rd
            p = P_DF(k); bIRS = betaIRS; bSum = betaSR + betaRD - betaSD;
            Nmin(i) = (sqrt((sqrt(1 + (2*p*bIRS / bSum / sigma2)) - 1)*(sigma2/p))...
                - sqrt(betaSD)) / (alpha * sqrt(bIRS));
        end
    end

    %
    % plot simulation results
    %
    figure;
    hold on; box on; grid on;
    %
    plot(d1range, 10*log10(P_SISO), 'k--', 'LineWidth', 2);
    plot(d1range, 10*log10(P_IRS(:,1)), 'r-', 'LineWidth', 2);
    plot(d1range, 10*log10(P_DF), 'b-', 'LineWidth', 2);
    for n = 2:length(N)
        plot(d1range, 10*log10(P_IRS(:,n)), 'r-','LineWidth', 2);
    end
```

```
    %
    title('Figure 4');
    xlabel('Distance d_1 [m]');
    ylabel('Transmit power [dBm]');
    %
    legend('SISO', 'IRS', 'DF relay', 'Location', 'NorthWest');
    set(gca, 'fontsize', 12);
    xlim([40 100]);
end
%
% define the channel gain functions based on the 3GPP Urban Micro (UMi)
%
function out = pathloss_3GPP_LOS(x, fc)
    % x is measured in m, antenna gains are included separately in the code
    out = db2pow(-28.0 - 20*log10(fc) - 22.0*log10(x));
end
function out = pathloss_3GPP_NLOS(x, fc)
    % x is measured in m, antenna gains are included separately in the code
    out = db2pow(-22.7 - 26*log10(fc) - 36.7*log10(x));
end
%
```

```
%
% Figure 5 - The energy efficiency as a function of the rate R¯
% ref. E. Björnson, Ö. Özdogan and E. G. Larsson, "Intelligent Reflecting Surface
%      Versus Decode-and-Forward: How Large Surfaces are Needed to Beat Relaying?,"
%      in IEEE Wireless Communications Letters, vol.9, no.2, pp.244-248, Feb.2020
%
% close all;
clear;
clc;
%
% set simulation parameters
%
% carrier frequency f_c = 3GHz
%
fc = 3;
%
% bandwidth B = 10 MHz
%
B = 10e6;
%
% noise figure in dB
%
noiseFiguredB = 10;
%
% compute the noise power in dBm
%
sigma2dBm = -174 + 10*log10(B) + noiseFiguredB;
sigma2 = db2pow(sigma2dBm);
```

```
%
% define the channel gain functions based on the 3GPP Urban Micro (UMi)
%
% pathloss_3GPP_LOS  = @(x) db2pow(-28.0 - 20*log10(fc) - 22.0*log10(x));
% pathloss_3GPP_NLOS = @(x) db2pow(-22.7 - 26*log10(fc) - 36.7*log10(x));
%
% define the antenna gains at the source, relay/IRS, and destination.
% (the numbers are in linear scale)
%
Gs = db2pow(5); % antenna gains at the source
Gr = db2pow(5); % antenna gains at the relay/IRS
Gd = db2pow(0); % antenna gains at the destination
%
% set the amplitude reflection coefficient
%
alpha = 1;
%
% set the range of rate values
%
Rbar = [0.01 0.1:0.1:10];
%
% set parameters related to circuit power consumption
%
Ps = 100; % Power dissipation in the transceiver hardware of the source
Pd = 100; % Power dissipation in the transceiver hardware of the destination
Pe = 5;   % Power dissipation per element in the IRS (mW)
Pr = 100; % Power dissipation in the transceiver hardware of the relay
nu = 0.5; % Efficiency of the power amplifier at the source
%
% define distances in simulation setup
%
d_SR = 80; % distance between the source and IRS/relay
dv = 10;   % minimum distance between destination and the IRS/relay
%
% define the range of d1 values in the simulation setup
%
d1 = 70;
%
% copmute distance between the source and destination
%
d_SD = sqrt(d1^2+dv^2);
%
% compute distance between the IRS/relay and destination
%
d_RD = sqrt((d1-d_SR)^2+dv^2);
%
% compute the channel gains using the 3GPP models and antenna gains
%
betaSR = pathloss_3GPP_LOS(d_SR, fc) * Gs * Gr;  % β_sr
```

```
betaRD = pathloss_3GPP_LOS(d_RD, fc) * Gr * Gd;  % β_rd
betaSD = pathloss_3GPP_NLOS(d_SD, fc) * Gs * Gd; % β_sd
betaIRS = betaSR * betaRD;  % β_IRS = β_sr * β_rd
%
% prepare to save simulation results
%
EE_SISO = zeros(length(Rbar), 1);
EE_IRS  = zeros(length(Rbar), 1);
EE_DF   = zeros(length(Rbar), 1);
Nopt    = zeros(length(Rbar), 1);
%
% go through all rate values
%
for i = 1:length(Rbar)
    %
    % compute required SINR values
    %
    SINR = 2^(Rbar(i)) - 1;         % SISO and IRS
    SINR_DF = 2^(2 * Rbar(i)) - 1; % DF relaying
    %
    % compute the transmit power in the SISO case, using Eq.(17)
    %
    P_SISO = SINR * sigma2 / betaSD;
    %
    % compute the energy efficiency in the SISO case, using B * R¯ / P_total
    %
    % EE = B * R¯ / P_total (the factor 1000 is used to convert mW to W)
    EE_SISO(i) = 1000 * B * Rbar(i) / (P_SISO/nu + Ps + Pd);
    %
    % compute the transmit power in the DF relaying case, using Eq.(19)
    %
    P_DF = SINR_DF * sigma2 * (betaSR + betaRD - betaSD) / (2 * betaIRS);
    %
    % compute the energy efficiency in the DF relaying case
    %
    % EE = B * R¯ / P_total (the factor 1000 is used to convert mW to W)
    EE_DF(i) = 1000 * B * Rbar(i) / (P_DF/nu + Ps/2 + Pd + Pr);

    %
    % compute the power-minimizing number of reflecting elements, using Eq.(22)
    %
    Nopt(i) = (2 * SINR * sigma2 / (alpha^2 * betaIRS * Pe))^(1/3) ...
            - sqrt(betaSD / betaIRS) / alpha;
    if Nopt(i) < 0
        Nopt(i) = 0;
    end
    %
    % compute the transmit power in the IRS case, using Eq.(18)
    %
    P_IRS = SINR * sigma2 ./ (sqrt(betaSD) + Nopt(i) * alpha * sqrt(betaIRS)).^2;
    %
```

```
    % compute the energy efficiency in the IRS case, using B * R¯ / P_total
    %
    % EE = B * R¯ / P_total (the factor 1000 is used to convert mW to W)
    EE_IRS(i) = 1000 * B * Rbar(i) / (P_IRS/nu + Ps + Pd + Nopt(i)*Pe);
end
%
% plot simulation results
%
figure;
hold on; box on; grid on;
%
plot(Rbar, EE_DF/1e6, 'b-', 'LineWidth', 2);
plot(Rbar, EE_IRS/1e6, 'r-', 'LineWidth', 2);
plot(Rbar, EE_SISO/1e6, 'k--', 'LineWidth', 2);
%
title('Figure 5');
xlabel('Achievable rate [bit/s/Hz]');
ylabel('Energy efficiency [Mbit/Joule]');
%
legend('DF relay', 'IRS', 'SISO', 'Location', 'NorthWest');
set(gca,'fontsize', 12);
%
% define the channel gain functions based on the 3GPP Urban Micro (UMi)
%

function out = pathloss_3GPP_LOS(x, fc)
    % x is measured in m, antenna gains are included separately in the code
    out = db2pow(-28.0 - 20*log10(fc) - 22.0*log10(x));
end
function out = pathloss_3GPP_NLOS(x, fc)
    % x is measured in m, antenna gains are included separately in the code
    out = db2pow(-22.7 - 26*log10(fc) - 36.7*log10(x));
end
%
```