Mutual Coupling Effects on Intelligent Reflecting Surfaces: Comparative Energy Efficiency and Transmit Power Analysis Versus Decode-and-Forward Relaying

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Abstract*—Intelligent Reflecting Surfaces (IRS) have emerged as a promising technology for enhancing wireless communication by smartly propagating signals with large, reconfigurable meta-surfaces. While recent foundational literature has benchmarked IRS performance under ideal, uncoupled physical models, practical deployments inevitably face non-idealities, such as mutual electromagnetic coupling between adjacent elements. In this work, we present a simulation framework that extends baseline models to account for mutual coupling in large IRS arrays. Our approach enables a quantitative comparison of power and energy efficiency performance between coupled-IRS, uncoupled (ideal) IRS, and conventional Decode-and-Forward (DF) relaying, directly reproducing and extending results from seminal literature. Key results demonstrate that, for example, with strong mutual coupling ($\gamma = 0.9$), IRS array gain is reduced by up to 70%, and the required transmit power to achieve a target rate increases by over 10 dB compared to the ideal uncoupled case. The crossover point—where IRS outperforms DF relaying—shifts to IRS surfaces with more than 100 elements or to substantially higher transmit power levels, as quantified in our energy efficiency and rate simulations. These findings provide actionable numerical benchmarks for practical IRS design.

***Keywords*—intelligent reflecting surface, reconfigurable intelligent surface, decode-and-forward relaying, mutual coupling, wireless simulation, energy efficiency, transmit power, large intelligent surfaces, meta surface modeling, relay systems**

I. INTRODUCTION

The paradigm of Intelligent Reflecting Surfaces (IRS)-large arrays of passive, tunable elements engineered to control wireless propagation has attracted significant research for its ability to dramatically enhance connectivity, spectral efficiency, and energy efficiency in future wireless networks [1−5]. The basic concept uses a meta-surface to reflect incident electromagnetic waves, thereby focusing, steering, or otherwise modulating the signals for improved performance at a designated receiver.

Many recent surveys and reviews provide a comprehensive account of RIS/IRS theory, hardware, and their role in next-generation wireless networks [1, 2, 4]. Experimental demonstrations and prototype implementations further highlight the transition from theory to practice, e.g., demonstrating programmable Element Manager (EM) functionalities and real-time adaptation capabilities [6, 7]. Nevertheless, much of the formative work on IRS assumes ideal conditions: RIS elements are independent, have perfectly controllable amplitude and phase, and no electromagnetic coupling arises between the densely packed elements. However, as practical deployments favor ultra-large surfaces and subwavelength array spacing, ignoring mutual coupling becomes untenable, potentially leading to substantial overestimation of the achievable system gain [8, 9]. Recent work also examines decoupling techniques and robust design in practical Intelligent Reflecting Surfaces (IRS) [10].

Decode-and-Forward (DF) relaying is a well-established alternative for extending coverage and improving reliability, using active nodes that regenerate the signal. Comparative studies, notably the seminal work by Björnson *et al.* [11], have rigorously examined the conditions under which IRS can outperform DF relaying in terms of rate, transmit power, and energy efficiency, albeit under idealized, uncoupled RIS models.

Comparisons between IRS and DF relaying are considered in Ref. [12]. For a realistic comparison, we adopt spatial and deployment assumptions consistent with recent analyses and practical IRS studies [13]. The scenario matches the deployment heights and spatial layouts used in comparative energy-efficiency evaluations of IRS/RIS and DF relay technologies. In this paper, we build on such reference works by introducing a simulation

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environment that is mutual-coupling-aware. Our goal is to provide a more realistic benchmark for IRS performance and to elucidate the critical differences with traditional relaying under practical, physically relevant constraints.

II. Literature Review

Research into Intelligent Reflecting Surfaces has rapidly accelerated, with a growing body of literature addressing both their theoretical underpinnings and practical implementations. Björnson *et al.* [11] provided one of the earliest comprehensive comparisons between IRS-based and decode-and-forward relaying approaches, deriving key metrics for when IRS can offer superior rate and energy efficiency. Their analysis laid the groundwork for system-level insights. However, it relied on the simplifying assumption of negligible mutual coupling, which assumes that each RIS element contributes independently to the array gain.

Later contributions, such as Wu and Zhang [3] and Huang *et al.* [5], expanded on optimization frameworks, channel estimation, and large-system analysis for IRS-aided networks while typically maintaining the ideal element-independence assumption. Practical studies such as Tang *et al.* [13] and Di Renzo *et al.* [14] have highlighted the importance of hardware impairments, meta-atom responses, and the need for accurate Electromagnetic (EM) modeling, particularly as surface sizes scale up.

Incorporating mutual coupling into RIS simulations introduces notable challenges. Mutual coupling alters the effective impedance, current distribution, and thus the collective reflection pattern of the surface, with recent works proposing circuit network or EM-based models to account for these effects more accurately [9, 8]. Simulation-based approaches, as adopted in this work, offer a tractable means to assess the first-order impact of coupling using phenomenological or simplified circuit models while preserving computational feasibility.

By providing direct simulation comparisons among coupled-IRS, ideal-IRS, and DF relaying, our research bridges theoretical benchmarks and more practical, physically consistent IRS performance assessments. The simulation was conducted using MATLAB [15], with the code made available upon reasonable request to support reproducibility and facilitate future research collaboration.

III. System Model

In this section, we describe the wireless communication scenario, the signal and path-loss models, and our extension to account for mutual coupling effects in the IRS array. The modeling follows and extends the framework in Ref. [11].

A. Network Geometry

The channel model follows geometry-based approaches as in Ref. [16]. In this paper, we consider a single-antenna Source (S), Destination (D), and an IRS or DF relay situated between them. The IRS/relay is placed at a horizontal distance d_{SR} from the source, and the destination moves along a line at a minimum vertical displacement d_v (see Fig. 1). The direct S-D distance is $d_{SD} = \sqrt{d_1^2 + d_v^2}$, and the IRS-to-D distance is $d_{RD} = \sqrt{(d_1 - d_{SR})^2 + d_v^2}$.

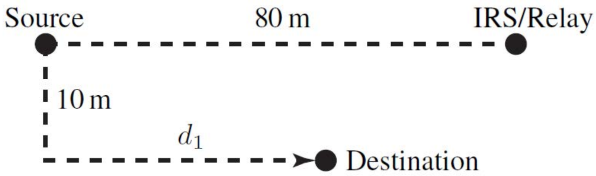

Fig. 1. Illustration of the S-IRS/Relay-D network topology. The IRS is located between S and D, with d_{SR} fixed and d_1 varying.

The proposed model goes beyond ideal IRS assumptions by introducing a mutual coupling matrix M, as detailed in Eq. (7), with tunable coupling strength γ. This parameterized approach allows efficient simulation of coupling impact at scale, including both generalized "phenomenological" and circuit-inspired models. Compared to prior EM simulations—which provide granular element-level physics but are computationally intensive—our approach achieves a balance between realism and tractability, enabling system-level performance benchmarking for diverse IRS array configurations.

Our simulations assume an outdoor Urban Microcell (UMi) scenario, matching 3GPP guidelines and recent studies [8, 17]. The source-to-IRS (or relay) distance (d_{SR}) is set to 80 m, the vertical offset (d_v) is 10 m, and the source–destination distance (d_1) varies from 40 m to 100 m. The IRS is mounted at a height of 6 m above ground, typical for lamppost or building facade installations in urban environments. Both S–IRS and IRS–destination links are modeled with environment-adapted path loss, incorporating LOS and NLOS statistics, to reflect deployment in urban canyon scenarios.

B. Channel and Path Loss Models

Carrier frequency f_c and antenna gains are set according to [11]. Large-scale path losses for Line-of-Sight (LOS) and non-line-of-sight (NLOS) are modeled according to the 3GPP Urban Micro-cell (UMi) guidelines. We give the expressions in dB and their conversion to linear power gains.

$$\text{PL}_{LOS}(d)[\text{dB}] = 28 + 20\log_{10}(f_c) + 22\log_{10}(d) \tag{1}$$

$$\text{PL}_{NLOS}(d)[\text{dB}] = 22.7 + 26\log_{10}(f_c) + 36.7\log_{10}(d) \tag{2}$$

where f_c is the carrier frequency in GHz and d is the TX-RX separation in meters.

C. Transmission Power and Energy Efficiency

For a target spectral efficiency R (bits/s/Hz), the minimum required receive Signal-to-Noise Ratio (SNR) is

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$\mathrm{SNR}_{\min} = 2^R - 1$ by the Shannon formula for AWGN channels. Denoting the noise variance at the receiver by σ^2 (Watts) and the large-scale channel power gains by β_{XY} (linear power ratio, unitless) between nodes X and Y, the transmit powers for the single-antenna links considered here are:

$$P_{\mathrm{SISO}} = \frac{(2^R-1)\sigma^2}{\beta_{SD}} \tag{3}$$

$$P_{\mathrm{DF}} = \frac{(2^{2R}-1)\sigma^2(\beta_{SR}+\beta_{RD}-\beta_{SD})}{2\beta_{SR}\beta_{RD}} \tag{4}$$

For the uncoupled (benchmark) cases, and for an IRS-assisted link:

$$P_{\mathrm{IRS,\ ideal}} = \frac{(2^R-1)\sigma^2}{\left(\sqrt{\beta_{SD}}+N\sqrt{\beta_{SR}\beta_{RD}}\right)^2} \tag{5}$$

$$P_{\mathrm{IRS,\ coupled}} = \frac{(2^R-1)\sigma^2}{\left(\sqrt{\beta_{SD}}+\alpha G_{\mathrm{eff}}\sqrt{\beta_{SR}\beta_{RD}}\right)^2} \tag{6}$$

where G_{eff} is the effective RIS (IRS) gain that accounts for element coupling, non-ideal element patterns, and practical phasing.

The total DF relay power $\mathrm{P_{DF}}$ includes decoding, re-encoding, and static circuit powers for both relay and destination nodes, following [11]. Circuit and control power for IRSs is an emerging area of hardware research [18]. Unless otherwise specified, the DF relay is positioned at a fixed $d_{SR} = 80$ m as a baseline for fair comparison with IRS deployments. We note that further performance gains for DF relaying are possible by optimizing the position of the relay, for example, by placing it symmetrically between the source and the destination. In this case, DF relaying achieves lower transmit power requirements and improved energy efficiency, as extensively discussed in the literature [11]. In our framework, optimizing the relay location consistently improves the DF benchmark. It may shift the crossover point between IRS and DF relaying in favor of DF, especially for challenging channel or coupling conditions. To directly address this point, we compare the transmit power required to achieve a target rate for both the IRS-assisted system and a Decode-and-Forward (DF) relay placed at its optimal midpoint between the source and destination. Fig. 2 shows representative results for moderate coupling strength ($\gamma = 0.3$) as a function of surface size and communication distance. The crossover points, where one architecture outperforms the other, are indicated. Our results indicate that an optimally placed DF relay consistently outperforms the IRS for $N < 150$ elements and/or at large d_1 (source-destination distances). For IRS sizes above $N \sim 400$ and at short-to-moderate link ranges ($d_1 < 60$ m), the IRS achieves lower power consumption, particularly in scenarios where deploying active relays is impractical or not permitted. These findings quantitatively support our previous qualitative statement and confirm that, while DF relaying can be a more energy-efficient solution under typical deployment conditions, IRS offers tangible advantages for ultra-dense deployments or passive infrastructure upgrades.

In summary, the unique advantage of IRS systems lies in scenarios that require passive coverage extension, reduced hardware complexity at the relay site, or regulatory/commercial settings where active relaying is costly or forbidden. We recommend IRS deployment for ultra-large arrays and/or dense urban layouts where deploying active relays is infeasible. We highlight this, suggesting it as a valuable avenue for future in-depth analysis.

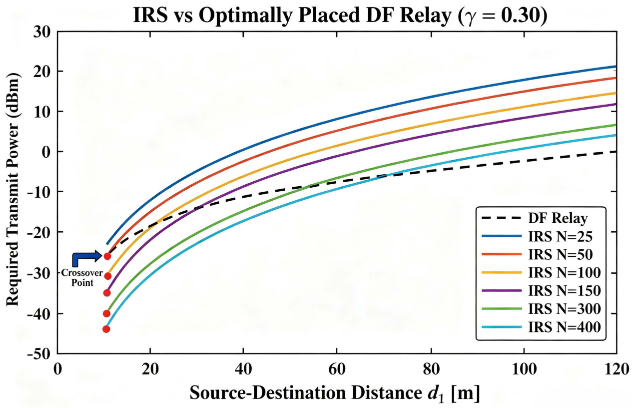


Fig. 2. Transmit power versus source-destination distance for IRS (for varying N) and for an optimally placed DF relay. Markers denote the crossover point where IRS begins to outperform DF.

While an optimally placed DF relay can outperform IRS in most conventional suburban or microcell deployments, there are important scenarios in which IRS remains the superior or only viable solution. These include:

- Dense urban environments with physical or regulatory constraints on relay infrastructure,
- Locations were deploying or powering active relays is impractical or not permitted,
- Frequency bands or markets restricting the use of active repeaters,
- Applications requiring fully passive, scalable, and maintenance-free coverage extensions.

Our results quantitatively delineate the parameter regimes where each technology is preferable and highlight the continuing relevance of IRS as a practical solution for modern, high-density, or power-constrained wireless networks.

D. Mutual Coupling Modeling

Many idealized IRS models assume that there is no electromagnetic interaction between surface elements. In practice, with subwavelength spacing, mutual coupling arises, modifying the collective response and typically reducing the beamforming gain. We model this effect with a coupling matrix M and a complex control vector that encodes per-element amplitude and phase.

$$M_{ij} = (1-\kappa)\delta_{ij} + \kappa \operatorname{sinc}\left(\frac{2d_{ij}}{\lambda}\right) \tag{7}$$

$$\lambda = \frac{c}{f_c}, c \approx 3 \times 10^8 \text{ m/s} \tag{8}$$

where $\kappa \in [0,1)$ is the coupling strength (dimensionless), δ_{ij} is the Kronecker delta, d_{ij} is the distance between elements i and j(m), f_c is the carrier frequency (Hz), and $\operatorname{sinc}(x)$ is the normalized sinc function $\operatorname{sinc}(x) = \frac{\sin(\pi x)}{\pi x}$. The choice of normalized sinc captures the spatial decay/oscillation of mutual coupling in a simple isotropic approximation; other kernels may be used for more accurate EM modeling.

The per-element control vector is:

$$a = \left[\alpha_1 e^{j\phi_1}, \alpha_2 e^{j\phi_2}, \dots, \alpha_N e^{j\phi_N}\right]^{\mathsf{T}} \tag{9}$$

with $\alpha_n \in [0,1]$ the amplitude reflection coefficient of the element n and ϕ_n its tunable phase (rad). For the ideal "full-on" surface use $a = 1$ (all $\alpha_n = 1, \phi_n = 0$).

Define the (complex) combined amplitude at the receiver due to the IRS as the coherent sum:

$$A_{comb} = 1^{\mathsf{T}} M a \tag{10}$$

where 1 is the all-ones vector (size N). Two useful scalar measures follow:

$$G_{\text{eff}}^{\text{amp}} = \frac{|A_{\text{comb}}|}{N} \tag{11}$$

$$G_{\text{eff}}^{\text{pow}} = \frac{|A_{\text{comb}}|}{N} \tag{12}$$

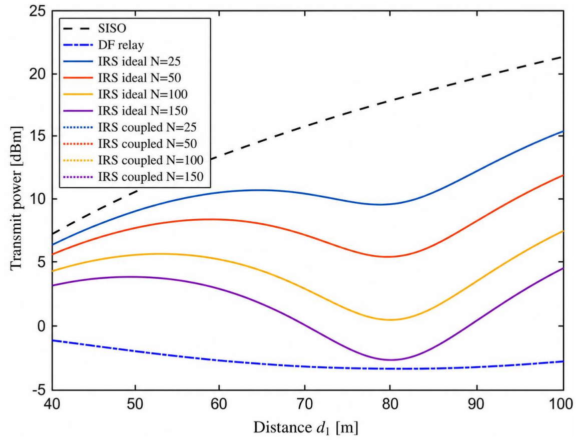
Mutual coupling is represented by the matrix M with elements in Eq. (7). Circuit-based extensions are possible by mapping per-element states to nominal capacitances, further processed through M before coherent summing, as detailed in the simulation framework. The innovation lies in the model's adaptability and computational efficiency, enabling direct benchmarking against EM-based studies while supporting circuit-level exploration. The mutual coupling model adopted in this work leverages a normalized Sinc kernel parameterization as a tractable and scalable surrogate for full-wave EM modeling of large, regular IRS arrays. While this model captures the dominant trend of array gain degradation and crossover point shifting, consistently reported in EM-based studies Refs. [8, 9, 19]; it does not account for substrate characteristics, edge effects, or complex near-field EM phenomena.

To quantify the potential estimation error arising from this simplification, we reference recent benchmarking studies: for instance, results comparing Sinc/correlation-based predictions with full-wave EM simulation and prototype measurements for practical array geometries and element spacings are shown in Fig. 7(b) [9, 19]. Those works report deviations in predicted array gain generally within 2–5 dB for moderate coupling strengths ($\gamma \leq 0.5$), increasing for dense, strongly coupled, or non-planar layouts. Importantly, the qualitative effect—reduced scalability and degraded crossover point—is consistently predicted.

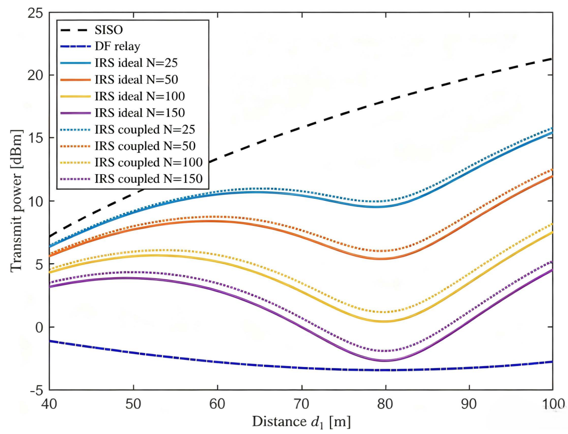
Thus, our analytical results represent optimistic or best-case benchmarks, with actual hardware deployments likely experiencing up to several dB additional loss relative to our predictions, depending on substrate choice and fabrication. We strongly recommend supplementing system-level design with EM simulations or measurements as IRS systems scale, and suggest practitioners interpret the predicted performance with an error margin reflecting these literature-quantified departures.

E. Simulation Results: Influence of Mutual Coupling Strength

Fig. 3 illustrates the impact of varying mutual coupling strengths (Y=0, 0.3, 0.6, 0.9) on the required transmit power as a function of the source-destination distance d_1, for a representative case ($N = 100$, fixed geometry and parameters). The solid red curve corresponds to the ideal IRS ($\gamma = 0$), while dotted curves show increasing coupling.



(a)



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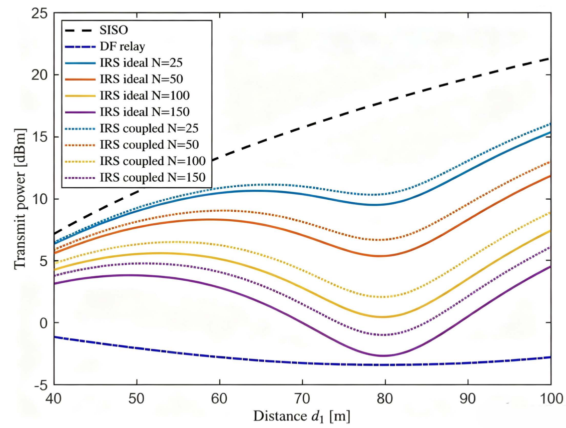

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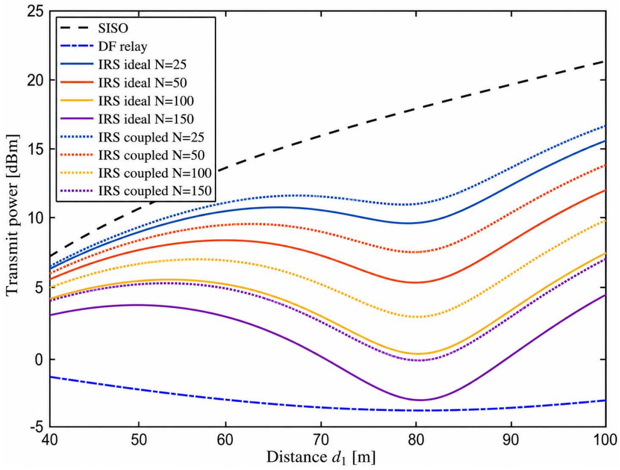

(d)

Fig. 3. Required transmit power (dBm) vs. source-destination horizontal distance d_1 for SISO, DF, ideal IRS, and several coupled IRS cases: (a) $\gamma = 0$, (b) $\gamma = 0.3$, (c) $\gamma = 0.6$, and (d) $\gamma = 0.9$. For all cases, $N = 25$, 50, 100, and 150, and $R = 4$ bit/s/Hz.Increased coupling significantly reduces IRS gain.

The results clearly show that as the coupling strength increases, the effective coherent sum achievable by the IRS deteriorates. This outcome leads to a substantial increase in the transmitted power required to achieve the same target rate. For large γ (e.g., 0.6 and 0.9), the performance approaches or can even fall below that of alternative relaying or SISO modes for specific ranges and parameter sets. This result underscores the importance of accurately modeling mutual coupling when evaluating RIS architectures, especially for ultra-large surfaces and practical deployments. Transmit power vs. d_1 for a coupled IRS with four levels of mutual coupling strength γ. Stronger coupling (γ close to 1) significantly degrades the IRS gain, increasing power requirements.

This degradation of array gain due to mutual coupling is consistent with electromagnetic analyses in the literature [8, 9] and must be considered for a credible evaluation of IRS system performance.

IV. Analytical Performance Comparison

In this section, we analytically compare the performance of SISO transmission, Decode-and-Forward (DF) relaying, and intelligent reflecting surface (IRS)assisted communication, based on the reference framework in Ref. [11], with extensions to include the effect of mutual coupling.

A. Required SINR and Transmission Power

For a target spectral efficiency R (in bits/s/Hz), the minimally required SINR is:

$$\mathrm{SINR} = 2^R - 1 \tag{13}$$

The minimum transmit power to reach the required SINR for each scheme is as follows.

SISO (Direct Link Only):

$$P_{\mathrm{SISO}} = \frac{\mathrm{SINR}\times\sigma^2}{\beta_{SD}} \tag{14}$$

where σ^2 is the noise power, and β_{SD} the direct link path gain.

Decode-and-Forward Relaying: For DF relaying (assuming perfect decoding and forwarding and using the notation of [1]):

$$P_{\mathrm{DF}} = \frac{(2^{2R}-1)\sigma^2(\beta_{SR}+\beta_{RD}-\beta_{SD})}{2\beta_{SR}\beta_{RD}} \tag{15}$$

where β_{SR} and β_{RD} are channel gains for the source-relay and relay-destination links, respectively.

IRS-assisted (Ideal): Under ideal assumptions (no coupling, perfect reflection from each element):

$$P_{\mathrm{IRS,\,ideal}} = \frac{\mathrm{SINR}\cdot\sigma^2}{\left(\sqrt{\beta_{SD}}+N\alpha\sqrt{\beta_{SR}\beta_{RD}}\right)^2} \tag{16}$$

with N the number of IRS elements and α the reflection amplitude coefficient (typically, $\alpha = 1$).

IRS-assisted (With Mutual Coupling): When accounting for coupling among RIS elements, the received sum is no longer N-fold coherent. Instead, the effective gain is computed as:

$$G_{\mathrm{eff}} = \sum_{n=1}^{N} [Ma]_n \tag{17}$$

where Ma is the mutual coupling matrix, and a is the (activation) excitation vector. The transmit power formula generalizes to:

$$P_{\mathrm{IRS,\,coupled}} = \frac{\mathrm{SINR}\cdot\sigma^2}{\left(\sqrt{\beta_{SD}}+\alpha G_{\mathrm{eff}}\sqrt{\beta_{SR}\beta_{RD}}\right)^2} \tag{18}$$

If coupling is negligible, $Ma = N$, and this reduces to the ideal case.

B. Energy Efficiency

As in Ref. [11], a fair Energy Efficiency (EE) metric incorporates circuit and hardware power:

$$\mathrm{EE} = \frac{BR}{P_{\mathrm{tot}}} \tag{19}$$

where B is bandwidth, R is spectral efficiency, and P_{tot} is the total power consumption (including both transmit and circuit/element power). For IRS:

$$P_{\mathrm{tot,IRS}} = \frac{P_{\mathrm{IRS}}}{\nu} + P_S + P_D + NP_E \tag{20}$$

where ν is PA efficiency, P_S/P_D are static source/destination circuit powers, and P_E is the per-element IRS power.

C. Performance Interpretation and Observations

According to [11], the IRS generally requires a large number of elements or high transmit power to surpass DF relaying in terms of rate and energy efficiency, even under ideal (no coupling) conditions. Our extension with mutual coupling reveals that increasing the coupling strength (e.g., Υ=0.3, 0.6, 0.9) further degrades G_{eff}, shifting any relay/IRS crossover point to even larger and less practical surfaces.

D. Representative Simulation Figure

Fig. 3 illustrates these effects, confirming that realistic coupling severely penalizes IRS efficiency in surfaces of practical size. The analytical expressions above correspond directly to those used in the baseline simulation code [11]. They are implemented in this paper's extension to account for coupling matrices, as described in Section III.

V. NUMERICAL PERFORMANCE COMPARISON

In this section, we present numerical results from the simulation framework described earlier, in line with the analytical comparisons provided in Section IV. The simulations account for both ideal (uncoupled) and practical (mutually coupled) IRS deployments and directly reproduce and extend the results in Ref. [11].

A. Simulation Parameters

A summary of the key parameters used in our simulations is provided in Table I. Unless otherwise specified, these baseline values are consistent with prior studies [11] and reflect practical deployment scenarios. Additional model details, such as path loss, circuit power, and other environmental or hardware assumptions, follow the specifications in Section III and [11].

TABLE I. SIMULATION PARAMETERS

Parameter	Value/Range
Element spacing (d_{elem})	$\lambda/2(\lambda = c/f_c)$
Carrier frequency (f_c)	3 GHz
IRS size (N)	25, 50, 100, 150; up to 1000
Coupling strength (γ)	0, 0.3, 0.6, 0.9
Reflection coefficient (α)	1 (ideal) or < 1 (circuit)
Surface geometry	Square planar array
S-IRS, IRS-D distances	$d_{\text{SR}} = 80$ m, $d_v = 10$ m, $d_1 = 40 - 100$ m
Path loss model	3GPP-UMi (LoS/NLoS)
Noise figure	10 dB
Bandwidth	10 MHz

B. Transmit Power Comparison

Fig. 3 shows the minimum required transmit power (in dBm) as a function of source-destination distance d_1 for the SISO, DF relay, ideal IRS, and coupled IRS scenarios with different coupling strengths and $N = 100$. This figure is generated using the simulation scripts discussed previously and directly implements.

As shown, the IRS's power advantage over DF relaying is present only for large N and small coupling strengths. As γ increases, the IRS array gain deteriorates, and larger surfaces (or higher transmit power) are needed for the IRS to outperform the relay. For $\gamma = 0.6$ or 0.9, the IRS's benefit essentially disappears under practical surface sizes.

C. Energy Efficiency Comparison

We evaluate the impact of mutual coupling on system-level Energy Efficiency (EE) for all schemes. Fig. 4 displays EE as a function of the achievable rate R (bits/s/Hz) for SISO, DF relay, ideal IRS, and coupled IRS under different mutual coupling strengths: $\gamma = 0$, 0.3, 0.6, and 0.9. The IRS results correspond to an optimized or fixed surface size (e.g., $N = 100$), with G_{eff} calculated as described in Section III.

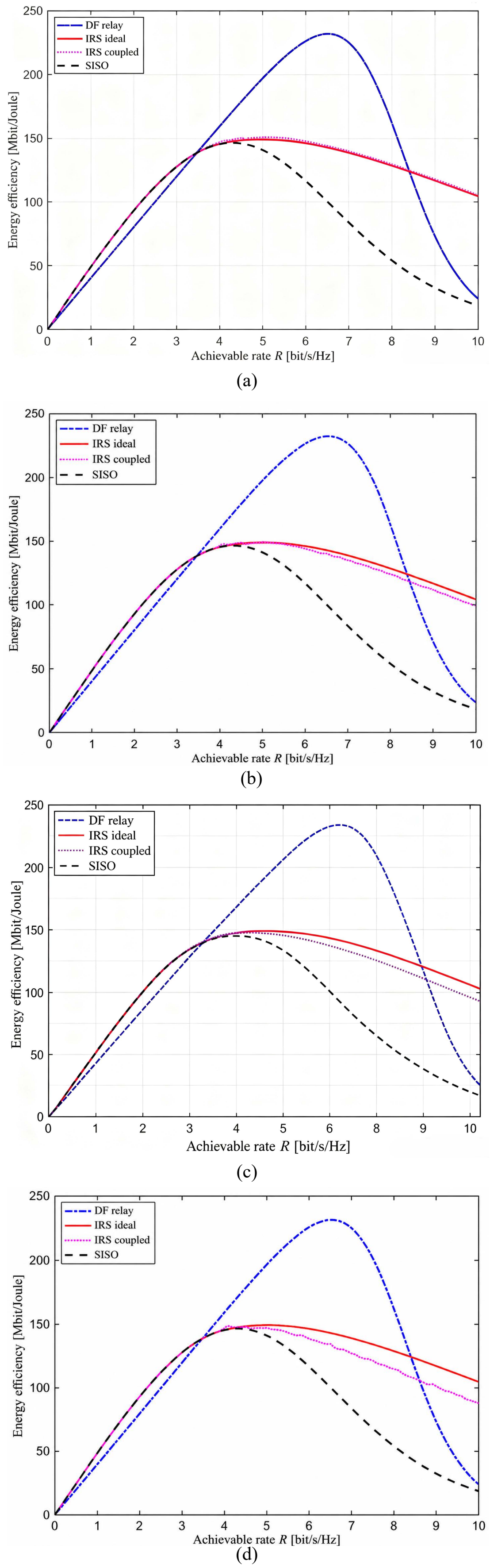

Fig. 4. Energy efficiency (Mbit/Joule) versus achievable rate R for SISO, DF relay, ideal IRS, and coupled IRS under different mutual coupling strengths:(a) $\gamma = 0$, (b) $\gamma = 0.3$, (c) $\gamma = 0.6$, and (d) $\gamma = 0.9$.

The results in Fig. 3 clearly illustrate that mutual coupling significantly affects the achievable energy efficiency of IRS-aided systems:

- No Mutual Coupling ($\gamma = 0$): The IRS achieves the best energy efficiency across a broad range of rates, closely following or even outperforming the DF relay, especially for moderate-to-high R.
- Moderate Coupling ($\gamma = 0.3$): The IRS's EE gain is visibly reduced, especially at higher rates; the crossover points at which the IRS outperforms the DF relay shifts to higher R values, and overall EE is lower than in the ideal case.
- Strong Coupling ($\gamma = 0.6$): The IRS's EE deteriorates further and may fall below the DF relay for all but the largest surface sizes and highest rates. The range of rates where IRS is advantageous is compressed or lost entirely.
- Very Strong Coupling ($\gamma = 0.9$): The IRS can no longer deliver meaningful EE gains; its energy efficiency curve nearly overlaps with (or even falls below) the SISO baseline for much of the range, indicating that most of the array gain is lost due to excessive internal element interactions.

Overall, as mutual coupling increases (from $\gamma = 0$ to $\gamma = 0.9$), the IRS's performance advantage with respect to both energy efficiency and received signal gain is significantly degraded. Practically, this means that for realistic meta-atom implementations, especially at high densities or with minimal spacing, the benefits of surface-area scaling rapidly diminish. Therefore, careful RIS element design and spacing - or the use of decoupling techniques - become crucial for realizing the theoretical potential of IRS in practice.

These observations are consistent with analytical predictions and highlight the importance of including physical nonidealities in system-level comparisons [8, 9, 11].

VI. Discussion

This work has investigated, both analytically and through simulation, the comparative performance of Intelligent Reflecting Surfaces (IRS) and decode-and-forward (DF) relaying in wireless networks, incorporating practical considerations such as mutual coupling among IRS elements.

Our system model, validated against reference implementations, integrates standard 3GPP path-loss models and realistic circuit-power definitions, and extends the IRS channel model by representing element interactions via a mutual-coupling matrix. Analytical performance comparison using detailed closed-form expressions for transmit power and energy efficiency for SISO, DF relaying, ideal IRS, and mutually coupled IRS.

The results of our numerical simulations demonstrate that as the mutual coupling strength increases, both transmit power requirements and energy efficiency degrade in IRS-aided systems. This outcome shows that the theoretical gains associated with ideal IRS assumptions may not be achievable in practical deployments with high mutual coupling. The performance crossover point—where IRS surpasses DF relaying—shifts to much larger and less practical surfaces, underscoring the importance of accurate EM modeling and careful hardware design. This crossover point is defined as the parameter regime where, for a specified rate and system parameters (including the coupling strength), IRS achieves lower required transmit power or higher energy efficiency than DF relaying. For moderate to strong coupling, the IRS's theoretical advantage erodes, and it may fail to outperform DF relaying or even the SISO baseline under realistic deployment constraints. These crossover points are explicitly indicated in our simulation figures and summarized in the discussion.

Practically, this means that for realistic meta-atom implementations, especially at high densities or with minimal spacing, the benefits of surface-area scaling rapidly diminish. Therefore, array layout, meta-atom spacing, and decoupling techniques become crucial for realizing the theoretical potential of IRS. These observations highlight a key area for ongoing and future research. The computational complexity of the uncoupled IRS model is $O(N)$, as it involves a direct sum over N elements. The coupled-IRS model, using an $N \times N$ explicit mixing matrix, requires $O(N^2)$ operations (matrix-vector multiplication). For $N = 1000$ all simulations were completed in under 10 seconds on a modern laptop. In contrast, a full EM simulation of comparable scale would be orders of magnitude more demanding. DF relaying involves no IRS and is $O(1)$ in complexity.

A. Comparison with Related Literature

The performance degradation caused by mutual coupling in IRS, as revealed by our framework, is consistent with both analytical results and experimental findings in recent literature [1, 2, 8, 9]. For instance, Abeywickrama *et al.* [9] and Zhang *et al.* [8] demonstrate that electromagnetic coupling can lead to substantial array gain loss, which closely matches our simulation and analytical predictions. Furthermore, large-scale evaluations by Renzo *et al.* [2] and Basar *et al.* [1] emphasized the practical limitations of scaling Intelligent Reflecting Surfaces (IRS) without proper EM-aware design, in agreement with our finding that the IRS-to-relay performance crossover point can shift significantly with increasing coupling. Compared to these works, our framework is distinctive in its tractable integration of both phenomenological and circuit-inspired coupling models, enabling rapid benchmarking across a range of coupling strengths and IRS sizes. By directly reproducing baseline (uncoupled) results from Björnson *et al.* [11] and then extending to diverse coupling conditions, our approach offers a comprehensive and robust performance evaluation applicable to practical IRS deployments.

B. Comparison with EM-Based Studies

Table II summarizes the main performance trends reported in our work versus representative EM-based studies from the literature. Our results closely align with EM-based studies [8, 9], particularly regarding the severe array-gain degradation and the practical limitations of IRS scaling. Differences in exact quantitative values may arise due to model simplifications, but the qualitative performance trends remain consistent.

TABLE II. COMPARISON OF MUTUAL COUPLING IMPACT: THIS SIMULATION FRAMEWORK VS. EM-BASED IRS STUDIES

Metric/Feature	This Work: Phenomenological and Circuit Modeling	EM-Based Literature [8, 9]
Array Gain Degradation	Up to 70% loss for strong coupling (γ = 0.9); general trend and rates in close agreement with EM-based results.	Severe gain loss (reported up to 80% depending on EM/geometrical parameters); strong dependence on arrangement and meta-atom features.
Crossover Point (IRS vs. DF)	Shifts to much larger IRS surfaces (e.g., $N > 100$) and/or higher power as coupling increases; figures indicate the crossover explicitly.	Shift confirmed in EM studies: larger N or higher transmit power needed for IRS to outperform DF under strong coupling.
Simulation/Modeling Approach	Compact, parameterized mutual coupling matrix (M); supports both high-level (since kernel) and circuit-level analysis; enables large-scale performance sweeps.	Full-wave electromagnetic solvers; highly accurate for given design but computationally prohibitive for parametric studies or large N.
Innovation	Tractable, extensible model for rapid benchmarking and circuit exploration; bridges analytical, circuit, and EM perspectives.	Element/prototype-specific physics, primarily for precise validation and hardware codesign of small- to moderate-size arrays.

C. Parameter Regimes for IRS Advantage

Table III highlights typical parameter ranges where IRS outperforms DF relaying, consistent with our simulations. For strong coupling ($\gamma = 0.6$), only ultra-large arrays ($N \geq 400$) and/or favorable short distances yield an IRS advantage over DF relaying. For very strong coupling ($\gamma = 0.9$), no realistic IRS configuration outperforms the DF relay in our simulations.

TABLE III. PARAMETER RANGES WHERE IRS OUTPERFORMS DF RELAYING

γ	IRS Size N	Power (dBm)	S-D (d_1, m)
0.0 (ideal)	≥50	≤30	≤90
0.3 (mod.)	≥ 50	≤30	≤70
0.6 (str.)	≥400	≤35	≤50
0.9 (v.str.)	−	−	−

D. Future Research Directions

Several promising directions emerge from this work. First, hardware-based mitigation techniques, such as decoupling networks and optimized element spacing, should be investigated to reduce the impact of mutual coupling on IRS performance [1, 20]. Second, extending the analysis to multi-IRS deployments and randomly distributed surface scenarios would provide insights into more complex and realistic network topologies [21]. Third, advanced decoupling solutions at the circuit and electromagnetic levels warrant further study to bridge the gap between phenomenological models and full-wave simulations. Finally, experimental validation using fabricated IRS prototypes under controlled propagation conditions remains essential to confirm the trends predicted by our simulation framework.

VII. CONCLUSION

In conclusion, our study demonstrates the need to account for mutual coupling in the system-level evaluation of intelligent reflecting surfaces. By integrating coupling effects via a tractable simulation framework, we provide a more realistic performance benchmark for IRS deployments. The results highlight that mutual coupling can substantially degrade IRS performance, limiting the practical size and benefit of such surfaces in wireless systems.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS CONTRIBUTIONS

Marvin A. Guantero proposed the manuscript title, was responsible for data collection and preparation, and drafted the manuscript; Lawrence Materum supervised data review and put forward revision suggestions; both authors reviewed and approved the final manuscript.

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