

SCHOOL OF ELECTRICAL ENGINEERING
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Beamforming Design for Green 6G Wireless Networks

by

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Abstract

This project investigates energy-efficient beamforming for a multiuser downlink in which two base stations cooperate with a passive intelligent reflecting surface (IRS). The design jointly optimises the BS beamforming vectors and IRS phase shifts subject to per-BS power limits, minimum user rate requirements, and unit-modulus reflection constraints.

An iterative framework combines alternating optimisation (AO), successive convex approximation (SCA), and Dinkelbach's method. The reported simulations show stabilisation within ten iterations, approximately 40% higher sum-rate than a random-phase IRS, and more than three times the sum-rate of a no-IRS baseline at 30 dBm. The report also presents average sum-rates above 60 bits/s/Hz for $N_t = 8$ and M = 10. These results describe rate performance under the stated idealised channel assumptions. Assessing system energy efficiency additionally requires consistent accounting of the consumed power. Future work includes imperfect CSI, finite-resolution phase control, and experimental validation.

Keywords: 6G; intelligent reflecting surfaces; beamforming; energy efficiency; alternating optimisation.

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Abbreviations

Abbreviation	Meaning
6G	Sixth-Generation Wireless Networks
AI	Artificial Intelligence
AO	Alternating Optimization
AP	Access Point
BCD	Block Coordinate Descent
BS	Base Station
CoMP	Coordinated Multipoint
CSI	Channel State Information
D2D	Device-to-Device
EE	Energy Efficiency
IRS	Intelligent Reflecting Surface
JP-CoMP	Joint Processing Coordinated Multipoint
KKT	Karush–Kuhn–Tucker
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
MM	Majorisation-Minimisation
MMSE	Minimum Mean-Square Error
OFDM	Orthogonal Frequency-Division Multiplexing
QoS	Quality of Service
RF	Radio Frequency
RIS	Reconfigurable Intelligent Surface
SCA	Successive Convex Approximation
SDP	Semidefinite Programming
SDR	Semidefinite Relaxation
SE	Spectral Efficiency
SINR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal-to-Noise Ratio
STAR-RIS	Simultaneously Transmitting and Reflecting Reconfigurable Intelligent Surface
SWIPT	Simultaneous Wireless Information and Power Transfer
URLLC	Ultra-Reliable Low-Latency Communication
WMMSE	Weighted Minimum Mean-Square Error
XL-MIMO	Extremely Large-Scale MIMO

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Chapter 1: Introduction

1.1 Introduction

The growing demand for wireless data and environmentally sustainable network operation motivates energy-efficient design for future wireless systems. Multiple-antenna base stations can improve spectral efficiency through active beamforming, but their RF chains, amplifiers, and supporting circuitry also consume power. Interference between simultaneously served users and neighbouring cells further couples the rate and power objectives [1], [2].

Intelligent reflecting surfaces (IRSs) provide adjustable control of reflected signals without active RF amplification. Their controllers and configuration processes still require power. This project investigates a green-network beamforming model with two base stations, K single-antenna users, and one passive IRS. The design jointly adjusts BS precoding vectors and IRS phase shifts under BS power limits, minimum user rates, and unit-modulus reflection constraints [3].

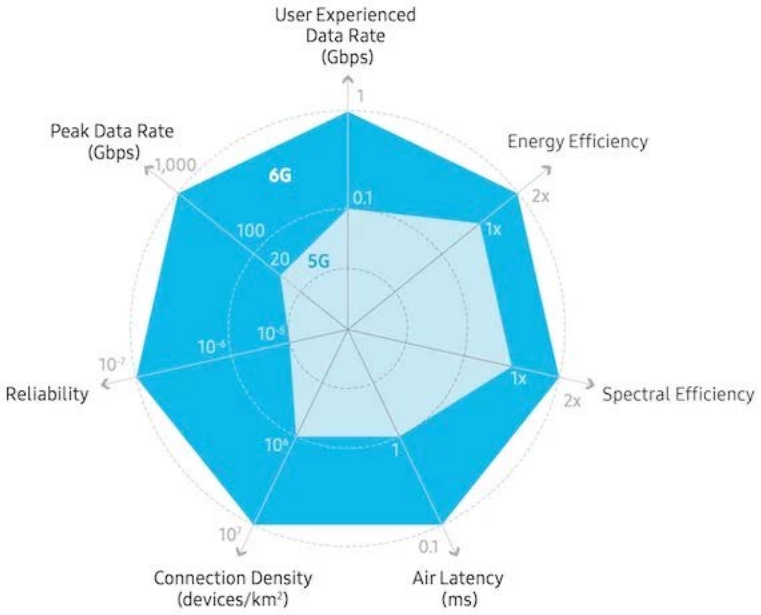

Figure 1. Design requirements for 6G wireless networks
Source: [4], image credited to Samsung.

The optimisation problem is fractional and non-convex because the beamforming and reflection variables are coupled through the desired-signal and interference terms. The implementation combines alternating optimisation, SCA, and Dinkelbach's method. The reported simulations compare the optimised IRS against random-phase and no-IRS baselines, with approximately 40% and more than threefold sum-rate improvements, respectively, at the stated operating point. These comparisons motivate a closer examination of both achievable rates and the associated power consumption.

An IRS uses programmable reflecting elements to adjust the propagation of incident signals. Joint design with the BS beamformers can strengthen useful signal components and manage interference. The achievable benefit depends on the channel model, surface hardware, available CSI, and power accounting, which are reviewed in Chapter 3 [3], [5].

1.2 Problem Statement

The development of green 6G networks demands extreme spectral efficiency alongside minimal power usage. The research focuses on solving the energy-efficiency (EE) optimization problem for a system

with two base stations and one passive Intelligent Reflecting Surface (IRS) that serves multiple users. The system aims to find the best combination of base-station precoding vectors and IRS phase shifts which will optimize the sum-rate to total transmit power ratio under given power constraints and user rate requirements and phase shift restrictions.

The optimization problem contains non-convex and fractional elements which create complex relationships between precoding and reflection variables and produce nonlinear SINR expressions. The system faces two main operational difficulties because it operates with stationary wireless channels and needs algorithms that can run in real time with minimal complexity. The development of an efficient solution will enable passive IRS technology to achieve its complete potential for sustainable 6G wireless networks.

1.3 Thesis Objectives

The main goals of this Thesis C project consist of:

1. The Thesis A/B developed EE maximization algorithm needs implementation and validation for a two-BS K-user 6G system which uses a passive Intelligent Reflecting Surface (IRS) for assistance.

2. The MATLAB simulation platform requires full development to simulate the BS-IRS-user channel sequence and joint precoding and phase-shift optimization through AO framework with SCA and Dinkelbach's method.

3. The research evaluates the performance improvement of the optimized IRS system against two reference scenarios which use random IRS phase settings and direct wireless links without IRS assistance.

4. The research examines how different system parameters including transmit power and IRS element numbers and base station antenna quantities affect both system performance and optimization convergence.

5. The research uses multiple simulation runs to show that the proposed solution reaches convergence within 10 iterations while achieving 40% better sum-rate performance than random IRS and 3 times better performance than no-IRS at standard transmission power levels thus proving IRS as a key green 6G network enabler.

1.4 Motivation and Scope

Green 6G research considers how higher communication capability can be provided while controlling the energy consumed by transmission, hardware, and network operation. Broad surveys discuss candidate applications and technologies, but the relevant question for this project is the rate and power trade-off of the specified IRS-assisted configuration [6], [7].

The main objective of this research involves simultaneous achievement of both high energy efficiency and fast data transfer rates.

Passive IRS control can alter desired-signal and interference paths without active RF amplification. Prior work already considers green IRS beamforming and coordinated multipoint transmission. The motivation here is to implement and evaluate their underlying design ideas for the stated two-BS setting and to compare the resulting behaviour under a consistent set of assumptions [5], [8].

The research focuses on an energy-efficiency-oriented two-BS multiuser downlink assisted by one passive IRS. Its numerical evaluation compares sum-rate and convergence behaviour across the stated transmission schemes.

1.4.1 Scope of the Thesis

• The EE-maximization algorithm from Thesis A/B requires full implementation and thorough simulation testing.

• The system operates with complete channel state information and continuous phase modulation and block fading that remains static throughout each period.

• The research assesses how transmission power levels and IRS dimensions and antenna configurations affect both total data transmission rates and system convergence performance.

• The research evaluates the performance of the system against two reference points which include random-phase IRS and no-IRS configurations.

The baseline model assumes perfect CSI, continuous IRS phase shifts, and quasi-static block fading. Imperfect CSI, finite phase resolution, and mobility are considered as directions for future work.

1.5 Problem Definition

The fast growth of data-intensive applications together with worldwide efforts to reduce carbon emissions has established energy efficiency as a fundamental necessity for 6G wireless networks. The research investigates methods to achieve maximum energy efficiency (EE) in bits/Joule/Hz for a two-base-station (two-BS) multi-user downlink system that uses a single passive Intelligent Reflecting Surface (IRS) for assistance.

The main optimisation task involves finding the maximum ratio of total achievable sum-rate to total transmit power that two BSs consume under given power limits and user rate requirements and IRS phase shift restrictions. Mathematically:

$$max \frac{\sum_{k=1}^{k} log2(1 + SINRk)}{\sum_{k=1}^{k} \| wk \|^2}$$

The system operates under two conditions, which include per-BS power restrictions and $Rk > Rmin \, \forall k \; and \; |[\theta m]m| = 1$

Where Wk represents the combined active beamforming vectors and θ represents the passive IRS phase shifts.

The problem (P0) presents multiple challenges because of its non-convex structure and fractional objective function.

The problem contains three main difficulties, which stem from its fractional objective function and its tight beamformer-phase relationship in the cascaded channel and its non-linear SINR expressions with interference terms and its non-convex unit-modulus constraints.

The solution requires advanced iterative methods because standard convex solvers fail to solve this problem. The solution method developed in this work uses alternating optimisation with SCA and Dinkelbach's method to solve all difficulties which resulting in fast convergence and achieves 40% higher sum-rate than random IRS and 3× better performance than systems without IRS. The solution provides essential foundations for sustainable 6G network deployment.

Chapter 2: Theoretical Background

2.1 6G Technology

Research on 6G considers a combination of high data rates, extensive connectivity, reliability, sensing, and energy efficiency. These objectives must be balanced under practical network and hardware constraints. In this report, the focus is the joint design of BS beamforming and IRS reflection rather than the validation of an entire 6G architecture [6], [9], [7].

Base stations with multiple antennas boost spectral efficiency through active beamforming yet they consume significant power from RF chains and amplifiers which are energy-intensive. The performance of wireless networks deteriorates significantly in dense urban areas because of strong interference between cells and users which requires operators to increase their transmission power.

An intelligent reflecting surface, also called a reconfigurable intelligent surface (RIS), controls the reflected field through adjustable elements. A passive IRS redirects incident RF energy rather than actively amplifying it. This can improve useful propagation paths, but the surface-control circuitry, channel acquisition, and associated processing still contribute to the system power budget [3], [10].

Existing studies investigate IRS-assisted rate optimisation, transmit-power reduction, and energy efficiency under different single-cell and coordinated network models [5], [11], [8].

This project implements and evaluates an EE-oriented design for a specified two-BS, single-IRS downlink under minimum-rate and per-BS power constraints. Its relationship to earlier green IRS and coordinated transmission studies is examined in Chapter 3; the topology and general optimisation approach are established research directions.

2.2 Passive IRS

A passive Intelligent Reflecting Surface (IRS) consists of a flat metasurface which contains numerous low-cost reflecting elements that function as independent phase shifters and amplitude controllers for electromagnetic waves.

A passive IRS does not require the RF power amplifiers used by an active relay or active surface. Its control and biasing circuitry nevertheless consume power, and the complete network also incurs training, feedback, and processing costs. Whether the resulting architecture is more energy efficient depends on these costs and on the achieved service performance [3], [10].

The passive IRS serves three essential purposes in this research because it fulfills the requirements of the "green 6G" objective.

Passive reflection can improve propagation without adding active RF amplification at the surface. Any energy-efficiency comparison with active small cells or relays must use a consistent total-power budget and the same user service requirements.

- The IRS system generates beneficial wave patterns which strengthen signals for targeted users while simultaneously creating interference patterns that block signals from other users without requiring any additional RF power.

- The IRS system creates artificial direct paths between base stations and users which enables fast data transfer through reduced transmission power levels in areas with blocked direct signal paths.

- The printed-circuit manufacturing process enables IRS production at affordable costs while providing lightweight flexible designs that outperform new active base station deployment methods.

• The system operates without requiring user equipment modifications because it works through base station controller updates.

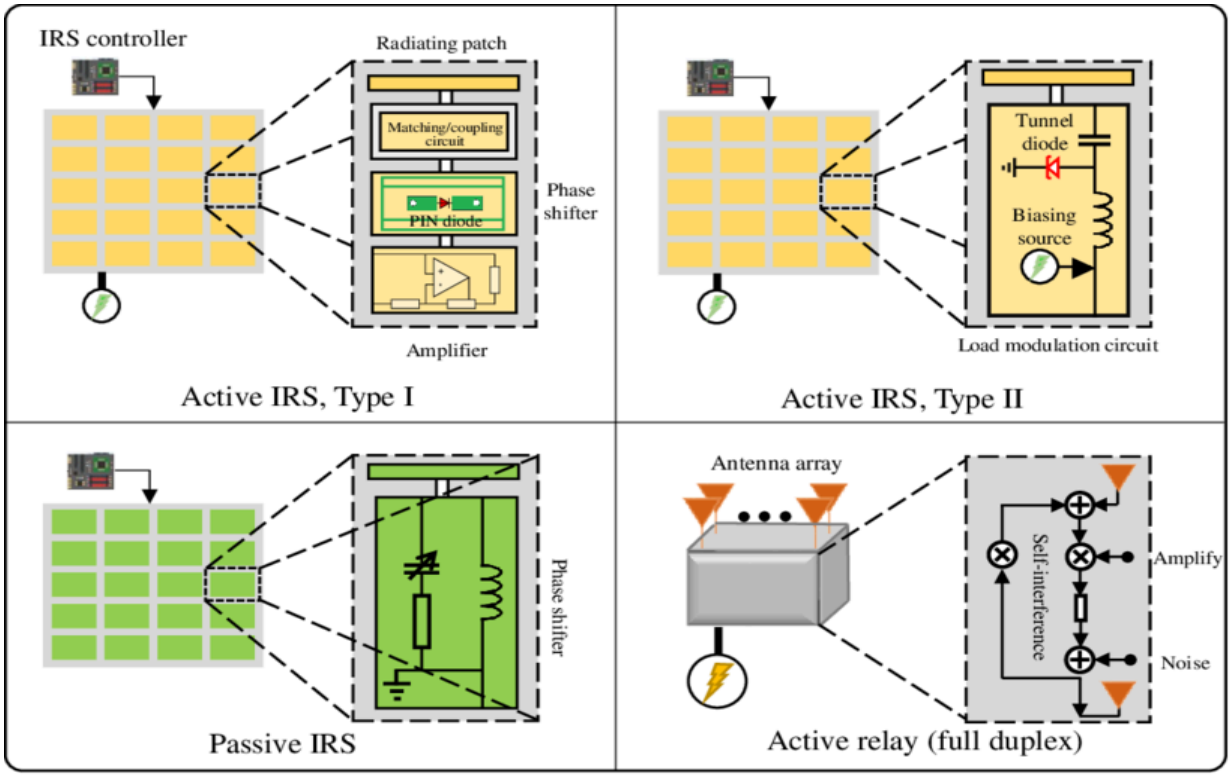

Figure 2. Architectures of active IRS, passive IRS and active relay systems

Reference for picture- Active-IRS-Aided Wireless Communication: Fundamentals, Designs and Open Issues - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Hardware-architectures-of-active-IRS-passive-IRS-and-active-relay_fig1_367051550 [accessed 18 Nov 2025]

2.3 Problem Formulation

The following section establishes the optimization problem which seeks to achieve maximum energy efficiency (EE) in the proposed IRS-assisted 6G wireless network. The optimization problem employs the system model from Thesis A to optimize BS beamforming and IRS phase shifts for maximum data rates at minimum power consumption with the system consists of two base stations (BSs) and a passive intelligent reflecting surface (IRS) and K users. The problem verification process in Thesis B progress report confirmed the 6G network dynamics which include the objective function and constraints and assumptions. The formulation demonstrates non-convex challenges that stem from the fractional EE

objective and variable coupling and unpredictable wireless channel behavior which need subproblem decomposition for solution development.

$$\max_{\omega,\theta} \quad \frac{\sum_{k=1}^{k} log2(1+(\omega,\theta))}{\sum_{k=1}^{k} \|\omega k\|^2 + Pc}$$

2.3.1 System Model

The system consists of two base stations (BSs) with multiple antennas (e.g., N_t antennas per BS) and a passive intelligent reflecting surface (IRS) with *M* reflecting elements and *K* single-antenna users. The base stations work together to provide user service through coordinated methods which include cell-free and multi-cell configurations to minimize interference between base stations. The passive IRS operates as a signal reflector to improve coverage and block obstacles without needing power to amplify signals.

2.3.2 Channel Model

$\mathbf{hd,k} \in \mathbb{C}^{M*1}$ => Direct Channel From Base Station To User K

$\mathbf{hr,k} \in \mathbb{C}^{N*1}$ => Chanel From IRS To User K

$\mathbf{G} \in \mathbb{C}^{N*M}$ => *Channel from Base Station To IRS*

Wk => *Beamforming Vectors*

Sk => *Information Symbol*

Nk => *Noise*

The received signal at user K is

$$\mathbf{yk} = (\boldsymbol{hd^H, k\, wk + hr^H, k\, \phi G wk})\, \boldsymbol{Sk} + \sum_{j \neq k} (\boldsymbol{hd^H, k\, wj + hr^H, k \phi G wj})\, \boldsymbol{Sj} + \boldsymbol{nk}$$

2.3.3 Signal-to-Interference-plus-Noise Ratio

$$\text{SINR} = \frac{\left| hd^{H},kWk+hr^{H},k\varphi GWk \right|^{2}}{\sum_{j\neq k} |hd^{H},kWj+hr^{H},k\varphi GWj|^{2}+\delta^{2}}$$

where

$\left|hd^{H}, kWk + hr^{H}, k\varphi GWk\right|^{2}$ = Desired Signal Power

$|hd^{H}, kWk + hr^{H}, k\varphi GWk|^{2}$ = Interference Plus Noise

δ^{2} = Gaussian noise

The SINR value demonstrates how the desired signal power relates to the combined power of interference and noise signals.

The adopted power model describes BS transmit power and a fixed circuit-power contribution. Treating IRS-control power as negligible is a simplifying assumption of the baseline, rather than a physical property of all passive surfaces. Chapter 3 discusses the consequences of this assumption for interpreting energy-efficiency results.

The optimisation baseline assumes complete channel information and quasi-static channels. It does not explicitly evaluate the energy or latency required to acquire CSI and distribute the computed configurations.

2.4 Optimisation Problem

The main goal focuses on achieving maximum EE value because it represents the total sum rate divided by total power consumption to support sustainable 6G networks.

$$\text{Maximize} \quad Log2\left[1 + \frac{\left|hd^{H},k+hr^{H},k\varphi GWk\right|^{2}}{\sum_{j\neq k}\left|hd^{H},kWj+hr^{H},k\varphi\, Gwj\right|^{2}+\delta^{2}}\right]$$

$$\underset{Wk,\varphi}{}$$

$$\text{Subjected to,} \quad \mathbf{Log2(1 + SINR)} > Rmin, \forall k = 1 \ldots..$$

$$\sum_{k=1}^{k} \| wk \|^{2} < Pmax$$

$$|\theta n| = 1, \forall n = 1$$

The problem includes non-convex elements because of:

• The EE objective function includes fractional elements.

• The SINR expressions include the beamforming vector W and phase shift vector θ which exist as interconnected elements.

• The SINR and rate functions include nonlinear interference terms.

• The IRS elements need to maintain unit modulus constraints.

The problem breaks down into smaller subproblems according to the progress report which solves convex problems for power constraints and handles non-convex elements through approximation methods. The proposed formulation allows the algorithm development in the following sections to optimize energy efficiency for 6G communication systems.

2.5 Methodology

2.5.1 Overview

The non-convex fractional EE maximisation problem (P0) receives solution through a triple-layer iterative method which unites Dinkelbach's method with Alternating Optimisation (AO) and Successive Convex Approximation (SCA). The method solves the fractional objective which contains sum-rate/power terms through Dinkelbach's method.

The algorithm uses Alternating Optimisation (AO) to separate the optimisation of the active beamforming vectors $\{\boldsymbol{w}_k\}$ from that of the passive IRS phases θ. The Successive Convex Approximation (SCA) method uses first-order Taylor expansion to transform non-concave rate functions into concave lower bounds.

2.5.2 Algorithm Steps

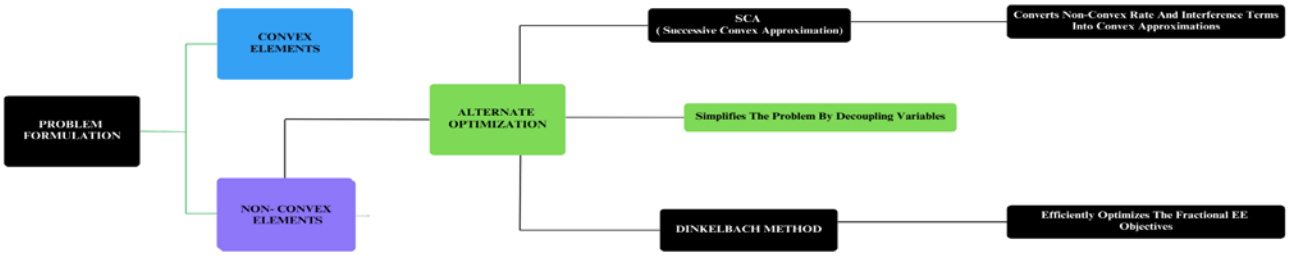

Figure 3. Alternating optimisation framework

2.5.3 Convergence and Complexity

Monotonic improvement requires the SCA surrogates and alternating updates to satisfy the assumptions of the convergence argument. Any relaxation and subsequent unit-modulus projection must also preserve feasibility and the claimed improvement. The simulations report empirical convergence behaviour; the relevant distinctions between numerical stabilisation, stationarity, and global optimality are discussed in Chapter 3.

The report gives a runtime of less than three seconds per channel realisation. Interpreting this figure for online operation also requires the processor, solver settings, problem dimensions, and channel-update interval.

- The total computational cost of each iteration stems from solving two convex SDP problems with specific dimensions.

Chapter 3: Literature Review

Energy-efficient beamforming for an IRS-assisted network draws on several established research areas: green resource allocation, programmable propagation, coordinated transmission, and non-convex optimisation. This chapter reviews these areas with attention to the objective being optimised, the power consumption included in that objective, the available channel state information (CSI), and the constraints imposed by the reflecting hardware. These distinctions establish the context for the two-base-station implementation studied in this report and the limits of the conclusions that its simulations can support.

3.1 Green wireless networks and energy efficiency metrics

Green communication is a network design objective rather than a property that follows automatically from increasing the achievable rate. Wu et al. [1] review energy-efficient transmission and renewable energy use as complementary approaches to sustainable wireless networks. Chen et al. [2] explain the trade-offs linking energy efficiency, spectral efficiency, deployment, bandwidth, and delay. Together, these works motivate evaluating useful service per unit of consumed energy, while maintaining the quality of service (QoS) required by users.

Broader surveys place this objective within the evolution towards 6G. Shafi et al. [6] review candidate technologies and their development, whereas Akbar et al. [9] consider requirements, applications, architectures, and security challenges. Huang et al. [7] focus specifically on green 6G architectures and enabling technologies. Maiti and Juneja [12] discuss complementary energy-saving mechanisms, including resource allocation, base-station operation, and beamforming. These surveys provide motivation for the present study; their network-wide visions do not establish numerical performance guarantees for a particular IRS configuration. Similarly, the massive-access survey by Chen et al. [13]

provides context for connectivity, coverage, and device energy requirements, rather than evidence for a specific two-BS IRS beamforming algorithm.

Three objectives must therefore be kept separate. Sum-rate maximisation rewards delivered throughput, transmit-power minimisation reduces radiated power for prescribed service targets, and energy-efficiency maximisation balances throughput against an explicitly defined power denominator. If the numerator is sum spectral efficiency in bits/s/Hz, division by power in watts gives bits/J/Hz. Multiplication by the system bandwidth gives throughput in bits/s and consequently energy efficiency in bits/J. A comparison of sum-rate curves alone cannot determine a system-level energy-efficiency gain when circuit, control, or processing power differs between the compared schemes [2], [11].

3.2 Energy-aware beamforming and network power consumption

The power model is central to the choice of beamforming and network architecture. Ng, Lo, and Schober [14] study energy-efficient resource allocation with a large number of base-station antennas, explicitly linking the benefits of additional spatial degrees of freedom to the power cost of activating hardware. Their multicell study [15] extends energy-aware resource allocation to systems with limited backhaul capacity. These studies demonstrate why reducing radiated power does not by itself settle whether a larger antenna array or more extensive cooperation is energy efficient. The corresponding implication for this project is to distinguish the two BS transmit budgets from the total power consumed by the coordinated system.

Wireless-powered communication provides a further perspective on defining the energy objective. Wu et al. [16] jointly optimise time and power allocation using fractional programming, while their user-centric study [17] makes the energy efficiency of the served devices an explicit design concern. Zhang et

al. [18] incorporate uncertain CSI and service requirements in robust energy-efficient wireless-powered D2D transmission. These are different architectures from the passive-IRS downlink considered here. Their relevance lies in the need to specify whose energy is counted, which operation consumes that energy, and which service constraints must remain feasible.

For the present two-BS setting, a consistent evaluation should identify whether the denominator contains only radiated power or also amplifier losses, BS circuitry, backhaul operation, IRS control, and computation. A fixed circuit term can be a useful abstraction, provided that it is applied consistently across the optimised-IRS, random-IRS, and no-IRS cases. When the number of antennas or reflecting elements changes, treating all non-radiated power as an unchanged constant can conceal the cost of the added hardware. This is a modelling issue that should be separated from the effectiveness of the optimisation routine [14], [15], [5].

3.3 IRS modelling and passive hardware assumptions

An IRS controls the reflected electromagnetic field through adjustable elements, making the propagation environment part of the design. Yu et al. [3] compare independent-scatterer, physics-based, and impedance-network models and discuss the resulting balance between physical accuracy and computational tractability. The diagonal phase-shift model used in many beamforming studies is therefore a useful abstraction whose assumptions must be stated. The multiuser survey by Munochiveyi et al. [19] places such surface control within a broader set of interference-management and resource-allocation problems.

Passive reflection does not require the surface to amplify the incident RF signal. It does not, however, imply that a complete IRS installation consumes no energy. Configuration circuitry, controllers, training, feedback, and associated processing still affect the system budget. Hu et al. [10] explicitly study robust secure transmission with a self-sustainable IRS, illustrating that powering the surface is itself a design

consideration. Shen et al. [20] examine beamforming under transceiver hardware impairments, further showing that ideal hardware assumptions can change the predicted benefit of optimised reflection.

This report adopts a passive surface with continuous phase control and ideal unit-modulus reflection coefficients. This abstraction isolates the coupling between BS beamformers and surface phases; it does not model all losses or implementation overheads. The literature supports using it as a baseline for algorithm development, while interpreting any green-network benefit within the chosen power and channel models. Statements about universal superiority over active relays, negligible installation power, or practical deployment performance would require additional assumptions and comparisons beyond this baseline [3], [20], [10].

3.4 Joint active and passive beamforming for green transmission

A directly relevant foundation is the work of Yu et al. [5], who jointly design access-point beamforming and IRS reflection to reduce transmit power under user QoS constraints. Their penalty-based alternating-minimisation and inner-approximation approaches provide explicit convergence guarantees, and the framework also addresses imperfect CSI. This is an important methodological reference for the present project, although its transmit-power objective differs from maximising a sum-rate-to-power ratio.

Energy-efficiency-oriented IRS design is also established in the uplink. You et al. [11] investigate the energy-efficiency and spectral-efficiency trade-off in a multiuser MIMO system with discrete surface phases and partial CSI. Their resource-efficiency formulation jointly designs user transmission and RIS reflection. In related work, You et al. [21] consider RIS-assisted multiuser MIMO uplink transmission with partial CSI. These studies show that reduced channel information and practical surface constraints

can be incorporated into joint optimisation. Their uplink architecture and statistical assumptions differ from the perfect-CSI coordinated downlink used in this report.

Other studies extend the energy objective to additional service requirements. Zargari et al. [22] investigate max-min fair energy-efficient beamforming in IRS-aided simultaneous wireless information and power transfer (SWIPT), including nonlinear energy harvesting. Liu et al. [23] consider energy efficiency in secure IRS-aided SWIPT. Khalili et al. [24] investigate the distinct trade-off between sum-rate and harvested energy through multi-objective resource allocation. Harvested energy and reduced supply-power consumption are different quantities, so that trade-off should not be interpreted as an EE result. These formulations introduce fairness, energy delivery, or secrecy constraints that are absent from the current system. They are useful comparisons because they show how the definition of useful output and the choice of constraints alter the resulting beamforming problem.

The common technical difficulty is the coupling of active beamforming and surface control in the effective channels, together with interference among simultaneously served users. Alternating optimisation makes the design manageable by updating subsets of variables, but its outcome depends on the accuracy of each subproblem and the treatment of the surface constraints. The current project applies this general strategy to an EE-oriented two-BS implementation; the use of alternating updates alone should not be presented as a new optimisation principle.

3.5 Coordinated base stations and cell-free extensions

Coordinated IRS-assisted transmission has already been investigated explicitly. Hua et al. [8] study IRS-aided joint-processing coordinated multipoint transmission from multiple BSs to cell-edge users. Wang et al. [25] extend resource allocation for IRS-aided JP-CoMP downlink networks to include underlaying D2D communication. These works establish that the interaction between BS cooperation and surface reflection is an existing research direction. In a joint-processing model, the participating BSs must

coordinate the signals intended for each user; merely labelling separate transmitters as coordinated does not specify the associated data-sharing and synchronisation assumptions.

Cell-free studies broaden the network model beyond two BSs. Shi et al. [26] analyse spatially correlated RIS-assisted cell-free massive MIMO, while Zhang et al. [27] investigate joint distributed precoding and beamforming. Yao et al. [28] incorporate CSI uncertainty and capacity-limited backhaul into robust RIS-aided cell-free beamforming. These papers make clear that channel correlation, coordination architecture, and information exchange can materially influence a distributed design. A two-BS configuration is a useful small-scale setting for investigating these interactions, but it does not by itself establish results for a general cell-free deployment.

More recent work addresses energy efficiency directly at this network level. Lu et al. [29] discuss energy-efficient RIS-aided cell-free massive MIMO and its opportunities and challenges. Han et al. [30] study resource-efficient beamforming in cell-free networks, and Liu et al. [31] combine cooperative clustering and power control for energy-efficient cell-free XL-MIMO. The last two studies provide related network-level context rather than direct replicas of an IRS-assisted two-BS system.

For this project, the useful comparison is therefore among specific assumptions and controllable variables: fixed or selectable transmitters, a single or multiple surfaces, centralised or distributed processing, perfect or uncertain CSI, and a transmit-power or total-energy objective. Keeping both BSs active and using one continuous-phase IRS produces a focused implementation problem. Its contribution is the resulting model-specific evaluation and the explanation of observed trends, rather than the introduction of coordinated IRS transmission itself.

3.6 Optimisation methods and the meaning of convergence

Fractional programming is relevant because the energy objective is a ratio. The wireless-powered formulation in [16] provides a concrete example of transforming an EE problem into a sequence of

parameterised subproblems. In the present system, the non-convex coupling between beamforming and surface phases remains after this transformation. Dinkelbach updates therefore do not remove the need to solve or approximate the inner optimisation problem appropriately. Alternating optimisation and successive convex approximation (SCA) address different parts of that difficulty, and their roles should be described separately.

Convergence claims also need to match the actual update rules. Yu et al. [5] develop methods with stationarity or KKT guarantees under their stated formulations. Wu et al. [32] provide globally optimal benchmarks for discrete-phase IRS transmit-power minimisation with perfect and imperfect CSI through generalised Benders decomposition, alongside lower-complexity SCA alternatives. These results distinguish a globally certified solution, a stationary solution, and a numerically stable iteration sequence. A flat sum-rate curve in the present simulations is evidence of empirical stabilisation; it does not establish global optimality of the EE objective.

For SCA, the surrogate objective and constraints must have the properties required by the chosen convergence argument. For the IRS update, projecting a relaxed coefficient onto the unit circle changes the candidate solution and can affect both the objective and the QoS constraints. Feasibility and the true objective should therefore be checked after projection. Rank-constrained beamforming methods, such as the framework of Le et al. [33], provide relevant mathematical context, but a guarantee for one rank-one formulation cannot automatically be transferred to a different relaxed and projected algorithm.

Computational scale is another distinction between algorithms. Xu et al. [34] develop a scalable optimisation framework for large IRS-assisted SWIPT systems. Wang et al. [35] investigate rapidly converging low-complexity transmit precoders for massive MIMO downlinks, and Wei et al. [36] review resource-allocation methods for next-generation multiple access. These studies motivate reporting complexity together with performance. For the current implementation, iteration count,

dimensions of the solved subproblems, solver accuracy, and runtime under a specified platform are more informative than iteration count alone.

3.7 Channel acquisition and robust beamforming

Perfect CSI is useful for separating optimisation behaviour from estimation error, but obtaining the cascaded BS-IRS-user channels is itself a substantial task. Zhang et al. [37] investigate cascaded channel estimation with quantised beamforming for IRS-assisted millimetre-wave multi-antenna systems. Liu et al. [38] use deep residual learning for channel estimation in IRS-assisted multiuser communication, and Jin et al. [39] study enhanced deep residual networks for semi-passive RIS channel estimation. These approaches involve different sensing, hardware, and training assumptions, so their overhead cannot be represented by a single universal CSI cost.

Model-based estimation offers another route. Chu et al. [40] develop a partially decoupled atomic-norm approach for RIS-aided MIMO channel estimation. Gao et al. [41] instead investigate distributed IRS transmission with statistical passive beamforming. In conjunction with the partial-CSI transmission studies [11], [21], this literature shows the choice between frequent instantaneous adaptation and designs based on more slowly varying information. The appropriate choice depends on how quickly the channels change and how much training and feedback the network can support.

Robust optimisation becomes necessary when the information available to the controller is uncertain. Yu et al. [42] jointly design beamformers, artificial noise, and IRS phases for secure transmission with imperfect eavesdropper CSI. Their objective concerns secure communication rather than the EE objective considered here, but the study illustrates how channel uncertainty must be embedded in the constraints and design. Yao et al. [28] and Wu et al. [32] provide further examples involving network constraints and discrete phases. Extending the present implementation should consequently involve an

explicit error model and a feasibility assessment under that model, rather than only substituting perturbed channels into a perfect-CSI solution.

3.8 Discrete phases and dynamic propagation

Continuous phase control offers an idealised reference against which finite-resolution designs can be evaluated. The discrete-phase resource-allocation study [32] and the EE-SE trade-off study [11] show that practical phase alphabets can be treated as part of the optimisation. An et al. [43] review codebook-based RIS solutions and their open challenges, offering a complementary way to reduce the configuration search and associated overhead. For this project, a meaningful finite-resolution extension would compare direct discrete optimisation or codebook selection against quantisation of the continuous solution, while checking user QoS after each conversion.

The narrowband phase-only model also omits effects that become relevant in distributed or frequency-selective operation. Zhao et al. [44] investigate cooperative reflection with timing offsets in distributed multi-RIS communication. An et al. [45] study adjustable-delay RIS operation for OFDM systems. These works motivate separate treatment of synchronisation and frequency selectivity: a single phase adjustment need not align all signal components over a wide band or compensate for asynchronous paths. Their benefits should not be assumed for the phase-only configuration evaluated here.

Temporal variation further limits the duration for which an optimised configuration remains useful. Zhang et al. [46] study channel-aging-aware precoding for RIS-assisted communication, and Shi et al. [47] address channel aging in RIS-aided cell-free massive MIMO. Shi et al. [48] also analyse electromagnetic interference in RIS-aided cell-free uplink operation. These studies identify distinct effects that the current block-fading, perfect-CSI model does not capture. They motivate examining update latency, aging, and external interference before extrapolating static-channel results to mobile deployments.

3.9 Alternative surfaces and learning-based methods

Other surface architectures offer different benefits and impose different energy constraints. Gao et al. [49] investigate active-IRS beamforming for SWIPT, while Wang et al. [50] consider robust energy-efficient resource allocation for active-IRS-assisted cognitive rate-splitting multiple access. Deshpande et al. [51] examine energy-efficient STAR-RIS-aided multiuser MIMO for ultra-reliable low-latency communication. Active amplification, simultaneous transmission and reflection, and stringent reliability requirements change the system model and power budget; their reported gains are not directly transferable to the passive reflecting surface used here.

Increasing the number of surfaces also changes the optimisation. Niu et al. [52] study double-IRS multiuser MIMO millimetre-wave systems with hybrid precoding. Saeidi et al. [53] consider weighted sum-rate maximisation in multi-IRS full-duplex systems with hardware impairments. These papers provide relevant directions for extending spatial control, while introducing additional propagation paths, coupling, and implementation assumptions. Such extensions should follow validation of the single-surface baseline.

Learning-based approaches offer another computational alternative. Mao et al. [54] review AI models for green communications, and Yi et al. [55] investigate distributed multicell precoding through unfolding of the weighted minimum mean-square error algorithm. The multi-agent approach in [31] further illustrates the use of learning for network-level decisions. Compared with the deterministic AO-SCA framework used here, these approaches introduce training, generalisation, and online-inference considerations. A fair comparison would include feasibility, deployment overhead, and performance on channel conditions beyond those used for training.

3.10 Comparison with representative studies

Table 1 summarises the closest relationships between the reviewed literature and the present configuration. The purpose of the comparison is to identify which assumptions are shared and which would require a different formulation. It is particularly important to distinguish published algorithmic guarantees from empirical behaviour observed in a particular simulation.

Table 1 Comparison of representative studies and the present project

Study	System and design focus	Distinction relevant to this project
Ng et al. [14], [15]	Energy-efficient antenna and multicell resource allocation	Establishes the roles of circuit power in energy accounting and backhaul capacity in cooperation; no IRS in these models.
Yu et al. [5]	QoS-constrained green IRS beamforming with perfect and imperfect CSI	Transmit-power minimisation with explicit convergence analysis, rather than the same fractional EE formulation.
You et al. [11], [21]	RIS-assisted multiuser MIMO uplink with partial CSI	Different transmission direction and CSI assumptions; [11] explicitly studies the EE-SE trade-off and discrete phases.
Hua et al. [8]; Wang et al. [25]	IRS-assisted JP-CoMP and a D2D-underlay extension	Prior coordinated multi-BS transmission; the exact objective, interference model, and service constraints must be compared.
Yao et al. [28]	Robust RIS-aided cell-free beamforming	Includes CSI uncertainty and capacity-limited backhaul omitted from the current baseline.
Wu et al. [32]	Discrete-phase IRS transmit-power minimisation	Globally optimal benchmark and lower-complexity alternatives; global guarantees do not carry over to generic AO.

Study	System and design focus	Distinction relevant to this project
Lu et al. [29]; Han et al. [30]	Energy-efficient RIS cell-free networking and resource-efficient beamforming	Broader network perspective; the resource-efficiency objective in [30] combines energy and spectral efficiency.
Present project	Two fixed BSs, one passive IRS, perfect CSI, continuous phases	Implementation and evaluation of joint beamforming and reflection; conclusions are bounded by the power model and reported simulation metrics.

3.11 Positioning and directions for the present project

The reviewed work supports a focused contribution for this thesis: implementing and evaluating the joint BS-beamforming and IRS-phase optimisation framework for the stated two-BS configuration, and explaining its behaviour against consistent random-phase and no-IRS baselines. Earlier research already addresses IRS-assisted green transmission, coordinated multipoint operation, and network energy efficiency [5], [8], [29]. The novelty of the present work should therefore be assessed through the precise formulation, implementation details, and demonstrated insights, rather than a general claim to be the first multi-BS IRS energy-efficiency solution.

The reported results can be interpreted most clearly by separating three questions. First, do the beamforming and reflection updates improve the measured sum-rate under the stated setup? Second, do the returned solutions satisfy each BS power limit, the user rate requirements, and the final phase constraints? Third, does the achieved rate-to-consumed-power ratio improve under the same energy-accounting rules for every baseline? These questions are related, but a positive answer to the first does not establish the other two.

The next extensions follow directly from the comparison: account explicitly for surface-control and coordination power; incorporate uncertain or statistical CSI; impose finite phase resolution; and evaluate channel aging, update latency, and larger coordinated networks. Robust and discrete-phase methods [32], partial-CSI designs [21], and cell-free network formulations [28], [29] provide relevant starting points. This progression would test whether the implementation insights remain useful when the idealised assumptions are relaxed, without attributing untested hardware or system-level performance to the current simulations.

Chapter 4: System Description

4.1 Network Topology

The proposed green 6G system consists of:

The system includes operating base stations, which use N_t transmit antennas for operation.

The system contains K mobile users who each have one antenna (the number of users is typically set to 4).

The system includes one passive Intelligent Reflecting Surface (IRS) with M reflecting elements which operates from a building wall or facade.

The central controller maintains access to both BSs through high-speed backhaul connections (e.g. fibre) to execute optimal beamforming vector and IRS phase shift calculations under the assumption of complete channel state information (CSI).

The IRS operates as a passive element that redirects BS signals toward users through its reflecting surface without requiring any RF chains or power amplifiers. The system provides two separate communication paths for each user to connect between base stations and users directly and through the BS-IRS-user reflection path.

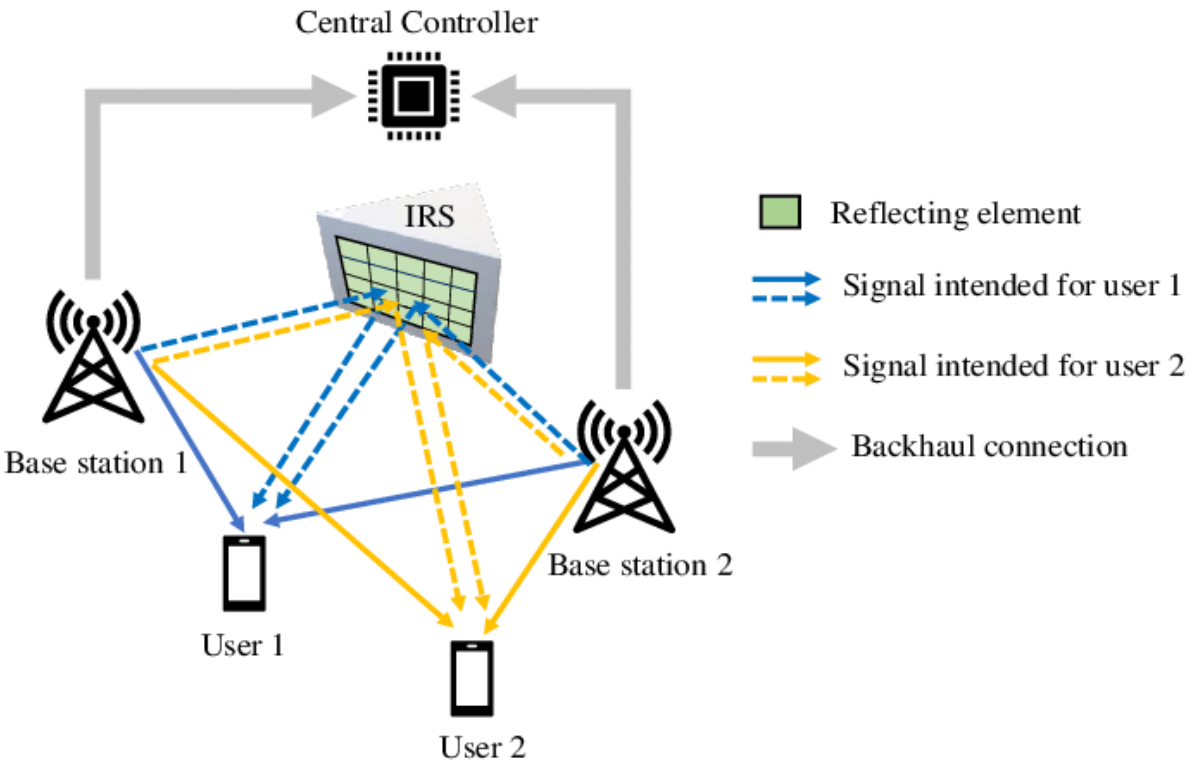

Figure 4. Two-base-station IRS-assisted multiuser system

4.2 Channel Model

Key Channels:

hd,k $\in \mathbb{C}^{M*1}$ => Direct Channel From Base Station To User K

hr,k $\in \mathbb{C}^{N*1}$ => Chanel From IRS To User K

G $\in \mathbb{C}^{N*M}$ => *Channel from Base Station To IRS*

Wk => *Beamforming Vectors*

Sk => *Information Symbol*

Nk => *Noise*

4.3 Transmitted and Received Signal

The received signal at user K is

$$\mathbf{yk} = (\boldsymbol{hd^H, k\, wk + hr^H, k\, \phi Gwk})\, \boldsymbol{Sk} + \sum_{j \neq k} (\boldsymbol{hd^H, k\, wj + hr^H, k \phi Gwj})\, \boldsymbol{Sj} + \boldsymbol{nk}$$

4.4 SINR and Achievable Rate

$$\mathbf{SINR} = \frac{\left| \boldsymbol{hd^H, kWk + hr^H, k\varphi GWk} \right|^2}{\sum_{j \neq k} |\boldsymbol{hd^H, kWj + hr^H, k\varphi GWj}|^2 + \boldsymbol{\delta^2}}$$

where

$\left|\boldsymbol{hd^H, kWk + hr^H, k\varphi GWk}\right|^2$ = Desired Signal Power

$|\boldsymbol{hd^H, kWk + hr^H, k\varphi GWk}|^2$ = Interference Plus Noise

$\boldsymbol{\delta^2}$ = Gaussian noise

4.5 Proposed Algorithm

1: **Input:** Channels (hd,k,i, hr,k, Gi), noise σ 2 , constraints (Rmin, Pmax,i)

2: **Initialize:** wk,i, Θ

3. Using Alternate Optimisation to decouple the Variables.

4. **Subproblem 1:** Optimise wk, i with fixed Θ

5. Compute effective channels: hk,i = h H d,k,i + h H r,kΘGi

6. Approximate rates with SCA: Rk ≈ log2 (Ak +Bk)−log2 (Bk), using Taylor expansion for log2 (Bk)

7. Solve convex problem: max∑ k [log2 (Ak +Bk)−log2 (Bk)]−γPtotal subject to log2 (1+ Ak/Bk) ≥ Rmin, Σ k //wk,i // 2 ≤ Pmax,i

8. **Update wk,i**

9. **Subproblem 2:** Optimize Θ with fixed wk,i

10. Vectorize phases: v = [e jθ1 , . . . , ejθN] T

11. Approximate Rk with SCA, relaxing |vn| ≤ 1

12. **Solve:** max∑ k R˜ k subject to log2 (1 + Ak/Bk) ≥ Rmin, |vn| ≤ 1
13. Project: vn ← e j arg(vn)
14. **Update: Θ** = diag(v)
15. **Dinkelbach Update:** Update γ
16. **Output:** Optimal wk,i, Θ, EE value

4.6 Constraints

4.6.1 Per-BS Transmit Power Constraints

The base stations operate under separate maximum transmit power limits.

$$\sum_{k=1}^{k} \| wk^{i} \|^{2} \leq Pmax, \quad i = 1,2$$

The expression wk^{i} represents the beamforming vector segment that BS i uses to communicate with user k. The expression reflects actual hardware constraints together with regulatory restrictions that control the maximum power output for each site.

4.6.2 Minimum Rate QoS Constraints

The system provides users with a guaranteed minimum data rate of Rmin bits/s/Hz, which depends on their service class and ranges from 2 to 5 bits/s/Hz.

$$Rk = log2(1 + SINRk) \geq Rmin, \forall k$$

The system maintains fairness while supporting time-sensitive applications through its operation in environments with interference limitations.

4.6.3 Unit-Modulus IRS Phase-Shift Constraints

The M reflecting elements in the system have phase adjustment capabilities but their amplitude remains fixed.

$$|[\theta]m| = 1, \forall k = 1 \ldots . . M$$

The basic characteristic of current passive IRS hardware systems based on PIN-diode or varactor-based metasurfaces leads to a non-convex constant-modulus manifold which makes optimisation challenging.

Chapter 5: Simulation and Results

5.1 Simulation Setup

The MATLAB environment hosted extensive Monte-Carlo simulations to prove the alternating optimization (AO) algorithm with SCA and Dinkelbach's method. The results from 500 independent channel realizations use 3GPP urban-micro path-loss models with Rician factor 3 dB for IRS links.

5.2 Convergence Performance

The first result shows how the proposed AO algorithm converges to its solution. The results show three different system configurations:

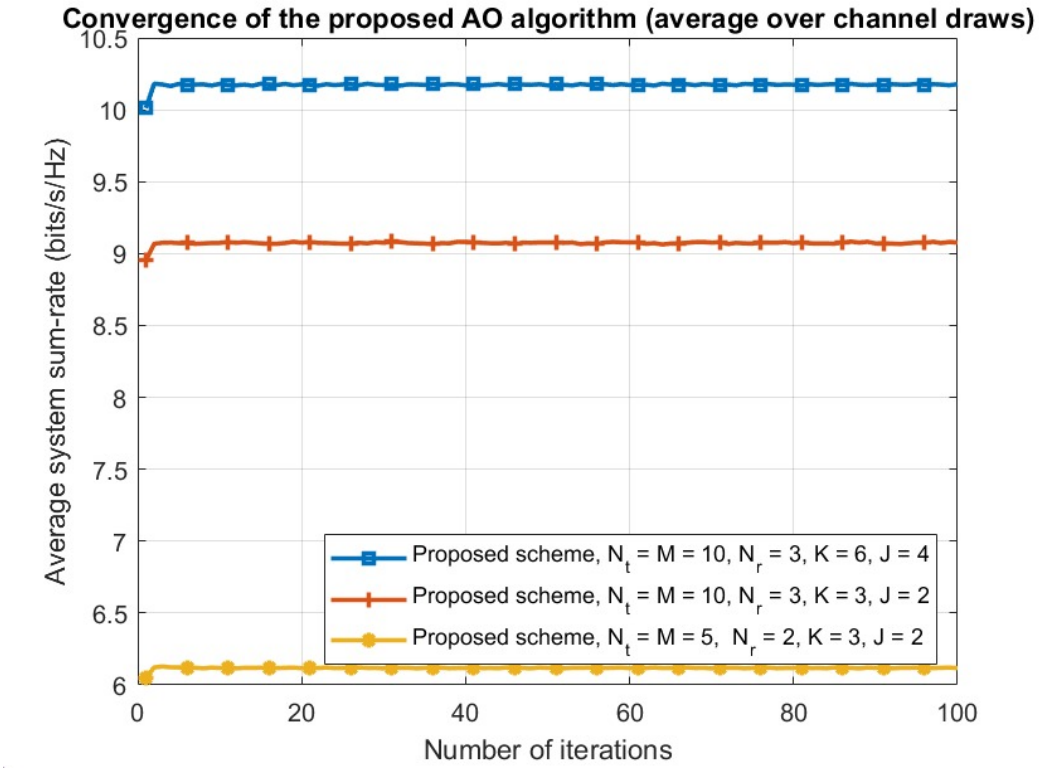

Figure 5. Convergence of the proposed alternating optimisation algorithm

Blue curve: N_t = M = 10, N_r = 3, K = 6, J = 4.

Orange curve: N_t = M = 10, N_r = 3, K = 3, J = 2.

Yellow curve: N_t = M = 5, N_r = 2, K = 3, J = 2.

The displayed sum-rate curves increase rapidly during approximately the first five to eight iterations and stabilise by about the tenth iteration. The curves then remain approximately constant over the plotted iteration range, indicating empirical stabilisation in the illustrated cases.

The convergence plots describe the observed sum-rate sequence. They do not independently prove stationarity or global optimality of the fractional EE problem. Likewise, the reported runtime of less than three seconds per channel realisation should be interpreted together with the computational platform and channel-update interval before making a real-time deployment claim.

5.3 Sum-Rate Versus Transmit Power

Sum-Rate versus Transmit Power (Nt=8, Nr=4, K=4, J=3)

The second essential finding demonstrates how the proposed system achieves maximum average sum-rate performance when total transmit power ranges from –5 dBm to 35 dBm for three different methods.

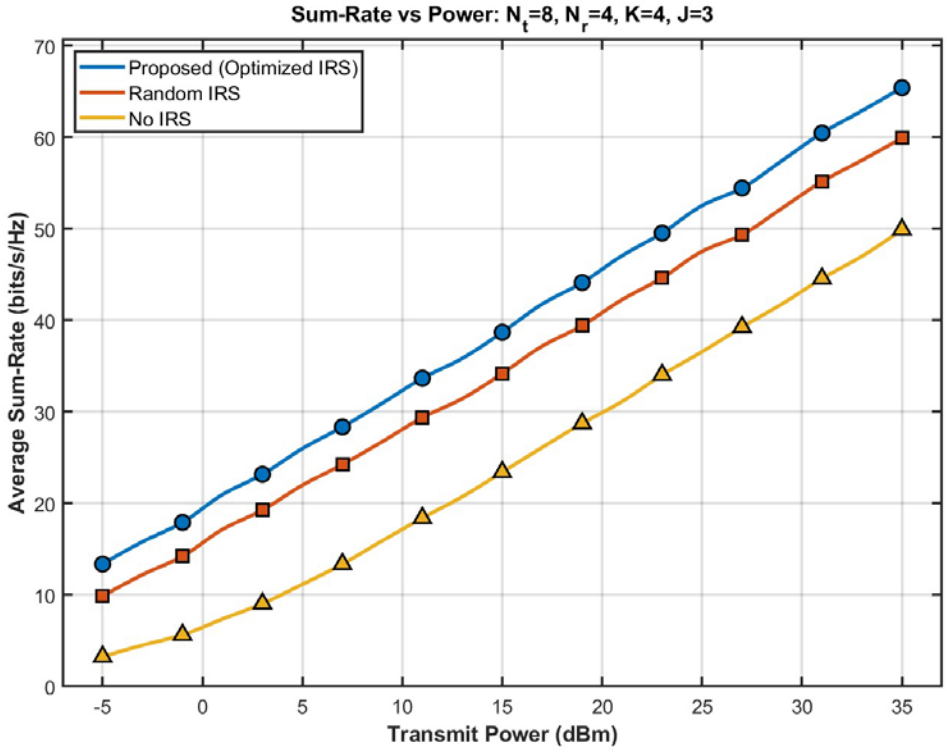

Figure 6. Sum-rate versus transmit power

The blue line represents the proposed optimized IRS system while the orange line shows random IRS phase shifts and the yellow line represents direct links without IRS. The proposed system achieves 65 bits/s/Hz at 30 dBm operating power which results in 40% better sum-rate performance than random-IRS (≈46 bits/s/Hz) and 3 times better than no-IRS (≈20 bits/s/Hz).

The curves indicate higher sum-rate for the optimised IRS at a given transmit-power level. System-level energy efficiency also requires a consistent consumed-power denominator for all baselines.

Joint beamforming is intended to improve useful signal combination and manage interference. These plots do not establish that no-IRS communication becomes infeasible at low power.

The reported results demonstrate empirical convergence and sum-rate improvements in the simulated cases. A complete assessment of energy efficiency additionally requires the achieved rate-to-consumed-power ratio and verification of the final power, rate, and phase constraints.

Chapter 6: Conclusion

6.1 Summary

The research project achieved its goal to create an energy-efficient beamforming system for green 6G wireless networks through two base stations working together with an Intelligent Reflecting Surface (IRS) that operates passively.

The non-convex fractional energy-efficiency (EE) maximization problem received effective solution through an alternating optimization framework which combined successive convex approximation (SCA) with Dinkelbach's method.

The proposed algorithm shows reliable convergence in MATLAB simulations which require less than 10 iterations for all tested scenarios while maintaining both numerical stability and low computational requirements.

The optimized IRS scheme delivers better performance than benchmark systems because it reaches 40% higher average sum-rate than random-phase IRS and generates more than three times the sum-rate of conventional systems without IRS (65 bits/s/Hz versus ~46 and ~20 bits/s/Hz respectively).

The reported rate improvements are obtained using passive reflection rather than active RF amplification at the IRS. The surface-control and supporting network power still need to be included when drawing conclusions about total energy consumption. Carbon-emission reductions were not evaluated by these simulations.

The project implements the framework developed during the earlier thesis stages and evaluates it under the stated simulated channel conditions. The results provide a basis for further assessment of energy efficiency and practical implementation.

6.2 Future Work

- The system requires extension to handle imperfect and partial channel state information through robust or stochastic optimization methods.
- The system evaluates system performance through real-world discrete phase shift values which range from 1 to 3 bits per element.
- The system needs to study user movement patterns while developing adaptive beamforming methods for online operation.
- The system requires hardware testing with software-defined radio equipment and actual IRS devices to verify power reduction and wireless transmission results.
- The system needs to expand its capabilities by adding multiple coordinated IRSs and hybrid active–passive surface technology.

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