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Feasibility Limits of Satellite-Assisted RF Wireless Power Transfer for Consumer Devices: A System-Level Analysis

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This study evaluates the physical feasibility of satellite-assisted RF wireless power transfer using a passive dual-hop relay architecture. A system-level analytical model based on the Friis transmission equation is developed to quantify propagation losses, frequency dependence, nonlinear rectenna behavior, and receiver sensitivity constraints. Numerical evaluation shows that received power ranges from approximately −140 dBm for Low Earth Orbit (LEO) scenarios to −232 dBm for Geostationary Earth Orbit (GEO), remaining substantially below both the rectenna activation threshold and the thermal noise floor under practical operating conditions.

Keywords: RF Wireless Power Transfer, Satellite Relay, Link Budget, Rectenna, Wireless Energy Harvesting, LEO, GEO.

Пределы осуществимости беспроводной передачи энергии в радиочастотном диапазоне с помощью спутников для потребительских устройств: анализ на системном уровне

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В данном исследовании оценивается физическая реализуемость беспроводной передачи энергии по радиочастотному каналу с использованием спутника и архитектуры пассивной двухскачковой ретрансляции. Для количественной оценки потерь при распространении сигнала, частотной зависимости, нелинейных характеристик ректенны и ограничений, связанных с чувствительностью приемника, была разработана аналитическая модель системного уровня, основанная на уравнении передачи Фрииса. Численный анализ показал, что уровень принимаемой мощности варьируется от примерно −140 дБм (для сценариев с использованием низких околоземных орбит − LEO) до −232 дБм (для геостационарной орбиты − GEO), оставаясь при этом значительно ниже как порога активации ректенны, так и уровня теплового шума в реальных условиях эксплуатации.

Ключевые слова: беспроводная передача энергии на радиочастотах, спутниковый ретранслятор, бюджет радиолинии, ректенна, сбор энергии из беспроводных источников, НОО, ГСО.

1. Introduction

Wireless power transfer (WPT) has become an important research area for powering low-energy electronic systems, particularly Internet of Things (IoT) devices operating in environments where wired charging is impractical. While near-field wireless charging has reached commercial maturity, far-field RF energy transfer remains limited by propagation losses, antenna characteristics, and RF-to-DC conversion efficiency [1, 3, 6, 8].

Recent advances in space-based solar power have demonstrated the feasibility of transmitting high-power microwave energy over orbital distances using large transmitting apertures and highly directional beams [11]. Nevertheless, these architectures are fundamentally different from systems intended to power commercial smartphones. Consumer mobile devices employ compact omnidirectional antennas with very limited gain and operate under strict constraints on antenna size, transmitted power, and receiver sensitivity [1, 10, 14]. Consequently, conclusions derived from large-scale space power systems cannot be directly extended to consumer electronics.

Another critical limitation arises from the nonlinear behavior of rectennas. Efficient RF-to-DC conversion requires the received signal to exceed a minimum activation threshold. At extremely low received power levels, conversion efficiency rapidly approaches zero, rendering harvested energy practically unusable regardless of rectifier design [2, 9]. When combined with severe free-space attenuation over orbital distances, these constraints raise fundamental questions regarding the feasibility of direct satellite-to-smartphone RF power transfer [4, 8].

Although previous studies have investigated RF wireless power transfer, rectenna optimization, and space-based power beaming, they primarily focus on short-range wireless charging, high-power microwave transmission, or utility-scale energy systems [1, 3, 6, 8, 11]. A quantitative feasibility analysis of passive dual-hop satellite-assisted RF energy transfer for commercial smartphones remains largely absent.

To address this gap, this paper develops a system-level analytical framework for evaluating passive satellite-assisted RF wireless power transfer. The study aims to:

– develop a dual-hop propagation model for satellite-assisted RF power transmission;

– analyze the combined effects of propagation loss, carrier frequency, and rectenna nonlinearity;

– quantify received power under representative LEO and GEO operating conditions;

– establish the fundamental physical feasibility limits of passive satellite-to-smartphone RF wireless power transfer.

The remainder of this paper is organized as follows. Section 2 presents the system model and analytical methodology. Section 3 discusses the numerical results and feasibility analysis. Finally, Section 4 summarizes the principal conclusions and practical implications of the study.

2. Materials and Methods

2.1. System Architecture

The proposed satellite-assisted wireless power transfer system consists of three principal components: a ground RF transmitter, a passive orbital relay satellite, and a ground receiver equipped with a rectenna [1, 11]. The satellite acts solely as a passive relay without onboard power amplification. Consequently, the transmitted RF signal experiences two independent free-space propagation stages before reaching the receiver [11].

The energy transfer process follows five sequential steps:

1. RF power generation by the terrestrial transmitter.
2. Uplink propagation from Earth to the satellite.
3. Passive signal reflection or retransmission by the satellite.
4. Downlink propagation toward the ground receiver.
5. RF-to-DC conversion through the receiving rectenna [2, 3, 8].

Unlike conventional single-hop RF wireless power transfer systems, this architecture introduces cumulative propagation losses over two independent links, making distance attenuation the dominant limiting factor [3, 4, 8].

2.2. Propagation Model

The analytical model is based on the classical Fries transmission equation applied independently to the uplink and downlink channels [3, 4, 10, 14]. The received power after the first propagation stage is

$$P_{r1} = P_t G_t G_s \left(\frac{\lambda}{4\pi R_1}\right)^2,$$

where

- P_t denotes transmitter power;
- G_t transmitter antenna gain;
- G_s satellite antenna gain;
- R_1 uplink distance;
- λ carrier wavelength.

The received signal is subsequently retransmitted toward the ground receiver, yielding

$$P_r = P_{r1} G_r \left(\frac{\lambda}{4\pi R_2}\right)^2,$$

where G_r is the receiver antenna gain and R_2 is the downlink distance. Combining both propagation stages gives the complete end-to-end link equation [3, 4, 10, 14].

2.3. Distance Scaling

For practical satellite communication, the uplink and downlink distances are approximately equal

$$R_1 \approx R_2 = R,$$

which simplifies the propagation model to

$$P_r \infty R^{-4}.$$

This quartic distance dependence constitutes the principal physical limitation of passive satellite-assisted RF wireless power transfer and distinguishes it from conventional terrestrial RF links that exhibit inverse-square attenuation [3, 4, 11, 14].

2.4. Frequency Dependence

Since wavelength is related to carrier frequency by

$$\lambda = c/f,$$

the received power decreases rapidly with increasing operating frequency. Consequently, microwave and millimeter-wave bands experience substantially greater propagation losses than lower-frequency systems. This frequency dependence is incorporated directly into the analytical model used throughout this study [1, 3, 14].

2.5. Rectenna Model

The receiver converts RF energy into DC power using a nonlinear rectenna. Conversion efficiency strongly depends on the received RF power level and decreases rapidly below the rectifier activation threshold. Therefore, even when RF energy reaches the receiver, useful power harvesting becomes negligible whenever the received signal falls below practical operating levels [2, 9].

The harvested DC power is expressed as

$$P_{DC} = \eta(P_r)P_r,$$

where $\eta(P_r)$ represents the nonlinear RF-to-DC conversion efficiency [2].

2.6. Feasibility Criterion

System feasibility was evaluated using two independent physical constraints.

The first constraint is the thermal noise floor

$$P_n = -174 + 10\log_{10}(B) + NF,$$

where B denotes receiver bandwidth and NF is the receiver noise figure [3, 8, 12].

The second constraint is the rectenna activation threshold required for efficient RF-to-DC conversion. A satellite-assisted RF power transfer system is considered practically feasible only when the received signal simultaneously exceeds both limits. Otherwise, the received energy cannot be reliably detected or converted into useful electrical power [2, 8].

2.7. System Assumptions

To establish an optimistic upper performance bound, the analysis adopts the following assumptions:

– transmit power limited to 0.1 W;
– passive satellite relay without onboard amplification;
– small low-gain antennas representative of commercial smartphones;
– line-of-sight free-space propagation;
– atmospheric attenuation, polarization mismatch, and pointing errors neglected;
– nonlinear rectenna behavior included in the energy conversion process [3, 8, 10, 14].

These assumptions intentionally favor system performance; therefore, any practical implementation would experience additional losses beyond those predicted by the analytical model [4, 10, 14].

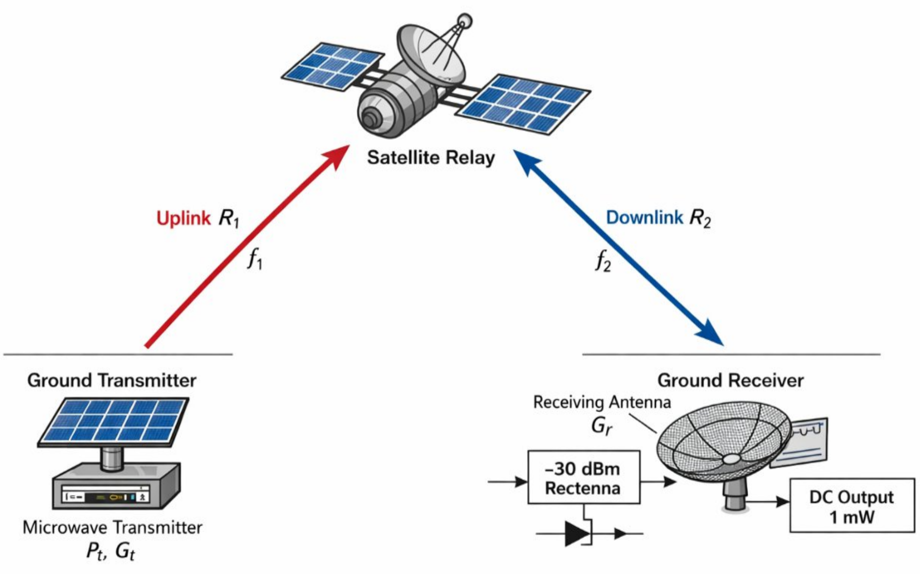

Figure 1. The proposed model for a dual-hop satellite wireless power transfer system

3. Results and Discussion

The proposed analytical framework was evaluated under representative Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO) operating conditions to determine the practical feasibility of passive satellite-assisted RF wireless power transfer [5, 11]. The numerical results consistently demonstrate that propagation loss dominates the system performance and prevents practical energy delivery to consumer mobile devices [1, 3, 8].

3.1. Received Power Analysis

Figure 1 illustrates the variation of received power as a function of transmission distance. The analytical results confirm the theoretical R^{-4} attenuation predicted by the dual-hop propagation model [3, 4, 10, 14]. Unlike conventional terrestrial wireless links, where received power decreases proportionally to the inverse square of distance, the passive satellite relay introduces two consecutive free-space propagation paths, producing significantly greater attenuation [4, 11, 14].

For representative orbital altitudes, the calculated received power is approximately −140 dBm for LEO and decreases to nearly −232 dBm for GEO. These values remain several orders of magnitude below the minimum power required for practical RF energy harvesting [2, 9]. The results therefore indicate that propagation distance alone constitutes a fundamental limitation independent of circuit implementation or rectenna design [3, 4, 8].

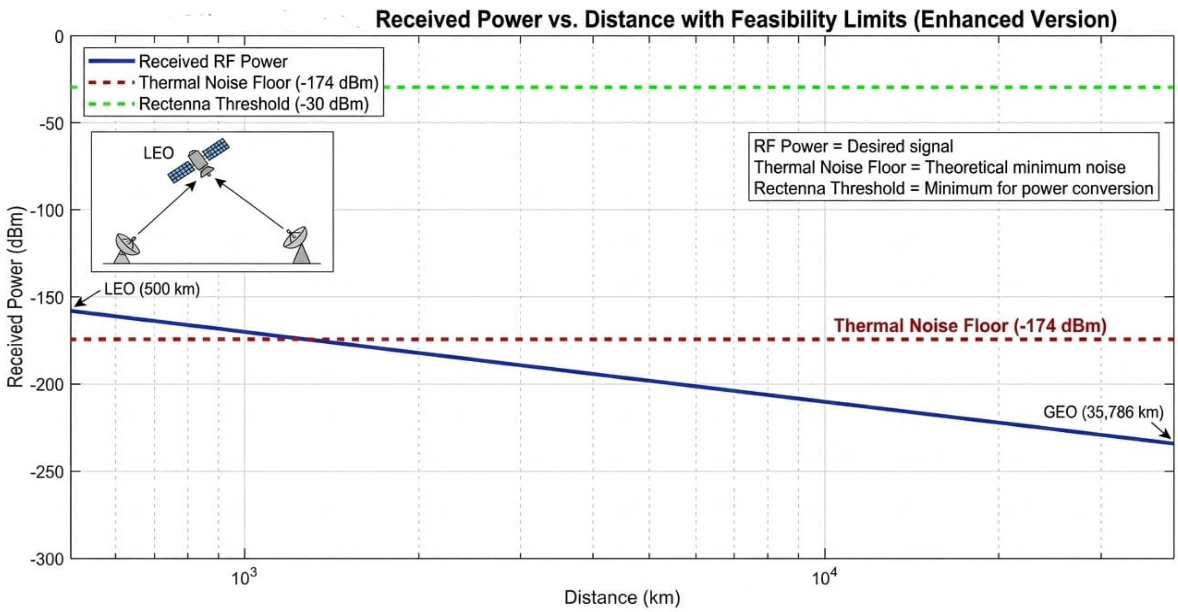

Figure 2. Received power vs. transmission distance for the dual-hop satellite model

The plot shows how the R^{-4} relationship causes very fast signal attenuation.

3.2. Frequency Influence

The analysis further demonstrates that carrier frequency has a significant influence on received power because free-space loss increases with decreasing wavelength [1, 3, 14]. Although lower frequencies reduce propagation loss, the improvement remains insufficient to compensate for the extreme attenuation produced by orbital transmission distances. Consequently, frequency optimization alone cannot establish a practical operating region for passive satellite-assisted RF power transfer [3, 8].

3.3. Feasibility Assessment

A practical wireless power transfer system must satisfy two simultaneous conditions:

– the received signal must exceed the receiver thermal noise floor;

– the received RF power must remain above the rectenna activation threshold required for efficient RF-to-DC conversion [2, 8].

The numerical analysis demonstrates that neither condition is satisfied under any investigated orbital scenario. Even under ideal free-space propagation, the received signal remains within approximately −140 dBm to −210 dBm, substantially below both the thermal noise limit (−174 dBm/Hz) and the rectenna sensitivity threshold (approximately −30 dBm) [2, 8, 9]. Consequently, reliable signal detection and useful energy harvesting cannot be achieved within the adopted system assumptions [2, 8, 12].

3.4. Receiver Antenna Requirements

To quantify the hardware requirements for practical operation, the minimum receiver antenna gain necessary to deliver approximately 1 mW (0 dBm) of harvested RF power was calculated.

The analysis indicates that the receiver must provide an antenna gain exceeding 70–80 dBi. At an operating frequency of 2.4 GHz, this requirement corresponds to an effective aperture diameter of approximately 126 m [10, 14].

Such dimensions exceed smartphone antenna sizes by several orders of magnitude. Therefore, the limitation is not associated with antenna fabrication technology but rather represents a direct consequence of electromagnetic propagation physics. Increasing satellite antenna gain alone cannot eliminate this requirement because the receiving terminal must still collect sufficient electromagnetic energy over its effective aperture [4, 10, 14].

3.5. Feasible Operating Region

Figure 2 summarizes the feasible operating region by relating received power to both propagation distance and receiver antenna gain.

The contour map shows that all realistic satellite distances lie entirely within the infeasible operating region. Only hypothetical receiver antennas exceeding approximately 70–80 dBi shift the operating point toward practical energy harvesting levels. Such gains require extremely large parabolic reflectors or massive phased-array antennas that cannot be integrated into handheld consumer devices [10, 11, 14].

Accordingly, no feasible operating region exists for passive satellite-to-smartphone RF wireless power transfer using realistic antenna dimensions [3, 8, 14].

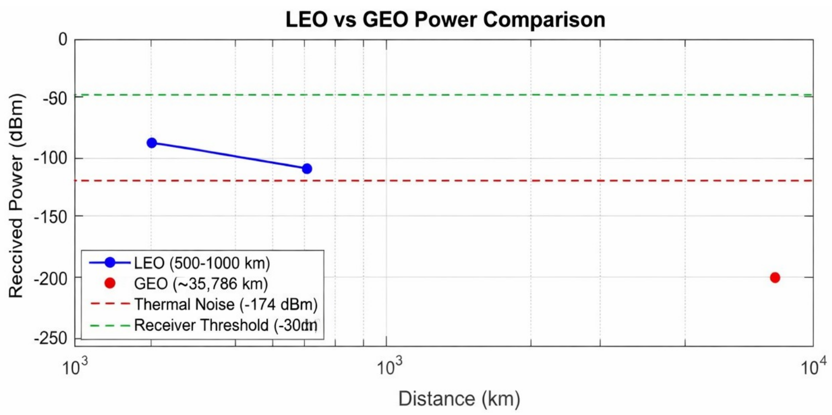

Figure 3. Comparison of received power between LEO and GEO distances

3.6. Practical Implications

Beyond the theoretical link-budget limitations, several engineering constraints further reduce system feasibility.

Current smartphones employ compact omnidirectional antennas with gains close to 0 dBi, whereas the proposed system requires gains exceeding 70 dBi [1, 10, 14]. Satellite platforms are similarly constrained by limited onboard power availability and cannot provide the extremely high effective isotropic radiated power required to compensate for orbital propagation losses [11]. Furthermore, international RF exposure regulations impose strict limits on permissible power density, preventing arbitrary increases in transmitted power [5]. Additional atmospheric attenuation, pointing inaccuracies, polarization mismatch, and multipath propagation would further reduce received power beyond the optimistic free-space estimates adopted in this study [4, 10, 14]. Finally, the economic cost of deploying dedicated satellites for delivering only microwatt-level power to individual consumer devices renders the proposed architecture commercially impractical [11].

3.7. Discussion

The analytical and numerical results consistently indicate that passive satellite-assisted RF wireless power transfer is fundamentally constrained by physical propagation laws rather than by current implementation technology [3, 4, 8]. The dominant limitation is the dual-hop free-space attenuation, which causes received power to decay according to the fourth power of transmission distance. This loss cannot be compensated through practical improvements in antenna design, operating frequency, or rectenna efficiency alone [3, 4, 10, 14].

The present findings should not be interpreted as a limitation of wireless power transfer in general. High-power microwave energy transmission using active beamforming, large transmitting apertures, or dedicated space-based solar power systems remains a scientifically valid research direction [11]. Instead, the present analysis establishes the feasibility boundary for passive satellite-to-smartphone RF wireless power transfer, demonstrating that no practical operating region exists under current physical, technological, and regulatory constraints [3, 5, 8, 11].

4. Conclusion

This study presented a system-level feasibility analysis of passive satellite-assisted RF wireless power transfer for consumer mobile devices. A dual-hop analytical model based on the Fries transmission equation was developed to evaluate the combined effects of propagation distance, operating frequency, receiver antenna characteristics, and rectenna sensitivity on the overall energy transfer performance.

The numerical results demonstrate that the received power decreases according to the fourth power of transmission distance, producing severe attenuation over orbital links. Under representative LEO and GEO operating conditions, the received RF power remains substantially below both the thermal noise floor and the minimum rectenna activation threshold required for efficient RF-to-DC conversion. Consequently, passive satellite-assisted RF power transfer cannot deliver useful electrical power to commercial smartphones within the investigated operating conditions.

The analysis further shows that achieving practical power levels would require receiver antenna gains exceeding 70–80 dBi, corresponding to antenna apertures on the order of 126 m at 2.4 GHz. Such requirements are fundamentally incompatible with the physical dimensions of handheld consumer devices and therefore represent a physical limitation rather than a technological implementation challenge.

Beyond propagation losses, practical deployment is additionally constrained by limited satellite power availability, international RF exposure regulations, atmospheric attenuation, pointing accuracy requirements, and economic feasibility. These factors further reinforce the conclusion that passive satellite-to-smartphone RF wireless power transfer is not a viable solution using current engineering technologies.

The principal contribution of this work is the establishment of a quantitative feasibility boundary for passive orbital RF power transfer. Rather than proposing a new transmission architecture, the study identifies the physical limits that separate theoretically possible operation from practically achievable implementation. These findings provide a useful analytical reference for future investigations of space-based wireless power systems and help distinguish passive relay architectures from active microwave power-beaming approaches.

Future research may extend the present framework by investigating active satellite relays, adaptive beamforming techniques, large-aperture transmitting arrays, and alternative space-based power transmission architectures. Such approaches fall outside the scope of the present study but may provide different feasibility characteristics under substantially different system assumptions.

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