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# Energy Efficient Hybrid Relay-IRS-Aided Wireless IoT Network for 6G Communications

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**Abstract:** Intelligent Reflecting Surfaces (IRS) have been recognized as presenting a highly energy-efficient and optimal solution for future fast-growing 6G communication systems by reflecting the incident signal towards the receiver. The large number of Internet of Things (IoT) devices are distributed randomly in order to serve users while providing a high data rate, seamless data transfer, and Quality of Service (QoS). The major challenge in satisfying the above requirements is the energy consumed by IoT network. Hence, in this paper, we examine the energy-efficiency (EE) of a hybrid relay-IRS-aided wireless IoT network for 6G communications. In our analysis, we study the EE performance of IRS-aided and DF relay-aided IoT networks separately, as well as a hybrid relay-IRS-aided IoT network. Our numerical results showed that the EE of the hybrid relay-IRS-aided system has better performance than both the conventional relay and the IRS-aided IoT network. Furthermore, we realized that the multiple IRS blocks can beat the relay in a high SNR regime, which results in lower hardware costs and reduced power consumption.

**Keywords:** Intelligent Reflecting Surfaces; Decode-and-Forward relaying; hybrid relay-IRS; IoT; energy efficiency; 6G



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## 1. Introduction

Future communication systems such as 6G and beyond rapidly have increased the demand for a number of Internet of Things (IoT)-based devices, which eventually requires a larger data rate. As a consequence, the related energy consumption is expected to grow exponentially [1–3]. Thus, recent investigations into energy-efficiency (EE) have been greatly increased. In [4,5], the authors claim that the EE problem may be obviated by combining different techniques, such as renewable energy sources or IoT devices, to name a few. The authors in [6,7] presented a framework to optimize the EE of IoT-based communication systems in which the system observes the on–off status of IoT devices and the quality of service required by the specific user; these observation values can then be utilized to reduce the energy consumption of the system. In [8], an IoT-based smart home network for communicating with smart devices such as washing machines, LEDs, and air conditioners was demonstrated. Multi-physics analysis methods have been adopted to control the IoT devices in different scenarios, which can reduce their energy requirements instead of allocating power to all the IoT devices at all times. A large number of IoT devices may be used to handle the resource management of users, which increases the power allocation problem [9,10]. The aforementioned complex problem is simplified by using Branch and Reduced Bound (BRB) algorithm to improve the EE. It is known that IoT devices in general consume a great deal of energy. One possible solution is to design low-power IoT devices, although this remains in the early stages. It is estimated that by either adding active or passive relay-assisted models or by reducing the distance between the IoT devices and the Base Station (BS), power consumption can be reduced. In the case of active relay models, active Radio-Frequency (RF) waves are used, which requires additional amplifiers, and thus demands more energy [11,12]. Similarly, when reducing the propagation distance user performance is degraded, as the coverage area is limited. In our previous works, we have investigated the EE for massive multiple-input–multiple-output (MIMO) non-orthogonal multiple access (NOMA) systems [13] and 5G cellular networks [14].

To alleviate energy consumption, Intelligent Reflecting Surfaces (IRS) have been identified as an alternative technology equipped with a massive number of passive elements that can reflect the incident signal towards IoT devices without the need for additional power sources [15]. In addition, recent works on IRS-aided IoT networks have been investigated for reducing power consumption and achieving a high sum-rate [16]. The formulated joint optimization problem has been resolved by adopting the Semi-definite Relaxation (SDR) approach followed by Majorization–Minimization (MM) and Karush–Kuhn–Tucker (KKT) algorithms; numerical results have shown better performance compared to the communication systems without IRS. More recently, Wireless Energy Transfer (WET) and Wireless Information Transmission (WIT) with IRS-assisted IoT systems have been studied for the enhancement of overall throughput considering the optimal power consumption. The non-convex problem has been solved by employing Alternating Optimization (AO) and SDR techniques [17]. Research work in [18] implemented an IRS-aided IoT network and examined the non-convex power optimization problem, which was simplified using the Riemannian AO scheme. Thus, the optimization of uplink power was minimized via an IRS block consisting of the number of passive elements. IRS-aided orthogonal frequency division multiplexing (OFDM) relaying networks have been investigated with and without IRS for maximization of the achievable rate. The joint optimization problem has been resolved by applying the branch-and-bound algorithm as well as by the SDR approach [19]. Alternatively, the IRS framework may simply be incorporated into various communication scenarios thanks to its small hardware size, which allows it to be easily deployed into building walls, office roofs, and even human clothes [20,21]. Multi-Agent Reinforcement Learning and Deep reinforcement learning-based relay selection have been utilized in IRS-aided cooperative networks to determine the secrecy rate [22,23].

In addition, a dual-hop NOMA wireless network has been presented with Decode-and-Forward (DF) relaying, which outperformed the well-known Amplify-and-Forward (AF) relaying [24]. The authors in [25] presented a novel cooperative relay and IRS-aided communication system to increase the coverage area and improve energy efficiency. A multiple IRS dual-hop DF relay network with Nakagami-m fading environment was considered in [26] in order to derive the achievable rate along with the enormous reflecting elements. Two IRS blocks connected through a full-duplex relay was proposed in [27], who then compared it with AF and DF relays. These authors' results have shown that hybrid IRS–relay-aided systems enjoy enhanced performance in comparison with conventional relays and IRS networks [28]. The significance of IRS elements has been demonstrated in [29], where the authors examined the achievable rate and EE of single-input–single-output (SISO) communication systems. However, a novel hybrid relay-IRS-aided wireless IoT network for determining EE has not been previously discussed. Therefore in this work we have analyzed the EE of a hybrid relay-IRS, conventional IRS and relay-aided wireless IoT network. The main contributions of this paper are as follows:

- To the best of our knowledge, we are the first to examine and compare the impact of relay-aided, IRS-aided, and novel hybrid relay-IRS-aided wireless IoT networks for 6G communications in terms of EE;
- We examine EE as a function of user distance and various SNR values. The EE with fixed and varying numbers of IRS elements is analysed for the proposed IoT network;

- Numerical results show that the proposed hybrid relay-IRS-assisted IoT network outperforms both the conventional relay and IRS-aided wireless IoT networks;
- Numerical results further validate that multiple IRS blocks can be deployed randomly with relays to increase the EE of the hybrid relay-IRS-aided IoT network instead of using multiple relays to cover longer distances.

The rest of the article is organized as follows. The system model, consisting of the relay, IRS, and hybrid relay-IRS-aided wireless IoT networks, is presented in Section 2. The energy efficiency formulation and performance analysis are illustrated in Section 3. Numerical results are provided in Section 4. Finally, we conclude the article in Section 5.

## 2. System Model

Here, we consider a wireless IoT network where BS and IoT devices communicate in three different scenarios. Case (i): the IoT network is supported by a relay-aided system, as shown in Figure 1a; Case (ii): a hybrid IRS–relay-aided system assists the user, as in Figure 1b; and Case (iii): multiple IRS blocks are deployed to support the IoT network, as shown in Figure 1c. The proposed wireless IoT network consists of a single BS ($B$), a relay ($R$), and an IRS with $N$ passive reflective elements ($I$) and IoT devices as a receiver ($D$). In wireless communication systems, the transmission of the signal takes place over longer distances, wherein $B$ needs more transmission power to increase the coverage area and EE. In order to overcome the above limitations, relays can be placed between BS and IoT devices. Later, IRS can be integrated with the relay to improve the EE and data rate required by the wireless IoT network. In order to reduce complexity, we neglected the transmission of signals between the IRS and relay. The deterministic channels between $B \rightarrow I$, $B \rightarrow R$, $I \rightarrow D$, and $R \rightarrow D$ with independent Rayleigh distribution are denoted as $h_{BI} \in \mathbb{C}^N$, $h_{BR} \in \mathbb{C}$, $h_{ID} \in \mathbb{C}^N$, and $h_{RD} \in \mathbb{C}$, respectively.

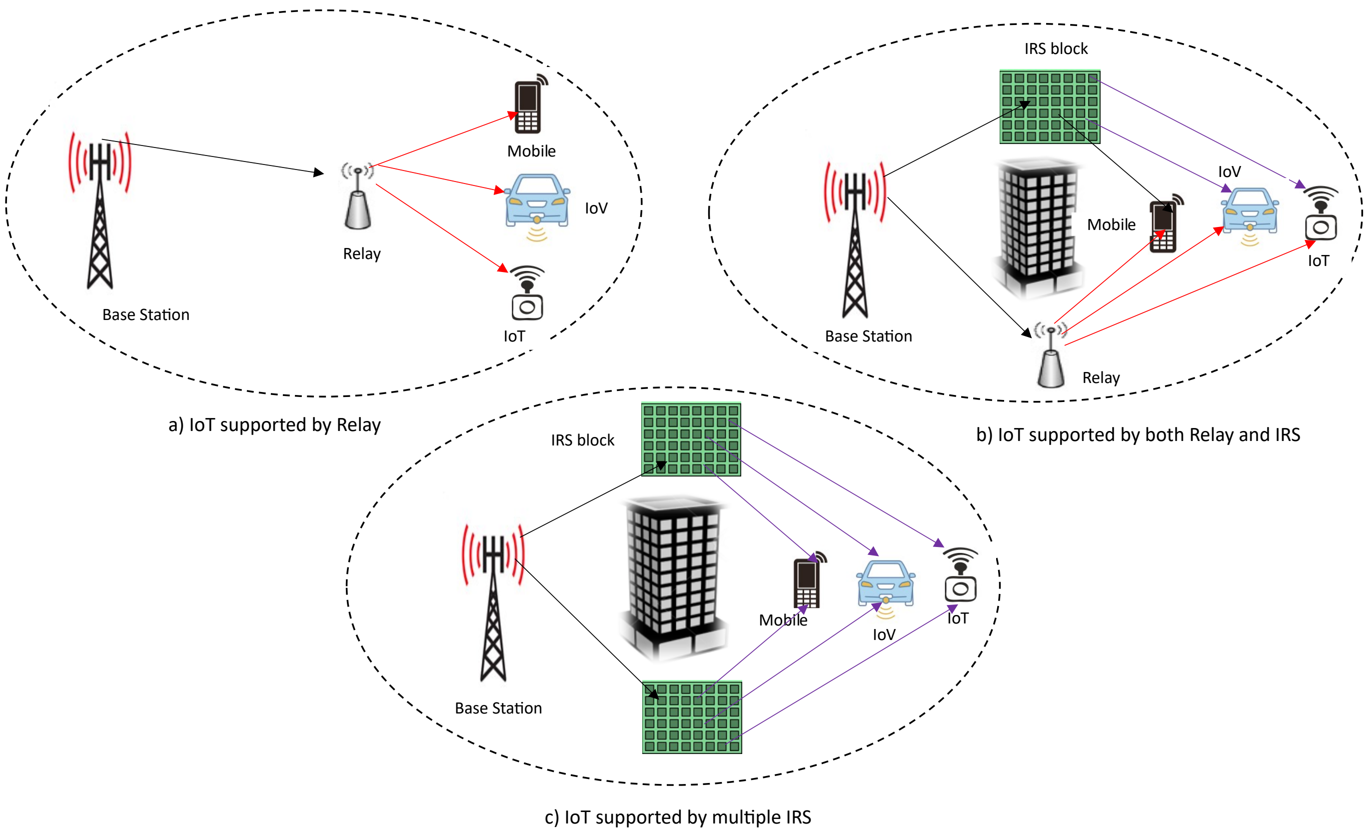


**Figure 1.** Relay and IRS-aided wireless IoT network.

## 3. Energy Efficiency Performance Analysis

Energy Efficiency (EE) is calculated as the ratio between the sum rate and the total power ($P_{Total}$).

$$\text{EE} = \frac{R_{sum}}{P_{Total}}, \tag{1}$$

where $R_{sum}$ is the sum rate and $P_{Total}$ is the total power consumed by the IoT network.

In this work, we considered both the individual and hybrid modes of networks in order to analyse the EE of moving objects. To improve the performance in terms of EE, IRS was utilized in certain areas instead of relays, which consume more power. In addition, IRS can be combined with relays in fully dense and crowded areas in order to serve users while reducing power usage. Based on the above analysis, we realized that combining the hybrid mode with a multiple IRS framework could help the wireless networks to achieve greater EE. From Equation (1), the sum rate of the hybrid IRS–relay network, $R_{sum}$ can be expressed as

$$R_{sum} = R_{IRS} + R_{DF}, \tag{2}$$

where $R_{IRS}$ and $R_{DF}$ are the achievable rates of the IRS and DF relay-aided wireless IoT networks, respectively. The total transmission power, $P_{Total}$, of the hybrid model can then be calculated as

$$P_{Total} = P_{IRS} + P_{DF}. \tag{3}$$

where $P_{IRS}$ and $P_{DF}$ are the total power consumed by the IRS and DF relay-aided wireless IoT networks, respectively.

### 3.1. Achievable Rate of Relay-Aided IoT Network

In Figure 1a, data transmission occurs in two time frames due to the half-duplex technique of DF relays. In the first time frame, the signal transmits from $B \rightarrow R$ and the signal is received at $R$, as shown below:

$$y_{1,R} = h_{BR}\sqrt{P}x + k_{1,R}, \tag{4}$$

where $h_{BR}$ is the channel between the $B$ and $R$. In the second time frame, the DF relay decodes the received signal and forwards it to the receiver $D$. Thus, a signal received at $D$ is expressed as

$$y_{2,D} = h_{RD}\sqrt{P}x + k_{2,D}, \tag{5}$$

where $h_{RD}$ is the channel between $R$ and $D$, $x$ is the transmitted signal, P is the transmission power, and $k_1, k_2$ are additive white Gaussian noise (AWGN), represented as $\mathcal{CN}(0, \sigma^2)$, with mean 0 and variance $\sigma^2$. From Equations (1) and (2), the achievable rate can be obtained as follows [30]:

$$R_{DF} = \frac{1}{2}log_2(1 + SNR_{DF}), \tag{6}$$

where $\frac{1}{2}$ represents the two time frames and $SNR_{DF}$ is the signal-to-noise ratio of the DF relay, which is obtained as $SNR_{DF} = \rho_{DF}min(|h_{BR}|^2, |h_{RD}|^2)$. The transmission power of the DF relay, $\rho_{DF}$, is calculated using the Maximum Ratio Combining (MRC) technique, obtained by $\rho_{DF} = \frac{P}{\sigma^2}$ .

### 3.2. Achievable Rate of IRS-Aided IoT Network

In Figure 1c, IRS can serve a user $D$ with N number of IRS elements and constant gain. The received signal at $I$ is expressed as

$$y_{IRS} = \sqrt{P}(h_{BI}^T \mathbf{\Theta} h_{IR})x + k_I, \tag{7}$$

where $k_I$ is the AWG noise received at the IRS, represented as $\mathcal{CN}(0, \sigma^2)$ with mean 0 and variance $\sigma^2$ and $\mathbf{\Theta} = diag(m_1 e^{j\theta_1}, m_2 e^{j\theta_2}, \ldots, m_N e^{j\theta_N})$ denotes the phase-shift matrix, wherein $m_i \in [0,1]$ and $\theta_i \in [0, 2\pi]$ for $i = [1, 2, 3, \ldots, N]$. Using Shannon's theory, the achievable rate of the IRS-aided wireless IoT network can be formulated as

$$R_{IRS} = \mathbf{B}log_2(1 + SNR_{IRS}), \tag{8}$$

where **B** is bandwidth with 1 MHz and $SNR_{IRS}$ can be obtained as follows:

$$SNR_{IRS} = \max_{\theta_i \ldots \theta_N} \rho_{IRS} |\sum_{i=1}^{N} m_i e^{j\theta_i} [h_{BI}]_i, [h_{ID}]_i|^2. \tag{9}$$

*3.3. Total Power Consumption of IRS and Relay-Aided IoT Network*

The total power consumed by the proposed hybrid relay-IRS-aided wireless network consists of the total power consumption of the IRS and DF relay-aided wireless network. To find the maximum EE with the achieved sum rate, we considered the energy wastage of hardware devices and reflective elements in the IRS block. The total power consumed by the IRS can be obtained as follows:

$$P_{IRS}(N) = \frac{\rho_{IRS}(N)}{\nu} + P_s + P_d + NP_e, \tag{10}$$

where $\rho_{IRS}$ is the IRS transmission power, $\nu$ is the power amplifier efficiency, $N$ is the number of reflecting elements, and $P_s$, $P_d$, and $P_e$ are the power dissipation of the source, destination, and each element of the IRS block, respectively. The total power consumed by DF relay is obtained as follows:

$$P_{DF} = \frac{\rho_{DF}}{\nu} + \frac{1}{2} P_s + P_d + P_r, \tag{11}$$

where $P_r$ represents the power dissipation of the relay and $\rho_{DF}$ the transmission power of the DF relay.

## 4. Results and Discussion

In this section, we analyse the EE performance of the hybrid relay-IRS-aided wireless IoT network. Recent studies on IRS and relay-aided networks have shown that more IRS elements are needed to beat the relay. More specifically, in [29] the authors demonstrated the importance of IRS elements in enhancing system performance in terms of both achievable rate and EE. However, the above paper did not concentrate on EE performance for hybrid relay-IRS-aided IoT networks, and did not examine EE with respect to distance or SNR using single or multiple IRS blocks. To the best of our knowledge, we are the first to examine the impact of relay-aided, IRS-aided, and novel hybrid relay-IRS-aided wireless IoT networks for 6G communications in terms of EE. We examined EE as a function of user distance and various SNR values. EE was analyzed with both a fixed and varying number of IRS elements for the proposed hybrid relay-IRS-aided wireless IoT network.

Numerical results shown that the proposed hybrid relay-IRS-aided IoT network outperforms both the IRS and the relay-aided network. The simulation setup consisted of a 3GPP Urban-Micro (UMi) ([31] Table B.1.2.1-1) environment with a carrier frequency of 3 GHz, which was used to model the channel gains. Then, in a UMi scenario with a line-of-sight (LoS) model, we considered the minimum distance to be $\geq$10 m. The transmitter and receiver antenna gains (dBi) are indicated as $G_t$ and $G_r$. To study EE more specifically, we considered the power dissipation at the $B$, $D$, and $R$ as $P_B = P_D = P_R = 50$ mW. The power dissipation factor of the IRS elements, $P_e = 3$ mW, and power amplifier efficiency, $\nu = 0.5$, were taken into consideration as well.

In the simulation setup, for the sake of simplicity, the distance from BS to the IRS block and relay were fixed and the user $D$ was considered to be a moving object, as shown in Figure 2. For better understanding, in our simulation figures we use IRS, Relay, and Relay-IRS to represent only IRS, only Relay, and only hybrid relay-IRS-aided wireless IoT networks, respectively. Figure 3 shows the EE versus user distance for three scenarios, i.e., (i) relay-aided; (ii) IRS-aided; and (iii) hybrid relay-IRS-aided wireless IoT networks. It can be observed that the EE of the hybrid relay-IRS network performs better than the relay and IRS-aided IoT networks. Thus, a hybrid relay-aided IRS can be utilized to cover longer distances instead of using another relay. This is because more power is required for the relay to serve users at longer distances; furthermore, above 400 m, it can be seen that the EE for the relay and hybrid relay-IRS-aided networks are 7.7 bits/joule and 8 bits/joule, respectively.

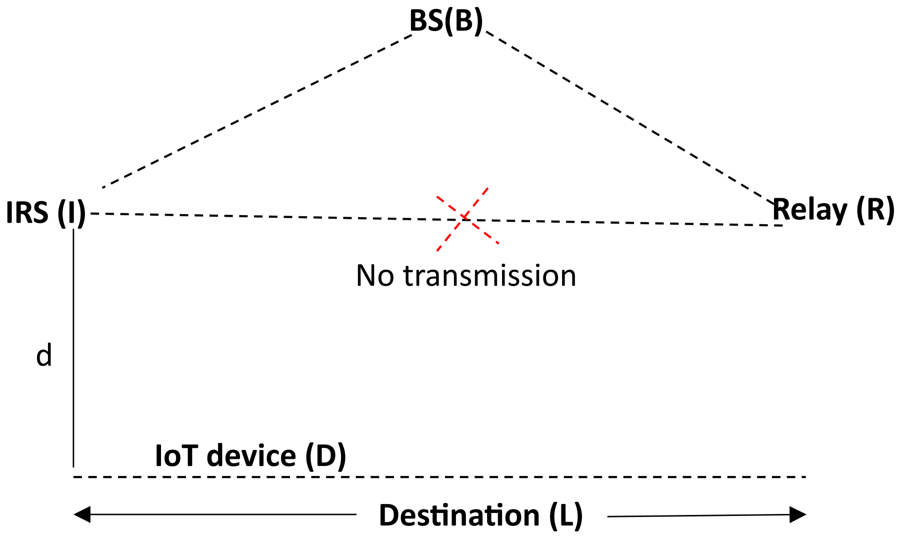


**Figure 2.** The simulation setup by varying distance L.

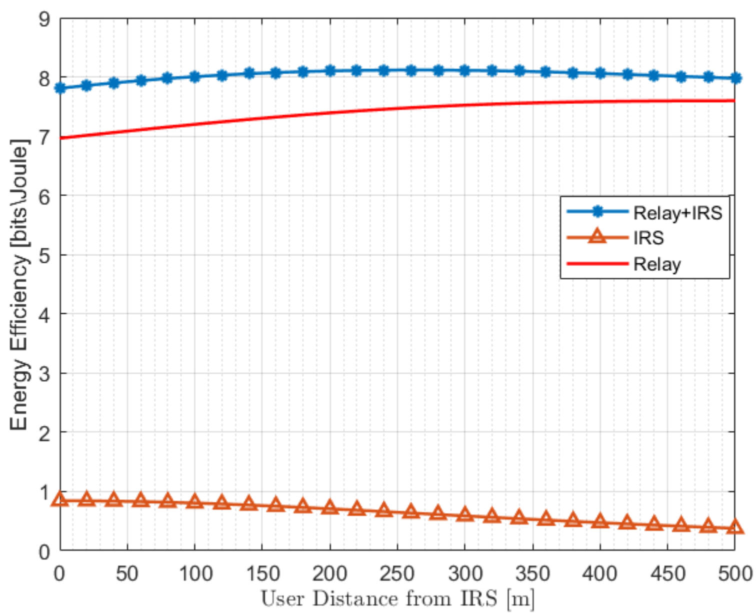


**Figure 3.** EE versus User Distance.

Figure 4 depicts EE versus user distance when varying the number of IRS elements for the hybrid relay-IRS-aided wireless IoT network. It can be seen that EE increases gradually until the user reaches a distance of around 500 m, at which point it slowly begins to decrease with increasing the user distance for all considered numbers of reflective elements. In particular, when distance = 500 m, the EE of the hybrid relay-IRS system is around 8 bits/joule, compared to 7.6 bits/joule as for $N = 200$. This is because the power consumed by these IRS elements for data transmission is very low.

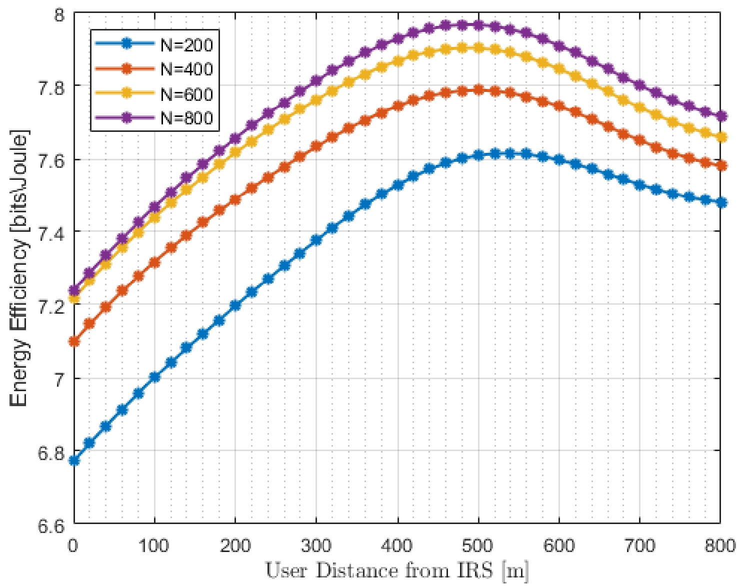


**Figure 4.** EE versus Distance with varying N.

Figure 5 shows EE versus user distance with multiple IRS blocks when each block contains $N = 400$ reflective passive elements. It can be seen that the EE with two and four IRS blocks tends to decrease with increasing user distance faster than the EE with a single IRS block. It is notable that increasing the number of IRS blocks can match the EE performance of conventional relays; more specifically, thus provides a hint that multiple IRS blocks can be used instead of relays in low-density areas with longer coverage, thereby improving EE.

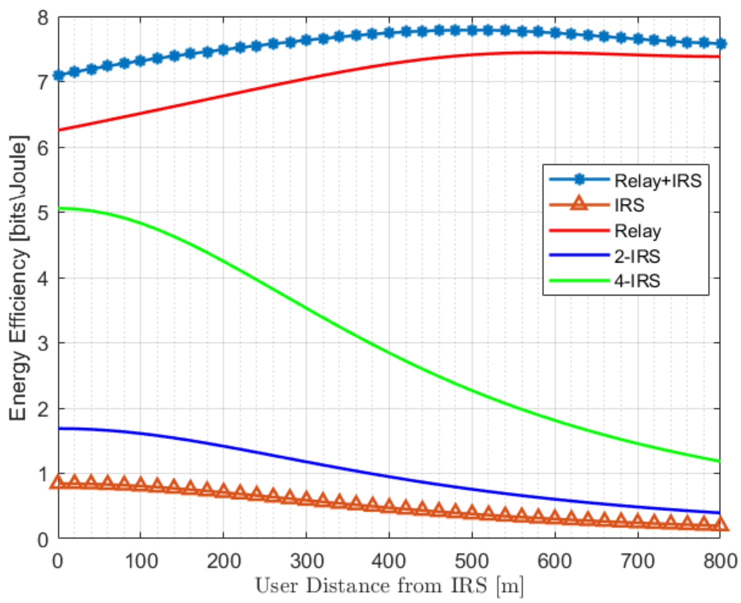


**Figure 5.** EE versus Distance with multiple IRS blocks.

Figure 6 shows the EE versus SNR with fixed passive elements $N = 400$ and a user distance of 100 m. It can be observed that the EE of the hybrid relay-IRS outperforms both the relay and the IRS-aided system for all values of SNR. In particular, at SNR = 80 dBm, the EE of the hybrid relay-IRS achieves close to 86 bits/joule, whereas the EE of the relay and IRS is only 65 and 22 bits/joule, respectively. It is notable that the EE of the IRS-aided IoT network becomes saturated after 80 dBm, then decreases slightly around 120 dBm.

However, the EE of the relay and hybrid relay-IRS system decreases gradually after SNR reaches 80 dBm. This decline in the EE of the relay and hybrid relay-IRS was expected on account of the large power consumption of DF relays.

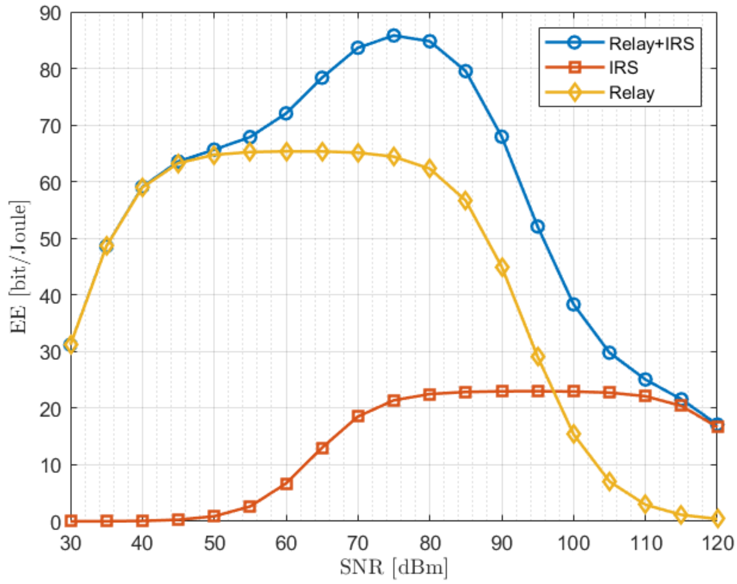


**Figure 6.** EE versus SNR with fixed N.

In Figure 7, the EE of the hybrid relay-IRS is evaluated versus SNR with varying IRS elements and a fixed user distance of 100 m. It can be clearly seen that EE increases linearly until the SNR reaches around 80 dBm for all values of N, whereas EE decreases steeply after 80 dBm until the SNR reaches 130 dBm, when it becomes saturated. In particular, at SNR = 70 dBm, the EE of the hybrid relay-IRS system is 25 bits/joule for $N = 2000$ and 22 bits/joule for $N = 400$, whereas at SNR = 130 dBm the EE for $N = 400$ and 2000 are 1.5 bits/joule and 0.5 bits/joule, respectively. This can be justified by the fact that the EE decreases with increasing transmission power after a certain threshold.

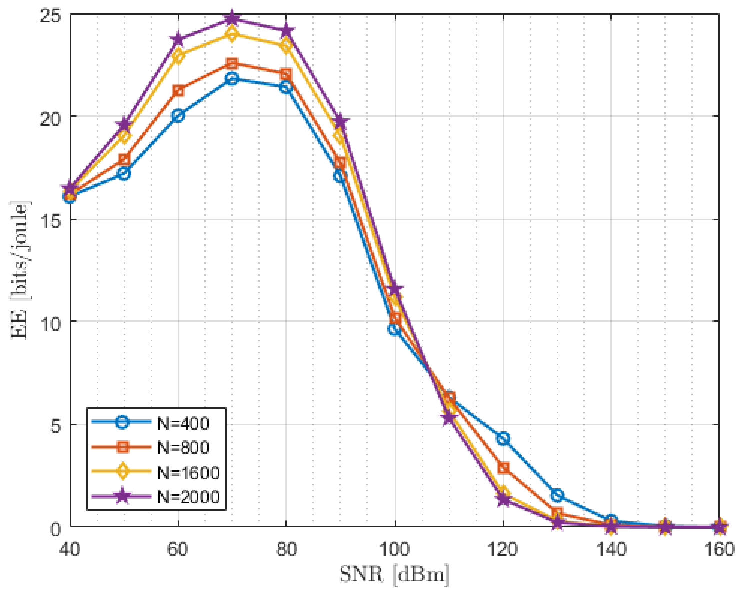


**Figure 7.** EE versus SNR with varying N.

Figure 8 demonstrates EE versus SNR for multiple IRS blocks where each block contains 400 passive elements. It is very clear that IRS-aided IoT systems with two and four blocks outperform the hybrid relay-IRS and relay-aided network after SNR reaches to 90 dBm and 95 dBm, respectively. In particular, at SNR = 100 dBm, the EE with two and four IRS blocks is 47 bits/joule and 68 bits/joule, respectively, whereas the EE of the conventional relay and hybrid relay-IRS is only 16 bits/joule and 39 bits/joule, respectively. From the above analyses, it can be seen that multiple IRS blocks have a greater influence on the EE performance of wireless IoT networks.

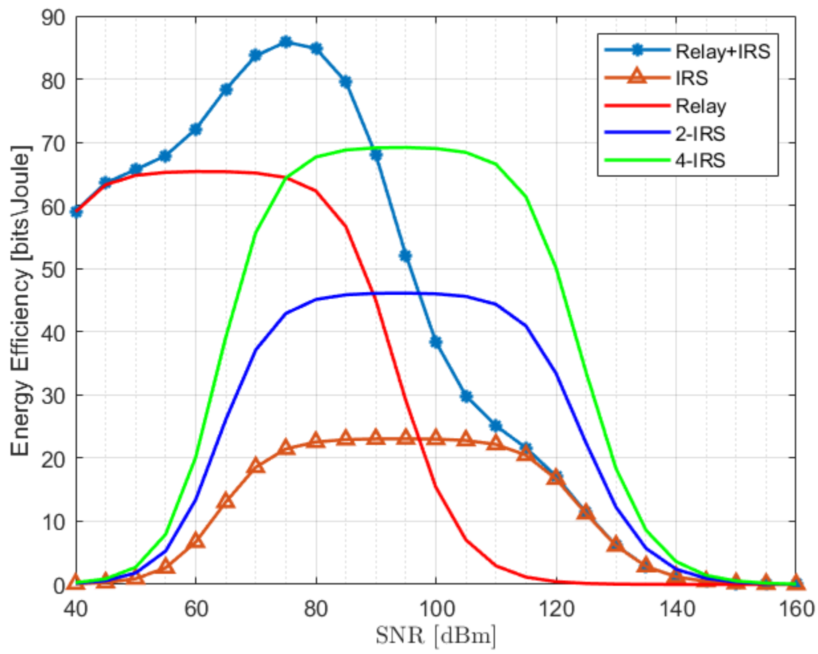


**Figure 8.** EE versus SNR with multiple IRS.

## 5. Conclusions

In this article, we have examined the EE of a novel hybrid relay-IRS-aided wireless IoT network in a Rayleigh fading environment. The hybrid relay-IRS-aided IoT network can fulfill the requirements of high data rate, reliable data transfer, and large bandwidth needed for 6G communications. In this paper, EE has been evaluated for three different scenarios: (i) relay-aided; (ii) hybrid relay-IRS; and (iii) multiple IRS block-assisted wireless IoT networks. Our numerical results show that the hybrid relay-IRS-assisted IoT network outperforms conventional relay- or IRS-aided wireless IoT networks. Furthermore, it is clearly that the multiple IRS concept can be used in 6G communications at high SNR values to reduce both the cost and additional power consumption of wireless IoT networks.

**Author Contributions:** Conceptualization, S.R.; methodology, S.R. and S.C.; software, S.R. and S.C.; validation, A.S.M.S.H. and I.M.; formal analysis, I.-H.R., K.E. and S.C.; investigation, A.S.M.S.H., I.M. and K.E.; resources, S.C., K.E. and I.M.; data curation, A.S.M.S.H. and S.C.; writing—original draft preparation S.R. and S.C.; writing—review and editing, A.S.M.S.H., I.-H.R. and I.M.; visualization, S.C., K.E. and A.S.M.S.H.; project administration S.C.; funding acquisition, I.-H.R. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The authors declare no conflict of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| AF | amplify-and-forward |
| BS | base station |
| BRB | branch and reduced bound |
| DF | decode-and-forward |
| EE | energy efficiency |
| IRS | intelligent reflecting surfaces |
| IoT | internet of things |
| KKT | Kaursh–Kuhn–Tucker |
| MM | majorization–minimization |
| MIMO | multiple-input–multiple-output |
| NOMA | non-orthogonal multiple access |
| OFDM | orthogonal frequency division multiplexing |
| QoS | quality of service |
| SDR | semi-definite relaxation |
| SNR | signal-to-noise ratio |
| SISO | single-input–single-output |
| WET | wireless energy transfer |
| WIT | wireless information transfer |

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