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Research Article

Adaptive Ku-Band Solar Rectenna for Internet-of-Things- (IoT)-over-Satellite Applications

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The emergence of new IoT applications in regional and remote areas has increased the need for a global IoT connectivity beyond existing terrestrial network coverage. However, in many cases, it is not economically viable to build a dedicated terrestrial network to cover these remote areas due to population sparsity and the lack of business case. In this paper, we propose a framework for designing a solar rectenna for IoT-over-satellite applications using nanosatellites. Utilizing such a framework will allow valuable radio spectrum resources to be shared between satellite and terrestrial users. Thus, the autonomous power supply of these objects becomes a big challenge. Indeed, the harvest of solar energy and the conversion of RF energy into electric voltage are a hot topic. Our contribution consists in offering a solar rectenna system to collect solar and RF energy as well as the radio frequency transmission. A parametric study is carried out to follow the influence on the performance of this system. A topology of rectifying circuits is proposed in the present work. The parametric study has shown that the efficiency RF/DC conversion can reach 23.2% for an input power of 5 dBm and a load resistance of 2 kΩ. To ensure the satellite communication of IoT-connected autonomous objects, this system is operated in the X or Ku band.

1. Introduction

The Internet of Things (IoT) market will continue to expand rapidly in the coming years [1]. It is estimated that 22.3 billion IoT devices will be connected to the Internet in 2024 [1]. This rapid growth is due to growing IoT applications in various sectors such as environmental monitoring, utility measurement, transport, and other services [2] where IoT is expected to meet many industrial needs and significantly improve their efficiency. Despite this requirement, providing IoT services for remote areas beyond the reach of terrestrial cell structures will be a major challenge. IoT satellite is one of the proposed cost-effective solutions for connecting IoT devices sent to remote locations [2–4]. In previous years, the development of an IoT over satellite is considered to be very expensive due to the high deployment costs of traditional satellite systems [5]. However, with recent developments in the space industry, it is possible to launch a full nanosatellite constellation at a fraction of traditional satellite costs [6]. Therefore, the IoT over satellite is a promising solution to complement the coverage of the terrestrial network and would open the door to the wider deployment of information technology outside the coverage areas of existing mobile networks. However, there are many challenges associated with the deployment of an IoT over satellite, such as increased interference levels, availability of connections, the huge signal loss caused by the large distance between the IoT devices and the serving satellite terrestrial networks, and battery consumption. In order to address this challenge, the use of photovoltaic in communication systems has recently been the subject of much research.

The photovoltaic systems of power generation when combined with communication systems can provide compact and reliable autonomous communication system, which can be used for many applications. Solar-powered communication systems have received considerable attention due to

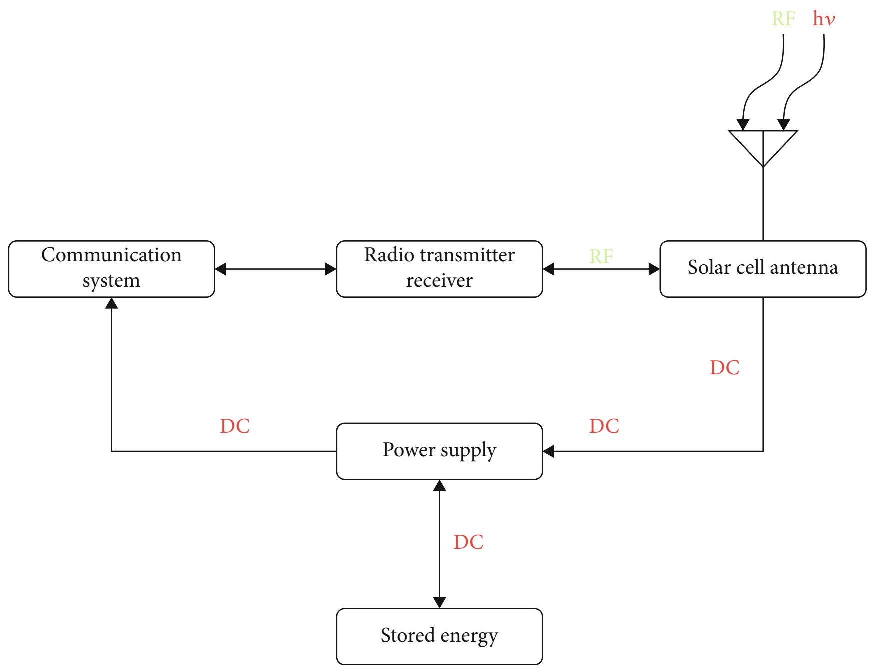

Figure 1: Solar cell antenna architecture.

their ability to operate without the necessity of being connected to an electricity grid. This has become a significant challenge when it comes to powering communication systems in remote places where the electricity grid is not available. At present, the photovoltaic generator and the antenna are two separate devices. They compete for the available space on mobile and stand-alone systems which are generally limited in size. Furthermore, they may be bulky and expensive and they limit the capabilities of product designs. The integration of photovoltaic solar cells with microwave antennas in a single multifunctional device potentially gives a wide range of advantages in terms of volume, weight, smart appearance, and electrical performance to many applications when compared with a simple juxtaposition of antennas and solar cells [6–9]. On this scale, the recovery of solar and electromagnetic energy may be possible since optical and electromagnetic waves exist everywhere in the environment. This vision gave birth to an RF/DC conversion system called rectenna. It is a system that collects and converts solar and electromagnetic waves into direct current (Figure 1). The antenna is an essential component in the rectenna system, it is considered as the interface between free space and the rectifier circuit.

2. Internet of Things

Internet of Things or Iot is a term heard in recent years. This term was discovered in 1990 and refers to the connection of billions of objects and people via the Internet. It can be considered one of the most powerful instruments together with other communication technologies such as RFID (Radio Frequency Identification), Wi-Fi, Bluetooth, Zigbee, and Sigfox. A connected object is an electronic object that has an IP address capable of exchanging, sharing, and modifying countless data on the Internet. In fact, a connected object is a whole capable of finding the capacity to interact and connect with its physical environment. This information is a gold mine for the IoT. These objects are used in different sectors: agriculture, health, and home automation. In the healthcare sector, for example, 60% of hospitals use the Internet of Things to improve remote patient care and monitoring, as well as to increase hospital productivity. The information collected would be transmitted in real time to the attending physician who could thus intervene more quickly. We are talking about industry; we can track equipment and monitor machines remotely. Indeed, the Smart Home, also called home automation, is the most used field of connected objects; a study anticipates a 200% increase in the number of connected objects by the end of 2021. Thanks to the Internet of Things, agriculture has become more manageable and more comfortable in its modest production process. Connected agriculture communicates essential information to you thanks to its sensors, allowing you to know precisely the state of your real-time operation: soil moisture level, presence of pests, etc.

The Internet of Things (IoT) is one of the emerging technologies which promises a lot of solutions in almost all the fields of engineering. Its applications are very attractive for complex situations. In defense, several complex problems and situations are encountered [2]. These problems and situations have to be resolved in a short span of time. Several mission-critical situations are very common in the defense sectors. IoT also provides solutions to these mission-critical problems. Integration of satellites with the IoTs is a win-win combination for many complex problems. In this context, it is shown that the hybridization of IoTs and satellite networks can provide excellent results which were not possible in the past. The utilities of this elegant combination are

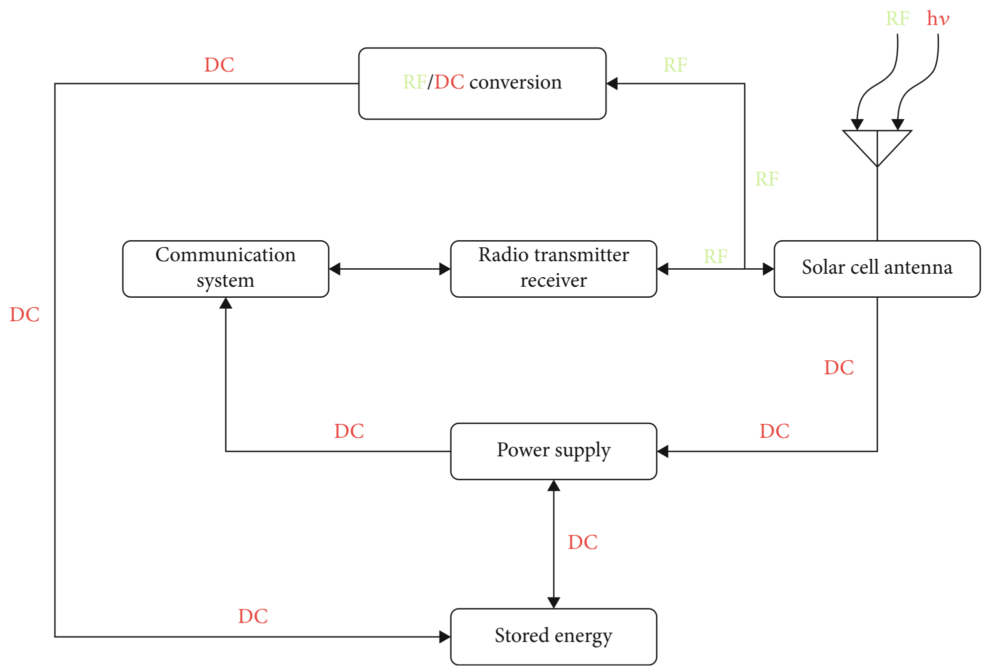

Figure 2: Structure of a solar rectenna system.

provided for handling the complex problems of the defense sectors. A few practical cases are also provided where satellite-based IoTs play critical and valuable roles. Finally, for the long-term sustainability of this combination, one of the resource-efficient versions of the IoTs, mainly narrow-band IoT (NBIoT), is focused on. It is shown that NBIoT and satellite combination can be sustainable in the long term.

The connection of connected devices is increasing around the world, and satellite communications are a solution to ensure connectivity at scale. The most significant IoT trend after years will be the full use of global connectivity through advances in satellite communications. Access to satellite services must be made more accessible and easier to take advantage of the real capabilities of the IoT. Devices currently connected via satellite in space are expected to quadruple in the coming years, from 2.7 million units in 2019 to 10 million units in 2025 with an annual growth rate of 25%. Device with integrated mobile connectivity can move to satellite networks if it is not within range of terrestrial infrastructure. In the other hand, satellite applications require the use of high-gain antennas. So the connection between satellite and IoT devices needs to be modeled and optimized properly. One possible optimization is to improve the antenna gain at both ends to counteract the effects of wavefront expansion and atmospheric absorption. The increase in antenna gain thus reduces the width of the light and thus the interference caused by terrestrial devices and other IoT-over-satellite users.

Satellite networks using Low Earth Orbit (LEO) are considered to supplement the terrestrial network infrastructure in the context of the 5th generation of wireless systems and particularly for IoT applications. Satellite networks can be envisaged to supplement terrestrial networks by providing connectivity to areas where a terrestrial link is difficult or expensive to establish. The satellite communication industry is driving new initiatives towards an integrated satellite and terrestrial network infrastructure in the context of the 5th generation of wireless systems (5G).

In recent years, the Internet of Things (IoT) technology has shown a good momentum of development and has been widely used in various fields of society. Satellite IoT, as an important complement and extension of the ground IoT, provides services in areas where oceanic and desert areas cannot build terrestrial IoT base stations. However, due to limited spectrum resources, spectrum sharing between terrestrial IoT and satellite IoT is likely to be required, which will inevitably lead to uplink and downlink cochannel interference between systems.

Satellite communication systems with a wide coverage cannot be affected by geographical and weather conditions. In addition, the low-orbit satellite communication system also has the characteristics of short transmission delay, low power consumption, and low propagation loss, so it was potential to realize satellite IoT. Due to the wide coverage and limited spectrum resources, satellite IoT requires to share spectrum with existing terrestrial IoT. Therefore, analysis of uplink and downlink interference between the terrestrial IoT and the satellite IoT has become an important issue. The IoT (Internet of Things) now comes with an extensive feature, using the capability of satellite reach. The Narrow-Band Low Earth Orbit Satellite has released a feature for IoT connect to Low Orbit Satellite and transmit the data from the sensor directly.

3. Antenna Requirements and Solar Rectenna for IoT-over-Satellite Applications

The proposed satellite IoT application is intended to use LEO nanosatellites using the free spectrum under license. In this

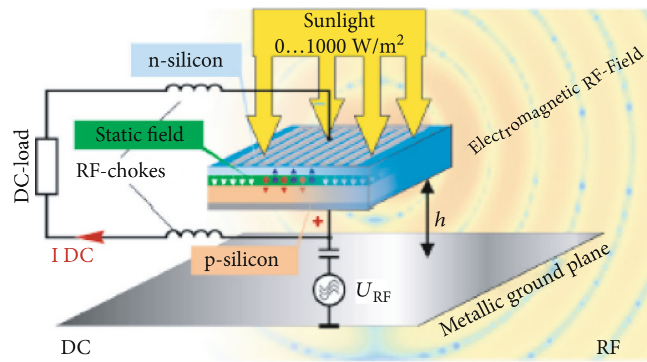

FIGURE 3: Basic principle of solar cell antenna proposed [11].

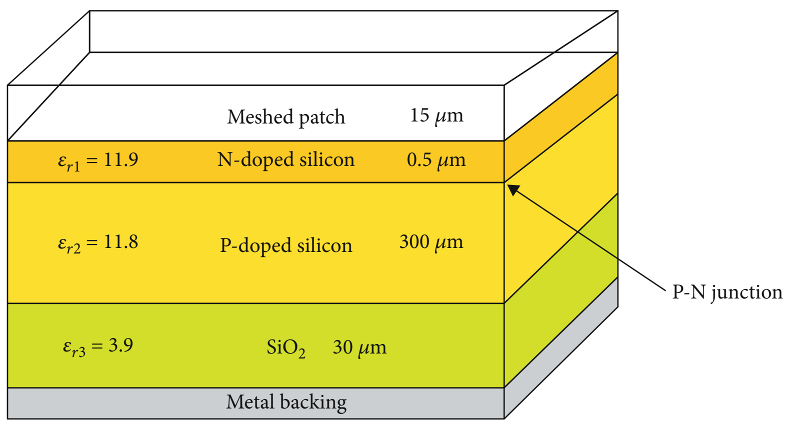

FIGURE 4: Multilayered substrate of solar cell antenna.

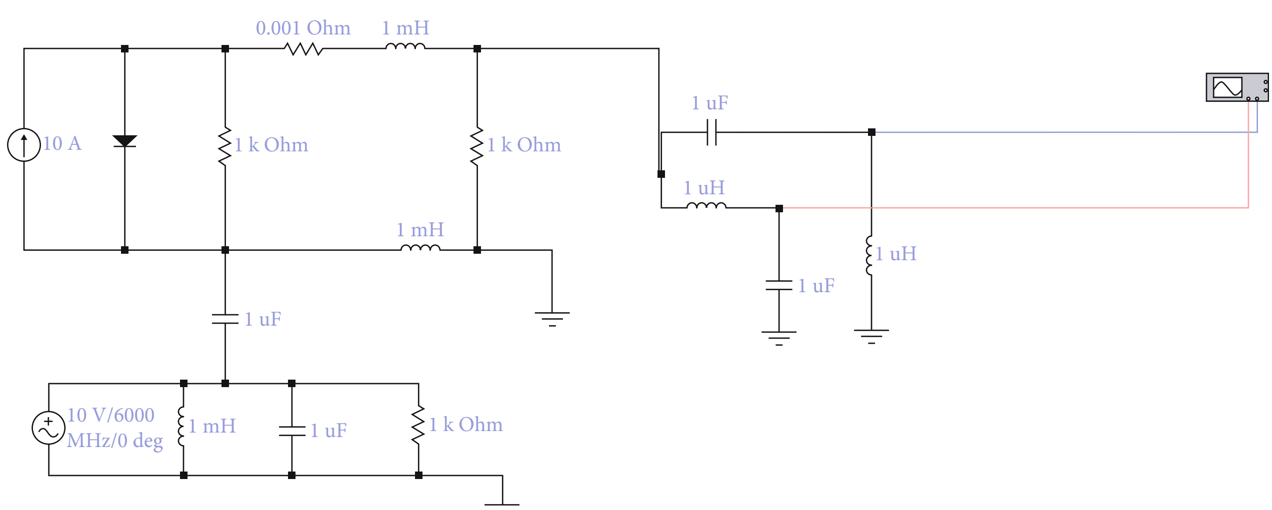

FIGURE 5: Equivalent circuit solar cell antenna separated RF from the DC current.

case, the antenna should be designed to provide dynamic coverage to remote areas while mitigating interference from urban areas. To achieve this dynamic coverage, the antenna must be able to direct its beam towards the desired target area. This Ku-band antenna will only be for satellite communications and therefore has less interference with terrestrial networks. These antennas will therefore be used for the design of a new solar rectenna system for energy harvesting and data transmission.

3.1. Approach. This work builds on previous work [10–13] in which we investigated and designed new patch antennas based on solar cells. However, in this work, antennas will be dedicated to both energy harvesting and data transmission via RF wave emission and reception (Figure 1).

The similarity between the patch antenna and the solar cell, the structure of this antenna, and the equivalent circuit and the RF/DC decoupling are well described in the following subsections for a good explanation because the current

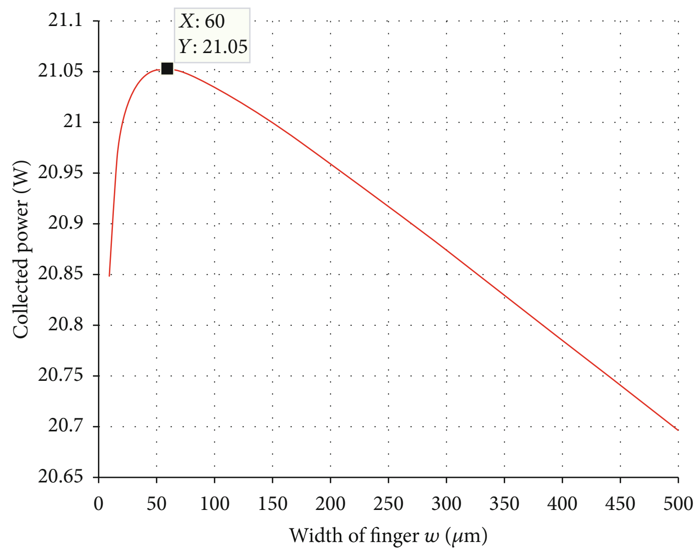

Figure 6: Variation of the power collected by finger width function.

work in this paper is an extension of previous work. From the solar cell antennas studied, we proposed a new hybrid system of a solar rectenna (optically transparent) for IoT-over-satellite applications (Figure 2).

Generally, the traditional rectenna based on a classic patch antenna is used to pick up RF waves from its surroundings and convert them into direct current (DC). A rectenna (rectifying antenna) is a special type of receiving antenna that is used for converting electromagnetic energy into direct current (DC) electricity. They are used in wireless power transmission systems that transmit power by radio waves. A simple rectenna element consists of a dipole antenna with an RF diode connected across the dipole elements. The diode rectifies the AC induced in the antenna by the microwaves, to produce DC power, which powers a load connected across the diode. Schottky diodes are usually used because they have the lowest voltage drop and highest speed and therefore have the lowest power losses due to conduction and switching.

Currently, the solar rectenna is based on a solar cell antenna and the latter will collect optical waves (photons) as a solar cell and RF waves as an antenna. A DC (direct current) will be directly recovered and the RF part will be split into two parts; one part for data transmission at a specific resonant frequency and another unitile RF part on either side around this resonant frequency will be converted into a direct current DC, and this one will then be used with the direct current (DC) of photons for the power of a wireless system which is in an environment deprived of electricity such as the case of small satellites whose application is described in this work as well as for the different sensors that we can use in an IoT system.

3.2. Similarity between Antenna and Solar Cell. A solar cell or a photovoltaic cell is a device that converts photons from the sun radiation into electricity. The development of the thin amorphous silicon on polymer substrate solar cell technology made it possible to easily cut and fit the solar cells to various shapes. The poly-Si solar cell consists of two metal contacts, a

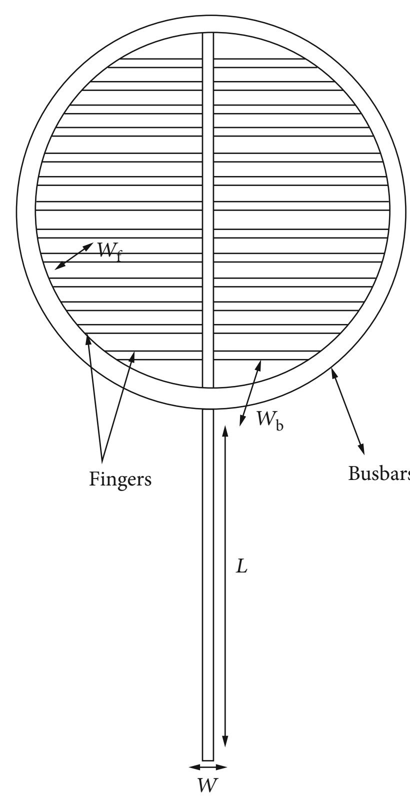

Figure 7: Solar cell antenna with two busbars $W_f = 60\,\mu$m, W_b = 0.5 mm, and $L = 4.2$ mm.

front grid (negative DC terminal) and a solid bottom (positive DC terminal) together with a silicon layer in between. Comparisons with microstrip antenna and solar cell show that they are similar. Patch antenna consists of metal patch, dielectric substrate, ground plan, and coaxial port [14].

The RF impedance between the DC contacts of a PV cell can be measured with a network analyzer and compared to metallic patch measurements.

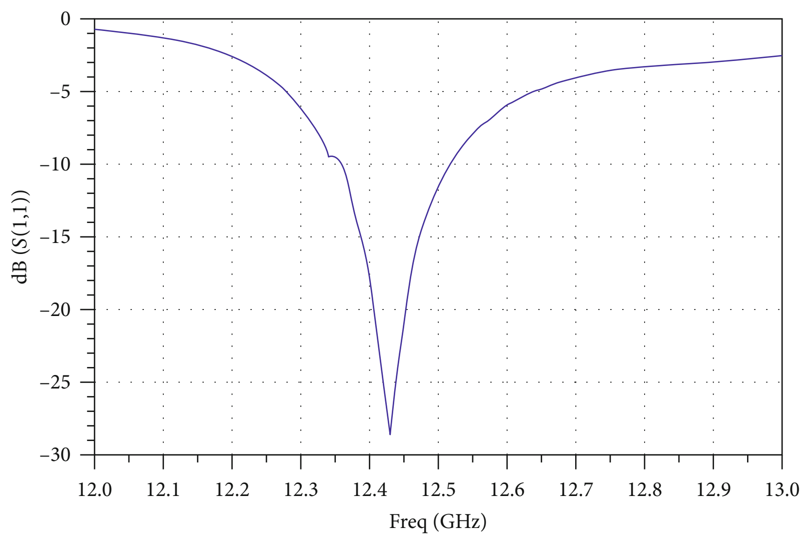

FIGURE 8: Reflection coefficient S_{11} at 12.43 GHz.

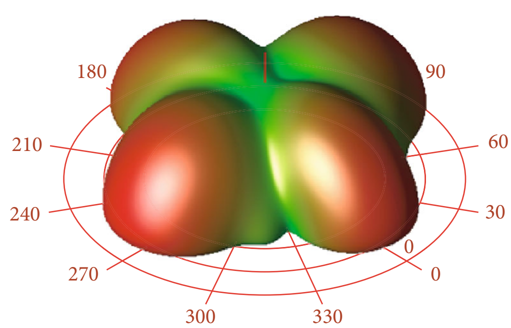

FIGURE 9: Radiation pattern at 12.43 GHz.

3.3. Structure of Solar Cell Antenna. Our contribution consists in combining the two devices into one to overcome all the above disadvantages. A new device for both energy harvesting and RF transmission is shown in Figure 3. The solar cell antenna architecture has been proposed and well studied in our previous research work [10–15]. The solar cell antenna structure proposed is given in Figure 4.

The designed structure was a printed antenna on a substrate compound of different layers of silicon, a layer of the n junction, 0.5 μm thick and relative permittivity of $\varepsilon_{r1} = 11.9$; a second layer below the P junction, 300 μm thick and $\varepsilon_{r2} = 11.8$; and a third layer SiO_2 having a thickness of 1.5 mm and $\varepsilon_{r3} = 3.9$ between the layer of connecting point P and the ground plane. The silicon on an insulating layer SiO_2 confers to the components that are realized, a higher operating frequency, an ability to operate at low voltage and low power consumption, and an insensitivity to the effects of ionizing radiation. For the collection grid, two variants can be developed: one with a copper resonator, which does not allow the passage of optical rays where the metal is deposited, but which guarantees very high performances for the antenna; and the other with a so-called transparent conductor, which favors the performance of the solar cell.

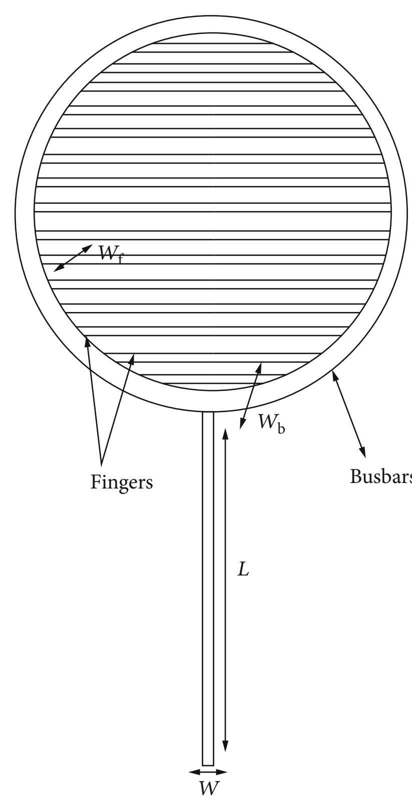

FIGURE 10: Solar cell antenna with a single busbar $W_f = 60\,\mu$m, $W_b = 0.5$ mm, $L = 4.1$ mm, and $W = 0.2$ mm.

3.4. Equivalent Circuit of Solar Cell Antenna and RF/DC Decoupling. Solar cell equivalent circuit is specially simulated in electronic work bench for measuring power (P), voltage (V), and current (I). Microstrip antenna equivalent circuit is separately simulated, and the same output is measured. Finally, both microstrip and solar cell circuits are combined and output is measured, while comparing both outputs,

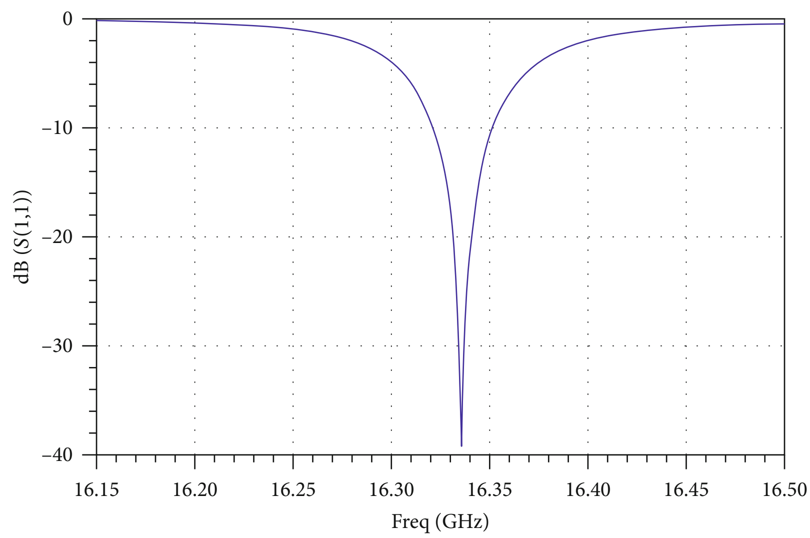

Figure 11: Reflection coefficient S_{11} at 16.34 GHz.

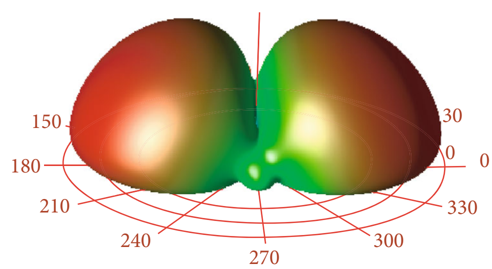

Figure 12: Radiation pattern at 16.34 GHz.

combination of microstrip and solar cell equivalent circuit produces high voltage (V), current (I), and power (P).

Here, we propose an equivalent circuit of a solar cell antenna. The separation of two signals RF and DC was conducted by a function of a low-pass filter and a high-pass filter (Figure 5). A low-pass filter is a filter that passes signals with a frequency lower than a certain cutoff frequency and attenuates signals with frequencies higher than the cutoff frequency and conversely for a high-pass filter. The simulation results of equivalent circuit solar cell antenna are shown, when RF and DC currents are separated.

4. Solar Rectenna

In this section, we first study the solar cell antennas proposed for the design of solar rectenna by determining the energy collected by each as a solar cell and the RF parameters such as gain, directivity, and reflection coefficient S_{11} as an antenna. In the second part of this section, we study the RF/DC conversion of solar rectenna proposed.

4.1. Simulation Results of DC and RF Parameters. The combination of solar cell and antenna technology requires special approaches because the demands of photovoltaic are often in opposite to antenna requirements [15, 16]. For example, the resonance frequency of the solar planar antenna depends on the patch size. Therefore, RF optimization criteria also affect the useful surface for the solar energy conversion.

In this paper, firstly, we are going to study the optimization of the collection grid front side of the solar cell antenna. Our study will focus in the width of metallic lines of the latter which will be chosen so that the losses (losses due to horizontal power in the transmitter, conduction losses in the metallic fingers, and losses due to shading created by the grid) of power produced by the voltage drop are minimal. This optimization therefore requires the right choice of the geometry of the grid and its manufacturing material. We chose a compromise between the optical losses and conduction losses to derive the geometrical dimensions of the optimized collecting grid which will give the maximum productivity of the cell. The power collected by the cell is therefore

$$P_{\mathrm{col}} = P_{\mathrm{ecl}} - P_{\mathrm{t}}, \tag{1}$$

where

(i) P_{ecl} is power cell lighting

(ii) P_{t} is total power dissipated due to resistive losses and shadow levels

In addition, to maximize absorption and minimize recombination, the final condition required to design a high performance of a solar cell antenna is to minimize its parasitic resistive losses, hence the conduction rate which is the relationship between the total power P_{t} lost by the joule effect to the power supplied without loss; therefore, from an optical point of view, the coverage rate or the shade rate must be low because the hidden surface by metallization is inactive. Thus, there is a compromise between these two situations, which tend to improve the energy conversion efficiency.

A mathematical model which would serve the minimization of power losses of the cell and therefore the improvement in the conversion efficiency was studied, and we give

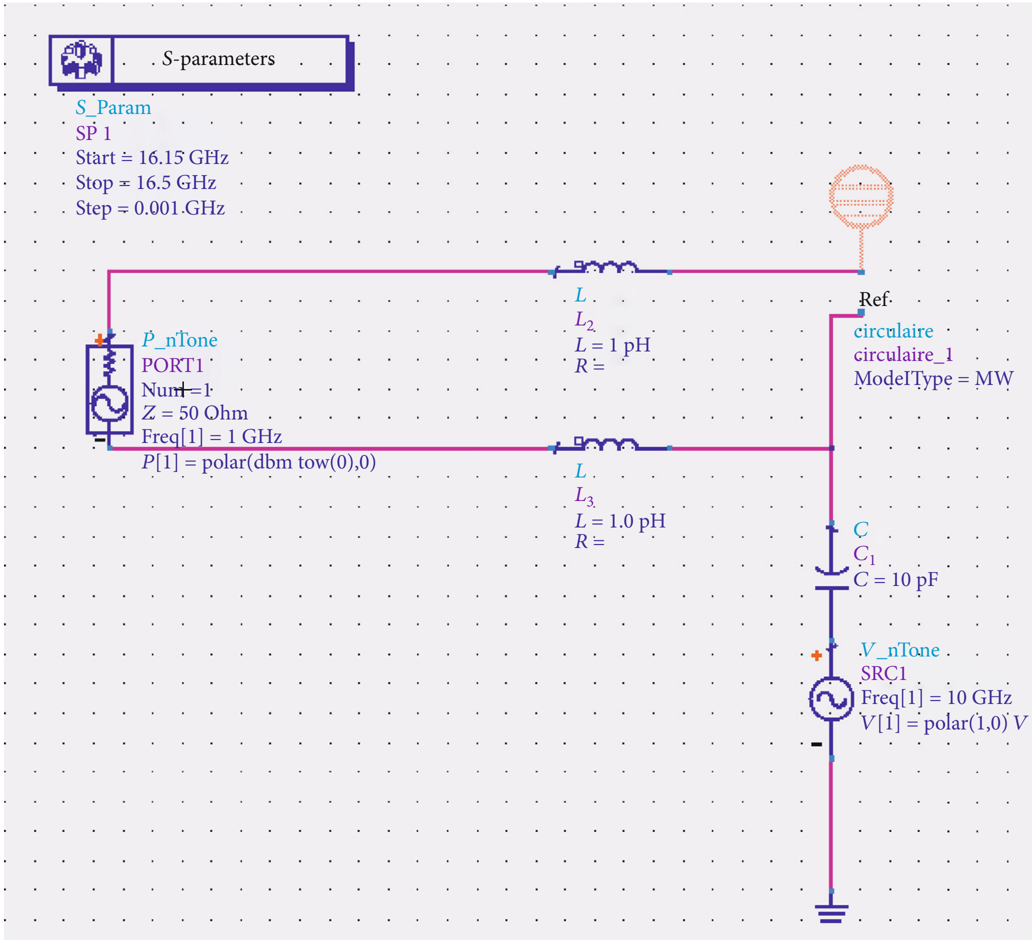

FIGURE 13: Solar cell antenna RF/DC decoupling circuit.

the optimization results here. Figure 6 shows the variation of the power according to the width w of a finger.

As a solar cell, we note that the maximum of the collected power for the solar cell antenna is 21 W for $12.5 \times 12.5\,\mathrm{cm}^2$ of the surface, for a lighting power of $P_{\mathrm{ecl}} = 1300\,\mathrm{W/m}^2$ and which corresponds to a width of a finger equal to 60 μm. This value of the finger width will be useful for the antenna patch conception on silicon dedicated to the radiofrequency transmission.

4.1.1. Solar Cell Antenna with Two Busbars. The solar cell antenna design proposed with two busbars is given by Figure 7. Rectilinear busbars have width $W_{\mathrm{b}} = 0.3$ mm, and width of circular busbars is $W_{\mathrm{b}} = 0.5$ mm. This solar cell antenna was excited by a microstrip line of 0.3 mm in width and characteristic impedance equal to 50 Ω.

As an antenna, solar cell antenna was simulated and the reflection coefficient S_{11} is presented in Figure 8. An antenna should be a perfect radiator, rather than perfect absorber. The amount of radiated power returned back through the port can be calculated for finding return loss at that resonating frequency. For the resonant frequencies, the reflection coefficient should be less than -10 dB, i.e., $S_{11} < -10$ dB. Simulation results show that the designed antenna can be used as a frequency antenna 12.43 GHz with an effective reflection coefficient of -28.42 dB and 175 MHz of bandwidth [12.35-12.525 GHz].

This radiation pattern shows that the antenna radiates more power in a certain direction than another direction. The antenna is said to have certain directivity. The radiation pattern of this solar cell antenna at a frequency of 12.43 GHz is shown in Figure 9. The polarization of the radiated field was linear. Antenna gain describes how much power is transmitted in the direction of peak radiation to that of an isotropic source. The gain of antenna is 5.70 dBi and directivity of 9.26 dB at 12.43 GHz.

4.1.2. Solar Cell Antenna with a Single Busbar. The solar cell antenna design proposed with a single busbar is given by Figure 10. The width of circular busbars is W_{b}=0.5 mm.

The simulation results of the proposed solar cell antenna are given in Figures 11 and 12. Figure 11 shows the reflection coefficient S_{11} and the resonance frequency at a 16.34 GHz with a refection coefficient -39.19 dB and 40 MHz of bandwidth [16.32-16.36 GHz]. The radiation pattern of this solar cell antenna at a frequency of 16.34 GHz is shown in Figure 12. The gain is 6.93 dBi, and the directivity 8.64 dB.

The solar cell antenna RF/DC decoupling circuit proposed is given in Figure 13. The reflection coefficient simulation result confirms well that which we obtained previously,

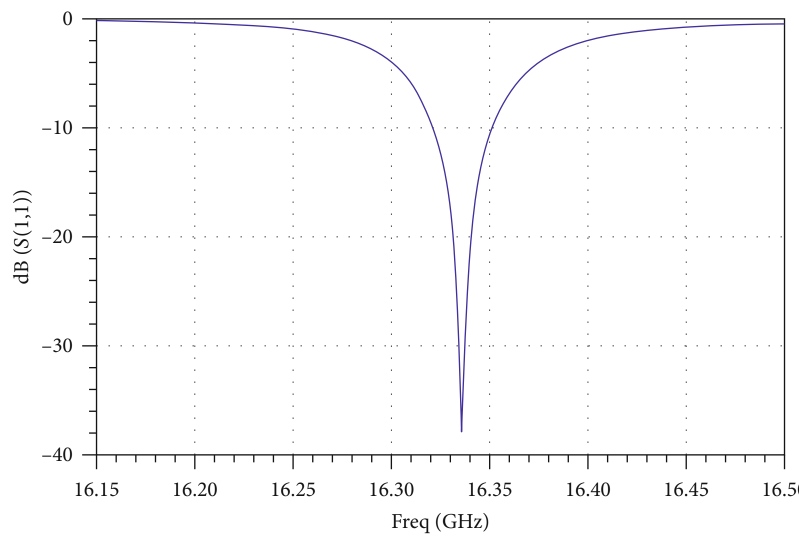

Figure 14: Reflection coefficient S_{11}.

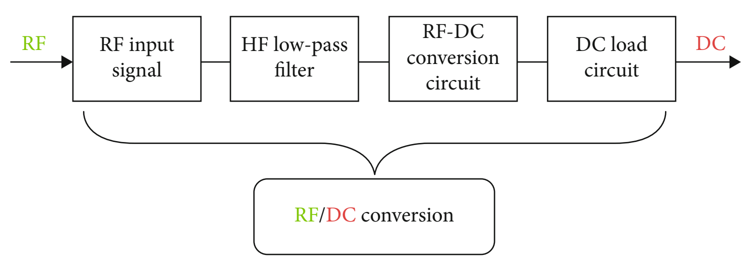

Figure 15: RF/DC conversion block.

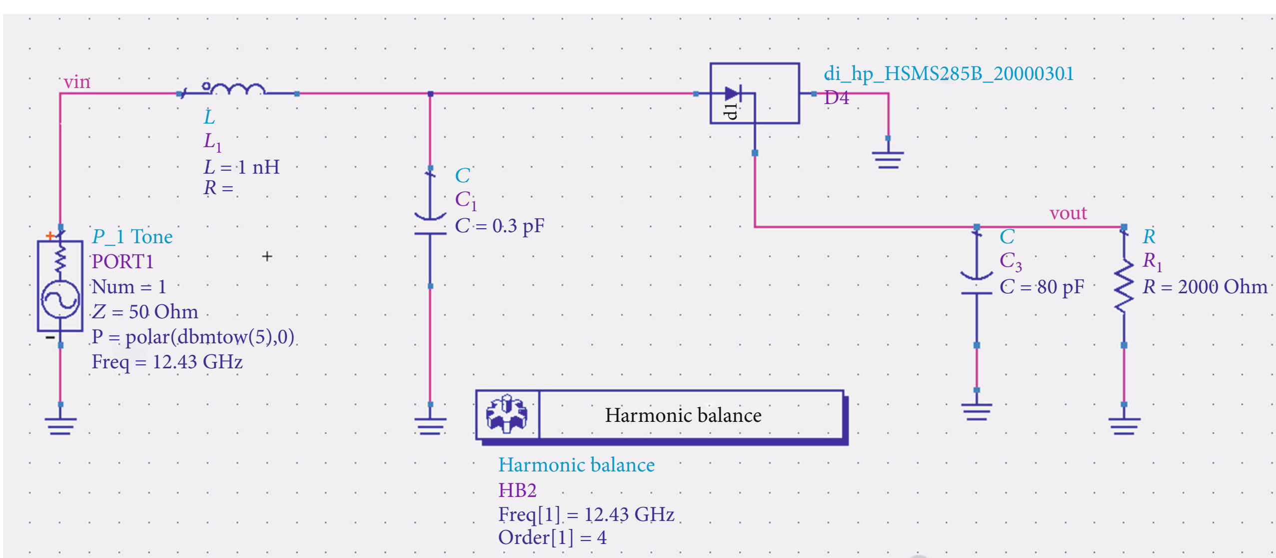

Figure 16: Single-diode rectenna circuit in a series at 12.43 GHz.

the resonance frequency at 16.34 GHz with a slight change in return loss -37.75 dB (Figure 14).

4.2. RF/DC Conversion. The main role of a rectenna is to harvest, from free space, RF waves and convert it into direct current [17–21]. In this work, we study a novel solar rectenna based on a solar cell antenna dedicated to energy harvesting and RF transmission at the same time (Figure 2). The solar waves will be transmitted in the form of DC signals, and the electromagnetic waves will be divided into two parts;

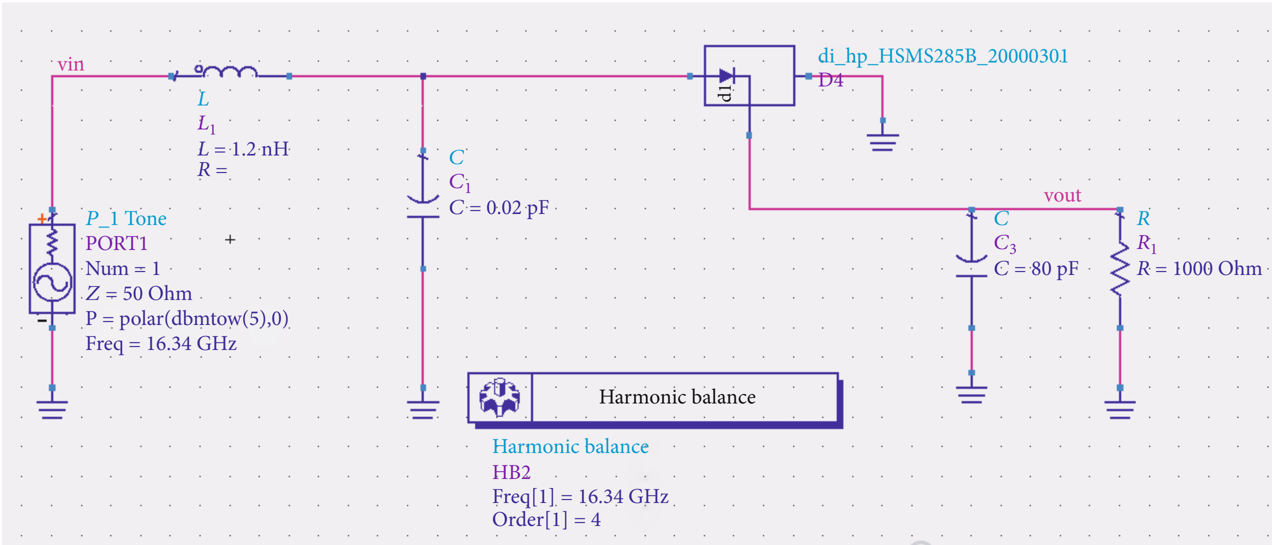

Figure 17: Single-diode rectenna circuit in a series at 16.34 GHz.

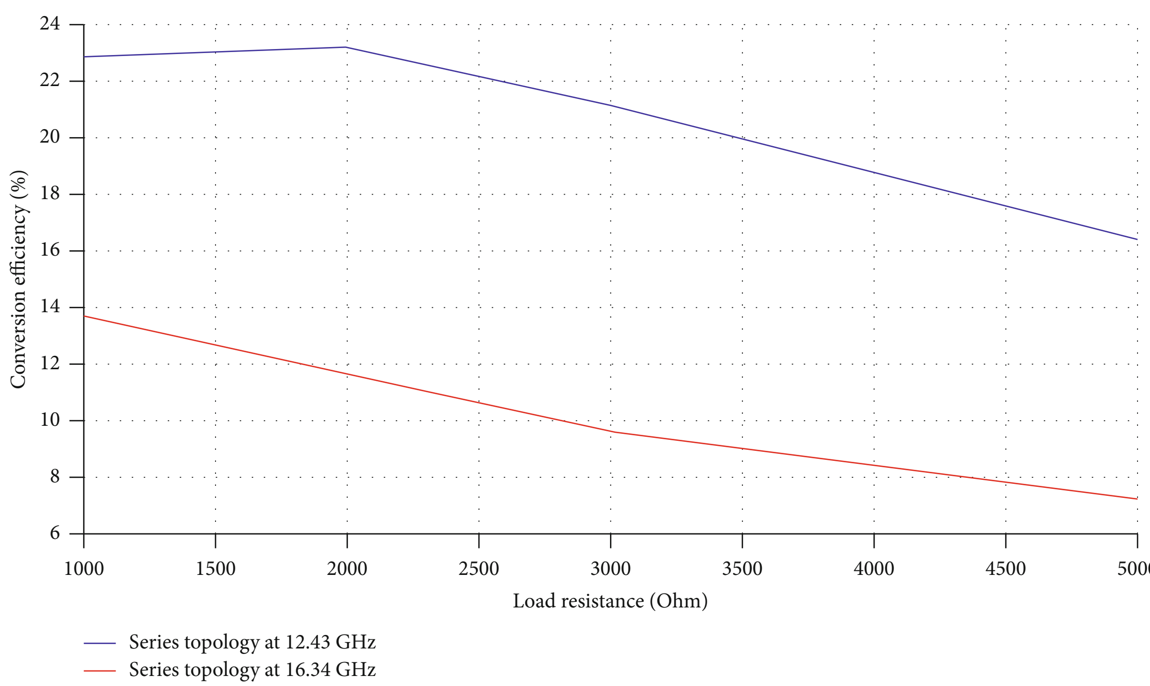

Figure 18: Variation of conversion efficiency as a function of resistance.

one part contains the transmitted data, and the other nonusable part will be filtered, by a band-pass filter allowing only one band to pass or frequency interval between [12.35-12.525 GHz] and [16.32-16.36 GHz] for antenna 1 and antenna 2, respectively, and converted by the rectifier circuit into DC signals. The conversion circuit converts the part not usable from RF waves into a DC signal. A HF low-pass filter, a RF-DC conversion circuit, and a DC load circuit composed the chain of rectifier circuit (Figure 15). The function of the high-frequency low-pass filter is as follows: on the one hand, it avoids the harmonics generated by the Schottky diode; on the other hand, it performs the impedance matching between the antenna of the solar cell and the rectifier. On the other side of the conversion circuit, there is a DC filter whose principle is to ensure the impedance matching between the rectifier circuit and the resistive load; it is a low-pass filter [22–28].

We present in this paragraph the study of a rectenna system formed by the monodiode series structure. This is the simplest structure, widely used in low-power applications. Figure 16 shows the design of the monodiode series circuit at the frequency 12.43 GHz. It consists of a Schottky diode of the type HSMS-285b with a capacitor of 80 pF and a load resistance of 2 kΩ. Figure 17 shows the design of the monodiode series circuit at the frequency 16.34 GHz. It consists of a Schottky diode of the HSMS-285b type with an 80 pF capacitor and a load resistance of 1 kΩ.

The rectenna conversion efficiency is calculated numerically as the ratio of the output power at the load level to the amount of RF power at the input.

$$\eta = \frac{P_{DC}}{P_{RF}} = \frac{V_{DC}^2}{P_{RF} \cdot R_L}, \quad (2)$$

where

(i) P_{DC} is output DC power

(ii) P_{RF} is input RF power

(iii) V_{DC} is output DC voltage

(iv) R_L is resistive load

This study allows to observe the variation of the efficiency according to the resistive load (RL) going from 1 kΩ to 5 kΩ (Figure 18). The maximum efficiency presents a value of 23.2% for an incident power of 5 dBm, a frequency of 12.43 GHz, and at an optimal load level 2 kΩ and reaches a value of 13.6% for an incident power of 5 dBm, a frequency 16.34 GHz, and at an optimal load level of 1 kΩ.

5. Conclusion

In this work, we have presented a new hybrid solar rectenna system based on the design of solar cell antenna dedicated to IoT over satellite. This work allowed us to evaluate the performance of a new model of solar cell and patch antenna combination which is very advantageous and practical. This solution approved the designed solar rectenna capable of harvesting solar energy and RF energy and converts it into electrical energy as well as transmitting data. The prototype of this work is particularly well suited to energy harvesting and Ku-band RF transmission with significant gain. This is a promising and innovative solution to autonomous object connected energy for IoT over satellite. Also, from a rectification point of view, this system has shown that the serial topology at a given conversion efficiency is equal to 23.2% at a frequency of 12.43 GHz and 13.6% at a frequency of 16.34 GHz.

Both realization and design of the solar cell antenna and the measures of their parameters such as the reflection coefficient S_{11}, gain, directivity, and the radiated power will be studied in another work. Far and away, measurement results obtained will be compared with those of the simulations studied in this work.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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