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Standardization of simulation conditions for radio frequency energy harvesters

JAKUB SZUT ✉, MARIUSZ PAULUK, PAWEŁ PIĄTEK

Faculty of Electrical Engineering, Automation, Computer Science and Biomedical Engineering
AGH University of Krakow
al. A. Mickiewicza 30, 30-059 Kraków, Poland
e-mail: {✉ szut/mp/ppi}@agh.edu.pl

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Abstract: RF energy harvesters require a precise design and verification. Power conversion efficiency (PCE) is affected by a number of factors. Among others, there are: design of emitting and transmitting circuits, transmission conditions, frequency, bandwidth and distance between antennas. All of those factors contribute to the final effectiveness of RF energy harvesting (RFEH) circuits. This is why it is important to standardize conditions of simulating and measuring the circuits performance. Only then it will be possible to compare usefulness of different designs. This article discusses such conditions and proposes some standardizations.

Key words: conditions standardization, RF energy harvesters, RF energy harvesting, simulation, SPICE

1. Introduction

Every single year there is a need for more and more energy [1]. Industry, science, and private users need access to cheap and reliable energy sources. In the meantime, the energy consumed by a single device is being limited. The power consumption of particular utilities is optimized [2]. The miniaturization in electronic devices design leads us to the energy requirements close to zero. This is why we cannot base only on highly efficient energy sources like fossil fuel power stations or renewable energy like solar or wind power plants. The use of ambient energy sources emerges in low-energy use cases. Ambient energy comes from different phenomena occurring in the environment. Both naturally and triggered by human activity. Energy is anticipated via motion, temperature, or transmission of electromagnetic waves [3]. Use of the latter one to transfer wireless energy was already dreamed about over a century ago by Nikola Tesla [4]. However, it is only recent years that the sensitivity and efficiency of electronic elements made it possible to acquire enough energy from RF transmission to power up sensors or pump additional power into the device [5]. Although usually energy used to transmit data via electromagnetic waves is dissipated in the environment, it is possible to collect and reuse that ambient energy. To achieve that goal, special circuits called RF energy harvesters are used. Such devices consist of various blocks such as: antenna, impedance matching network, rectifier, and often power management unit [6]. The current that is excited on the antenna during receiving signal from transmitter is forwarded via impedance matching network to rectifier, in which it is rectified and very often voltage is multiplied to meet power management requirements. Such a circuit can harvest ambient energy that is transmitted via FM radio stations, mobile network base stations and various other devices such as WiFi routers. It is important to mention that the RF energy harvesters can differ in both technology and topology [7]. One can distinguish designs based on diodes [8, 9] and CMOS [10, 11]. Most often diode-based approaches will be based on Schottky diode due to its low threshold voltage (around 0.3 V) and the CMOS one will provide diode-like behaviour based on transistors. When it comes to topology, there are also different approaches depending on the proposed design [12]. Generally, one can name half and full wave designs [13], cell [14] and CCDD rectifiers [15] or ones with pumping capacitors [16] or utilizing piezoelectric transformer [47]. Technologies and topologies can be mixed to achieve best performance depending on operational frequency, power spectral density and other requirements. Recent increase in the research on RF energy harvesting circuits led us to the question of how to properly compare different designs. As there is a number of circuit designs propositions for both diode and CMOS, it is crucial to be able to verify their performance. However, researchers tend to verify their circuits in various conditions that are difficult to compare. This paper proposes standardized conditions for both simulation and measurement to unify RF energy harvesters' performance verification. In Section 2 the most important parameters in RF energy harvesting are presented, Section 3 contains analysis and suggestion for standardized frequency parameters, Section 4 standardizes transmission signal power and Section 5 discusses possible solutions defining propagation conditions. Section 6 discusses possible further research and Section 7 summarizes this paper.

2. Parameters important in RF energy harvesting

The RF energy harvester performance is affected by various factors. Also, performance on particular designs can be different with different conditions provided during simulation and measurement. We can define a few factors that are most crucial for harvester performance. Emission frequency is key when considering energy transfer via electromagnetic waves. Signal power which is defined not only by transmitting antenna output power, a gain and directivity but also by the gain and directivity of receiving antenna, a distance between them and the propagation in the medium described by a power density, and last but not least, propagation conditions such as humidity and temperature affect the RF transmission [17].

Currently, there is no unified approach to present conditions in which proposed harvesters are simulated or measured. It is very common to provide information regarding operating frequency of the circuit [18–20]. If it is a part of the research, the data regarding bandwidth is provided [21].

In most of the papers studied during the research there are no more details describing conditions in which circuits were tested. From time to time, a description of a receiving antenna is provided, so its type and the gain is known [22]. It can be also find papers in which applied transmitters are described [23], then the gain and the output power of the transmitted signal is known. There is often no data regarding propagation conditions. Researchers do not provide detailed information regarding test environment. One cannot know if RFEH modules are isolated from external transmissions or what are the environmental conditions during the measurements. Some papers contain photos of testbenches [24], where measurements are done. To obtain best measurements results echoless chamber that can isolate the testbench from other electromagnetic radiation sources should be used or clean-room conditions to control environmental parameters during measurements should be provided.

Taking all above into account, one can figure out that currently available comparisons [7, 12] of different RF energy harvesters cannot provide reliable information in order to compare performance of different designs as they are based on results provided for different conditions. A circuit having a power conversion efficiency (PCE) of 80% at 2.4 GHz can be worse than the one having PCE equal to 60% at 433 MHz as the first one matching network can be less efficient for lower frequency ranges. Therefore, there is a need to clarify which conditions should be used to test circuits and provide in research reports in order to provide common ground for performance comparison of harvesters. The simulations might be ideal first step to create identical conditions for testing the harvesters. However, the results can be fraught by modelling errors.

3. Frequency ranges

Frequency is one of the factors, which describes characteristics of disturbance in electromagnetic field caused by the wave that is propagating in the medium [25]. The higher the frequency the more propagation energy is needed for the wave to reach the target with satisfying level. On the other hand, the lower the frequency, the less energy is lost during the transmission. This is one of the problems that have to be taken into account when choosing the frequency range for FM (frequency modulation) transmission. From the data transmission rate perspective, the higher frequencies provide higher volume of information to be transferred in single unit of time. This is one of the reasons why every new generation of mobile network uses increasing frequency ranges. For example, 5G FR2 standard by 3GPP uses channels that are over 3 GHz, in some cases use of bands over 24 GHz is also defined [26]. On the other hand, lower frequencies which provide better coverage of signal in the wide area (i.e. rural) are also included in FR1 standard.

There is a number of research concerning the frequency congestion which are helpful in defining standards for frequency range used in RF energy harvesting circuits research [27]. As RF energy harvesters are supposed to operate on ambient energy, it is important to find out in which frequency ranges there is the most power available. Those values may vary depending on local laws, which define not only the bands themselves but also the highest possible emission per band [28]. However, those values are often agreed on in given region and adapted by most of the local regulatory authorities. Europe, Asia, Middle East and Africa use GSM 900 and GSM 1 800 bands, whereas Americas use mostly GSM 850 and GSM 1 900 bands [29]. Research shows that the highest emission occurs in 900 MHz, 1 900 MHz and 2 400 MHz bands in urban areas [30, 31].

Being able to harvest in those ranges it will provide the most available power for rectifying circuits. However, those bands are licensed ones. It means that transmitting in those frequencies requires formal authorization from local regulatory office. Therefore, it is difficult to use exactly the same frequencies for research purposes. For that reason, there is a worldwide agreement on providing so called ISM (industrial, scientific, and medical frequency purposes) bands [32]. As it was mentioned, there are different regional sets of licensed bands. Hence, there are differences in regionally available ISM bands. For the European and Asian region, it is 433 MHz band and for United States of America it is 915 MHz band [33]. Nevertheless, use of ISM and other publicly available to transmit bands is our proposition as standard for testing RF energy harvesting circuits. They are close to the commercially used frequency ranges and some of them as 2.4 GHz band is used directly in some use cases, such as WiFi routers. Often ISM bands are close to each other for different regions, the biggest difference is for 433 MHz (Europe and Asia) and 915 MHz (USA). However, it can be possibly overcome using 868 MHz band in Europe as this is semi-open band that allows for low energy transmission [34]. As ambient energy does not tend to be high, 868 MHz can be used to verify design of harvesters. The proposed frequencies are presented in Table 1.

Table 1. Frequencies proposed as standard for RF energy harvesters' simulation and measurement

Frequency range	**Frequency**	**Frequency type**	**Reason**
Low	433 MHz	ISM (Europe)	ISM frequency used in amateur radio control and sensor communication.
Low	915 MHz	ISM (USA)	Equivalent of European 433 MHz. To conduct comparison, 868 MHz may be used in Europe for low power transmission.
Medium	2.4 GHz	ISM	Widely used in general purpose wireless communication.
High	24 GHz	ISM	ISM frequency close to 5G FR2 bands. It can be used to study telecommunication transmission behaviour.

Using frequencies proposed in Table 1, comparative study can be conducted to compare performance of particular harvesters. Number of different bands is recommended to address different use cases appearing in RF energy harvesting studies and even combine to compare not only narrowband circuits but also wideband hardware that can get power from different frequencies.

4. Signal power

RF transmission on given frequency can give different levels of harvester energy depending on signal power output from the transmitter. In this section, signal power recommendations will be presented in order to reach common ground in studies of RF energy harvesting circuits. The most important concept here is effective isotropic radiated power (EIRP) [35]. Transmission of any signal requires antenna that generates electromagnetic radiation. Oscillating or alternating current signal is used to transfer data wirelessly [36].

Probably one of the first approach to propose some standardization in the subject matter was the Friis paper from 1946 [37], where the following Formula (1) was emphasized.

$$\frac{P_r}{P_t} = \frac{A_r A_t}{d^2 \lambda^2}. \tag{1}$$

P_t is the power fed into the transmitting antenna, P_r is the power at the output of the receiving antenna, A_t is the effective area of the transmitting antenna, A_r is the effective area of the receiving antenna, d is the distance between the antennas, λ is the length of the wave.

Friis proposed to adopt the following definition of the effective area as per Formula (2).

$$A_{\text{eff}} = P_r / P_0, \tag{2}$$

where P_0 describes power, which flows through a unit area of the antenna. The effective area eventually may be treated as a gain of the antennas, the parameter is often leveraged in concurrent considerations, also in the further part of this work [1].

In ideal model, antenna transmits power uniformly in all directions [38]. In spite of being able to use that model in simulations, such approach is almost impossible in real-life testing. Therefore, we propose to standardize parameters for both isotropic model in simulations and real antennas in measurements.

In the case of simulations, model is often subject to simplification. In terms of transmitting antenna, very often this element is neglected and the power received by receiver is represented by Thévenin's equivalent voltage source [39]. This approach makes it possible to simulate circuit only in regard to the current flow. To use that method, it is crucial to calculate power that is available on the receiving antenna. Here, it depends on the EIRP of the transmitter, propagation of wave in the medium and antenna's gain. To calculate that value, Friis equation can be used [6].

To define parameters of the signal power, it is necessary to declare power that should be available on the receiving antenna. This value can be taken from previous studies in the RF transmission [40] or calculated based on technical documentation of wireless systems that often state average and maximum values of transmission [41]. Local restrictions based on regulators policies can be also taken into account [42]. It is important to keep the final value of the power available in the receiving antenna close to the one that can be observed in reality. As longitude of the wavelength is based on the frequency used for the transmission, other parameters such as gain and power may differ for different frequency ranges. Proposed values of transmission power and gain have been presented in Table 2.

Table 2. Proposed characteristic of signal power in simulations

Frequency range	**Power of the transmitter**	**Gain of the transmitting antenna**	**Gain of the receiving antenna**
Low	20 dBm	20 dBi	20 dBi
Medium	38 dBm	20 dBi	20 dBi
High	50 dBm	20 dBi	20 dBi

Table 2 presents values for isotropic antenna. However, that model cannot be used in real test benches. Ideal antenna has to be replaced by omnidirectional or directional antenna. Despite the fact that the first one is closer to the isotropic model, directional antennas are more frequently used as they provide better results in wireless transmission. Based on the real radio transmission equipment and values of power available on the receiving antennas, parameters proposed for transmitting antenna are presented in Table 3.

Table 3. Proposed characteristic of signal power in measurements

Frequency range	**Power of the transmitter**	**Gain of the transmitting antenna**
Low	38 dBm	20 dBi
Medium	20 dBm	20 dBi
High	50 dBm	20 dBi

Table 3 contains only parameters for the transmitting antenna. It is purposefully done as very often new designs of RF energy harvesters focus not only on the rectifiers or voltage multipliers but also on the design of the receiving antenna itself. Therefore, standardizing receiving antenna should not be done to avoid limiting development of receivers.

5. Propagation conditions

Friis equation mentioned in the previous section has one more parameter, that was not yet discussed. It is distance between transmitter and receiver. This parameter is next to the medium permittivity one of the propagation conditions. RF transmission is often described in simplified conditions of free space. Although this estimation is enough for most of the cases, for high frequency transmission of small amounts of energy, propagation conditions are crucial in power dissipation and should not be random. Even telecommunication systems that are operating on daily basis take into account the weather conditions and possibility that transmission range will differ under different circumstances.

Distance between transmitter and receiver depends on the environment setup. Whenever RFEH system with dedicated transmitter is taken into consideration, this distance can be set to value best serving purpose of delivering wireless energy. It is also often a matter of a few meters. In technical specification of such systems, it is up to 120 feet (around 36 meters) [43]. On the other hand, RFEH that is supposed to harvest ambient energy from the environment, distance is often bigger and may vary in time. For urban environments it can be from dozens to a few hundred meters and in the case of rural areas it can be even well over 1 kilometer. The number of transmitters nearby is greater, but they use different frequencies at the same time. In the case of simulations, setting different distances is a matter of parameters setup whereas for test benches in laboratory distance over a few meters is a no-go. The proposed distance for standardization purpose should be then defined as 5 meters. Such value is intact with ranges of already available RFEH systems using dedicated transmitters. In closed spaces it is also a possible distance from router or private network base station. Finally, it is also feasible to prepare a test bench with 5 meters distance between transmitting and receiving antennas. Set of longer distances such as: 10 meters, 100 meters and 300 meters can be proposed for simulations and on the field testing.

Permittivity is influenced by medium type: air or free space [44]. In the case of air, permittivity differs with humidity, temperature and pressure. Permittivity of perfect vacuum is equal to 1. Such a value can be used during simulations but assuming it for real live measurements can lead to miscalculations. The way to achieve permittivity close to the one of perfect vacuum in on Earth conditions is to undertake measurements under standard temperature and pressure conditions. The standard temperature and pressure are defined by various organizations, however a lot of them do not standardize the humidity. Therefore, the choice of ISO 13443:1996 standard is proposed as it defines all parameters [45]. Values for parameters defined in ISO 13443:1996 are presented in Table 4.

Table 4. ISO 13443:1996 parameters for standard temperature and pressure

Parameter	**Temperature**	**Pressure**	**Humidity**
Value	15°C	101.325 kPa	0%

Special chamber should be prepared, not only to provide those atmospheric conditions but also to prevent echoing of transmitted signal and block any external sources of RF transmission.

6. Simulations

6.1. Assumptions

At the beginning of preparations simulations, it was needed to assess expected levels of the voltage at the receiving antenna. It was assumed that power of the transmitter is equal to $P_t = 38$ dBm and frequencies of the electromagnetic waves are equal to 433 MHz, 915 MHz and 2.4 GHz, length of the waves: λ (needed for the Friis model) are appropriately: 0.69 m, 0.33 m and 0.13 m. Taking into account that power in dB is represented as in Eq. (3).

$$P\ [\text{dB}] = 10 \log \frac{P}{P_{\text{ref}}}, \tag{3}$$

where P_{ref} is the reference power. Analogically, power expressed in dBm units is a power expressed in reference to 1 mW. Being super correctly the unit symbol should look like dBmW, but it is generally accepted to use dBm, and as per Eq. (4).

$$P\ [\text{dBm}] = 10 \log \frac{P}{1\ \text{mW}}. \tag{4}$$

Hence, the power of the transmitter, which is presented in Eq. (5).

$$P_t = 38\ \text{dBm} \cong 6.31\ \text{W}. \tag{5}$$

It is also presumed that efficiency of the transmitter: G_t and receiver: G_r antennas are equal to 20 dBi. Similarly, as above, dBi units express in a logarithmic scale efficiency quotient in reference to isotropic antenna efficiency. The distance between transmitter and receiver is accepted as 100 m. So basing on the above assumptions and leveraging Friis model [37, 46], the receiver power may be modelled as follows in Eq. (6).

$$P_t = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right), \tag{6}$$

where the factor in Formula (7) is so called "free space path loss".

$$\left(\frac{\lambda}{4\pi d}\right), \tag{7}$$

which in the logarithmic scale is as per Eq. (8):

$$P_t\ [\text{dBm}] = P_t\ [\text{dBm}] + G_t\ [\text{dBi}] + G_r\ [\text{dBi}] + 20\log\left(\frac{\lambda}{4\pi d}\right). \tag{8}$$

Results of the initial calculation for the setting-up next simulations when transmitter and receiver are located in a 100 m distance, are presented in Table 5.

Table 5. Assumptions for simulation experiments

Frequency [MHz]	P_t **[dBm]**	P_r **[dBm]**	P_r **[mW]**
433	38	12.83	19.2
915	38	6.33	4.3
2 400	38	–2.05	0.62

6.2. Simulation experiments

In order to present results of using proposed parameters in RF energy harvesting circuits examination, RFEH circuit is designed and simulated. Circuit was designed in KiCad environment which uses ngspice simulation engine. The model designed is a simple RFEH circuit with diode D1 of internal capacitance equal to 0. Using this value maximizes the output power on the load and therefore can serve as a reference for models using real diodes. The model is presented on Fig. 1. It consists of antenna model with voltage source V1 and internal resistance R1. Further, there is a rectifier unit with capacitor C1, coil L1 and the already mentioned diode D1. In the end of the circuit there is a capacitor C2 and a load R2. Model is simulated and voltages are measured using point Vin and Vout.

Model from Fig. 1 was simulated with standardized parameters. The frequency 915 MHz is the closest one to the 900 MHz band used in Poland for civil telecommunication services. The power of the transmitter was set to 38 dBm as per LTE/NR standard both transmitting and receiving antennas gains were set to 20 dBi. As this is a simulation, the distance between transmitter and receiver was chosen to be 100 meters which best describes real live distance for base station and receiver. For simulation purposes, it was chosen to assume perfect vacuum hence permittivity

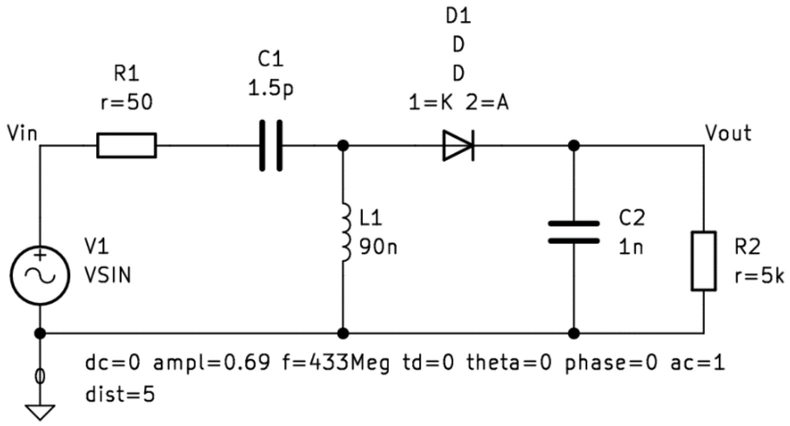

Fig. 1. RF energy harvester model designed in KiCad EDA

is equal to 1 and the peak-to-peak voltage for the AC input replacing receiving antenna is equal to 0.33 V. The load can depend on the application, for purpose of this paper, it was set to 5 kΩ. Diode used is HSMS-2850.

Below, in this section, there are presented results of simulations with the frequencies from Table 6 for an ideal diode and for a model of the real one: HSMS 2851.

Table 6. Parameters used in simulation RFEH circuit

Frequency [MHz]	**Voltage [V]**	**LC capacitance [pF]**
433	0.69	1.5
915	0.33	0.3365
2 400	0.12	0.0489

In the following figures there are presented: current of the diode, voltage on the output of the circuit.

Figure 2 presents results of the simulation: the ideal diode current and output voltage for the frequency 433 MHz.

It perfectly agrees with the theory. Current flows only for one half of the input signal period, and the output voltage increases in every cycle

To observe how the voltage reaches the maximum value and stabilizes, the simulation for longer time period was run and presented in Fig. 3.

For the ideal case for 433 MHz, the output voltage reaches 1.6 V when the load is equal to 5 kΩ. The output voltage stabilizes after approx. 5.5 μs. The experiment takes into account the value 0.69 V as the receiving by the antenna voltage in the 100 m distance (see Table 5).

In Figs. 4 and 5, there are results of the experiments with the ideal diode for 915 MHz frequency. No backward current may be observed which agrees with assumptions of the experiments.

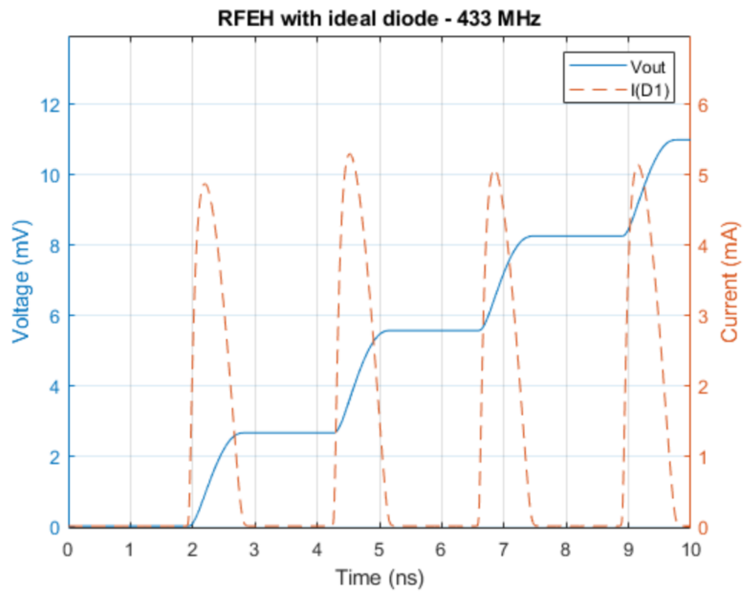

Fig. 2. Simulation of RFEH circuit with the ideal diode. Frequency is 433 MHz. The solid line shows the voltage across the load, and the dashed line shows the diode's current

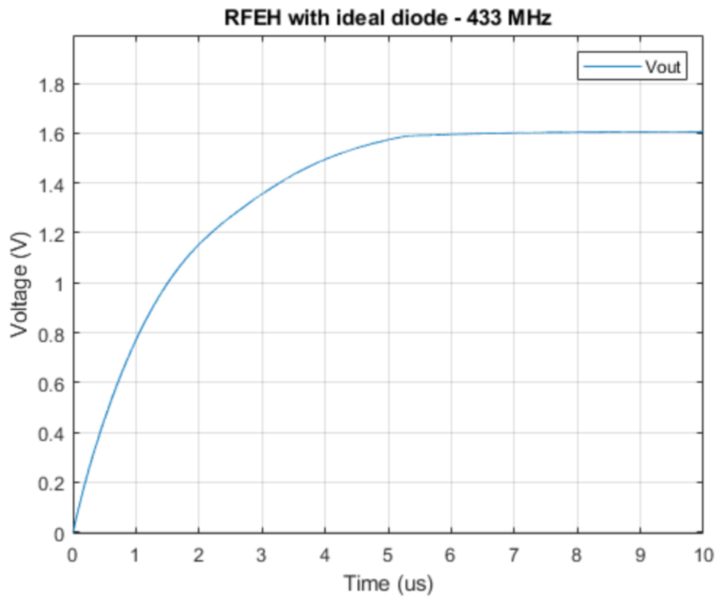

Fig. 3. Simulation of RFEH circuit with ideal diode. Frequency is 433 MHz.
The output voltage in the 10 µs scale

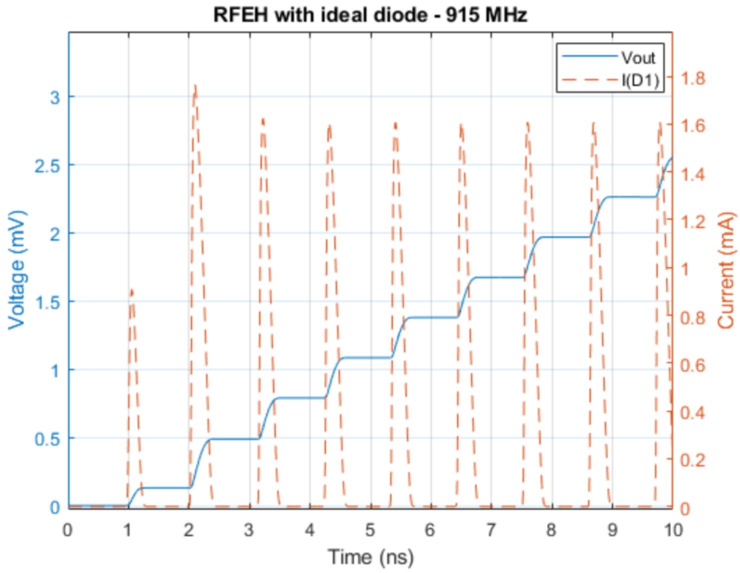

Fig. 4. Simulation of RFEH circuit with ideal diode. Frequency is 915 MHz. The solid line shows the voltage across the load, and the dashed line shows the diode's current

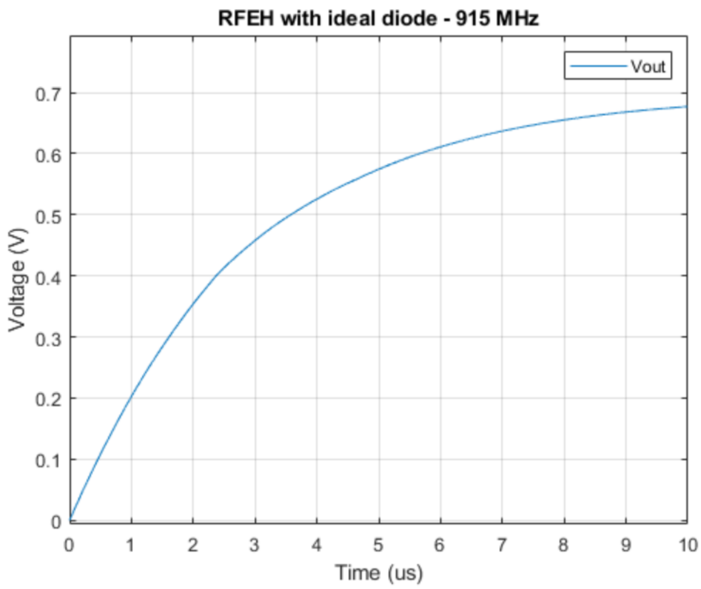

Fig. 5. Simulation of RFEH circuit with the ideal diode. Frequency equals 915 MHz. The voltage on the output in a 10 µs scale

The output voltage approaches to the lower value: 0.7 V than in the 433 MHz case: 1.7 V due to lower voltage received by the antenna (see Table 5). The time of approaching the maximum output voltage value is also smaller than in the previous case. For the frequency 433 MHz it is approx. 5.5 µs, and for 915 MHz it is approx. 13 µs.

For all presented in the section experiments there are kept the same values of the inductance and capacitances.

Figures 6 and 7 show the same signals but for the next frequency: 2.4 GHz according to Table 5. The tendency observed in the above experiments is kept. The maximum voltage of the output is smaller and the time of approaching the maximum value extends to much more, then 10 µs.

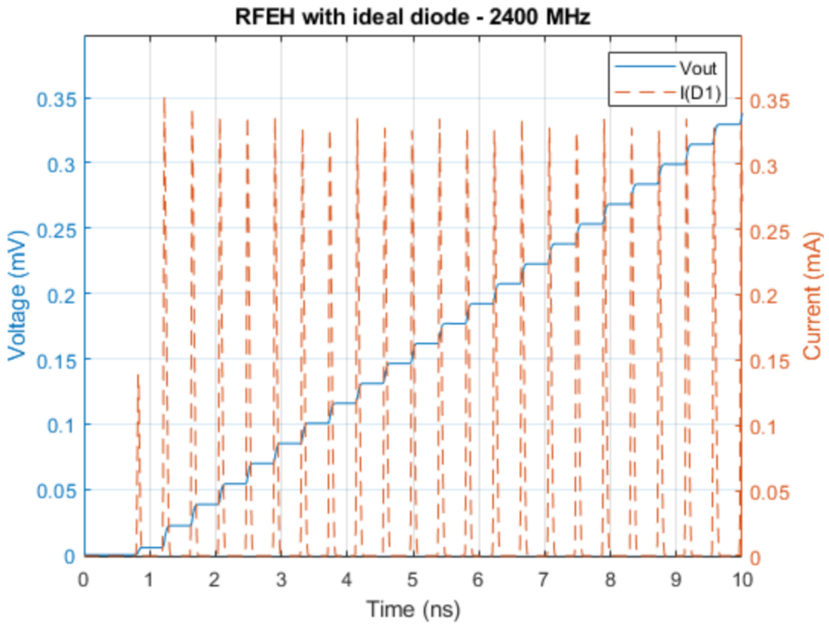

Fig. 6. Simulation of RFEH circuit with ideal diode. Frequency set is 2.4 GHz. The solid line shows the voltage across the load, and the dashed line shows the diode's current

The next experiments, which results are presented in Figs. 8–13 corresponds to the results showed in Figs. 2–7. The difference is that the ideal diode is replaced with the diode HSMS-2851 SPICE model. One may observe a non-zero backward current, which is caused by the diode capacitance, equal to 0.18 pF. The effect of existence of this parasite capacitance is particularly visible for the 2.4GHz frequency simulations, see Fig. 12.

The output voltage of the circuit with HSMS-2851 diode for 433 MHz, 915 MHz and 2.4 GHz is, respectively, equal to approx.: 1.7 V, 0.4 V and 0.32 mV while in the case of simulations with the ideal one, the output voltage is respectively :1.7 V, 0.7 V and 130 mV.

The simulations show poor effects of the harvester circuit with HSMS-2851 for 2.4 GHz.

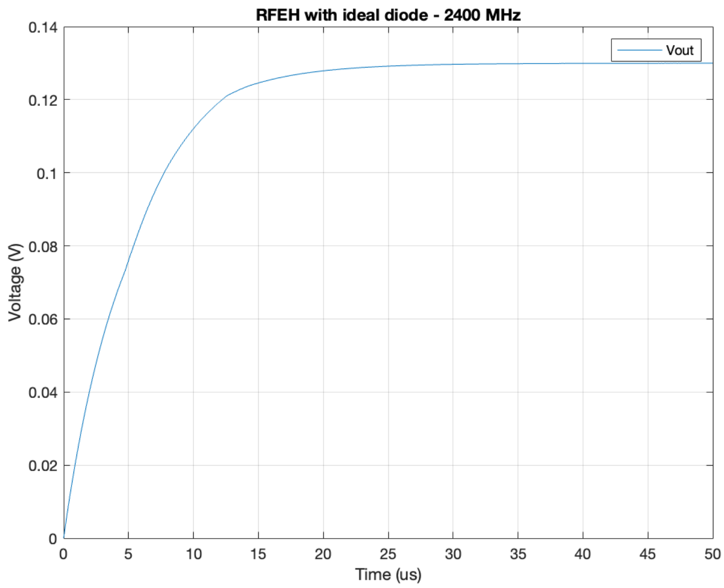

Fig. 7. Simulation of RFEH circuit with the ideal diode. Frequency is equal to 2.4 GHz. The voltage on the output in a 50 µs scale

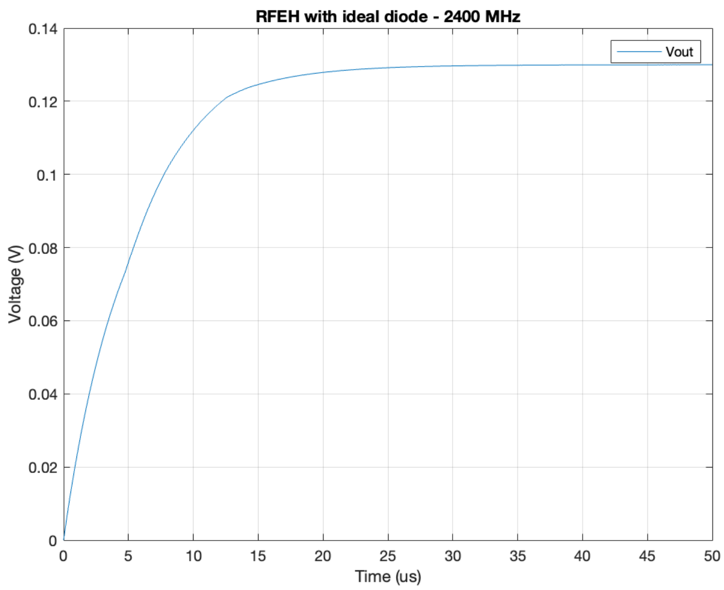

Fig. 8. Simulation of RFEH circuit with the real diode HSMS-2851 SPICE model. Frequency is 433 MHz. The solid line shows the voltage across the load, and the dashed line shows the diode's current

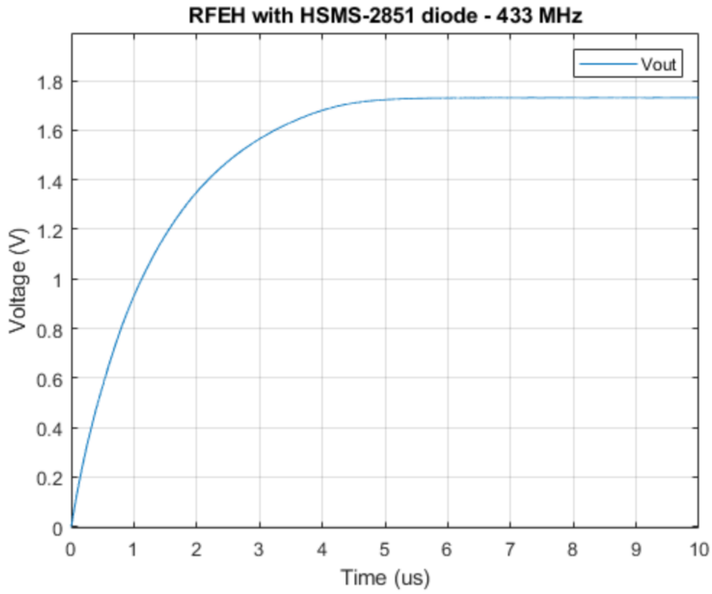

Fig. 9. Simulation of RFEH circuit with the real diode HSMS-2851 SPICE model. Frequency is equal to 433 MHz. The voltage on the output in a 10 µs scale

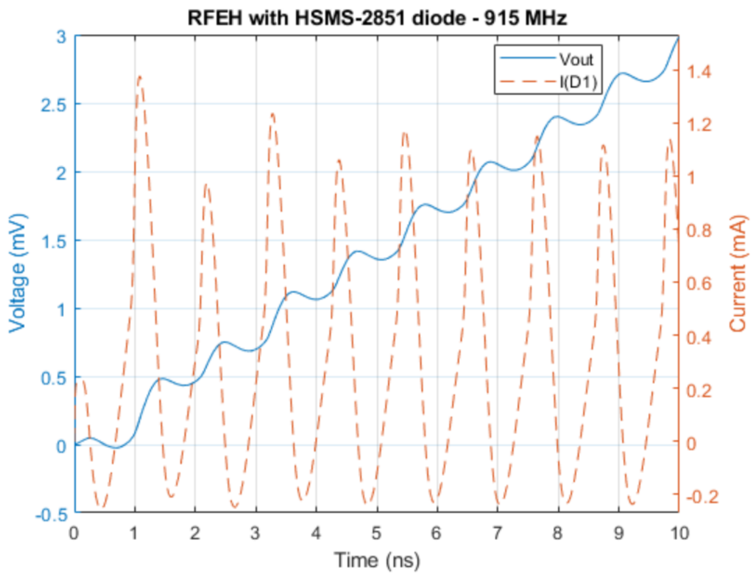

Fig. 10. Simulation of RFEH circuit with the real diode HSMS-2851 SPICE model. Frequency is 915 MHz. The solid line shows the voltage across the load, and the dashed line shows the diode's current

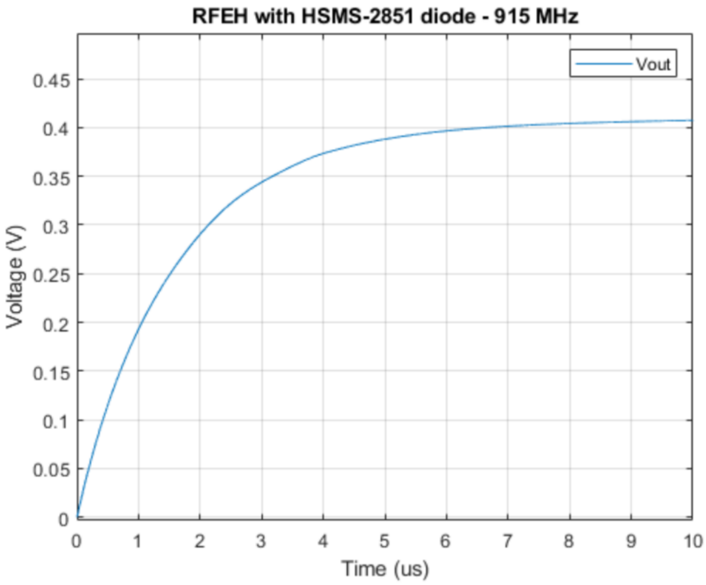

Fig. 11. Simulation of RFEH circuit with the real diode HSMS-2851 SPICE model. Frequency is 915 MHz. The voltage on the output in a 10 μs scale

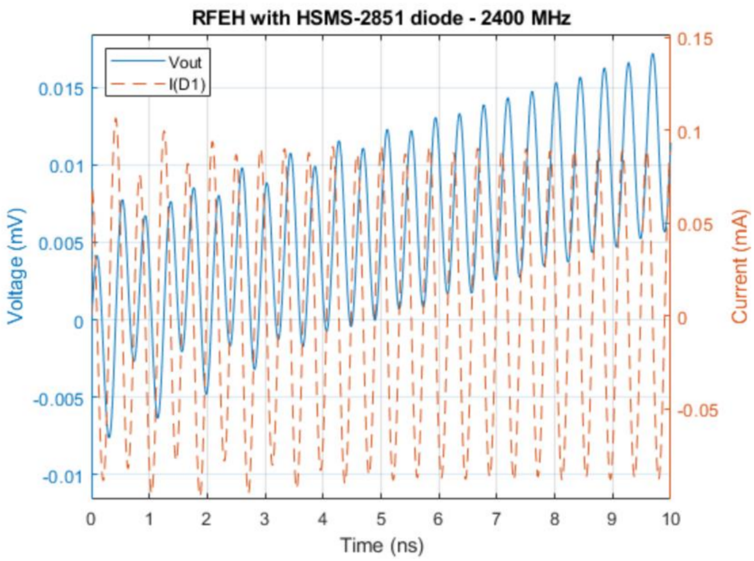

Fig. 12. Results of time simulation for RFEH circuit with the real diode HSMS-2851 SPICE model for 2.4 GHz. The solid line shows the voltage across the load, and the dashed line shows the diode's current

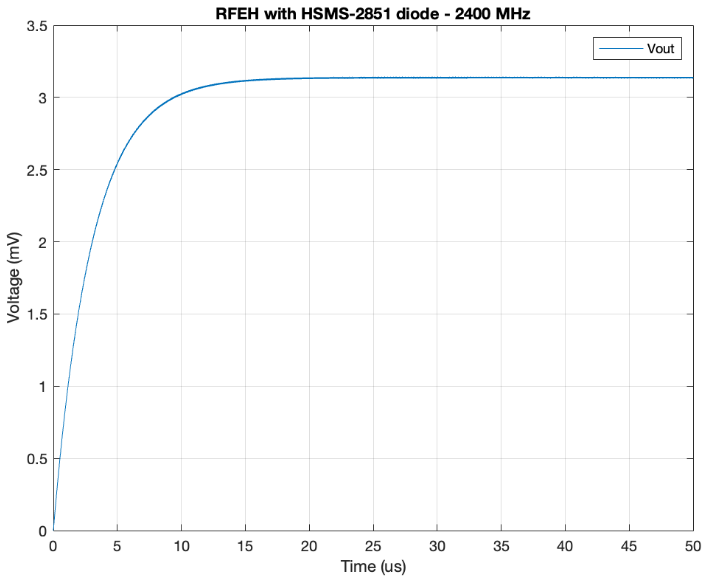

Fig. 13. Simulation of RFEH circuit with the real diode HSMS-2851 SPICE model. Frequency is 2.4 GHz. The voltage on the output in a 50 µs scale

7. Conclusions

This paper presents proposition of standardizing parameters used in simulation and measurements of RF energy harvesting circuits. The parameters and conditions that influence RFEH circuits performance are discussed. Relevant standards were briefly introduced. Based on the already conducted research and experience from discovering state-of-the-art papers, the set of parameters was proposed for both simulations and real-life measurements. Those parameters were divided into few categories: frequency, signal power and propagation conditions.

The ISM frequency bands were suggested to serve as a standard set of frequencies to test new or modified RFEH designs. The abundance of ISM bands in all ranges, make it possible to legally test circuits and compare results. Both in simulations and real test beds.

The signal power is influenced by a number of parameters of both transmitting and receiving antennas. Those values were proposed based on the available commercial solutions and international standards. However, it is strongly advised to verify if testing setup meets local authority requirements as those may differ from each other for particular regions.

Propagation conditions are mostly relevant to the real device measurements. However, slight differences in particular parameters do not influence permittivity of the medium in a way that it affects the results. It is important to keep conditions consistent throughout the whole experiment time, but it is weather conditions such as rain or snow that drastically limit the energy available on the receiver.

To verify the proposed standardising parameters some simulations of a simple RF energy harvesting circuit are conducted. The maximum voltage level on the load was presented and the model's efficiency was calculated.

Next step in this research is to prepare test bed for commercial RFEH products and measure their performance. It will allow one to compare results with values provided by the vendor. Further study plans are to compare wide- and narrowband designs. It may be necessary to introduce yet another standard parameter such as spectral density to standardize the amount of energy that is available for the antenna to be received. Then, antenna parameters such as gain could be part of the whole model and evaluated under circumstances defined by spectral density. This area is also connected with beamforming techniques. The use of direct beams in telecommunication technology can provide receiving antenna with a focused RF beam and therefore provide more energy to be harvested.

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