Ultra Low Power RF Energy Harvesting System using a Super Capacitor as an Energy Reservoir for an IoT Node

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Abstract: In this paper, we propose a 2.45 GHz RF energy harvesting system to power a battery free Internet of Things (IoT) sensor node. The system operates from an RF signal with a power as low as -20 dBm and includes an RF to DC converter, a storage super capacitor and a voltage DC/DC up-conversion. The system components are sized to provide the required electric energy to operate the connected object. The tested connected object includes an ARM microcontroller, an ultra low-power sensor (temperature, pressure and humidity) and a Bluetooth Low Energy interface for a wireless transmission toward a terminal such as a smartphone or tablet. It requires 200 µJ per transmission cycle, which must be provided by the proposed harvesting system. This system is tested in an anechoic chamber and using a constant power RF signal to characterize the energy recovery time needed for measuring and transmitting the sensor data. Promising results show that the system is capable of sending data after 5 hours of RF energy harvesting from a source distant with one meter.

1 INTRODUCTION

Climate change issues are pushing us to innovate to solve the question of our energy sources for the future. How can we reduce our carbon footprint? How can we produce electricity that is healthier for the environment? We also see steps to reduce our consumption with the least possible impact on our lifestyles. We then provide an optimization work of the energy consumption of our industries. To achieve this, the key element of the solution is the ever increasing feedback of information on all our systems.

This is where the Internet of Things (IoT) comes into play. Today, the IoT represents billions of connected objects and the number is still growing exponentially. It has multiple uses such as Industry 4.0 with predictive maintenance, the development of connected cities with smart grids to optimize the distribution of electricity in the network or more simply, the management of heating at home which represents more than two thirds of energy consumption in Europe (Commission, 2020).

However, the multiplication of these connected objects has the side effect of increasing the environmental impact of digital technology. Indeed, these billions of connected objects are generally powered by batteries that need to be renewed every year on average. While the carbon footprint of an AAA battery is 65 gCO2e (ADEME, 2019), the production of batteries for the IoT sector could generate 0.01 % of Greenhouse Gas (GHG) in 2025 and 0.02 % by 2030 (IEA, 2021).

A new filed of research is developing to find alternative energy sources for the IoT called energy harvesting.

The principle is to recover energy from our environment, natural or not. We then have connected objects powered by solar energy with the development of organic photovoltaic panels without rare-earth elements (Wu et al., 2017); but also with mechanical energy as proposed by the company ZF Electronics (ZFE, 2022) allowing the installation of switch connected lamps without batteries. We also find other sources of energy in research such as thermoelectric energy (Correa-Betanzo et al., 2019) working with Seebeck effect, vibratory energy (Balguvhar and Bhalla, 2018) and the one that interests us in this work, electromagnetic energy (Franciscatto et al., 2013) and more specifically here the WiFi radio waves.

The objective is to develop a system capable of recovering and converting the surrounding RadioFre-

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quency (RF) WiFi signals into a direct current (DC) capable of powering a sensor in a connected object. The principle of radio energy harvesting has been developed in research for nearly twenty years now and has seen several evolutions, especially on the type of signals used. Indeed, we can see research papers focused on TV signals (Parks et al., 2013) (Lacerna et al., 2022) in the early 2010s, whose frequencies are around a few hundred MHz to papers more on the Industrial, Scientific and Medical (ISM) band at 2.45 GHz (Bergès et al., 2015) and GSM at 900 MHz and 1800 MHz (Ho et al., 2016) with the massive development of WiFi, 3G, 4G systems in the world in recent years.

The RF energy harvesting discipline is also split into two: remote power on the one hand with RadioFrequency Identification (RFID) and the Near Field Communication (NFC) standards for short distances or over longer distances that can have uses in particular in the medical (Jin et al., 2019) or application like the one proposed by Archos at CES2022. A system with a power station supplying energy to bateryless sensors operating with the principle of beam forming to optimize power transmission over radio waves (Archos, 2021). On the other hand, we have power supply by opportunistic harvesting of ambient signals and this is what interests us here. Can we power a connected object by harvesting the surrounding WiFi signals in a building?

We can find several works dealing about this principle (Kim et al., 2014) (Tran et al., 2017), especially in the 2.45 GHz ISM band that interests us. They concern the development of the RF/DC converter which is more or less complex with its theoretical characterization. In this work, we wish to go further by proposing a study of the complete ecosystem in which the RF energy harvester is supposed to operate properly in order to conclude about the feasibility of such a system. We present in section 2 the development of a harvester for 2.45 GHz WiFi signals which will be integrated into our system presenter in section 3. Finally, the section 4 presents the measurement results under laboratory conditions.

2 RECTIFIER

To convert a RF WiFi signal into DC voltage, it is necessary to develop a Rectenna circuit following the schematic represented in FIG.1, meaning the combination of an antenna and a rectifier circuit which will convert the RF signal into DC voltage.

The received RF signal is converted into DC thanks to a non-linear device based on a Schottky

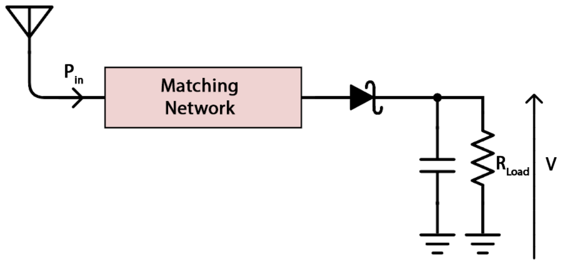


Figure 1: A simple rectenna schematic.

diode. A matching network must be inserted between the antenna and the diode for a maximal power transfer. The diode is loaded by a low pass filter using a capacitor and a resistor corresponding the equivalent impedance of the connected object.

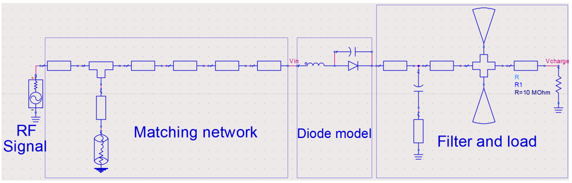
For the antenna part, we decided to use a classical WiFi whip antenna as we can find it on routers, and we focus on the development of the rectifier. Some works on specific antenna can be found like (Srinivasu et al., 2020), (Shen et al., 2018) or (Trinh et al., 2019).

We wish to work with ambient WiFi signals and our different measurement campaigns of the available power at a distance of 1 meter from the WiFi access point led us to realize a system that must operate at an incident power as low as -20 dBm.

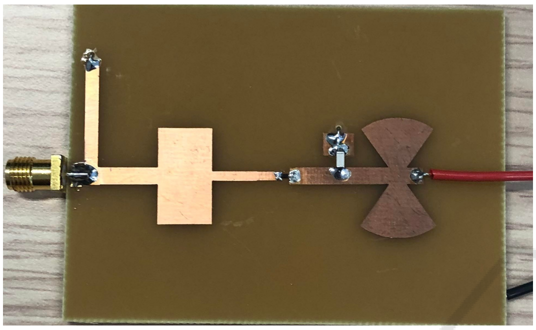
For this reason, we restrict ourselves to a single-wave rectifier composed of a single Schottky diode in order to minimize the losses. We use the Skyworks SMS7630 Schottky diode that is widely used in the state of the art on rectennas for RF energy harvesting (Trinh et al., 2019) (Kim et al., 2015). The circuit is optimized thanks to simulations performed on Keysight Advanced Design System (ADS) software and represented in FIG.2. The matching network is synthesized thanks to microstrip transmission lines. We used a 10 $M\Omega$ load resistance, which can be assimilated to an infinite resistance in DC, because we will use a capacitor to store the energy and whose impedance tends to infinite in DC. The recovered output DC voltage is about 178 mV for an input RF power of -20 dBm at 2.45 GHz. Then, the optimized rectifier circuit is realized (FIG.2) and characterized.

A measurement of $|S_{11}|$, the input reflection coefficient of the rectifier circuit, is shown in FIG.3 The measured value below -8 dB at 2.45 GHz ensures that our impedance matching network optimizes the power transfer from the antenna to the diode.

As the goal is to recover a DC voltage at the rectifier's output, we can characterize the performance of the circuit by measuring this DC output voltage as a function of the signal frequency, which can be seen in FIG.3. We can note a maximum voltage of 159 mV obtained for an incident signal of 2390 MHz at -20 dBm, which is close to the 178 mV obtained through simulation. According to FIG.3, we can expect an output voltage between 98 mV and 155 mV over the ISM band (2.4 GHz - 2.5 GHz).

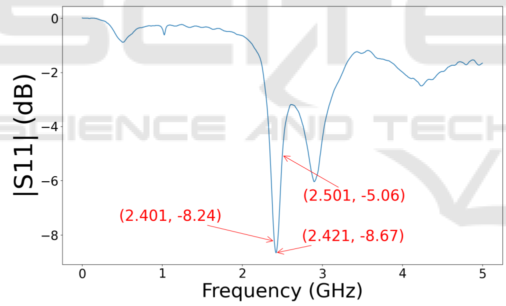


(a) Rectifier schematic (Keysight ADS)

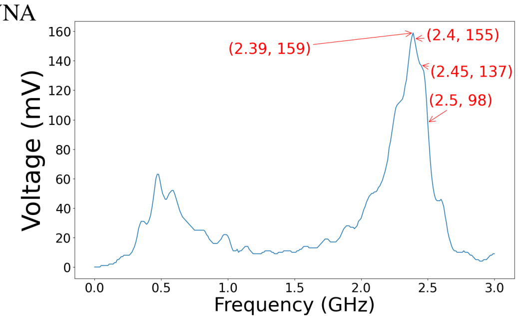


(b) PCB made in our laboratory

Figure 2: Schematic and PCB of the rectifier.



(a) $|S_{11}|$ measurement with an Anritsu MS46122B USB VNA



(b) DC output voltage measurement Vs. input signal frequency at -20 dBm

Figure 3: Rectifier characterization.

3 VOLTAGE BOOST

A DC voltage of 155 mV obtained in the ISM band is insufficient to power a connected object whose supply voltage is usually defined between 1.8 V and 3.3 V. We must therefore use a voltage DC/DC boost to up-convert the recovered low voltage.

The only voltage boost we know of that can operate over such a low voltage range in the industry is the LTC3108 from Analog Devices. Still, this voltage boost is designed for a thermoelectric generator such as a Peltier module, which has, in particular, a very low impedance of few Ohms. If we connect this voltage boost directly to the rectifier output, it will lead to an insufficient rectifier output voltage because of this low impedance.

We have therefore imagined an intermediate system between the rectifier and the voltage DC/DC boost: a kind of energy reservoir that come and go composed of a super capacitor surrounded by switches. The complete system is shown in FIG.4.

The super capacitor reservoir is then sometimes connected to the rectifier to recover the DC energy. This capacitor being then the only load on the rectifier and thus allow the best possible voltage by its infinite DC impedance. And sometimes, it is connected to the voltage DC/DC boost to discharge and thus, convert the accumulated energy to a voltage level adapted to our connected object. This boosted DC voltage will be stored in the capacitor placed at the boost output.

This raises the question of the technology for the switches. It is indeed essential to choose switches that have the lowest possible leakage current and that can toggle with a low voltage and current. As our key value here is the voltage, we can eliminate the bipolar transistors, which is controlled by a current whose value cannot be controlled. MOSFETs on the other hand can be considered because they are controlled in voltage by the gate.

Another solution is the electromechanical relays. Indeed, the switching is mechanical, so a real open circuit is present and can be considered as no leakage switches. The challenge is to find electromechanical relays or MOSFETs without leakage that we can control with a voltage as low as 100 mV (Liu et al., 2014).

Voltage supervisors under 1 V exist and are used in applications close to ours like the UB20M (UB2,

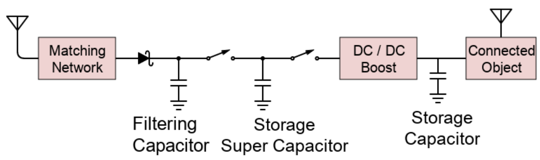


Figure 4: Schematic of our proposed circuit.

2017) which is able to detect a rectifier output voltage as low as 0.6 V. Even if it is still too high for our system which must operate around 0.1 V, research papers seem promising on the subject, especially on the side of electromechanical relays (Qian et al., 2017). Even if they present constraints that do not allow to use them as they are presented in the study, they allow to realize a switch activating at 100 mV with a hysteresis up to 20 mV.

4 MEASUREMENTS AND TESTS

Now that we are able to rectify the RF WiFi signal into a 3.3 V DC voltage, we would like to test the whole system to see if it is able to power a connected object to transmit data.

To ensure if our proposed design works, we will use classical relays, which will be controlled and powered by and additional circuit based on a microcontroller, here an Arduino. The electric consumption of these relays is not considered because they are not supposed to be present in the final circuit. The complete schematic of our system is represented FIG.5.

The circuit after the voltage DC/DC boost is a capacitor that stores the energy and a voltage supervisor that is supposed to enable the Low DropOut (LDO) regulator when the voltage is above the threshold of 2.63 V.

The connected object is made up of an ON-Semi RSL10-SIP microcontroller based on an ARM Cortex-M3 core and a Bluetooth Low Energy (BLE) 5.2 interface for a wireless transmission. It measures temperature, pressure and humidity using an ultra-low-power BME680 sensor from Bosch Sensortec. It advertises a 25 bytes data frame following the pattern on TAB.1 where UUID refers to a custom Universally Unique IDentifier to identify which node is advertinsing the data. The energy need of this connected object is around 200 µJ per transmission cycle. The details of its energy consumption have been the subject of work and a previous publication (Grante et al., 2020).

For a proper study and characterization and in order to have control over the power of the RF signal source, a controlled environment is preferred. Thus, we carried out our measurements in an anechoic chamber (FIG.6) using a dedicated RF signal generator for transmission.

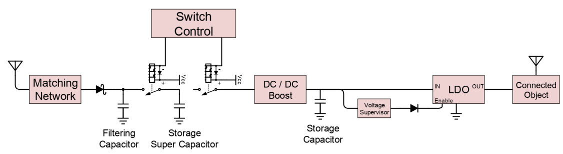


Figure 5: Schematic of our complete testing system.

Table 1: Sensor node data frame using BLE 5.2.

Byte	Field	Description
0	Frame Type	FLAGS for the receiver
1-16	UUID[0]-[15]	Custom 128-bit Service UUID
17-18	TEMP[0]-[1]	Beacon temperature
19-20	HUM[0]-[1]	Beacon humidity
21-23	PRESSURE[0]-[2]	Beacon atmospheric pressure
24	VERSION	Service frame version

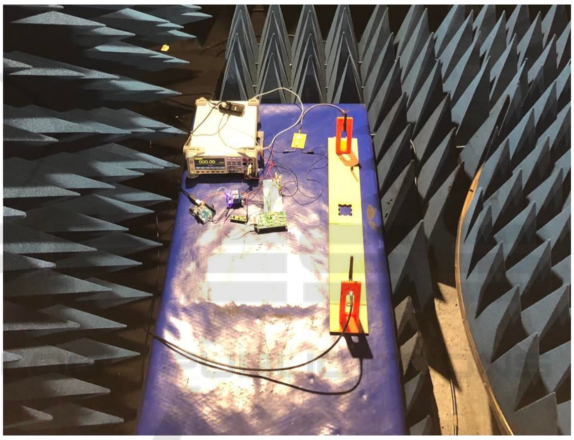


Figure 6: Photo of the test setup inside the anechoic chamber at Telecom Paris.

The output power of the RF generator is adjusted so as to obtain an Effective Isotropic Radiated Power (EIRP) of 20 dBm, which is the maximum emission power allowed by the European legislation (ETSI, 2019) on this frequency range.

A few tests have shown that a 100 µF capacitor loaded at 3.3 V ensure to give the 200 µJ necessary to power the connected object to measure and transmit its data. We were also able to determine that a super capacitor of 2 F at 100 mV upstream of the voltage boost can achieve these conditions at the voltage boost output in terms of voltage and amout of energy. We followed the following protocol:

1. Connect a transmitting whip antenna (Tx) to an RF signal generator and set the frequency to 2.45 GHz. The power is set to the maximum of what a device in Europe can transmit, i.e., 20 dBm EIRP

Table 2: Time needed to reach 100 mV across the super capacitor.

Distance (cm)	Time (seconds)	Time (HH:mm:ss)
25	786	00:13:06
50	7810	02:10:10
100	18716	05:11:56

2. The receiving whip antenna (Rx) is placed at 25 cm distant from the transmitter and is connected to our rectifier system
3. Relays are setup to connect the super capacitor to the rectifier to store energy
4. Monitoring the voltage using a voltmeter at the terminals of the super capacitor as a function of time until reaching 100 mV
5. When 100 mV is reached, the relays are switched to isolate the rectifier and connect the super capacitor to the voltage DC/DC boost
6. The 100 µF capacitor is charged, its voltage rises
7. When 3.3 V are reached, the voltage supervisor triggers the LDO regulator and allow discharging the 100 µF capacitor in the connected object to perform the measurement and transmit the data through a BLE. The data are received and displayed by a smartphone application (FIG.7).
8. This procedure is repeated for a Tx/Rx distance of 50 cm and 100 cm.

We measured the evolution of the super capacitor voltage as a function of time for the three distances. We present the curves in the FIG.8 and the duration to reach 100 mV in TAB.2. At 25 cm, a transmission is obtained after 786 seconds (13 minutes and 6 seconds). The curve has a linear appearance, which can be explained by the proximity between the Tx and Rx antennas. Indeed, the power received must be greater than -20 dBm and thus makes it possible to obtain a DC voltage at the rectifier's output greater than 100 mV and therefore, to reach this threshold more quickly.

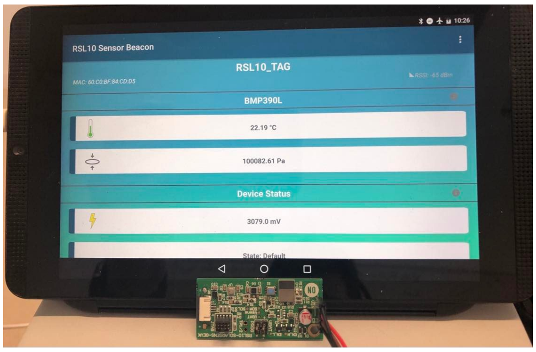


Figure 7: The connected object that send data to the tablet application.

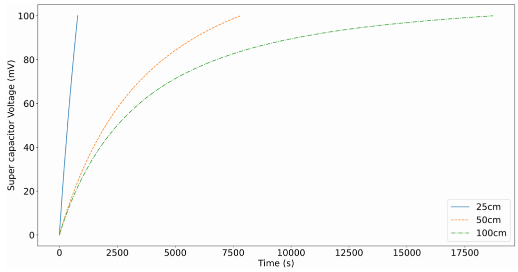


Figure 8: Evolution of super capacitor voltage Vs.time using a 2450 MHz, 20 dBm EIRP emitter signal generator at 25, 50 and 100 cm.

At 50 cm, we get 7810 seconds (2 hours, 10 minutes and 10 seconds). At constant efficiency, since we have doubled the distance, the well known Friis' formula for free-space path loss (dependence on the square of the distance) allows us to assume that it should take 4 times longer to complete a transmission. In practice, we observe that it takes 10 times longer. This can be explained by the non-linearity of the diode which implies a decrease in efficiency when the received powers are lower as we have shown in the characterization of a rectifier in (Grante et al., 2020). We can then approximate that we have an average efficiency that is $10/4 = 2.5$ times lower than if our system was linear.

At 100 cm, a transmission takes place after 18716 seconds (5 hours, 11 minutes and 56 seconds). Unlike the measurement at 25 cm, here we see a curve on FIG.8 that looks like the theoretical exponential charge curve of a capacitor which leads us to think that we have a rectifier output voltage close to the 100 mV threshold. We can then consider that it will be difficult to go beyond a Tx/Rx distance of 100 cm because we would not have the 100 mV necessary at the output of the rectifier.

5 CONCLUSION

We have proposed a rectifier capable of converting WiFi signals into a DC voltage in the order of 150 mV for a received power of -20 dBm. We have used the simplest possible rectifier using a single Schottky diode because the state of the art on the subject leads us to believe that it is not necessary to use more complex configurations for incident powers as low as -20 dBm as indicated on TAB.3.

To allow a more relevant comparison with some of the works in the table, a measurement of the output

Table 3: State of the art rectifier output voltage comparison.

Architecture	Number of Diodes	Load ($k\Omega$)	P_{in} (dBm)	Frequency (MHz)	V_{out} (mV)	Ref.
Full rectifier	2	8.2	-20	890	114	(Ho et al., 2016)
Full rectifier	2	5	-20	2450	$<$200	(Selim et al., 2020)
Full rectifier	4	NA	NA	2450	50	(Chen et al., 2017)
Single ended rectifier	1	Inf	-20	2450	150	This work
Single ended rectifier	1	Inf	-8	2450	542	This work
Dickson	4	NA	-8	2450	500	(Fan et al., 2018)
Full rectifier	2	5	-8	2450	$<$500	(Selim et al., 2020)

voltage (V_{out}) of our rectifier for an incident power (P_{in}) of -8 dBm has been performed.

This table shows some voltage values (V_{out}) obtained with different rectifier configurations. We can see that our single-ended rectifier obtains similar performance in terms of voltage as more complex schematics. This is due to the use of a super capacitor as a load that allows us to consider an infinite load and therefore to obtain a better voltage.

We could see that our system allowed us to transmit data from a connected object, which is battery free and powered thanks to an RF energy harvesting at 2.45 GHz. The association of our rectifier with a voltage DC/DC boost and storage capacitors is able to supply a voltage of 3.3 V with enough energy to allow the sensor data transmission. Whether at 25, 50 or even 100 cm Tx/Rx distance, we can expect at least, 4 transmissions per day.

We can then imagine application cases such as temperature monitoring in offices in order to optimize the heating of the building and thus hope to save fossil fuels.

However, currently, this has only been possible with an external system that manages the switches allowing passing to one side or the other of the system without losing energy. In-depth study work is necessary on these switches to have a fully autonomous device.

It will also be necessary to test this system not with a constant power RF signal generator but with a WiFi signal to determine a minimum network activity to allow transmission in a reasonable time.

REFERENCES

(2017). *UB20M High-Voltage, Low-Threshold, Ultra-Low Power Voltage Detector for Energy Harvesting, RF Power Transfer, and Event-Driven Sensing*. Bristol Energy. Rev 2.2.

ADEME (2019). Modélisation et évaluation environnementale de produits de consommation et biens d'équipement.

Archos (2021). Archos and ossia partner to bring inovative wirelessly powered consumer iot products to market.

Balguvhar, S. and Bhalla, S. (2018). Green Energy Harvesting Using Piezoelectric Materials from Bridge Vibrations. In *2018 2nd International Conference on Green Energy and Applications (ICGEA)*, pages 134–137.

Bergès, R., Fadel, L., Oyhenart, L., Vigneras, V., and Taris, T. (2015). A dual band 915MHz/2.44GHz RF energy harvester. In *2015 European Microwave Conference (EuMC)*, pages 307–310. ISSN: null.

Chen, X., Huang, L., Xing, J., Shi, Z., and Xie, Z. (2017). Energy harvesting system and circuits for ambient WiFi energy harvesting. In *2017 12th International Conference on Computer Science and Education (ICCSE)*, pages 769–772. ISSN: 2473-9464.

Commission, E. (2020). Heating and cooling.

Correa-Betanzo, C., Lopez-Perez, C., Rodriguez, A., and Lopez-Nuñez, A. (2019). Isolated DC-DC Converter for Thermoelectric Energy Harvesting Based on a Piezoelectric Transformer. In *2019 IEEE Applied Power Electronics Conference and Exposition (APEC)*, pages 3443–3447.

ETSI (2019). Etsi en 300 328 v2.2.2 (2019-07).

Fan, S., Zhao, Y., Gou, W., Song, C., Huang, Y., Zhou, J., and Geng, L. (2018). A high-efficiency radio frequency rectifier-booster regulator for ambient WLAN energy harvesting applications. In *2018 IEEE MTT-S International Wireless Symposium (IWS)*, pages 1–3.

Franciscatto, B. R., Freitas, V., Duchamp, J.-M., Defay, C., and Vuong, T. P. (2013). High-efficiency rectifier circuit at 2.45 GHz for low-input-power RF energy harvesting. In *2013 European Microwave Conference*, pages 507–510. ISSN: null.

Grante, F., Abib, G. I., Muller, M., and Samama, N. (2020). Autonomous sensor node powered over WiFi. In *WINSYS 2020: 17th International Conference on Wireless Networks and Mobile Systems*, volume 1: WINSYS, pages 127–132, Lieusaint, France. ScitePress.

Ho, D.-K., Kharrat, I., Ngo, V.-D., Vuong, T.-P., Nguyen, Q.-C., and Le, M.-T. (2016). Dual-band rectenna for ambient RF energy harvesting at GSM 900 MHz and 1800 MHz. In *2016 IEEE International Conference on Sustainable Energy Technologies (ICSET)*, pages 306–310. ISSN: null.

IEA (2021). Iea (2021), global energy review 2021, iea, paris.

Jin, Z., Hu, A., Liu, Z., and Liu, D. (2019). A 35μW Receiver Front-End with 35% wireless energy harvesting efficiency for Wearable Medical Applications. In *2019 IEEE 13th International Conference on ASIC (ASICON)*, pages 1–4. ISSN: 2162-755X.

Kim, J. H., Bito, J., and Tentzeris, M. M. (2015). Design optimization of an energy harvesting RF-DC conversion circuit operating at 2.45GHz. In *2015 IEEE International Symposium on Antennas and Propagation USNC/URSI National Radio Science Meeting*, pages 1280–1281. ISSN: 1947-1491.

Kim, S., Vyas, R., Bito, J., Niotaki, K., Collado, A., Georgiadis, A., and Tentzeris, M. M. (2014). Ambient RF Energy-Harvesting Technologies for Self-Sustainable Standalone Wireless Sensor Platforms. *Proceedings of the IEEE*, 102(11):1649–1666.

Lacerna, J. V. G., Guerra, E., and Jr, J. J. M. (2022). A Heuristic Approach to Classifying Different Multiple Urban Settings for Ambient RF Energy Harvesting Potential using TV Technology as an RF Energy Source. *International Journal of Computing Sciences Research*, 6.

Liu, T.-J. K., Xu, N., Chen, I.-R., Qian, C., and Fujiki, J. (2014). NEM relay design for compact, ultra-low-power digital logic circuits. In *2014 IEEE International Electron Devices Meeting*, pages 13.1.1–13.1.4. ISSN: 2156-017X.

Parks, A. N., Sample, A. P., Zhao, Y., and Smith, J. R. (2013). A wireless sensing platform utilizing ambient RF energy. In *2013 IEEE Topical Conference on Biomedical Wireless Technologies, Networks, and Sensing Systems*, pages 154–156.

Qian, C., Peschot, A., Osoba, B., Ye, Z. A., and Liu, T.-J. K. (2017). Sub-100 mV Computing With Electro-Mechanical Relays. *IEEE Transactions on Electron Devices*, 64(3):1323–1329. Conference Name: IEEE Transactions on Electron Devices.

Selim, K. K., Wu, S., and Saleeb, D. A. (2020). An Optimized Rectifier Design for RF Energy Harvesting at the 2.45 GHz WiFi Frequency Band. In *2020 27th International Conference on Telecommunications (ICT)*, pages 1–5.

Shen, S., Chiu, C.-Y., and Murch, R. D. (2018). Multiport Pixel Rectenna for Ambient RF Energy Harvesting. *IEEE Transactions on Antennas and Propagation*, 66(2):644–656. Conference Name: IEEE Transactions on Antennas and Propagation.

Srinivasu, G., Gayatri, T., Chaitanya, D., and Sharma, V. (2020). Performance Analysis of a Compact High Gain Antenna for RF Energy Harvesting in 1.71GHz to 12GHz. In *2020 IEEE International RF and Microwave Conference (RFM)*, pages 1–4.

Tran, L.-G., Cha, H.-K., and Park, W.-T. (2017). RF power harvesting: a review on designing methodologies and applications. *Micro and Nano Systems Letters*, 5(1):14.

Trinh, L. H., Vu Ngoc Anh, H., Trinh, V. H., Duy Phan, D., Thi Khanh, H. N., and Ferrero, F. (2019). Design of a Dual-band Rectenna for Small IoT Terminal. In *2019 International Symposium on Electrical and Electronics Engineering (ISEE)*, pages 150–154.

Wu, T., Arefin, M. S., Redouté, J., and Yuce, M. R. (2017). Flexible wearable sensor nodes with solar energy harvesting. In *2017 39th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pages 3273–3276.

ZFE (2022). ZF Switches & Sensors - Switches, Sensors & Wireless Technology.