Voltage Multiplier Design for Harmonic Communication in Harvester-Assisted Ultrahigh Frequency (UHF) Radio Frequency Identification (RFID) Systems

Andoni Beriain, Hector Solar, Yvan Duroc, and Smail Tedjini

Abstract – The development of low-cost environmental energy harvesters is opening new opportunities for harvester-assisted semipassive radio frequency identification (RFID) tags. In these systems, the tag to reader communication raises a design concern as it is the limiting factor of the maximum communication range. Harmonic communication is an option for enhancing this tag to reader communication in ultrahigh frequency RFID systems. In this work, different voltage multiplier (VM) configurations are evaluated at the simulation level to suggest VM design guides to increase the available harmonic power in harvester-assisted scenarios. The results show that single-ended topologies with the minimum number of stages are preferred. Regarding the diode, a proposed modified p-channel metal-oxide semiconductor (PMOS) diode has shown higher generated harmonic power than typical Schottky diodes.

1. Introduction

Radio frequency identification (RFID) has grown rapidly during recent years, becoming one of the most important technologies for tagging, tracking, and locating objects [1]. Among its different operation frequencies, the ultrahigh frequency (UHF) is the most relevant for applications that require communication with ranges above 1 m [2].

In most passive UHF RFID applications, the reader to tag link was demonstrated to be the limiting factor for the communication range. Specifically, the harvested power that reduces with the square of the distance between reader and tag is what limits that distance. In most cases, the tag to reader communication, based on backscattering, has not been a problem as high-sensitivity battery-powered readers are used. Because of that, most of the efforts in UHF RFID system development are focused on increasing the tag sensitivity in terms of minimum activation power and signal reception [3]. In these studies, the voltage multiplier (VM) is a key circuit element, as it is the block in charge of harvesting power from the incoming RF signal.

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However, with the development of low-cost environmental energy harvesting interfaces and generators, new opportunities are arising for UHF RFID-augmented systems, as continuous data logging without a reader nearby or 21 m of range in the reader to tag link [4]. In these scenarios, the harvested RF energy is no longer a limiting factor in the system communication range, but the uplink communication raises a design concern.

One of the most promising techniques to improve the tag to reader communication is to backscatter the harmonics of the fundamental carrier generated by the VM [5–10]. Several works have been presented for this aspect, where commercial RFID tags are used to build demonstrators. However, the harmonic generation has not been evaluated from a VM design perspective. This article faces this task in the scenario of harvester-assisted UHF RFID system.

The article is arranged as follows. In Section 2, the limitations of harvester-assisted RFID tags are obtained. A presentation of VM from a harmonic perspective is done in Section 3. Section 4 is devoted to the simulation results and its discussion and is followed by the conclusion.

2. Tag to Reader Communication Range in External Harvester-Assisted UHF RFID System

To evaluate the tag to reader communication range in environmental harvester-assisted UHF RFID systems, the work presented in [4] is taken as a reference. In this article, a novel RFID tag for *pick to light* applications is presented. In this kind of applications, the reader can ask to an individual RFID tag that includes a light-emitting diode (LED) to switch it on, among a number of tags.

The inclusion of the LED and its control comes with an extra power consumption that affects the communication range of the system in comparison with an only ID tag: without any battery, i.e., using only the RF-harvested power for communications, command processing, and LED switching on; the maximum communication range is limited to 3.7 m [4]. To increase this range, a solar cell combined with a boost regulator is used to supply the tag, transforming it into a semipassive device. This way, the operation range can

Table 1. Sensitivity of different UHF RFID commercial readers

Model	Sensitivity (dBm)
Impinj R700	−92
Impinj Speedway	−84
Nordic ID AR85	−81
Nordic ID HH85	−80

be theoretically increased up to 21 m. However, in this work, that range is only evaluated in the downlink. The uplink is not improved with the harvester inclusion in the tag, as it continues with the same backscattering principle.

If the uplink is theoretically evaluated, the 21 m of the downlink range reported is obtained with 2 W of effective isotropic radiated power (EIRP; 33 dBm) in the reader. The path losses corresponding to that distance with central frequency of 868 MHz are equal to 57.65 dB. Therefore, the minimum input power in the tag is –24.65 dBm. This means that with the implemented dipole antenna and supposing a reflection coefficient S11 equal to –10 dB, the backscattered power to the reader is approximately –30.35 dBm. Applying the same path loss in the uplink, the theoretical received power in the reader is –88 dBm. Considering that the European regulation limits the output power of the reader to a maximum of 2 W ERP instead of 2 W EIRP and with the same tag sensitivity, the path loss could be increased to 2.15 dB in each direction, with a final reader sensitivity requirement for the uplink of –92.3 dBm.

As shown in Table 1, the majority of the RFID readers available in the market are far (10 dB) from being adequate in this application scenario, and those with the best sensitivity are still not good enough. Therefore, to exploit the improvement in the overall communication range of semipassive with low-cost environmental harvesters, new expensive, high-sensitivity readers or new uplink communication methods are required. The harmonic communication is a promising solution to provide a long communication range (21 m or more) between the reader and the tag.

3. VM and Harmonics

The VM is the first block of a RFID chip and deals with the incoming RF signal provided by the antenna. Usually, between the tag antenna and the RFID chip, a matching network (MN) is required to ensure the maximum power transfer between both. The two main VM topologies are the differential and the single-ended topologies [11].

Both topologies are equivalent when they have a two to one ratio for the number of stages. However, the main difference appears in the input impedance (it is higher in differential architectures) and the ground terminal of the RFID chip (connected to one of the antenna inputs in the single-ended topology). In both cases, the more stages the VM has, the greater its voltage-multiplying capacity is but the less conversion efficiency [2]. For harmonic generation, due to the symmetry of the differential topology, the second harmonic wave is canceled [11]. Therefore, single-ended topology (Figure 1) is preferred to exploit second- and third-generated harmonics.

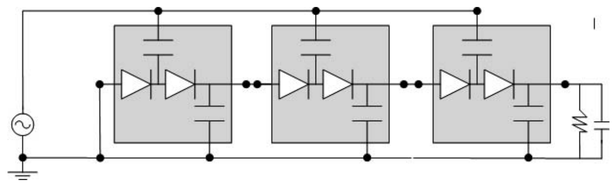

Figure 1. “Circuit diagram of single-ended three-stage VM.”

Regarding diode technology, minimum threshold, minimum on-resistance, and minimum reverse current are desirable on the VM diodes [2]. The VM simulations presented here have been done by using a standard 180 nm complementary metal-oxide semiconductor process with Schottky diodes available. The Schottky diode is, in most cases, the best option for VM implementation. In addition to it, a different diode was built, modifying a medium threshold p-channel metal-oxide semiconductor (PMOS) transistor, connected as shown in Figure 2.

The diode that originated between the source P+ diffusion and the N well is the one that was used as a commuting device. There is a second parasitic diode between the P substrate and the N well. As long as it may not be properly described in the model supplied by the foundry, future measurements are required to quantify its effects. Simulations of both diodes show that Schottky diodes have a lower threshold voltage but larger on-resistance than the modified PMOS option, which also present a larger nonlinearity around its threshold voltage.

As the VMs are built with diodes that typically show nonlinear I-V curves, when the incoming RF signal at the communication fundamental frequency arrives, harmonics of the tag voltage and current components are generated by the VM. These harmonic components are reflected, travel through the MN, arrive at the antenna, and propagate. On a VM, in principle, there is no interest on backscattering harmonics of the fundamental frequency, so the MN is designed only to

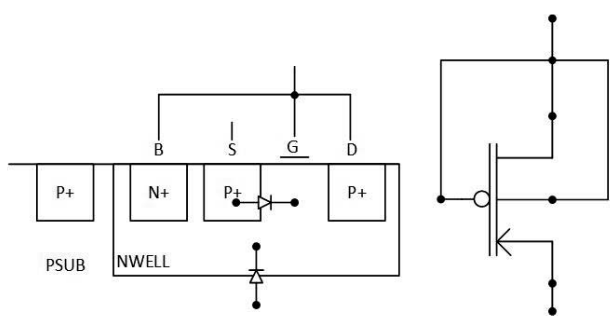

Figure 2. Diagram of the implemented modified PMOS diode.

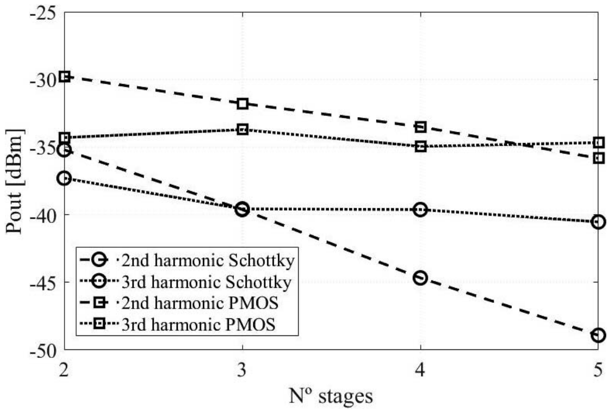

Figure 3. Harmonics generated with single-ended topology with PMOS and Schottky diodes.

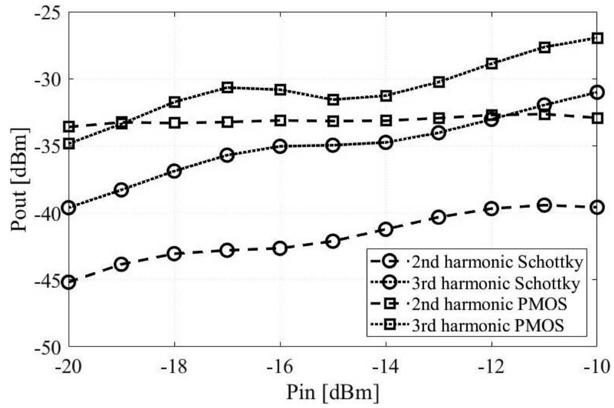

Figure 4. Harmonics generated with different input powers with a MN matched with –20 dBm of input power with a modified PMOS diode and Schottky diode.

match the antenna and the VM impedances at that frequency.

Therefore, although the VM generates harmonics, they are attenuated due to the VM-MN mismatch at the harmonic frequencies. This implies that second and third harmonics are typically backscattered by the tag with a power approximately 50 dB below the input power of the fundamental frequency [7]. The higher harmonics (fourth and beyond) show lower power level and have no interest from a harmonic communication perspective.

The use of a four-component MN that matches the impedance of the antenna and the VM, both at the fundamental frequency and at a selected harmonic, is of high interest because it can reduce the difference between the input power and the backscattered harmonic power to 15 dB [8]. This was the implemented MN for the simulations presented in Section 4.

4. Results and Discussion

In this section, the harmonics generated by different VM topologies are evaluated with an input power of –20 dBm to determine a VM design criteria for harvester-assisted operation. These criteria will differ from the typical VM design, in which power conversion efficiency maximization is the objective. In this work, the VM efficiency is not a limiting factor anymore due to the use of the environmental energy harvester to supply the tag. The objective now is to maximize the generated available harmonic power. To do that, first, the number of stages of the single-ended VM with the two proposed diode types have been evaluated. The results are presented in Figure 3.

From Figure 3, it is concluded that the number of stages is an important design parameter for the second-order harmonics, with differences up to 20 dB in the available power, depending on the number of stages. Conversely, the available has a maximum variation of only 5 dB. In both cases, the smaller number of stages, the greater the generated harmonic power. Regarding the diode type, simulations show that it is a critical aspect, with 5 dB average power gain in both harmonics when using the PMOS diode instead of the Schottky diode.

In addition, simulations show that the second harmonic power is much more sensitive to the different design parameters than the third harmonic. The second-order harmonic can achieve higher power values (–30 dBm at PIN = –20 dBm) with both diode types, if the number of stages is reduced. However, third-order harmonics are much more predictable and stable, yet with a decent power level (–34 dBm at PIN = –20 dBm).

Note the importance of the MN to transmit the generated harmonics. In RFID tags, the input impedance and, therefore, the matching are highly dependent on the input power. This means that there is an impedance mismatch between the antenna and the RFID chip when the input power changes may affect the available harmonic power. The effect of this mismatch is evaluated in Figure 4 for a single, four-stage topology, with a MN optimized for Pin at –20 dBm.

Note that the mismatch generated by increasing the input power does not negatively affect the generated harmonic power. Moreover, with the exception of the second-order harmonic with the PMOS diode, the harmonic power levels actually grow.

5. Conclusion

In passive RFID systems, the limiting factor in the communication range was usually the downlink. This was more obvious in augmented RFID tags, where sensors, actioners, LEDs, or microprocessors were added to the tag for extra features but with extra power consumption. Low-cost environmental power harvesters allow the RFID system to increase that downlink range up to 21 m. However, under this new scenario, the uplink raised a design concern, as most of the commercial readers did not have enough sensitivity to receive the tag answer (–90 dBm or more was required). Harmonic communication was demonstrated as a technique to improve the overall tag to reader communication in UHF RFID systems. In this work, the available power corresponding to the second and third harmonic was evaluated at the simulation level with different VM configurations and diode types.

Once that single-ended topology was chosen to allow second and third harmonic generation, simulations showed that the minimum number of stages was the best option. At the simulation level, the proposed modified PMOS diode showed a better performance for energy harvesting and harmonic generation than the Schottky diode available in the technology. Future measurements, considering all the diode parasitics, can validate these results.

Regarding the number of harmonic to be used, from a complete system design perspective, it seems that with a specific VM design, the available second harmonic power can be higher than the third. However, from the perspective of designing a harmonic communication system compliant with different commercial RFID chips, the third harmonic seems a better choice, as it is more stable and presents a better average power level. Finally, regarding the operation point, the MN should be defined in the worst input power case, as more input power will increase the available harmonic power, despite the generated mismatch.

6. Acknowledgement

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7. References

1. R. Das, *RFID Forecasts, Players and Opportunities 2019–2029*, IDTechEx Research, Xxxx, December 2019.
2. D. Pardo, A. Vaz, S. Gil, J. Gomez, and A. Ubarretxena, et al., "Design Criteria for Full Passive Long Range UHF RFID Sensor for Human Body Temperature Monitoring," 2007 IEEE International Conference on RFID, Grapevine, TX, USA, March 26–28 2007, pp. 141-148.
3. J. Lee, B. Lee, and H. Kang, "A High Sensitivity, CoSi2–Si Schottky Diode Voltage Multiplier for UHF-Band Passive RFID Tag Chips," *IEEE Microwave and Wireless Components Letters*, **18**, 12, December 2008, pp. 830-832.
4. A. Astigarraga, A. Lopez-Gasso, D. Golpe, A. Beriain, H. Solar, et al., "A 21 m Operation Range RFID Tag for 'Pick to Light' Applications With a Photovoltaic Harvester," *Micromachines*, **11**, 11, November 2020, p. 1013.
5. P. V. Nikitin and K. V. S. Rao, "Harmonic Scattering From Passive UHF RFID Tags," 2009 IEEE Antennas and Propagation Society International Symposium, North Charleston, SC, USA, June 1–5, 2009, pp. 1-4.
6. X. Chen, Y. Chen, H. Zhang, N. Yan, J. Wang, et al., "Long Read Range Class-3 UHF RFID System Based on Harmonic Backscattering," *Electronics Letters*, **54**, 22, November 2018, pp. 1262-1264.
7. G. Andía Vera, Y. Duroc, and S. Tedjini, "Analysis of Harmonics in UHF RFID Signals," *IEEE Transactions on Microwave Theory and Techniques*, **61**, 6, June 2013, pp. 2481-2490.
8. G. Andía Vera, Y. Duroc, and S. Tedjini, "Third Harmonic Exploitation in Passive UHF RFID," *IEEE Transactions on Microwave Theory and Techniques*, **63**, 9, September 2015, pp. 2991-3004.
9. S. Mondal and P. Chahal, "A Passive Harmonic RFID Tag and Interrogator Development," *IEEE Journal of Radio Frequency Identification*, **3**, 2, June 2019, pp. 98-107.
10. D. Kumar, S. Mondal, S. Karuppuswami, Y. Deng, and P. Chahal, "Harmonic RFID Communication Using Conventional UHF System," *IEEE Journal of Radio Frequency Identification*, **3**, 4, December 2019, pp. 227-235.
11. A. Beriain, H. Solar, Y. Duroc, and S. Tedjini, "UHF RFID Voltage Multiplier Design From a Harmonic Communication Perspective," 2021 XXXIVth General Assembly and Scientific Symposium of the International Union of Radio Science, Rome, Italy, August 28–September 4, 2021, pp. 1-4.