

University of Novi Sad DSpace-CRIS Repository

https://open.uns.ac.rs

2022-01-21

# Wireless Readout of Resistive Sensors

Mitar Simić, Milan Radovanović, Adrian K. Stavrakis, Varun Jeoti

Mitar Simić, Milan Radovanović, Adrian K. Stavrakis, and Varun Jeoti. 2022. Wireless Readout of Resistive Sensors. IEEE Sensors Journal 22(5): 4235–4245. doi: 10.1109/JSEN.2022.3145875. https://open.uns.ac.rs/handle/123456789/32467 Downloaded from DSpace-CRIS - University of Novi Sad This article has been accepted for publication in IEEE Sensors Journal. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JSEN.2022.3145875

IEEE SENSORS JOURNAL, VOL. XX, NO. XX, MONTH X, XXXX

Sensors Council

# Wireless Readout of Resistive Sensors

Mitar Simić, IEEE Member, Milan Radovanović, IEEE Member, Adrian K. Stavrakis, IEEE Student Member, and Varun Jeoti, Senior IEEE Member

Abstract— In this paper we present a method for wireless readout of resistive sensors. Our approach is based on the topology where resistive sensor and reference resistor form a voltage divider network, with reference resistor connected in parallel with a varactor diode. Variation of the sensor resistance causes voltage changes over the varactor, and consequently capacitance of the varactor. Varactor is placed in the LC circuit, thus a change of resonant frequency occurs due to the change of the sensor resistance. Resonant frequency can be detected with external readout inductor connected to the inductance measurement device. The proposed method is theoretically



analyzed and experimentally verified with discrete resistors and resistive force sensor. Main advantages of our approach are: (1) it keeps simplicity of the voltage divider network interface with resistive sensors, (2) energy autonomy of sensor tag is extended as energy needed for readout is provided by an external reader, (3) proposed method can be easily adopted for various dynamic range of resistive sensors, and (4) two methods for power supply (battery and energy harvesting with inductive coupling) were analyzed.

Index Terms—Wireless readout, inductive coupling, resonant frequency, resistive sensors, wireless power transmission.

#### I. INTRODUCTION

**R**ESISTIVE sensors are very important for various applications, from soft robotics [1,2], gas sensors [3-5], humidity sensors [6] to pressure sensors in biomedical applications [7, 8]. In addition to the above mentioned resistive sensors, a Metal Oxide Semiconductor (MOS) type of sensors are also very important class, as they are very common in gas sensing applications [9]-[12]. Sensing principle of MOS sensors is based on the change of the resistance of the sensing material when it is exposed to some specific gas or gasses [9].

Readout of resistive sensors can be very simple using voltage divider network. Voltage over resistive sensor is then usually measured with analog to digital converter and microcontroller. For some type of sensors (for example, MOS) presence of the voltage supply is necessary as they must be pre-heated over several hours to reach stable operating temperature. Moreover, gas sensing is usually performed in harsh environments which triggers need for remote access to the measured values. Therefore, communication modules for data transmissions or displays are also necessary. However, communication modules and displays are components that require power supply resources that are not negligible. They also increase overall size and price. In addition to that, some applications require just periodical readout of the sensed variable. For example, height increase over time with Force Sensing Resistor (FSRs) or with micro force resonant sensor [13]. For such kind of sensors, it is convenient to save energy by putting sensor node to sleep or standby while measurements are not performed, or to provide wireless energy transfer required for short time operation.

Wireless readout of resistive sensors is important in applications where sensor nodes are placed in inaccessible place with limited energy resources. Typical readout system includes impedance analyzer, primary inductor connected to the impedance analyzer and secondary inductor connected to the sensor. With analytical modelling, it is possible to establish expression for secondary components brought to primary side, and to obtain phase minimum and corresponding frequency as functions of the sensor resistance, as it was shown in [14]. However, use of impedance analyzers is not very practical outside the laboratory environment because of the size, weight and need for grid power supply. Very interesting approach is to convert the resistance of the resistive sensor to the resonant frequency of the LC circuit, because readout methods used for wireless interface with the passive LC sensors can be used with resistive sensor nodes as well. There are several methods presented in the literature with aim to replace commercial impedance analyzer in the interface with passive LC sensors [15]-[21]. For example, one approach is that the readout inductor is a part of the voltage controlled oscillator with frequency dependence on the inductance of the readout inductor, while inductance changes because of the mutual

Corresponding author: Mitar Simić

Authors are with the Faculty of Technical Sciences, University of Novi Sad, 21000 Novi Sad, Serbia (e-mails: mitar.simic@uns.ac.rs, rmilan@uns.ac.rs, sadrian@uns.ac.rs, varunjeoti@uns.ac.rs).

XXXX-XXXX © XXXX IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission.
 See http://www.ieee.org/publications\_standards/publications/rights/index.html for more information.
 © 2022 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This research was funded through the European Union's Horizon 2020 research and innovation programme under grant agreement No. 854194.



Fig. 23. Inductance plots of the readout inductor for different values of load applied to the FRS 402 sensor.

We measured resonant frequencies for 3 loads in the range from 0 N to 10 N, as it is shown in Table VII.

 TABLE VII

 RESONANT FREQUENCIES FOR DIFFERENT LOADS.

 Load (N) Resonant frequency (MHz)

 2
 16.9

 5
 17.2

 10
 17.4

Applying non-linear regression (second order polynomial), we defined calibration curve of the sensor:

$$y = 0.8897x^2 - 14.95x \tag{21}$$

where y is load in N, and x is the resonant frequency in MHz. With  $R^2=0.9386$ , and the standard deviation of the residuals Sy.x=1.417, it can be concluded that the presented system exhibits excellent correlation between applied loads and measured resonant frequency. After calibration, we performed measurement with 7.5 N load and measured resonant frequency was 17.3 MHz. Estimated load with Eq. (21) is 7.643 N. Therefore, relative error is 1.9%.

In addition to the performed analysis of the developed readout system and the FSR sensor, an important fact was observed. The utilized force sensor was enclosed into a protective plastic sheath, both to prevent the sensing element from being damaged and from coming in contact with potentially conductive surfaces. However, this has created a "sandwich" effect, adding two more layers on each side of the sensor. Given that these layers are plastic, they are relatively elastic, and thus, they can act as an absorber of some of the applied force, since they will partially deform as an effect of it. Therefore, some irregularities are to be expected in calibrating the sensor, due to either some of the applied force being absorbed by the casing or the force being unevenly applied throughout the whole sensing area of the sensor.

## C. Figures of merit

After provided comprehensive and detailed analysis regarding the technical aspects of our proposed method, before conclusion we will provide a figure of merit and to characterize the performance relative to its alternatives. Readouts of resistive sensors based on two methods were usually reported: (1) voltamperometric (VA) based on conversion of resistance to a voltage or current [36, 37], and (2) current/resistance to time conversion (RTC) [38]-[41]. Since the compared solutions are quite different in terms of architecture and implementation, comparison of different typologies, readout time, power consumption and cost is given in Table VIII. A possible implementation with discrete component readout board from [16] has been considered for the evaluation of the cost of readout system for our sensor tag topology.

TABLE VIII FIGURES OF MERIT: COMPARISON OF THE PROPOSED SYSTEM WITH OTHER SIMILAR SOLUTIONS IN THE LITERATURE.

Ref.	Topology	Wireless readout	Readout time	Power	Cost
[36]	VA	No	100 ms	5 mW @3.3 V	~50 USD
[37]	VA with logarithmic amplifier	No	<1 ms	50 mW @3.3 V	~30 USD
[38]	RTC based on pulse- width modulation	No	<1 ms	40 μW @1 V	$\sim \! 10 \text{ USD}$
[39]	RTC with voltage- mode oscillator	No	<15 s	4 mW @3.3 V	$\sim \! 10 \text{ USD}$
[40]	RTC with current mode oscillator	No	<15 ms	700 μW @0.75 V	$\sim \! 10 \text{ USD}$
[41]	RTC based on moving threshold oscillator with reset	No	<30 ms	25 mW @3.3 V	~10 USD
This work	Resonant frequency shift due to the change of the sensor resistance	Yes	<1 s	3.15 mW @9 V	~75 USD

#### IV. CONCLUSION

In this work, we presented a method for wireless readout of resistive sensors based on the topology where change in resistance of the sensor is detected with external readout inductor. Readout inductor and sensor tag are inductively coupled, thus sensor tag does not consume additional energy for data delivery and display. Such approach increases energy autonomy of the sensor tag, and therefore its operational period.

Obtained results reveled that proposed approach is reliable method for interface with resistive sensors as voltage drop on the varactor caused by the resistance change of the sensor, resulted in resonant frequency shift. We also showed that change in coupling factor does not affects readout functionality. Results with battery powered sensors tags, as well as with energy harvesting were also presented.

Our future work is directed towards interface of the proposed method with in-house developed sensors, especially on textile and flexible substrates. Moreover, our focus will be on the development of the portable device for impedance/inductance measurement and data acquisition.

### REFERENCES

- J. Shintake, E. Piskarev, S. H. Jeong, D. Floreano, "Ultrastretchable Strain Sensors Using Carbon Black-Filled Elastomer Composites and Comparison of Capacitive Versus Resistive Sensors", Adv. Mater. Technol., vol. 3, pp. 1700284-, 2018. doi:10.1002/admt.201700284
- [2] S. Mousavi, D. Howard, F. Zhang, J. Leng, and C. H. Wang, "Direct 3D Printing of Highly Anisotropic, Flexible, Constriction-Resistive Sensors for Multidirectional Proprioception in Soft Robots", ACS Applied Materials & Interfaces, vol. 12, no. 13, pp. 15631-15643, 2020. doi: 10.1021/acsami.9b21816
- [3] B. Urasinska-Wojcik and J. W. Gardner, "Identification of H2S Impurity in Hydrogen Using Temperature Modulated Metal Oxide Resistive Sensors with a Novel Signal Processing Technique," *IEEE Sensors Letters*, vol. 1, no. 4, pp. 1-4, 2017. doi: 10.1109/LSENS.2017.2709345.

- [4] Z. Cai et al., "A Ratiometric Readout Circuit for Thermal-Conductivity-Based Resistive CO2 Sensors," *IEEE Journal of Solid-State Circuits*, vol. 51, no. 10, pp. 2463-2474, 2016, doi: 10.1109/JSSC.2016.2587861
- [5] S. Bongiovanni Abel et al., "Resistive Sensors for Organic Vapors Based on Nanostructured and Chemically Modified Polyanilines," *IEEE Sensors Journal*, vol. 18, no. 16, pp. 6510-6516, 2018, doi: 10.1109/JSEN.2018.2848843.
- [6] X. Zhang et al., "Printed Carbon Nanotubes-Based Flexible Resistive Humidity Sensor," *IEEE Sensors Journal*, vol. 20, no. 21, pp. 12592-12601, 2020, doi: 10.1109/JSEN.2020.3002951.
- [7] L.-W. Lo, H. Shi, H. Wan, Z. Xu, X. Tan, C. Wang, "Inkjet-Printed Soft Resistive Pressure Sensor Patch for Wearable Electronics Applications", *Adv. Mater. Technol.*, Vol. 5, pp. 1900717, 2020. doi: 10.1002/admt.201900717
- [8] Y. Jeong, J. Park, J. Lee, K. Kim, and I. Park, "Ultrathin, Biocompatible, and Flexible Pressure Sensor with a Wide Pressure Range and Its Biomedical Application", ACS Sens., vol. 5, no. 2, pp. 481–489, 2020. doi.org/10.1021/acssensors.9b02260
- [9] J. Zhang, Z. Qin, D. Zeng and C. Xie, "Metal-oxide-semiconductor based gas sensors: screening, preparation, and integration", *Phys. Chem.*, vol. vol. 19, pp. 6313, 2019. doi: 10.1039/c6cp07799d
- [10] X. Pan, X. Zhao, A. Bermak and Z. Fan, "A Humidity-Insensitive NO2 Gas Sensor with High Selectivity," *IEEE Electron Device Letters*, vol. 37, no. 1, pp. 92-95, 2016, doi: 10.1109/LED.2015.2504260.
- [11] M. A. H. Khan, B. Thomson, R. Debnath, A. Motayed and M. V. Rao, "Nanowire-Based Sensor Array for Detection of Cross-Sensitive Gases Using PCA and Machine Learning Algorithms," *IEEE Sensors Journal*, vol. 20, no. 11, pp. 6020-6028, 2020, doi: 10.1109/JSEN.2020.2972542.
- [12] D. Xie, D. Chen, S. Peng, Y. Yang, L. Xu and F. Wu, "A Low Power Cantilever-Based Metal Oxide Semiconductor Gas Sensor," *IEEE Electron Device Letters*, vol. 40, no. 7, pp. 1178-1181, 2019, doi: 10.1109/LED.2019.2914271.
- [13] G. Radosavljevic, W. Smetana, A. Maric, Lj. Živanov, M. Unger, and G. Stojanovic, "Micro Force Sensor Fabricated in the LTCC Technology", *Proc. 27th Int. Conf. on Microelectronics (MIEL'2010)*, Nis, Serbia, 16-19 May, 2010.
- [14] M. Bona, E. Sardini, and M. Serpelloni. "Telemetric model for passive resistive sensors in biomedical applications," *Procedia Engineering*, vol. 87, pp. 444-447, 2014, doi: 10.1016/j.proeng.2014.11.332.
- [15] P. Escobedo, A. Martínez-Olmos, J. Fernandez-Salmeron, A. Rivadeneyra, L. F. Capitan-Vallvey, A. J. Palma, and M. A. Carvajal, "Compact readout system for chipless passive LC tags and its application for humidity monitoring", *Sensors and Actuators A: Physical*, vol. 280, pp. 287-294, 2018, doi: 1 0.1016/j.sna.2018.07.040.
- [16] Y. Hong, T. Liang, T. Zheng, Q. Cao, W. Zhang, W. Liu, H. Zhang, and J. Xiong, "A distance compensated approach used in wireless passive pressure sensor readout system for high temperature application", *Journal* of Sensors, Article ID 5923825, 8 pages 2016.
- [17] B. E. Ge, T. Liang, Y. P. Hong, C. Li, W. Wang, and J. Xiong, "A New Readout System for LC Resonant Sensors. *Key Engineering Materials*, Vol. 609, pp. 957-963. 2014, doi: 10.4028/www.scientific.net/KEM.609-610.957.
- [18] A. Baldi, W. Choi and B. Ziaie, "A self-resonant frequency-modulated micromachined passive pressure transensor", *IEEE Sensors Journal*, vol. 3, no. 6, pp. 728-733, 2003, doi: 10.1109/JSEN.2003.820362.
- [19] J. Garcia-Canton, A. Merlos and A. Baldi, "High-Quality Factor Electrolyte Insulator Silicon Capacitor for Wireless Chemical Sensing", *IEEE Electron Device Letters*, vol. 28, no. 1, pp. 27-29, 2007, doi: 10.1109/LED.2006.888189.
- [20] T. J. Harpster, S. Hauvespre, M. R. Dokmeci and K. Najafi, "A passive humidity monitoring system for in situ remote wireless testing of micropackages", *Journal of Microelectromechanical Systems*, vol. 11, no. 1, pp. 61-67, 2002, doi: 10.1109/84.982864.
- [21] R. Nopper, R. Niekrawietz and L. Reindl, "Wireless Readout of Passive LC Sensors", *IEEE Transactions on Instrumentation and Measurement*, vol. 59, no. 9, pp. 2450-2457, 2010, doi: 10.1109/TIM.2009.2032966.
- [22] Varactor SPICE Models for RF VCO Applications, Application Note, Skyworks Solutions, Inc. 2015.
- [23] G. Stojanović, M. Radovanović, M. Malešev and V. Radonjanin, "Monitoring of Water Content in Building Materials Using a Wireless Passive Sensor", *Sensors*, vol. 10, no. 5, pp. 4270-428, 2010. https://doi.org/10.3390/s100504270
- [24] S. Djuric, G. Stojanovic, M. Damnjanovic, M. Radovanovic and E. Laboure, "Design, Modeling, kand Analysis of a Compact Planar

Transformer," *IEEE Transactions on Magnetics*, vol. 48, no. 11, pp. 4135-4138, 2012, doi: 10.1109/TMAG.2012.2202642.

- [25] H. A. Aebischer, "Inductance Formula for Rectangular Planar Spiral Inductors with Rectangular Conductor Cross Section", Advanced Electromagnetics, vol. 9, no. 1, pp. 1–18, 2020. https://doi.org/10.7716/aem.v9i1.1346
- [26] S. Stalf, "Printed inductors in RF consumer applications," *IEEE Transactions on Consumer Electronics*, vol. 47, no. 3, pp. 426-435, 2001, doi: 10.1109/30.964130.
- [27] W. Liang, J. Glaser and J. Rivas, "13.56 MHz High Density DC–DC Converter with PCB Inductors," *IEEE Transactions on Power Electronics*, vol. 30, no. 8, pp. 4291-4301, 2015, doi: 10.1109/TPEL.2014.2357398.
- [28] M. Simić, G. M. Stojanović, L. Manjakkal and K. Zaraska, "Multi-sensor system for remote environmental (air and water) quality monitoring", 24th Telecommunications Forum (TELFOR), 2016, pp. 1-4, doi: 10.1109/TELFOR.2016.7818711.
- [29] B. T. Malik, V. Doychinov, A. M. Hayajneh, S. A. R. Zaidi, I. D. Robertson and N. Somjit, "Wireless Power Transfer System for Battery-Less Sensor Nodes," *IEEE Access*, vol. 8, pp. 95878-95887, 2020, doi: 10.1109/ACCESS.2020.2995783.
- [30] Y. Li, H. Yu, B. Su and Y. Shang, "Hybrid Micropower Source for Wireless Sensor Network," *IEEE Sensors Journal*, vol. 8, no. 6, pp. 678-681, 2008, doi: 10.1109/JSEN.2008.922692.
- [31] Varactor SMV1237, Datasheet, Skyworks Solutions, Inc. 2020.
- [32] S. Mehri, A. C. Ammari, J. B. H. Slama and M. Sawan, "Design Optimization of Multiple-Layer PSCs with Minimal Losses for Efficient and Robust Inductive Wireless Power Transfer," *IEEE Access*, vol. 6, pp. 31924-31934, 2018, doi: 10.1109/ACCESS.2018.2831785.
- [33] https://www.seeedstudio.com/Wireless-Charging-Module-5V-1A-p-1912.html (Accessed on July 22nd, 2021)
- [34] FSR 402, Data Sheet, Trossen Robotics.
- [35] 34SC-2, Datasheet, Instron, USA
- [36] M. Grassi, P. Malcovati, and A. Baschirotto, "A high-precision wide range front-end for resistive gas sensors arrays", *Sensors and Actuators B*, *Chemical*, vols. 111–112, pp. 281–285, 2005, doi: 10.1016/j.snb.2005.03.103
- [37] L. Bissi, M. Cicioni, P. Placidi, S. Zampolli, I. Elmi and A. Scorzoni, "A Programmable Interface Circuit for an Ultralow Power Gas Sensor," *IEEE Transactions on Instrumentation and Measurement*, vol. 60, no. 1, pp. 282-289, 2011, doi: 10.1109/TIM.2010.2049182..
- [38] J. H. Lu, M. Inerowicz, S. Joo, J. Kwon and B. Jung, "A Low-Power, Wide-Dynamic-Range Semi-Digital Universal Sensor Readout Circuit Using Pulsewidth Modulation," *IEEE Sensors Journal*, vol. 11, no. 5, pp. 1134-1144, 2011, doi: 10.1109/JSEN.2010.2085430.
- [39] G. Ferri, C. Di Carlo, V. Stornelli, A. De Marcellis, A. Flammini, A. Depari, and N. Jand, "A single-chip integrated interfacing circuit for wide-range resistive gas sensor arrays", *Sensors and Actuators B, Chemical*, vol. 143, no. 1, pp. 218–225, 2009, doi: 10.1016/j.snb.2009.09.002.
- [40] G. Ferri, A. De Marcellis, C. Di Carlo, V. Stornelli, A. Flammini, A. Depari, D. Marioli, and E. Sisinni, "A CCII-based low-voltage low-power read-out circuit for DC-excited resistive gas sensors", *IEEE Sensors Journal*, vol. 9, no. 12, pp. 2035-2041, 2009, doi: 10.1109/JSEN.2009.2033197.
- [41] A. Depari, A. Flammini, E. Sisinni, A. De Marcellis, G. Ferri and P. Mantenuto, "Fast, Versatile, and Low-Cost Interface Circuit for Electrochemical and Resistive Gas Sensor", *IEEE Sensors Journal*, vol. 14, no. 2, pp. 315-323, 2014, doi: 10.1109/JSEN.2013.2282122.



Dr. Mitar Simić (S'16, M'18) was born in Ljubovija, Republic of Serbia in 1987. He received the B.Sc. and M.Sc. degrees in electrical engineering from the University of East Sarajevo, Bosnia and Herzegovina, in 2010 and 2012 respectively. He received the Ph.D. degree in electrical engineering from the University of Novi Sad, Serbia in 2017. He is a Postdoctoral Researcher within the

STRENTEX project at the Faculty of Technical Sciences, University of Novi Sad, Serbia.

He is an author/coauthor of one monograph and more than 40 scientific papers, including 12 in leading peer-reviewed journals with impact factor. His research interests include sensors, flexible electronics,

impedance spectroscopy analysis, equivalent circuit modeling, and development of devices for impedance measurement and data acquisition.



Milan Radovanović was born in Pljevljima, Serbia in 1981. He received the M.Sc. and Ph.D. degrees in electrical engineering from the University of Novi Sad, Serbia in 2006 and 2016, respectively.

He is a research associate and member of the Group for nano and flexible electronics at the Faculty of Technical Sciences, University of Novi Sad, Novi Sad.

He is an author or co-author of 65 scientific

papers including 26 articles in leading international peer-reviewed journals and 2 patents. He was awarded with "Dr Vladan Desnica" to the Best master-graduate work in 2006. in the field of modelling, simulation and design of electronic circuits, in Novi Sad. Also, he was the winner of the Gold Medal on the International symposium of patents and innovation technologies "ARCHIMEDES'2011", Moscow, Russia, April 2011, for the innovation of the sensor for measuring water content in building materials.



Adrian K. Stavrakis (S'21) was born in Samothraki, Greece, in 1992. He received his B.Sc. degree in Electronics Engineering from the Intenational Hellenic University (ex. named ATEITH) in Thessaloniki Greece in 2016, followed by a postgraduate certification in Smart Systems Integration from Heriot-Watt University in Edinburgh, UK (2018), and a full scholarship under the Erasmus+ scheme for a joint M.Eng. in

electrical and optical engineering by Télécom SudParis in France and an M.Sc. in Smart Telecom and Sensing Networks by Aston University, Birmingham, UK (2020).

He is currently pursuing his Ph.D. at the University of Novi Sad, Serbia in the domain of flexible and textile electronics.

His research interests include systems design, simulation and characterization, antennas, remote sensing, electronics, microfluidics, and cross platform integration.



Varun Jeoti, (SM'13) received his Ph.D. degree from Indian Institute of Technology, Delhi, India in 1992. He has over 30 years of teaching experience in leading Indian and Malaysian universities teaching students from various social and cultural backgrounds. He has been conducting frontier research for over 41 years in the area of surface acoustic wave (SAW) devices, signal processing and wireless communication. Starting in 1980 from IIT Delhi soon after his

graduation, he worked on government sponsored projects developing SAW Pulse Compression filters, and underwater optical receivers in IIT Madras. He was a Visiting Faculty in Electronics department in Madras Institute of Technology, Anna University for about a year during 1989 to 1990 and joined Delhi Institute of Technology for next 5 years till 1995. He moved to School of Electrical & Electronic Engineering (E. & E. Engg.) in Universiti Sains Malaysia in 1995 and later moved to Dept. of E. & E. Eng. in Universiti Teknologi PETRONAS in 2001. He is presently working in Faculty of Technical Sciences, University of Novi Sad, Serbia as ERA Chair leading research efforts in Stretchable and Textile Electronics. His research interests include, among others, signal processing, sensors, SAW sensor-tags, SAW microfluidics and wireless communication for various applications.