Science Talks 4 (2022) 100100

Contents lists available at ScienceDirect

Science Talks

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# Battery state of charge estimation using machine learning and electrochemical impedance spectroscopy measurements

Emanuele Buchicchio [a,*], Francesco Bianconi [a], Fabrizio Smeraldi [b], Alessio De Angelis [a], Francesco Santoni [a], Paolo Carbone [a]

[a] Department of Engineering, University of Perugia, Perugia, Italy
[b] School of Electronic Engineering and Computer Science Queen Mary University of London, UK

ARTICLE INFO

*Keywords:*
Lithium-Ion batteries
Electrochemical impedance spectroscopy
State of charge
Machine learning

ABSTRACT

Efficient energy management in battery-powered devices requires reliable estimation of the battery state of charge. We developed a data-driven state-of-charge estimation method based on machine learning and electrochemical impedance spectroscopy. Several states-of-charge models were trained and tested using an original measurement dataset from a set of commercial Samsung ICR18650-26 J lithium-Ion batteries. The implications of the curse of dimensionality for this task have been analyzed, and the effectiveness of different feature reduction techniques to avoid classification model overfitting was investigated.

Video to this article can be found online at https://doi.org/10.1016/j.sctalk.2022.100100.

**Figures and tables**

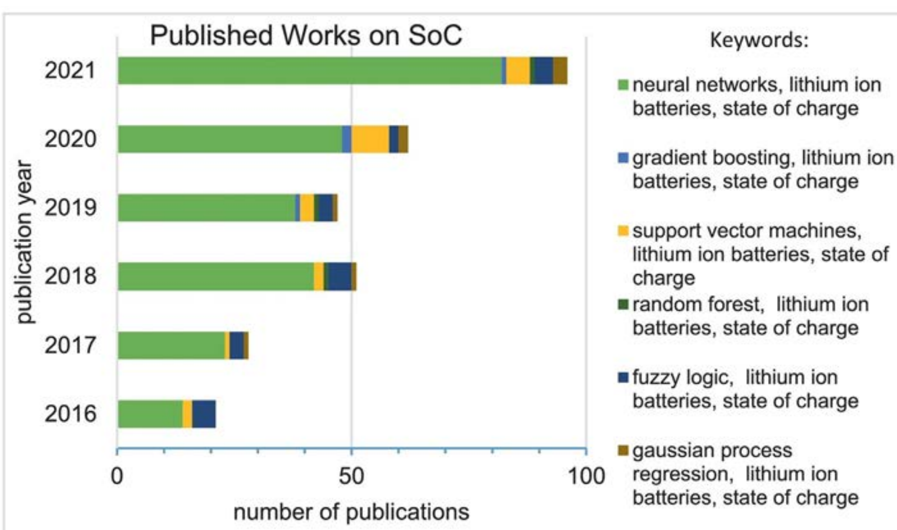


**Fig. 1.** Number of publications proposing data driven methods for SoC. From [1].

*Abbreviations:* SOC, State of Charge; EIS, Electrochemical Impedance Spectroscopy.

* Corresponding author.
*E-mail address:* emanuele.buchicchio@studenti.unipg.it (E. Buchicchio).

http://dx.doi.org/10.1016/j.sctalk.2022.100100
Received 2 November 2022; Received in revised form 19 November 2022; Accepted 20 November 2022

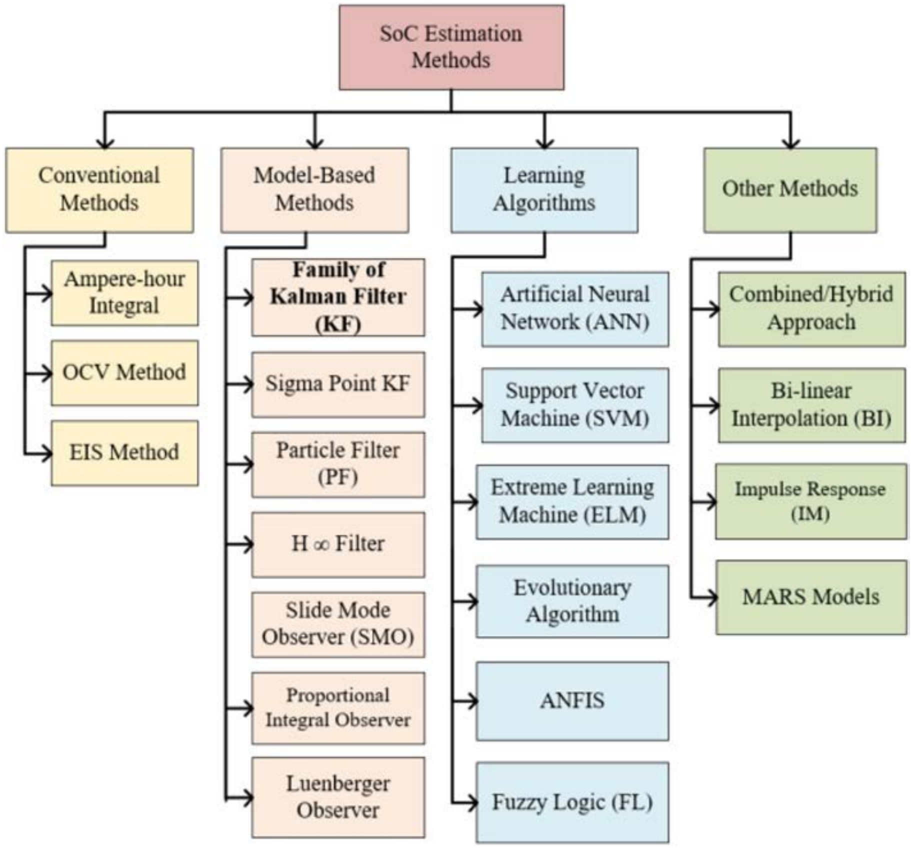


**Fig. 2.** Classifications of battery SoC estimation methods. From [2].

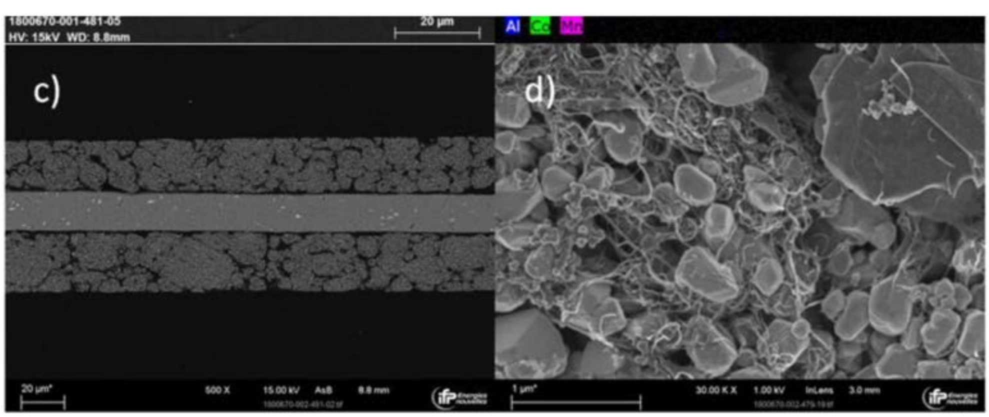


**Fig. 3.** Electronic microscopy analysis of negative electrode (c and d). From [3].

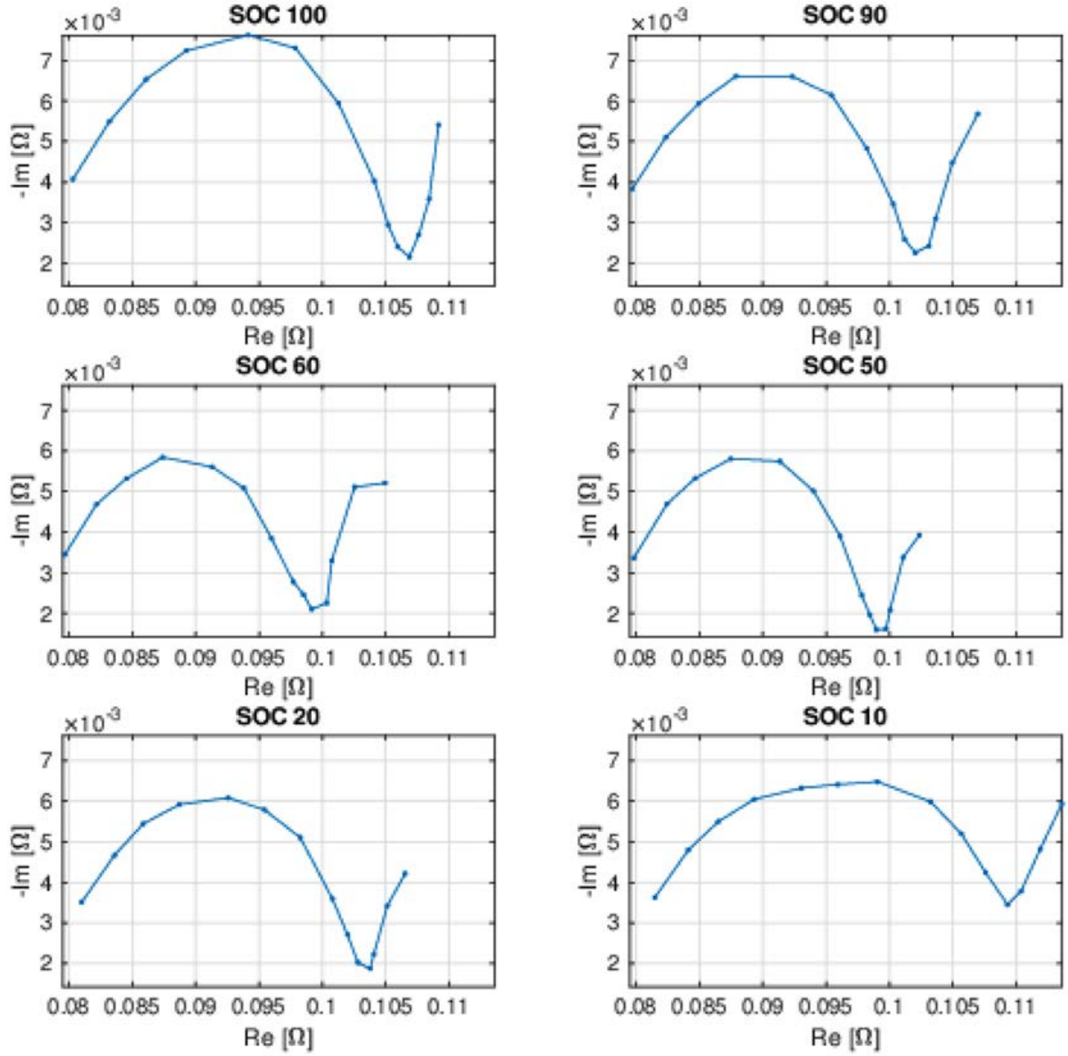


**Fig. 4.** An example of Cole-Cole plot representations of EIS measurement data for a battery belonging to the dataset. From [4].

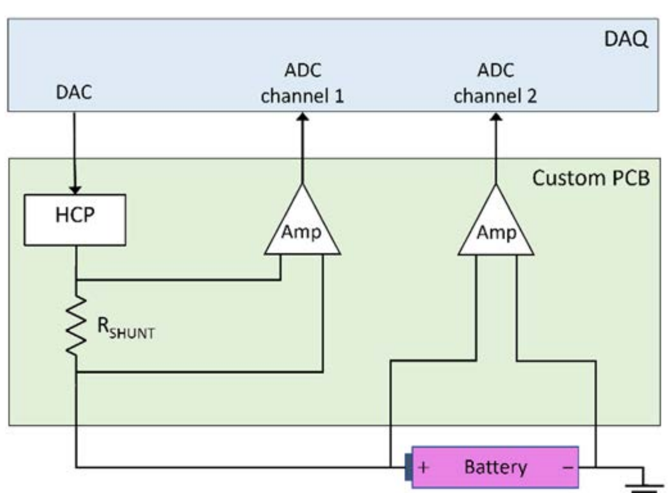


**Fig. 5.** Block diagram of the custom-made impedance measurement system used for collecting the data. From [4].

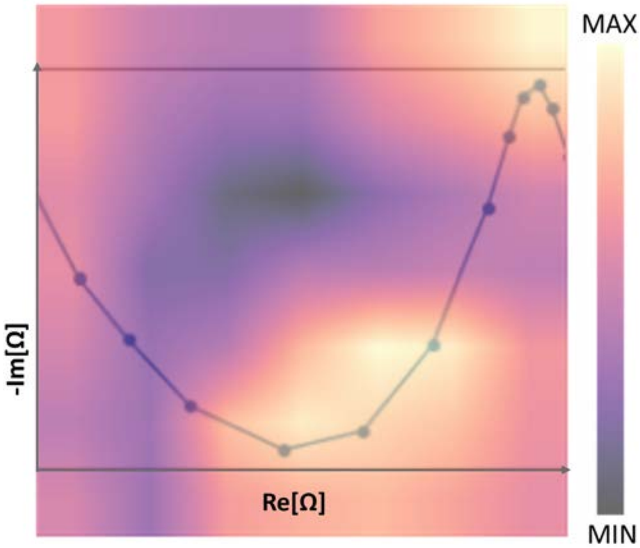


**Fig. 6.** Under the hypothesis that the whole curve shape has a stronger correlation with SOC than single feature values, we tried a visual CNN classification approach on the EIS curve. A ResNet 18 CNN model, fine-tuned on EIS curve representation, achieved 90% accuracy in SOC estimation for a battery included in the training. On an unknown battery, the system scores 62% accuracy. We compute the class activation map (CAM) on some inference results to verify that the SOC estimation is based on a reasonable set of image features. CAMs allow us to visually highlight the image areas more relevant to the final classification performed by the neural network. In this example 7 ×7 class activation map overlay on an EIS spectrum, the brighter colors indicate a relatively more significant contribution of feature (image pixels) in the area to the final classification. CAM shows that the main contributions to the SOC classification came from the peak and valley areas of the EIS curves, whose shape changes with SOC. From [5].

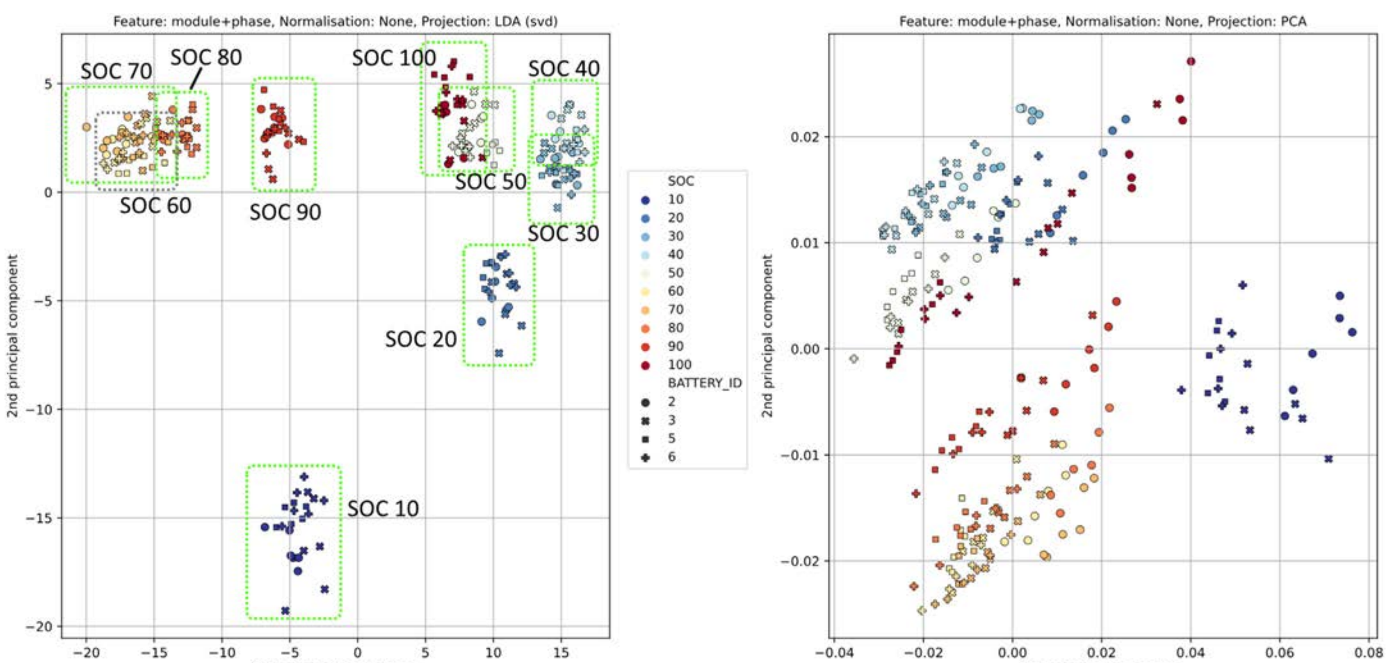


**Fig. 7.** Example of the output of LDA and PCA transformation: in the resulting two dimensional space the measurement from different state of charge condition are distributed in quite well separate clusters. From [6].

## CRediT authorship contribution statement

**Emanuele Buchicchio:** Conceptualization, Methodology, Software, Data curation, Writing – original draft, Writing – review & editing. **Francesco Bianconi:** Data curation, Software, Writing – review & editing. **Fabrizio Smeraldi:** Data curation, Conceptualization, Methodology, Writing – review & editing. **Alessio De Angelis:** Conceptualization, Methodology, Software, Data curation, Writing – original draft, Writing – review & editing. **Francesco Santoni:** Conceptualization, Methodology, Software, Data curation, Writing – original draft, Writing – review & editing. **Paolo Carbone:** Conceptualization, Methodology, Writing – review & editing, Supervision.

## Data availability

Data and code already published on mendeley data repository (https://doi.org/10.1016/j.dib.2022.108589) and code Ocean (https://codeocean.com/capsule/9473632/tree/v2)


## Acknowledgments

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.


## Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References


[1] Aaruththiran Manoharan, K.M. Begam, Vimal Rau Aparow, Denesh Sooriamoorthy, Artificial Neural Networks, Gradient Boosting and Support Vector Machines for electric vehicle battery state estimation: a review, J. Energy Storage 55 (Part A) (2022) 105384, ISSN 2352-152X. https://doi.org/10.1016/j.est.2022.105384.

[2] M. Hossain, M.E. Haque, M.T. Arif, Kalman filtering techniques for the online model parameters and state of charge estimation of the Li-ion batteries: a comparative analysis, J. Energy Storage 51 (2022) 104174, ISSN 2352-152X. https://doi.org/10.1016/j.est.2022.104174.

[3] Martin Petit, Elisa Calas, Julien Bernard, A simplified electrochemical model for modelling Li-ion batteries comprising blend and bidispersed electrodes for high power applications, J. Power Sources 479 (2020), https://doi.org/10.1016/j.jpowsour.2020.228766.

[4] Emanuele Buchicchio, Alessio De Angelis, Francesco Santoni, Paolo Carbone, Dataset on broadband electrochemical impedance spectroscopy of lithium-ion batteries for different values of the state-of-charge, Data in Brief 45 (2022) 108589, 2022. ISSN 2352-3409. https://doi.org/10.1016/j.dib.2022.108589.

[5] E. Buchicchio, A. De Angelis, F. Santoni, P. Carbone, Lithium-ion batteries state of charge estimation based on electrochemical impedance spectroscopy and convolutional neural network, accepted in 25th IMEKO TC4 International Symposium 23rd International Workshop on ADC and DAC Modelling and Testing IMEKO TC-4 2020 Brescia, Italy, September 12-14, 2022.

[6] Emanuele Buchicchio, Alessio De Angelis, Francesco Santoni, Paolo Carbone, Francesco Bianconi, Fabrizio Smeraldi, LiBEIS : A software tool for broadband electrochemical impedance spectroscopy of lithium-ion batteries, Software Impacts (2022), 100447, https://doi.org/10.1016/j.simpa.2022.100447; https://www.sciencedirect.com/science/article/pii/S2665963822001312.


## Further reading


[1] O. Kanoun, et al., Impedance spectroscopy: applications, advances and future trends, IEEE Instrument. Measur. Mag. 25 (3) (May 2022) 11–21, https://doi.org/10.1109/MIM.2022.9759355.

[2] A. De Angelis, P. Carbone, A. Moschitta, M. Crescentini, R. Ramilli, P.A. Traverso, A fast and simple broadband EIS measurement system for Li-Ion batteries, 24th IMEKO TC4 International Symposium and 22nd International Workshop on ADC and DAC Modelling and Testing 2020, pp. 157–161.

[3] A. De Angelis, E. Buchicchio, F. Santoni, A. Moschitta, P. Carbone, Uncertainty characterization of a practical system for broadband measurement of battery EIS, IEEE Trans. Instrum. Meas. 71 (2022), https://doi.org/10.1109/TIM.2022.3156994.

[4] Guha, A. Patra, Online estimation of the electrochemical impedance spectrum and remaining useful life of lithium-ion batteries, IEEE Trans. Instrum. Meas. 67 (2018), https://doi.org/10.1109/TIM.2018.2809138.

[5] B. Zhou, A. Khosla, A. Lapedriza, A. Oliva, A. Torralba, Learning deep features for discriminative localization, 2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR) 2016, pp. 2921–2929, https://doi.org/10.1109/CVPR.2016.319.


**Emanuele Buchicchio** (Student Member, IEEE) received the master's degree from the University of Perugia, Perugia, Italy, in 2006, where he is currently pursuing the Ph.D. degree in information engineering.

In 2016, he joined the Smartpeg software firm, and since 2019, he has been holding the position of the Chief Technology Officer (CTO). He is also a Software Engineer with a great passion for science and technology. He has gained broad experience working on many different software projects and products. His scientific and professional interests, in addition to software development, include measurement, sensors, machine learning, cloud computing, DevOps, cybersecurity, Internet of Things, and software quality metrics.

**Francesco Bianconi** Received the M.Eng. in Mechanical Engineering from the University of Perugia, Italy, and the Ph.D. in computer-aided design from a consortium of Italian universities. He has been a Visiting Researcher with the University of Vigo, Spain; the University of East Anglia, U.K.; Queen Mary University of London, U.K. and City, University of London, U.K. He is currently an Associate Professor in the Department of Engineering, University of Perugia, where he conducts research on computer vision, image processing, and pattern recognition with special focus on texture and colour analysis for industrial and biomedical applications. Prof. Bianconi is an IEEE Senior Member, Chartered Engineer and Court-Appointed Expert; he has served as Guest Editor for various journals and is currently Associate Editor for PLoS ONE.

**Fabrizio Smeraldi** is Senior Lecturer (Associate Professor) in AI in the School of Electronic Engineering at Queen Mary, University of London. His research spans applications of Machine Learning to Computer Vision, Bioinformatics, Cybersecurity and general pattern recognition; he has a special interest in non-parametric classifiers and descriptors. He is a co-founder of Mebomine Ltd, a digital health startup focusing on the extraction of real world evidence from online health boards.

**Alessio De Angelis** obtained the PhD degree in Information Engineering in 2009 from the University of Perugia, Italy. From 2010 to 2013 he was a researcher with the Signal Processing Lab, KTH Royal Institute of Technology, Stockholm, Sweden. Since July 2013 he has been with the Department of Engineering of the University of Perugia, Italy, where he became an Associate Professor in May 2018. Since 2019, he serves as an Associate Editor for IEEE Transactions on Instrumentation and Measurement. His research interests include instrumentation and measurement, positioning systems (using magnetic field and ultrasound), statistical signal processing, and battery measurement and modeling.

**Francesco Santoni** earned a master's degree in physics in 2010 from University of Perugia, and a Ph.D. degree in microelectronics engineering in 2015 from University of Roma "Tor Vergata".

He has been a postdoctoral researcher at the University of Roma "Tor Vergata" from 2015 to 2017, where his research work was mainly focused on mathematical models of charge transport in organic semiconductors and simulations of organic electronic devices. In May 2017 he started working at the Engineering Department of the University of Perugia as a postdoc, and in 2022 he became Researcher. He is currently researching on magnetic positioning systems, battery management systems and signal analysis.

**Paolo Carbone** received both the the Master's and the Ph.D. degrees from the University of Padova, Padova, Italy, in 1990 and 1994, respectively. From 1994 to 1997, he was a Researcher with the Third University of Rome. From 1997 to 2002, he was first a Researcher and then an Associate Professor with the University of Perugia, Perugia, Italy. Since 2002, he has been a Full Professor with the University of Perugia, where he teaches courses in Instrumentation and Measurement and in Statistical Signal Processing. He has been involved in various research projects, sponsored by private and public funds. He has authored/coauthored more than 200 papers, appeared in international journals and conference proceedings. He was the President of the IEEE Systems Council (2016-17). Since 2018, he is the Editor-in-Chief of the journal Measurement