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SenSys '21

Proceedings of the 2021

The 19th ACM Conference on Embedded Networked Sensor Systems

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Message from the ACM SenSys 2021 General Co-Chairs

Welcome to ACM SenSys 2021, the 19th ACM Conference on Embedded Networked Sensor Systems, the premier computer systems conference focused on networked sensing systems and applications. The resilience and perseverance of the SenSys community has made it possible to organize a mixed in-person and virtual event, despite all the difficulties created by the COVID-19 pandemic.

For those that could make it to the beautiful, historical city of Coimbra, in Portugal, we wish you a very pleasant and exciting stay. ACM SenSys 2021 is being hosted by the University of Coimbra - one of the oldest universities in the World, founded in the year 1290 - and the Municipality of Coimbra.

For all the participants, whether local or remote, we sincerely thank you for your contribution to the success of ACM Sensys 2021, and wish you an exciting and rewarding conference, with a technical program composed by two keynote speeches (one jointly with BuildSys), 25 full papers, 6 workshops (including the PhD forum with BuildSys), 21 posters, and 6 demos. All presentations, whether they are delivered in-person or remotely, will be live streamed, and recordings will be made available after the conference.

SenSys 2021 would not have been possible without the commitment of many people, who generously contributed with their work to a successful conference, specifically the Technical Program Committee Chairs and Members, Workshop Chair, Journal Track Chairs, PhD Forum Chair, Local Arrangements and Online Support Chair, Poster and Demo Chair, Web Chair, Finance Chairs, Publicity Chairs, Publication Chairs, Sponsorship Chairs, Student Volunteers Chair and, last but not least, the Student Volunteers. A word of thanks should also go to the Department of Informatics Engineering of the University of Coimbra for the IT technical and human resources they generously provided.

Last but not least, please join us to thank our sponsors, namely QUALCOMM, INRIA, and INESC-C. Special thanks are due to April Mosqus, of ACM, for her patience and competent support, and to SIGMOBILE EC for offering all of the eleven student travel grants.

Jorge Sá Silva (*University of Coimbra, Portugal*)
Fernando Boavida (*University of Coimbra, Portugal*)
ACM SenSys 2021 General Co-Chairs

André Rodrigues (*University of Coimbra and Coimbra Business School, Portugal*)
ACM SenSys 2021 General Vice-Chair

Message from the ACM SenSys 2021 Program Co-Chairs

Welcome to the 19th ACM Conference on Embedded Networked Sensor Systems (SenSys 2021), a leading single-track conference focusing on research advances in sensor systems. SenSys focuses on all aspects of system design, development, deployment, and use of networked sensing systems, therefore encompassing topics ranging from embedded computation and communication hardware all the way up to stack to the application layer. As such, it is an ideal venue to disseminate and discuss recent developments in the field, as witnessed by its history of active participation from both academia and industry. This year, the conference proceedings are no exception - there is no doubt that you will find inspiration among the high quality papers overviewing all aspects of sensing and wireless networking.

The papers included in the proceedings have been selected via a rigorous multi-stage review process by a Technical Program Committee (TPC) that consisted of 55 world-class experts. Submissions were required to be anonymized, yielding a double-blind review process that preserved the anonymity of both authors and reviewers. The 139 submissions underwent a first round of review by 4 TPC members, followed by online discussion via the HotCRP conference management system. 61 papers (43%) were considered sufficiently strong to advance to the next phase, which involved soliciting further reviews (including from external subject-matter experts) and additional discussion. A virtual TPC meeting discussed the relative merits of submissions where a consensus had not yet been reached, leading to a total of 25 (18%) papers being conditionally accepted. Each paper was assigned an anonymous shepherd, who supervised the revision necessary to address the comments by the reviewers and TPC at large, before preparation of the camera-ready version. All these papers were eventually accepted. This year, we introduce a new "journal-first" track - papers accepted to ACM Transactions on Internet of Things (TIOT) have been given an opportunity to also present at ACM SenSys. Based on quality and relevance to the conference, 8 papers will be presented in this "journal-first" track.

We are deeply thankful to the TPC members, who provided timely and in-depth reviews for a high number of submissions, and in particular to those who also served as shepherds, a role crucial in ensuring an even higher quality of the published papers. At the same time, we also want to thank authors, who contributed outstanding work and patiently worked with shepherds to address the review comments.

We also would like to thank the conference General Chairs, Jorge Sá Silva and Fernando Boavida, for their input and support with logistics, designing the programme, and many other matters throughout the conference organization. We also thank Pei Zhang and Gian Pietro Picco for leading the "journal-first" initiative.

Finally, we thank the conference attendees (both online and in-person) for making SenSys a place where lively discussions and creative exchange advance the state of the art. We hope that these proceedings will seed new ideas and research interactions, by providing a high-quality, diverse, and thought-provoking technical program. We sincerely hope you enjoy the program, whether you attend online or in person in Coimbra, Portugal!

Andrew Markham (*University of Oxford, UK*)
Rong Zheng (*McMaster University, Canada*)
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ACM SenSys 2021 Workshops
Message from the ACM SenSys 2021 Workshop Chair

Welcome to the five workshops organized in co-location met ACM SenSys 2021. The five workshops address a multitude of very relevant emerging topics, closely related to research advances in sensor systems. In particular, the following workshops are organized on Wednesday November 17th 2021:

- 9th ACM International Workshop on Energy Harvesting & Energy-Neutral Sensing Systems (ENSsys 2021), (http://www.enssys.org/2021/), organized by:
  - Pat Pannuto, University of California, San Diego, USA
  - Sebastian Bader, Mid Sweden University, Sweden
  - Colleen Josephson, VMWare Research, USA
  - Michele Magno, ETH Zurich, Switzerland
  - Geoff V. Merrett, University of Southampton, UK
- 4th ACM International Workshop on Data: Acquisition To Analysis (DATA 2021) (https://data-workshop.github.io/DATA2021/), organized by:
  - Gabe Fierro, University of California, Berkeley, USA
  - Yang Zhao, GE Research, USA
- 3rd ACM International Workshop on Blockchain-enabled Networked Sensor Systems (BlockSys 2021), (https://acmblocksys.github.io/blocksys2021/), organized by:
  - Bhaskar Krishnamachari, University of Southern California, USA
  - Salil Kanhere, University of New South Wales, Australia
  - Ali Dorri, Queensland University of Technology, Australia
  - Gowri Sankar Ramachandran, Queensland University of Technology, Australia
  - Shantanu Pal, Queensland University of Technology, Australia
  - Ambrose Hill, CSIRO, Australia
- 3rd ACM International Workshop on Challenges in Artificial Intelligence and Machine Learning for Internet of Things (AIChallengeIoT 2021), (https://aichallengeiot.github.io/), organized by:
  - Shuochao Yao, George Mason University, USA
  - Bharathan Balaji, Amazon AI Lab, USA
  - Shiqiang Wang, IBM T. J. Watson Research Center, USA
  - Jorge Ortiz, Rutgers University, USA
  - Mani Srivastava, University of California, Los Angeles, USA
- 2nd ACM International Workshop on Nanoscale Computing, Communication, and Applications (NanoCoCoA 2021), (https://www.nanococoa.org/), organized by:
  - Filip Lemic, University of Antwerp - imec, Belgium and Polytechnic University of Catalonia, Spain
  - Chong Han, Shanghai Jiao Tong University, China
  - Jeroen Famaey, University of Antwerp - imec, Belgium
  - Sergi Abadal, Polytechnic University of Catalonia, Spain

On behalf of the Organizing Committee, we are very thankful to the workshop organizers for their appreciated efforts. Furthermore, we would like to sincerely thank the workshop authors for submitting their interesting work, and the workshop TPC members for their timely and constructive reviews. Last but not least, I would like to explicitly thank the General Chairs Jorge and Fernando for their strong support along the process!
Please enjoy the workshops and take advantage of the inspiring workshop sessions! Hopefully, the workshops will be instrumental for shaping your future work and contributions to the research community!

Filip De Turck (*Ghent University-imec, Belgium*)
-SenSys 2021 Workshop Chair

ACM Workshop AIChallengeIoT 2021

Message from Organizers

It is our pleasure to welcome you to the 3rd International Workshop on Challenges in Artificial Intelligence and Machine Learning for Internet of Things (AIChallengeIoT 2021), which is held in conjunction with ACM SenSys 2021 on November 17, 2021.

Artificial intelligence (AI) and machine learning (ML) are key enabling technologies for many Internet of Things (IoT) applications. However, the collection and processing of data for AI and ML is very challenging in the IoT domain. For example, there are usually a large number of low-powered sensors deployed in large geographical areas with possibly intermittent network connectivity. The sensors and their collected data may be owned by different users or organizations, which can bring further obstacles to data collection due to privacy concerns and noisy labels provided by different users. The successful application of AI/ML approaches in such scenarios with noisy and decentralized data is difficult. In addition, the amount of collected data that can be used for training AI/ML models is usually proportional to the number of users in the system, but the system may not be able to attract many users without a well-trained AI/ML model, and it is challenging to solve this dilemma.

This workshop focuses on how to address the above and other unique challenges of applying AI/ML in IoT systems. The call for papers attracted submissions from Asia, Europe, and North America. Out of 17 submitted papers, 11 regular papers and 1 position paper have been accepted after a thorough review by the program. The papers were evaluated for novelty, relevance, and quality. Papers with forward-looking ideas that may initiate new research directions have been particularly encouraged.

This workshop would not have been successful without the help of many people. We would like to thank all the authors who submitted their work to AIChallengeIoT and the Technical Program Committee members who provided high-quality and timely reviews for the papers. We also thank the SenSys workshop chairs Filip De Turck and publication chair Rita Girão and Lúcia Martins for their assistance in putting together the workshop program and proceedings.

Finally, we hope that you enjoy this year's AIChallengeIoT workshop, whether you are presenting, attending, or just reading the proceedings on the web. We appreciate for your support for AIChallengeIoT and hope that you will continue supporting this workshop in future years.

Shuochao Yao (*George Mason University, USA*)
On behalf of the ACM Workshop AIChallengeIoT 2021 Organization Committee

ACM Workshop AIChallengeIoT 2021

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ACM Workshop BlockSys 2021

Message from Organizers

It is with great pleasure that we welcome you to the technical program of BlockSys 2021, the 3rd Workshop on Blockchain-enabled Networked Sensor Systems. BlockSys workshop focuses on research problems at the intersection of networked sensor systems and Blockchain. Networked sensor systems as a key component of internet of things (IoT) have been widely used in various environments such as smart home, smart building, vehicular network, wearable computing, robotics systems, industrial control systems, etc. They capture human and physical-world dynamics and feed the data into large-scale analytical backends. Today's cloud-centric paradigm, however, does not genetically support trust management and privacy preservation; it also does not encourage information sharing in multi-stakeholder settings through incentives and payment mechanisms. As a result, complementary technologies that can offer to ensure data protection, incentivize information exchange, and reduce sharing and maintenance costs are highly desired.

We have seen the increasing interest in tackling such problems by using emerging blockchain and other distributed ledger technologies. BlockSys-2021 aims to set up a stage for industry and academia to share wins and lessons. We have five papers this year, including invited papers. The program also includes speakers from industry, including IOTA, NetObjex, and BlockLab.

We would like to thank the TPC members for providing valuable suggestions and reviews to all the submitted papers. Finally, we would also like to thank the authors for their contributions to BlockSys-2021. We would like to thank the conference organizers, in particular, general chairs Jorge Sá Silva and Fernando Boavida for arranging and diligently monitoring key logistical issues. We also would like to thank Filip De Turck for his support. Last but not least, we would like to thank the attendees for sharing their ideas with others, and providing valuable feedback for improvements. We hope you will find the technical program thought-provoking and stimulating, we sincerely hope you enjoy the workshop!

Ali Dorri (*Queensland University of Technology*)
Gowri Ramachandran (*Queensland University of Technology*)
ACM Workshop BlockSys 2021 Technical Program Committee Chairs

Bhaskar Krishnamachari (*University of Southern California*)
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ACM Workshop Data 2021

Message from the Chairs

We are happy to welcome you to the technical program of the 4th workshop International Workshop on Data: Acquisition To Analysis --- DATA'21, --- co-located with ACM conferences BuildSys '21 and SenSys '21. As the enthusiasm for and success of the Internet of Things (IoT), Cyber-Physical Systems (CPS), and Smart Buildings grows, so too does the volume and variety of data collected by these systems. How do we ensure that this data is of high quality, and how do we maximize the utility of collected data such that many projects can benefit from the time, cost, and effort of deployments? The Data: Acquisition To Analysis (DATA) workshop aims to look broadly at interesting data, bringing together a community of application and algorithm researchers in the sensing systems and building domains to promote breakthroughs from the integration of the generators and users of datasets.

The workshop is co-located with the BuildSys and SenSys conferences because these communities attract researchers and practitioners who develop new sensors and other sources of data and integrate data into novel applications in a variety of settings. In many cases, interesting data are collected and potentially made available to the broader community, but without any specific venue to advertise and describe the data. Conversely, it can be difficult for data consumers to discover datasets that meet their needs. DATA aims to bridge that gap.

The call for papers resulted in the acceptance of 11 of 14 submissions, comprising 9 datasets and 2 full papers. The DATA workshop incorporates an expert-led panel to facilitate discussion on topics of data collection, data reuse and how these topics intersect with questions of fairness and bias in AI/ML applications. The topic of the panel discussion is "Data Acquisition, Analysis and Reuse for AI + IoT Applications." Four panelists have generously accepted our invitation: Dr. Shijia Pan (University of California Merced), Dr. Radislav Potyrailo (GE Research), Dr. Tao Gao (University of California Los Angeles), and Dr. Qiang Xu (XYZ10).

We would like to thank the TPC members for their insightful reviews and contributions, the artifact evaluation committee for carefully vetting the datasets, the panel members, and for all those who submitted work for consideration. We would also like to thank the SenSys publication chairs Rita Girão-Silva and Lúcia Martins (University of Coimbra, Portugal) as well as the workshop chair Filip De Turck (Ghent University, Belgium) and general chairs Jorge Sá Silva and André Rodrigues (University of Coimbra, Portugal) for giving us the opportunity to hold ACM DATA 2021 this year.

Gabe Fierro

DATA '21 Co-Chair

Colorado School of Mines, USA

National Renewable Energy Laboratory, USA

Yang Zhao

DATA '21 Co-Chair

GE Research

ACM Workshop Data 2021

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ENSsys@SenSys 2021 Chairs' Welcome

It is our pleasure to welcome you to the 9th International Workshop on Energy Harvesting and Energy Neutral Sensing Systems – ENSsys ’21, co-located with ACM SenSys ’21. Our previous events have been held in Rome (Italy), Memphis (USA), Seoul (South Korea), Stanford (USA), Delft (The Netherlands), Shenzhen (China), New York (USA), and most recently in an online, virtual format last year. As we begin a transition out of the acute phase of the global pandemic, ENSsys is being held in a hybrid format for the first time.

ENSsys reflects the growing worldwide interest and research activity in energy-harvesting and energy-neutral sensing systems. Complementing the topics of ACM SenSys, ENSsys brings together international researchers to explore the challenges, issues, and opportunities in the research, design, and engineering of energy-constrained and energy-aware sensing systems. These are a technological cornerstone for new applications in smart energy, future transportation, environmental monitoring, and smart cities.

New this year, ENSsys will run twice, first as a part of SenSys 2021 and then (tentatively) as a part of ASPLOS 2022. Our goal is to leverage the success of ENSsys to both continue to support our home in the wireless sensor networking community and to grow interest and excitement for energy neutral, energy harvesting, and intermittent systems in the computer architecture and systems communities. ENSsys@SenSys invited 1-2 page demo abstracts and 2-3 page short papers. The short papers are intended as a means to workshop early ideas with the community and will seed breakout discussions in the afternoon of ENSsys@SenSys. Short papers that grow to full paper submissions in time for the second iteration of ENSsys@ASPLOS will receive special consideration and the same set of reviewers (where possible). Accepted demos are also invited to repeat their demo at ENSsys@ASPLOS.

The call for papers and demos attracted 14 submissions (8 papers and 6 demos) from Asia, North America, and Europe. All papers that were submitted received at least two reviews from experts in the area, and were evaluated for relevance, novelty, technical contribution, and presentation. An online TPC meeting was held to discuss all of the reviews and to decide upon the final technical program. Owing to the high quality of submissions, five papers were finally selected for discussion at ENSsys@SenSys.

Delivering the ENSsys workshop is a significant undertaking and could not have been achieved without the help of many people. First and foremost, we would like to thank all of the authors who submitted contributions to ENSsys, and the members of the Technical Program Committee for their excellent and timely work reviewing submissions and helping to put together an excellent technical program. We would also like to thank our Website Chair Geoff Merrett for his assistance in promoting ENSsys and soliciting high quality submissions.

Finally, and most of all, we hope that you thoroughly enjoy this year’s workshop – whether you are presenting, attending, or just reading these proceedings on the web! We also hope that you continue to support ENSsys in future years as this exciting field grows and continues to develop.

Enjoy ENSsys@SenSys!

Pat Pannuto
ENSsys ’21 General Chair
UC San Diego, USA

Sebastian Bader
ENSsys ’21 Technical Program Chair
Mid Sweden University, Sweden

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ACM Workshop NanoCoCoA 2021

Message from the Organizing Committee

The papers in this volume form the proceedings of the 2nd ACM International Workshop on Nanoscale Computing, Communication, and Applications (NanoCoCoA 2021), held on November 17, 2021, in conjunction with the 19th ACM Conference on Embedded Networked Sensor Systems (SenSys 2021), November 15-17, 2021. The workshop and conference took place as hybrid events in Coimbra, Portugal.

Nanotechnology gave us the basis for this workshop, as it is revolutionizing a variety of fields by paving the way toward sub-µm scale devices (i.e., in the order of a few hundred nanometers). Controlling materials on such a scale will give rise to integrated nanodevices with simple sensing, actuation, data processing and storage, and communication capabilities, opening the horizon to a variety of ground-breaking applications. By equipping nanodevices with communications capabilities, nanotechnology will facilitate the advance of multiple disruptive applications, the most prominent ones being in-body communication, software-defined metamaterials, wireless robotic materials, and on-chip communication.

The overall objective of the NanoCoCoA'21 workshop was to bring together a broad range of experts working in this interesting field of research to outline, discuss, and address emerging topics pertaining to designing nanodevices and wireless systems of nanodevices for this novel set of disruptive nanoscale applications.

This year's edition of NanoCoCoA received 15 paper submissions from different institutions from all over the world. All papers were reviewed by three to four expert reviewers selected from the pool of 21 Technical Program Committee (TPC) members with a strong balance between all NanoCoCoA-related expertises. The papers were judged based on their originality, quality, and relevance to the subject area of NanoCoCoA, and the TPC has selected 7 full papers for presentation at the workshop, complemented by 3 work-in-progress (WiP) papers. The program of the workshop has been enriched by an outstanding keynote talk by Prof. Max C. Lemme from RWTH Aachen University and AMO GmbH, Germany.

We would like to thank all of those who submitted papers for consideration, all the presenters, the TPC members for their invaluable contributions, our excellent keynote presenter Prof. Lemme, and the ACM SenSys'21 organizing committee, especially this year's workshop chair Prof. Filip De Turck (Ghent University – imec, Belgium), as well as the general chairs Prof. Jorge Sá Silva and Prof. Fernando Boavida (University of Coimbra, Portugal) for giving us the opportunity to host the ACM NanoCoCoA'21 workshop. Finally, we would like to acknowledge the EU H2020-MSCA-IF-2019 Project "Scalable Localization-enabled In-body Terahertz Nanonetwork" (ScaLeITN, nr. 893760) that provided support in the organization of this year's edition of the workshop.

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ACM Workshop NanoCoCoA 2021 Organizing Committee

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Keynote Talk

Max C. Lemme
RWTH Aachen University and AMO GmbH

Title: 2-Dimensional Materials as Enablers of Autonomous Sensor Systems?

Abstract: Two-dimensional (2D) layered materials are defined by the fact that they have covalent chemical bonds in-plane, but much weaker van der Waals bonds to the next 2D layer in the third dimension. This material class is being investigated intensely for applications in electronics, optoelectronics and sensing, because of their (sometimes) exceptional properties. Here, Prof. Lemme will provide a brief overview of sensor device options with superior performance compared to the state of the art. He will also touch upon opportunities for high frequency 2D electronics, which may be suitable for wireless sensor-node communications. 2D materials have further shown memristive behavior, which could lead to neuromorphic computing hardware that may enable sensor fusion and energy efficient data processing at the sensor node. Even energy harvesting and storage may be possible in a 2D materials-based sensor system, and this will be demonstrated with several examples. Finally, Prof. Lemme will describe some of the bottlenecks in 2D material manufacturing technology that currently prevent industrial uptake.

Short Bio: Prof. Max C. Lemme is Full Professor at RWTH Aachen University and Scientific Director of AMO GmbH, a nanotechnology company in Aachen, Germany. He is a co-founder of Black Semiconductor GmbH, Aachen. He obtained his PhD degree from RWTH Aachen in 2004. He has worked in the field of nano-CMOS devices, including FinFETs and SOI-MOSFETs, high-k /metal gate stacks, graphene and 2D materials and Perovskites. The work includes the world's first top-gated graphene MOSFET, graphene-based non-volatile memory, vertical graphene hot electron transistors, graphene NEMS, ion-based memristive switches from molybdenum disulfide and silicon photonics-integrated Perovskite Lasers. He received the "NanoFutur" young researchers' award from the German Ministry for Education and Research in 2006 and a Lynen Research Fellowship from the Alexander von Humboldt Foundation in 2007. From 1998 to 2008, he worked at AMO, where his last position was as Head of the Technology Department. In 2008, he joined Harvard University in Cambridge, USA, where he pioneered a helium ion-based nanolithography method for graphene and investigated graphene photodetectors. In September 2010, he became Guest Professor at KTH, where he initiated the graphene activities within the School of ICT. He received an ERC Starting Grant in 2012 and became Heisenberg Professor at the University of Siegen in Germany in the same year. In February 2017, Prof. Lemme was appointed Full Professor at RWTH Aachen University and Scientific Director of AMO GmbH. In 2018, he received an ERC Proof of Concept grant. He has managed numerous national and international research projects with academic and industrial partners. His current research interests include electronic, optoelectronic and nanoelectromechanical devices and sensors made from novel materials like graphene and related 2-D materials, Perovskites or phase change materials and their integration into the silicon technology platform. Recently, his research interests include materials and electronic devices for neuromorphic computing. Lemme is coordinator of the Cluster "NeuroSys – Neuromorphic Computing for Autonomous Artificial Intelligence Systems", which is funded by the German Ministry of Education and Research.