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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 Moskus, 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 overviews 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*)  
SenSys 2021 Program Chairs

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Chenren Xu (*Peking University*)  
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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 17<sup>th</sup> 2021:

- 9th ACM International Workshop on Energy Harvesting & Energy-Neutral Sensing Systems (ENSys 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
- 4<sup>th</sup> 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
- 3<sup>rd</sup> ACM International Workshop on Blockchain-enabled Networked Sensor Systems (BlockSys 2021), (<https://acmblocksys.github.io/blocksyst2021/>), 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
- 3<sup>rd</sup> 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
- 2<sup>nd</sup> 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 AIChallengeloT 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 (AIChallengeloT 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 AIChallengeloT 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 AIChallengeloT workshop, whether you are presenting, attending, or just reading the proceedings on the web. We appreciate for your support for AIChallengeloT and hope that you will continue supporting this workshop in future years.

**Shuochao Yao** (*George Mason University, USA*)

On behalf of the ACM Workshop AIChallengeloT 2021 Organization Committee

# ACM Workshop AIChallengeIoT 2021

## Organization Committee

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Bharathan Balaji (*Amazon AI Lab, USA*)

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Urmish Thakker (*ARM, USA*)

# 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*)

**Salil Kanhere** (*University of New South Wales*)

ACM Workshop BlockSys 2021 General Chairs

# ACM Workshop BlockSys 2021

## Organization Committee

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## ACM Workshop Data 2021

### Message from the Chairs

We are happy to welcome you to the technical program of the 4<sup>th</sup> 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

## ENSsys 2021 Workshop Organization

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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- $\mu\text{m}$  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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# Contents

<b>Workshop NanoCoCoA 2021 - Keynote Talk</b> . . . . .	xxviii
---	--------

## **Session 1: Distributed Computing and Learning for Sensing Data Processing**

<b>RT-mDL: Supporting Real-Time Mixed Deep Learning Tasks on Edge Platforms</b> . . . . .	1
---	---

Neiwen Ling, Kai Wang, Yuze He, Guoliang Xing (*The Chinese University of Hong Kong*); Daqi Xie (*Edge Cloud Innovation Lab, Huawei Cloud*)

<b>FedDL: Federated Learning via Dynamic Layer Sharing for Human Activity Recognition</b> . . . . .	15
---	----

Linlin Tu (*Michigan State University*); Xiaomin OUYANG (*The Chinese University of Hong Kong*); Jiayu Zhou (*Michigan State University*); Yuze He, Guoliang Xing (*The Chinese University of Hong Kong*)

<b>Mercury: Efficient On-Device Distributed DNN Training via Stochastic Importance Sampling</b> . . . . .	29
---	----

Xiao Zeng, Ming Yan, Mi Zhang (*Michigan State University*)

<b>FedMask: Joint Computation and Communication-Efficient Personalized Federated Learning via Heterogeneous Masking</b> . . . . .	42
---	----

Ang Li, Jingwei Sun (*Duke University*); Xiao Zeng, Mi Zhang (*Michigan State University*); Hai "Helen" Li, Yiran Chen (*Duke University*)

## **Session 2: Physical Layer Design for Batteryless and Low-power Networked Sensor Systems**

<b>NELoRa: Towards Ultra-low SNR LoRa Communication with Neural-enhanced Demodulation</b> . . . . .	56
---	----

Chenning Li, Hanqing Guo (*Michigan State University*); Shuai Tong (*Tsinghua University*); Xiao Zeng, Zhichao Cao, Mi Zhang, Qiben Yan, Li Xiao (*Michigan State University*); Jiliang Wang, Yunhao Liu (*Tsinghua University*)

<b>MultiScatter: Multistatic Backscatter Networking for Battery-Free Sensors</b> . . . . .	69
--	----

Mohamad Katanbaf, Ali Saffari, Joshua R. Smith (*University of Washington*)

<b>COCOON - A Conductive Substrate-based Coupled Oscillator Network for Wireless Communication</b> . . . . .	84
--	----

Xingda Chen, Deepak Ganesan, Jeremy Gummesson, Mohammad Rostami (*UMass Amherst*)

## **Session 3: Human Sensing using Radio Frequency Signals**

<b>Wavevoice: A Noise-resistant Multi-modal Speech Recognition System Fusing mmWave and Audio Signals</b> . . . . .	97
---	----

Tiantian Liu, Ming Gao, Feng Lin, Chao Wang, Zhongjie Ba, Jinsong Han (*Zhejiang University*); Wen Yao Xu (*SUNY Buffalo*); Kui Ren (*Zhejiang University*)

<b>MoRe-Fi: Motion-robust and Fine-grained Respiration Monitoring via Deep-Learning UWB Radar</b> . . . . .	111
---	-----

Tianyue Zheng (*Nanyang Technological University*); Zhe Chen (*China-Singapore International Joint Research Institute*); Shujie Zhang, Chao Cai, Jun Luo (*Nanyang Technological University*)

<b>Sense Me on the Ride: Accurate Mobile Sensing over a LoRa Backscatter Channel</b> . . . . .	125
Haotian Jiang, Jiacheng Zhang, Xiuzhen Guo, Yuan He ( <i>Tsinghua University</i> )	
<b>LTE-based Pervasive Sensing Across Indoor and Outdoor</b> . . . . .	138
Yuda Feng ( <i>University of Massachusetts Amherst</i> ); Yaxiong Xie ( <i>Princeton University</i> ); Deepak Ganesan, Jie Xiong ( <i>University of Massachusetts Amherst</i> )	
<b>Session 4: Localization</b>	
<b>CurveLight: An Accurate and Practical Indoor Positioning System</b> . . . . .	152
Shangyao Yan ( <i>Sun Yat-sen University</i> ); Zhimeng Yin ( <i>City University of Hong Kong</i> ); Guang Tan ( <i>Sun Yat-sen University</i> )	
<b>SnapperGPS: Algorithms for Energy-Efficient Low-Cost Location Estimation Using GNSS Signal Snapshots</b> . . . . .	165
Jonas Beuchert, Alex Rogers ( <i>University of Oxford</i> )	
<b>Enabling Passive Backscatter Tag Localization Without Active Receivers</b> . . . . .	178
Abeer Ahmad, Xiao Sha, Milutin Stanacevic, Akshay Athalye, Petar Djuric, Samir R Das ( <i>Stony Brook University</i> )	
<b>RFusion: Robotic Grasping via RF-Visual Sensing and Learning</b> . . . . .	192
Tara Boroushaki, Isaac Perper, Mergen Nachin, Alberto Rodriguez, Fadel Adib ( <i>Massachusetts Institute of Technology</i> )	
<b>Session 5: Knowledge-driven Machine Learning for Sensing</b>	
<b>OneFi: One-Shot Recognition for Unseen Gesture via COTS WiFi</b> . . . . .	206
Rui Xiao, Jianwei Liu, Jinsong Han, Kui Ren ( <i>Zhejiang University</i> )	
<b>LIMU-BERT: Unleashing the Potential of Unlabeled Data for IMU Sensing Applications</b> . . . . .	220
Huatao Xu, Pengfei Zhou, Rui Tan, Mo Li ( <i>Nanyang Technological University</i> ); Guobin Shen ( <i>Alibaba Local Services Lab, Alibaba Group</i> )	
<b>UniTS: Short-Time Fourier Inspired Neural Networks for Sensory Time Series Classification</b> . . . .	234
Shuheng Li ( <i>University of California, San Diego</i> ); Ranak Roy Chowdhury ( <i>University of California San Diego</i> ); Jingbo Shang, Rajesh K. Gupta, Dezhi Hong ( <i>University of California, San Diego</i> )	
<b>Session 6: Protocol and Systems Supports for Low-power Networked Sensor Systems</b>	
<b>Morphy: Software Defined Charge Storage for the IoT</b> . . . . .	248
Fan Yang, Ashok Samraj Thangarajan, Sam Michiels, Wouter Joosen, Danny Hughes ( <i>KU Leuven</i> )	
<b>ALFRED: Virtual Memory for Intermittent Computing</b> . . . . .	261
Andrea Maioli ( <i>Politecnico di Milano, Italy</i> ); Luca Mottola ( <i>Politecnico di Milano, Italy and RI.SE Computer Science and Uppsala University, Sweden</i> )	
<b>STeC: Exploiting Spatial and Temporal Correlation for Event-based Communication in WSNs</b> . .	274
Andreas Biri, Reto Da Forno, Tonio Gsell, Tobias Gatschet ( <i>Computer Engineering and Networks Laboratory, ETH Zurich</i> ); Jan Beutel ( <i>University of Innsbruck</i> ); Lothar Thiele ( <i>Computer Engineering and Networks Laboratory, ETH Zurich</i> )	

## Session 7: Light-based Sensing and Communication

### LAPD: Hidden Spy Camera Detection using Smartphone Time-of-Flight Sensors . . . . . 288

Sriram Sami, Sean Rui Xiang Tan, Bangjie Sun (*National University of Singapore*); Jun Han (*Yonsei University*)

### UltraDepth: Exposing High-Resolution Texture from Depth Cameras . . . . . 302

Zhiyuan Xie, Xiaomin Ouyang (*The Chinese University of Hong Kong*); Xiaoming Liu (*Michigan State University*); Guoliang Xing (*The Chinese University of Hong Kong*)

### SpiderWeb: Enabling Through-Screen Visible Light Communication . . . . . 316

Hanting Ye, Qing Wang (*Delft University of Technology*)

### Adversarial Attacks against LiDAR Semantic Segmentation in Autonomous Driving . . . . . 329

Yi Zhu (*State University of New York at Buffalo*); Chenglin Miao (*University of Georgia*); Foad Hajiaghajani (*Department of Computer Science and Engineering, University at Buffalo, SUNY*); Mengdi Huai (*University of Virginia*); Lu Su (*Purdue University*); Chunming Qiao (*SUNY at Buffalo*)

## Demo Session

### Demo Abstract: Infrastructure-Free Smartphone Indoor Localization Using Room Acoustic Responses . . . . . 343

Dongfang Guo, Wenjie Luo (*Nanyang Technological University*); Chaojie Gu (*Zhejiang University*); Yuting Wu, Qun Song (*Nanyang Technological University*); Zhenyu Yan (*The Chinese University of Hong Kong*); Rui Tan (*Nanyang Technological University*)

### Demo Abstract: ROMEasure: Smartwatch-Based Practical Solution To Accurately Calculate Joint Range Of Motion . . . . . 345

Vivek Chandel (*TCS Research*); Murali Poduval (*Tata Consultancy Services*); Avik Ghose (*TCS Research*)

### Demo Abstract: Cognisense: A contactless rotation speed measurement system . . . . . 347

Mohammad Heggo, Laksh Bhatia, Julie McCann (*Imperial College London*)

### Demo Abstract: A Drone-based System for Intelligent and Autonomous Homes . . . . . 349

Stephen Xia (*Columbia University*); Rishikanth Chandrasekaran (*University of California, San Diego*); Yanchen Liu, Chenye Yang (*Columbia University*); Tajana Simunic Rosing (*University of California, San Diego*); Xiaofan Jiang (*Columbia University*)

### Demo Abstract: A Compliance Monitoring System for Open SDR Platforms . . . . . 351

Jie Wang (*Washington University in St. Louis*); Jacobus Van der Merwe (*University of Utah*); Neal Patwari (*Washington University in St. Louis*)

### Demo Abstract: BLE Location-based Services via WiFi . . . . . 353

Ruofeng Liu (*University of Minnesota*); Zhimeng Yin (*City University of Hong Kong*); Wenchao Jiang (*Singapore University of Technology and Design*); Tian He (*University of Minnesota*)

## Poster Session

### Poster Abstract: Are CNN based Malware Detection Models Robust? Developing Superior Models using Adversarial Attack and Defense . . . . . 355

Hemant Rathore, Taeab Bandwala, Sanjay K. Sahay (*BITS Pilani, India*); Mohit Sewak (*Microsoft R & D, India*)

<b>Poster Abstract: Cyber-Physical System for Collecting Data on Moisture Inside the Walls of Buildings</b> . . . . .	<b>357</b>
Grzegorz Klosowski ( <i>Lublin University of Technology</i> ); Tomasz Rymarczyk, Marcin Kowalski ( <i>University of Economics and Innovation in Lublin</i> )	
<b>Poster Abstract: Exploring an Extensible Children Game Framework based on Augmented Reality Building Blocks</b> . . . . .	<b>359</b>
Xingyu Chen ( <i>CU Denver</i> ); Xinmin Fang ( <i>Guangdong University of Technology</i> ); Wenchuan Wei ( <i>UCSD</i> ); Wen Yao Xu ( <i>SUNY Buffalo</i> ); Zhengxiong Li ( <i>University of Colorado Denver</i> )	
<b>Poster Abstract: Enhanced Virtual Reality: Exploring an Immersive and Realistic Virtual Reality Training for Nursing</b> . . . . .	<b>361</b>
Xinmin Fang ( <i>Guangdong University of Technology</i> ); Xingyu Chen ( <i>University of Colorado Denver</i> ); Wen Yao Xu ( <i>SUNY Buffalo</i> ); Zhengxiong Li ( <i>University of Colorado Denver</i> )	
<b>Poster Abstract: 3D Human Pose Estimation Using WiFi Signals</b> . . . . .	<b>363</b>
Yili Ren, Zi Wang, Yichao Wang ( <i>Florida State University</i> ); Sheng Tan ( <i>Trinity University</i> ); Yingying Chen ( <i>Rutgers University</i> ); Jie Yang ( <i>Florida State University</i> )	
<b>Poster Abstract: A Wearable-based Distracted Driving Detection Leveraging BLE</b> . . . . .	<b>365</b>
Travis Mewborne ( <i>Trinity University</i> ); Linghan Zhang ( <i>George Mason University</i> ); Sheng Tan ( <i>Trinity University</i> )	
<b>Poster Abstract: Pushing the Limits of Respiration Sensing with Reconfigurable Metasurface</b> . .	<b>367</b>
Yangfan Zhang, Xiaojing Wang, Chao Feng ( <i>Northwest University</i> ); Xinyi Li ( <i>Northwest University</i> ); Yuanming Cai ( <i>Xidian University</i> ); Yuhui Ren, Fuwei Wang, Ke Li ( <i>Northwest University</i> )	
<b>Poster Abstract: Algorithm for Distributed Duty Cycle Adherence in Multi-Hop RPL Networks</b> . .	<b>369</b>
Dries Van Leemput ( <i>IDLab Ghent University - imec</i> ); Armand Naessens ( <i>Ghent University</i> ); Robbe Elsas, Jeroen Hoebeke, Eli De Poorter ( <i>IDLab Ghent University - imec</i> )	
<b>Poster Abstract: Muscle-Mind: towards the Strength Training Monitoring via the Neuro-Muscular Connection Sensing</b> . . . . .	<b>371</b>
Aslan B. Wong, Dongliang Tu, ZiQi Huang ( <i>Shenzhen University</i> ); Xia Chen ( <i>University of Wisconsin-Milwaukee</i> ); Lu Wang, Kaishun Wu ( <i>Shenzhen University</i> )	
<b>Poster Abstract: Image Reconstruction and Compression in Ultrasound Tomography Using Discrete Cosine Transform</b> . . . . .	<b>373</b>
Konrad Kania ( <i>Lublin University of Technology</i> ); Mariusz Mazurek ( <i>Institute of Philosophy and Sociology of the Polish Academy of Sciences</i> ); Tomasz Rymarczyk ( <i>University of Economics and Innovation in Lublin and R&amp;D Center Netrix S.A. Lublin</i> ); Tomasz Cieplak, Grzegorz Kłosowski ( <i>Lublin University of Technology</i> ); Konrad Gauda ( <i>University of Economics and Innovation in Lublin</i> )	
<b>Poster Abstract: Identifying Bluetooth Low Energy Devices</b> . . . . .	<b>375</b>
Daniel Nilsson, Wenqing Yan ( <i>Uppsala University</i> )	
<b>Poster Abstract: Determining Position of People in Closed Spaces using Radio Tomography Imaging</b> . . . . .	<b>377</b>
Michał Styła, Andrzej Zawadzki ( <i>Research and Development Center Information Technology, Poland</i> ); Tomasz Cieplak ( <i>Department of Organization of Enterprise, Faculty of Management, Lublin University of Technology</i> ); Przemysław Adamkiewicz ( <i>University of Economics and Innovation, Lublin, Poland</i> )	

<b>Poster Abstract: Diagnosing Cardiovascular Diseases with Machine Learning on Body Surface Potential Mapping Data</b> . . . . .	<b>379</b>
Dariusz Wójcik ( <i>Research and Development Center Netrix S.A, Lublin, ul. Związkowa 26</i> ); Tomasz Rymarczyk ( <i>University of Economics and Innovation in Lublin</i> ); Michał Oleszek, Łukasz Maciura ( <i>Research and Development Center Netrix S.A, Lublin, ul. Związkowa 26</i> ); Piotr Bednarczuk ( <i>University of Economics and Innovation in Lublin</i> )	
<b>Poster Abstract: ElastiCL: Elastic Quantization for Communication Efficient Collaborative Learning in IoT</b> . . . . .	<b>382</b>
Bharath Sudharsan ( <i>Confirm SFI Research Centre for Smart Manufacturing, Data Science Institute, NUI Galway, Ireland</i> ); Dhruv Sheth ( <i>Edge Impulse, San Jose, California, USA</i> ); Shailesh Arya ( <i>Nirma University, Ahmedabad, Gujarat, India</i> ); Federica Rollo ( <i>'Enzo Ferrari' Engineering Department, University of Modena and Reggio Emilia, Italy</i> ); Piyush Yadav ( <i>Insight SFI Research Centre for Data Analytics, Data Science Institute, NUI Galway, Ireland</i> ); Pankesh Patel ( <i>Artificial Intelligence Institute, University of South Carolina, Columbia, USA</i> ); John G. Breslin ( <i>Confirm SFI Research Centre for Smart Manufacturing, Data Science Institute, NUI Galway, Ireland</i> ); Muhammad Intizar Ali ( <i>School of Electronic Engineering, Dublin City University, Ireland</i> )	
<b>Poster Abstract: On Utilizing Smartphone Time-of-Flight Sensors to Detect Hidden Spy Cameras</b> . . . . .	<b>384</b>
Sriram Sami, Sean Rui Xiang Tan, Bangjie Sun ( <i>National University of Singapore</i> ); Jun Han ( <i>Yonsei University</i> )	
<b>Poster Abstract: ECSRL: A Learning-Based Scheduling Framework for AI Workloads in Heterogeneous Edge-Cloud Systems</b> . . . . .	<b>386</b>
Changyao Lin, Ziyang Zhang ( <i>Harbin Institute of Technology</i> ); Huan Li, Jie Liu ( <i>Harbin Institute of Technology (Shenzhen)</i> )	
<b>Poster Abstract: Ultrasound Tomography for Monitoring the Lower Urinary Tract</b> . . . . .	<b>388</b>
Dariusz Wójcik ( <i>Research and Development Center Netrix S.A, Lublin, ul. Związkowa 26</i> ); Tomasz Rymarczyk ( <i>University of Economics and Innovation in Lublin</i> ); Edward Kozłowski ( <i>Lublin University of Technology</i> ); Michał Gołębek ( <i>Research and Development Center Netrix S.A, Lublin, ul. Związkowa 26</i> ); Mirosław Guzik ( <i>University of Economics and Innovation in Lublin</i> )	
<b>Poster Abstract: Can Image Style Transfer Save Automotive Radar?</b> . . . . .	<b>391</b>
Jianning Deng ( <i>University of Edinburgh</i> ); Kaiwen Cai ( <i>University of Liverpool</i> ); Chris Xiaoxuan Lu ( <i>University of Edinburgh</i> )	
<b>Poster Abstract: Pseudo Random Binary Sequence Excitation for Electrical Impedance Tomography</b> . . . . .	<b>393</b>
Oleksii Hyka, Andres Vejar ( <i>Research &amp; Development Centre Netrix S.A. Lublin, Poland</i> ); Tomasz Rymarczyk ( <i>University of Economics and Innovation Projektowa 4 Lublin Lubelskie Poland 20-209</i> )	
<b>Poster Abstract: Enabling Elasticity on the Edge using Heterogeneous Gateways</b> . . . . .	<b>395</b>
Nabeel Nasir, Bradford Campbell ( <i>University of Virginia</i> )	
<b>Poster Abstract: Adaptive Video Transmission Strategy Based on Ising Machine</b> . . . . .	<b>397</b>
Bo Wei ( <i>Waseda University</i> ); Hang Song ( <i>The University of Tokyo</i> ); Jiro Katto ( <i>Waseda University</i> )	



<b>Poster Abstract: Social Distancing Compliance Monitoring for COVID-19 Recovery Through Footstep-Induced Floor Vibrations</b> . . . . .	399
Yiwen Dong ( <i>Stanford University</i> ); Yuyan Wu ( <i>University of Science and Technology of China</i> ); Haeyoung Noh ( <i>Stanford University</i> )	
<b>Poster Abstract: Throughput Maximization in Low-Power IoT Networks via Tuning the Size of the TSCH Slotframe</b> . . . . .	401
Omid Tavallaie ( <i>The University of Sydney</i> ); Javid Taheri ( <i>Karlstad University</i> ); Albert Zomaya ( <i>The University of Sydney</i> )	
<b>PhD Forum Session</b>	
<b>PhD Forum Abstract: Robust and Affordable Deep Learning Models for Multimodal Sensor Fusion</b> . . . . .	403
Sanju Xaviar ( <i>University of Alberta</i> )	
<b>PhD Forum Abstract: ECCO-Box - An Edge Computing and Connectivity Framework</b> . . . . .	405
Jannik Blähser ( <i>TH Köln</i> )	
<b>PhD Forum Abstract: Privacy-Preserving Mechanisms for Heterogeneous Data Types</b> . . . . .	407
Mariana Cunha ( <i>University of Porto</i> )	
<b>PhD Forum Abstract: Untangling the Cloud from Edge Computing for IoT</b> . . . . .	409
Nabeel Nasir ( <i>University of Virginia</i> )	
<b>PhD Forum Abstract: Decentralised and Scalable Security for IoT Devices</b> . . . . .	411
Munkenyi Mukhandi ( <i>University of Coimbra</i> )	
<b>Workshop - AIChallengeloT 21</b>	
<b>Federated Learning for Internet of Things</b> . . . . .	413
Tuo Zhang, Chaoyang He, Tianhao Ma, Lei Gao, Mark Ma, Salman Avestimehr ( <i>University of Southern California</i> )	
<b>OntoAugment: Ontology Matching through Weakly-Supervised Label Augmentation</b> . . . . .	420
Fabio Maresca ( <i>University of Naples Federico II</i> ); Gürkan Solmaz, Flavio Cirillo ( <i>NEC Laboratories Europe</i> )	
<b>Better Never Than Late: Timely Edge Video Analytics Over the Air</b> . . . . .	426
Vinod Nigade, Ramon Winder, Henri Bal ( <i>VU Amsterdam</i> ); Lin Wang ( <i>VU Amsterdam &amp; TU Darmstadt</i> )	
<b>Exploring Co-dependency of IoT Data Quality and Model Robustness in Precision Cattle Farming</b> . . . . .	433
Franz Papst ( <i>TU Graz / CSH Vienna</i> ); Katharina Schodl ( <i>ZuchtData EDV-Dienstleistungen GmbH</i> ); Olga Saukh ( <i>TU Graz / CSH Vienna</i> )	
<b>Characterising the Role of Pre-Processing Parameters in Audio-based Embedded Machine Learning</b> . . . . .	439
Wiebke Toussaint ( <i>Delft University of Technology</i> ); Akhil Mathur ( <i>Nokia Bell Labs</i> ); Aaron Yi Ding ( <i>Delft University of Technology</i> ); Fahim Kawsar ( <i>Nokia Bell Labs</i> )	
<b>Device or User: Rethinking Federated Learning in Personal-Scale Multi-Device Environments</b> . .	446
Hyunsung Cho ( <i>Carnegie Mellon University</i> ); Akhil Mathur, Fahim Kawsar ( <i>Nokia Bell Labs</i> )	

<b>Decentralized Federated Learning Framework for the Neighborhood: A Case Study on Residential Building Load Forecasting</b> . . . . .	<b>453</b>
Jiechao Gao ( <i>University of Virginia</i> ); Wenpeng Wang ( <i>Computer Science Department, University of Virginia, Virginia, USA</i> ); Zetian Liu, Md Fazlay Rabbi Masum Billah, Brad Campbell ( <i>University of Virginia</i> )	
<b>Sensor Virtualization for Efficient Sharing of Mobile and Wearable Sensors</b> . . . . .	<b>460</b>
Jian Xu ( <i>Stony Brook University</i> ); Arani Bhattacharya ( <i>IIIT-Delhi</i> ); Aruna Balasubramanian ( <i>Stony Brook University</i> ); Donald E. Porter ( <i>UNC Chapel Hill</i> )	
<b>Deep Contextualized Compressive Offloading for Images</b> . . . . .	<b>467</b>
Bo Chen ( <i>University of Illinois at Urbana-Champaign</i> ); Zhisheng Yan ( <i>George Mason University</i> ); Hongpeng Guo, Zhe Yang ( <i>University of Illinois at Urbana-Champaign</i> ); Ahmed Ali-Eldin ( <i>Chalmers University of Technology and UMass Amherst</i> ); Prashant Shenoy ( <i>University of Massachusetts Amherst</i> ); Klara Nahrstedt ( <i>University of Illinois at Urbana-Champaign</i> )	
<b>Vision Paper: Towards Software-Defined Video Analytics with Cross-Camera Collaboration</b> . . .	<b>474</b>
Juheon Yi ( <i>Seoul National University</i> ); Chulhong Min ( <i>Nokia Bell Labs</i> ); Fahim Kawsar ( <i>Bell Labs</i> )	
<b>Through-Screen Visible Light Sensing Empowered by Embedded Deep Learning</b> . . . . .	<b>478</b>
Hao Liu, Hanting Ye, Jie Yang, Qing Wang ( <i>Delft University of Technology</i> )	
<b>AI-assisted Cell-Level Fault Detection and Localization in Solar PV Electroluminescence Images</b> .	<b>485</b>
Ahan M R, Akshay Nambi, Tanuja Ganu, Dhananjay Nahata, Shivkumar Kalyanaraman ( <i>Microsoft Research</i> )	
<b>Workshop - BlockSys'21</b>	
<b>Experimental Scalability Study of Consortium Blockchains with BFT Consensus for IoT Automotive Use Case</b> . . . . .	<b>492</b>
Luc Gerrits, Cyril Naves Samuel, Roland Kromes, François Verdier ( <i>University Côte-d'Azur</i> ); Severine Glock, Patricia Guitton-Ouhamou ( <i>Renault Software Labs</i> )	
<b>The convergence of Blockchain and Machine Learning for Decentralized Trust Management in IoT Ecosystems</b> . . . . .	<b>499</b>
Tharindu Ranathunga, Alan McGibney, Susan Rea ( <i>Munster Technological University</i> )	
<b>Detecting Compromised Edge Smart Cameras using Lightweight Environmental Fingerprint Consensus</b> . . . . .	<b>505</b>
Deeraj Nagothu, Ronghua Xu, Yu Chen ( <i>Binghamton University</i> ); Erik Blasch, Alexander Aved ( <i>The U.S. Air Force Research Laboratory Rome, New York, USA</i> )	
<b>A Blockchain and Machine Learning based Framework for Efficient Health Insurance Management</b> . . . . .	<b>511</b>
Adit Goyal ( <i>Department of Computer Science &amp; Engineering and IT, JIIT, Noida, India</i> ); Anubhav Elhence ( <i>Department of Electrical and Electronics Engineering, BITS Pilani, Pilani Campus</i> ); Vinay Chamola ( <i>Department of Electrical and Electronics Engineering, BITS Pilani, Pilani Campus, India</i> ); Biplob Sikdar ( <i>National University of Singapore</i> )	
<b>Blockchain-based Decentralized Service Provisioning in Local 6G Mobile Networks</b> . . . . .	<b>516</b>
Taras Maksymyuk ( <i>Lviv Polytechnic National University, Lviv, Ukraine</i> ); Marcel Volosin, Juraj Gazda ( <i>Technical University of Kosice, Slovakia</i> ); Madhusanka Liyanage ( <i>University College Dublin, Ireland / University of Oulu, Finland</i> )	

## Workshop - DATA'21

### **Dataset: Thermal Energy Harvesting Profiles in Residential Settings . . . . . 520**

Victor Ariel Leal Sobral (*University of Virginia*); John Lach (*The George Washington University*);  
Jonathan L. Goodall, Bradford Campbell (*University of Virginia*)

### **Dataset: Enabling Offline Tuning of Fat Channel Communication . . . . . 524**

Konrad-Felix Krentz, Padmal Madhushanka, Bappaditya Mandal, Robin Augustine, Thiemo Voigt  
(*Uppsala universitet*)

### **Person Re-ID Testbed with Multi-Modal Sensors . . . . . 526**

Guangliang Zhao, Guy Ben-yosef, Jianwei Qiu, Yang Zhao, Prabhu Janakaraj, Sriram Boppana,  
Austars R Schnore (*General Electric Research*)

### **Dataset: Container Escape Detection for Edge Devices . . . . . 532**

James Pope, Francesco Raimondo (*University of Bristol*); Vijay Kumar (*Toshiba Europe Limited*);  
Ryan McConville, Robert Piechocki, George Oikonomou (*University of Bristol*); Thomas Pasquier  
(*University of British Columbia*); Bo Luo, Dan Howarth (*Smartia Ltd*); Ioannis Mavromatis, Pietro Carnelli,  
Adrian Sanchez-Mompo, Theodoros Spyridopoulos, Aftab Khan (*Toshiba Europe Limited*)

### **Dataset: Analysis of IFTTT Recipes to Study How Humans Use Internet-of-Things (IoT) Devices . 537**

Haoxiang Yu, Jie Hua, Christine Julien (*University of Texas at Austin*)

### **Dataset: Motion Tracklet Oriented 6-DoF Inertial Tracking Using Commodity Smartphones . . . 542**

Peize Li, Chris Xiaoxuan Lu (*University of Edinburgh*)

### **Footstep-Induced Floor Vibration Dataset: Reusability and Transferability Analysis . . . . . 546**

Zhizhang Hu, Yue Zhang, Shijia Pan (*University of California, Merced*)

### **Dataset: A Low-resolution infrared thermal dataset and potential privacy-preserving applications . . . . . 552**

Shuai Zhu, Thiemo Voigt, Daniel F. Perez-Ramirez, Joakim Eriksson (*RISE Research Institutes of Sweden*)

### **Dataset: Longitudinal personal thermal comfort preference data in the wild . . . . . 556**

Matias Quintana, Mahmoud Abdelrahman, Mario Frei (*National University of Singapore*);  
Federico Tartarini (*Berkeley Education Alliance for Research in Singapore*); Clayton Miller (*National University of Singapore*)

### **Dataset: Large-scale Urban IoT Activity Data for DDoS Attack Emulation . . . . . 560**

Arvin Hekmati, Eugenio Grippo, Bhaskar Krishnamachari (*University of Southern California*)

### **Dataset: Environmental Impact on the Long-Term Connectivity and Link Quality of an Outdoor LoRa Network . . . . . 565**

Pei Tian (*Shanghai Advanced Research Institute, CAS*); Fengxu Yang (*Shanghai Advanced Research Institute, CAS & ShanghaiTech University*); Xiaoyuan Ma (*SKF Group, China*); Carlo Alberto Boano (*Graz University of Technology*); Xin Tian (*Shanghai Advanced Research Institute, CAS*); Ye Liu (*Nanjing Agricultural University*); Jianming Wei (*Shanghai Advanced Research Institute, CAS*)

## Workshop - ENSsys 2021

### **Autonomous Energy Status Sharing and Synchronization for Batteryless Sensor Networks . . . . 569**

Alessandro Torrisi, Kasim Sinan YILDIRIM, Davide Brunelli (*University of Trento*)

<b>Persistent Timekeeping Using Harvested Power Measurements . . . . .</b>	<b>572</b>
Eren Yildiz ( <i>Ege University</i> ); Kasim Sinan Yildirim ( <i>University of Trento</i> )	
<b>Joint Energy Management for Distributed Energy Harvesting Systems . . . . .</b>	<b>575</b>
Naomi Stricker ( <i>ETH Zurich</i> ); Yingzhao Lian ( <i>EPFL</i> ); Yuning Jiang ( <i>EPLF</i> ); Colin N. Jones ( <i>EPFL</i> ); Lothar Thiele ( <i>ETH Zurich</i> )	
<b>RESERVE: Remote Attestation of Intermittent IoT devices . . . . .</b>	<b>578</b>
Md Masoom Rabbani ( <i>ES&amp;S, imec-COSIC, ESAT, KU Leuven</i> ); Edlira Dushku ( <i>DTU Compute, Technical University of Denmark</i> ); Jo Vliegen ( <i>ES&amp;S, imec-COSIC, ESAT, KU Leuven</i> ); An Braeken ( <i>Faculty of Engineering, Vrije Universiteit Brussel (VUB)</i> ); Nicola Dragoni ( <i>DTU Compute, Technical University of Denmark</i> ); Nele Mentens ( <i>ES&amp;S, imec-COSIC, ESAT, KU Leuven and LIACS, Leiden University</i> )	
<b>Designing a General Purpose Development Platform for Energy-harvesting Applications . . . . .</b>	<b>581</b>
Nurani Saoda, Md Fazlay Rabbi Masum Billah, Brad Campbell ( <i>University of Virginia</i> )	
<b>Demo Abstract: Energy-Aware Battery-Less Bluetooth Low Energy Device Prototype Powered By Ambient Light . . . . .</b>	<b>584</b>
Ashish Kumar Sultania, Jeroen Famaey ( <i>University of Antwerp - imec</i> )	
<b>Demo Abstract: Demonstration of an Energy-Aware Task Scheduler for Battery-Less IoT Devices . . . . .</b>	<b>586</b>
Adnan Sabovic, Ashish Kumar Sultania, Jeroen Famaey ( <i>IDLab, University of Antwerp - imec</i> )	
<b>Demo Abstract: A Simulation and Prototyping Toolkit for Airflow Energy Harvesting in Vehicles . . . . .</b>	<b>588</b>
Jung Wook Park, Alishan Hassan, Tingyu Cheng, Rosa Arriaga ( <i>Georgia Institute of Technology</i> ); Gregory Abowd ( <i>Northeastern University</i> )	
<b>Demo Abstract: Powering an E-Ink Display from Soil Bacteria . . . . .</b>	<b>590</b>
Gabriel Marcano, Pat Pannuto ( <i>UC San Diego</i> )	
<b>Demo Abstract: RF Power Transmission: Energy Harvesting for Self-Sustaining Miniaturized Sensor Nodes . . . . .</b>	<b>592</b>
Federico Villani, Philipp Mayer, Michele Magno ( <i>ETH Zurich</i> )	
<b>Demo Abstract: A Battery-Free Long-Range Wireless Smart Camera for Face Recognition . . . . .</b>	<b>594</b>
Marco Giordano ( <i>ETH Zürich</i> ); Michele Magno ( <i>ETH Zurich</i> )	
 <b>Workshop - NanoCoCoA 2021</b>	
<b>A Machine Learning Approach for Abnormality Detection in Blood Vessels via Mobile Nanosensors . . . . .</b>	<b>596</b>
Jorge Torres Gómez, Anke Kuestner, Ketki Pitke ( <i>TU Berlin</i> ); Jennifer Simonjan ( <i>Silicon Austria Labs</i> ); Bige Deniz Unluturk ( <i>Michigan State University</i> ); Falko Dressler ( <i>TU Berlin</i> )	
<b>Enabling Protein Interactions Using Terahertz Signals for Intra-body Communication . . . . .</b>	<b>603</b>
Hadeel Elayan ( <i>University of Toronto</i> ); Andrew W. Eckford ( <i>York University</i> ); Raviraj Adve ( <i>University of Toronto</i> )	

<b>Modulated Molecular Channel Coding Scheme for Multi-Bacterial Transmitters . . . . .</b>	<b>610</b>
Daniel P. Martins, Jennifer Drohan ( <i>VistaMilk Research Centre</i> ); Sarah Foley, Lee Coffey ( <i>Pharmaceutical and Molecular Biotechnology Research Centre</i> ); Sasitharan Balasubramaniam ( <i>University of Nebraska-Lincoln</i> )	
<b>Dynamic application mapping on CTH network: a performance-centric approach . . . . .</b>	<b>616</b>
Avik Bose, Prasun Ghosal ( <i>Indian Institute of Engineering Science and Technology, Shibpur</i> )	
<b>An analytical framework for Reconfigurable Intelligent Surfaces placement in a mobile user environment . . . . .</b>	<b>623</b>
Gorgos Stratidakis, Sotiris Droulias, Angeliki Alexiou ( <i>University of Piraeus</i> )	
<b>Design Exploration and Scalability Analysis of a CMOS-Integrated, Polymorphic, Nanophotonic Arithmetic-Logic Unit . . . . .</b>	<b>628</b>
Venkata Sai Praneeth Karempudi ( <i>University of Kentucky Lexington, Kentucky, USA</i> ); Shreyan Datta ( <i>National Institute of Technology Durgapur, India</i> ); Ishan Thakkar ( <i>University of Kentucky Lexington, Kentucky, USA</i> )	
<b>Coordinating a Swarm of Micro-Robots Under Lossy Communication . . . . .</b>	<b>635</b>
Razanne Abu-Aisheh ( <i>Nokia Bell Labs, France</i> ); Francesco Bronzino ( <i>Université Savoie Mont Blanc, France</i> ); Myriana Rifai, Lou Salaün ( <i>Nokia Bell Labs, France</i> ); Thomas Watteyne ( <i>Inria, France</i> )	
<b>On-Demand SIMO Channel Impulse Response Shaping in Smart On-Chip Electromagnetic Environments . . . . .</b>	<b>642</b>
Mohammadreza F. Imani ( <i>ECEE, Arizona State University</i> ); Sergi Abadal ( <i>N3Cat, Universitat Politècnica de Catalunya</i> ); Philipp del Hougne ( <i>IETR, CNRS - Univ. Rennes</i> )	
<b>Cardiac Bio-Nanonetwork: Extracellular Matrix Modeling for the Propagation of Extracellular Vesicles . . . . .</b>	<b>645</b>
Hamid Khoshfekar Rudsari ( <i>Oslo University Hospital &amp; University of Oslo</i> ); Mladen Veletic, Jacob Bergsland ( <i>Oslo University Hospital</i> ); Ilanko Balasingham ( <i>Oslo University Hospital &amp; Norwegian University of Science &amp; Technology</i> )	
<b>Mitigating the Retroactivity Impact on Molecular Communications . . . . .</b>	<b>649</b>
Francesca Ratti, Maurizio Magarini ( <i>Politecnico di Milano</i> ); Hamdan Awan ( <i>Waterford Institute of Technology</i> )	
<b>Author index . . . . .</b>	<b>653</b>

## 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.