Report on the 5th Workshop of the NSF mmW RCN

January 28-29, 2019

North Carolina State University, Raleigh

Executive Summary: The 5rd workshop of the NSF RCN (research coordination network) on mmW (millimeter-wave) wireless (RF frequencies between 30 GHz and 300 GHz) networks was held on Jan 28-29, 2019 on the campus of the North Carolina State University in Raleigh. Steering committee member Ismail Guvenc was responsible for the local arrangements. The workshop started with introductory remarks by Guvenc reminding the attendees of the premise of the RCN: to create a platform for academic-industrial and cross-disciplinary collaboration in the three key research areas driving mmW technology: i) communications and signal processing (CSP) techniques, ii) networking (NET) protocols, and ii) hardware (HW) design, including antennas, mmW circuits, and data converters.

Building on the discussions from the previous workshops and recent development, three main themes were emphasized in the 5th workshop, which were reflected in the panels and breakouts:

- Research and Technology Roadmap for RCN contributions at the HW-CSP interface
- Research and Technology Roadmap for RCN contributions at the CSP-NET interface
- Development of Cost-Effective Community Testbeds

Several significant recent developments were noted, including:

- The developments on the 3GPP 5G NR (new standard)
- Ongoing work and results from prototype testbeds and trials
- Opening of new spectrum and interest in higher frequency bands

The importance of cross-disciplinary research continued to resonate with the attendees as evident from the panel and breakout discussions at the interface topics. In particular:

- CSP-HW research for development of new beamforming architectures, prototypes and testbeds.
- CSP-NET research for development of new network simulation tools by augmenting the ns-3 simulator with mmW physical layer.
- Development of channel models with new channel measurements from the viewpoint of standard development and accurate network performance prediction. In particular, capturing temporal channel dynamics in accurate network simulation.
- Integrated communication and sensing.
- Autonomous vehicles – considered by some as a killer app for mmW technology – was identified as an important use case that drives many of the cross-disciplinary research challenges
- The use of machine learning techniques was also noted as a promising direction.

Conclusions and Action Items for Next Steps before the 6th Workshop: Given the interest from the first four workshops, formation of working groups for the following areas would be useful for continuing the work between workshops and to make the workshops more effective:

- HW-CSP interface, in particular prototype and testbed development
- CSP-NET interface, in particular network simulation tools
- Channel modeling and measurement (in collaboration with NIST 5G Channel Model Alliance)
- Emerging mmW standards, including 5G NR and WiGig/802.11ay
- Moonshot problems for 2020-2025 to galvanize academic-industry collaboration

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Summary of Key Activities and Outcomes from the Workshop

Day 1: Monday, Jan 28, 2019

Keynote 1: The workshop was kicked off by an informative and engaging keynote presentation by **Dr. Sanyogita Shamsunder**, VP Ecosystems & Innovation at Verizon. Dr. Shamsunder's presentation summarized recent activities at Verizon regarding initial 5G mmW trials and deployments. She presented few preliminary results from the trials that show that the coverage of 5G mmW deployments are satisfactory. She also identified industrial IoT as the enabling application for 5G mmW systems in the immediate future.

Panel 1: State of mmW Technology and Outlook: A View from Industry

Moderator: I. Guvenc (NSCU); **Panelists:** Ozge Koymen (Qualcomm), Carlos Cordiero (Intel), Kate Remley (NIST), and Joonyoung Cho (Samsung)

Summary of Key Discussion Points, Takeaways, and Future Tasks: There has been a tremendous development of mmWave research in the last few years. The first 3GPP standard is complete, vendors have demonstrated complete systems, operators have announced trials and the FCC has opened up spectrum. Given this context, the panel addressed the following three questions.

- Is mmWave now more of engineering challenge than a research challenge?
- What should we expect by the end of 2019 on products and services?
- What is the role of universities? How can they contribute given the huge investments already made in industry?

The panelists agreed that there are still many research challenges to be addressed. The trials from vendors such as AT&T and Verizon are still fairly small. Although the results are promising, the performances are still far from what will be needed to fully realize the potentials of 5G technology. Panelists Ozge Koymen also presented a timeline of expected 5G mmWave products among the over 30 commercial 5G mobiles devices planned to be launched by middle of 2019. He also presented the spectrum allocation/usage plan in the 24-28 GHz, 37-40 GHz, and 64-71 GHz space around the world. Panelist Carlos Cordiero identified several compelling use cases including fixed wireless access, video/AR/VR delivery, connected vehicles, and industrial IoT. He also said that the following five common myths about mmWave *have been dispelled*: (i) build a mmWave radio and they will come, (ii) it only works in line-of-sight channels, (iii) range is limited to few tens of meters, (iv) power consumption is too large for small form factor devices, and (v) cost is too large for consumer devices. Panelist Cho was optimistic about mmWave deployments. His companies is focusing on moving trains, autonomous cars, and autonomous driving as the key applications for this technology.

Poster Sessions: Three poster sessions, two with 14 posters and one with 15, were held sequentially (one before lunch, one after lunch, and one after the breakout sessions) with an hour dedicated to each poster session. The poster sessions spanned the whole range on ongoing research in the three areas as well as prototypes and testbeds. A list of posters and authors is provided in Appendix C.

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Demonstrations: There were four demonstrations. Industrial Technology Research Institute demonstrated M3FORCE: mmWave RF Module. NCSU demonstrated their 28 GHz channel sounder. NIST demonstrated their ray tracing-based channel simulator. Analog Devices gave a presentation on a 5G mmWave Basestation.

Breakout Sessions: Summary of Discussion Points, Takeaways and Future Tasks

The three breakout sessions were aimed at *interface* topics. Summary of discussion for the three breakouts is presented below.

HW-CSP Interface Breakout: Leaders: James Buckwalter (UCSB), Kate Remley (NIST), Rui Ma (Mitsubishi Electric), Mark Rodwell (UCSB), and Dave Matolak (U. South Carolina).

Research problems to be addressed at the intersection of hardware and antenna design and communication and signal processing techniques. Build on the discussions from previous workshops.

Panelist Rui Ma argued that GaN devices are suitable for dense urban to rural deployments, especially for high-power M-MIMO power amplifiers. He also mentioned that low-power MMICs are still an open challenge. Panelist Jim Buckwalter described some promising SiGe solutions for the mmWave bands. Panelist Mark Rodwell presented some design challenges in the 140-340 GHz spectrum. Not much research has been done in this spectrum, although it is a very interesting spectrum for ultra-compact imaging using drones because of the large spectrum availability and massive number of parallel channels. The panelists identified major research challenges as the large computational complexity of massive spatial multiplexing, the need for ultra-high resolution imaging systems, high-frequency parasitics, and gaining FCC access to useful frequency bands. The other major challenges include training models for students across the interface boundaries, need for packaging an foundry service for mmWave hardware prototyping and testing, and the need for repository to capture hardware designs.

CSP-NET Interface Breakout: Leaders: Marco Mezzavilla (NYU), Ismail Guvenc (NCSU), Kim Mahler (Fraunhofer HHI), Michele Polese (U. Padova), Tanguy Ropitault (NIST), and Jing Zhu (Intel)

Research problems to be addressed at the intersection of communication and signal processing and networking techniques; including the role of channel models and testbeds. In particular, the role of accurate physical layer and channel models in end-to-end network simulations (using the ns-3 platform, e.g.). Builds on the issues and challenges identified in previous workshops.

The session began with a discussion on two NSF mid-scale infrastructure solicitations, and reviewed the deadlines, scope, budgets, among other logistics. A survey link was provided where participants could fill their capabilities in community infrastructure efforts. Marco Mezzavilla (NYU) the described the end-to-end mmW network simulator, referring to their IEEE COMST paper on the same topic. Beam tracking, integrated access and backhaul, 3GPP CSI-RS are implemented in the simulator. Ongoing efforts related to simulator include integration of robotic control, drone traces, aerial communications, and vehicular communications. In the future, simulation framework from Interdigital will also be integrated, including new error models and scalability aspects.

Michele Polese (University of Padova) discussed about three different channel modeling approaches and talked about how the computational complexity in Matlab increases linearly with the number of

antenna elements. How to simulate complex environments with a lot of different obstacles and objects is a challenge. Since mmW channels are more reflective, there will be more NLOS channel reflections (hence the problems in scalability).

One possible solution is to develop some benchmark scenarios (similar to a look up table), upload them somewhere, and make them available for the community to access (e.g. urban scenario benchmarks). However, the computation of the beamforming gain is the main complexity even when such a lookup table is available.

Next, Jing Zhu from Intel took the stage to talk about two trends. Trend-1 is on edge computing (MEC), where ETSI has been working on defining a framework for MEC. Trend-2 is multi-access/radio convergence. In the generic multi-access convergence, different technologies have their own link layers, and we need a generic convergence layer above all these to merge the link layers from multiple different technologies in a controlled manner. Network transformation is necessary and critical for handling new features and requirements emerging with 5G technologies (low latency, high reliability, high data rate, etc.), and multi-access convergence helps in this direction.

Kim Mahler from Fraunhofer Institute presented slides on machine learning for future networks including 5G, based on his participation in a related ITU activity. First, he polled people in the audience who have been using machine learning for wireless research. Several people in the audience briefly explained about how they use machine learning in different contexts for wireless communications. It was commented that a main limitation for mmW is the availability of data sets. Kim later on discussed about the focus group in ITU to study use of ML for wireless: they have been working on it for a year under ITU, may extend further. So far there have been 4 meetings, fifth one to be in China in March 2019. There are three working group activities: 1) use cases, services, requirements, 2) data formats and ML technology, 3) ML-aware network architecture. Use case categorization includes ML objective (classification, clustering, prediction, inference), cost associated with architectural changes, cost associated with ML data, network domain use cases (Application/Service Domain, Core Network Domain, Transport Network Domain, Access Network Domain, End-to-End Network), and network phase use cases (Planning and Design, Deployment, Provisioning, Operation and Management, Maintenance). In total, 23 specific use cases have been identified for use of ML for wireless. For example, use case 20 is on big-data aided channel modeling and prediction, while use case 3 is on ML-based mobility pattern prediction. Jing from Intel asked about the goals and the outcome, and Kim responded that the goal is to come up with standardization gaps for study group 13.

Development of Cost-Effective Community Testbeds: **Leaders:** Brian Floyd (NCSU), Dan Baker (NI), Kira Theuer (NI), Manu Gosain (Northeastern, PAWR PPO), and Arjuna Madanayake (FIU)

Discussion of the feasible pathways for developing flexible and cost-effective testbeds to enable research and experimentation in mmWave. The testbed would: i) enable experimentation and optimization at all layers, ii) have a modular structure to swap different components (e.g, antennas, RF chains), iii) enable end-to-end experimentation in a network setting; and iv) have an intuitive graphical user interface. The objective is for the RCN community to create a roadmap of activities to generate a concrete proposal and a team of researchers to execute it. Builds on discussions from the 4th workshop.

The key questions are: (i) why do we need a testbed?, (ii) what are the hurdles in developing a community testbed?, (iii) what are the key applications for this testbed?, (iv) what frequency range of operation is important for the testbed?, and (v) what are the most important features?

First, participants gave brief overview of various research testbeds possibly available to the community including PAWR COSMOS, FIU's mmWave vehicular communication testbed, X60 phase arrays, CORNET, Idaho National Lab's Wireless Network Testbed, NYU's wireless open research testbed, etc. National Instruments mentioned that it is already building a lot of "boring parts" of the testbed so that the researchers can focus on the more interesting parts. The participants agreed that a testbed needs to have a long-term vision (say 10-year vision). The panelists also agreed that there are a lot of research topics in this area. The topics include:

- High mobility scenario such as in vehicular situation
- Reconfigurable hardware for array processing
- Mixed signal design
- MAC layer optimization
- Spectrum sharing
- Low-latency support for interactive applications
- mmWave sensing
- etc.

Day 2: Friday, Jan 19 2018

Keynote 2: The second day started with an informative keynote presentation by Dr. Timothy Hancock, program manager, DARPA Microsystems Technology Office, entitled *Application of Heterogenous Integration to Advanced Transceivers and Millimeter Wave Phased Arrays.*

Readouts from Breakout Sessions: J. Buckwalter (HW-CSP), M. Mezzavilla (CSP-NET), B. Floyd (community testbeds) – see the above discussion summaries for the breakouts.

The Panel 2 Discussion was primed by readouts of the breakout session discussions.

Panel 2: Academic-Industry Collaboration for "Moonshot" RCN Contributions

Moderators: Brian Floyd (NCSU) and Ismail Guvenc (NCSU).

Panelists: Carlos Cordeiro (Intel), Ozge Koymen (Qualcomm), Nada Golmie (NIST), Joonyoung Cho (Samsung), Dan Mittleman (Brown), Tim Hancock (DARPA)

Summary of Key Discussion Points, Takeaways, and Future Tasks: The moderator encouraged the panelists to be bold and noted the diversity of the panel. Several interesting responses were offered to the opening question to the panelists: *What moonshot problem will drive innovation and/or new applications?* These included

- Integration of communication and computing to meet delay and energy requirements
- Bandwidth vs latency tradeoffs that vary with use cases
- The use of higher frequency bands above 100GHz

- Sustained (rather than peak) Gbps data rates
- Business models and economic considerations
- Cross-layer and inter-operability issues for verticals
- New uses cases for driving innovation

The panel began with a discussion on "what will 6G be?" In particular, what will be the frequency band for 6G? We will need channel characterization and device development in those bands pretty soon. Since 6G will most likely focus on higher frequency bands, there needs to be greater focus on increase spatial bandwidth. Massive MIMO, if done right, may be good solution approach.

Integrated communication and sensing, including radar and channel estimates, was noted as a promising direction for new use cases.

Enabling mobile networks at mmW frequencies was noted as necessary for disruptive innovations.

A particular use case of interest – considered a killer app by some – is autonomous vehicles which will not only require high rates and low latency but would also benefit from integrated communication and sensing and many of the key operational functionalities enabled by mmW technology. Machine learning could also play an important role in this use case. 6G technologies may have leverage machine learning. Although killer applications for 5G are still to become evident, we have to start thinking about killer applications for 6G now.

Appendices: additional information on the summary provided in this report:

- Appendix A: Workshop agenda.
- Appendix B: List of attendees and affiliations, including the SC members and keynote speakers.
- Appendix C: List of posters and demos with names of authors and presenters.

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Appendix A: Workshop Agenda

Day 1: Monday, Jan 28, 2019

8:00am-8:45am: Registration and Breakfast (Duke Energy Hall A/B)

8:45am-9am: Welcome and Opening Remarks (Duke Energy Hall C/D) *slides*

9:00am-10:30am: Panel 1: State of mmW Technology and Outlook: A View from Industry (Duke Energy Hall C/D)

Moderator: Ismail Guvenc *slides*

Panelists: Ozge Koymen (Qualcomm, *slides*), Carlos Cordeiro (Intel, *slides*), Kate Remley (NIST), Joonyoung Cho (Samsung, *slides*)

Industry updates and discussion on technology advances, use cases, business models, regulations, and standardization.

10:30am-11:00am: **Keynote 1:** Dr. Sanyogita Shamsunder, VP – *5G Ecosystems & Innovation, Verizon* (Duke Energy Hall C/D)

11:00am-11:30am: **Coffee Break** (Duke Energy Hall A/B)

11:30am-12:30pm: Poster/Demo Session 1 (Duke Energy Hall A/B)

12:30pm-1:30pm: Lunch (Duke Energy Hall A/B)

1:30pm-2:30pm: Poster/Demo Session 2 (Duke Energy Hall A/B)

2:30pm-4:00pm: Breakout Sessions: Research and Technology Development Roadmap

Three Parallel Sessions

A. HW-CSP Interface: Hardware, Circuits, Antennas & Communication/Signal Processing & Prototypes/Testbeds (Duke Energy Hall C/D)

Discussion leaders: Jim Buckwalter (UCSB), Kate Remley (NIST), Rui Ma (Mitsubishi Electric), Mark Rodwell (UCSB), Dave Matolak (U. South Carolina) *slides*

Research problems to be addressed at the intersection of hardware and antenna design and communication and signal processing techniques, including development of prototypes and testbeds. Build on the discussions from previous workshops as part of the Technology Roadmap; https://mmwrcn.ece.wisc.edu/?page_id=724

B. CSP-NET Interface: Communication and Signal Processing & Networking (Teaching and Visualization Lab)

Discussion Leaders: Marco Mezzavilla (NYU), Ismail Guvenc (NCSU), Kim Mahler (Fraunhofer HHI), Michele Polese (U. Padova), Tanguy Ropitault (NIST), Jing Zhu (Intel)

Research problems to be addressed at the intersection of communication and signal processing and networking techniques; including the role of channel models and testbeds. In particular, the role of accurate physical layer and channel models in end-to-end network simulations (using the ns-3 platform, e.g.). Builds on the issues and challenges identified in the previous workshops; https://mmwrcn.ece.wisc.edu/?page_id=724

C. Development of Cost-Effective Community Testbeds for Research and Experimentation (Creativity Studio)

Discussion leaders: Brian Floyd (NCSU)**,** Dan Baker (NI), Kira Theuer (NI), Manu Gosain (Northeastern, PAWR PPO), Arjuna Madanayake (FIU) *slides*

Discussion of the feasible pathways for developing flexible and cost-effective testbeds to enable research and experimentation in mmW. The testbed would: i) enable experimentation and optimization at all layers, ii) have a modular structure to swap different components (e.g, antennas, RF chains), iii) enable end-to-end experimentation in a network setting; and iv) have an intuitive graphical user interface. The objective is for the RCN community to create a roadmap of activities to generate a concrete proposal and a team of researchers to execute it. Builds on discussions from earlier workshops; https://mmwrcn.ece.wisc.edu/?page_id=724; video link of the breakout session at the 4th workshop (NYU)

4:00pm-4:30pm: Coffee Break (Duke Energy Hall A/B)

4:30pm-5:30pm: Poster/Demo Session 3 (Duke Energy Hall A/B)

6:00pm: Dinner (Lonnie Poole Golf Course Dining)

Day 2: Tuesday, Jan 29, 2019

Day 2 Live Stream Link

8:00am-8:30am: Registration and Breakfast (Duke Energy Hall A/B)

8:30am-9:00am: Keynote 2: Application of Heterogenous Integration to Advanced Transceivers and Millimeter Wave Phased Arrays**, Dr. Timothy Hancock,** *DARPA Microsystems Technology Office* (Duke Energy Hall C/D) *slides*

9:00am-10:00am: Readout from Breakout Sessions (Duke Energy Hall C/D)

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CSP-NET Breakout, *Community Testbed Breakout*

10:00am-10:30am: Coffee Break (Energy Hall A/B)

10:30am-noon: Panel 2: Academic-Industry Collaboration for "Moonshot" mmW RCN Contributions (Duke Energy Hall C/D)

Moderators: Brian Floyd (NCSU) and Ismail Guvenc (NCSU) *slides*

Panelists: Carlos Cordeiro (Intel), Ozge Koymen (Qualcomm), Nada Golmie (NIST), Joonyoung Cho (Samsung)(*slides*), Dan Mittleman (Brown) (*slides*), Tim Hancock (DARPA)

Goals and Deliverables for RCN 2020 RCN 2025 (seeded by the preceding readout from breakouts)

noon-12:15pm: Closing Remarks (Duke Energy Hall C/D)

Parmesh Ramanathan, UW-Madison

12:15pm: Boxed lunch (Duke Energy Hall A/B)

Appendix B: List of Participants

Name	Institution
Mohammed Abdelghany	UCSB
Husheng Li	University of Tennessee Knoxville
Ahmed Alkhateeb	Arizona State University
Chethan Kumar Anjinappa	NC State University
Jacob Adams	NC State University
Ahmed I. Sulyman	Embry Riddle Aeronautical University
Jacob Chakareski,	University of Alabama
Aditya Dhananjay	NYU
Hao Xu	Univ. Nevada Reno
Ming Feng	Univ. Nevada Reno
Brian Floyd	NC State University
Sandeep Hari	NC State University
Tiantong Ren	NC State University
Yasaman Ghasempour	Rice University
Anant Gupta	UCSB
Subhanshu Gupta	WSU
Anoosheh Heidarzadeh	TAMU
Carlos Herranz	Universitat Politecnica de Valencia
Jesus Omar Lacruz	Imdea
Arjuna Madanayake	FIU
Nicolo Michelusi	Purdue
David W. Matolak	Univ. South Carolina
Soumyajit Mandal	Case Western University
Ahmed Ibrahim	FIU
Michele Polese	University of Padova
Michele Zorzi	University of Padova
Mattia Rebato	University of Padova
M. Rodwell	UCSB
Yavuz Yapici	NC State University
Swetank Kumar Saha	University at Buffalo
Shivang Aggarwal	University at Buffalo
Omid Semiari	Georgia Southern University
Georgios C. Trichopoulos	Arizona State University
Zongshen Wu	UW Madison
Han Yan	UCLA
Zhicheng Yang	UC Davis
Murat Yuksel	University of Central Florida
Masoud Zarifneshat	Michigan State University

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Ding Zhang	George Mason University
Marco Mezzavilla	New York University
Xiaomeng Wang	Stony Brook University
Xiaomin Meng	Sussex University
Chin-Ya Huang	NTUST
Dror Baron	NC State University
Arupjyoti Bhuyan	Idaho National Labs
Ren-Jr Chen	ITRI
Wen Chiang Chen	ITRI
Dan Baker	National Instruments
Hang Liu	Catholic University of America
Jim Buckwalter	UCSB
Nada Golmie	NIST
Tanguy Ropitault	NIST
Kate Remley	NIST
Carlos Cordeiro	Intel
Ali Sadri	Intel
Igor Alvarado	National Instruments
Ozge Koymen	Qualcomm
Kira Theuer	National Instruments
Panneer Selvam Santhalingam	George Mason University
Xin Wang	Stony Brook University
Bernard McKibben	Cable Labs
Balkan Kececioglu	Cable Labs
Sanjay Patel	Cable Labs
Abhimanyu Gosain	North Eastern University
Mohanad Mohsen	University of South Carolina
Jing Zhu	Intel
Kim Mahler	Fraunhofer HHI
Dimitrios Koutsonikolas	University at Buffalo
Tommy Azzino	NIST
Mustafa Aljumaily	University of Tennessee Knoxville
Theodore Rappaport	NYU
Daniel Mittleman	Brown University
Parth Pathak	George Mason University
Joonyoung Cho	Samsung
Munirah Boufarsan	NC State University
Tony Montalvo	Analog Devices
Zafer Sahinoglu	Mitsubishi Electric
Rui Ma	Mitsubishi Electric Research Labs

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Rudra Dutta	NC State University
Ozgur Ozdemir	NC State University
Fatih Erden	NC State University
Ismail Guvenc	NC State University
Moin Chowdhury	NC State University
Priyanka Sinha	NC State University
Mihail Sichitiu	NC State University
Alexandra Duel-Hallen	NC State University
Dong Kam	NC State University
Michael Steer	NC State University
Parmesh Ramanathan	UW Madison
Akbar Sayeed	NSF
Vuk Marojevic	Mississipi State University
John Oates	Analog Devices
Steven Gross	N/A
Timothy Hancock	DARPA
Carl Dietrich	Virginia Tech
Menglei Zhang	NYU
Taha Yekan	Metawave, Inc
Murali Rangachari	N/A
Sanyogita Shamsunder	Verizon

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Appendix C: Posters and Demonstrations

Demos: (Duke Energy Hall A/B)

- M3FORCE: 5G mmWave RF Module, Ren-Jr Chen and Wen Chiang Chen, Industrial Technology Research Institute, Taiwan.
- NCSU 28 GHz Channel Sounder, Ozgur Ozdemir and Ismail Guvenc.
- NIST's Ray Tracing Based Channel Simulator
- 5G Millimeter-Wave Basestation, John Oates, Vandita Raikar, Steve Dorn, Analog Devices.

Poster Session 1: 11:30am-12:30pm, 01/28/19 (Duke Energy Hall A/B)

1. Leveraging Machine Learning To Enable Mobility and Enhance Reliability in mmWave Systems, **Ahmed Alkhateeb**, Arizona State University
2. Cell Coverage in the Millimeter Wave Unmanned Aerial Vehicle Communications, Jingchao Bao, **Husheng Li**, and Dengfeng Sun, The University of Tennessee, Knoxville and Purdue University
3. MillimeterWave Communications and Edge Computing for Next Generation Tetherless Mobile Virtual Reality, **Jacob Chakareski** and Petar Popovski, University of Alabama and Aalborg University
4. Online Biologically Inspired Learning based Intelligent Multi-User mmWave MIMO Systems, **Ming Feng** and **Hao Xu**, University of Nevada, Reno
5. Signals and Systems for mm-Wave Sensing, **Anant Gupta** and Upamanyu Madhow, University of California, Santa Barbara
6. User Localization in MmWave Cells: A Non-Adaptive Quantitative Group Testing Approach based on Sparse Graph Codes, **Anoosheh Heidarzadeh**, Esmaeil Karimi, Fatemeh Kazemi, and Alex Sprintson, Texas A&M University
7. 30 GHz Path Loss Measurement and Modeling for Airport Surface Areas, Mohanad Mohsen, Alexander Grant, and **David W. Matolak**, University of South Carolina
8. Ray Tracing Investigation for Drone-assisted Out-of-Band Integrated Access and Backhaul Millimeter Wave Networks, Alberto Perez, Abdurrahman Fouda, and **Ahmed S. Ibrahim**, Florida International University
9. Antenna Optimization in mmWave Mobile Scenarios through Machine Learning, **Mattia Rebato**, Paolo Testolina, Mattia Lecci, **Michele Zorzi**, Jonathan Gambini, Roberto Flamini, and Christian Mazzucco, University of Padova, Italy and HUAWEI Technologies, Milan, Italy
10. Exploiting Short Wavelengths: Potential Application of 100-300GHz Carriers in Imaging and Massively Spatially Multiplexed Communications, **Rodwell**, UC Santa Barbara; A. Niknejad, UC Berkeley; H. Krishnaswamy, Columbia; D. Jena, A. Molnar, C. Studer, H. Xing, Cornell; D. Katabi,

MIT; S. Rangan, NYU; A. Arbabian, Stanford; E. Alon, B. Nikolic, V. Stojanovic, UC Berkeley; S. Chowdhury, UC Davis; G. Rebeiz, UC San Diego; J. Buckwalter, U. Madhow, U. Mishra, S. Stemmer, UC Santa Barbara; A. Molisch, H. Hashemi, USC; K. O, UT Dallas

11. Physical Layer Security for mmWave Drone Links with NOMA, Nadisanka Rupasinghe, **Yavuz Yapici**, **Ismail Guvenc**, Huaiyu Dai, and **Arupjyoti Bhuyan**, North Carolina State University and Idaho National Laboratory
12. AMuSe: An Agile Multipath TCP Scheduler for Dual-Band 802.11ad/ac Wireless LANs, **Swetank Kumar Saha**, **Shivang Aggarwal**, Dimitrios Koutsonikolas, and Joerg Widmer, University at Buffalo, The State University of New York and IMDEA Neworks Institute, Madrid, Spain
13. Stochastic 3D Beam Training for Low-Latency Services in Millimeter Wave Networks, **Omid Semiari** and Walid Saad, Georgia Southern University and Virginia Tech
14. Towards Millimeter Wave Access Point Deployment and Novel Sensing Applications, **Zhicheng Yang**, and Prasant Mohapatra, University of California, Davis

Poster Session 2: 1:30am-2:30pm, 01/28/19 (Duke Energy Hall A/B)

1. Opportunistic Routing in Mobile Ad-Hoc Networks Using Millimeter Wave and Random Beamforming, Mustafa S. Aljumaily and **Husheng Li**, The University of Tennessee, Knoxville
2. Investigation of Proximity Coupled Patch Antennas with a Universal Feed for Flexible mm-Wave Design, M. A. Boufarsan and **J. Adams**, North Carolina State University
3. Effects of Solar Radio Emissions on Time-varying Impulse Response of Wireless Channels at 38 GHz, Steven Buck, Thomas J. Montano, and **Ahmed Iyanda Sulyman**, Embry-Riddle Aeronautical University, Prescott, Arizona
4. Fully-Digital 60 GHz Prototyping Platform, Aditya Dhananjay, **Marco Mezzavilla**, and Sundeep Rangan, New York University
5. Toward Plug-and-Play Phased Array Systems Using Reusable, Extendable Platforms, **Brian Floyd**, Sandeep Hari, Tiantong Ren, Vikas Chauhan, Yi-Shin Yeh, and Charley Wilson, North Carolina State University
6. mmW-SpICa: Reconfigurable millimeter-wave transceiver with wideband spatial interference cancellation, Deukhyoun Heo and **Subhanshu Gupta**, Washington State University
7. Wideband Millimeter-Wave Open Experimentation Platform, **Jesus Omar Lacruz,** Diego Juara, and Joerg Widmer, IMDEA Networks Institute, Madrid, Spain
8. Reducing ADC Count in Fully-Digital Arrays without Losing Degrees of Freedom, **Arjuna Madanayake**, Najath Akram, Viduneth Ariyarathna **Soumyajit Mandal**, and Ted Rappaport, Florida International University, Case Western Reserve University, and New York University
9. End-to-End Performance of Integrated Access and Backhaul at Millimeter Waves, **Michele Polese**, Marco Giordani, and **Michele Zorzi**, University of Padova, Italy

10. X60: A Programmable Testbed for Wideband 60 GHz WLANs with Phased Arrays, **Swetank Kumar Saha**, **Yasaman Ghasempour**, Muhammad Kumail Haider, Josep Miquel Jornet, Edward Knightly, Dimitrios Koutsonikolas, Dimitris Pados, and Zhi Sun, The University at Buffalo, SUNY and Rice University
11. Leveraging mmWave Imaging for NLoS Localization and Highly-Mobile Communications, **Georgios C. Trichopoulos** and **Ahmed Alkhateeb**, Arizona State University
12. Immersive Content Delivery in Millimeter Wave Access Networks, **Zongshen Wu**, **Chin-Ya Huang**, and Parameswaran Ramanathan, University of Wisconsin, Madison and National Taiwan University of Science
13. In-Band LOS Discovery in 3D Using Highly Directional 60+GHz Transceivers, **Murat Yuksel** and Mahmudur R. Khan, University of Central Florida and University of Alabama
14. Enabling Robust Links in Dynamic Outdoor Millimeter Wave Networks, **Masoud Zarifneshat**, Michigan State University

Poster Session 3: 4:30am-5:30pm, 01/28/19 (Duke Energy Hall A/B)

1. Towards All-Digital Massive MIMO: Designing around Nonlinearities, **Mohammed Abdelghany**, Ali Farid, Upamanyu Madhow, and **Mark Rodwell**, University of California, Santa Barbara
2. Channel Estimation in mmWave Hybrid MIMO System via Off-Grid Dirichlet Kernels, **Chethan Kumar Anjinappa**, You Zhou, **Yavuz Yapici, Dror Baron**, and **Ismail Guvenc**, North Carolina State University
3. Motion Aware Beam Tracking in Mobile Millimeter Wave Communications: A Data-Driven Approach, Jingchao Bao and **Husheng Li**, The University of Tennessee, Knoxville
4. Intelligent Multi-User Millimeter-Wave MIMO Systems with Multiple Mobile Relays, **Ming Feng** and **Hao Xu**, University of Nevada, Reno
5. Spatial Multiplexing in mmWave Wireless Networks, **Yasaman Ghasempour** and Edward Knightly, Rice University
6. Achieving mmWave Beam Tracking Within 3GPP New Radio Release 15, **Carlos Herranz**, Universitat Politecnica de Valencia, Spain
7. UAV-assisted Multi-path Routing for Millimeter Wave Networks, Mai A. Abdel-Malek, Nico Sapurto, **Ahmed S. Ibrahim**, and Kemal Akkaya, Florida International University
8. Coded Energy-Efficient Beam-Alignment in Millimeter Wave Networks, **Nicolo Michelusi** and Muddassar Hussain, Purdue University
9. A Radix-2 Algorithm For Forming N True-Time-Delay RF Beams at Complexity O(N logN), Sirani Perera, **Arjuna Madanayake**, Udara de Silva, and Viduneth Ariyarathna, Embry-Riddle Aeronautical University and The University of Akron

10. Scalable and Accurate Channel Models for Analysis and Large-Scale Simulations at mmWaves, **Michele Polese**, Mattia Lecci, Paolo Testolina, and **Michele Zorzi**, University of Padova, Italy

11. Compressive Initial Discovery, Synchronization and Beamforming Training in Millimeter-Wave Networks, **Han Yan** and Danijela Cabric. University of California, Los Angeles

12. Interference Modeling and Scheduling with Joint Transmissions in Dense 60GHz mmWave WLANs mmW RCN Area: Wireless Networking, **Ding Zhang**, Panneer Se Santhalingam, and Parth Pathak, George Mason University

13. Improving Google's BBR for Reduced Latency and Increased Fairness, Menglei Zhang, **Marco Mezzavilla**, Sundeep Rangan, and Shivendra Panwar New York University

14. Compressed Beam Alignment with Out-of-Band Assistance in Millimeter Wave Cellular Networks, Jie Zhao and Xin Wang, Stony Brook University

15. Metasurface Based Reconfigurable Beamforming/Beam-steering for Sub-MilimeterWave and THz Communications, **Xiaomin Meng** and Maziar Nekovee, University of Sussex, UK