Report on the 6th Workshop of the NSF mmW RCN

July 23-24, 2019

National Institute of Standards and Technology, Boulder, CO

Executive Summary: The 6th 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 July 23-24, 2019 at the National Institute of Standards and Technology (NIST) in Boulder, CO. Steering committee member Kate Remley and her colleague Jeanne Quimby were responsible for the local arrangements. The workshop started with introductory remarks by Akbar Sayeed reminding the attendees of the goal 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. The introductory remarks also reviewed some of the notable industry developments in the field, posted on the RCN website, since the 5th workshop in Raleigh in January 2019.

Day 1 opened with a keynote by Emil Olbrich of Signals Research Group who presented results from the recent Verizon 5G NR launch in Minneapolis and Chicago**.** On Day 2, in lieu of a second keynote, Akbar Sayeed gave a presentation reflecting on the accomplishments and shortcomings of the RCN since the kickoff workshop in December 2016. Given that this was the last of the initially planned six workshops, panel 2 discussion on Day 2 also discussed future efforts to build on the RCN activities.

Building on the discussions from the previous workshops, especially the last one, and recent developments, three main themes were emphasized in the three breakout sessions on Day 1:

- Research and Technology Challenges at the HW-CSP interface
- Research and Technology Challenges at the CSP-NET interface
- Opportunities and Challenges for Developing Cost-Effective Community Testbeds.

Day 1 also included three sequential one-hour sessions for poster presentations and demos.

The key takeaways from the 6th mmW RCN workshop are summarized below (and elaborated in the subsequent summary of activities):

Recent Developments (Panel 1): The 5G NR standard is quite flexible and working well. However, performance of devices can vary across different original equipment manufacturers (OEMs) while satisfying the constraints of the standard. The devices, especially mobile devices and consumer premise equipment (CPE), are in their relative infancy and need further refinement. The link layer performance of 5G NR is close to theoretically expected values in terms of traditional metrics of rate versus SNR in point-to-point links. However, the picture is not clear in network settings and from the viewpoint of overall power consumption. 5G research and development in the last decade has underscored the importance of prototypes and testbeds for accelerating innovation. Furthermore, going forward, there is a great need for accurate channel models and network simulators to enable predictive network simulation.

HW-CSP breakout: The breakout discussion identified several important challenges at the HW-CSP interface, including: i) the cost and complexity of packaging, ii) the role of CMOS, SiGe, and GaN or hybrid approaches in future RFICs, iii) the need to design devices, antennas and systems from the viewpoint of interference management in co-existing applications.

CSP-NET breakout: The discussion in this breakout build on the recent developments in quasi-deterministic channel modeling and simulation tools for 802.11ay, link level simulation of 5G NR, and new directions for improving ns-3 based channel simulators through measurements from testbeds.

Community Testbeds: The breakout discussion emphasized the need for cost-effective and flexible testbeds but the organizational and funding mechanisms were not clear. There was a discussion of application- or problem-specific testbed development for higher impact and usefulness. Another idea was to develop a GNU-like framework for mmW testbeds but with a less steep learning curve.

Future Directions (Panel 2): While initial 5G deployments are underway, it is far from at-scale deployment, and this will require further innovations in device development and network optimization. At the same time, the industry is already looking at 6G, which will enhance all aspects of 5G, exploit higher frequencies (e.g. THz) and will be more device-centric. There is a need for application-focused testbeds and for unifying analysis, simulation and experimental tools. Machine learning (ML) and artificial intelligence (AI) techniques are also expected to play an important role in 5G and beyond.

Future of RCN (Panel 2): There was a unanimous and strong support for continuing the cross-disciplinary research and community development as well as industry-academic interaction started by the mmW RCN. Several themes for a future RCN were proposed, including THz communication and sensing, and testbed-centric RCN. Several attendees volunteered to lead such a future RCN.

Summary of Key Activities and Outcomes from the Workshop

Day 1: Tuesday, July 23, 2019

Keynote 1: The workshop was kicked off by an informative and engaging keynote presentation by **Emil Olbrich**, Founder, PrimeLime and VP for Networks, Signals Research Group. Mr. Olbrich's presented analysis and results from the Verizon 5G NR launch in Minneapolis and Chicago. His presentation highlighted the following key findings: i) rates over 1Gbps were demonstrated, ii) 5G mmW mobile devices not fully functional, iii) beam management and handoff remains challenging, iv) unexpected propagation opportunities observed, and v) these are early days and a lot more needs to be done to achieve consistent coverage and mobility.

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

Moderators: I. Guvenc (NSCU) and Parmesh Ramanathan (UW-Madison); **Panelists:** Emil Olbrich (PrimeLime), Vasanthan Raghavan (Qualcomm), Tommy Svensson (Chalmers U.), Sarah Yost (National Instruments), and Charlie Zhang (Samsung).

Summary of Key Discussion Points, Takeaways, and Future Tasks:

The panelists made brief opening remarks at the beginning of the panel before addressing questions from the moderators and the audience. Zhang noted the extensive pre-commercial and commercial 5G deployments and continued evolution of the 5G NR (new radio) standard. Future releases (Rel 16 and higher) of the standards would address higher frequencies (50-115 GHz) and new applications such as positioning and new vertical markets. He also noted that many practical issues still remain to be addressed

in terms of beam tracking and present exciting opportunities. Yost noted that the discussion on higher frequencies (< 50 GHz) is going to gain more traction in the future. She also emphasized that the key technical issues relate to mobile access and beam management. She also highlighted business challenges and the development of NR-U (unlicensed) as an interesting opportunity. Svensson provided a European perspective and presented results from the mmMagic Horizon 2020 project, which highlighted some of the challenges: coordination of mmW with sub 6 GHz bands, initial access, hybrid ARQ protocols, hybrid beamforming architectures, and convergence of core and fronthaul network. Raghavan noted the significant progress in consumer devices (e.g., smartphones and consumer premise equipment (CPE)) thanks to the chipsets developed by Qualcomm. However, these devices are still bulky and expensive and require further improvement which will involve interplay between theory, measurements, and prototype development.

The key discussion points and takeaways from the panel discussion:

- **mmW devices (e.g. smartphones, CPEs):** mobile device availability is still in its infancy and undergoing testing and development. There are two US smartphones (3+ in China) that support mmW and more are being tested. A related issue is the lack of pervasive infrastructure (e.g. access points) to support them. At least half a dozen mmW smartphones are expected by end of 2019 in the US. However, the beam tracking and management functionality in these early devices still needs further development, which will also be addressed in future releases of the 5G NR standard.
- **5G NR Standard:** The view of the panelists was that the 5G NR standard is quite flexible and its functionality will broaden in future releases (e.g. integrated access and backhaul (IAB), NR-U, V2X). However, there is a lot of room for optimization in terms of the devices built by Original Equipment Manufacturers (OEMs) and how they are configured and optimized by the operators in their network deployments. For example, the standard specifies the signals and maximum time for beam tracking/management but devices from different OEMs may exhibit different operational characteristics while satisfying the standard.
- **How far is 5G from the theoretically optimum performance?:** In terms of the link layer performance, the panelists thought that 5G was close to optimum, however from the restricted perspective of bits/s/Hz as a function of signal-to-noise ratio in point-to-point links. The answer is not clear when we consider beam tracking and management, power consumption, coverage and user experience. Scaling to a large multiuser network accentuates all these issues and raises additional issues in terms of power efficiency and cost.
- **Challenges and opportunities moving forward:** It was noted that the 5G vision from 10 years ago was more grandiose than the reality we have now. Going to higher frequencies (above 100 GHz) may get us closer to that vision. However, that represents new challenges and opportunities:
    - The propagation characteristics are different, the design of devices is different and the availability of RF devices is limited (no current RF components at THz, e.g.).
    - We may need to go beyond OFDM waveforms as we move to higher frequencies and large number of beams/antennas and that opens up new areas of PHY research.
    - The last decade of research in mmW has underscored the importance of prototype and testbed development. There is room for improvement in the space of mmW testbeds, but the landspace in the THz space is wide open. Given the importance of FPGAs, and the high

learning curve associated with them, it would be useful to simply the interface. New developments in RF SoCs (systems on chip) may present an opportunity.

- Accurate channel measurement and modeling is going to be important going forward. However, the requirements for channel models are different for different uses: e.g., for comparing algorithms/protocols versus network performance prediction.

Poster Sessions: Three poster sessions, each with 12 posters, 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 D.

Demonstrations: Tanguy Ropitault of NIST demonstrated tools for IEEE 802.11ad High-Fidelity Simulation. Jyh-Cheng Chen of National Chiao Tung University, Taiwan, provided an overview of free5GC, a tool for simulating the 5G mobile core network.

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. Detailed notes on the breakout discussion are provided in Appendix E.

HW-CSP Interface Breakout:

Leaders: Arun Natarajan (Oregon State), Michael Marcus (Virginia Tech), Jeyanandh Paramesh (Carnegie Mellon).

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

The discussion leaders opened the breakout with short presentations emphasizing the critical challenges. Paramesh gave an overview of issues in four areas:

1. **System level issues:** hardware complexity of massive MIMO systems, transceiver architectures for hybrid beamforming, energy consumption issues, and the potential role of machine learning techniques.
2. **Signal processing and algorithms:** validity of assumptions underlying CSP algorithms, impact of hardware imperfections, partitioning of processing across digital and analog domains, potential of could RAN approaches, energy cost of error correcting codes.
3. **Chip-level challenges:** transmitter power consumption for hybrid beamforming, CMOS versus III-V + CMOS realizations, ultrawide frequency ranges, LO distribution and phase noise, ADC/DAC design and power consumption.
4. **Packaging and non-chip challenges:** antenna design, mechanical beamforming, lens array-based beamforming, test challenges at various levels – chip, module, over-the air.
5. **Future systems:** approaches for increasing spectral and energy efficiency, physical layer security, integrated sensing and communications.

Report on the 6th Workshop of the NSF mmW RCN

July 23-24, 2019

National Institute of Standards and Technology, Boulder, CO

Natarajan opened with five critical challenges: i) high peak to average power (PAPR) issues and PA back-off efficiency, ii) cost of packaging at mm-wave as the number of antenna elements increases at higher frequencies, iii) testing of arrays, iv) power consumption of LO distribution and synchronization, and v) design of antennas and RFICs to operate in multiple bands. He then gave an overview of the evolution of phased array design over the past 15 years noting that novel approaches for large arrays has been possible with a co-design of EM interfaces and mmW ICs. Going forward, he identified four challenges for the next decade: i) antenna-IC co-design for achieving half-wavelength fill factor, ii) transmitter array efficiency under modulation, iii) receiver linearity and dynamic range, and iv) LO and IF interfaces and packaging complexity. He ended by presenting two approaches for simplifying packaging: wafer scale antenna-IC integration, and single-wire interface for distributing LO and IF via frequency multiplexing.

Marcus emphasized antenna design issues in his opening remarks especially as they relate FCC spectrum allocations and interference issues with regard to co-existence with other applications in those frequency bands. For example, the recent 24 GHz FCC spectral allocation for 5G has received significant pushback from National Oceanic and Atmospheric Administration (NOAA) and NASA regarding the interference impact of 5G transmission on weather satellites. Similar concerns have been raised by radio astronomy community. In closing, he emphasized the design of mmW beamforming antennas and transceivers which take into account the impact of interference on other applications and the need to develop approaches that can limit interference between co-existing systems.

Following the opening presentations, the discussion was opened to the breakout attendees and resulted in a vibrant exchange of ideas. The discussion led to the identification of the following critical technical challenges at the HW-CSP interface:

- **CMOS vs SiGe vs GaN**: What is best underlying substrate for mmW ICs? Is CMOS sufficient or do we need SiGe at 100 GHz or higher frequencies? GaN can result in power amplifiers (Pas) with higher power and thus what is the role of GaN in future systems. What is the role of heterogenous systems that combine CMOS, SiGe, and GaN?
- **Application Specific mmW Hardware Requirements**: Achieving the three main 5G requirements of high rate, low latency and mobility impose different constraints. Do they also entail different mmW hardware design requirements? Similarly communication or sensing/radar applications may also entail different constraints.
- **Antenna Array Design Tools:** Antenna array design at mmW frequencies may require new CAD design tools that can account for different co-design issues and constraints. E.g., thermal issues relating to heat dissipation.
- **Power Consumption:** Array power consumption is still high, particularly when waveforms with high PAPR are considered. This along with antenna and thermal challenges creates several barriers for low-cost commercial deployment.
- **Packaging Issues:** Packaging and integration yield is currently very poor especially for large number of array elements and half-wavelength fill requirements at higher frequencies. Can commercial packaging houses handle the needs of mm-wave array packaging at 60 GHz and above? Can a one-size-fits-all packaging approach work for a huge frequency range from 28 GHz to 200 GHz? If not, what new changes are needed?

- **Co-existence and Interference Issues:** Terrestrial 5G communication is horizontal, but leakage through uncontrolled sidelobes can cause interference to atmospheric monitoring satellite radars. For example, satellites have very sensitive receivers at 114 GHz to detect atmospheric molecular resonances. However, these overlap future communication bands. Also, the maximum contiguous bandwidth availability above 100 GHz is in chunks of 26 GHz. Such chunks are separated by bands reserved for satellite radars. Potential interference from 5G mmW allocations is also a concern for radio astronomy applications. Thus, there is a need for a new approach to antenna and system design to limit interference and enable co-existence.

CSP-NET Interface Breakout:

Leaders: Marco Mezzavilla (NYU), Tanguy Ropitault (NIST), Michele Polese (U. Padova), and David Matolak (U. South Carolina)

Scope: 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 this breakout from the previous workshops.

The CSP-NET interface breakout discussion was centered around four discussion points that were primed with corresponding introductory presentations from the discussion leaders:

- **Quasi-deterministic (Q-D) 802.11ad/ay simulation framework:** The framework uses a Q-D channel model and has four components: the Q-D realization software, IEEE 802.11ad codebook generator, the IEEE 802.11ad ns-3 implementation, and the Q-D visualizer. (NIST)
- **Link abstraction and error models above 6 GHz for IEEE 802.11ay and 3GPP 5G NR.** Overview of different approaches (EESM, MMIB, Q-Table) to generate error models for 802.11ay protocols and link abstraction for LDPC-based NR PHY. (Collaboration between InterDigital and NYU).
- **802.11ay proposed MIMO architectures:** Introduction to a proposal to implement IEEE 802.11ay MIMO in the ns-3 system-level simulator.
- **The use of prototyping platforms to validate and improve the mmW simulator:** Discussion of the main elements that require validation and further study through experimental evaluation.

The discussion points and the presentations reflect a significant and sustained effort (over multiple workshops) by a number of RCN researchers, led by Marco Mezzavilla of NYU, and represent the significant accomplishments of the collaborative work done by this group starting with the 2nd RCN workshop in July 2017. In particular, the development of the Q-D simulation framework has been led by Tanguy Ropitault of NIST who gave a very informative presentation on the results and the component tools. The work on link abstractions for 802.11ay and 5G NR represents a collaboration between InterDigital and NYU that was initiated in the 4th RCN workshop in July 2018. The work by this group is ongoing and will continue in the future.

The most important next step identified in this breakout was to refine and validate the different simulation frameworks by leveraging measurement results that are being generated by mmW prototypes and testbeds within the RCN research community as well as the 5G mmW Channel Model Alliance led by

NIST. Specifically, three aspects of mmW systems were identified for this experimentation validation and refinement of simulation tools:

- **Beam management** issues incorporating antenna rotation and antenna beam patterns at multiple time scales.
- **Mobility issues** spanning handoff, beam management, and cross-layer interactions.
- **Applications, especially VR/AR applications,** involving adaptive streaming for high quality VR experience over variable mmW channels.

Development of Cost-Effective Community Testbeds:

Leaders: Ismail Guvenc (NCSU), Aditya Dhananjay (NYU), Sarah Yost (NI) and Arup Bhuyan (Idaho National Lab)

Scope: 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 earlier workshops, especially the 4th and 5th workshops. See the video link of the breakout sessions at the 4th (NYU) workshop at which this discussion was started initially.

The discussion on the need for cost-effective community mmW testbeds started with a breakout discussion on the topic at the 4th RCN workshop in July 2018. Aditya Dhananjay gave an opening presentation reiterating the reasons: i) currently available testbeds are provided by commercial vendors and are very expensive, ii) they have limited functionality that does not support experimentation of different aspects (e.g. the RF front end and antenna arrays), and iii) the academic mmW research community needs to work together flexible and cost-effective testbeds that can be adapted to their needs. Sarah Yost noted that a lot more goes into an operational testbed than just the hardware to make it usable by the wider community. For example, the GNU radio platform is very inexpensive but has a very high learning curve, whereas the NI platform is expensive but has a relatively lower learning curve. It was noted by the group that with vendors providing evaluation boards for various hardware components, perhaps there is an opportunity to reach some middle ground in terms of cost and ease of use. One idea was to build a GNU-like framework for mmW that is more user friendly given all the advances in computing and software. From the discussion, it was clear that the community was overall supportive of pursuing this idea further but it was not clear how to coordinate and fund the effort. NSF programs, such as the mid-scale critical infrastructure, were noted as one possibility and some RCN members planned to respond to this opportunity.

Day 2: Wednesday, July 24 2019

Special Presentations: The second day started with a special presentation reflecting on RCN's accomplishments and shortcomings since the kickoff workshop in Dec 2016, and on future directions and possibilities. An overview of related work at NIST was also presented.

Report on the 6th Workshop of the NSF mmW RCN

July 23-24, 2019

National Institute of Standards and Technology, Boulder, CO

Akbar Sayeed gave the reflective presentation on RCN's accomplishments. He noted four key themes that emerged over the course of the six RCN workshops:

1. Interdisciplinary Research Challenges at the Interface of the three technical areas (HW, CSP, NET):
    a. **HW-CSP interface:** new system models that accurately account for hardware characteristics.
    b. **CSP-NET interface:** more accurate abstraction of the mmW PHY-MAC layer for network simulators.
    c. **mmW standards:** 5G NR and 802.11ay/ad and relationship between them.
    d. **Appropriate channel models** for both a) and b).
2. The need for cost-effective and flexible testbeds for research and experimentation in academia.
3. Need for new conferences, journals and other venues for publication of cross-disciplinary work.
4. The need for closer and more impactful industry-academic collaboration.

Sayeed gave a quick overview of the previous five workshops:

- **Kickoff Workshop (Catholic University of America, Dec 2016):** Jon Wilkins and Julius Knapp gave keynotes at the kickoff reflecting on the significance of FCC's landmark *Spectrum Frontiers* announcement in June 2016 for opening up the mmW spectrum for 5G wireless. There were three breakout discussions on the technical areas: HW, CSP, NET. There were two key findings at the workshop: i) the key technical challenges are at the HW-CSP and CSP-NET interfaces, and ii) there is a need for mmW testbeds accelerating innovation.
- **2nd Workshop (UW-Madison, July 2017):** Ted Woodward gave a keynote on DARPA's 100G program for creating a 100 Gb/s ground-to-space mmW communication link, and Boon Loong Ng of Samsung gave an informative presentation on the 5G NR (new radio) standard. The RCN attendees showed great interest in 5G NR. One breakout was on the HW-CSP interface, another on CSP-NET interface, and a third one on hardware and tools for effective testing and development of mmW technology.
- **3rd Workshop (U. Arizona, Jan 2018):** Amitava Ghosh of Nokia gave a keynote on the 5G NR and Carlos Cordiero of Intel gave a keynote on mmW challenges and opportunities. In addition to two breakouts on HW-CSP and CSP-NET interfaces, a third one was focused on 5G NR and 802.11ay mmW standards. There was a hands-on workshop provided by NI.
- **4th Workshop (NYU, July 2018):** John Cioffi of Assia gave a keynote on Terabit DSL and Ted Rappaport gave a keynote on recent mmW developments. In addition to two breakouts on HW-CSP and CSP-NET interfaces, a third one was focused on community testbeds, which generated significant interest.
- **5th Workshop (NCSU, Jan 2019):** Sanyogita Shamsunder of Verizon gave a keynote on Verizon's 5G trials and deployments, and Tim Hancock of DARPA gave a keynote on Application of Heterogenous Integration to Advanced Transceivers and mmW Phased Arrays. In addition to the two breakouts on HW-CSP and CSP-NET interfaces, a third one continued the discussion on community testbeds from the 4th workshop.

Sayeed then commented on RCN's accomplishments and shortcomings on three RCN objectives:

1. Advancement of basic research and development of mmW technology.
2. Facilitation of research interaction and collaboration across the three areas: HW, CSP, NET
3. Interaction and collaboration between industry and academia to accelerate mmW innovation

He noted that the RCN had been very successful with regard to objectives 1 and 2. Specifically, the RCN activities had greatly facilitated research and innovation at the HW-CSP and CSP-NET interfaces, as well

developing ideas for community testbed developments. On the other hand, with regard to objective 3, Sayeed noted that while the RCN was successful in bringing together academic and industry researchers, it fell short of catalyzing meaningful and impactful industry-academic collaboration – more effort was needed on this front. He also noted that in terms of research and innovation at the two interfaces, the CSP-NET interface community had achieved more than the HW-CSP community and more effort was needed on the latter. These impressions were also supported by the somewhat limited responses of the RCN community to a series of survey questions prior to the workshop.

Following Sayeed's presentation, Nada Golmie gave a short presentation on NIST's recent accomplishment in mmW research and technology development. She noted that the RCN and NIST had worked very synergistically in the past three years, especially in the context of NIST's 5G mmW Channel Model Alliance. In particular, Golmie noted NIST's significant accomplishments in: i) mmW channel modeling and measurement, ii) development mmW channel sounders at 28, 60 and 83 GHz, iii) facilities for MIMO antenna testing and measurement, iv) modeling and simulation of beamforming for system-level performance evaluation, and v) ongoing collaboration with various industry players.

Readouts from Breakout Sessions: M. Marcus (HW-CSP), M. Mezzavilla (CSP-NET), I. Guvenc (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: Nada Golmie (NIST) and Akbar Sayeed (UW-Madison).

Panelists: Charlie Zhang (Samsung), Kira Theuer (NI), Michele Zorzi (U. Padova), Thyaga Nandagopal (NSF), Ali Niknejad (UC-Berkeley).

Some of the panelists gave opening remarks. Charlie Zhang (Samsung) reflected on the challenges going from 5G to 6G. He noted that technology had accelerated with 5G and early preparation in industry and academic research is key to success going forward. Zhang noted that the main focus of 6G will be to enhance all interaction aspects of 5G. While 5G is primarily human- and network-centric, 6G would be more device-centric with converged communication and computing and intelligent machine interaction. Further, it will enable more business models. He noted the following as key 6G enabling technologies: higher band spectrum (including THz) and spectrum sharing, distributed MIMO and mesh networks, AI/ML for wireless and quantum computing. He then noted some technical challenges for THz communication: much lower PA power and higher noise LNAs. THz wireless require new devices, transceivers and architectures for achieving project 1 Tbps rates and 100 microsecond latency by 2030.

Ali Niknejad (UC-Berkeley) presented his outlook for integrated communication and sensing at THz frequencies and new applications. He noted that SIC RFIC development indicates x10 reduction in power savings with x8 increase in bandwidth. He closed by highlighting some major technical challenges that demand more research: packing and testing of mmW and THz systems, ADCs/DACs and signal processing architectures, the need to more general purpose RFICs in terms of frequency, bandwidth and architecture, new opportunities above 100GHz.

Michele Zorzi (U. Padova) emphasized the need for new channel and network models for accurate performance prediction at scale and the need for unifying analysis, simulations and experimental research. He also noted the potential of using machine learning techniques, in conjunction with real measured data, for optimizing simulation models and realizing improved prediction performance.

Kira Theuer (NI) noted the importance of both basic research and testbeds. She noted that current testbeds are perhaps too general purpose, aimed at all conceivable applications. That potentially limits impact and application-specific relevance. Perhaps it is time to flip the model and design prototypes and testbeds with specific important applications in mind.

Thyaga Nandagopal (NSF) congratulated the RCN community for really growing over the past three years and coming together. He also emphasized the need to publicize and evangelize our accomplishments to industry and government to enhance impact of our research. He urged the RCN community, with a mailing list of 400+, to work together to unleash its collective network power. For example, by engaging with relevant IEEE societies in workshops, conferences, and other activities.

The panel discussion was seeded by the breakout readouts and the following questions:

- What are big trends (technological, business, regulatory) in mmW technology in particular and 5G in general that will shape the next 1-5 years?
- What are the significant challenges facing 5G and mmW technology *development* and *deployment?*
- What big new insights (if any) have we learned from the recent mmW trials and initial deployments?
- How significant are health concerns associated with 5G and mmW infrastructure deployments that are getting underway across the US and the rest of the world?
- Would a continuation of this mmW RCN effort be valuable? If so, what are new R&D trends in 5G and beyond that it ought to address?
- Are you satisfied with the level of academic-industry-government interaction and collaboration for accelerating innovation in spectrum and wireless related issues? How could it be improved?

Summary of Discussion, Key Takeaways, and Future Tasks:

The panel generated a lot of exciting and animated discussion. The key takeaways are summarized below:

- **Industry-academia collaboration:** There was a general consensus that industry-academic collaboration is needed to accelerate innovation but is also challenging due to IP and competition-related challenges. There is no simple solution but more can be done. Perhaps, the industry can share ideas and plans a little more, especially longer-horizon plans. Academics need to proactively engage with industry to learn about their problems and challenges.
- **Top-down versus bottom-up research:** While US generally pursues a bottom-up research model, especially at NSF, big European programs often adopt a top-down model. There are pros and cons to both models and perhaps the mmW RCN community needs to pursue both. E.g. a combination of both top-down and bottom-up ideas in testbed development projects.

- **Funding models:** NSF generally funds more radical/risky proposals, whereas industry funds more focused projects with near-term payoffs. There is a need for government-industry partnership to fund both kinds of research.
- **Testbeds and experimentation:** There is a great need for research testbeds but not a clear pathway how to move forward. The mmW RCN community has made significant progress in parts of this big puzzle and perhaps its time to develop a roadmap and plan for testbed development.
- **Grand challenges:** Grand challenges are very good at focusing attention and galvanizing the community but in addition to articulating a grand challenge, the process of working to achieve a grand challenge is equally important. Identifying one or two grand challenges, and articulating the process of achieving them, may be a good exercise for the mmW RCN community. E.g., a testbed grand challenge, or a predictive network simulator grand challenge that combines analytical and simulations tools with measurements and testbeds.
- **Future of the mmW RCN:** There was unanimous support amongst the attendees (and those who responded to the survey) that the cross-disciplinary mmW RCN effort should continue. A number of themes for a future RCN were suggested: testbed-focused RCN, or one aimed at building on the RCN work at the CSP-NET or HW-CSP interfaces; THz RCN; UAV-centric RCN. Several attendees volunteered to be a part of leading a future RCN, including David Matolak (U. South Carolina) and Chris Anderson (Naval Academy).

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.

APPENDIX A
WORKSHOP AGENDA

6th mmW RCN Workshop
July 23-24, 2019
NIST, Boulder, CO

Agenda

Day 1: Tuesday, July 23, 2019

8:00 am-8:45 am: Registration (NIST Building 1 Lobby) and Breakfast (Tent Outdoors)

8:45 am-9:00 am: Welcome and Opening Remarks (Auditorium) *slides*

9:00 am-9:30 am: **Keynote 1 (Auditorium):** Emil Olbrich, *Founder, PrimeLime* and *VP for Networks, Signals Research Group* slides

9:30 am-11:00 am: Panel 1 (Auditorium): State of mmW Technology and Outlook: A View from Industry

Moderators: Ismail Guvenc (NCSU) and Parmesh Ramanathan (UW-Madison)

Panelists: Charlie Zhang (Samsung, *slides*), Vasanthan Raghavan (Qualcomm, *slides*), Sarah Yost (NI, *slides*), Tommy Svensson (Chalmers, *slides*), and Emil Olbrich (PrimeLime)

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

Discussion Items

11:00 am-11:30 am: **Coffee Break (Tent)**

11:30 am-12:30 pm: Poster/Demo Session 1 (Lobby)

12:30 pm-1:30 pm: Lunch (Tent)

1:30 pm-2:30 pm: Poster/Demo Session 2 (Lobby)

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

Three Parallel Sessions

A. HW-CSP Interface: **Hardware, Circuits, Antennas & Communication/Signal Processing & Prototypes/Testbeds (Auditorium)**

Discussion leaders: Arun Natarajan (Oregon State), Michael Marcus (VTech), and Jeyanandh Paramesh (Carnegie Mellon U.)

Overview 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 (Room 1-1103)**

Discussion Leaders: Marco Mezzavilla (NYU), Tanguy Ropitault (NIST), Michele Polese (U. Padova), and David Matolak (U. South Carolina)

Overview Slides

Discussion items

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 (Room 1-1107)**

Discussion leaders: Ismail Guvenc (NCSU), Aditya Dhananjay (NYU), Sarah Yost (NI), and Arup Bhuyan (Idaho National Lab)

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 earlier workshops; https://mmwrcn.ece.wisc.edu/?page_id=724; video link of the breakout sessions at the 4th (NYU) and 5th (NCSU) workshops

4:00 pm-4:30 pm: Coffee Break (Tent)

4:30 pm-5:30 pm: Poster/Demo Session 3 (Lobby)

6:00 pm: Dinner (Millenium Harvest House Outdoor Patio)

Day 2: Wedesday, July 24, 2019

8:00 am-8:30 am: Registration (NIST Building 1 Lobby) and Breakfast (Tent Outdoors)

8:30 am-9:00 am: Special presentation (Auditorium) – reflections on RCN's accomplishments and shortcomings since the kickoff workshop in Dec. 2016, and future directions and possibilities. *slides*

Overview of NIST's related work

9:00 am-10:00 am: Readout from Breakout Sessions (Auditorium)

CSP-NET Breakout, *Community Testbed Breakout*, *HW-CSP Breakout*

10:00 am-10:30 am: Coffee Break (Tent)

10:30 am-noon: Panel 2 (Auditorium): Academic-Industry Collaboration for "Moonshot" mmW RCN Contributions

Moderators: Nada Golmie (NIST) and Akbar Sayeed (UW-Madison)

Panelists: Charlie Zhang (Samsung, *slides*), Kira Theuer (NI), Michele Zorzi (U. Padova, *slides*), Thyaga Nandagopal (NSF), Ali Niknejad (UC-Berkeley, *slides*)

Future trends and RCN goals (seeded by the preceding readout from breakouts)

noon-12:15 pm: Closing Remarks

12:15 pm: Boxed lunch (tent) – RCN workshop adjourns.

1:00-4:00 pm: NIST 5G mmWave Channel Model Alliance Meeting; Agenda

APPENDIX B
LIST OF PARTICIPANTS

First Name	Last Name	Institution	Email
Husheng	Li	University of Tennessee, Knoxville	hli31@tennessee.edu
Ozgur	Ozdemir	North Carolina State University	oozdemi@ncsu.edu
Chao	Fang	Chalmers University of Technology	fchao@chalmers.se
Lu	Duan	University of Wisconsin-Madison	lu.duan@wisc.edu
Arun	Natarajan	Oregon State University	arun.natarajan@oregonstate.edu
Mattia	Rebato	University of Padova	rebatoma@dei.unipd.it
Marco	Giordani	University of Padova	giordani@dei.unipd.it
Michele	Polese	University of Padova	michele.polese@gmail.com
Stepan	Kucera	Nokia	stepan.kucera@nokia-bell-labs.com
Tanguy	Ropitault	NIST	tanguy.ropitault@nist.gov
Ali	Rahmati	NC state university	arahmat@ncsu.edu
Han	Yan	University of California, Los Angeles	yhaddint@ucla.edu
Zhicheng	Yang	University of California, Davis	zcyang@ucdavis.edu
Jacov	Cakareski	The University of Alabama	jacob@ua.edu
Yaguang	Zhang	Purdue University	ygzhang@purdue.edu
Nicolo	Michelusi	Purdue University	michelus@purdue.edu
Masoud	Zarifneshat	Michigan State University	zarifnes@cse.msu.edu
Omid	Semiari	Georgia Southern University	osemiari@gmail.com
Tai-Lin	Chin	National Taiwan University of Science and Technology	tchin@mail.ntust.edu.tw
Zongshen	Wu	University of Wisconsin, Madison	zongshen.wu@wisc.edu
Thommy	Svensson	Chalmers University of Technology	tommy.svensson@chalmers.se
Jyh-Cheng	Chen	National Chiao Tung University	jcc@cs.nctu.edu.tw
Xin	Wang	Stony Brook University	x.wang@stonybrook.edu
Anant	Gupta	UC Santa Barbara	anantgupta@ucsb.edu
David	Matolak	University of South Carolina	matolak@cec.sc.edu
Xiao	Zhang	Michigan State University	zhan1387@msu.edu
Marco	Mezzavilla	NYU	mezzavilla@nyu.edu
Chin-Ya	Huang	National Taiwan University of Science and Technology	chinya@gapps.ntust.edu.tw
Michele	Zorzi	University of Padova	zorzi@dei.unipd.it
Michael	Marcus	Virginia Tech	mjmarcus@alum.mit.edu
Harrison	Lew	UC Berkeley	harrisonliew@berkeley.edu
David	Michelson	U. British Columbia	davem@ece.ubc.ca
Ismail	Guvenc	NCSU	iguvenc@ncsu.edu
Ali	Niknejad	UC Berkeley	niknejad@berkeley.edu
Charlie	Zhang	Samsung	jianzhong.z@samsung.com
Nada	Golmie	NIST	nada.golmie@nist.gov
Kate	Remley	NIST	kate.remley@nist.gov
Parmesh	Ramanathan	UW Madison	parmesh.ramanathan@wisc.edu
Akbar	Sayeed	UW Madison	akbar.sayeed@wisc.edu
Jeyanandh	Paramesh	CMU	paramesh@ece.cmu.edu
Aditya	Dhananjay	NYU	aditya.dhananjay@gmail.com
Mustafa	Aljumaily	U. Tennessee, Knoxville	mlatief@vols.utk.edu
Christopher	Anderson	US Naval Academy	canderso@usna.edu
Arupjyoti	Bhuyan	Idaho National Lab	arupjyoti.bhuyan@inl.gov
James	Buckwalter	UC Santa Barbara	buckwalter@ucsb.edu
Hung-Cheng	Chang	National Chiao Tung University	changhcs@cs.nctu.edu.tw
Hyeonjin	Chung	Hanyang U. Korea	hyeonjingo@hanyang.ac.kr
Mohammed	Elbadry	Stony Brook University	mohammed.elbadry@stonybrook.edu
Ming	Feng	U. Nevada Reno	mingf@nevada.unr.edu
Junyeol	Hong		ftsh610@gmail.com
Weiting	Hu		zxc6752@gmail.com
Seungmo	Kim	Georgia Southern U.	seungmokim@georgiasouthern.edu
Mattia	Lecci	U. Padova	leccimat@dei.unipd.it
Robert	Muller	TU Ilmenau	mueller.robert@tu-ilmenau.de
Emily	Naviasky	UC Berkeley	enaviasky@berkeley.edu
Vasanthan	Raghavan	Qualcomm	vraghava@qti.qualcomm.com
Tanguy	Ropitault	NIST	t.ropitault@prometheuscomputing.com
Fu-lian	Weng		turtle11311@gmail.com
Zongxing	Xie	Stony Brook University	zongxing.xie@stonybrook.edu
Hao	Xu	U. Nevada Reno	haoxu@unr.edu
Sarah	Yost	National Instruments	sarah.yost@ni.com

APPENDIX C:
LIST OF POSTERS & DEMOS

6th mmW RCN Workshop
July 23-24, 2019
NIST, Boulder, CO

Demos:

- Demo: free5GC, Tze-Jie Tan, Wei-Ting Hu, Fu-Lian Weng, Hung-Cheng Chang, **Jyh-Cheng Chen** and Yi-Bing Lin, National Chiao Tung University, Taiwan.
- Tools for IEEE 802.11ad High-Fidelity Simulation, **Tanguy Ropitault** and Nada Golmie (NIST), Hany Assasa and Joerg Widmer (IMDEA Networks Institute).

Poster Session 1: 11:30am-12:30pm, 07/23/19

1. Optimization for mmWave Mobile Networks using Random Beamforming, **Mustafa Aljumaily** and Husheng Li, University of Tennessee, Knoxville.
2. Self-Learning based Multi-User Millimeter-Wave MIMO Systems with Multiple Mobile Relays, Ming Feng and **Hao Xu**, University of Nevada, Reno.
3. Reflection, Diffraction, and Interference of Millimeter Wave: Experimental Results, Zhiyang Zhang and **Husheng Li,** University of Tennessee, Knoxville.
4. Correction of Clock-Drift and Antenna Rotation Error for NCSU 28 GHz mmWave Channel Sounder, **Ozgur Ozdemir,** Fatih Erden, Wahab Khawaja and Ismail Guvenc, North Carolina State University.
5. Energy-efficient Hybrid Precoding for Cooperative Millimeter Wave Systems, **Chao Fang,** Behrooz Makki and Tommy Svensson, Chalmers University of Technology.
6. An Implementation of 5G NR MAC Layer Protocol in NS-3 and FPGA, **Lu Duan** and Paramesh Ramanathan, University of Wisconsin-Madison
7. Efficient mm-Wave and IF Interfaces for Scalable mm-Wave MIMO Arrays, **Arun Natarajan** (Oregon State University), Harish Krishnaswamy (Columbia University), Manoj Johnson, Robin Garg and Gaurav Sharma (Oregon State University), Sohail Ahasan, Armagan Dascurcu, Ali Binaie and Mahmood Baran (Columbia University).
8. Performance Assessment of MIMO Precoding on Realistic mmWave Channel, **Mattia Rebato** (U. Padova), Luca Rose (Nokia Bell Labs, Paris) and Michele Zorzi (U. Padova).
9. End-to-end Vehicle-to-Vehicle Operations at mmWaves in ns-3, **Marco Giordani**, **Michele Polese,** Tommaso Zugno, Matteo Drago and Michele Zorzi, U. Padova.
10. Modeling the Millimeter Wave Channel in a Scalable and Accurate Way, **Mattia Lecci**, Paolo Testolina, Michele Polese, Marco Giordani and Michelle Zorzi (U. Padova), **Tanguy Ropitault** and Nada Golmie (NIST).

11. QoS Provisioning in 60 GHz Link: A Cross-Layer Approach, Matteo Drago and **Michele Polese** (U. Padova), **Stepan Kucera** and Dmitry Kozlov (Nokia Bell Labs, Dublin), and Michele Zorzi (U. Padova).
12. CMOS Millimetre-wave MIMO Transceivers and Mobile Testbed, Susnata Mondal, Swarun Kumar, and **Jeyanandh Paramesh**, Carnegie Mellon U.

Poster Session 2: 1:30am-2:30pm, 07/23/19

1. Sensing Wind Velocity by Leveraging Millimeter Wave Communications, Zhiyang Zhang, Jingchao Bao, Yawen Fan and **Husheng Li,** University of Tennessee, Knoxville.
2. Energy Efficiency of RSMA and NOMA in Cellular-Connected mmWave UAV Networks, **Ali Rahmati,** Yavuz Yapici, Nadisanka Rupasinghe, Ismail Guvenc and Huaiyu Dai, NC State University, and Arupjyoti Bhuyan, Idaho National Laboratory.
3. Human RF Exposure in mmW Wearable Communications, Imtiaz Nasim and **Seungmo Kim,** Georgia Southern University.
4. Wideband Millimeter-Wave Beam Training with True-Time-Delay Array Architecture **Han Yan,** Veljko Boljanovic and Danijela Cabric, University of California, Los Angeles.
5. Enriching Millimeter-Wave WLANs with Novel Sensing Applications, **Zhicheng Yang** and Prasant Mohapatra, University of California, Davis.
6. Millimeter Wave Communications and Edge Computing for Future Untethered High-Fidelity Virtual Reality, **Jakob Chakareski,** University of Alabama and Petar Popovski, Aalborg University.
7. Propagation Modeling Through Foliage in a Coniferous Forest at 28 GHz, **Yaguang Zhang** (Purdue), **Christopher R. Anderson** (US Naval Academy) and James V. Krogmeier (Purdue).
8. Second-best Beam-Alignment via Bayesian Multi-Armed Bandits, **Nicolo Michelusi** and Muddassar Hussain, Purdue University.
9. User Association Based on Blockage and Load in Millimeter Wave Networks – A Lagrangian Dual Approach, **Masoud Zarifneshat,** Proteek Roy and Li Xiao, Michigan State University.
10. Fast Beam Training Protocol for Low-Latency Services Over Terahertz Frequency Bands, **Omid Semiari,** Georgia Southern University.
11. Energy-Conserved Millimeter-Wave Wireless Access Networks, **Tai-Lin Chin,** National Taiwan University of Science and Technology.
12. Towards 6G Networks: Non-Terrestrial Millimeter Wave Communications to Support eMBB, **Marco Giordani** and **Michele Zorzi**, University of Padova.

Poster Session 3: 4:30am-5:30pm, 07/23/19

1. Coordinated Beam Prediction based on Deep Learning for Millimeter-wave Vehicular Networks, Jie Zhao, **Xin Wang** and Xiaomeng Wang, Stony Brook University.
2. Evolving sensing algorithms to harness mm-Wave, **Anant Gupta** and Upamanyu Madhow, University of California, Santa Barbara.
3. Example Attenuations for Common Materials at 90 GHz, Mohanad Mohsen, **David Matolak** and Jinwn Liu, University of South Carolina.
4. Effective Subcarrier Pairing Scheme in mmWave-based Relay System, **Xiao Zhang** and Li Xiao, Michigan State University.
5. End-to-end Evaluation of mmWave Networks for Public Safety Scenarios, **Michele Polese,** William Xia, Tommaso Zugno, **Marco Mezzavilla**, Giuseppe Loianno, Sundeep Rangan and **Michele Zorzi**, University of Padova and NYU.
6. Enhancing TCP Throughput in mmWave Wireless Mesh Backhaul Networks, **Chin-Ya Huang** and Bing-Sheng Lin, National Taiwan University of Science and Technology.
7. Antenna Optimization in mmWave Mobile Scenarios through Machine Learning, **Mattia Rebato**, Paolo Testolina, Mattia Lecci, Alberto Testolina and **Michele Zorzi** (U. Padova), Jonathan Gambini, Roberto Flamini and Christian Mazzucco (Huawei, Milan)
8. Moonshot Problem: Opening Large Contiguous Blocks Above 100 GHz by interference-free sharing with passive satellites enabled by new antenna technology, **Michael Marcus,** Virginia Tech, Daniel Mittleman and Rabi Shrestha, Brown U.
9. Hydra: mmWave massive MIMO testbed development, Greg Lacaille, **Emily Naviasky**, Lorenzo Iotti**,** Harrison Liew, Elad Alon, Borivoje Nikolic and Ali Niknejad, UC Berkeley.
10. Multiantenna Wireless Architectures for Next-Generation Wireless Systems, **Tommy Svensson,** Chalmers University of Technology.
11. Enhancing Transport Layer Performance in Millimeter Wave Access Networks, **Zongshen Wu,** Chin-Ya Huang and Parmesh Ramnathan, University of Wisconsin-Madison and National Taiwan University of Science and Technology.
12. Joint Communications and Radar with FM Waveform in Millimeter Wave Band, Yawen Fan and **Husheng Li** University of Tennessee, Knoxville.