Report on the 2nd Workshop of the NSF mmW RCN

July 19-20, 2017

University of Wisconsin-Madison

https://mmwrcn.ece.wisc.edu/?page_id=356

Executive Summary: The 2nd workshop of the NSF RCN (research coordination network) on mmW (millimeter-wave) wireless (RF frequencies between 10 GHz and 300 GHz) networks was held on July 19-20, 2017 on the campus of the University of Wisconsin-Madison. The PI Akbar Sayeed and co-PI Xinyu Zhang were responsible for the local arrangements. The workshop started with introductory remarks by PI Sayeed 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 Kickoff Workshop and recent developments, three main themes were emphasized in the 2nd 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
- Research and Technology Roadmap for prototype and testbed development

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 3rd Workshop: Given the interest from the first two 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: Wednesday, July 19, 2017

Keynote 1: The workshop was kicked off by an informative and engaging keynote presentation by **Dr. Ted Woodward**, a program manager in the Strategic Technology Office at DARPA. Dr. Woodward shared valuable insights from his involvement and leadership of the 100G RF backbone program that is aimed at developing dynamic mmW communication links capable of supporting 100 Gb/s from ground to space.

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

Moderator: A. Sayeed; **Panelists:** A. Ghosh, A. Sampath, I. Wong, B. Loong Ng, and T. Svensson

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

In terms of recent significant developments, the panelists noted: i) the 5G NR (new radio) standard work; studies on the impact of mobility on beamforming; new spectrum opening throughout the world, including China and Japan; new prototypes and field trials from industry; 3GPP work on channel modeling for standardization; investigation of higher frequencies 70-90GHz; relevant work in Europe (Horizon 2020, mmMagic). In terms of significant next steps, the following aspects were noted: over the air (OTA) testing with mobility, multiple users and base stations; mitigating blockage effects; integrated backhaul and access (a new 3GPP study item); thermal management at access points; and cross-layer design issues.

In response to how the new NSF PAWR program could benefit mmW research, panelists noted the following aspects: testing and experimentation on city/scale with high densification; A/B testing; and collaboration between industry and academia.

In relation to WiGig/802.11ay work, it was noted that while there are some similarities in terms of beamforming protocols, 802.11ay is aimed at shorter WiFi links whereas 5G NR standard was aimed a larger scale cellular networks.

Design of efficient power amplifiers was identified as an important outstanding challenge.

Integrated communication and sensing, including mmW radar, was identified as a promising area, especially in automotive industry.

The need for accurate channel models for different environments (urban, rural, indoor, outdoors, etc) and for different use cases (e.g., UAVs and V2X) was noted.

There was a general consensus that fixed wireless access is the likely first use case that will take traction.

Poster Sessions: Three poster sessions, each with 10-11 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: There were six demonstrations, involving both hardware and software innovations, that were presented during the poster sessions. A description of demos is also included in Appendix D.

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: J. Paramesh, S. Gupta, V. Saxena, and S. Yost

Communication system design has traditionally relied on separating hardware (HW) design from development of communication and signal processing (CSP) techniques. Such separation is not feasible in mmW systems due to the high operating frequency, ultra-wide bandwidth, large antenna arrays, and advanced beamforming and MIMO signal processing algorithms that lead to prohibitively high cost and energy consumption. In fact there is an urgent need for "HW-aware CSP design" and "CSP-aware HW design" through a closer collaboration between the HW and CSP communities. The objective of the HW-CSP breakout session was to identify open challenges at the intersection of HW and CSP areas.

Advanced Beamforming and MIMO: A central thread of the discussion related to the design and efficient implementation of advanced beamforming algorithms. Digital beamforming provides maximum flexibility but is extremely power hungry, while analog (single-beam) beamforming offers low power consumption at the expense of severely limited spatial multiplexing flexibility. Hybrid multi-beamforming combines the best features of the two approaches and is gaining interest from research labs, academia, and industry. For example, lens-based beamspace MIMO can be attractive at access points for reducing overall energy consumption and accommodate very wideband channels, but may entail different trade-offs in terms of beam acquisition, beam shaping, latency etc. compared to phased-array beamforming. However, this area is still in its infancy, and many open problems at the HW-CSP interface need to be addressed.

Energy-efficiency of Spatio-Temporal Signal Processing: The energy consumption of signal processing functions has a significant impact on energy efficiency. The signaling bandwidth, modulation schemes (e.g. OFDM), and spatial processing techniques, such as beamforming and MIMO, need to be designed while accounting for their interaction with hardware constraints, including PA efficiency, ADC/DAC resolution, LO distribution and synchronization, and phase noise. Fundamental tradeoffs in this joint design space need to be identified. Given the enormous interest and research in machine learning algorithms, it may be worthwhile to explore their role at the physical/link level and at the network/multi-user level, for beam management etc. Centralized radio-access networks (C-RAN) add another dimension to the partitioning of signal processing across the network.

Millimeter-wave Radar/Imaging: Integrating radar or imaging functionality into the communication system opens up new operational possibilities. Such sensing may be valuable on its own or as an assistive tool for communication. E.g., exploiting mmW signals for time-of-flight ranging, directional-of-arrival estimation, and/or centimeter-/millimeter-accuracy localization can be useful in industrial control or future sensing applications, or as a tool to manage beam tracking overhead and latency.

Physical Hardware-based Security: Security and privacy are important concerns in mmW networks but also in emerging applications including vehicular communication, autonomous vehicles and wireless sensing. In addition to security through encryption, introducing security features at the hardware level can be valuable including beam hopping, frequency hopping, and multipath-based methods. The security of such schemes needs to be rigorously established for which HW-CSP interaction can be fruitful.

Testbeds: The NSF PAWR program is an invaluable opportunity for creating testbeds that can support large-scale mmW experimentation. The RCN is an excellent forum for the mmW community to engage in the design and development of mmW testbeds, in close collaboration with equipment vendors.

CSP-NET Interface Breakout: **Leaders:** M. Mezzavilla, I. Guvenc, H. Hassanieh, T. Henderson, R. Yang, Y. Kakishima, M. Andrews, and J. Zhu

Major remarks:

- The temporal directional dynamics of mmW propagation (including blocking effects, interference statistics with directional beams) are not fully modeled yet but this is critical to design network protocols and assess the performance of higher communication layers. One of the key preliminary ideas is to overlay a simplified version of raytracing on top of end-to-end network simulations. Can we think of other approaches?
- Should we capture/abstract also phase noise and antenna radiation patterns? If so, how? For what aspects is the binary power modeling of the antenna radiation pattern (fixed high-power at main beam and fixed low-power at side-lobe beams) an adequate approximation?
- A large community is familiar with link-level simulations and are skeptical about PHY layer abstractions while moving up the network stack. What is the sweet spot between fidelity and complexity? How can we scale with the number of nodes?
- PHY-abstraction will vary depending on the scenario, and the specific research goal. E.g., relative to raytracing, we should define different levels of tracing details that can be mapped onto specific research needs. Can we generalize?
- Do we need more sophisticated heterogeneous traffic models?

Moving forward:

- Try and define a reference CSP-NET 'dictionary/language' that can help push a productive dialogue forward.
- Create a taskforce and invite appropriate researchers to participate (mailing list?).
- Continue this cross-community interaction offline, (mailing list?), aiming to
  - let the signal processing community better understand the details of current PHY/MAC abstraction schemes, such as the ones adopted as part of the mmW module for ns3;
  - let the networking community better grasp the signal processing angles/needs.
- Lay the foundation for a white paper on these topics.

Tools, Prototypes, and Testbeds Breakout: **Leaders:** I. Wong, X. Zhang, K. Remley, and R. Shimon

The group identified a few key requirements for mmW testbeds, including full-fledge modules from baseband to RF to antennas, low-cost (especially for networking researchers), deep accessibility into intermediate modules along the RF chain (esp. for RF and circuit researchers), etc. The group recognized that the testing specification for industry products may be much more stringent than research prototype, and one probably should not try to design a too ambitious testbed that satisfy both.

In terms of the available testbeds, NIST is developing a phased-array beamforming simulator, which may be available in one year. Due to the cost constraint, large-scale mmW network testbed is still not quite feasible, but small scale deployment and testing is definitely feasible. One critical component for mmW is phased-array, a few research groups (e.g., in UCSD) have made their 28 GHz and 60 GHz phased-arrays publicly available, but the cost may still be an issue for most researchers. A modular lens-array-based testbed is being developed at UW-Madison that may be provide a lower cost alternative. Collaborative use of costly testbeds, among research groups, and between academia and industry, may be a viable option. Industry and academia may also collaborate in the development of testbeds.

Looking forward, to build a large-scale mmW testbed, one may repurpose commodity mmW devices (e.g., Qualcomm 802.11 network cards) as a basic node. But the key challenge is that such devices keep the driver and firmware closed-source. Ideally, this challenge can be overcome if we can figure out a viable collaboration mechanism with such vendors, even with constrained accessibility under certain licensing terms. In future, as the cost of mmW platforms lowers (e.g., to the level of USRP), then fully programmable large scale mmW testbed would be more viable.

Day 2: Thursday, July 20, 2017

Keynote 2: The second day started with two informative keynote presentations on the topic of the 3GPP **5G NR (new radio) standards**. The first keynote by **Dr. Boon Loong Ng.** (Samsung) focused on beam management issues, whereas the second keynote by **Dr. Amitava Ghosh** (Nokia-Bell Labs) focused on performance across multiple frequency bands (28-80 GHz). See the workshop agenda page for slides.

Readouts from Breakout Sessions: J. Paramesh (HW-CSP), M. Mezzavilla (CSP-NET), X. Zhang (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

Moderator: S. Rangan. **Panelists:** N. Golmie, A. Niknejad, T. Svensson, J. Chen, and A. Ghosh

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

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.

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: Panel 1 discussion notes.
- Appendix D: List of posters and demos with names of authors and presenters.
- Appendix E: Breakout sessions discussion notes.
- Appendix F: Panel 2 discussion notes.