Report on the Kickoff Workshop of the NSF mmW RCN

Dec 7-8, 2016

Catholic University of America

Executive Summary: The kickoff workshop of the new NSF RCN (research coordination network) on mmW (millimeter-wave) wireless (RF frequencies between 10 GHz and 300 GHz) networks was held on Dec 7-8, 2016 on the campus of Catholic University of America. The steering committee (SC) member H. Liu was responsible for the local arrangements. The workshop started with introductory remarks by PI Akbar Sayeed and NSF Program Director Thyaga Nandagopal on the motivation and premise of the RCN: to create a platform for academic-industrial and cross-disciplinary collaboration in the three key research areas driving mmW technology development: i) communications and signal processing (CSP) techniques, ii) networking (NET) protocols, and ii) hardware (HW) design, including antennas, mmW circuits, and analog-to-digital converters (ADC) and digital-to-analog (DAC) converters.

It was clear from the lively discussions in the two panels, three breakout sessions, and three poster sessions that the core premise of this RCN resonates on multiple fronts. Many new ideas were generated during the workshop. In particular, the following items stood out for action moving forward:

i) Creation of collaborative workgroups to address interdisciplinary problems. Two possibilities: i) HW-CSP interface: better system models that account for hardware characteristics; ii) CSP-NET interface: more accurate abstraction of the mmW PHY-MAC layer to incorporate into network simulators. Appropriate channel models for both i) and ii). The results of this work could be published in appropriate venues to increase impact.

ii) Identification of existing conferences and journals for publishing the results from RCN efforts. Proposals for creating of new venues if needed.

iii) Development of mmW Technology Roadmap: i) identification of short-term (RCN 2020) and longer-term (RCN 2025) research goals.

iv) Identification of moonshot programs, research thrusts, and target dates for crystallizing academic-industrial collaboration and generating additional funding in this space.

The feedback from the participants was generally very positive with many suggestions for improvements going forward. Overall, it is clear that there are many aspects in which this RCN could make significant contributions to moving mmW technology forward and create a new model for interdisciplinary industrial-academic collaboration. There is momentum in mmW research right now and it is up to the research community to capitalize on it.

Conclusions and Action Items for Next Steps before the 2nd Workshop: Before the next workshop, the PIs will work with the SC members and other participants to address all the important issues raised during the kickoff workshop, and also make a stronger case for the industry to come to this event. Specifically, we plan to build on the ideas and energy generated in the kickoff to:

1. Identify work groups and leaders for addressing some of the action items above.
2. Broadcast the call for participation for the 2nd workshop to a wider audience.
3. Flesh out the technology roadmap for this RCN’s contributions spanning the three areas for RCN 2020 and RCN 2025.
4. Develop a list of “moonshot problems”, especially with input from industrial SC members, to sharpen research focus and to materialize new government and industrial funding in mmW.

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Summary of Key Activities and Outcomes from the Workshop

Day 1: Wednesday, Dec. 7, 2016

Keynote I: The workshop was kicked off by an informative, engaging and inspiring keynote speech by **Jon Wilkins**, *Chief of the Wireless Telecommunications Bureau at the FCC*. Jon underscored the FCC's support and expectations for 5G wireless in general and mmW technology in particular, especially in view of the recent Spectrum Frontier's announcement. He also mentioned ongoing work at the FCC for opening up additional bands.

Panel 1: State of mmW Technology, Challenges & Opportunities – Industry & Regulatory Aspects

Moderator: A. Sayeed; **Panelists:** M. Nekovee, A. Sadri, A. Sampath, T. Thomas, and I. Wong

Summary of Key Discussion Points:

Industry is moving faster than research: Especially, for technology development below 40GHz. Some industry representatives felt that it would be better for academia to focus on problems that are longer term and complement industry research. In terms of deployment, the initial deployments will be in niche fixed wireless scenarios likely in the next 3-5 years; small cell mobile networks and more "massive deployments" will take longer, possibly 10 years.

Pressing Technical Challenges:

- **Beam tracking and mobility** – Beam discovery, channel estimation, and tracking remain a critical open problem for making mmW viable for mobile access. Some challenging issues include, closed form hybrid beamforming, efficient access point (AP) discovery by mobile user equipment (UE), and dealing with obstructions and foliage.
- **Network architecture to achieve low latency** – This will require high-bandwidth backhaul networks, cooperation across multiple access points (APs) to maintain connectivity to UEs, and improved interaction with the TCP layer. A related question is where to place the required computational power (in the cloud or at the AP).
- **Power, RF impairments and antennas –** Significant challenges need to be addressed in mmW hardware: the need to support multiple mmW bands; power amplifier efficiency, especially for the uplink (UL); phased locked loops (PLLs) with lower phase noise; multiple antenna arrays to provide full (sectorized) coverage.
- **Channel models –** Existing channel models are inadequate in fully capturing mmW propagation characteristics, and new operational scenarios, including: impact of foliage and high mobility, small-cell networks, and drone-based networks.

Lack of Affordable mmW Hardware Platforms for Academic Research: There is a need for industrial partners to share hardware platforms with academic researchers. The next best thing would be to share channel measurements with academic researchers. The EU mmMAGIC project is planning to do that, and the NIST 5G Channel Model Alliance is another resource for this.

New Applications Beyond Cellular and WiFi: Synergistic research issues may be identified by exploring new applications, including: mmW imaging and sensing; virtual reality/augmented reality; automotive applications; high-bandwidth video shared in automated robots.

Poster Sessions: Three poster sessions, each with about 12-13 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 testbed. A list of posters and authors is provided in Appendix D.

Demonstrations: A live mmW prototype link was demonstrated by the National Instruments team led by the steering committee member Ian Wong. It consisted of a point-to-point link operating at 73 GHz and a host PC showed the channel frequency and impulse response of the channel. Steering committee member Ashwin Sampath shared videos of initial demonstrations of a 28 GHz prototype developed by Qualcomm. The demonstration showed beamforming capability of AP and UE prototype nodes to maintain a link as the UE moved in a coverage area.

Breakout Sessions: Summary of Discussion Points

HW Breakout Session: Leaders: J. Buckwalter & A. Niknejad; **Scribes:** V. Saxena & S. Gupta

1. Substantial (x10) reduction in energy consumption possible, especially through post-CMOS (complementary metal oxide semiconductor) circuits.
2. Investigation of hybrid analog-digital approaches for wideband multi-beamforming and beyond is an important area for energy-efficient implementations.
3. Optimization of sub-circuits such as PAs, PLLs, and ADCs is important form the viewpoint of energy efficiency. Collaboration with other groups, such as CSP, would be important for identifying system-level metrics.
4. There is need for addressing the challenges in creating prototypes for academic research – too costly and time consuming at this time for individual academics to develop.
5. Academic participants expressed interest in developing a shared hardware IP (intellectual property) repository to reduce the cost of prototyping.
6. Fruitful opportunities exist for cross collaboration, particularly with the CSP community.
7. There is a need for appropriate venues for publication, journals and conferences, where interdisciplinary "system-level" work can be published and appreciated.

CSP Breakout Session: Leaders: S. Rangan & L. Swindlehurst; **Scribes:** M. Vu & C. Gursoy

1. Prototypes/testbeds – very much needed but costly and challenging for development by individual academics.
2. Energy consumption – processing of multiple high-bandwidth channels is computationally challenging and power hungry. Thus there is a need to optimize signal processing and communication protocols for energy efficiency. This will require collaboration across CSP-HW and CSP-NET areas.
3. Channel modeling – several issues remain unaddressed fully including dynamics, simulation tools (accurate models for NET layer on one hand and better modeling of HW effects on the other), vehicular models, foliage, and lower frequency-band aided estimation.

4. Directionality, synchronization, and tracking – this is a critical problem for enabling mobile mmW access, requires HW coordination, and has implications across the NET protocol layers, especially the MAC layer.
5. Resource allocation – efficient and dynamic resource allocation in beam-frequency is critical for achieving low latency in both fixed and mobile mmW networks. It requires cross-collaboration across CSP and NET areas and efficient HW realizations.
6. Network simulation – There is a need for more accurate network simulation tools to assess performance, complexity, energy tradeoffs. Initially, better abstractions of the physical (PHY) layer would enhance the accuracy of network level simulators. Further refinements could be obtained by incorporating models for HW components. Stochastic geometry tools, interference models, and evaluation of MAC protocols via testbed experimentation could be leveraged.
7. Waveforms – Investigation of appropriate waveforms, such as OFDM (orthogonal frequency division multiplexing) and SC (single carrier) waveforms, for the mmW air interface.
8. Use cases – Exploration of important use cases, such as vehicular networks, VR (virtual reality)/AR (augmented reality), backhaul networks, and small-cell access networks.
9. Multi-point connectivity (AP coordination) – to ensure mobile UE connectivity and low latency.
10. Implications of PHY layer design for core network protocols, and transport layer.

NET Breakout Session: **Leaders:** M. Krunz and I. Guvenc; **Scribes:** A. Mackenzie & N. Michelusi

Major Research Issues:

1. Network/node discovery and initial coordination – this issue is critical for mobile access and, is related to channel discovery and tracking and would require coordination with CSP area.
2. Scheduling and resource allocation in time, frequency, and space – this issue is critical for network optimization and low latency and would require coordination with CSP protocols.
3. Network protocols and architecture – issues include cross-layer design, coordinated multipoint (CoMP) communication, and control- and data-plane separation.
4. Heterogeneous coexistence and spectrum sharing – issues involve interference management and inter-network coordination, and would require collaboration with the CSP area.
5. Coverage, capacity, latency, and energy-efficiency tradeoffs – these tradeoffs need to be explored for network optimization in different use cases and would entail collaboration across HW, CSP, and NET areas.
6. Testbeds and Experimentation – there is a need for them in academic research and naturally requires resource and collaboration across researchers in the three areas.
7. Applications – different use cases may underscore different aspects of network optimization.

Moving forward:

- Identifying short- to medium-term goals to facilitate collaboration and progress.
- Continued collaboration between industry/academia/government.
- Need to approach goals using metrics; e.g., spectral or power efficiency, and also networking related metrics, such as spatial capacity density (bits/sec/m^2), or area spectral efficiency.
- In the longer term, need to look above 40 GHz. May be this RCN could identify and address big challenges, such as full-dimensional MIMO or the use of very high-dimensional antenna arrays.

Post-Breakout Session Discussion: Cross-Disciplinary Research Themes

After the breakout sessions, at least one leader from each breakout (Rangan, Buckwalter, Krunz), and the moderator for Panel 2 (Golmie), met to discuss the key cross-disciplinary research themes that emerged from the breakouts to seed the Panel 2 discussion on Day 2, and to identify near-term research problems to work on. In terms of the latter, the CSP area provides a natural bridge between the NET and HW areas, and this was evident from the breakout session discussions as well. So, it makes sense that collaborative research between CSP-HW areas and CSP-NET areas is pursued initially.

CSP-HW: In this interface, the issue of incorporating the (non-ideal) HW characteristics, such as frequency selectivity over the bandwidth or phase noise characteristics, into the CSP algorithm design. In addition, suitably abstracted models for HW components could be incorporated into the PHY layer system model. This would lead to more accurate system models for simulation, energy consumption, and optimization.

CSP-NW: Channel modeling provides a natural glue for this interface and came up in the discussions of both breakouts. In particular, the channel characteristics play an important role in CSP techniques in terms of initial channel discovery and channel estimation and beam tracking. On the other hand, the importance of cross-layer design in mmW networks was also recognized. In particular, PHY-MAC interactions for resource allocation and the impact of higher layer protocols, such as TCP, on overall latency. So, a natural direction here would be to develop appropriate channel models at the right level of abstractions to enable PHY optimization, PHY-MAC design, and MAC and higher layer optimizations.

Day 2: Thursday, Dec 8, 2016

Keynote 2: The second day started with an informative keynote by **Julius Knapp**, *Chief of the Office of Engineering and Technology at the FCC*, including a short presentation by **Walter Johnston**, *Chief of the Electromagnetic Compatibility Division*, on the new process for obtaining experimental licenses.

The Panel 2 Discussion was primed by a **readout of the breakout sessions and the discussion on collaborative research directions** by S. Rangan (CSP), J. Buckwater (HW), M. Krunz (NET). The key research themes identified for short-term collaboration are highlighted above.

Panel 2: Cross-disciplinary Collaboration in mmW Research – Scoping the Landscape and Charting a Course for RCN Contributions

Moderator: N. Golmie; **Panelists:** Amativa Ghosh, Arun Ghosh, Charile Zhang, Ian Wong, Mythri Hunukumbure, Sundeep Rangan, Jim Buckwalter, Marwan Krunz

Summary of Key Discussion Points:

Interdisciplinary Research Collaboration: The panel emphasized the need for interdisciplinary research to solve the major technical challenges, echoing the discussion from breakout sessions. Some problems that could benefit from interdisciplinary collaboration between HW, CSP and NET communities:

- CSP-NET: Interaction between beamforming front-end and MAC and higher layers.
- HW-CSP: PA design and signal design for peak-to-average-power-ratio (PAPR) reduction.
- HW-CSP: Trading bit resolution at ADC with dense spatial sampling at the antennas.

- HW-CSP: Hardware design that supports both communication and sensing.
- HW-CSP-NET: Potential of full-duplex in mmW networks.
- HW-CSP-NET: Advanced network simulators that take into account channel models and PHY protocols; better PHY models that take into account HW component characteristics.
- NET-CSP: Joint optimization of PHY-MAC interface and interaction with the TCP layer.
- NET-CSP: Backhaul network architectures, including static and mobile.
- NET-CSP: Cross-domain optimization to achieve high rate and reliability and low latency.
- NET-CSP: Resource allocation and scheduling in mmW networks

The Need for Large Scale Testbeds: It was noted that the lack of large scale experimental testbeds in academia is hindering research. New strategies are needed to address this problem, including better collaboration between academics developing testbeds and help from industry.

The Lack of Appropriate Venues for Publishing Interdisciplinary Research: It also noted that there is a lack of appropriate venues – conferences and journals – for publishing interdisciplinary research. This can impact junior researchers significantly. Thus, there is a need for creating such venues. It was also noted that some of the recent conference workshops on mmW wireless may provide one such venue.

Vertical Integration for New Use Cases: The need for collaboration across different use cases was also emphasized to increase the impact of mmW research research.

Collaboration Between Industry and Academia: The collaboration between industry and academia could be more complementary in which academic researchers are working on problems informed by industry and perhaps more longer-term problems. Academic researchers emphasized the need for funding from both government and industry sources. Industrial partners indicated that even cross fertilization of ideas, without funding, could be impactful. However, IP issues can hinder such interaction. Industry representatives noted that perhaps some "moonshot" problems need to be identified by this RCN for academic-industrial collaboration to generate more interest and support from industry. Associated research challenges could also lead to new federal funding. Some possible moonshot problems and target metrics: i) higher spectral efficiency in mmW bands, ii) lower power consumption (x10, e.g.) at mmW frequencies to make it comparable to sub-6 GHz bands, iii) can we achieve full digital beamforming with 128/256 element arrays and possibly low-bit ADCs?, and iv) Can we design a PA with 70dBm output power and with an efficiency of at least 35%?

RCN Role and Future: It was noted that the mmW RCN can play several important roles in facilitating mmW research and development: i) bring together researchers from different areas, academia and industry, ii) help identify big and impactful research problems and thrust areas, which could then be used to generate government and industry funding, iii) help identify short- and longer-term goals and organize projects with a 10-year time-frame for RCN 2026 deliverables, iv) perhaps pool relevant resources to create a competition for solving a major research challenge, analogous to the DARPA spectrum challenge, v) broadening academic/industrial participation, vi) new strategies for testbed development for academic research, and vii) identifying and creating new avenues for publishing system-level interdisciplinary mmW research.

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Summary from Feedback Survey: We conducted a survey after the workshop, and requested the participants to provide feedback to improve the workshop quality. Below is a summary of the feedback.

Expectations of participants: Most people came with a learning mind, and expect to have live interaction with the industry. Many would like to find interdisciplinary research opportunities, based on interaction with people working on different aspects of mmW. It is recommended that the RCN workshop have clearly defined goals, e.g., defining the research thrusts areas, defining funding mechanisms, and potentially drafting large proposals as a group.

Key takeaways: The participants are excited about the big push from industry and government in the mmW area. They learned about latest progress and interesting research problems. In addition to the huge potential, participants became aware of the challenges in making mmW a reality, including barriers from: hardware, signal processing, channel measurements, mobility support, energy efficiency, and testbeds. Academic participants look forward to industry's "willingness to share and collaborate".

What was missing: Greater levels of industry involvement was desired; e.g., from Google, Microsoft, Facebook, AT&T, and SiBeam who have ongoing mmW project. Also, different regions (Asia, Europe) and areas (antennas, network systems, mmW sensing) should be represented, along with funding agencies other than NSF. It would be better if the panel discussions can include more detailed presentations of the progress/perspectives from the industry. The poster session should be longer to give people more time for meaningful discussion. The breakout sessions are also too short to cover the lengthy list of items (which should be prioritized). Overall, some deemed that the discussion was a bit all over the place, and it would be better to aim for some concrete outcomes, e.g., defining major thrust areas.

Suggestions for subsequent meetings: We should define a few major research thrusts and use cases for the next 10 years and encourage the community to work on them. After each workshop, we should be able to itemize the discussion outcome, e.g., define a set of specifications for an open testbed. What is still lacking is the model of operation and work and how this RCN is actually going to facilitate coordinated research and development between the academia and industry. It would be useful to have an industry participant present an update on what the 'standards' are up to in terms of study items, work items, current state of standardization, and expected timelines. It is also recommended that we propose a journal or conference dedicated to mmW.

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

- Appendix A: Workshop agenda.
- Appendix B: A list of attendees and affiliations, including the SC members and keynote speakers.
- Appendix C: Panel 1 discussion notes.
- Appendix D: A list of posters along with the names of authors.
- Appendix E: Breakout sessions discussion notes.
- Appendix F: Panel 2 discussion notes.
- Appendix G: Pre-workshop discussion points.