# 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.

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**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.

# APPENDICES

**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.

# APPENDIX A:
# WORKSHOP AGENDA

# Workshop Agenda
# Kickoff Workshop of the NSF RCN on mmW Wireless
# December 7-8, 2016
# Catholic University of America

**Day 1: Wednesday, Dec 7, 2016**

**8:00am-8:45am:** Registration and (Yummy) Breakfast

**8:45am-9am:** Welcome and Opening Remarks, Keynote Introduction. Slides

**9:00am-9:30am**: **Keynote – Jon Wilkins**, *Chief, Wireless Telecommunications Bureau, FCC*

**9:30am-11:00am: Panel Discussion 1 (90 mins)**: **State of mmW Technology, Challenges & Opportunities – Industry & Regulatory Aspects**

**Moderator:** Akbar Sayeed

**Panelists:** Timothy Thomas (Nokia-Bell Labs), Maziar Nekovee, (EU mmMAGIC), Ali Sadri (Intel), Ashwin Sampath (Qualcomm), Ian Wong (National Instruments)

**Scribes:** Haitham Hassanieh & Xinyu Zhang

**11:00am-11:30am**: Coffee Break

**11:30am-12:30pm Poster Session 1 (60 mins)**: 13 posters

**12:30pm-1:30pm:** Catered Lunch

**1:30pm-2:30pm: Poster Session 2 (60 mins)**: 12 posters

**2:30pm-4:00pm: Breakout Sessions: Development of Technology Roadmap for mmW Research**

**Three parallel sessions (90 min each):**

A) **Communication and signal processing; Discussion leaders:** Sundeep Rangan & Lee Swindlehurst; **Scribes**: Mai Vu & Cenk Gursoy

B) **mmW hardware, circuits, antennas, digital hardware, prototypes and testbed**s; **Discussion leaders:** Jim Buckwalter & Ali Niknejad; **Scribes**: Vishal Saxena & Subhanshu Gupta

C) **Networking protocols**; **Discussion leaders:** Ismail Guvenc and Marwan Krunz; **Scribes:** Allen MacKenzie & Nicolo Michelusi

**4:00pm-4:30pm**: Coffee Break

**4:30pm-5:30pm: Poster Session 3 (60 mins)**: 12 posters

**4:30pm – 5:30pm: Breakout session leaders meet to brainstorm discussion items for Panel 2**

**6:00pm:** Catered Dinner

**Workshop Agenda**
**Kickoff Workshop of the NSF RCN on mmW Wireless**
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**Day 2: Thursday, Dec 8, 2016**

**8:00am-8:30am:** Breakfast and Registration

**8:30am-9:00am: Keynote** – Julius Knapp, *Chief, Office of Engineering and Technology, FCC.* Slides

**9:00am-9:30am: Readout from Breakout Sessions to Seed the Panel 2 Discussion (One discussion leader from each breakout)**

**9:30am-11:00am: Panel Discussion 2 (90 mins): Cross-disciplinary Collaboration in mmW Research – Scoping the Landspace and Charting a Course for RCN Contributions**

**Moderator:** Nada Golmie

**Panelists:** Marwan Krunz (Arizona), Sundeep Rangan (NYU), Charlie Zhang (Samsung), Ian Wong (NI), Mythri Hunukumbure (mmMAGIC), Amitava Ghosh (Nokia-Bell Labs), Arun Ghosh (AT&T), Jim Buckwalter (UCSB)

**Scribes:** Haitham Hassanieh & Xinyu Zhang

This panel will build on the discussion from the breakout sessions from Day 1 to identify key directions for cross-disciplinary collaborations as part of the RCN contributions. We expect strong and free-flowing participation from all attendees, especially those who have been engaged in cross-disciplinary research and/or who may want to be actively involved in cross-disciplinary research as part of this RCN.

What are some big problems that will require cross-disciplinary collaboration? What kind of contributions can we expect from this RCN in the next 3 years?How do we facilitate cross-disciplinary collaboration? What are the key elements of cross-disciplinary collaboration? What are some common hindrances to collaboration that we need to be aware of? What are some key cross-disciplinary topics for initial focus?

**11:00am-11:15am: Closing Remarks (15 mins):** including participant impressions and feedback, suggestions for future workshops

Akbar Sayeed, Xinyu Zhang, and Hang Liu

**11:15am-noon:** Coffee and Boxed Lunch

# APPENDIX B:
# LIST OF ATTENDEES

| | First Name | Last Name | Affiliation |
|---|---|---|---|
| | **Steering Committee:** | | |
| 1 | Akbar | Sayeed (PI) | University of Wisconsin-Madison |
| 2 | Xinyu | Zhang (co-PI) | University of Wisconsin-Madison |
| 3 | James | Buckwalter | UC-Santa Barbara |
| 4 | Amitava | Ghosh | Nokia Bell Labs |
| 5 | Arunabha | Ghosh | AT&T |
| 6 | Nada | Golmie | NIST |
| 7 | Ismail | Guvenc | North Carolina State University |
| 8 | Mythri | Hunukumbure | Samsung, UK (mmMAGIC project) |
| 9 | Marwan | Krunz | U. Arizona |
| 10 | Hang | Liu | Catholic U. of America |
| 11 | Maziar | Nekovee | Samsung, UK (mmMAGIC project) |
| 12 | Ali | Niknejad | UC-Berkeley |
| 13 | Sundeep | Rangan | New York Univesity |
| 14 | Ali | Sadri | Intel |
| 15 | Ashwin | Sampath | Qualcomm |
| 16 | Ian | Wong | National Instruuments |
| 17 | Charlie | Zhang | Samsung, US |
| | | | |
| | **NSF Program Director:** | | |
| 18 | Thyagarajan | Nandagopal | NSF CISE |
| | | | |
| | **Keynote Speakers:** | | |
| 19 | Jon | Wilkins | FCC, Wireless Telecommunications Bureau |
| 20 | Julius | Knapp | FCC, Office of Engineering & Technology |
| 21 | Walter | Johnston | FCC, Office of Engineering & Technology |
| | | | |
| | **List of Attendees:** | | |
| 22 | Morteza | Abbasi | North Carolina State University |
| 23 | Ahsan | Aziz | National Instruments |
| 24 | Alpaslan | Demir | InterDigital |
| 25 | Amal | Ekbal | National Instruments |
| 26 | Hussain | Elkotby | Tufts University |
| 27 | Mohammed | ElTayeb | UT-Austin |
| 28 | Brian | Floyd | North Carolina State University |
| 29 | Stefano | Galli | Huawei |
| 30 | Monisha | Ghosh | U. Chicago |
| 31 | James | Gigrich | Keysight |
| 32 | Nuria | Gonzalez-Prelcic | University of Vigo, Spain |
| 33 | Mohsen | Guizani | U. Idaho |
| 34 | Subhanshu | Gupta | Washington State U. |
| 35 | M. Cenk | Gursoy | Syracuse U. |
| 36 | Muhammad Kumail | Haider | Rice University |
| 37 | Haitham | Hassanieh | University of Illinois at Urbana-Champaign |
| 38 | Robert W. | Heath, Jr. | UT-Austin |

| | | | |
|---|---|---|---|
| 39 | Anoosheh | Heidarzadeh | Texas A&M University |
| 40 | Deukhyoun | Heo | Washington State U. |
| 41 | Wen | Huang | University of Illinois at Urbana-Champaign |
| 42 | Taejoon | Kim | City University of Hong Kong |
| 43 | Valencia | Koomson | Tufts University |
| 44 | Harish | Krishnaswamy | Columbia University |
| 45 | Greg | LaCaille | UC-Berkeley |
| 46 | Xiuling | Li | University of Illinois at Urbana-Champaign |
| 47 | Min | Liang | University of Arizona |
| 48 | David | Love | Purdue University |
| 49 | Allen B. | MacKenzie | Virginia Tech |
| 50 | Soumyajit | Mandal | Case Western |
| 51 | Arjuna | Mandanayake | University of Akron |
| 52 | Hani | Mehrpouyan | Boise State U. |
| 53 | Marco | Mezzavilla | New York University |
| 54 | David G | Michelson | U. British Columbia |
| 55 | Nicolo | Michelusi | Purdue University |
| 56 | Jeyanandh | Paramesh | Carnegin Mellon |
| 57 | Jeyanandh | Paramesh | Carnegin Mellon University |
| 58 | Parth H. | Pathak | George Mason University |
| 59 | Borja | Peleato | Purdue University |
| 60 | Antonio | Puglielli | UC-Berkeley |
| 61 | Zouheir | Rezki | U. Idaho |
| 62 | Vishal | Saxena | U. Idaho |
| 63 | Kaushik | Sengupta | Princeton University |
| 64 | Tommy | Svensson | Chalmers University, Sweden |
| 65 | Lee | Swindlehurst | University of California, Irvine |
| 66 | Timothy | Thomas | Nokia Bell Labs |
| 67 | Vutha | Va | UT-Austin |
| 68 | Mai | Vu | Tufts University |
| 69 | Hao | Xin | University of Arizona |
| 70 | Sarah | Yost | National Instruments |
| 71 | Seyed A. (Reza) | Zekavat | Michigan Tech U. |
| 72 | Yanzi | Zhu | UC-Santa Barbara |
| 73 | Michele | Zorzi | University Padova, Italy |

# APPENDIX C:
# PANEL 1 DISCUSSION NOTES

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

**Panelists:** Timothy Thomas (Nokia-Bell Labs), Maziar Nekovee, (EU mmMAGIC), Ali Sadri (Intel), Ashwin Sampath (Qualcomm), Ian Wong (National Instruments)
**Moderator:** Akbar Sayeed
**Scribe:** Haitham Hassanieh

## Summary of Key Points:

### (1) Industry Is Moving Much Faster Than Research

Industry has already moved into standardization and 3GPP has already looked at systems up to 40GHz. Their standards are based on suburban channel measurements and do not reflect urban environments. 3GPP standards are also pushing towards forward compatibility with which limits efficiency. Similarly, Verizon developed specifications by modeling the channel using ray tracing and without measurements which does not capture a wide range of problems such as foliage, blockage and penetration losses. The first deployment of mm Wave systems for static links is expected to happen by 2018 winter olympics. However, some predict that initial prototypes for small cells can take up to 3-5 years and 10 years before actual wide deployment.

### (2) Millimeter Wave Challenges

### (2.1) Beam Tracking and Mobility:

Tracking and mobility remain an open problem. Enabling mobility is needed for the success of millimeter wave. Digital beamforming is prohibitively expensive and hence analog or hybrid beamforming is needed. Some of the questions posed by the panel include: How to preform closed loop hybrid beamforming? How to measure the channel and get CSI feedback quickly? How to avoid spending many RX cycles searching for the BS? How to track the beam once you find it? How to deal and work around foliage? …

### (2.2) Network Architecture and Latency:

Achieving low latency will be challenging and is needed for mmWave to meet the 5G requirements. The panelists emphasized the need for backhauling that can support very high bandwidth. Moreover, due to the large latency introduced during link establishment, multiple base stations must cooperate. Perhaps a user needs to connect to multiple base stations at once to always sustain the link and avoid disruptions. This suggest the need to bring the control down all the way to the lower layers. Furthermore, while EU with mmMagic is moving to a CRAN architecture, it is not clear that CRAN can provide the required low latency. Mobile edge computing will be needed to reduce the end to end latency. Finally, there is also a need to rethink the transport layer since TCP can significantly increase latency especially with mmWave channels which are susceptible to link disruptions.

### (2.3) Power, RF Impairments and Antennas:

- mmWave bands are fragmented and hence multiple RF radios and antennas will be required to support different bands.
- Power amplifier efficiency is very low which is a problem especially for the uplink.
- PLLs with lower phase noise are needed. Otherwise we will have to compromise and use much wider subcarrier spacing to be able to track the phase.
- Antennas do not give 360 degree coverage and hence multiple arrays are required on the device.

### (3) Lack of Affordable mmWave Platforms for Research

Millimeter wave testing platforms are extremely expensive for academics. National Instruments expects their platform cost to go down with time! Other companies are not in the business of providing platforms. However, mmMagic project did a lot of measurements which are available for download and they are planning to provide channel emulators around 2018.

### (4) Millimeter Wave Applications Beyond Cellular and WiFi

- Millimeter Wave Imaging and Sensing
- Virtual Reality and Augmented Reality.
- Automotive Space: 77 GHz Radar, V2X applications, autonomous vehicles.
- Automated Robots: factories of the future where robots send 360 deg video on the uplink and downlink is used for control.

**Panel 1 Scribe Notes: Xinyu Zhang**

Introductory comments:

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Ashwin (Qualcomm)

A summary of recent experiences and progress in mmWave communications.

From the channel modeling perspective, we have made the following observations:

1) NLOS is feasible! -- This has become a widely accepted concept with ample experimental verifications.

2) Reflection is possible, though weak. This has also been verified through comprehensive experiments.

3) Suburban area is challenging; foliage in outdoor;

4) Delay spread may be worse due to shorter wavelength

5) Pathloss exponent differs slightly from microwave

From the hardware perspective, phase-noise (from both hardware and air interface) has been a significant challenge for mmWave. PA efficiency, and associated power consumption remains a challenging problem for battery-powered mmWave devices.

From the communication network perspective, one unique problem of mmWave is the bursty interference, in contrast to the Gaussian interference (based on averaging effect) model in low-frequency networks. An efficient closed-loop network protocol is still needed, with low network management overhead (scanning, discovery, beam searching, etc.). Modulation scheme, i.e., the choice between single-carrier and OFDM, remains debatable. Multi-carrier modulation is sensitive to phase noise, and the problem becomes pronounced in mmWave.

From the deployment perspective, heavy overlapping is needed between cells to ensure coverage and alleviate the irregular cell shape.

One benefit, though, is that mmWave links themselves can serve for backhaul connectivity, which significantly reduces deployment/maintenance overhead.

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Amitava (Nokia)

A general observation is that industry moves faster than academia in the mmWave area. More accurate channel modeling and measurement is needed to ease research and standardization.

mmWave networks can benefit from a mesh backhaul, which comprises fixed beam mmWave links.

mmWave will encounter substantial challenge in suburban environment, due to foliage, penetration loss, moving vehicles, etc.

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Ian Wong (NI)

I would like to summarize my observation of the mmWave challenges in 4 Ps:

1) Propagation: Channel modeling/sounding efforts are still ongoing.

Innovative channel measurement techniques are needed to facilitate modeling, especially for mobile scenarios.

2) Protocol: The most outstanding aspect lies in hybrid beamforming (analog plus digital). In the microwave band, massive MIMO already started adopting this technology. For mmWave, it becomes a must.

3) Performance: The holy-grails lies in high-bandwidth, low-latency, as expected for 5G. Several challenges in achieving such performance include: CSI feedback overhead, handling truly mobile scenario, etc. To achieve coverage and mobility, mmWave CoMP will be a niche solution.

4) Price: We need an economical architecture to move massive data around.

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Ali Sadri (Intel)

In the mmWave domain, the following problems are considered solved by the industry: beamforming, silicon, modulation. But there exist quite a few outstanding issue, especially beam tracking and mobility.

The mmWave usage models are often constrained by range.

Despite the split spectrum domains the industry and academia are working on, there are no significant differences: 28 to 60 GHz behaves quite similarly.

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Maziar Nekovee (EU mmMAGIC)

EU is investing 600m per year in developing 5G technologies, including mmWave.

There exist non-trivial deployment challenges for mmWave, particularly in achieving smooth coverage. Network coordination may be a solution – Samsung Europe has demonstrated handover across basestations. In terms of network architecture, EU will move to C-RAN, with 100Gbps links to connect BBU and RRU. This may be combined with self-organizing networks, comprised of small-cells with an order of magnitude higher density.

One note about channel modeling: mmMAGIC already built a channel modeling software, publicly accessible.

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Audience Q&A

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Q: What is needed on the networking layer and backend to achieve 1mm latency?

How about power consumption (transmission/computation)?

A:

Maziar: Mobile edge computing can be the eventual solution to reduce latency.  In addition, across-layer interaction is needed between physical layer and TCP, using techniques such as network coding.

Ali: The energy per bit of mmWave devices should be lower than WiFi---We just need to make sure utilization is high with proper sleep scheduling. Processing power is low because beamforming is done in analog; digital power consumption should be similar to sub-6GHz.

Amitava: Although the transmission latency may be low, latency worsens under blockage (need handover).

Ashwin: To achieve ultra-low latency, we need to distribute the data, e.g., through caching. Power consumption can be cut through waveform optimization, multi-band cooperation, etc.

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Q: When will mmWave networks be deployed?

A:

Amitava: According to vendors, the deployment should start to roll out during the 2017-2018 time frame. The deployment will start at 28 GHz, and later go to even higher frequencies.

Ali: My personal view is that mmWave won't get "massive" deployment in the next 10 years, because of the aforementioned challenges.

Maziar: Trial deployment is already happening at EU, Korea, etc. Beside cellular networking, there are also niche use cases such as fiber to home.

Ashwin: Software compatibility is the main hindrance for deployment. We need to make sure users experience a smooth transition from 4G to 5G.

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Q: How to make mmWave work together with other verticals?

A:

Ian: mmWave for V2X (automotive scenarios) can be a disruptive technology, but may take another 10 to 15 years.

Amitava: There is ongoing investment on using 60/76 GHz for consumer use cases: radar imaging, VR, etc. This will take some time to penetrate the real-world, because people need to get used to new devices on 10 year cycles.

Maziar: Many industrial application exist: autonomous robot, VR control of robot, VR streaming, etc.

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Q: How to address form factor and cost at scale?

A:

Ian: It won't a problem when deployed/sold at scale.

Ashwin: It comes down to hardware architecture, e.g., how to partition the RF chain.

Amitava: One noteworthy observation is that the basestation power needs to be higher due to the use of multiple sectors.

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Q: What are the challenges for circuit components

A:

Ashwin: PA efficiency (to ensure uplink rate/range), PLL with low phase noise, support for multiple bands

Ian: Some of the challenges can be resolved by examining prior research in aerospace, e.g., radar phased array

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Q: How challenging is phase noise? Are there any opportunities for antenna designs the solve problems in tracking/coverage/loss-compensation?

A:

Ashwin: How severe phase noise is depends on which band you are using---higher frequencies are more vulnerable to phase noise.

For beam tracking, the key thing is to make the protocols simpler and schedule the tracking intelligently.

As for coverage, you don't necessarily need 360-degree in practice.

Polarization also needs to be considered.

Amitava: Digital compensation can alleviate phase noise.

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Q: How to ensure better cooperation between industry and academia to make channel modeling easier and cost effective?

A:

Ian: Cost of channel measurement hardware is a challenge; portability is also in our mind. These issues will be solved over time, e.g., through a mmWave version of USRP.

Maziar: An accurate open-source channel emulator from mmMAGIC will be released in 2017-2018.

Ashwin: It is not our business to build channel sounder.

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Q: Cost effectiveness for wireless optical communications, in comparison with mmWave?

A:

Ali: LOS propagation of optical is a disadvantage

Ian: RF over fiber can be a solution for partitioning baseband and RF front-end

# APPENDIX D:
# LIST OF POSTERS

**Poster Session 1:**

1. One-Bit Quantization for mm-Wave Massive MIMO Systems, A. Lee Swindlehurst (UC-Irvine), Amine Mezghani, Yongzhi Li, Amodh Saxena
2. Design and Fabrication of Millimeter-wave Integrated Circuits Using Hexagonal Nanoferrite Materials, Valencia Joyner Koomson, Mohammed Afsar, Tufts University
3. Mobility Resilience and Overhead Constrained Adaptation in Mobile 60 GHz Networks, Muhammad Kumail Haider, Edward W. Knightly, Rice University
4. Sigma-Delta Arrays for Rejecting Amplifier Noise, Distortion and Quantization Noise, Arjuna Madanayake and Soumyajit Mandal, University of Akron
5. Extreme Miniaturization of Passive Electronic Devices for Millimeter Wave Applications, Wen Huang, Moyang Li, Jingchao Zhou, Paul Froeter, Julian Michaels, and Xiuling Li, UIUC
6. QC-LDPC codes for mmWave, Borja Peleato, Purdue University
7. Channel estimation and hybrid precoding in frequency selective mmWave channels, Nuria Gonzalez-Prelcic, University of Vigo, Spain
8. mmMAGIC: Pioneering Enabling Technologies for 5G mm-wave Adoption, Mythri Hunukumbure and Maziar Nekovee, and Miurel Tercero
9. Infrastructure-assisted Reliability in 60 GHz WLANs, Parth H. Pathak, George Mason University
10. Luneburg lens based wireless system and channel modeling at millimeter wave frequency, Min Liang, Hao Xin and Tamal Bose, U. Arizona
11. The Millimeter-Wave Revolution, Amitava Ghosh, Nokia-Bell Labs
12. Millimeter-Wave UAV Communications and Channel Modeling, Monisha Ghosh (U. Chicago) and Ismail Guvenc (NC State)
13. Multipath Transmission Scheduling in Millimeter Wave Cellular Networks, Xianfu Chen (VTT), Pei Liu (NYU), Shenghe Xu (NYU), and Hang Liu (CUA)

**Poster Session 2:**

1. Hybrid CMOS Photonic Integrated Circuits for Millimeter Wave Communication, Vishal Saxena, U. Idaho
2. 60-GHz Communications: Fundamental Limits and Practical Challenges, Zouheir Rezki, Vishal Saxena and Mohsen Guizani, U. Idaho
3. The Bufferbloat Problem over Intermittent Multi-Gbps mmWave Links, Menglei Zhang* , Marco Mezzavilla* , Jing Zhu^, Sundeep Rangan* , Shivendra Panwar*, * = NYU, ^ = Intel.
4. Millimeter-wave MIMO for Backhaul Networks, James Buckwalter, UCSB

5. MIMO mmWave Communications via Reconfigurable Antennas, Hani Mehrpouyan (Boise State U.), Vida Vakilian, Hamid Jafarkhani, and Nader Behdad
6. Cross-Layer control of Dense, Mobile, Millimeter wave Networks, Nicolo Michelusi, Purdue.
7. Reconfigurable, Efficient, and Scalable Millimeter-Wave Systems, Brian Floyd (NC State), Charley Wilson, Anirban Sarkar, Kevin Greene, and Yi-Shin Yeh
8. Networks Exploiting Millimeter-wave Opportunities, Allen B. MacKenzie, Virginia Tech
9. Millimeter Wave Communications: from Point-to-Point Links to Agile Network Connections, Haitham Hassanieh, UIUC
10. OpenMili: a 60 GHz Software-Radio with a Programmable Phased-Array Antenna, Jialiang Zhang, Xinyu Zhang, Pushkar Kulkarni, and Parameswaran Ramanathan, UW-Madison
11. Creating Diversity in 5G via Beam Pattern Jittering, Seyed Zekavat, Michigan Tech.
12. Open platform for mmWave research and prototyping, Ian Wong and Amal Ekbal, National Instruments

**Poster Session 3:**

1. Millimeter Wave communication using out of band information, Robert W. Heath Jr., UT-Austin
2. A Modular Array Architecture for Millimeter Wave Massive MIMO, Greg LaCaille, Antonio Puglielli, Lorenzo Iotti, Emily Naviasky, Elad Alon, Borivoje Nikolic, and Ali M. Niknejad, UC-Berkeley
3. Modeling and design techniques for Energy-Efficient and Scalable MIMO Transceivers for Gigabit Mobile Access, Deukhyoun Heo and Subhanshu Gupta, Washington State U.
4. Emerging Scenarios for MmWave Channel Models, David G Michelson, U. British Columbia
5. Optimizing Millimeter Wave Systems for User EM Exposure Constraints, M. Rodrigo Castellanos, David Love (Purdue), and Bertrand Hochwald
6. Interference Modeling for 5G Networks with Millimeter Wave Beamforming, Hussain Elkotby and Mai Vu, Tufts U.
7. Generalization of Reconfigurable mm-Wave Transmitter Architectures and Antenna Interfaces through Multi-port Network Synthesis Approach, Kaushik Sengupta, Princeton
8. Millimeter-Wave Communications over Heterogeneous Cellular Networks, Cenk Gursoy and Esma Turgut, Syracuse University.
9. Millimeter-Wave Channel Sounding, Taejoon Kim, City U. Hong Kong.
10. Multi-beam CAP-MIMO Transceiver Architecture and Prototype for Multiuser Communication at 28 GHz, John Brady, John Hogan, Chris Hall, Kevin Zhu, and Akbar Sayeed, UW-Madison

11. Reusing 60GHz Networking Radios for Imaging, Yanzi Zhu and Heather Zheng, UC Santa Barbara
12. Directional Array in Initial Cell-searching for Millimeter-Wave Cellular Networks, Toan K. Vo Dai, Hang Liu, and Ozlem Kilic (CUA)

# APPENDIX E: BREAKOUT SESSIONS DISCUSSION NOTES

## Hardware (HW) and Prototyping: Breakout Discussion Summary

**Leaders**: Jim Buckwalter and Ali Niknejad
**Scribes**: Vishal Saxena and Subhanshu Gupta

Our panel found that short, medium, and long-term priorities will continue to exist in the performance optimization of millimeter-wave circuitry. For example, it is widely believed that substantial energy reduction, i.e. 10x, should be possible for millimeter-wave circuit architectures optimized to support multibeam, MIMO, and array of arrays architectures. Improving power consumption will occur through a number of research endeavors including the heterogeneous integration of "beyond-CMOS" devices with conventional CMOS ICs for improved millimeter-wave performance as well as working carefully with signal-processing and network researchers to streamline architectures according to the network requirements. These efforts will require collaboration between hardware, signal processing, and systems researchers and offer an opportunity for the National Science Foundation to pursue approaches that could be complementary to industry efforts.

The primary long term priority that our panel identified is to continue to investigate hybrid approaches that consider the interplay between analog and digital signal processing to support complex beamforming tasks. Signal processing could play a number of critical roles beyond simply forming one or multiple beams and will also play a role in interference mitigation in the array or for full duplex systems as well as linearization of the array to support complex waveforms.

A second priority near term priority is to continue to explore optimization of subcircuits, such as power amplifiers, ADCs, and PLLs, for performance constraints such as power, wideband operation, or compliance against the standards associated with upcoming 5G interfaces. Individual circuit improvements can yield much better efficiency as power amplifiers are currently optimized primarily to frequency bands and output power levels. As the waveforms that are required for 5G interfaces and the number of beams/users that will be supported is determined, research into optimizing components will help to support systems researchers who seek to figure out the overall power constraints for the system. Again, our panel believed that more clarity regarding the performance requirements of components will be developed through close collaboration with other communities.

A final priority – however, no less long term critical need for our community - is rethinking how millimeter-wave prototyping is done to improve the time of development for millimeter-wave systems and aid the rapid development of research program outcomes that fall in line with the NSF funding model. Hardware researchers broadly agree that millimeter-wave prototyping is difficult for a number of reasons related to CAD, foundry support, and packaging costs. Notably, the landscape for millimeter-wave prototyping has not changed drastically over the past ten years and continues to prevent rapid development of phased array prototypes that are required by millimeter-wave system researchers. While the IC community has rapidly developed substantially and a number millimeter-wave chips have been demonstrated as research outcomes to prior NSF programs, there continues to exist significant impediments to packaging these chips and providing the packaged systems to other researchers due to the time and money required package chips to a point that they can be integrated into millimeter-wave systems with appropriate digital interfaces. Several facts were recognized by the panel. First, university researchers will broadly be unable to take advantage of future scaling in CMOS to improve millimeter-wave systems. There are a number of reasons that CMOS for millimeter-wave systems has not progressed with CMOS scaling. First, the cost of scaled CMOS is tremendous and outside the NSF program funding constraints. Second, the development of existing millimeter-wave IP is critical to first-pass silicon success. Second, packaging continues to plague system development and must be standardized ahead of beginning any millimeter-wave circuit design, particularly as scaled systems are sought. There was recognition that the NSF research community must disrupt the current ASIC development model that is undertaken to build a mm-wave chip or the NSF will simply not be able to fund any reasonably sophisticated chip design. Our panel discussed the possibility to develop an IP repository for chip designs developed by NSF program participants and shared between NSF program participants. The goal would be to significantly shorten the development time required for future millimeter-wave ICs by allowing the student to focus on high-level system design without spending a great deal of effort on subcomponent blocks. Such an effort might ultimately revolutionize the fabless semiconductor industry by developing IP libraries similar to those available for digital ASIC development. There are a number of legal and logistical issues that must be considered but the panel felt that informal discussions should begin to suss out these issues.

**Identification of Cross-disciplinary Themes**

Members of our panel are well aware of the complex relationship between device technologies and systems. The audience of the hardware breakout group was eager to learn about the outcomes from signal processing efforts and systems/networking research that might help refine the circuit architectural goals for future research programs. Most notably, it was recognized through discussions in the second day panel session that there is a need –perhaps served through the RCN – to have publication outlets and conferences that will publish the outcomes of such inter-disciplinary research since each individual research community will not recognize the immediate value of broad work on millimeter-wave circuits and systems. Moreover, the RCN serves as an excellent opportunity for researchers in different millimeter-wave areas to meet and develop future collaboration efforts for future NSF program solicitations.

**Scribe Notes**

***1. Open Session***

Question/comment from a PhD student from UCB: Packaging of chip designed for mmWave and its cost is an issue. If the package parasitics don't reduce, there is no incentive to go to more advanced CMOS nodes, as the package will ultimately limit performance. Most work in mmWave is now being done in 65-nm CMOS node. CAD tools overhead is higher at smaller nodes

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Q. from Tufts: Is there any interest in mmWave circulators using nanoferrite materials?
New materials for higher inductor densities, role of ferrites , miniaturization and SoC solutions.
New materials can have impact in Pas (CMOS peak efficiency is 20%), matching networks and power combining. Using reciprocal components/materials helps in full duplex.
Miniaturizing inductor, transformers, filters is an area of interest. CMOS compatible passives for 3D inductors could also play a role.

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Need for collaboration with system people to get all the pieces to work together.

Universities need to collaborate more as industry does. Also, it makes more sense if the IC design group focuses on innovating on a specific circuit than designing the whole system from scratch.
Academia should collaborate with industry to look at their roadmap.
Leverage IPs will help from the community. IP repositories from other Universities could help an academic group to succeed. Collaboration among the people who work in the space will accelerate advances in the field. The community should arrive at an IP sharing mechanism which will make students more productive for the cost (as student cost is now higher than the chip fabrication cost itself). Further, the circuit block specifications should be provided to the signal processing researchers, which can be used as a starting point for their work. Some sort of metrics to describe the circuit IP blocks must be used so that SP researchers can directly use them. "Need to relook at the circuit-aware communication theory for mmWave bands."
Cut design times and sizes through collaboration by sharing IPs, as the intellectual contribution is coming from system level. Students need not waste time designing individual processes or circuit blocks. The community should democratize the mmWave design process, similar to what has occurred in the Rapberry Pi community. Academic groups should stop being protective and start sharing more with the community. New startups can come from the community in this way.
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Build bigger systems from smaller components at the testbed level. Algorithms and circuits need to come together as a test bed.
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Q. from Mortaza@NCSU: There seems to be a resistance to using new material system or technologies, labeled as exotic or expensive and would never make it commercially.
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Robert Heath, U Texas: Stuff communication and signal processing groups are doing should be practically relevant. Need for accessible interaction between different communities.
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Brian Floyd@NCSU: Evolution to a platform, we shouldn't restrict ourselves to specific implementations
Instrumentation platform with digitization limits beyond the current art, open new research areas for the community, vision platforms for the community. Need for resources to buy expensive equipment is a limitation. There is much room for testbed and platform collaboration. Reasonably larger platforms that can bring people together, systems mixed-signal folks, the community should come together.
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Arjuna Madanayke@U Akron: Investigation of multi-beam mmWave is important from signal processing perspective. How many beams is a practical scenario at mmWave?

A. Depends upon the scenario. 1000 elements are not unimaginable. Number of antennas should be 10 times the number of beams - Ali

There are applications from few beams to 100s of beams.
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Mythri@mmMAGIC: Rather than going for more complex systems, solve simpler systems problems, such as RF leakage, etc. Get the simple systems right and then worry about scaling to larger array sizes.
The number of beams required depends upon the capacity of the cell. Infrastructure should scale up depending upon the usage.

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There is a need for more collaboration, open sourcing of IP blocks, coordination and discussion about which foundry to develop IPs for. Academic researchers mostly use TSMC, some GFUS. How can we share the IP across the Universities and Industry partners?

**Need for Packaging Community Resource:**

New devices, packaging, can be part of the portfolio. There is lot of room for new materials and device technologies. Silicon is not the costliest part of the equation as packaging is beginning to dominate. In- house device, packaging is very resource intensive. A cleanroom is needed to be maintained. Students who do IC design and the ones who perform fabrication are with different skill sets. Circuit students are reluctant to go into cleanroom and work on fabrication. The community could benefit from something like MOSIS for IC MPW, but for packaging. Low volume packaging (flip-chip, antenna integration, etc) facility would greatly serve the community.

Facilities created by AIM photonics facilities at SUNY Albany could be leveraged for low volume packaging. -VS

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**Open-Source antenna platforms for mmWave prototyping**

There was a concern that at this point no phased array antennas are available to test out the systems, and algorithms. There is no open-source platform for mmWave system prototyping. The closest we have is the Google SiBeam setup available to select academic partners. There are export control issues with mmWave system. There needs to be a discussion on whether the export control regime in US has it stifled innovation in this space.

**Hardware Testbed**

The available testbed should be configurable. Algorithms researchers are looking at higher level protocols and need hardware testbed for experimental test.

Example configurations could include fast-switching 32 element dipole arrays, with microseconds switching. In the USRP software radio testbed, 500MHz-1GHz is the upper limit for antenna parts, but we could benefit from even wider bandwidths. Further, we need to look at the scalability of the hardware systems as and when more and more bands are added. What would be implications for hardware: would a new TX/RX chain for every band will be included or some other approach will be needed?

Community developed IP could be at any level – ICs, antennae, PCBs, discrete component level IPs, etc.

**Open Source Sharing and making mmWave space lucrative for VC Investors**

There was a suggestion that we should have had other industry partners including Keysight attend the workshop. Industry tends to be secretive but we need to start cooperating. Some research groups are using the SiBeam platform. There was a realization that researchers and developers need to be more open and we need more startup companies. This could enable an environment when investors should see value. A reduction in development times and cost would convince VCs to fund more start-ups in mmWave space. The community could look at developing Raspberry PI like mmWave platform.

There needs to be a change in the perception from the venture capital point of view. Need to solve the whole chain problem.

Software (CAD/EDA) licenses are very expensive when we get out of the academic setting. Some of the NDAs can be difficult and time-taking to execute. eSilicon MPW sharing has made things easier for academic researchers, but NDAs still complicate matters. For example TSMC requires a 3-way NDA between eSilicon, TSMC and the University.

**Need Antenna Experts in the Community**
There is a strong need for antenna experts in the workshop group. Their participation is critical for determining the best form factor for the potential mmWave IP under discussion.
**Mixed-Signal Circuits**
System specifications are in the flux for interferers etc. The community should bring together system and circuits experts to determine the specifications on the mixed-signal blocks (ADC, DAC, PLL, filters). Spatial filtering, blocking considerations, and other specifications for mmWave systems must be determined so that the mixed-signal designers can focus on their blocks.
**Printed Flexible Antennas**
*Comment from a U Arizona researcher:* 2D flexible printed antennas with phase shifters can help prototype at the lower frequencies. Conductive inks are used to inkjet print antenna structures on polymers substrates. Challenges include the speed of the printed switches and the resolution of the inkjet printing that limits the frequency of operation. [VS- I believe the FlexTech alliance has had interest in flexible antennas solutions. However the basic limitations are from the loss of the polymer substrate used instead of the printed resolution]
**What would you fund as an NSF Program Manager?**

- Shared community infrastructure for prototyping and test. Typically test infrastructure costs millions of dollars and is only used for 1% the time during the test cycles. Researchers should be able to share infrastructure where they can just bring their own probes, and other consumables, use the facilities for a short time to finish their work.  NSF could fund national/regional labs which will house mmWave probe stations, VNAs, etc.
- Efforts to standardizing the  package interface will also help. There was an example of a standardized package from Nuvotonics (?) for 3D packaging technology, which could be widely used with standard interfaces.
- Focused funding for scenario specific testbeds which can feature narrowly defines baseband+Antenna+Circuit interfaces for researchers to validate relevant system ideas.
- NSF should fund  Large scale projects where individual contributors could develop specific blocks for shared community use. This would be similar to the multi-University Research Initiative (MURI) program from DoD. NSF can fund with common IP: High-speed ADCs, High Speed IOs, PAs, Front ends, phase shifters, etc.
- CISE is a good fit and fund large scale system testbed effort
- Organize conferences and create journals specifically for mmWave systems.
- Programs to look at the scalability aspects of performance vs reconfigurability
- Fund communication theory for circuits; develop models for theoretical frameworks to go along with circuits.
- More materials research - Isolators, circulators, and make them accessible to everyone.

# Communication and Signal Processing (CSP): Summary of Breakout Discussion

**Discussion Leaders:** S. Rangan and L. Swindlehurst
**Scribes:** M. Vu and C. Gursoy
**Prepared by:** Sundeep Rangan

- Prototyping / testbed
  - A common theme through various group was the difficulty in developing adequate testbeds that could be developed on university budgets without significant staff. This situation has arisen largely due to the complexity of mmWave systems, the need to support very high data rates and low latencies, and the protocols (particularly for cellular systems) that run on top of them.
  - There was widespread agreement that too many groups starting from scratch and there was insufficient sharing of hardware and software.
  - In this regard, it would be desirable if there was a common platform that circuits, signal processing and networking groups can build on.
  - An additional difficulty is the need for funding mid-size test beds. Multiple nodes are particularly important for networking research.
- MmWave energy consumption
  - It was widely-agreed that energy consumption is a key challenge for developing practical mmWave systems, esp. in handsets and low-power access points.
  - The circuits groups had identified the need to develop high efficiency power amplifiers and PLLs as key areas for tackling this issue.
  - But, the efforts should be coordinated with signal processing techniques such as low resolution A/Ds, as well as adaptive scaling techniques.
  - Networking / scheduling groups can also contribute by looking at use of idle mode, bandwidth scheduling, etc.
  - What is needed for better collaboration are more accurate models for circuits that abstract the cost in terms of power and area. In this regard, it would be useful to identify a few common architectures.
  - Blockers and interference models will also be necessary to evaluate various circuit techniques.
- Packaging and interface design
  - The circuits groups identified packaging as a key challenge for mmWave. This is a significant and dominant cost in most commercial circuits/
  - One issue what that academics had few ways to get low-cost packaging.
  - Effects of antenna. Layout
  - One overlap issue with SP is the design of the dataflow in multi-chip architectures which could dictate the interface requirements between chips.
- Advanced circuits
  - This is a longer term research item that would include beyond CMOS technologies and phase change switches.
  - Photonic solutions could also be considered
- Channel modeling

  - Despite progress by 3GPP and other bodies, it was agreed channel modeling remains an area with a large number of outstanding issues. Several key components need to be better understood
  - Dynamics of the channel, particularly with regard to blocking and orientation (although there have been a few recent studies in this)
  - Vehicular channel models, particularly with regard to placement of the antenna
  - Foilage (with snow)
  - Coverage planning / ray tracing tools.
  - Simulation tools. A broad question here is how to provide more accurate link-layer modeling to account for receiver imperfections (channel estimation, beam tracking, phase noise, etc). Also, how do we abstract channel models for faster simulation while capturing the salient features of the mmWave channel.
  - Low band estimation: How much of the mmWave channel can be learned from low and mid-band channel?
- Directionality, synchronization and tracking
  - A key feature of mmWave channels is the need for directional transmission. It was agreed that this had widespread implications throughout the stack.
  - At the signal processing side, there is still need for better channel tracking / estimation algorithms. A related issue here is beamwidth optimization.
  - The SP issues are also closely related to the MIMO architecture, in particular, the support of fully digital solutions
  - At the MAC side, virtually all control plane protocols (cell search, broadcast channels, …) need to revisited with particular attention to delay.
  - Side channel from 4G or low frequencies should also be investigated.
- Full-duplex
  - Although this topic was not considered a high priority, active cancelation is worth considering. Most of the benefit was improved control plane functionality
  - A general research question are circuit architectures for this purpose.
- MAC
  - There are several features of the MAC that need to be investigated.
  - Directionality (see above)
  - Feedback (CQI, beam tracking, scheduling, capability reports)
  - Protocols for initial access, beam search, tracking, …
  - Frequency decomposition, sub-band and related ADCs.
  - Efficient HARQ, particularly for low latency and variable decoding times.
- Resource allocation
  - Resource allocation problems will address two key features in the mmWave:
  - Spatial division multiplexing
  - Low latency, prioritization
  - These have obvious ties to various sub-groups including channel modeling, SP and MAC.
- Spectrum
  - Licensed, semi-licensed, unlicensed. How does directionality effect these?
  - Cellular and LAN co-existence
  - Spectrum sharing

- Interference assessment

- Low-band anchoring
  - Protocols, C-plane / U-plane split
- Idle
  - This research topic is closely connected to the power consumption and scheduling / resource allocation topics above and considers how to address power consumption via idle models.
  - From a circuits perspective, there is an issue of how to perform and model power gating.
  - MAC and high layers will also need to consider how to store state
  - There are several open issues on protocols for idle mode transitions
  - BS can also consider idle mode for network-level power reduction
  - Closely related is how to perform dynamic bandwidth allocation
- Network simulation
  - There is a need to develop a common simulation framework for network-layer simulation. Some useful work has begun on ns3 although this can be extended.
  - There are a large number of outstanding issues to making a complete simulation.
  - First, is the channel modeling. See above. Note that this must include the directional modeling of interference.
  - Second is the modeling of the beamforming tracking. See the directionality thrust above.
  - Finally, there is a need for a flexible / configurable MAC and core network architecture to enable experimentation in these area.
  - Closely related to the topic of network simulation are new classes of stochastic geometry tools that can account for the directionality as well as the coordinated scheduling.
- Waveform design
  - There remains an ongoing research topic of OFDM vs. single carrier, and the various flavors within OFDM. This needs careful collaboration with the MAC thrusts as well as the circuits thrusts.
  - A key issue identified by 3GPP is the desire for a scalable waveform design.
- Emerging use cases
  - vehicular
  - AR / VR
  - aerial / drone
  - What are requirements
  - wireless hospitals
  - factory automation
  - chip-to-chip
- Backhaul
  - An business case question here is the value / availability of mmWave vs. fiber backhaul.
  - Forr mmWave backhaul. the challenge with interemittency / latency / reliability.

- For self-backhaul systems, MAC layer structures will be needed to support dynamic TDDs. Self-backhauling means sharing with access links

- Mobility of the blockers is also issue and is connected to the channel modeling thrust.

- Multi-point connectivity
  - Due to the unreliability of links, multi-point connectivity is widely-believed to be an essential feature in mmWave.
  - A channel modeling question is how to assess macro-diversity. Can we use ray tracing to develop these statistical models.
  - How to design fast protocols and measurement reports for multi-connectivity and handover.
- Core network architectures
  - There are several issues open on how CN needs to evolve.
  - Distributed gateways
  - Caching content closer to the edge
  - Multi-point routing within the CN
- Transport layer
  - At a high level, mmWave links create very high data rate but unreliable links. How this manifests at the transport layer needs further study.
  - The most immediate goal should look at Congestion control, TCP, esp. Cross-layer optimizations, split TCP and machine learning methods for congestion control.
  - Also of importance is buffer management at various points in the network.
  - Multi-point TCP can also play a role both within the mmWave network and multi-network connections.

***Scribe Notes:***

***What are the broad challenges, requirements and use cases that will drive CSP research in mmWave. What are the fundamental goals that we are trying to address that are not delivered by current systems*?**

***What are the main technical challenges?***

- As potential use cases, robotics and factory environments were mentioned. In these applications, large amount of data is being generated. mmWave can be used to support the high data rates needed in such scenarios.
- Design of mmWave systems in multimodal applications in the presence of blockages was discussed.
- Hardware-aware design for mmWave applications was emphasized.
- mmWave systems being deployed for fixed-wireless access in the short term was highlighted. Cost of deployment in fixed-wireless is a key consideration.
- Participants from industry emphasized the importance of self-backhaul. It was noted that how to efficiently design backhaul was critical. For instance, how many hops can we afford without sacrificing performance (in terms of latency and throughput)?

- There was discussion on whether backhaul could be handled by fiber. It was said that the expected high density deployments of mmWave access points may render fiber as infeasible.
- It is desirable to have overlap in coverage so that reasonable levels of reliability in the presence of potential blockages can be attained.
- If access point is blocked, fast handover and fast rerouting are needed.
- What are business challenges vs. technical challenges? Self-backhauling can be technically difficult. The goal is to have an optimal self-backhauling design. Again, how many hops? Topology is important.
- More research is needed for channel modeling in mmWave freq. bands. Ray-tracing may not be enough for complete characterization. Polarization should be taken into account. More measurements are needed, identifying e.g., elevation angles, blockages. Local geometry should be modeled. How well do we model the blockage/outage probability? Dynamic nature of the channel has not been well-understood yet.

***What advances in hardware architectures / devices / RF will impact CSP and how do we leverage these? What oversimplifications does the CSP community make regarding hardware when studying mmWave systems and how can we address these?"***

- Power efficiency is a key concern.
- What are the requirements from the hardware architecture? Low PAPR is needed. ADC/DAC and beamforming are critical elements.
- There was a discussion on phase noise in mmWave systems. The consensus was that this issue could be addressed in practice.
- There was a remark on the discrepancy in challenges raised by hardware and signal processing experts.
    - Large bandwidth and large data rate can have significant implications on hardware/circuit design.
    - Some communication/signal processing claims may not be feasible in hardware implementation or can be costly. For instance, for beamforming, a certain minimum number of RF chains is needed. Also, movement of digital data within the circuitry can be an issue. Data flow is an underexplored consideration.
    - Can we do digital beamforming? Fully digital, low-bit rate architecture would be preferable.
- Channel models still remain to be not completely characterized. For instance, the impact of mobility has not been investigated extensively yet. Additionally, as more freq. bands become available, how should channel measurements be conducted? How can we make this process scalable? It is important to note that several features/properties e.g., LOS probability, remain the same regardless of the freq. band. Parameters of the model change with the freq. band.
- Why is there a need to modify the MAC layer?
    - Low latency is a key requirement. With analog beamforming, we may serve one user at a time. Control messaging is also handled similarly (e.g., one ACK at a time).
    - Interference management and avoidance are critical.
    - Initial access and initial beam acquisition are important steps as well as shortening the latency for beam tracking. Additional delay experienced at these stages affects the MAC

layer. Intermittency of the channel has an impact on the MAC layer, together with the high variability of the interference.

- Are we confident about indoor models e.g., 802.11ad channel modeling? Indoor is important for enterprise environment. How to design indoor with licensed and unlicensed access? How to handle randomness of the local characteristics?
- Beam spacing, backhaul access, hybrid ARQ, and mobility were mentioned as challenges in vehicular networking.
- In Industrial automation, can wireless be reliable enough? How much value is there in establishing wireless links instead of wired links?
- There were comments on establishing mmWave links for chip-to-chip communication.
- In data centers, cables can be costly. Rack-to-rack communication with short distance and LOS links can be accomplished via mmWave systems.
- Channel modeling for aerial mmWave communications is needed. We need to understand the dependency of the channel model on moisture level. Humidity can have significant impact on wave guiding effects. Also, there is a need to characterize how foliage, snow, rain, etc. affect propagation conditions?

***What do we need and how can we benefit from related fields (e.g. information theory, optimization, signal processing, machine learning)?***

- Channel coding and decoding high-data rate flows were pointed out. Finite block-length coding techniques and LDPC were mentioned.

**Summary Discussion:**

- Better channel modeling and improved understanding of the dynamics of the channel together with effective channel estimation schemes were identified as short/medium-term challenges.
- One long-term challenge was pointed out as mmWave communication in freq. bands beyond 100GHz (e.g., 120 – 130 GHz). At such high frequencies, potentially more antennas can be deployed and more bandwidth is available. Noise models could be different. Propagation characteristics are not known. One overarching goal in such high freq. bands can be to provide Terabit/s data rates under 100 mph mobility. Applications may include virtual reality and robotics (e.g., 1-cm localization for robotics).
- Having ultra-high density mmWave deployments with self-organizing and plug-and-play-type architectures together with effective self-backhauling can be key to providing mmWave access to masses.

***<u>Additional Scribe Notes:</u>***

- Start with round introduction of all attendees: affiliation and dominant challenges
  - Approx. 20 attendees
  - Did not capture all introduction, here are a few
  - Heath: all aspects of phy layers, signal proc, compress sensing within standard, challenges in vertical integration, factory robotics, requirements for mmWave, control, blockage engineer the network to robust to robot locations, sensor data process all data and just send decision bit, or send all data (among cars) to produce 3D view of environment – need high data rate, radar lightdar, same for factories robotics

- Gosh (Nokia): 5G, mmWave, 45 people team. Verizon use case fixed network main use case, challenge penetration loss, how to have deployment model without truck loads. Multimode devices LTE+mmWave how to design antennas, design of UE/CPE for multimodal, low battery consumption, blockage
- Idaho: Interference , multirate, coexistence, mmWave
- Sweden: moving base stations, beam tracking, backhaul access (60% in Europe), driving, cost? Bandwidth and delay are key challenge. Need to find receiver.
- UC Berkeley: MIMO mmWave prototype, signal processing and hardware, system architecture, design / partition system in a way to easily implement in HW
- Postdoc: Security issues

- Discussion: use case of fixed wireless
  - Fiber access expensive, do not want to run to all BS. How to efficiently do backhaul without scarifying latency and throughput (Gosh)
  - Heavy overlap of coverage: condition on orientation, reasonable reliability 100-200 meters. Cannot have fiber in all place. Fast exchange information, fast rerouting. May not be a pure handover, need integrate phy/mac (Qualcomm)
  - CPE 5G-enable, CPE at your home, no wired backhaul connection to internet
  - Debate on feasibility of wireless backhaul but Verizon is pursuing this direction
  - Dual connectivity is given in 4G but is challenging in 5G. If CPE inside house then high signal loss
  - Business challenges vs technical issues?
    - Cell backhaul is technical issue, need optimized backhaul solution. Scheduling and signal processing problems, how many hops, how to schedule the hops, connectivity
    - Node discovery
  - RF/coverage prediction per physical area is satisfied, or need ray tracing research?
    - Ray tracing alone is not enough, need models for behavior of walls, ground. Combine models spm, curve of approximation. Diffused scattering models exist.
    - Need more measurements
    - Where is the most concern in measurement: elevation angle, polarization, blockage
    - Need automated process to estimate coverage
    - Is this a worthwhile academic endeavor? – unclear, probably more related to industry developing. Takes long time, need simplified model to estimate coverage
    - Need statistical models for performance characterization
    - Modeling exact foliage from house to house is not practical
    - Need both theoretical and practical solutions, but modeling tools are for industry

- Power efficiency
  - (Gosh – Nokia) Low PAPR waveforms, beamforming arch both hybrid and analog. Below 40GHz OFDM cyclic prefix, above 40GHz single carrier (Nokia’s position). Can leverage MIMO simple beamforming schemes
  - Want academia to investigate if OFDM is effective at 60, 70 GHz?

- 256 antenna elements per polarization, perform MU-MIMO
- Very short TDI, but can do MIMO hybrid beamforming
- Not good line of comm between people in hardware and signal proc/comm sides (one says phase noise is not important, one say it is)
- Phase noise is understood for specific signal constellation size or OFDM. May not be a topic for academia research

- Cross layer design
  - What RF spec can be backed up by exploiting array gain
  - Many comm/signal proc papers have incorrect assumption about hard and achievable hardware
  - RF beamforming – there is a min amount of RF chains per antenna, need a PA per element on transmit side, not splitting – not capture well in literature
  - Movement of digital data is expensive for hardware – huge channel BW data rate per antenna is high, second most expensive after PA
  - Fully digital transceiver (NYU) – data flow is important
  - Power amplifier vendors nervous about DPD – old topic (30-40 years old)
  - Hybrid and analog beamforming. Can we do digital bf but with just one or two bits? Need low bit DAC

- Related field: Information theory, optimization, machine learning

- Channel modeling
  - Connectivity is hybrid below 6GHz and mmWave network
  - Current channel model captures many aspects, but parameters of model change
  - Do we need more measurement campaign to confirm model? Yes for measurement the parameters for diff environment
  - Spatial dynamic: going in and out of LOS
  - Why does MAC layer need to change? – control issue, only one user at a time in analog mmWave beamforming, not a problem for fully digital architecture
  - High variability: average, correlated interference as tradition, or do interference avoidance as in WiFi? Not clear which one better.
  - Initial beam acquisition – how to shorten time to acquire a beam, then track the beam. How to manage these beams
  - Beam is related to MAC layer because of directionality, intermittency of channel
  - How is the state of indoor model, can use WiFi 802.11ad modeling? Don't have people involved in this modeling effort here. How is indoor modeling for 28 GHz?
  - Indoor is very important because of high penetration loss
  - Separate networks for outdoor and indoor
  - How to design indoor network?
  - Concern: are there adequate variances in the model to capture all the local characteristics of each setting/environment
  - Orientation modeling? (Dina Katabi's work?)
  - Is there need to track orientation of phone around body?

- Vertical direction? Important in vehicular.
- How to do hybrid ARQ work in vehicular
- Channel modeling is important in vehicular
- Beam tracking in vehicular
- Electric cars have effect? Signals go through the roof or others? Channel modeling in this area is important

- How much does channel modeling depend on density and high moist environment
  - Even below 6GHz (2.6GHz) experience extreme interference in high moisture environment (Shanghai), channel sounders is blocked just 2 blocks away
  - How will the effect be in mmWave?
  - Effect of snow – put snow on top of channel sounder

- Reliability:
  - Can 5G/wireless be reliable enough for important application that could involve human safety (vehicular, factory / industry application)
  - replacing factory cable by wireless, or hospital cables/wires by wireless, attractive but need high reliability and low latency

- Chip-to-chip comm, data center application:
  - 5G and broadband wireless (10 years ago)
  - Now use optic?
  - What is the role of mmWave?
  - Short distance LOS
  - Processing and latency for data center are important

- UAV/visible light comm:
  - Ariel comm mmWave for data center? DARPA had a program along this line before

- How does mmWave affect coding: LDPC codes
  - Cannot have lots of iteration in decoder because of short delay
  - Need more understanding
  - Finite block length effect too – result from information theory
  - LDPC compare to Turbo: short term solution, still standing problems

- Short and medium term challenges, no standout long-term challenges

- Long term challenge (beyond 6 years): above 100 GHz
  - 120 GHz, 140 GHz
  - LightFi
  - Bandwidth is higher, noise model may be different, propagation don't know
  - Pie in the sky: huge BW systems, really high data rate, can create virtual meeting environment just as face to face, need lots of bandwidth
  - Terra bit per second link, anywhere

- Augmented reality, everything is synch in real time, high data rate. Latency and data rate both important
- Localization (eg robotic application)
- Plug and play cell backhaul – standing challenge
- Can make mmWave ubiquitous? – need to have cheap equipment to deploy in many cities in developing countries, or even rural parts
- Convergence of satellite and mmWave? Is it possible, technical or political?
- Satellite/cellular conflict. Even satellite community now realizes need for more spectral efficiency. Need precoding etc. Want to make military chip set cheaper.

# Networking (NET): Summary of Breakout Discussion

**Discussion leaders:** M. Krunz and I. Guvenc
**Scribes:** A. Mackenzie & N. Michelusi

**Context:** On December 7, 2016, at the kickoff workshop of the NSF Millimeter Wave Research Coordination Network (RCN), a one-and-a-half-hour breakout session on Networking Protocols for Millimeter Wave (mmW) Networks was held. This session was one of three parallel breakout sessions, the other two being on communications and signal processing (CSP) and hardware challenges. The discussion was led by Ismail Guvenc and Marwan Krunz; the scribes were Allen MacKenzie and Nicolo Michelusi. The majority of the time was spent on discussing networking-related research challenges related to mmW systems. Towards the end, participants attempted to summarize and prioritize these issues, and to plan of how to move forward.

**Major Networking Research Issues**

- **Network/Node Discovery and Initial Coordination.** Because of the high directionality of mmW communication links and the potential efficiency improvements that come from very narrow beams, the problems of node and network discovery become critical. Among the identified challenges are: 1) designing computationally efficient fast beam finding and tracking algorithms, 2) designing reference signals (pilots) for downlink transmissions, 3) user association with mmW base stations (including the possibility to connect to multiple base stations), and 4) role of big data for facilitating mobility predictions and leveraging such predictions in beam tracking. Additionally, for envisioned dense and mobile deployments, the discovery/tracking overhead can severely compromise network throughput; thus, it is of great importance to optimize such overhead to maximize communication performance.

- **Scheduling and Resource Allocation in Time, Space, and Frequency.** Given the challenges of deploying massive-MIMO technology in mmW networks, resource allocation is critically important in such environments. Multiple modes of operation are possible for these MIMO systems, and the selection of appropriate Hybrid MIMO modes in a given situation is challenging. In addition, the nature of the mmW channels (where the difference between a strong interferer and a virtually nonexistent one may be only a few degrees of beam angle or a few centimeters in position) also creates resource allocation challenges that do not exist in conventional wireless networks. The ability to perform efficient resource allocation for mmW systems hinges on accurate characterization of interference. This is particularly significant for mmW networks, where multiple transmissions contend over the same channel. Tools to appropriately characterize and mathematically model interference in mmW systems are urgently needed, as well as more sophisticated channel models. For example, it has recently been shown in the literature that dual slope path loss model (i.e., having different path loss exponents at different distances between transmitter and receiver) may significantly degrade coverage and capacity performance when compared to single path loss models in densely deployed small cell networks. Similar tradeoffs are also expected in densely deployed mmW networks, which may be further affected by directional transmissions and specific propagation characteristics of different bands.

  Another key issue that was identified is the low spectral efficiency of mmW systems. Despite the abundance of bandwidth in mmW bands, the currently low spectral efficiency (a few bits/sec/Hz at best) threatens to degrade the overall transport capacity of mmW networks. Novel coding and modulation techniques with much higher spectral efficiency are needed. Assessing such techniques would also depend on the ability to accurately characterize the mmW channel and also model interference in a multi-user directional setting.

- **Network Protocols and Architectures.** Building on the themes of directionality mentioned above, there is a need for further development of channel access protocols in highly directional and mobile environments. Although some initial work has been previously done on access protocols with directional antennas, this work did not anticipate the extremely narrow beam widths, mobility, or brittle nature of mmW links, which make prior designs inapplicable or computationally impractical for the mmW operational environment. The directionality of mmW links will also impact the design of reference signals to provide coordination and synchronization among devices, and a rethinking of these physical-layer protocols are thus needed.

  Moreover, some basic physical-layer choices, such as analog versus digital beamforming, will have a significant impact on the performance seen at higher layers. There are significant issues related to handover in a multi-base station environment, as well as the possible need to use multiple points of attachment, or even multiple network technologies simultaneously (multi-homing or coordinated multi-point (CoMP)). Attempts to use technologies such as coordinated multipoint may also make network synchronization and coordination a key issue. Additional issues arise with respect to the transport protocol—solutions such as multi-path TCP are one possibility, but it is unclear if they are appropriate in the mmW environment.

  Optimization of protocols at different layers and across layers (cross-layer optimization) in a mmW network can provide many benefits, and should be further explored. In particular, understanding how lower-layer protocols communicate and interface with upper-level ones so as to maximize flexibility and adaptability of the network is an open question; additionally, this should be done with minimal modifications to "universal" protocols such as TCP. There are also challenges associated with multi-hop operation, and with backhaul architecture needed to sustain the required throughput and latency to support mmW access points. One particular issue is whether or not full-duplex technology can be applied for wireless backhauling between mmW access points. It is an open question whether wireless backhaul can sustain the high capacity and low latency requirements of backhaul, in light of the mmW channel characteristics (such as blockage). Dynamic allocation of backhaul resources across different frequencies may be needed to leverage the full potential.

  Further, there are substantial tradeoffs to be explored with respect to control- and data-plane separation in mmW systems, and the possible benefits of standalone versus non-standalone (i.e. backed by a conventional RF-based system) mmW systems. There may be significant benefits associated with "anchoring" mmW data channels with lower-frequency channels for the purpose of achieving mobility-resilient communications. This is somewhat analogous to channel/subcarrier anchoring currently proposed for LTE operation in the unlicensed 5 GHz band (LAA or LTE-U), with the key difference that the anchor channel in the case of mmW lies in a significantly lower frequency band (e.g., below 5 GHz) than the mmW data channel. Implications of such anchoring on the latency and reliability of control messages need to be further explored.

  Higher-layer issues such as the placement of content/caching in the network as well as delay tolerant network (DTN) approaches are also important.

- **Heterogeneous Coexistence and Spectrum Sharing.** There are substantial issues regarding the use of unlicensed spectrum and the management of interference and access rights in millimeter wave bands, due to the difference in propagation characteristics at these frequencies. Some unlicensed bands may be accessed by heterogeneous radio access technologies (RATs) using different protocols (similar to WiFi and LTE coexistence in unlicensed bands), and it is of interest to study how to maintain coexistence among such potentially different RATs. The economics associated with mmW spectrum licensing are also quite uncertain, in light of both the above-mentioned coverage concerns and the additional spectrum sharing possibilities outlined in recent FCC rulings on mmW bands.

- **Coverage, Capacity, Latency, and Energy-Efficiency Tradeoffs.** Because of the differences in expected capabilities of mmW base stations and the different propagation environments, developing new understandings of the tradeoffs between coverage, capacity, latency, and energy efficiency in mmW networks is critical. The use and further development of stochastic-geometry tools is expected to be particularly relevant to studying the placement of base stations. These problems, as well as above resource allocation and network protocol problems, may also be made more difficult by the extremely high densities at which mmW infrastructure may be deployed, and the resulting need for robust energy-saving measures such as sleep mode.

- **Testbeds and Experimentation.** The need for robust testbed, experimentation, and simulation capabilities was discussed at length in the breakout session. It was generally felt that existing simulation tools, in particular, may be inadequate for investigating mmW networks, given the tight interaction between the physical-layer characteristics of the mmW channel and the resulting performance at higher layers. Moreover, it was felt that channel dynamics and spatial correlations of mmW channels were critical, and these temporal and spatial characteristics are often ignored in conventional network simulators for studying mmW networks.

  There was also a discussion on how hardware design may impact network protocols. For example, energy consumption of a mmW base station during active, idle, and sleep modes may affect network protocol decisions for sleep mode optimization and energy efficiency enhancements.

- **Applications.** Different use cases for mmW networks may expose different system requirements and catalyze the development of additional networking solutions. Applications of interest include vehicular networks, UAV networks, virtual reality or augmented reality, wearables, smart cities, and IoT systems in general. Moreover, the employment of ideas such as those developed in the context of disruption/delay tolerant networking (DTN) may have relevance to improving user experience in an environment in which mmW links experience intermittent disruption.

**Moving Forward**

- Participants in the breakout session agreed that there was a need to consolidate around a set of clearly defined short- to medium-term research goals that researchers participating in the RCN (and related communities) should address, along with research investments and a funding model to support the kinds of cross-layer, cross-disciplinary projects that will be required to address some of the research problems raised above (along with related problems identified in other breakout sessions). In particular, breakout session participants advocated a model that included collaboration between academia, industry, and government.

- One possible way to approach the development of research goals is through the development of appropriate target metrics. Although some obvious targets such as spectrum efficiency (bits/second/Hz) or power efficiency (bits/second/Watt) could be included, additional metrics that attempt to measure wireless *network* capabilities (such as spatial capacity, in bits/second/$m^2$), system or area spectral efficiency, and network capacity may also be appropriate.

- Longer-term, breakout session participants felt that the RCN should look at frequencies above 40 GHz. One thought was that the RCN could tackle a few challenging projects and big thrust areas, such as design of fully digital MIMO systems.

# APPENDIX F:
# PANEL 2 DISCUSSION NOTES

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

**Panelists:** Marwan Krunz (Arizona), Sundeep Rangan (NYU), Charlie Zhang (Samsung), Ian Wong (NI), Mythri Hunukumbure (mmMAGIC), Amitava Ghosh (Nokia), Jim Buckwalter (UCSB), Arun Ghosh (AT&T),
**Moderator:** Nada Golme
**Scribe:** Haitham Hassanieh

## Summary of Key Points:

### (1) Collaboration Between Different Communities:

The panel emphasized the need for interdisciplinary research to solve major challenges in millimeter wave. The hardware, the PHY protocols, the MAC and the network are all intertwined and need to talk to each other. There is a need to put some intelligence in the network. Hence, the circuits community, the signal processing community and the networking community should all come together to build end-to-end millimeter wave systems.

The panel pointed out some of the problems that would require interdisciplinary research to solve:

- The design of phased array and how it interacts and affects the higher layers.
- PA efficiency with high peak-to-average ratio signals.
- Trading bit resolution for dense spatial sampling to enable a low resolution end-to-end system.
- Hardware that supports both communication and sensing, enabling sensing and localization applications.
- Full duplex radios and how they change the networking protocols and applications.
- Advanced network simulators that take into account the channel model, hardware and PHY.
- Best signaling approach from a networking and signal processing perspective.
- Backhaul architecture.
- Achieving ultra reliable low latency for 5G.
- Resource allocation in millimeter wave networks.

The panel pointed out the need for a large scale testbed which individual researchers today cannot afford. The panel also pointed out the difficulty in publishing interdisciplinary research which might turn academics away from mmWave research. Hence, there might be a need for using this RCN to establish a new venue for mmWave publications.

Finally, the panel stressed the need for vertical interaction and collaboration with other communities to deliver the best use cases and applications of mmWave. These include: the automotive sector with V2X style applications, the energy sector, the e-health space, and the industry/factory automation space.

### (2) Collaboration Between Industry and Academia:

From an industry stand point, most of the problems below 40GHz will be solved by the industry itself through standardization. However, there are some remaining problems like backhauling, full duplex, coverage, and phased arrays that work across multiple bands. It is not clear whether the industry will be able to provide the best solutions on its own. Industry would require clear targets and deliverables from academics to incentivize them to collaborate. They would also like a lot more access and the ability to influence research without having to fund the projects. Only moon shot projects might incentivize industry to provide funding.

From an academic stand point, funding has to come first and industry must fund if they want to drive the ideas and research thrusts. NSF funding is not sufficient to build and realize mmWave prototypes and systems. Industry must be willing at least to share their platforms to help push research forward.

The panels also provided some examples of targets that industry would like to see:

- Achieve a spectral efficiency similar to lower frequency bands. Currently the efficiency is 1 bit/sec/Hz. Can we deliver 5 bits/sec/Hz or more?
- Can we achieve 10x lower power than today and make mmWave power consumption comparable to sub 6 GHz bands?
- Can we achieve full digital beamforming with 128/256 channels using efficient low bit ADCs at mmWave?
- Can we design a 70 dBm PA with efficiency of 35%?

### (3) RCN Role and Future:

This RCN can play several major roles when it comes to millimeter wave research. First, the RCN can serve as an umbrella to bring mmWave researchers from different communities together with industry. Second, the RCN can organize ideas into big problems and thrust areas. These thrusts can be tied to NSF proposals and can drive NSF funding for mmWave by identifying the needs and demands of the research community. The RCN can also help create an NSF engineering center for mmWave research with Industry collaboration. Third, the RCN can identify long and short terms goals and target projects with deliverables with a 10 year timeline for RCN 2026. Finally, the RCN can also pool resources together and design a competition with a big prize to solve major challenges in mmWave. This is similar to the DARPA spectrum challenge model and can excite industry and bring academics to work together.

**Panel 2 Scribe Notes: Xinyu Zhang**

Warm-up Questions:

Q1:

Thyaga: Is sensing an important issue we should look into?

Marwin: Full-duplex can enable simultaneous sensing/communication.

Akbar: Channel estimation is a natural enabler for sensing, e.g., OFDM radar.

Comment: Low-resolution sampling has great potential but still lacks an end-to-end system design. It's uniquely applicable for mmwave.

Q2:

Thyaga: What needs to be done to enable usable and accurate simulators? What type of abstractions is needed?

Comment: This line of work hasn't been started. The key is for the simulator developers to understand what's needed by the network designers.

Q3:

What's the most fundamental challenge that warrant the next 5-10 years of research?

Comment: Key thing is to enable reliable connectivity, e.g., through multiple basestations.

Marwin: Reliability was also discussed in backhaul design. Some redundancy is needed, e.g., multiple APs.

Charlie: High capacity may be an illusion. It's all about spectrum efficiency (microwave band can get to 20 bits/s/Hz; but mmwave is only a few bits/s/Hz).

Q: What's the coverage and practical capacity?  Also, is there a business case for fixed wireless access?

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Panel2 introductory comments:

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Arun: It would be nice here to have an end-to-end view. ATT's view is that networks will be more intelligent and self-organizing, self-reconfigurable. We need to bring AI into network framework.

Charlie: World's first two 5G trials have been done by Samsung. We've learned a lot, but there are a few key system challenges to enable business cases for 5G mmwave: spectrum efficiency, coverage, capacity.  Fixed wireless is easier; but mobiles are not there yet.  Besides, channel modeling remains an issue.  All in all, we need to set a performance target for the research community.

Ian: It is hard to afford end-to-end experimental systems. Collaboration is needed between industry and academia to make this happen.

From my perspective, the key features of 5G are: Ultra-wide band, Massive IoT, Ultra low latency. These are still open problems that block our 10 year vision of smart city, IoT, etc.

Sundeep: We do need collaboration from PHY layer signal processing to networking/application.

Jim: We do need high efficiency circuit (e.g., PAs) to enable high spectrum efficiency.

Mythri: Interacting with other verticals is key issue and been actively investigated by mmMAGIC

Amitava: 5G application space is huge: VR/AR, smart homes, etc. But 5G != mmWave. 5G is also not just RAN. It also involves network slicing and other architectural aspects. Nokia has been involved in various proof-of-concept systems at 28, 70 Ghz. One key challenge is availability of phased-array, for both CPEs and APs. There also needs to be multi-band support for antennas.

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Panel Discussion

Q: What are the common research themes across each community?

A:

Sundeep: Below are a few themes we discussed:

1) comm/hardware collaboration;

2) channel modeling: what's the right model.

3) Prototyping/testbed;

4) Directionality and synchronization;

5) MIMO architecture: analog, digital and hybrid beamforming;

6) MAC layer protocol design.

7) Resource allocation.

8) Macro diversity permeating multiple layers.

9) Backhaul architecture.

Jim: Whether full-duplex should be supported.

Marwin: Signaling and channel modeling for network protocol designs.

Amitava: How to solve MAC, control, mobility below 40 GHz --- these issues will solved in next a few years.

The key question is: what's beyond these --- we need to look beyond 5 years.

Specific research questions include: How to design up to 120 GHz? How to design phased-array for higher band? How about backhauling? Full duplex a solution? How to ensure future systems coexist with incumbent systems?

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Q: How can this RCN enable collaboration?

A:

Charlie: We need to understand the bottleneck/pain point. RCN is a good way to start the discussion. Again, we need to define the performance target; from there on, we can break down into requirements for communication, hardware, etc. There is no need to repeat all efforts in addressing below-40 GHz, although certain issues still need to be solved, like coverage/mobility.

Amitava: Hope this RCN can be beneficial for cross-Atlantic collaboration. Although a funding model still needs to be set up. For example, partnership can be set up through the Piccaso project.

Arun: What RCN should do is to identify the big-thrust areas that each community should work on, Such as channel model, new software design to support mmwave firmware... Important deliverable is periodical report, collection of papers, etc.

Jim: We should tie up the discussion to NSF proposal programs, potentially developing proposal collaborations based the RCN workshop. We should also engage junior faculty more and create opportunities for them.

Sundeep: It's challenging to get system level research accepted in IEEE conferences/journals, which favor theoretical studies. Maybe this RCN can become a point to convince the community about the values of system work.

Amitava: How to differentiate this RCN from Horizon2020 (EU 5G research effort)?

Related with 5GPP (comprising private companies). NSF needs to commit funding in order to materialize the impact of RCN.

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Q:

Thyaga: What is it that you want to see that makes you come here.

Arun: We do research by funding universities. We can benefit from RCN if we can still access research resources without committing funding by ourselves.

Charlie: Our incentives include access to broader topics, and influence.

We really want to see researchers working on things ahead of us to derisk our efforts.

Amitava: aim for deployment at 2020; establish partnership between industry and university; establish trans-atlantic relation.

Thyaga: This effort is continuing; there is no strict timeline from the government. We also have a program for SpecEff that also fits.

We as an entire community to voice so that the funding admin can hear us.

Comment: Prototype cost for mmWave research is very high---100k for phased-array chip, packaging doubles it. NSF funding doesn't allow such end-to-end prototyping. NSF funding is mostly for students.

Amitava: We also need to consider whether the university prototype can have commercial potential.

Marwin: It's very important to identify short-term and long-term goals for this RCN. 5G is a short term goal.

Arun: How do we want the RCN really be? 1) How do we streamline our efforts? 2) Can we set a few targets?

Charlie: Industry already made the basic exploration effort. But again we need to aim for some advanced topics/target. We can use lower band as a guidance: Lower band gets a capacity of 20 bits/s/Hz. mmWave only gets 1 bit/s/Hz. In the short-term maybe we can target 5 bits/s/Hz. In terms of power efficiency, there's 10x gap. We have to bridge that gap.

(Jim: Power efficiency of PA at 60 GHz is around 20%)

Ian: Sometimes the target is not so clear. So the academia needs to do some horizon exploration work to crystalize it, e.g., some conceptual exploration of mmwave massive mimo, hybrid beamforming, etc. Also, academia needs to push the boundary ahead of industry.

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Q: What are the hindrances for collaboration?

A:

Arun: The first thing is to clear the scope? What's the goal by 2020, 2025...? What are the thrust areas?

Akbar: Industry should also contribute to clarifying the research thrust areas and target goals.

Charlie: Yes, we industry partners can define the goals together.

Ian: Yes, we can pool our resources/funds together towards the goals.

Mythri: Cost and IPR are very important issues and often become the barrier.

Comment: Can we generate some research center based on RCN? Maybe we can develop an ERC proposal.

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Audience questions

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Q: Funding model has to come first, to engage researchers.

Akbar: funding alone does not facilitate collaboration.

Charlie: Industry incentive is not just for money. Identifying the key thrust areas is also important for us.

Comment: There is little incentives for junior faculty to publish across disciplines.

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Thyaga: RCN is not aiming for one thing. What we hope for is an organic initiative. This is a place to get people's interest and form a community.

Amitava: We can together identify a Moonshot like vision and then we can convince the industry higher layers to invest.

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Comment: hope industry can share their trial experience, and share their testbed/prototype to facilitate research.

Ian: DARPA has some 2m project; Whitehouse has PAWR initiate;... all these should incentivize industry as well.

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Closing comments

Amitava: We need to define RCN targets (2025?), funding model, leveraging existing projects for collaboration.

Arun: An ERC proposal will be a great idea.

Charlie: Let's put ambitious goals towards RCN 2025.

Ian: I suggest we connect with IEEE societies to speed up the initiatives.

Jim: It would be exciting to use RCN to provide a road map.

Marwin: This RCN is a great starting point and opportunity to know the state-of-the-art in this area.

# APPENDIX G:
# PRE-WORKSHOP DISCUSSION POINTS

# Millimeter-Wave RCN Kickoff Workshop
# Summary of Discussion Points
# Panels and Breakouts

## Day 1

### Panel 1 (90 min): State of mmW Technology, Challenges & Opportunities–Industry & Regulatory Aspects

**Moderator:** Akbar Sayeed

**Panelists:** Arun Ghosh (AT&T), Amitava Ghosh (Nokia-Bell Labs), Maziar Nekovee, (EU mmMAGIC), Ali Sadri (Intel), Ashwin Sampath (Qualcomm), and Ian Wong (National Instruments)

**Scribes:** Xinyu Zhang and Haitham Hassanieh

**Format:** 3 min opening remarks from the panelists followed by discussion.

**Discussion points:**

- Where is the 5G standardization process with regard to mmW?
- What are the initial use cases are the focus of technology development?
- What is the expected timeframe frame for initial products?
- Any major recent noteworthy breakthroughs?
- What are the major obstacles to mmW wave technology in 5G?
- Are there new regulatory developments, or in the making, that could influence mmW technology development?
- Current status and 2020 roadmap of industry-led European collaborative R&D and planned trial activities on 5G including mm-wave (mmMAGIC and mmMAGIC-II projects and others) in Europe towards 5G standards
- Current status/perspectives of 5G spectrum identification (which bands including those in mm-range) in Europe in preparation for WRC'19, what are the synergies and difference with the US
- Key outcomes on 5G mm-wave channel models from Europe
- How important is self-backhauling for mmWave deployments?
- Maturity of mmWave technology for form factor ready for UE's and CPE's?
- Will there be any difference between 28/39 GHz vs. 60/70 GHz mmWave technology?
- What are hardware-related obstacles to deployment of 5G?
  [It seems like there are issues with creating cost-effective hardware for even simple components like couplers and filters, not to mention the more complicated subsystems like antenna arrays and amplifiers. Perhaps some participants would have insight into these issues and ideas for overcoming them.]
- What are measurement-related issues?
  [As we have been discussing in the Channel Alliance, calibrations and measurement verification is much more important at mmWave frequencies. Verification of massive antenna systems presents a real challenge: how to do you efficiently test systems that can operate in an uncountable number of states? Test equipment is also a challenge: Because the electronics in the instruments is operating at the state of the art, it is complicated to characterize devices that are also operating at the state of the art, maybe NI can weigh in on this]\
- What air interface aspects should we pay special attention to so that mmw performance in NLOS and mobile scenarios is acceptable? (this will zoom in on the dynamic BF aspects, including fast adaptation, and how they could be supported).

# Millimeter-Wave RCN Kickoff Workshop
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- What RF design and regulatory challenges need to be addressed to make mmw a viable technology for mobile devices? (this will cover PA design, antenna module design/placement and some discussion on MPE aspects. We could also talk a bit about spectrum sharing.)
- What do system modeling results tell us about anticipated performance? (people can talk about some of the channel models being used in 3GPP and associated link/system level results so far)
- Propagation channel measurements and modeling – what role do they play?
- What are some important system design, implementation, and test challenges in mmWave?
- How does mmWave technology stack up against other candidate technologies for 5G, e.g Massive MIMO, Network densification?
- What are the key research problems left to be solved to make mmW a true commercial success?
- What is path to 5G and what are the prerequisite for the next generation cellular network to get deployed.

## Parallel Breakouts(60 min): Development of Technology Roadmap for mmW Research

**Format:** 5min opening remarks by the leaders to seed the discussion, followed by discussion.

- What are the key problems in the three technical areas that need to be addressed in the next 3-5 years?
- What kind of contributions can we expect from this RCN in the next 3 years?
- What are the problems for which cross-disciplinary collaboration will be critical?
- What do you hope will happen?
- What are you afraid will happen?
- What are you doing about it?

## Breakout 1: Hardware: mmW hardware, antennas, digital hardware, prototypes and testbeds

**Discussion Leaders:** Jim Buckwalter and Ali Niknejad
**Scribes:** Vishal Saxena and Subhanshu Gupta

1) What are industry vs academic participant perspectives on phased array hardware and readiness?

i) State of art
ii) Perspectives for future research (Frequency scaling, etc)

2) What are key roadblocks to the current industry development of phased arrays, particularly for mobile (i.e. handset) applications? For backhaul? Will arrays only occupy a few niche applications in industry ultimately? Regulation/Cost/Power Considerations

3) Why does most mm-wave (prototype) hardware remain out of the hands of most academics? Can we find a way to prototype faster & cheaper to get it in the hands of more researchers? Is there a CAD gap?

4) What are the most critical barriers to producing a phased array in an industry versus academic environment? Man-power, cost of silicon. How can NSF-funded research lower barriers in the future?

5) Continuing hardware challenges:

i) Low power architectures for digital beamforming

ii) Power Amplifiers – Peak efficiency/ Backoff efficiency is unsolved problem for CMOS technologies. Power density for lowering silicon area/costs. Heat dissipation.

iii) Frequency Scaling – Is there a rush to 140 GHz? 220 GHz?

iv) Full-duplex techniques for mm-wave; Is there an argument for channel estimation/control through full-duplex?

v) Mixed-signal for millimeter-wave. What are the academic challenges for DAC/ADC design for arrays? Is this a standalone problem any longer?

vi) Digital Signal Processing – Will software-defined arrays in DSP meet cost/power constraints?

vii) Alternative approaches for arrays: Multiplier arrays, Switched beam, Lens, Silicon photonics? Are these part of a portfolio ultimately?

viii) Foundry processes for phased arrays – Is there any role in NSF funded research when considering the CMOS processes required to push hardware capabilities? Is 65-nm CMOS the end of the road for mm-wave academic research?

ix) Are there enabling devices that might change the architectures/capabilities? For instance, low-loss mm-wave switches (GeTe) or low-loss passives.

x) Antenna design challenges, especially for mobile devices.

Prototyping at millimeter-wave bands to be limited by 1) packaging, 2) foundry, 3) CAD, and 4) man-power. In each of these items, the issue is cost and access to a technology or tool.

The complexity for phased arrays is likely to outpace the ability of academia to solve these problems. This suggests that we need to solve the prototyping hurdles with other research efforts.

- Power consumption/heat dissipation issues in RF hardware, ADCs/DACs, digital backend?
- Power amplifiers: challenges and opportunities?
- Switches, phase shifters, phased arrays, lens arrays: opportunities and challenges?
- RF integration, and RF + digital integration?
- Architectures for high-rate digital processing in the backend?

## Breakout 2: Communication and Signal Processing Techniques

**Discussion Leaders**: Sundeep Rangan and Lee Swindlehurst
**Scribes:** Mai Vu and Cenk Gursoy

- What are the broad challenges, requirements and use cases that will drive CSP research in mmWave.
- What are the fundamental goals that we are trying to address that are not delivered by current systems?
- What are the main technical challenges?

- What advances in hardware architectures / devices / RF will impact CSP and how do we leverage these? What oversimplifications
- does the CSP community make regarding hardware when studying mmWave systems and how can we address these?"
- What do we need and how can we benefit from related fields (e.g. information theory, optimization, signal processing, machine learning)?
- What are some promising strategies for reducing computational complexity of the digital backend?
- What are some promising strategies for reducing the complexity of the analog-digital interface?
- What would we like to accomplish in the next 3 years?
- How to address the propagation challenges, such blockage?

## Breakout 3: Networking Techniques

**Discussion Leaders:** Ismail Guvenc and Marwan Krunz
**Scribes:** Allen MacKenzie and Nicolo Michelusi

1. Network/Node Discovery and Initial Coordination
   a. Computationally efficient beam finding and tracking algorithms
   b. Design of reference signal (pilot) in downlink
   c. Random access in uplink
   d. User-BS association and handover in a multi-BS environment
2. Scheduling and Resource Allocation.
   a. Time/frequency/spatial (MIMO/beamforming) resource allocation
   b. Impact of mmWave channel models on scheduling and resource Allocation
   c. Interference characterization
3. Network Architectures & Protocols
   a. Backhaul architecture
   b. Channel access protocols
   c. Multi-hop operation (routing protocols)
   d. Contention between multiple systems (game theory, reinforcement/machine learning)
   e. Mobility-resilient designs
   f. Heterogeneous coexistence in mmW bands (role of spectrum sharing)
4. Coverage/Capacity/Latency/Energy-Efficiency Tradeoffs
   a. Placement of base stations & cell distribution (stochastic geometry tools)
   b. Sleep-mode optimization
5. Testbeds and Experimentation
6. Networking Applications:
   a. Vehicular networks
   b. UAV networks
   c. VR/AR, Wearables
   d. Smart cities

- What are the key challenges for achieving multi-Gigabits/s end-to-end rates?
- What are the key challenges to achieving millisecond latency?
- What are the implications for cross-layer design?

# Millimeter-Wave RCN Kickoff Workshop
# Summary of Discussion Points
# Panels and Breakouts

## Day 2:

### Readouts from Day 1 Breakouts (Discussion Leaders) to prime the Panel 2 Discussion (30min)

### Panel 2 (90 mins): Cross-disciplinary Collaboration in mmW Research – Scoping the Landspace and Charting a Course for RCN Contributions

**Moderators:** Nada Golmie

**Panelists:** Marwan Krunz (Arizona), Sundeep Rangan (NYU), Charlie Zhang (Samsung), Ian Wong (NI), Mythri Hunukumbure (mmMAGIC), Amitava Ghosh (Nokia)

**Scribes:** Xinyu Zhang and Haitham Hassanieh

**Format:** opening 3 min statements from Moderator/Panelists followed by Discussion

**Discussion points:**

- What the big problems that will require cross-disciplinary problems?
- What kind of contributions can we expect from this RCN in the next 3 years?
- How do we facilitate cross-disciplinary collaboration?
- What are the key elements of successful cross-disciplinary collaboration?
- What are some common hindrances to collaboration that we need to be aware of?
- Collaborative research themes across hardware-comm./signal processing?
- Collaborative research themes across comm./signal processing/networking?

The 'cross disciplinary' term also refers to wider disciplines that can benefit from the mm-wave communications such as V2X, IoT, industry automation etc. There is already significant ongoing research in these verticals. The importance of such collaboration is recognized in the proposed mmMAGIC-II project and it strives to address the challenges in these verticals, with key players as project partners. One example is using mm-wave for communications in disaster and emergency situations, with drones, robots, emergency vehicles and crew all connected through mm-wave. It is important to forge this kind of ties with the key players in these vertical industries and RCN. This will enable us to understand the real requirements, development time scales and challenges in these verticals. Specific discussion points:

- How can we effectively engage with these vertical industries, grasping their requirements and challenges and then looking to develop solutions
- At least in some of the verticals, there is already disparity in the wireless technology adaptation (e.g, in V2X, preference for 802.11p in US, for LTE in China). Should we try to avoid this in other verticals or we should accept this and let the market decide the best-fit technologies?

- What is the role of academia vs.government vs. industry in terms of end-to-end large-scale testbeds and prototyping in mmWave research?
- How do you see the mmWave RCN working with the PAWR initiative?
- Is there value in a DARPA grand challenge around mmWave technology?