Report on the 2nd Workshop of the NSF mmW RCN

July 19-20, 2017

University of Wisconsin-Madison

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

Executive Summary: The 2nd workshop of the NSF RCN (research coordination network) on mmW (millimeter-wave) wireless (RF frequencies between 10 GHz and 300 GHz) networks was held on July 19-20, 2017 on the campus of the University of Wisconsin-Madison. The PI Akbar Sayeed and co-PI Xinyu Zhang were responsible for the local arrangements. The workshop started with introductory remarks by PI Sayeed reminding the attendees of the premise of the RCN: to create a platform for academic-industrial and cross-disciplinary collaboration in the three key research areas driving mmW technology: i) communications and signal processing (CSP) techniques, ii) networking (NET) protocols, and ii) hardware (HW) design, including antennas, mmW circuits, and data converters.

Building on the discussions from the Kickoff Workshop and recent developments, three main themes were emphasized in the 2nd workshop, which were reflected in the panels and breakouts:

- Research and Technology Roadmap for RCN contributions at the HW-CSP interface
- Research and Technology Roadmap for RCN contributions at the CSP-NET interface
- Research and Technology Roadmap for prototype and testbed development

Several significant recent developments were noted, including:

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

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

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

Conclusions and Action Items for Next Steps before the 3rd Workshop: Given the interest from the first two workshops, formation of working groups for the following areas would be useful for continuing the work between workshops and to make the workshops more effective:

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

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Summary of Key Activities and Outcomes from the Workshop

Day 1: Wednesday, July 19, 2017

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

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

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

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

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

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

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

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

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

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

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

Poster Sessions: Three poster sessions, each with 10-11 posters, were held sequentially (one before lunch, one after lunch, and one after the breakout sessions) with an hour dedicated to each poster session. The poster sessions spanned the whole range on ongoing research in the three areas as well as prototypes and testbeds. A list of posters and authors is provided in Appendix D.

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Demonstrations: There were six demonstrations, involving both hardware and software innovations, that were presented during the poster sessions. A description of demos is also included in Appendix D.

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

The three breakout sessions were aimed at *interface* topics. Summary of discussion for the three breakouts is presented below. Detailed notes on the breakout discussion are provided in Appendix E.

HW-CSP Interface Breakout: **Leaders:** J. Paramesh, S. Gupta, V. Saxena, and S. Yost

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

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

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

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

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

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

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

Major remarks:

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

Moving forward:

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

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

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

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

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

Day 2: Thursday, July 20, 2017

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

Readouts from Breakout Sessions: J. Paramesh (HW-CSP), M. Mezzavilla (CSP-NET), X. Zhang (testbeds) – see the above discussion summaries for the breakouts.

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

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

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

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

- Integration of communication and computing to meet delay and energy requirements
- Bandwidth vs latency tradeoffs that vary with use cases
- The use of higher frequency bands above 100GHz
- Sustained (rather than peak) Gbps data rates
- Business models and economic considerations
- Cross-layer and inter-operability issues for verticals

- New uses cases for driving innovation

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

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

A particular use case of interest – considered a killer app by some – is autonomous vehicles which will not only require high rates and low latency but would also benefit from integrated communication and sensing and many of the key operational functionalities enabled by mmW technology. Machine learning could also play an important role in this use case.

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

- Appendix A: Workshop agenda.
- Appendix B: List of attendees and affiliations, including the SC members and keynote speakers.
- Appendix C: Panel 1 discussion notes.
- Appendix D: List of posters and demos with names of authors and presenters.
- Appendix E: Breakout sessions discussion notes.
- Appendix F: Panel 2 discussion notes.

APPENDIX A
WORKSHOP AGENDA

Second mmW RCN Workshop
July 19-20, 2017
Madison, WI
Agenda

Online Agenda link (with links to videos)

Day 1: Wednesday, July 19, 2017

8:00am-8:45am: Registration (Lobby) and Breakfast (1413 EH Cheney Room)

8:45am-9am: Welcome and Opening Remarks (1610 EH); slides

9:00am-9:30am: **Keynote (1610EH) –** Dr. Ted Woodward**,** *Program Manager, Strategic Technology Office, DARPA* Slides

9:30am-11:00am: Panel 1 (1610 EH): State of mmW Technology and Outlook: A View from Industry

Discussion Questions; slides

Moderator: Akbar Sayeed

Panelists: Amitava Ghosh (Nokia Bell Labs), Ashwin Sampath (Qualcomm), Ian Wong (National Instruments), Boon Loong Ng (Samsung), Tommy Svensson (Chalmers)

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

Slides: Boon Loong

11:00am-11:30am: Coffee Break (Lobby)

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

12:30pm-1:30pm: Lunch (1413 EH Cheney Room)

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

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

A. HW-CSP Interface: Hardware, Circuits and Antennas & Communication and Signal Processing (2309 EH)

Discussion Questions; Slides

Discussion leaders: Jeyanandh Paramesh (CMU), Subhanshu Gupta (WSU), Vishal Saxena (UIdaho), Sarah Yost (NI)

Research problems to be addressed at the intersection of hardware and antenna design and communication and signal processing techniques. Build on the initial list identified in the Kickoff as part of the Technology Roadmap; see kickoff report.

B. CSP-NET Interface: Communication and Signal Processing & Networking (1610 EH)

Discussion Questions; Slides

Discussion Leaders: Marco Mezzavilla (NYU), Ismail Guvenc (NCSU), Haitham Hassanieh (UIUC), Tom Henderson (ns-3 consortium), Rui Yang (InterDigital), Yuichi Kakishima (NTT Docomo), Matthew Andrews (Nokia Bell Labs), Jing Zhu (Intel)

Research problems to be addressed at the intersection of communication and signal processing and networking techniques; including the role of channel models and testbeds. Build on the initial list identified in the Kickoff as part of the Technology Roadmap; see kickoff report.

C. H**ardware and Tools for Effective Testing and Development of mmW Technology (2317 EH)**

Discussion Questions; slides

Discussion leaders: Ian Wong (NI), Xinyu Zhang (UW-Madison), Kate Remley (NIST), Robert Shimon (Keysight)

Testbeds, open, programmable hardware, software platforms, simulation and emulation tools, channel modeling methodologies, mobility models, etc for effective testing of mmWave technology.

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

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

6:00pm: Dinner. Hotel Red, 1501 Monroe St, Madison, WI 53711, (608) 819-8228. Location on Map

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Day 2: Thursday, July 20, 2017

8:00am-8:30am: Registration (Lobby) and Breakfast (1413 EH – Cheney Room)

8:30am-9:15am: Keynotes (1610 EH)

1. 3GPP Status on mmWave 5G New Radio (NR) Standard Beam Management Issues, Dr. Boon Loong Ng, *Samsung Research America* slides

2. Performance Across Frequency Bands (28-80GHz), Dr. Amitava Ghosh, *Nokia Bell Labs* slides

9:15am-10:00am: Readout from Breakout Sessions + Discussion (1610 EH): i) HW-CSP, ii) CSP-NET, iii) Testbed Development

10:00am-noon: Panel 2 (1610 EH): Academic-Industry Collaboration for "Moonshot" RCN Contributions

Discussion Questions

Moderator: Sundeep Rangan (NYU)

Panelists: Nada Golmie (NIST), Ali Niknejad (UCB), Tommy Svensson (Chalmers U.) slides, Jason Chen (Huawei), Amitava Ghosh (Nokia Bell Labs) slides

Goals and Deliverables for RCN 2020 and RCN 2025

noon-12:15pm: Closing Remarks: Akbar Sayeed and Xinyu Zhang (1610 EH)

12:15pm: Boxed lunch (Lobby)

APPENDIX B
LIST OF PARTICIPANTS

List of Participants and Affiliations

First Name Last Name	Affiliation
1. Hisham Abuella	Oklahoma State
2. Parisa Amirieliasi	NYU Wireless
3. Matthew Andrews	Nokia
4. Jingchao Bao	U. Tennessee
5. Diane Benz	Keysight
6. Nicholas Buris	Comparny
7. John Burke	Western New England University
8. Danijela Cabric	UCLA
9. Jason Chen	Huawei
10. Harsha Chenji	Ohio University
11. Steve Chiu	Idaho State U.
12. Aditya Dhananjay	NYU Wireless
13. Numan Dogan	North Carolina A&T State University
14. Sabit Ekin	Oklahoma State
15. Salim ElRouayheb	IIT
16. Maryam Eslami Rasekh	UC Santa Barbara
17. Leah Fagerson	Keysight
18. Stefano Galli	Huawei
19. Xinyu Gao	Tsinghua U.
20. Chuhan Gao	UW-Madison
21. Monisha Ghosh	University of Chicago
22. Amitava Ghosh	Nokia Bell Labs
23. Nada Golmie	NIST
24. Subhanshu Gupta	Washington State U.
25. Ismail Guvenc	North Carolina State U.
26. Mohammad Habibi	UW Platville
27. Muhammad K. Haider	Rice
28. Chris Hall	UW-Madison
29. Haitham Hassanieh	UIUC
30. Anoosheh Heidarzadeh	Texas A&M U.
31. Tom Henderson	UW-Seattle
32. Carlos Herranz	NYU Wireless
33. Yu Hen Hu	UW-Madison
34. Chin-ya Huang	National Central University, Taiwan
35. Muddassar Hussain	Purdue University
36. Ahmed Ibrahim	Florida International U.
37. Rao Jayanthi	Ford
38. Suraj Jog	UIUC
39. Yuichi Kakishima	DOCOMO Innovations, Inc.
40. Kashyap Kalavapudi	Idaho State U.
41. Marwan Krunz	U. Arizona

42.	Jenshan Lin	NSF
43.	Chin-Jung Liu	Michigan State University
44.	Hang Liu	Catholic U.
45.	Boon Loong Ng	Samsung
46.	Soumyajit Mandal	Case Western
47.	Marco Mezzavilla	NYU WIRELESS
48.	David Michelson	University of British Columbia
49.	Nicolo Michelusi	Purdue University
50.	Paul Milenkovic	UW-Madison
51.	Dale Mugler	Ocius Technologies LLC
52.	Thyaga Nandagopal	NSF
53.	Duy Nguyen	San Diego State University
54.	Ali Niknejad	UC Berkeley
55.	Ozgur Ozdemir	North Carolina State U.
56.	Jeyanandh Paramesh	CMU
57.	Nitin Parsa	U. Akron
58.	Parth Pathak	Geoge Mason U.
59.	Borja Peleato	Purdue University
60.	Michele Polese	U. Padova
61.	Geoffrey Porter	MOSIS
62.	Parmesh Ramanathan	UW-Madison
63.	Sundeep Rangan	NYU Wireless
64.	Kate Remley	NIST
65.	Ashwin Sampath	Qualcomm
66.	Vishal Saxena	U. Idaho
67.	Akbar Sayeed	UW-Madison
68.	Gerhard Schoenthal	Virginia Diodes
69.	Omid Semiari	Georgia Southern University
70.	Robert Shimon	Keysight
71.	Alex Sprinston	Texas A&M U.
72.	Tommy Svensson	Chalmers U.
73.	Timohty Talty	GM
74.	Yahya Tousi	U. Minnesota
75.	Mai Vu	Tufts
76.	Fujio Watanabe	DOCOMO Innovations
77.	Ian Wong	National Instruments
78.	Ted Woodward	DARPA
79.	Xiufeng Xie	UW-Madison
80.	Hao Xin	U. Arizona
81.	Rui Yang	InterDigital, Inc.
82.	Yavuv Yapici	North Carolina State U.
83.	Sarah Yost	National Instruments
84.	Masoud Zarifneshat	Michigan State University
85.	Ding Zhang	George Mason U.

86. Xinyu Zhang	UC-San Diego
87. Hao Zhou	Northwestern U.
88. Jing Zhu	Intel
89. Kevin Zhu	UW-Madison

APPENDIX C
PANEL 1 DISCUSSION NOTES

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

Moderator: Akbar Sayeed

Panelists: Amitava Ghosh (Nokia Bell Labs), Ashwin Sampath (Qualcomm), Ian Wong (National Instruments), Boon Loong Ng (Samsung), Tommy Svensson (Chalmers)

Theme: Updates and discussion on technology advances, use cases, business models, regulations, and standardization.

Format: Moderator opening remarks (5 min); panelists opening remarks (3-5 minutes each), followed by panel discussion and audience questions.

Some questions to seed the discussion:

1. What is the biggest advancement in the last 6-12 months?
2. What is the biggest new challenge that has emerged in the last 6-12 months?
3. What is the first use case that is going to take hold? And when? Fixed wireless
4. Any particular issues regarding < 40 GHz vs > 40GHz?
5. Any particular comments on 5G NR Standards?
6. How can industry and academia collaborate through this RCN for advancing mmWave research and technology through the NSF PAWR (platforms for advanced wireless research) initiative

Panel Discussion Summary: In terms of recent significant developments, the panelists noted: i) the 5G NR (new radio) standard work; impact of mobility on beamforming; new spectrum opening throughout the world, including China and Japan; new prototypes and field trials from industry; 3GPP work on channel modeling for standardization; investigation of higher frequencies 70-90GHz; relevant work in Europe (Horizon 2020, mmMagic). In terms of significant next steps, the following aspects were noted: over the air (OTA) testing with mobility, multiple users and base stations; mitigating blockage effects; integrated backhaul and access (a new 3GPP study item); thermal management at access points; and cross-layer design issues. In response to how the new NSF PAWR program could benefit mmWave research, panelists noted the following aspects: testing and experimentation on city/scale with high densification; A/B testing; and collaboration between industry and academia. In relation to WiGig/802.11ay work, it was noted that while there are some similarities in terms of beamforming protocols, 802.11ay is aimed at shorter WiFi links whereas 5G NR standard was aimed a larger scale cellular networks. Design of efficient power amplifiers was identified as an important outstanding challenge. Integrated communication and sensing, including mmWave radar, was identified as a promising area, especially in automotive industry. The need for accurate channel models for different environments (urban, rural, indoor, outdoors, etc) and for different use cases (e.g., UAVs and V2X) was noted. With regard to the first use case that will take traction, there was a general consensus on fixed wireless access.

Panel Discussion Notes:

<u>Progress in the past 6 months</u>

Ashwin:
1. Substantial progress in 3GPP in pushing mmWave in 5G. If you work on mmWave algorithms, then take a look at the document.
2. Lots of support in beamforming and beam management. Leveraging CSI for beam sweeping. I encourage you to look at the 3GPP documents.
3. Mobility under beamforming setting.
4. UE side: relatively less progress, esp. in power management.
5. A new study item on backhaul latency.
6. Spectrum: Japan opens up 28GHz band for 5G. Other countries are following.
7. Robustness under mobility is the key issue.
8. A discussion around doing more OTA testing with mobility, environment dynamics, multiple users, multiple base stations etc. would be useful.

Ian Wong:
1. Spectrum: China opens up 24 GHz. 39 GHz band available all over the world.
2. NI released a 28 GHz SDR, with a phased-array.
3. Verizon 5G demo: proof of concept demo of how 5G looks like.

Amitava (see also slides on agenda page):
1. 3GPP channel modeling is almost complete (from a standards perspective), but more measurement is needed to verify the models.
2. A lot of proof-of-concept systems. How to design the systems to overcome blockage/mobility?
3. Regulation: 24, 28, 39 GHz bands are already approved by FCC. Nokia is promoting 70-80 GHz band, showing it's not so different from 20-40 GHz bands
4. Interference to existing backhaul links: can be mitigated, demoed through a Nokia 3GPP filing.
5. Thermal management at the access point is a challenge

Boon (see also slides on agenda page):

1. Integrated access and backhaul (IAB): a 5G NR Phase 2 study item approved in March 2017, led by Qualcomm and Samsung
2. Backhaul reduces cost of deploying NR mmWave
3. Beamforming and backhaul and access significantly mitigates cross-link interference
4. Lots of cross-layer topics: Topology management, route optimization, dynamic resource allocation between backhaul and access, high efficiency and reliable backhaul

Tommy (see also slides on agenda page):

1. Background: Horizon 2020 5G projects, multiple projects in mmWave
2. mmMAGIC project use cases: cloud, tactile, media, immerse, high mobility, dense urban
3. Key results: concept based on LTE-A RAN, initial access, SDMA, active/idle mode mobility, fast HARQ, scalable OFDM waveform, hybrid beamforming based on a sub-array architecture
4. MANTURA project: mmWave MIMO

Akbar: seems a lot of emphasis on 5G NR

Akbar: **what is the progress/status of channel modeling?**

Amitava: 3GPP channel models are based on measurements and ray tracing, across a 2-year period. Similar model was done by ITU, approved last month.

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Akbar: **Thoughts on connecting with PAWR?**

Ian: NI is partnering with academia, developing mmWave SDRs.

Ashwin: Range will be a challenge. That's why integrated access/backhaul is critical. A city scale testbed that stresses the network, and allows testing of ultra-dense networks, is critical. Football stadium? Backhauling is an issue.
Tommy: It's critical that industry helps expose the academia to the hardware.

Boon: Such a testbed for A-B testing is indeed very useful. It could be a target for next 3-5 years of exploration.

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Akbar: densification is an important feature. Can a small testbed be useful for testing densified network?

Amitava: You have to densify to a point where you have sufficient coverage.

__Audience questions:__

Q1: Many companies are working on 802.11ad/ay? Can you comment on progress on this aspect, besides the 5G NR? What are the lessons learned there? (Monisha Ghosh)

Amitava: 11ad is for short range communication. Facebook has the Teragraph project based on this. But not much other activity.

Ashwin: Bidirectional beam training was addressed in 802.11ad. Use case is the key. 11ad aims for short range comm. 5G NR is for achieving rate/range, same as conventional cellular network technologies.

Ian: 11ad has been there for a while. Quite some people have been using 11ad devices for research.

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Q2: Coexistence on the mmWave band?

Amitava: It'll be similar to LAA.

Boon: Similar to LAA, there will be mmWave licensed/unlicensed coexistence on the 60 GHz band.

Tommy: ITS 5G connectivity for cars is a relevant project.

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Q3: Comment on power efficiency, esp. efficiency of the PAs? (Stefano Galli)

Amitava: Hybrid beamforming reduces the ADC/DAC power cost. PA efficiency still an open problem.

Ashwin: Improving PA efficiency is definitely an area with substantial active research. a lot of work in industry but not shared publicly (competitive advantage).

Ian: Fundamental shift of PA design: one RF in, multiple antenna ports out. Also, new paradigms such as on-chip antennas open new opportunities.

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Q4: Any lessons from military mmWave Radar?

Ian: Yes, our phased-array partner actually had decades of experience in phased-array radar. But the problems are different: need to scale down the cost for commercial radios.

Ashwin: UE side is the key difference.

Tommy: mmWave radars on cars can offer lessons. Integrated communication and sensing could be useful as well.

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Q5: From networking perspective, what's the range we need to handle?

Ashwin: Practically speaking, uplink should be 150-200m (for 28 GHz licensed).

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Q6: What sorts of data would be most useful to facilitate next steps for channel modeling (and for testing)? (Kate Remley)

Amitava: 3GPP has models for various different environments (office, shopping mall, suburban, rural). Indoor is interesting for unlicensed technologies.

Boon: A-B testing requires new channel models, especially for UAV communication and integrated access and backhaul.

V2X is another useful use case for which models and measurements would be useful.

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Q7: What are the roles of the channel models? (Kate Remley)

Amitava: Estimating capacity and user experience. Can we satisfy the 5G user experience requirements?

Ian: The model should be iteratively refined

Ashwin: Benchmark for performance comparison among proposals. Don't take the absolute model results too seriously (comparison vs prediction)>

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Q8: It seems mmWave can be used in a lot of different cases. What's the first use case that'll happen and when? (Ted Woodward)

Amitava: 5G mmWave broadband will be the first use case.

Ian: Fixed wireless will be the first, e.g., between BS and CPE. likely by 2020.

Ashwin: Indoor with drywall works very well. Room coverage is likely to happen soon.

Boon: From Samsung's view, fixed wireless will be the first use case. Indoor inside a room, with beam management and diversity, it's likely to be solved.

Tommy: Wireless backhaul will be the first use case.

Ian: Wireless fiber access also has great potential and has strong motivation.

Amitava: For that to happen, you also need window-monted CPE, set-top box...

APPENDIX E
BREAKOUT DISCUSSION NOTES

Hardware (HW) & Communication and Signal Processing (CSP)

Transcript of Breakout Discussion

Discussion Leaders: Jeyanandh Paramesh (CMU), Subhanshu Gupta (Washington State U.), Vishal Saxena (U. Idaho), Sarah Yost (NI)

Synopsis of Breakout Discussion:

Traditional communication system design has relied on a fairly strict separation between the hardware (HW) community on the one hand and the communication-signal processing (CSP) community on the other hand. For example, the RF/analog front-end in a radio is abstracted during algorithm/system design as a baseband-passband translation. Similarly, analog-digital interface is abstracted so that the desired signal can be assumed to be isolated (after filtering interference) and Nyquist-sampled, whereupon CSP algorithms are implemented digitally.

The HW-CSP panel recognized that such separation may not be feasible in emerging millimeter-wave systems due to the high operating frequency, ultra-wide channel bandwidth, large antenna arrays, advanced beamforming and other signal processing algorithms that lead to prohibitively high cost and energy consumption. In other words, the panel recognized an urgent need for "HW-aware CSP design" and "CSP-aware HW design", and the resulting need for closer collaboration between the HW and CSP communities. Accordingly, the objective of the HW-CSP breakout session was to identify open challenges at the intersection of hardware and the communication/signal processing communities in the ongoing push towards communication and networking in the millimeter-wave frequency bands.

Advanced Beamforming and MIMO: A central thread of the panel discussion related to the design and efficient implementation of advanced beamforming algorithms. Digital beamforming provides maximum flexibility but is extremely power hungry, while analog beamforming offers low power consumption at the expense of severely limited algorithmic flexibility. While the latter has matured for wireless LAN systems, hardware manufacturers for millimeter-wave cellular systems appear to be pursuing full digital beamforming solutions, especially in basestations where energy or space constraints are not as severe as in mobile units. Hybrid beamforming hardware that combines the best of both these approaches is invoking interest from research labs and academia, as are algorithms that are particularly tailored around: (1) the constraints of hybrid beamforming transceivers and, (2) certain assumptions on millimeter-wave channels (e.g., sparsity). It was noted that this area is still in its infancy, and many open problems at the HW-CSP interface require attention before such research can be incorporated into standards. Questions of this nature include: how should closed-loop beamforming algorithms should be designed to minimize link latency? What are the implications of MIMO algorithms on power amplifier efficiency? What are the computational needs of such algorithms?

The efficacy of other beamforming approaches was also discussed. For example, lens-based beamspace MIMO can be attractive to reduce overall energy consumption and accommodate very wideband channels, but may entail different trade-offs in terms of beam acquisition, beam shaping, latency etc. compared to phased-array beamforming. Further research is necessary to understand these trade-offs and their implications on performance, cost, size and energy consumption. Furthermore, alternative beamforming methods may be predicated on less mature underlying technologies which in turn can spur component-level research.

Energy-efficiency of spatio-temporal signal processing: The energy consumption of traditional signal processing functions in radios will continue to have a significant influence on energy efficiency. For example, what type of signal modulations and bandwidth are optimum for overall energy efficiency, considering their direct impact on component level specifications such as PA efficiency, ADC/DAC resolution, frequency synthesizer phase noise and settling speed, equalizer complexity? Should OFDM continue to be the modulation of choice? Should alternative modulations such as FB-OFDM and constant envelope modulation be considered at millimeter-wave? Moreover, such considerations should be "modulated" by the addition of beamforming and MIMO. For example, what is the impact of MIMO on PA efficiency? What are the considerations in generating, distributing and synchronizing LO signals across a large array while achieving low phase noise and maintaining coherence? How can the size, complexity and energy efficiency of the beamformer and the back-end spatio-temporal equalizer be traded-off against each other?

Centralized radio-access networks (C-RAN) add another dimension to the partitioning of signal processing across the network. It was noted that with fastest timescale could be handled at the access point, and slower timescales in the centralized server.

The applicability of artificial intelligence adds another interesting dimension, considering that there is an enormous interest in machine learning algorithms and in the design of energy-efficient hardware for their implementation. It is interesting to explore the role that machine learning can play at the physical/link level, at the network/multi-user level, for beam management etc.

Millimeter-wave Radar/Imaging: Incorporating radar or imaging inspired modalities opens up the possibility of merging sensing functionality into the communication system. Such sensing can be valuable on its own or as an assistive tool for the communication system. For example, exploiting millimeter-wave signals for time-of-flight ranging, directional-of-arrival estimation or centimeter- or even millimeter-accurate localization can be useful in industrial control or future sensing applications, or as a tool to reduce beam management overhead and latency. In this context, we note that beam management imposes significant overheads on communication system performance, and therefore there is a need to investigate techniques to reduce such overheads. Is it possible to sense location and orientation at very small length scales to overcome the adverse effects of blockage, and to perhaps limit the exposure of user to millimeter-wave radiation? How must channel models be developed to mode location/orientation awareness in communication systems?

Physical Hardware-based Security: Security and privacy are important concerns in millimeter-wave communication networks but also in emerging applications including vehicular communication, autonomous vehicles and wireless sensing. In addition to security through encryption, introducing security features at the hardware level can be valuable despite the fact that such methods haven't been shown to be provably secure. Different approaches to hardware security including beam hopping, frequency hopping, multipath-based methods etc. can be considered, many of which have direct implications at the HW-CSP interface. Such research is of high current interest to the NSF Engineering Directorate.

Testbeds: The emerging NSF PAWR program provides an invaluable opportunity for the creation of testbeds that can, for the first time, support large-scale millimeter-wave wireless experimentation. These RCN workshops are an excellent forum for the millimeter-wave community to plan these testbeds. Such planning may include consideration of what hardware would be useful for performing city scale research on wireless testbeds being planned in this program. What are possible experiemtns that would be performed on the testbed? How can researchers work with equipment vendors instead of simply providing specifications? How should the testbed be designed to effectively manage the trade-off between performance stability and reconfigurability/programmability?

Discussion Questions:

- What are the main issues at the HW-CSP interface that drive system design at the physical layer? (e.g., energy consumption, HW-CSP co-design signal processing across RF/analog/digital domains and more broadly to mechanical, acoustic or photonic domains, etc.)
- What are the HW-CSP pros/cons of alternative beamforming approaches (e.g, photonic, lens-based, mechanical)?
- What are the most promising directions to pursue in advanced systems beyond 5G and how do they impact on HW-CSP challenges? (higher frequencies, spatial multiplexing MIMO, point-to-point MIMO, high-order modulation, full-duplex etc.)
- What frequencies and bandwidths to target at millimeter-wave?
- What are the most promising emerging physical/device technologies, circuit or algorithmic concepts?
- Should we intelligently partition the signal processing across RF, analog and digital domains? Or should we strive for an all-digital approach?
- What HW-CSP-NET co-design approaches are necessary to address interference and co-existence issues (with other communication systems, or with radar)?
- What role can machine learning play not only at the HW-CSP level, but also at the network level?
- How important is physical layer and hardware level security? What are some of the key HW-CSP considerations related to this?
- Training/Education: How should we train researchers with sufficient breadth for effective collaboration at the HW-CSP interface? How must university curricula adapt?

Detailed Summary of Breakout Discussion:

- **What are the main issues at the HW-CSP interface that drive system design at the physical layer?** (e.g., energy consumption, HW-CSP co-design signal processing across RF/analog/digital domains and more broadly to mechanical, acoustic or photonic domains, etc.)
    - In general, we should strive intelligently partition the signal processing across RF, analog and digital domains.
- **Modulations, bandwidths and target frequencies** have direct influence on the HW-CSP interface. Main pain points are PA, data converters and low-phase noise PLL's
    - The main contenders being considered for emerging standards will continue to by single-carrier and OFDM. Trade-offs and their impact on HW performance are well-understood. OFDM easier for MIMO receivers, but SC better for transmitter, so use different modulations for uplink and downlink. Both SC and OFDM will be in the standard, with OFDM up to 40 GHz in Phase I and SC beyond 40 GHz.

    - Where do other modulation techniques stand in the standardization process? It was noted that other modulation techniques such as FB-OFDM weren't considered for Phase I, but could be considered later. Constant envelope modulations are not being considered for MIMO, but could be useful.
    - Modulations beyond 256 QAM not likely in cellular due to EVM challenges.
    - Linear PA will continue to be the biggest challenge for high-order QAM. Spectral mask is tight and more important than EVM.
    - Max channel bandwidth is 400 MHz, and additional bandwidth possible through carrier aggregation. Ultra-wideband channels are not being considered for cellular currently.
    - There was some discussions on whether 1-bit ADC's and DAC's make sense.
- **What are the HW-CSP pros/cons of alternative beamforming approaches?**
    - Is hybrid beamforming the most likely future approach? Or will basestations simply use full digital beamforming and absorb the cost and power consumption?
    - There was a discussion on full aperture hybrid beamformers vs array-of-subarrays beamformers.
    - Ultimately, cost will be the deciding factor.
    - Systems will be noise limited, so maximizing the link budget at the lowest cost is paramount.
    - Closed-loop beamforming systems must not ignore latency. Beamshaping for initial acquisition (using broader or squinted beams), with progressive narrowing during normal operation. Speed of beam acquisition must be considered.
    - For access points, lens arrays could be interesting as an alternative to phased arrays. When should one be chosen over the others? Back-end and cost could be less, but form factor could be challenge. There was a question if beam shaping is possible in lens arrays – possible but harder than in phased arrays. Can they be combined?
    - What are the latency issues associated with lens arrays? Need to scan through +/- 60 degrees. Have to switch through several narrow beams, so possible trade-off with channel coherence time. Full comparison hasn't been done, and is in progress.
    - What hardware would be useful for performing city scale research on wireless testbeds being planned for the PAWR program? How can researchers work with equipment vendors instead of just providing specifications? Need a trade-off between performance stability and reconfigurability/programmability.
    - Centralized RAN adds another dimension to partitioning of signal processing requirements. Partitioning becomes a matter of time-scales, with fastest timescale being handled at access point, and slower timescales in the centralized server.
- **Is it useful to merge radar-like properties into mm-wave communication systems**, since mm-wave can offer accurate time-of-flight ranging and directionality estimation?

    - While this is not being actively considered in emerging standards, there was a sense that location awareness could be extremely important with benefits percolating to the network level. Small cell beam management overhead is quite significant. For example, opportunistic beamforming could be enabled with precise localization.
    - Another interesting possibility is sensing location and orientation at very small length scales to overcome the adverse effects of blockage, and to perhaps limit the exposure of user to mm-wave radiation.
    - Potentially use location/orientation information to reduce latency (e.g., in arena with 4 AP's, use location/orientation of users to tune beam with minimal feedback).
    - What sort of simulation models must be developed to understand/study merged sensing/communication systems?
    - Are there any coexistence considerations?
- **What role can machine learning play?**
    - Learning algorithms could be useful in baseband signal processing. Can they be energy efficient?
    - Industry view → not much use at the link level, but could be useful at the multi-user level (multi-core asset management, memory access).
    - Machine learning concepts can be useful for fusing sensing data and using it for beam management.
- **How important is physical layer and hardware security, as opposed to encryption? What are some of the key HW-CSP considerations related to this?**
    - Different approaches include beam hopping, frequency hopping, multipath based security.
    - Plenty of gains from encryption alone. This is not currently a priority in standardization programs.
    - Basic philosophical difference between algorithms and hardware communities. For former, systems need to be provably secure, this hasn't been shown rigorously. But physical layer security is of interest to the ENG directorate in NSF.
    - Security is extremely important in future applications, especially merged automotive applications.
- **Training/Education: How should we train researchers with sufficient breadth for effective collaboration at the HW-CSP interface? How must university curricula adapt?**
    - Millimeter-wave comm systems are breaking down abstraction barriers in system design. This is a real problem in industry, as well as in academia. More inter-disciplinary training is required, but not at the expense of depth.
- **Potential for a new journal**: 3 special issues of the journal every year – 1 on HW-CSP, 1 on CSP-NET, 1 on HW-CSP-NET.

Communication and Signal Processing (CSP) & Networking (NET)
Transcript of Breakout Discussion

Leaders: Marco Mezzavilla (NYU), Ismail Guvenc (NCSU), Haitham Hassanieh (UIUC), Tom Henderson (ns-3 consortium), Rui Yang (InterDigital), Yuichi Kakishima (NTT Docomo), Matthew Andrews (Nokia Bell Labs), Jing Zhu (Intel)

Scribes: Michele Polese (University of Padova), Sundeep Rangan (NYU)

Synopsis of Breakout Discussion:

Major remarks:

- The time-directional dynamics of mmWave propagation are not yet modeled but this is critical to design network protocols and assess the performance of higher communication layers. One of the key preliminary ideas is to overlay a simplified version of raytracing on top of end-to-end network simulations. Can we think of other approaches?
- Should we capture/abstract also phase noise and antenna radiation patterns? If so, how?
- A large community is familiar with link-level simulations and are skeptical about PHY layer abstractions while moving up the network stack. What is the sweet spot between fidelity and complexity? How can we scale with the number of nodes?
- PHY-abstraction will vary depending on the scenario, and the specific research goal. E.g., relatively to raytracing, we should define different levels of tracing details that can be mapped onto specific research needs. Can we generalize?
- Do we need more sophisticated heterogeneous traffic models?

Moving forward:

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

Breakout Format and Discussion Questions:

Part 1: 30 minute intro/presentations from discussion leaders (10' academic, 20' industry)

- What's the biggest pain point in mmWave research?
- What's the most important challenge within the interface CSP/NET?
- What's the ideal simulation/emulation tool for mmWave?
- What's the biggest challenge for 2020? How about 2025?

Academics: 2' minutes each (1 slide - punchline)

- Brief introduction (affiliation, general research interest/experience)

- mmWave-related topic: Ismail - Raytracing, Haitham - Platforms, Tom - ns3 PHY abstraction, Marco - ns3 e2e mmWave

Industry: 5' minutes each

- Brief introduction (affiliation, general research interest/experience)
- mmWave-related topic: NTT DOCOMO - Experimental trials, Interdigital - Standardization, Nokia - multi-hop in ns3, Intel - TCP in ns3

Part 2: Open discussion, 60 minutes, based on a list of questions, including

- Channel abstraction. The main challenges are (i) directional time-dynamics and (ii) blockage: traces or statistical models?
- Are there components of the channel models that we still need to understand to perform reasonable simulations?
- Antenna abstraction: how much should we simplify the antenna pattern? What's the impact on interference characterization, MAC, et cetera?
- What are the appropriate tools for networking research? What simplifications are reasonable at the physical layer to scale up the number of nodes?
- Some PHY-MAC layer procedures may be centralized. What is the appropriate interface to the coordinator? What are the bandwidth / delay requirements?
- How can we model delayed/imperfect CSI, pilot contamination, beam non-alignment, et cetera, to measure the impact on the network performance?
- What traffic models should we use, in order to capture the key 5G requirements?
- Network discovery / tracking. How do we model this at a network layer in order to model handover / cell selection?
- Similarly, how are we going to design and test PHY/MAC for new use cases like vehicular and aerial communications?

Detailed Summary of Breakout Discussion:

The goal of the discussion was identifying which are the main needs in terms of capabilities of network level simulators/emulators and analysis frameworks that would satisfy the digital signal processing, physical layer and hardware communities. The session started with a 40-minutes introduction from the leaders from academia and industry, and then there was an hour-long discussion with the audience on some topics proposed by the panel.

Introduction

Haitham Hassanieh (UIUC) presented hardware platforms for mmWave that can be used to extend simulation/emulation, showing a variety of options:

- Commercial cards with very diverse cost and capabilities:
  - 1000 dollars -> 802.11ad, small range, beam selection, bidirectional
  - WiGig cards very cheap (10 $) but designed for laptop docking stations (700 $), and there is no lower layer control
  - Analog radio frontends range from ~3000 to ~14000 $, however you need to build the software part
  - NI has a complete platform but it is too expensive.

- Custom-built platform, with an overall cost of 10000 $ for a 90-meters range radio at 24 GHz, with up to 256 QAM. The main issue is with phased array, which are very hard to build because of lack of phase shifters for mmWave frequencies.

Ismail Guvenc (NCState) discussed ray tracing software as an alternative to experiments:
- There are several commercial tools available capable of modeling outdoor/indoor multipath, oxygen absorption, with built-in graphical editors (Remcom Wireless Insite RT, WinProp).
- The main motivation is the difficulty in making experiments in certain scenarios (e.g., a moving car). Data generation is easy with ray-tracing, and many papers already use ray-tracing software.
- There are differences between measurements and ray-tracing (real measurements show a larger delay spread, see Z. Zhang et al, Coverage and Channel Characteristics of Millimeter Wave Band Using Ray Tracing, ICC 2015).
- UAV mmWave drones performance can be characterized with ray-tracing, at different frequencies, heights and different scenarios (urban, suburban, etc.).

Tom Henderson (UWash - lead maintainer ns-3 simulator) was pleased by the strong uptake of ns-3 in the mmWave networking community. He briefly described the main characteristics of ns-3:
- Discrete event network simulator – packet level abstraction (no symbol by symbol transmission) – it enables full stack simulations – spectrum model gives a frequency representation of the signal In order to improve the fidelity of the simulation, Tom identified some challenges:
- Scope issues:
    - Difficult for simulators to keep the pace of standards
    - There is the need to choose what to implement and design non-standard components (for example, the schedulers in LTE base stations)
    - Reference scenarios are sometimes not available in the standards
    - Possible approaches:
        - creation of communities of interest that maintain and add features to certain modules
        - identification of common scenarios across different communities (e.g., vehicular)
        - assistance from vendors
- Scale issues: parallel and distributed simulation for wireless scenarios is hard

Recently, in ns-3 the following features have been implemented:
- The 3GPP TR 38.900 -> next step: specific error model, blockage models for mmWave?
- A new WiFi PHY layer abstraction

The main need is related to the PHY layer community requirements to have a good-enough PHY layer abstraction. For example, in mmWave is the modeling of the phase noise needed?

Marco Mezzavilla (NYU) presented the NYU + Univ. of Padova ns-3 mmWave end-to-end module:
- Open source
- It includes 3GPP TR 38.900 channel models -> channel matrix allows to play with beamforming, and possibly beam tracking/switching in the future (not yet implemented)
- Since it is in ns-3, it is possible to leverage the presence of other models (WiFi, LTE, and other technologies/protocols)
- Full-stack 3GPP-like mmWave
- Capture latencies in the core network
- Possibility of playing with the PHY layer frame structure

Moreover, NYU has a complete end-to-end research platform composed of
- ns-3 simulator
- Channel emulator

- Dynamic channel sounder (FPGAs + SiBeam phased array)

and it is possible to interconnect the different components.

Yuichi Kakishima (NTT Docomo) presented the results from collaboration with different partners and verticals. He showed the results of two trials:

- Outdoor trial in Japan – different throughput measurements from a base station at a height of 25 m. The coverage in LOS is in the order of 500 m (2 Gbps @ 480 m from base station, LOS). The performance in NLOS largely depends on the reflections. If there are no scatterers around a building (such as in sub-urban scenarios), behind a building can be out of coverage.
- Indoor trial – 20 x 50 meter rom – very high throughput in LOS – there are several reflections that improve the NLOS performance and provide better coverage

Matthew Andrews (Nokia Bell Labs) provided a wish list of features for a network-level simulator. Each should come with an appropriate level of abstraction:

- Grid of beams / interference / beam coordination -> how should we model them in the simulator? Statically or dynamically?
- Antenna abstraction -> full antenna or single beam? How to model hybrid BF / MU MIMO?
- Deployment models -> PPP or structured (Manhattan Grid with obstacles)?
- Multi-hop support (Integrated Access and Backhaul)

Rui Yang (Interdigital) described the main standards for mmWave communications and their standardization timelines

- 3GPP NR for mobile networks. Mentioned the ITU WRC-19 conference.
- IEEE 802.11 for WLAN and WPAN
  - 802.15.3c Sept 2009
    - WPAN (10 m range, up to 3.8 Gbps)
    - Not used commercially
  - 802.11ad (WiGig) 2012 and integrated in the 2016 standard document
    - WLAN (6.7 Gbps)
    - Procedures for beam selection, refinement and tracking (very similar ideas with 3GPP NR)
  - 802.11ay spec 0.3 – next release in March 2018
    - Enhancement of 802.11ad (backward compatible)
    - Channel bonding and aggregation
    - MU MIMO (8 spatial streams)
    - Hybrid BF
    - Non uniform modulation
    - Mesh
  - 802.11aj
    - Support Chinese mmWave unlicensed bands (45 GHz, 59-64 GHz)

Question (Thyaga Nandagopal, NSF): why backward compatibility from 802.11ay to 802.11ad when there are so few products? **Rui Yang**: there are actually some products (I agree they are not too many), but industries want to keep a consistency on the design, especially with respect to channel access.

Jing Zhu (INTEL) discussed possible optimizations of TCP over mmWave, highlighting the key role of network-level simulations and cross layer research in showing the main flaws of TCP on these links. The main problem is how to maximize the end-to-end performance of mmWave, even if lower-layer issues are addressed.

He identified a few issues:

- No longer losses on wireless links (advanced link-layer technologies)
- Buffer-bloat because of variation of available data rate
- Long link outage (3GPP R2-1701686)
- ACK congestion (3GPP R2-168036) – UL congestion may limit the max throughput of a DL TCP flow
- Routing in multihop introduces another layer of complexity

And possible solutions:

- Active queue management (AQM) with predefined delay threshold -> still long time to recover because of very high bandwidth delay product
- Cross-layer solutions -> much faster response, but aggressiveness towards other flows
- Split TCP/proxy functionality

He described the Intel 2020-2025 vision:

- Low-latency
- High density
- High reliability
- The applications are autonomous communications (sensing info, autonomous connected car, control loops for robots, etc)

Open Discussion: The discussion was guided by a list of questions and problems identified by Marco Mezzavilla, moving from the mmWave channel to the higher layers.
Questions and discussion from the audience:

- **Sundeep Rangan (NYU):** *from a network layer perspective, how people model the MIMO technology provided by the PHY layer?* **-> Tom Henderson**: not so many details other than reflecting the bitrate that MIMO can provide. **Marco Mezzavilla**: there is the need to find better abstractions for MIMO since now transmissions are highly directional – time dynamics must be better understood.
- **Sundeep follow-up:** *5 years ago was MIMO important to networking people (in top-tier networking conferences)?* **-> Marco**: in networking it was important mainly from a enhanced-rate persepctive. **Matthew Andrews**: ICIC papers did not model MIMO details, but now with directionality MIMO becomes the main factor of interference.
- **Harsha Chenji (Ohio University):** *we tend to model the radio range, but is this a real thing?* **-> Jing Zhu**: moving forward, we have very accurate channel models. Given any TX-RX pair, you can compute the channel gain given any distance, thus the maximum radio range is not needed anymore in most of the simulations. The modeling of MIMO is still an open issue, but if you can get mapping from the channel to the SINR, and from the latter to the rate curve, then you have a pretty accurate system.
- **Monisha Ghosh (U. Chicago):** *how does ns-3 model MIMO for WiFi?* **-> Tom**: people have worked on directional antenna models that depend on the technology (mainly in terms of increased gain).
- **Monisha Follow up:** *is the mismatch between control and data range addressed?* **->** Tom: no
- **Marco Mezzavilla** explains how BF is addressed in the mmWave module. With the 3GPP model we can compute the channel matrix. For beam tracking, additional latency is considered in order to capture the required signaling.
- **Ahmed Ibrahim (FIU):** *Has anyone proposed a more accurate abstraction of the PHY? How costly is it to include the full PHY layer? How do abstractions impact research?* **-> Tom**: there has been desire on both fronts. A large community is familiar with link-level simulations and are against PHY layer abstractions. There is the need to find the sweet spot between fidelity and complexity. There are people doing cross-layer. So far, we added features to the PHY layer abstraction to make it more realistic. **Matthew Andrews:** there is not a right answer, it depends on what you want to do. As the tech changes, older models and assumptions become less defensible, and there is the

need for more precise descriptions. Maybe you have to model streets now. **Yuichi Kakishima (NTT Docomo):** we have a lot of challenges from layer 1 (beam management, blockage, oxygen). L1 should not be a bottleneck for the whole design. Antenna modeling is important.

- **Nada Golmie (NIST):** *in mmWave channel modeling map-based models are generally used, but how can you understand the dynamics for beam tracking? You have to know what you're solving and size it properly.* **-> Haitham:** we need to solve first a static scenario, and then transfer solutions to mobile. As you move, the channel is changing more.
- **Nada Golmie (NIST) and Stefano Galli (Huawei):** even if you don't move, the channel changes because obstacles move!

Then a discussion on PHY layer abstraction among different members of the audience starts:

- **Stefano Galli:** maybe now it is easier to increase the level of abstraction, because of directionality. Why using ns-3 if you have just to test beamforming? **Nada:** you usually use ns-3 for large systems, and beamforming modeling is needed to understand where the antenna points and which interference they create. **Ted Woodward (DARPA):** Have we understood enough of PHY layer to provide just an abstraction or do we still need the full thing? I think it's the latter. **Rui Yang:** link estimation too is different in mmWave. We need to understand the link level better before we can abstract it completely. **Stefano:** I do not propose to abstract everything, but we need to understand what we can abstract at the right point to decrease the simulation complexity. Maybe there is not a single generalization, but multiple ones. **Nada:** the community is looking for these abstractions. A lot is understood of the single parts, what do we need of each part from mmWave that we didn't have need in previous abstractions? What is the right abstraction that gives enough precision?

More questions:

- **Ahmed Ibrahim:** *what about integration? Can we put hardware in the loop, so that we have an actual mmWave transmission and ns-3 on top?* **-> Tom:** the next question is "I have only two nodes in my testbed, how can I extend it?". Abstractions are used to scale. **Jing:** ns-3 can get you closer to a real deployment scenario. With this tool we can improve schedulers and congestion controls, but not improve L1. If you can capture the issues of misalignments, and the latencies involved with tracking at PHY layer, then you have a good abstraction to be used by the higher layers.
- **Monisha Ghosh:** *There are very sophisticated ray-tracing tools that can extract very detailed traces. Can you integrate ns-3 with these measures and then the PHY abstraction just uses the bit error rate?* **-> Nada:** that's exactly what we're doing, we are developing a ray tracing module that plugs into ns-3, and hopefully it will be available to the community. **Matthew:** how much detailed is it? **Nada:** we are trying not to cut corners, but we want to be scalable (e.g., how many paths do we need?). **Marco:** the main issue of ray-tracing is the complexity, the second is that ray-tracing is optimistic (metal reflections, door knobs, small details that may make the difference). **Nada:** there are tools that do this very well, we are trying to do enough given a certain geometry and interface with ns-3. This is the piece we thought it was missing. **Marco:** my way of facing the loss of dynamics would be to plug the phased array traces into ns-3, but it is just for a single setup. However, we can compare the different abstractions for the channel. **Ted:** in airborne networking simulation, there has been attention to these details. The mobile-hotspots program includes ray-tracing in simulations to determine whether you could acquire a link or not, and you needed to know the extent of your antenna to understand when you are locked or not. We reached a realistic abstraction that however was capable of simulating 20-30 nodes. Some of the antenna details can be skipped. Moreover, you need to think about general scenarios (outdoor, conference rooms, indoors).

- **Tommy Svensson (Chalmers)**: *I am a PHY and MAC guy, but I would like to understand how the network layer behaves as a function of the PHY/MAC model I am using. Also the upper layers can give indications to lower layers. Given what you need at upper layers, we can see what we can do below.* **-> Jing:** you need to identify the PHY/MAC limitations. For example, you don't have reflections and the link is blocked, at the upper layers you have to live with that. If the beam is reliable, then you may not have problems at upper layers. When we do congestion control, we assume packet loss. But it may not be due to congestion but to unreliable channel. Thus we need to model this. **Matthew:** for the URLLC traffic, link adaptation is important for low latency even if sometimes gives lower throughput. **Jing:** a full stack end-to-end simulator is important because otherwise you may not even see the problem. E.g., PHY layer design may be completely unresponsive to the need of higher layers.
- **Tom:** *do we need for more sophisticated heterogeneous traffic models? 3GPP indications are very simplistic and outdated. This is also beyond mmWave. What should be used?* **-> Matthew:** this is valid also for the deployment scenario. **Tom:** can this room collaborate on a good heterogeneous traffic model? Is there one? **Jing:** Tom wants to add another element of complexity and there has a continuous debate on this, and application layer is also shaped by transport protocols. Moreover, application demands change very frequently. Application abstraction may even be more challenging than PHY layer abstraction. **Boon Loong Ng (Samsung):** 3GPP models are simplistic, but it comes down to which problems you are trying to solve. Sometimes sophisticated models are not needed. In some cases companies provided data. The application layer abstraction is very problem-specific.

Final question: Marco: 5 to 10 years from now, what will be the most challenging abstraction? **Nada:** we are having problems right now! :)

Prototypes and Testbed Breakout: Detailed Transcript of Breakout Discussion

Discussion Leaders: Xinyu Zhang (UC-San Diego), Ian Wong (NI), Kate Remley (NIST), Robert Shimon (Keysight)

Synopsis of Breakout Discussion:

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

In terms of the available testbeds, NIST is developing a phased-array beamforming simulator, which may be available in one year. Due to the cost constraint, large-scale mmWave network testbed is still not quite feasible, but small scale deployment and testing is definitely feasible. One critical component for mmWave is phased-array, a few research groups (e.g., in UCSD) have made their 28 GHz and 60 GHz phased-arrays publicly available, but the cost may still be an issue for most researchers. Collaborative use of costly testbed, among research groups, and between academia and industry, may be a viable option.

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

Discussion Questions:

1) Hardware testbed development: What're the key requirements? What are the use cases?

2) What are the available mmWave testbeds for research use? What's the cost/programmability?

3) Why does most mm-wave (prototype) hardware remain out of the hands of most academics? Can we find no way to prototype arrays faster and cheaper to get these in the hands of more researchers? Is there a CAD gap?

4) What the key roadblocks to the development of a publicly accessible and programmable phased-array for networking/communications research? How can NSF-funded research lower barriers in the future?

5) How should we motivate the industry to open their commercial mmWave devices' driver, just like Qualcomm did for the 2.4GHz/5GHz band WiFi driver?

6) Are there any research issues involved in the design of the testbed itself? e.g., hardware architecture, programming language, low power design? Will this motivate researchers to participate in the testbed design?

7) What would be a practical way of testing mmWave solutions at large-scale in practical environment? How should the large-scale testbed look like?

8) How should simulators (e.g., ray tracing simulation or numerical simulator of channel propagation) help/complement hardware testbed?

9) How does one generate a known test field for multiple-element antenna arrays?

10) What is the role of statistics in testing arrays that operate in more states than you can count?

11) What are measurement issues related to distributed array timing and synchronization?

12) How to calibrate large-scale, system-level hardware testbeds, separating out non-idealities due to the infrastructure hardware from nonidealities of the DUTs? Do you see a role for uncertainty and/or traceability?

<u>Detailed Summary of Breakout Discussion:</u>

Lead Presentation Notes

1. Lead presentation: Dr. Xinyu Zhang, UC San Diego

- WiMi, 2014, OpenMili 2016 and OpenMili 2.0 under development
- Bandwidth improvement and cost reduction
- Potential integration with UCSD phased-array

2. Lead presentation: Dr. Ian Wong, NI

- Challenges of HW: Performance, Flexibility/scalability, Availability, Cost
- Challenges of SW: Learning curve; Training/Support; NI mmWave Transceiver System (MTS)

3. Lead presentation: Dr. Kate Remley, NIST

- Measurement and testing: channel characterization, OTA tests; hardware imperfectness: harmnonics
- Beamforming algorithm: phased array model
- NS-3 mmWave simulator

4. Lead presentation: Dr. Rober Shimon, Keysight

- mmWave testbeds
- Different flavor of OTA
- Understand mmWave propagation. How precise?
- Determine performance of the testbed.
- Design & implement a testbed: interface? calibration? protect IP while sharing the results?

Breakout Discussion:

1. HW testbed development: What are the key requirement? What are the use cases?

- Low cost is a key requirement, esp. for networking researchers.
- What research questions need the HW? What do you want from the HW?
- The platform should be accessible and should be packaged for the protocol/app developers.
- Challenge: Antenna out-of-the box and in a device is different. Prototype product satisfies the spec, but final product does not work as expected in throughput measurement.
    - Intermediate specs in each step
    - Measurement errors?
    - Spec met, but product does not translate to performance is an issue.
- Different people have different focus, and hence different requirements. Industry/academia may have different requirement as well.
- Challenge: scalability. How to scale to city-level? Cost is a major barrier. Small-scale testbed is more realistic.

2. What are the available mmWave testbeds for research use? What is the cost and programmability?

- Answers partly covered by lead presentation.
- NIST's beamforming algorithm testbed: A year past and another year possibly required.

3. Why does most mmWave (prototype) HW remain out of the hands of most academics? Can we find no way to prototype arrays faster and cheaper to get these in the hands of most researchers? Is there a CAD gap?

- Cost is the major barrier. Another challenge is that it requires coordinated efforts from very different domains (e.g., network protocol designer and antenna hardware designer).
- Researchers want packages that have everything, instead of just antenna, that can be programmed easily.

- It still takes 2 to 3 years to developi a cost-effective HW/testbed.

4. What are the key roadblocks to the development of a publicly accessible and programmable phased-array for networking/comm research? How can NSF funded research lower barriers in the future?

- UCSD group considers to make their 28 and 60 GHz phased array public.
- PAWR program provides an excellent opportunity.
- Collaboration between the industry and the academia

5. How should we motivate the industry to open their commercial mmWave devices' driver, just like Qualcomm did for the 2.4/5GHz WiFi driver?

- 802.11ad cards exist for good price. Possible to build testbed with them, but the proprietary drivers limit the possibility. Also, 802.11ad range may be limited and much shorter than expected in 5G.
- There may be mmWave version of USRP from NI in the near future.
- Big companies have instrumentation level HW, but are they willing to open to the academia?

APPENDIX D:
LIST OF POSTERS & DEMOS

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

1. Wideband Millimeter-Wave MIMO Systems with Lens Array: Architecture and Precoding Design, **Xinyu Gao**, Linglong Dai, and **Akbar M. Sayeed**
2. V-Band Faraday Rotation Measurement Apparatus, **Nitin Parsa**, Nathaniel Hawk, Michael Gasper, Ryan Toonen
3. Integrated Multi-Stream Hybrid Beamformers and Low Phase-Noise Digital Frequency Synthesizers for Millimeter-wave MIMO Communication, Susnata Mondal, Rahul Singh, Ahmed I. Hussein, **Jeyanandh Paramesh**
4. 3D printed Luneburg lens antenna for millimeter wave system, Min Liang and **Hao Xin**
5. UAV Positioning for Improving Coverage-Connectivity Tradeoff in Millimeter-Wave Wireless Channels, Mai A. Abdel-Malek, **Ahmed S. Ibrahim**, and Mohamed Mokhtar
6. MmWave Receiver Array with Wideband Spectrum Sensing, Pawan Agarwal, Deukhyoun Heo and **Subhanshu Gupta**
7. Coordinated Beam Discovery, Association, and Handover in Ultra-Dense Millimeter-Wave Network, **Danijela Cabric**
8. Frequency-Agile Transfer-Function Adaptable Filters and Low SWaP mmW Multi-Beamformers using Mixed Passives and Analog/Digital CMOS Integrated Circuits, Arjuna Madanayake, **Soumyajit Mandal**, Dimitra Psychogiou, Renato Cintra, Leo Belostotski, Chamith Wijenayake, Ted Rappaport, Viduneth Ariyarathna, Diego Coelho, Nilan Udayanga, and Xinyao Tang
9. Multicasting in Highly Directional Networks, Michael Atakora, and **Harsha Chenji**
10. Integrated Millimeter Wave and Sub-6 GHz Resource Management for Low-Latency Communications in 5G Cellular Networks, **Omid Semiari** and Walid Saad
11. Improved Handover Through Dual Connectivity in 5G mmWave Mobile Networks, **Michele Polese,** Marco Giordani**, Marco Mezzavilla, Sundeep Rangan** and Michele Zorzi

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

1. MmWave Phased-Array Based Dynamic Channel Measurements, Christopher Slezak, **Aditya Dhananjay**, **Sundeep Rangan**
2. Cross-layer Design for Reliable 60 GHz WLANs, **Ding Zhang**, and **Parth Pathak**
3. Quantized Angular Beamforming for mmWave Channels with Limited Training, **Hao Zhou**, Dongning Guo, and Michael L. Honig

4. Challenges and Opportunities with mm-wave Communications in 5G, **Tommy Svensson**
5. Toward Large Scale mm-Wave Phased Arrays, **Yahya Tousi**
6. 60 GHz Networking with Mobile Clients: System Design and Implementation, **Muhammad Kumail Haider** and Edward W. Knightly
7. Mobility support in Mm-wave Networks with Minimal Overhead, **Nicolo Michelus**i, Muddassar Hussain, Anoosheh Heidarzadeh, and **Alex Sprintson**
8. Noncoherent compressive estimation of multipath channels for large arrays, **Maryam Eslami Rasekh** and Upamanyu Madhow
9. A Parallel Fast Fourier Transform for millimeter-wave applications, **Dale Mugler**, and Arjuna Madanayake
10. Multi-Phase Signal Source for Millimeter-Wave Applications, **Numan S. Dogan** and Zhijian Xie

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

1. Multi-User Wireless Virtual Reality with Millimeter Wave Networks, Suraj Jog, Anadi Chaman, and **Haitham Hassanieh**
2. End-to-End Network Simulation of mmWave Cellular Systems, **Marco Mezzavilla**, Menglei Zhang, Sourjya Dutta, **Sundeep Rangan**
3. 5G Antenna Systems; A Rigorous Treatment and a Software Tool, **Nick Buris**
4. Linearized CMOS Photonic Modulators for Millimeter-Wave Wireless, **Vishal Saxena**
5. MmWave Channel Emulation, **Aditya Dhananjay, Sundeep Rangan**
6. User Association in mmWave MIMO Network, Alireza Alizadeh and **Mai Vu**
7. Efficient Beamforming for Link Establishment in mmWave Systems, Irmak Aykin and **Marwan Krunz**
8. TCP in 5G mmWave Networks: Time and Path Diversity, **Michele Polese** and Michele Zorzi
9. Feedback-Assisted Incremental Redundancy in mmWave Communications, **Borja Peleato**
10. Enhanced-Gain Antenna Array Design for Millimeter-Wave Systems, **Kashyap Kalavapudi** and **Steve Chiu**
11. 5G Experimental Trial of 28 GHz Band in NTT DOCOMO, **Yuichi Kakishima** (DOCOMO Innovations, Inc./NTT DOCOMO, INC.

Demonstrations with Brief Descriptions:

- **NI mmWave Platforms:** Sarah Yost and Ian Wong

  NI will be demoing an over the air, real-time mmWave communications system. With 2 GHz of bandwidth and FPGA co-processors, this system is used to create a full link in real-time. This system runs a physical layer that is being proposed for Phase 2 New Radio. The combination of SDR hardware and flexible, open software allow researchers accurately prototype 5G mmWave systems in everyday scenarios, from the lab to outdoors.

  Local equipment needs: 2 mice, 2 monitors (with VGA cables), 2 keyboards. ideally 2 tables, or one 6ft table.

- **Qualcomm mmWave prototype demo (video)**: Ashwin Sampath

  Local equipment needs: laptop, mouse, display and a table

- **NYU mmWave Channel Emulator:** Aditya Dhananjay and Marco Mezzavilla

  Channel emulation is a basic tool for the design and evaluation of wireless systems. In channel emulation, the TX and RX devices under test (DUTs) are physically connected to a channel emulator which is a box that simulates a configurable wireless channel between the two devices. The wireless channel is generally described via multipath fading profile which can be configured to reproduce measured traces or standard profiles such as in the 3GPP models. In contrast to over-the-air (OTA) testing, channel emulation enables reproducible and highly configurable test cases that can be performed at much lower costs. The challenge with traditional emulation for mmWave scenarios is the need to support high-dimensional phased arrays. The traditional emulation paradigm, when applied to DUTs having a large number of antenna elements, breaks down due to the following reasons: a) prohibitive computational complexity; b) expensive hardware requirements; and c) cumbersome interfaces between the DUTs and the emulator.

  We demonstrate a prototype mmWave channel emulation where the DUTs interface with the emulator entirely in baseband. The emulator not only emulates the wireless channel, but also the multi-antenna RF front-ends on the DUTs themselves. In other words, the emulator emulates the effective baseband SISO channel between the TX and RX DUTs. The advantages of this approach are: a) it de-couples the design of the baseband algorithms from the design of the RF front-end, leading to faster iterations of system design and testing; b) significantly lower computational complexity of O(1), irrespective of the number of antennas in the emulated front-ends; c) lower hardware costs; d) suitable for implementation over generic SDR components (such as FPGAs). We demonstrate an emulator built on top of National Instruments SDR platform with 3 GHz of instantaneous bandwidth simulating a 5G New Radio-type connection.

Local equipment needs: monitor, mouse, keyboard and a table

- **MIMObit: A Cross Layer Design Tool for 5G and …much more:** Nick Buris

Multi Element Antenna (MEA) systems for Multiple Input Multiple Output (MIMO) capable products are employed in WiFi to increase robustness and throughput and are key to the deployment of Cognitive Radio, 4G and 5G wireless systems. But, unlike past practices, MIMO antenna systems cannot be adequately described with traditional attributes of gain and radiation efficiency alone. Additionally, for very wideband antenna systems and for the envisioned high frequencies of 5G, high fidelity antenna description and coupling is expected to play a significant role. Furthermore, the same techniques that optimize MIMO systems have the greatest potential in optimizing Spectrum Utilization and Dynamic Spectrum Access (DSA) approaches. Thus, integrated approaches, where antenna design decisions are made at the Capacity/Throughput level, while DSA decisions are made at the Spectrum Utilization Efficiency (SUE) level are required for optimal cost-performance product and network solutions.

MIMObit provides just that! For the antenna designer, MIMObit provides performance evaluation of MEA systems in terms of Throughput and Capacity (Open Loop, Beamforming, Waterfilling). Based on an EM exact formulation, MIMObit treats antenna systems very accurately, including antenna terminations, element coupling, matching circuits, full active E-field gains and various RF propagation models (these models include the latest 3GPP New Radio models valid in the 0.5 to 100 GHz range, the IEEE as well as models based on Ray Tracing of actual propagation environments). For the DSA designer and spectrum manager, MIMObit provides Signal and Interference Tx radio user-defined power masks and temporal behaviors which allow the evaluation of RF Radio Maps, Harmful Interference, Spectrograms and Spectrum Utilization.

MIMObit 2.0 will be demonstrated on a number of problems to showcase some of the aforementioned concepts and the ability to handle them in a consistent and quantitatively robust way.

Local equipment needs: table.

- **WiMi 60 GHz platform at UW-Madison**: Chuhan Gao, UW-Madison.

A demonstration of the 60 GHz WiMi platform.

- **28 GHz CAP-MIMO Testbed at UW-Madison**: Kevin Zhu and Chris Hall, UW-Madison.

A demonstration of the CAP-MIMO testbed for single user and multiuser communication in both LoS and NLoS conditions.

APPENDIX F
PANEL 2 DISCUSSION NOTES

Panel 2: Academia-Industry Collaboration for "Moonshot" RCN Contributions Discussion Notes

Moderator: Sundeep Rangan (NYU)

Panelists: Nada Golmie (NIST), Ali Niknejad (Berkeley), Tommy Svensson (Chalmers), Jason Chen (Huawei), Amitava Ghosh (Nokia-Bell Labs)

Scribes: David Michelson (UBC) + Ismail Guvenc (NCSU)

Panel Discussion Summary: The moderator encouraged the panelists to be bold and noted the diversity of the panel. Several interesting responses were offered to the opening question to the panelists: What is the moonshot problem that will drive us? These included

- Integration of communication and computing to meet delay and energy requirements
- Bandwidth vs latency tradeoffs are key and vary with use cases; >100GHz frequencies
- Sustained (rather than peak) Gbps data rates will be key to enabling new applications
- Business models and economic considerations
- Cross-layer and inter-operability issues for verticals
- New uses cases will drive innovation

Integrated communication and sensing, including radar and channel estimates, was noted as a promising direction for new use cases.
Enabling mobile networks at mmWave frequencies was noted as necessary for disruptive innovations.

A particular use case of interest – considered a killer app by some – is autonomous vehicles which will not only require high rates and low latency but would also benefit from integrated communication and sensing and many of the key attributes noted above enabled by mmWave. Machine learning could play an important role in this use case.

Panel Discussion Notes:

Opening comments from Rangan: Suspend worries about tech limitations, think boldly, disagreement encouraged
-diversity of panel: academic/industry and Europe/America was noted
-absence of government and service provider reps was also noted

Q: What is the moonshot application that will drive us?

Tommy Svensson:
-- Bigger picture: integration of computing and communication to meet stringent delay and energy efficiency requirements
-- will involve moving significant cloud computing capability from the core to the edge to most 5G aspirations

Amitava Ghosh:
-- Bandwidth vs. Latency slide from Nokia (new digital experiences that save time)
-- 5G pushes the limits on both, but each application has their own combination of requirements
-- Star Trek thinking time: smartphone, VR, 3D printer. All Star Trek coming to reality. No transporter or

Tricoder yet.
-- Should decrease distance and increase knowledge to save time. But this remains to be done.
— bandwidth is key to achieving capacity /and/ reducing latency
— spectrum > 100 GHz will likely be key; several bands seem accessible

Niknejad:
-- iPhone: putting the whole thing together, reducing the cost, then it was widely adopted
— too much emphasis on peak data rates; the key is to deliver sustained data rates
— Sustained data rates (Gbps), for every device, simultaneously
-- Once you enable Gbps, applications will follow (VR/AR etc)
-- Reliability, latency, understanding interference, energy consumption, cost are important

Jason:
-- Not only technology issues, but also economic and business issues
-- Inter-operability issues, considering cross-layer issues and enabling verticals
-- Reason WiFi works: single device. Cellular has a big network behind it, which is expensive.
— new applications and use cases will always drive innovation

Q: Any of the panelists wish to talk more about the use cases?

Question from audience: communications with moon or undersea (alternative to fiber?)
-- There are existing applications satellite-to-ground or in space
(NASA/ESA have standardized mmWave communications for new remote sensing LEO satellites)
(mmWave has been used for GEO satcom for decades)

Question from audience: everyone talks about cost, any concrete numbers for BS, UE etc?
— Stefano Galli: Is there a huge disconnect between the 3GPP standards and user expectations?
— What about coexistence with old tech?
-- People spend $100-$200 on WiFi APs, should bring the cost to similar levels, people can install the network themselves

Thyaga: What are some moonshot problems? NSF RCN is not only 3GPP.

Ismail: as Michelson mentioned, mmWave Radar and positioning integration with communications. Use of big data and machine learning in that context.

Niknejad: Channel sounding is being done, can use it in for also radar.
-- Distributed computation is important moonshot application.
-- Resource allocation will be key

Monisha Ghosh: Data center connectivity using mmWave in 802.11ay. Is that a use case that makes sense for mmWave; data rate makes sense but deployment?

Various: What about mmWave for high speed, very short range interconnect

Question from audience: Autonomous vehicles was voted as the killer app for 5G, any comments?
-- Huawei: All sounds very good, but it is also an ownership issue. Who owns it?
— Various: Integrating mobile networks is key to enabling disruptive business applications

Tim (GM): Automotive vehicles IS the killer app! Need to think bigger than that. Collaborative transportation is the bigger challenge; how mobility fundamentally changes how all the vehicles behave collectively.

Niknejad: Exchange raw information among the cars help. But modifying the data is sensitive; one car may say the surrounding object is a dog, but it may be a kid.

Matthew Andrews: Does mmWave change the data plans? E.g. for AR/VR or automated vehicle applications?

Sundeep: NSF's effort (NSF-WINS) to increase access to data, how does mmWave relate?

Monisha: What about using mmWave to cover underserved areas? Rural vs. Urban?

Niknejad: Can fly around drones where they are needed to provide connectivity.

Monisha: One of the ways mmWave can be used is to serve as a backhaul. Can do even with today's technology. Question is why it is (mmWave backhaul) not being done today?