WIRELESS

www.nyuwireless.com

NYU WIRELESS: Overview, Research, Perspectives

GAO MEETING

30 MARCH 2020

Overview

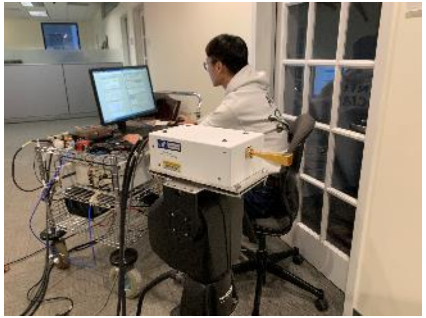
NYU WIRELESS: Mission and Expertise

- World leading academic center in wireless communications
  - 25 faculty, post-docs, research engineers
  - 60 students
  - 15 industrial affiliates
  - Largest research center in NYU Tandon

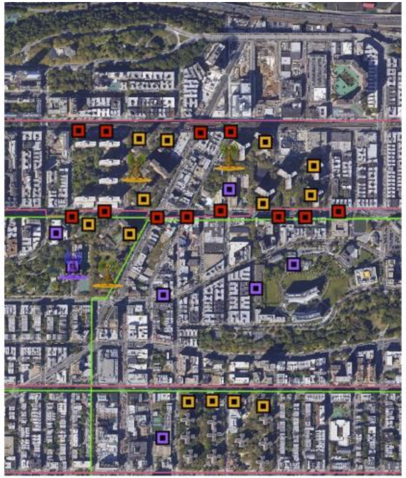
- Our mission:
  - Fundamental research: Lead the way to the next generations
  - Solve problems for industry
  - Create leaders
- Current in force funding
  - Over $10 Million/annually from NSF, NIH, and Corporate sponsors

Theory to Practice

- NYU WIRELESS: Technologies and students that impact the real world!



- We focus on wireless technologies: “end-to-end”
  - How wireless interacts with upper layer protocols and applications
  - How wireless works in the real world!
- NYU WIRELESS tools are widely-used in industry and academia
  - NYUSIM Statistical Channel Model
  - Channel Sounders, Propagation Data, software, chips
  - Ns3 network simulator
  - Widespread industry and academic use – over 80,000 NYUSIM users

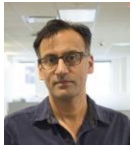


- NYU WIRELESS has leading roles in two largest nationwide testbed programs
  - NSF PAWR: COSMOS: Large-scale city wide testbed in NYC
  - SRC/DARPA: JUMP: Multi-university center on THz

Directors

- Ted Rappaport, Founding Director and Professor, ECE
  - Pioneer in millimeter wave wireless communications
  - Author of "Principles of Wireless Communications"
  - Previously founded wireless centers at UT Austin and Virgina Tech

- Tom Marzetta, Director and Distinguished Industry Professor, ECE
  - Pioneer in MIMO and Massive MIMO: lead-author "Fundamentals of Massive MIMO"
  - Joined NYU 2017 from Bell Labs
  - NAE member, 2020



- Sundeep Rangan, Associate Director and Professor, ECE
  - > 15 years experience in cellular industry
  - Co-founder Flarion Technologies (developed first cellular OFDM data system)

- Dennis Shasha, Associate Director and Professor, Courant Institute of Mathematical Sciences
  - Machine learning, databases, bio-informatics

- JR Rizzo, Associate Director and Assistant Professor, NYU School of Medicine
  - Technologies for the blind and visually impaired

Recent Honors

- Ted Rappaport:
  - Wireless Hall of Fame, 2019
  - 2020 Eric Summer Award
- Tom Marzetta: NAE member 2019
- Elza Erkip:
  - ComSoc CTTC Technical Achievement 2018
- Numerous Best Paper Awards:
  - Marzetta: 2019 Fred W. Ellersick Prize
  - Erkip: 2019 Best Tutorial Paper Award

Industrial Affiliates

ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™
at&t
CableLabs
CACI
EVER VIGILANT
CROWN CASTLE
ERICSSON
HUAWEI
interdigital
KEYSIGHT TECHNOLOGIES
NOKIA
NSF
oppo
QUALCOMM
SONY
Sprint
UMC

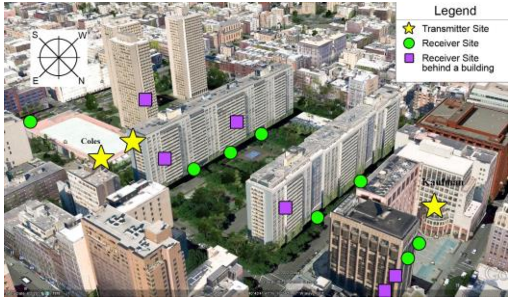
Events

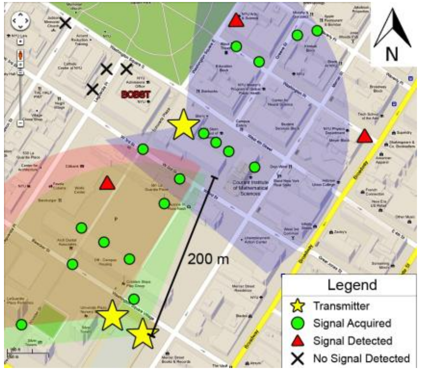
- Open house and recruiting day, January
  - Connects students to companies
  - Internships and full-time positions
- Brooklyn 5G Summit, April
  - Pre-eminent conference on 5G
- New Annual NYU WIRELESS Workshop
  - Initial theme: “Re-Inventing the Physical Layer”
  - Convene wireless researchers across multiple disciplines
  - First workshop to be held 2020

Education and Outreach

- Graduate classes:
  - Digital communications, wireless, info theory, …
- Monthly webinars for affiliates
  - The latest research directly from our labs!
- High school outreach in NYC
  - High school lab development
  - Teacher training

Millimeter Wave and NYU



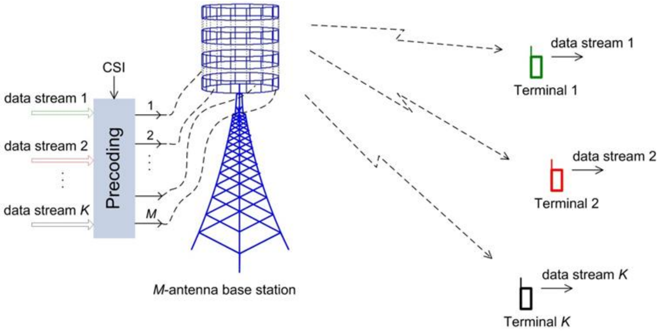


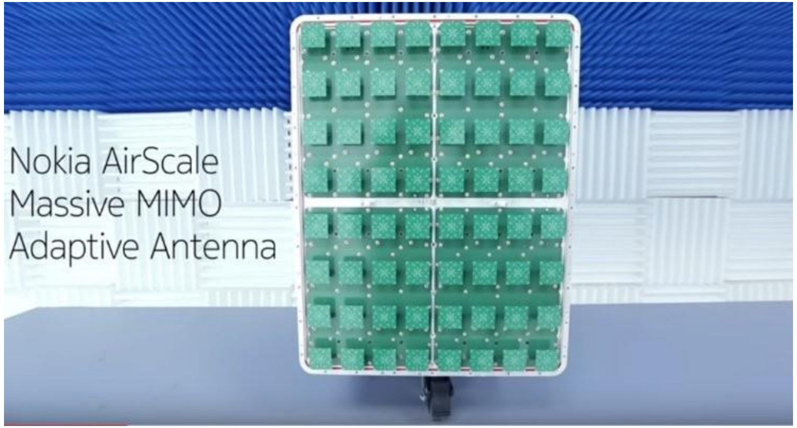
- NYU was a leader in 5G mmWave
- Millimeter wave: It can work!
  - First measurements in urban canyon environment in 2013
  - Demonstrated cellular connectivity was possible
- First Brooklyn 5G Summit in 2013

Rappaport, Theodore S., et al. "Millimeter wave mobile communications for 5G cellular: It will work!." *IEEE access* 1 (2013): 335-349 (4600 Google citations)

Massive MIMO

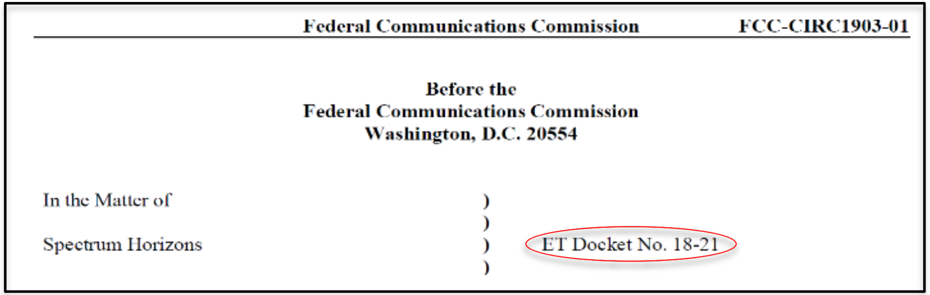
- Second key technology for 5G
- Data transmitted via focused beams
- The most efficient wireless technology ever devised
- Pioneered by NYU Prof Tom Marzetta





Marzetta, Thomas L., "Noncooperative cellular wireless with unlimited numbers of base station antennas" *IEEE Trans Wireless Communications, 2010 (4800 Google citations)*

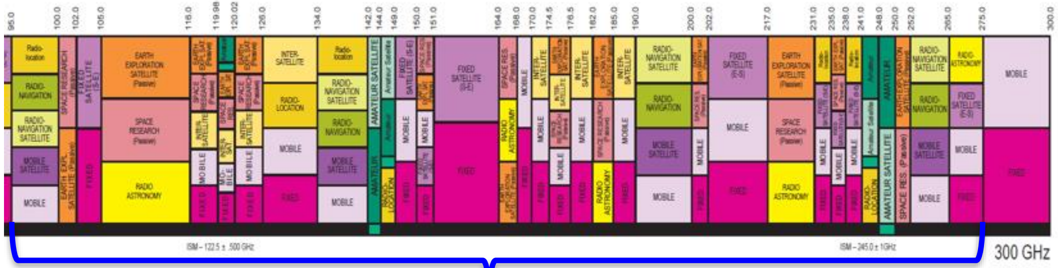
Spectrum Policy Leadership


Federal Communications Commission FCC-CIRC1903-01

Before the
Federal Communications Commission
Washington, D.C. 20554

In the Matter of)
)
Spectrum Horizons) ET Docket No. 18-21
)

Report and Order ET Docket 18-21
Feb 22, 2019



95 GHz

275 GHz

40 frequency bands

- NYU WIRELESS first university in the mmWave Coalition- pushed for rules > 95 GHz
- Experimental licenses for 95 GHz to 3 THz - **Spectrum Horizons ET Docket 18-21**
- 21.2 GHz **Unlicensed Spectrum** to be allocated.
- Rules on Licensed spectrum deferred until sufficient technical and market data is obtained (NYU Thurst area)

http://mmwavecoalition.org/wp-content/uploads/2019/02/DOC-356297A1-FCC-Report-Order.pdf

ET DOCKET 18-21 SPECTRUM HORIZONS

Spectrum Horizons Experimental Radio Licenses

- Frequency within **95 GHz to 3 THz**
- No interference protection from pre-allocated services.
- Interference analysis before license grant.

FCC Approved on March 15th 2019

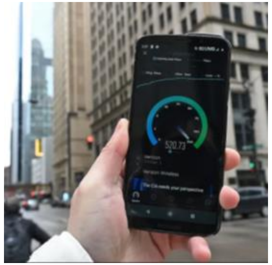
Unlicensed Operation

- Maximum EIRP of 40 dBm (average) and 43 dBm (peak) for **mobile**.
- Maximum EIRP of $82-2*(51-G_{TX})$ dBm (average) and $85-2*(51-G_{TX})$ dBm (peak) for **fixed point-to-point**.
- Out-of-band emission limit 90 pW/cm^2 at three meters.

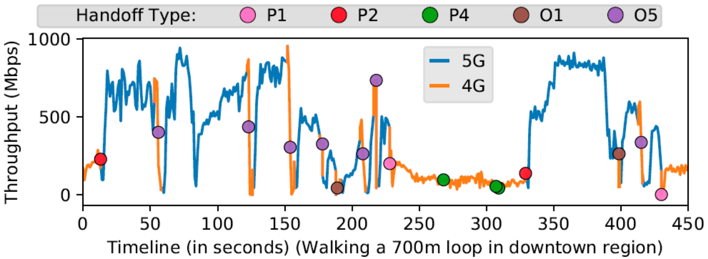
Frequency Band (GHz)	Contiguous Bandwidth (GHz)
116-123	7
174.8-182	7.2
185-190	5
244-246	2
Total	21.2

http://mmwavecoalition.org/wp-content/uploads/2019/02/DOC-356297A1-FCC-Report-Order.pdf

5G is Here … and the Research Continues



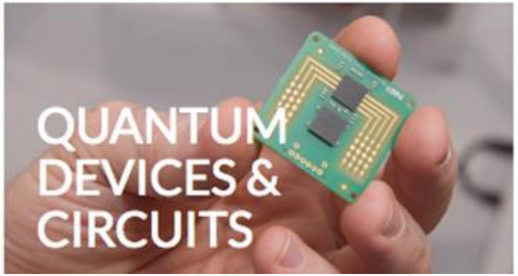
VZ handset Sam Rutherford, gizmodo



Narayanan et al, A First Measurement Study of Commercial mmWave 5G Performance on smartphones, Sept 2019.

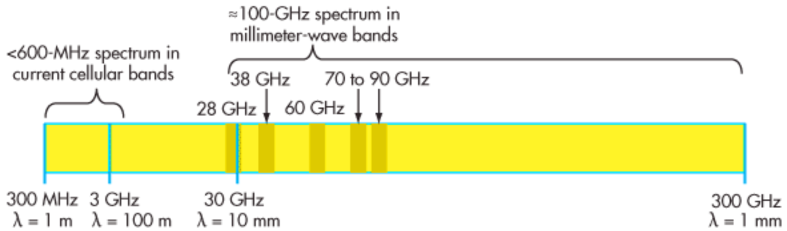
- 5G is here!
  - FCC has released spectrum
  - 3GPP completed Phase 1 and 2 specifications
  - Service is now available in the US
- High peak data rates: > 1 Gpbs
- Better coverage than expected
- But, many challenges remain:
  - Coverage, power?
  - Networking?
  - How will we use it?
- NYU continues to lead 5G and beyond

NYU WIRELESS Research Thrusts



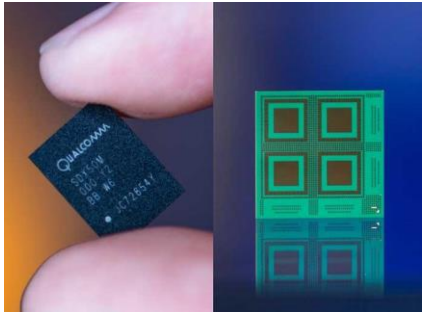
Research Highlights

Millimeter Wave for 5G



From Electronic Design

- 1-10 mm wavelength = 30 to 300 GHz
  - Massive unused spectrum
  - Supports high data rates for 5G
- Networks with
  - Highly directed beams
  - Small cells (typically ~100 to 200m cell radius)



Snapdragon X50 5G modem chip
28GHz mmWave antenna module
Source: qualcomm.com

Millimeter Wave Prototyping

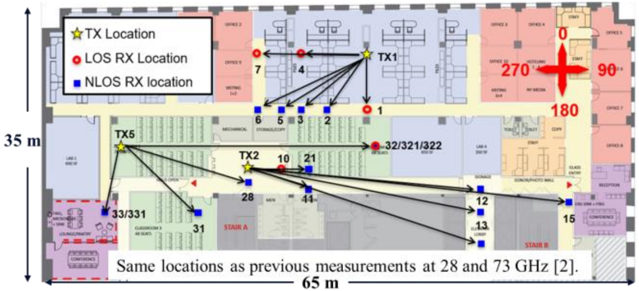
- ❑ 4 channel 60 GHz fully-digital transceiver
  - ADI HMC6300 mmWave up-converters
  - ADI HMC6301 mmWave down-converters
  - ~15dBm per channel
- ❑ Phase-synchronized LO
  - TI LMX2595, ADI LNA and PA for amplification
  - Knowles Dielectric Wilkinson dividers
- ❑ Antenna design by Aalto University, Finland
- ❑ Coming soon: Integration with 140 GHz parts!
  - Collaboration with ComSenTer and UCSB

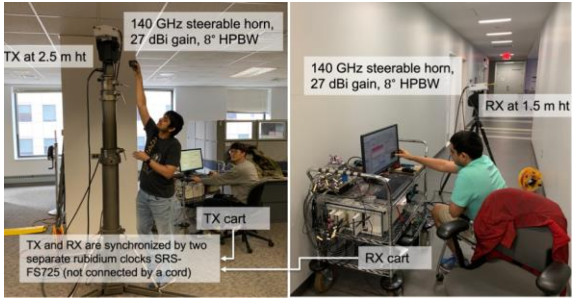
Xilinx ZCU111 w/
Pi-Radio custom 60 GHz analog FE

- K. Zheng, A. Dhananjay, M. Mezzavilla, et al, "*Software-defined Radios to Accelerate mmWave Wireless Innovation*", IEEE DySpan 2019.
- M. Polese et al, "*Toward A Large-Scale Open-Source mmWave and (Sub)Terahertz Experimental Testbed*", ACM MobiCom 2019, mmNets Workshop.
- J. Haarla, V. Semkin, K. Zheng, A. Dhananjay, M. Mezzavilla, et al, "*Characterizing 60 GHz Patch Antenna Segments for Fully Digital Transceiver*", IEEE EuCAP 2020.

Communication Above 100 GHz

- ❑Rappaport leading measurements above 100 GHz
- ❑Released models for 140 GHz indoor
- ❑Outdoor measurements coming soon
- ❑State of the art high bandwidth channel sounder



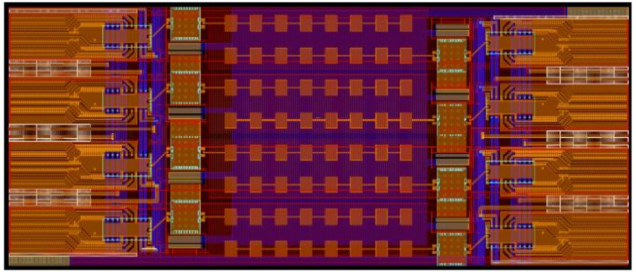


[1] Y. Xing et al., “Propagation Measurement System and approach at 140 GHz- Moving to 6G and Above 100 GHz,” IEEE 2018 Global Communications Conference, Dec. 2018, pp. 1–6.

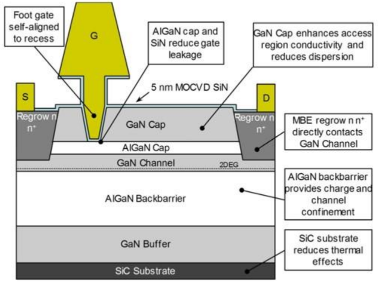
[2] G. R. Maccartney, T. S. Rappaport, S. Sun and S. Deng, "Indoor Office Wideband Millimeter-Wave Propagation Measurements and Channel Models at 28 and 73 GHz for Ultra-Dense 5G Wireless Networks," in *IEEE Access*, vol. 3, pp. 2388-2424, 2015

ComSenTer for THz

- Center for Converged THz Communication and Sensing
  - UCSB lead, NYU is systems lead
  - $27 million program from SRC and DARPA JUMP
  - Team with leaders in the field
- 140 to 640 GHz
  - 6G Communications, radar
- Demonstration vehicles
  - 1000 stream MIMO
  - Ultra-high resolution radar
- Builds on leading advanced THz devices
  - SiGe HBT, GaN, InP HBT, InP MOS HEMT

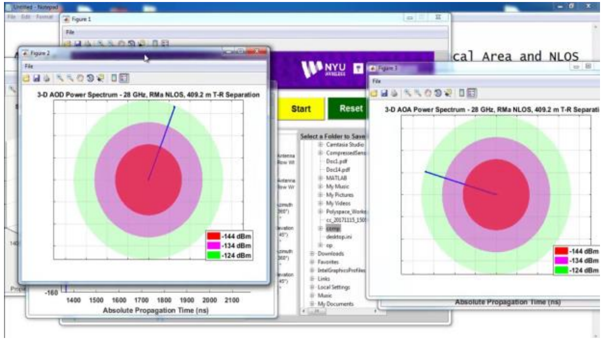


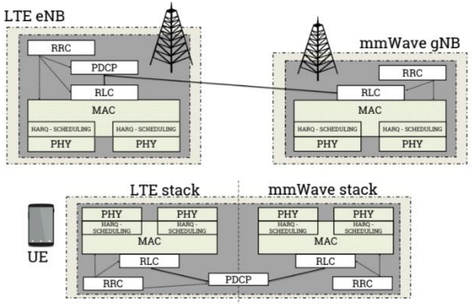
8 channel tileable 140 GHz board
Currently in development targeting mid 2020



GaN device by U Mitra

NYUSim and NS3 Network Simulator



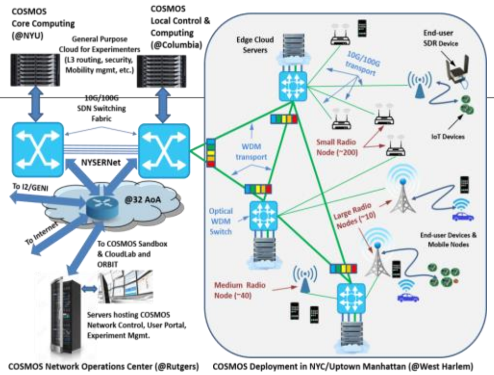


- NYUSim for mmWave channel modeling:
  - Widely-used statistical modeling software
  - Incorporates latest measurements
  - 1000s of downloads
  - Models for 28, 37, 73 and 140 GHz
- NS3 network simulator
  - First and most extensive end-to-end simulator
  - Detailed channel models (ray tracing, measurements, statistical)
  - Full stack and core network emulation
- Our simulators are:
  - Fully open source
  - Used by our affiliates and many others

NYU TANDON SCHOOL OF ENGINEERING

NYU WIRELESS

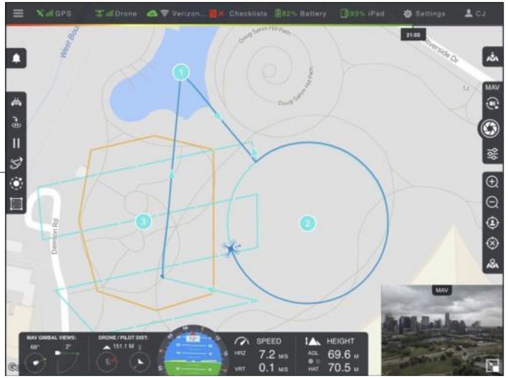
NSF PAWR: COSMOS



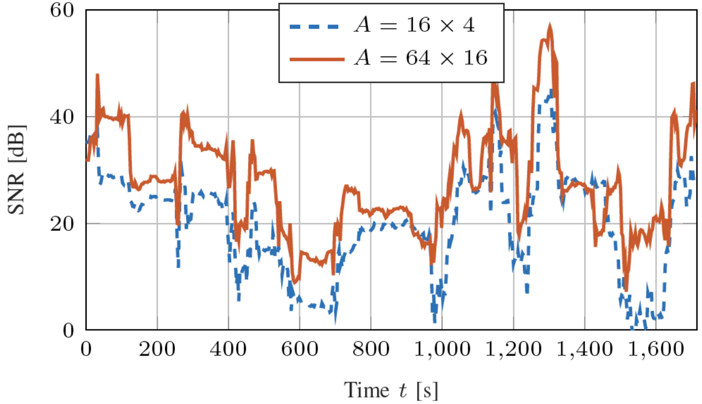
- ❑ Cloud Enhanced Open Software Defined Mobile Wireless City-Scale Deployment
  - Rutgers (lead), NYU and Columbia
  - Largest university testbed in nation
  - Open to any company or university for experimentation

- ❑ Deployment plan:
  - 20 city blocks upper Manhattan
  - Small, medium, large nodes
  - MmWave capabilities
  - Phase 1 is complete

MmWave UAV Communication

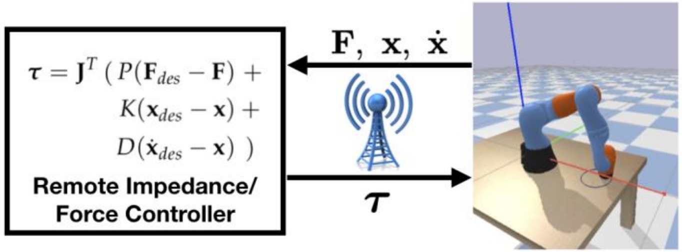


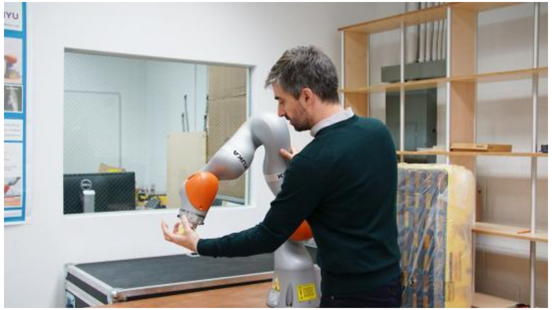
- Exploring mmWave communication for:
  - Remote low-latency control and video / sensor feeds
  - Wireless connectivity to first responders
- Joint work with G. Loianno (drone robotics)
- Detailed simulation of UAV link at 28 GHz:
  - Mission flight data from DroneSense
  - Channel and network modeling from ns3
- Key challenges:
  - Beam tracking, 360 coverage



Xia et al, “Millimeter Wave Remote UAV Control and Communications for Public Safety Scenarios”, IEEE SECON 2019

Edge Control for Robotics



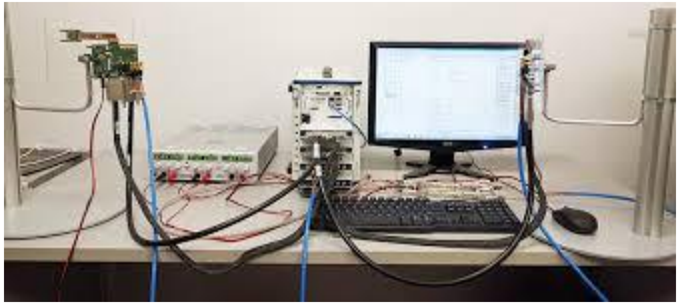


- ❑Robotic control demand high computation
- ❑But, offloading presents challenges
- ❑Torque control
  - Low bandwidth, but…
  - 1 to 5 ms latency requirement!
- ❑Perception / motion planning:
  - High bandwidth
  - Multiple cameras / LIDAR
- ❑Multi-robot scenarios
  - Interference / network loading

Righetti, Garg, Rangan, Erkip, Rappaport

National Instruments Major Testbed Donation

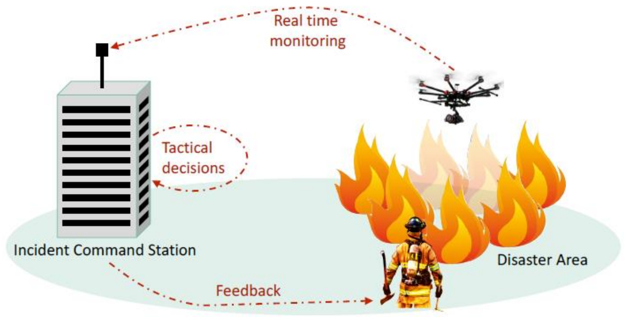
- Close to $1million donation from NI
- Four advanced mmWave nodes
  - 60 GHz phased array
  - 28 GHz may be available later
  - OFDM 3GPP New Radio stack
- Applications
  - Network testbed with applications
  - Channel emulation
  - Advanced channel sounding
- Can be incorporated into PAWR



NATIONAL INSTRUMENTS™

Public Safety Communications above 6 GHz

- NIST project for mmWave for PSC
  - $2.7 million grant over 3 years
- Develop tools for assessing mmWave:
  - Channel measurements, emulation
  - SDR, network simulation
- Collaboration with Austin Fire Dept, U Padova
  - Focus on drone to command center communication



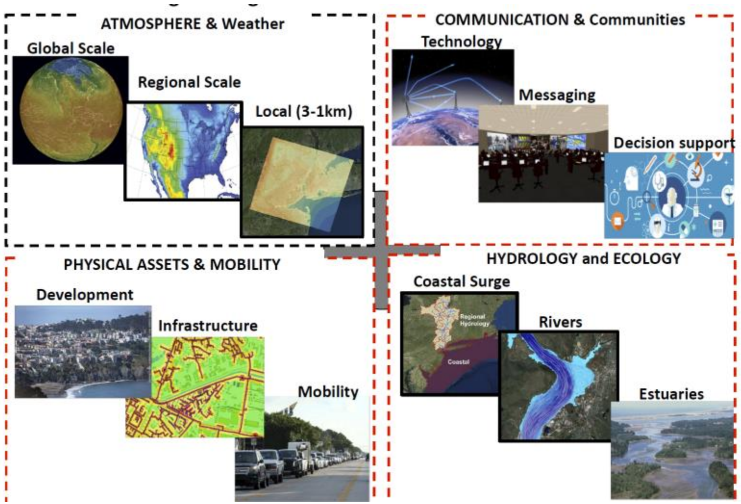
Mezzavilla et al, “Public Safety Communications above 6 GHz: Challenges and Opportunities”, IEEE Access on Mission Critical Services, 2017

NSF ERC: SERC

- Smart Engineering Resilient Coastlines
  - Partnership with leading climatologists, civil engineering, communications
  - CCNY (Lead), Princeton and NYU
  - Proposal selected for final 10 out ~190

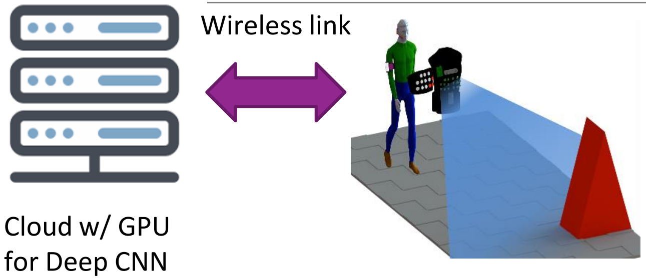
- NYU lead: Masoud Ghandehari
  - Lead infrastructure information systems

- Key wireless focus:
  - Resilient cellular infrastructure
  - Fast deployable emergency services
  - Advanced wireless location services (esp. mmWave and THz)
  - Environmental sensors and IoT

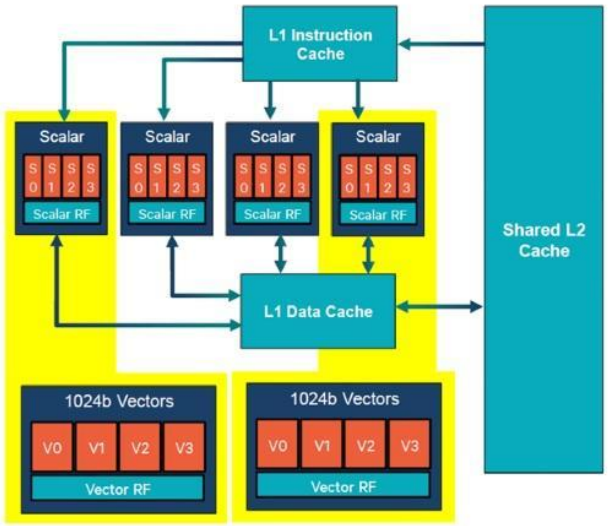


Wireless Edge Computing for Visually Impaired

- JR Rizzo, PI
- New visually assistive technologies
  - Cameras, GPUs and haptic feedback
- Combines many state-of-the-art technologies
  - High bandwidth wireless
  - Edge computing & AI
- Developments will translate to other domains
  - Autonomous driving, mobile ML, …

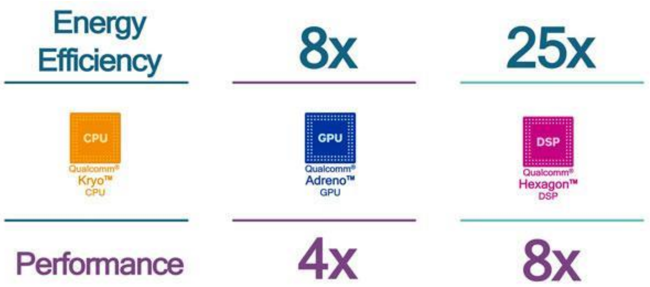


ML Accelerators Are Going Mobile



Source: Qualcomm.com

- Qualcomm Hexagon 685 DSP
  - Embedded in SnapDragon 835
  - Support for TensorFlow, TensorFlow Lite, Caffe2.
  - 8 bit support
- Similar efforts at Apple's A12 Bionic

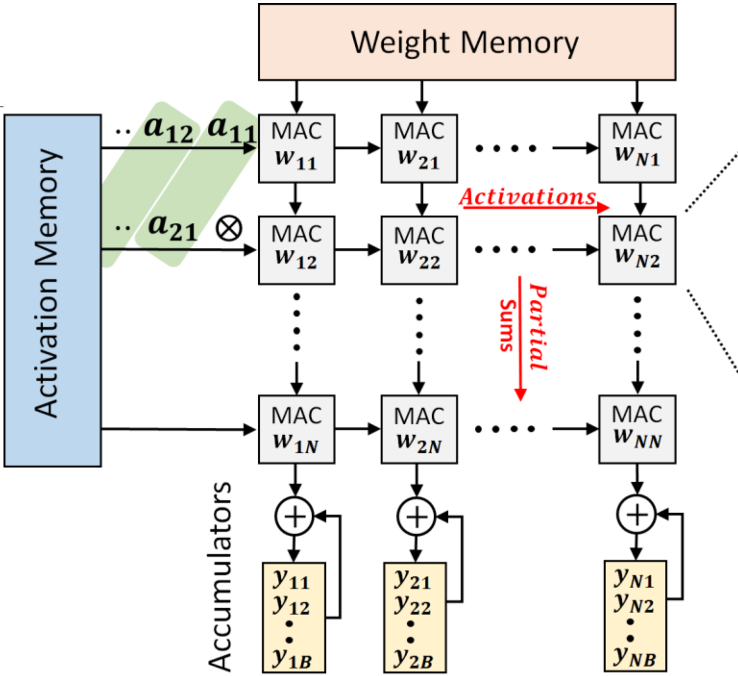


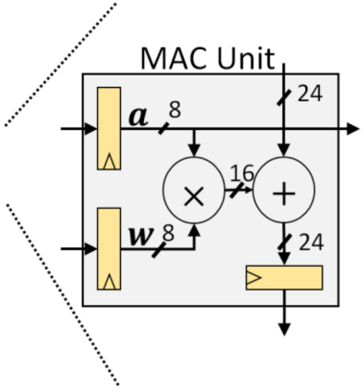
Hardware Acceleration for Deep Learning

S. Garg

- **Systolic Array**
  - accelerates matrix mults and convolutions

- **2-D grid of MAC units**
  - nearest neighbor communication
  - amortizes memory access cost





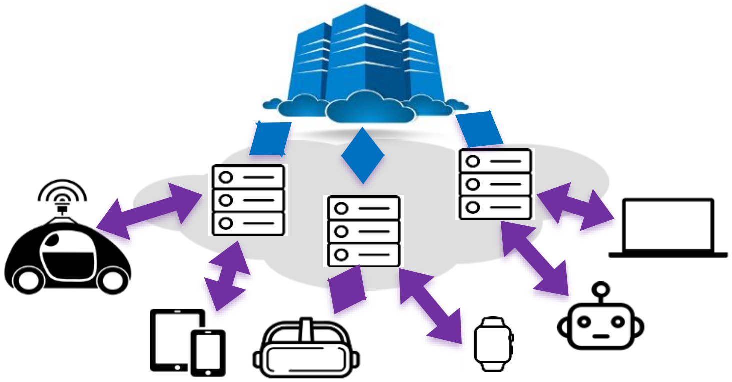
Google's AI Engine

- **30x-100x greater TOPs/Watt vs. GPU**

[1] **N. Jouppi** et al., "In-datacenter performance analysis of a tensor processing unit", ISCA'17.

Mobile Machine Learning

- Machine learning successes depend on:
  - Incredible computation power
  - Access to massive data
- Desire to making it mobile and ubiquitous
  - Handsets, robots, vehicles, …
  - Power / area constraints
- Interactive
  - Connections to sensors at low latency



Wireless is Key

Tele-commuting, VR and Beyond

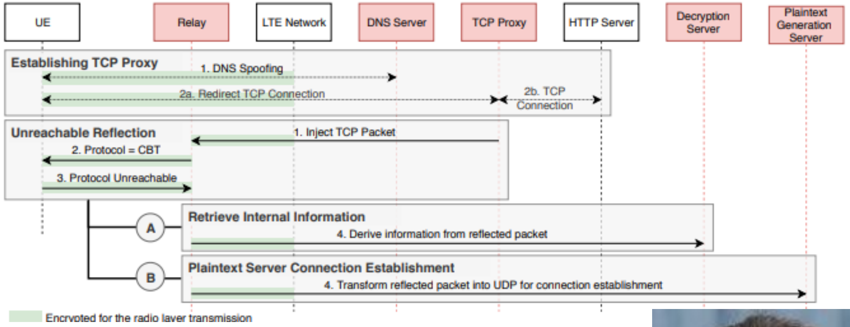
- Home office is increasing massively during Covid-19
  - 90% increase in home traffic Italy, Bloomberg
  - Need better connectivity for low-income households
  - Many trends will remain after the virus
- Better / higher bandwidth technologies needed
  - VR/AR, immersive environments
- Wireless / communications technology will be key
- NYU Wireless has many potential partners:
  - Rlab in Navy Lab (with $5.6 million grant from NY State)
  - Future Reality Lab (Ken Perlin)
  - NYU Holodeck for remote medical training

Rlab Open House in the Navy Yard

NYU holodeck

5G and Security

- ❑5G closed many security vulnerabilities
  - Ex: Data plane integrity protection
- ❑But, new threats will arise:
  - Distributed core network
  - Multiple vendors and mobile cloud
  - Attacks from within the core network
- ❑NYU Center for Cybersecurity
  - One of the largest centers at NYU
  - 22 faculty in CS, ECE, law and policy
  - Host of the annual CSAW



DNS spoof attack on LTE described in Rupprecht et al, ¨IMP4GT: IMPersonation Attacks in 4G NeTworks” NDSS 2020

Christina Pöpper, cellular security expert, NYU Abu Dhabi

Massive MIMO for 6G

- Cell-Free Massive MIMO: serve an entire city by a network of distributed access points
  - Confers shadow-fading diversity
  - Enables transmission of multiple data streams to each user, even under line-of-sight conditions
- Holographic MIMO: replace arrays of discrete antennas with continuous radiating/receiving surfaces
  - Simpler and cheaper
- Large Intelligent Surfaces: surround users by physically large arrays or controlled reflecting surfaces
  - New phenomenology: all users are in the near-field
  - Field curvature provides multiplexing degrees-of-freedom even under line-of-sight conditions

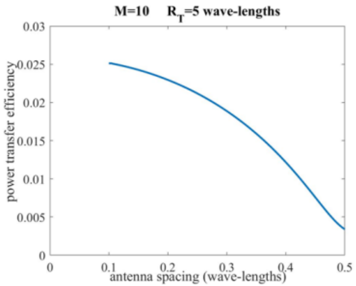
A. Pizzo, T. L. Marzetta, and L. Sanguinetti, “Spatially-Stationary Model for Holographic MIMO Small-Scale Fading,” accepted for publication in *IEEE Journal on Selected Areas in Communications*, 2020

Super-Directive Antenna Arrays

For example, consider a transmitting horn antenna, with an aperture about 10 wavelengths on a side, located in outer space roughly aimed at the earth, With a one wavelength diameter supergain antenna on the earth it is possible to receive virtually all of the power radiated by the horn antenna

- All of today's wireless systems operate far from any limits imposed by physical law
  - Super-directivity (Schelkunoff, 1943)
  - Place antennas close together ($< \lambda/2$) to create strong mutual coupling
  - Exploit mutual coupling to create array gains proportional to the square of the number of antennas
  - Potentially applicable to wireless power transfer as well as communications

T.L. Marzetta, "Super-directive antenna arrays: Fundamentals and new perspectives", *Proc. 53nd Asilomar Conference on Signals, Systems, and Computers*, 2019



Policy Options

Inefficient Use of Available Spectrum

The U.S. should adopt Massive MIMO on a large scale: But with TDD!

- Massive MIMO is the most spectrally-efficient (bits/second/Hz) technology ever devised
  - All active users in the cell are served with the full time/frequency resources
  - Performance always improves with increasing numbers of base station antennas
- In mobile environments, Frequency Division Duplex (FDD) operation severely limits the number of base station antennas
  - Time needed to learn the channel is proportional to number of antennas
- In contrast, Time Division Duplex (TDD) operation supports unlimited numbers of antennas
- Verizon, AT&T, T-Mobile are entirely FDD; only Sprint has TDD spectrum
- In the absence of a shift to TDD, the supremely valuable sub-6 spectrum will be under-utilized

Cybersecurity Risks

Privacy Concerns

Concern Over R.F. Health Effects

Reduce radiated power levels through Massive MIMO

- Massive MIMO is the most energy-efficient technology yet devised
- For the same level of service, radiated power is inversely proportional to the number of base station antennas
  - Radiated energy efficiency (bits/Joule) is proportional to the number of antennas
- Energy efficiency established by GreenTouch Consortium (2010-2015) https://s3-us-west-2.amazonaws.com/belllabs-microsite-greentouch/index.php@page=about-us.html
  - Begun by Bell Labs
  - 40 companies and universities
  - Goal was to improve total energy efficiency of all modes of communication by a factor of 1000

Additional Policy Options

The U.S. should leap-frog the competition through a national 6G R&D effort

- Leading manufacturers of 5G infrastructure are outside the U.S.
  - A national security issue
  - Hinders the U.S. in obtaining/maintaining its technological edge
  - Effectively moves jobs overseas
- 6G: The U.S. is already behind
  - Oulu University 6G Flagship: 250M euros over 8 years
  - South Korea is considering a $100B 6G initiative
  - China has announced a national 6G R&D initiative
- Many parallel approaches, some risky, should be supported
  - Generous funding for early laboratory experiments and demonstrations
  - Huge funding for city-wide trials