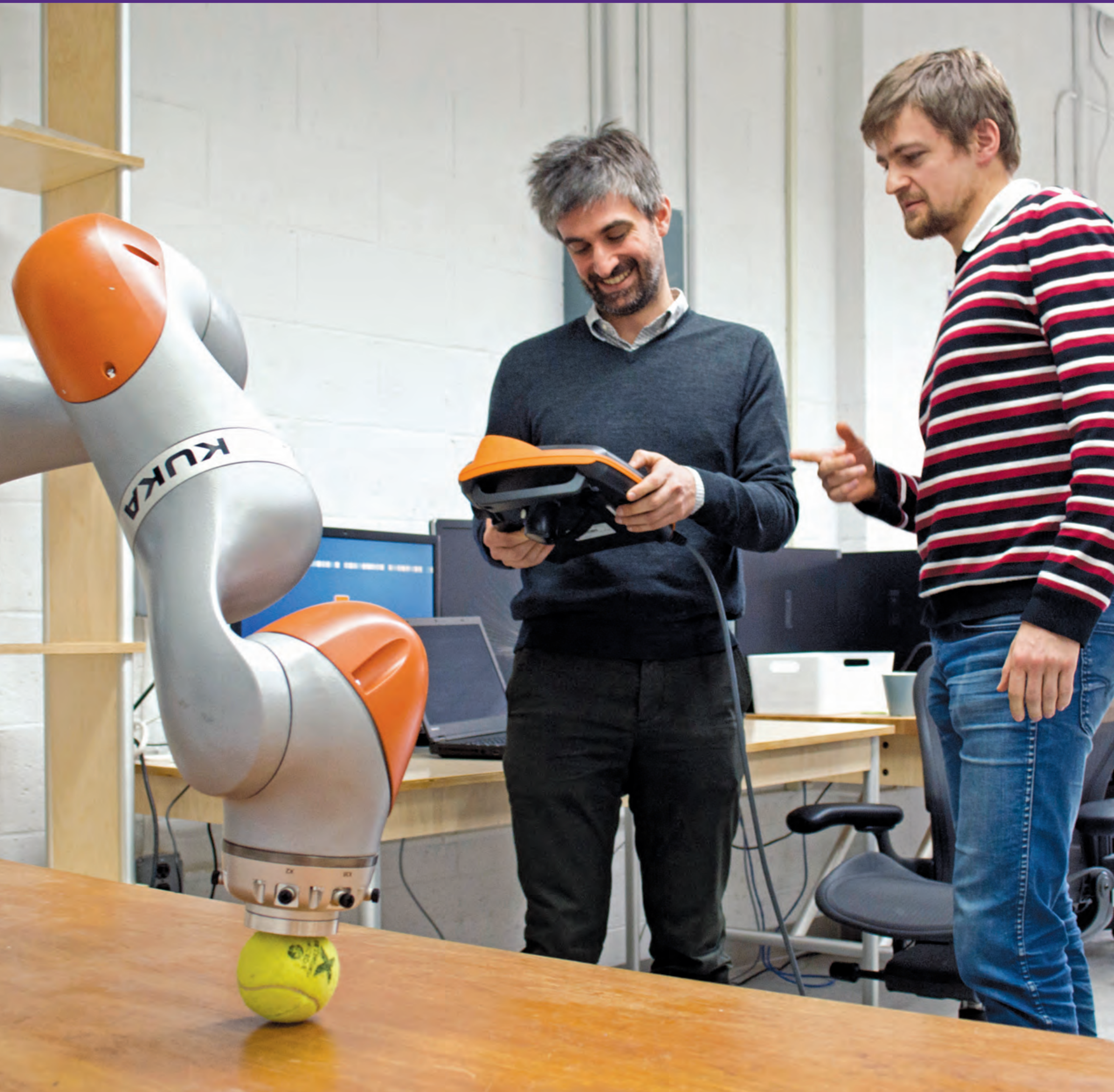
NYU WIRELESS

SPRING 2019 • VOL. 6, NO. 1 • NYUWIRELESS.COM

Pulse

Featured Articles:



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NYU WIRELESS is a vibrant academic research center pushing the boundaries of wireless communications, sensing, networking, and devices.

Centered at the NYU Tandon School of Engineering, and involving leaders from industry, faculty, and students throughout the entire NYU community, NYU WIRELESS offers its Industrial Affiliate members, students, and faculty members a world-class research environment that is creating fundamental knowledge, theories, and techniques for future mass-deployable wireless devices in a wide range of applications and markets.

Every January, NYU WIRELESS hosts an annual Open House for all of its students and Industrial Affiliate members, and hosts a major invitation-only wireless summit every April, in cooperation with Nokia Bell Laboratories, for the center's Industrial Affiliates and thought leaders throughout the global telecommunications industry.

NYU WIRELESS, info@nyuwireless.com

Leadership

Founding Director Ted Rappaport and Associate Directors Sundeep Rangan, Thomas L Marzetta, John-Ross Rizzo, and Dennis Shasha manage NYU WIRELESS across Brooklyn and Manhattan campuses of NYU. Prof. Rappaport has powered the 5G millimeter wave era, and is a leading educator in the wireless arena, having authored many books and started three major academic wireless research centers. Prof. Rangan is an Electrical Engineering professor at NYU Tandon, and was a co-founder of Flarion Technologies, which developed Flash OFDM, one of the first cellular OFDM data systems. Prof. Marzetta originated the concept of Massive MIMO, and continues to sustain contributions to the development and promotion of Massive MIMO. Prof. J.R. Rizzo is an assistant professor in the Departments of Rehabilitation Medicine and Neurology at NYU Langone Health. His research is focused on wearable technology and blindness and visual impairment. Prof. Shasha of Courant's Computer Science Department is widely known for his expertise in data-intensive algorithms, streaming data, and is a highly acclaimed inventor of mathematical puzzles.

The Industrial Affiliates Program

NYU WIRELESS invites corporate supporters to join our Industrial Affiliates program. The NYU WIRELESS Industrial Affiliates program offers a mutually beneficial relationship between NYU WIRELESS researchers, students, and facilities, and leading industry partners, while fostering innovative research. NYU WIRELESS would like to thank our Industrial Affiliate Partners and NSF for their continued support. Learn more about our Industrial Affiliate program by visiting nyuwireless.com/industrial-affiliates

About the cover:

Prof. Ludovic Righetti and visiting Ph.D. student Johannes Pfleging from Zurich explore a robot for eventual wireless control.

Welcome from the Director

5G—what does it mean and when will it "happen?" To help answer this question, this issue of the Pulse has a primer on 5G, and briefly explains how it differs from the previous four generations of cellular telephones. NYU WIRELESS has been fortunate to have played a major role in setting a vision and demonstrating the viability of new frequency bands, millimeter wave bands, never before believed to be viable for mobile communications, so we are in a strong position to see beyond 5G, and to ask the question "what comes next?"

But we are not the only ones asking "what comes next?" US President Donald Trump, and FCC Chairman Ajit Pai, in the third week of February of this year, asked the world what might be next—and even though 5G is in its infancy, President Trump expressed his desire for 6G. At the same time, the FCC took a bold step with proposed rules and pending authorization of its Spectrum Horizons initiative, which will be discussed and voted on by the FCC Commissioners in its March 15, 2019 meeting. The Spectrum Horizons initiative at the Commission seeks to open up spectrum above 95 GHz for the first time in the history of the US. In this particular arena, the US trails Europe and Asia, who have already identified potential spectrum usage above 95 GHz, but this recognition by the FCC is huge for propelling US companies and universities into the race for "what's next."

At such high frequencies, massive bandwidths—on the order of tens of GHz for a single radio channel—become possible for communication and sensing. The FCC Spectrum Horizons order provides the spectrum sandbox in which true 'space age' applications can be invented. Things such as the family flying vehicle, depicted in the Jetson's cartoon show, or the Star Trek Tricorder, the smart phone that functions as an all-in-one medical device complete with imaging and sensing, will be possible through the use of such wide swaths of radio spectrum (for more details, see a talk I gave at North Carolina State University for their 100th year anniversary of the Electrical and Computer Engineering Department, where I was tasked to envision what wireless might enable in the next 100 years: https://www.youtube.com/watch?time_continue=14&v=SVMqTVZopDk).

Prof. Ted Rappaport, Director of NYU WIRELESS

Thanks to new thinking and spectrum policy in Washington, the US research complex is now on the path to experiment with and create visionary applications thought impossible just a few years ago. Our NYU WIRELESS Industrial Affiliate companies already know some of these applications through their close association with our center, as we have been working above 100 GHz and exploring exciting new frontiers for the past couple of years. We also were the first academic institution to join the mmWave Coalition, a forward thinking group that sought to create a dialogue for opening up frequencies above 95 GHz in the US, precisely what the FCC announced in February.

NYU WIRELESS has been fortunate to have played a major role in setting a vision and demonstrating the viability of new frequency bands, millimeter wave bands, never before believed to be viable for mobile communications, so we are in a strong position to see beyond 5G, and to ask the question "what comes next?"

With the Spectrum Horizons activity at the FCC, and with new 5G millimeter wave cellphones and base station equipment finally coming on the market, and with the global standards body, 3GPP, ratifying the 5G New Radio (5GNR) standard, the race is on to 6G, whatever that is! We look forward to working with you, as we collectively explore, discover, and define the next generation of wireless technologies.

Ted Rappaport, Director, NYU WIRELESS

Momentum Continues at NYU WIRELESS with New Industrial Affiliates

NYU WIRELESS welcomed back AT&T and Samsung, two Industrial Affiliate members who were earlier involved in the formative years of the research center. Upon rejoining the Center's iconic roster of corporate members, Samsung America's vice president and head of its research and mobility innovation lab, Charlie Zhang, said, "...we believe close collaborations between academia and industry leaders are the key to sustained innovation for the future of 5G and beyond." Samsung expressed particular interest in beyond massive-MIMO, a research thrust being led by NYU WIRELESS Associate Director Tom Marzetta.

Ph.D. student Parisa Hassanzadeh discussed her reserach at the NYU WIRELESS open house on January 25, 2019

AT&T's Chief Technology Officer and President, AT&T Labs, Andre Fuetsch, remarked, "We're excited to rejoin NYU WIRELESS this year and work with the research center on next generation and innovative projects in V2X, as well as positioning and sensing technologies in the coming year."

NYU WIRELESS Director Ted Rappaport expressed his gratitude for the Center's two newest Industrial Affiliate member companies, "We are delighted to have AT&T, one of America's leading carriers, and a true visionary in 5G, and Samsung, a world leader in wireless, rejoin our Center. As we move into 6G and its applications, such as robotics, UAVs, and autonomous vehicles, 6G testbeds, terahertz communications and sensing, and other exciting areas of wireless, we will benefit from the connection that we have with our Industrial Affiliate members. Importantly, our students also gain by experiencing internships and potential careers with member companies."

Armstrong Medal Awarded to Ted Rappaport

The Radio Club of America (RCA) awarded NYU WIRELESS director Ted Rappaport its prestigious Armstrong Medal for his demonstrated excellence and lasting contributions to radio arts and sciences. In accepting the medal on Nov. 17, 2018, Prof. Rappaport spoke about his career and interests in wireless communication before an enthusiastic gathering at the Westin New York Times Square Hotel, where RCA also held their technical symposium on the same day. Ted was joined by several fellow faculty members and students from the NYU Tandon School of Engineering, as well as members of his family, close friends, and colleagues. Past recipients of the RCA Armstrong Medal include beloved broadcaster Walter Cronkite, Nextel Founder Morgan O'Brien, radio pioneer Arthur Collins, and FM and superheterodyne receiver inventor Edwin H. Armstrong, himself.

RCA was founded in 1909, and is the oldest group of wireless communications professionals in the world. One of the goals of RCA is to foster interest in engineering, broadcast, or other wireless-related areas among young people, which aligns perfectly with the NYU WIRELESS mission to educate the next generation of wireless professionals and researchers.

Presentation of Armstrong Medal to Professor Ted Rappaport by Tim Duffy, President of the Radio Club of America

Charles B. Kirmuss

Primer: The Year of 5G: 2019

2019 will be the year in which the world's first 5G phones become available, and with them will come super-fast download speeds for consumers, up to 10 Gigabits per second.

Unlike the previous four generations of cellphones, 5G will usher in the use of millimeter wave (mmWave) spectrum, from 24 through 39 GHz, at frequencies that are an order of magnitude higher than frequencies used in the previous four generations.

The FCC, in prior years, authorized the sale of mmWave spectrum holdings by Nextwave and Straight Path (both were NYU WIRELESS Industrial Affiliate members) to Verizon, and the sale of Fibertower's 24 GHz spectrum to NYU WIRELESS Affiliate AT&T. FCC Auctions 101 and 102 are providing mmWave spectrum for incumbents and other 5G entrants throughout the USA.

Around the world, lower cellular frequencies (at 700 MHz through 3 GHz) are being used for 4G LTE, and many global carriers, including NYU WIRELESS Industrial Affiliate member Sprint, are exploring small cells with in-band backhaul, and massive MIMO (the brain child of NYU WIRELESS Professor Tom Marzetta).

To put 5G into perspective, the single channel bandwidths that carry data to each user's phone will be 200 MHz wide, or wider. This compares with 20 MHz for 4G's LTE, 5 MHz for 3G, about 1 MHz for 2G, and a measly 30 kHz for the first generation analog FM cellphones. The move to millimeter waves is what allows these bandwidths to expand so rapidly, since "narrowband electronics" are easily manufactured when they are tasked with operating over a small percentage of the carrier frequency. By moving up an order of magnitude in carrier frequency, into the millimeter wave bands for 5G (e.g., 24–39 GHz), vastly wider channels may be used, thus allowing much faster data rates for the consumer. The previous four generations of cellular used much lower microwave or UHF carrier frequencies, down around 1–2 GHz. By moving up to millimeter wave frequencies, the law of physics also allows the antennas inside the phone, for a given physical size, to become much more directional, more like telescopes or megaphones or magnifying glasses, rather than omnidirectional in nature. This new-found directionality at the millimeter wave frequencies allows the radio energy to be focused in specific directions, so that the signal may bounce off reflectors or be focused on the desired base station, and in order to steer the beams of these directional antenna arrays used by the phone and the base station as people move about, computations are needed to rapidly move the antenna beams, the way we rapidly scan a scene with our eyes. This move to the higher millimeter wave frequency bands presents engineering challenges in many areas, not just in the antennas, and the packaging and interconnection of circuits, but also in how to efficiently amplify and receive the signals with minimal battery drain at millimeter wave frequencies. NYU WIRELESS Industrial Affiliate companies are conquering these problems in their products.

By moving up an order of magnitude in carrier frequency, into the millimeter wave bands for 5G (e.g. 24–39 GHz), vastly wider channels may be used, thus allowing much faster data rates for the consumer.

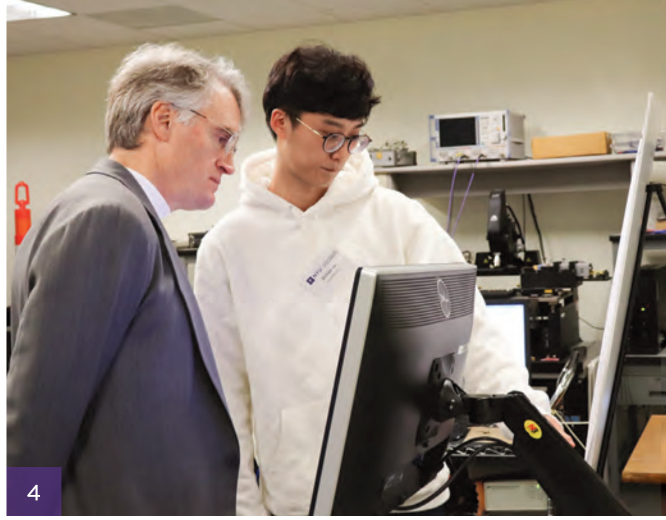
This massive, expansive increase in capacity is why NYU WIRELESS founder and director Ted Rappaport believes that 5G will usher in the renaissance of wireless, as the speed of fiber optics meets the internet, all in the palm of your hand. It was Rappaport's pioneering work in Austin and New York City that proved to the world that mmWave could offer unprecedented speeds and could work better than the previous four generations of cellular. The world came to believe through NYU WIRELESS, and now the center is working on 6G and revolutionary applications in robotics, sensing, and imaging that were once thought to be science fiction.

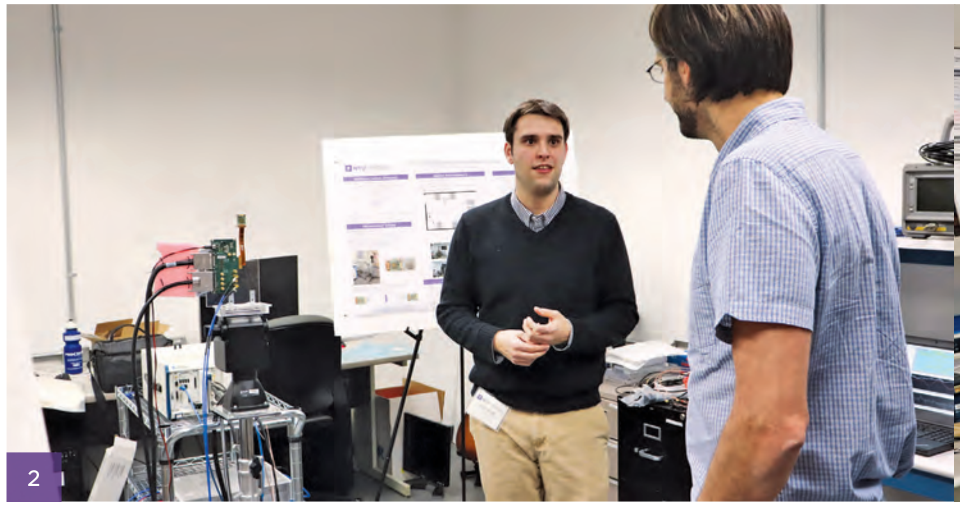
Recap: NYU WIRELESS Annual Open House

January 25, 2019

The NYU WIRELESS Open House and Recruiting Day, held on the Friday before the start of each Spring semester in January, was a remarkable success this year. The all-day event featured 34 research posters and lab tours, and hosted 25 Industrial Affiliate and potential Industrial Affiliate executives who traveled to campus to meet the students, faculty, and to see the research activities of NYU WIRELESS. This year, the center experienced the largest attendance and most number of posters and lab tours in its seven- year history. NYU WIRELESS is grateful to the Industrial Affiliate members who took the time to travel to Brooklyn to attend the event, and to the students and their advisors for taking the time to prepare and demonstrate their research.

As part of the open house, meeting rooms are provided for Industrial Affiliate companies to interview students for full time and co-op/summer positions, based on hiring needs of each Affiliate, from matches that are easily identified by Industrial Affiliate companies through the use of the NYU WIRELESS on-line resume book (an Industrial Affiliate member benefit). Up to five (5) representatives from each Industrial Affiliate member are invited to attend the Open House at no cost. Assistance is given to each Industrial Affiliate member in the recruiting process, enabling each Affiliate access to graduate and undergraduate students of NYU Tandon School of Engineering, and other NYU Colleges, departments and entities, through deep-dive collaboration, classroom interaction, and connections with student society activities.





1. NYU WIRELESS Open house meeting "kickoff" led by founder Ted Rappaport; **2.** Ph.D. student Chris Slezak **3.** NYU WIRLEESS Associate Director Professor Sundeep Rangan; **4.** Ph.D. student Shihao Ju speaking with Industrial Affiliate member Roger Nichols from Keysight; **5.** Ph.D. student Abbas Khalili Olam; **6.** Discussion at Open House kickoff meeting; **7.** (l to r) Ph.D. students Ziming Qiu, Jack Langerman, Amir Hossain, and Nitin Nair, speaking with Industrial Affiliate member Howard Wong from Nokia; **8.** NYU WIRELESS Associate Director J.R. Rizzo, MD; **9.** Ph.D. student Menglei Zhang speaking with NYU WIRELESS Industrial Affiliate member Amitava Ghosh from Nokia; **10.** Ph.D. student Manali Sharma

New NSF Grant to Focus on Robot's Interaction with its Environment

NYU WIRELESS Associate Professor Ludovic Righetti has received a grant from the National Science Foundation to study the robust physical interaction between a robot and its environment. Such interaction includes activities such as walking across unexplored terrain or manipulating unknown objects. The project approaches this problem in two ways. The first builds upon findings that humans respond to uncertainty by varying the effective springiness of their limbs. The project will formulate

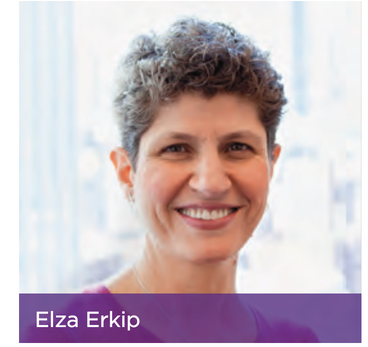
The project will formulate a corresponding approach to robot control by finding the robot limb stiffness that minimizes a probabilistic measure of risk under uncertainty about the location of the objects or the floor.

a corresponding approach to robot control by finding the robot limb stiffness that minimizes a probabilistic measure of risk under uncertainty about the location of the objects or the floor. That is, the first part of the project will find the best possible outcome of a movement, while taking into account a spread of possible interactions with the environment. The second part of the project considers all the ways in which small changes to intermittent contacts—such as when a foot hits the ground, or where a finger touches a tool—can propagate through a larger task without leading to a failure.

The team will characterize the optimal mechanical impedance modulation for robust contact interactions and provide a methodology to compute motions that are open-loop robust despite environmental uncertainties. It will leverage recent results in risk-sensitive optimal control and robust optimization to explicitly consider uncertainty about the environment while ensuring low computational complexity.

The last but key objective of the project is to conduct extensive robotic experiments with a one-legged jumping robot, a manipulator grasping unknown objects, a quadruped walking and jumping and a humanoid robot climbing up high steps using its arms and legs, therefore demonstrating the general applicability of the methodology in realistic and diverse robotic scenarios. The application of 5G wireless links to these applications will also be studied, through collaboration with many other faculty members in NYU WIRELESS.

In recognition of his work, Associate Professor Righetti was recently named the 2018-2019 Vivian G. Prins Global Scholar at NYU by the NYU Provost's Office together with the NYU Tandon School of Engineering. The Vivian G. Prins Fund for Emigrating Scholars provides assistance and encourages scholars in other countries who wish to join the NYU community and emigrate to the United States. You can learn more about Professor Righetti's work at https://wireless.engineering.nyu.edu/robotics.


Elza Erkip


Siddharth Garg


Farhad Shirani

NSF Award to Study Web Privacy

NYU WIRELESS faculty members Elza Erkip, Siddharth Garg, and NYU WIRELESS Research Assistant Professor Farhad Shirani have received a three-year grant from the National Science Foundation to study web privacy. The project addresses the problem of online user tracking and data extraction. As web tracking technologies become more sophisticated and pervasive, there is a critical need to protect users' data from privacy attacks. The project is a step towards addressing the privacy problem by quantifying web users' privacy risks.

The project evaluates privacy in several research focus areas, including:

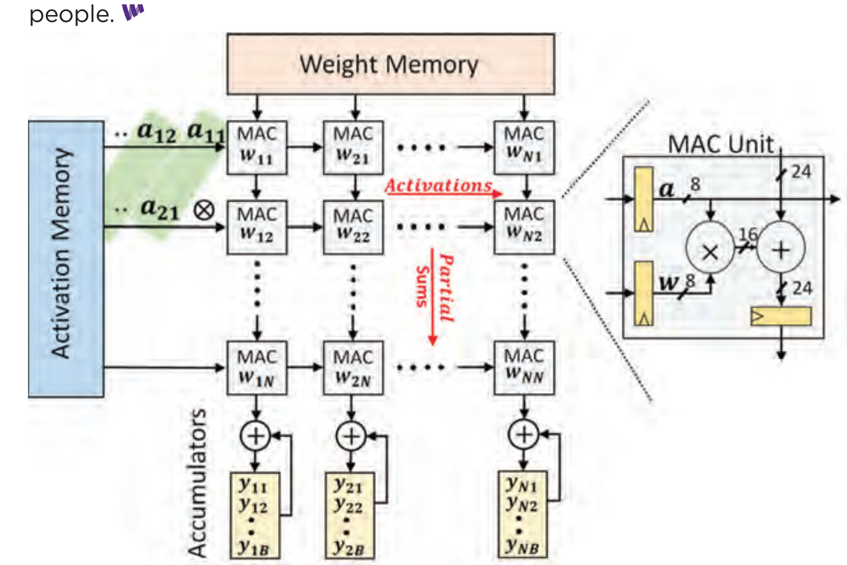
- Fingerprinting attacks, where the attacker queries the users' device about their browsing habits to extract personal information;
- Matching attacks, where the attacker uses publicly available data on social network memberships and relationships to de-anonymize users; and
- Synergistic attacks, where the attacker combines the publicly available data and the query responses from the user's device for the purposes of deanonymization and data extraction.

Low Power Hardware Accelerators for Deep Learning

There is growing interest in the design of special-purpose hardware accelerators for deep learning, the Google TPU (tensor processing unit) being one example. In ongoing research in NYU WIRELESS Professor Siddharth Garg's lab, investigators are seeking to enable 2x or more reduction in the power consumption of TPU and TPU-like accelerators using an old hardware trick: voltage underscaling. They propose to run the chip at a reduced voltage to dramatically cut its power consumption, but at nominal frequency. In return for lower power, voltage underscaling results in occasional errors in computation (referred to as timing errors). Motivated by techniques such as DropOut that are commonly used in training deep nets, the group has shown that the TPU can simply detect and "drop" these erroneous computations with minimal loss in classification accuracy. They are thus able to cut power by more than 60% with only a 1% loss in accuracy for benchmark deep neural nets. Similar techniques can be used to enhance the resilience of TPU-like accelerators to permanent faults.

More information about Professor Garg's work can be found at www.nyuwireless.com/people.

Below: Tensor processing unit

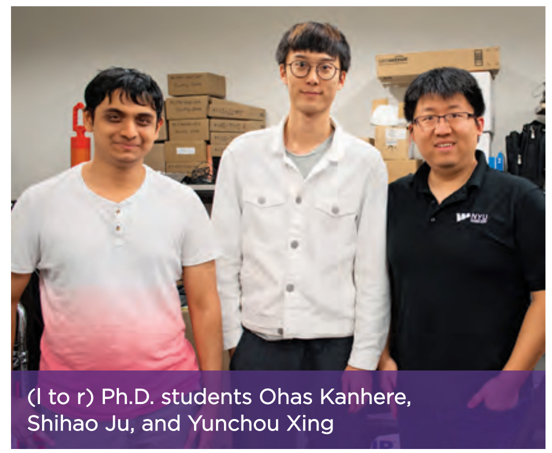


NYU WIRELESS Makes an Impact at Globecom 2019

Professor Rappaport's students presented three papers at the 2018 IEEE Global Communications Conference (Globecom), which was held in Abu Dhabi in December, 2018. Ojas Kanhere's paper was entitled, "Position Locationing for Millimeter Wave Systems," and discussed the issue of positioning in communications systems, which includes finding the location of a user, given the known locations of other stations, which may be mobile or fixed. The work showed that accurate estimates of the position of an unknown node can be determined using estimates of time of arrival, angle of arrival, and data fusion or machine learning. https://arxiv.org/abs/1808.07094

Shihao Ju's paper, "Millimeter-wave Extended NYUSIM Channel Model for Spatial Consistency," explored accurate channel modeling approach for closely spaced users when operating at millimeter wave (mmWave) frequencies, which is especially important given that mmWave cells are likely to be smaller with more dense coverage than today's cellular systems. The NYUSIM channel model, further discussed on page 9, provides a method of using realistic large-scale and small-scale parameters to study various scenarios, environments, and antenna patterns, and is now being updated to include spatial consistency for closely-spaced users or movement over a local area, as discussed in the paper. https://arxiv.org/abs/1808.07099

Yunchou Xing's paper was entitled, "Propagation Measurement System and Approach at

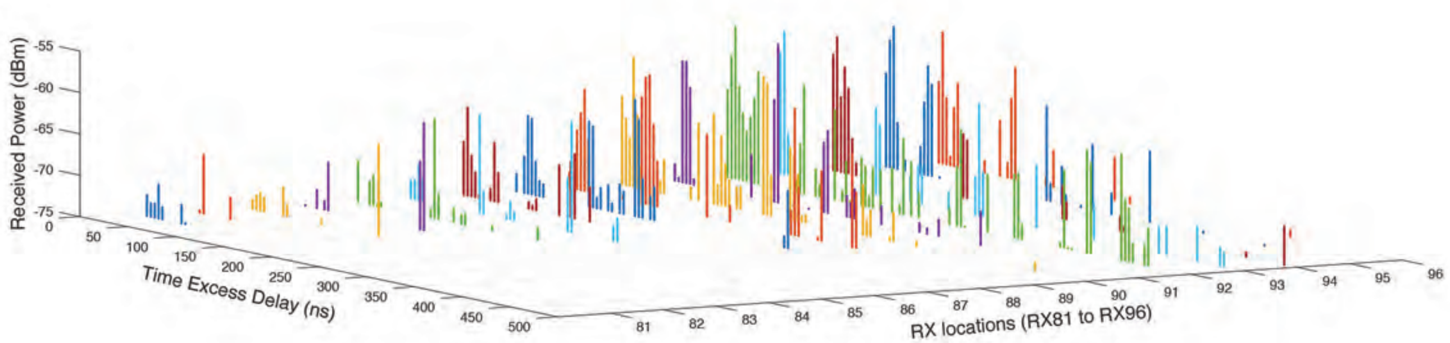


(l to r) Ph.D. students Ohas Kanhere, Shihao Ju, and Yunchou Xing

140 GHz—Moving to 6G and Above 100 GHz." The paper showed that little is known about radio channels above 100 GHz, where there are wider unused bandwidth slots available. In the work, the authors examined the results of previously published propagation measurements at D-band (110-170 GHz), provided the design of a 140 GHz wideband channel sounder system, and proposed indoor wideband propagation measurements and provided the early results of penetration measurements for common materials at 140 GHz. The paper showed that common building materials are a few dB more lossy at 140 GHz than at 28 or 73 GHz. https://arxiv.org/abs/1808.07594.

NYU WIRELESS Industrial Affiliate members are able to instantly access all of the NYU WIRELESS conference and journal papers, including the papers described above, at https://wireless.engineering.nyu.edu/publications-listing/

Below: Spatial Consistency model in NYUSIM accurately predicts change in multipath clusters and time delays over a track.



New Release of NYUSIM Now Available

The NYU WIRELESS open-source Millimeter Wave/5G Channel Simulator, NYUSIM, was recently updated and is now available in Version 1.6.1. NYUSIM is a popular research tool, and provides a complete statistical channel model and simulation code with an easy-to-use interface for generating realistic spatial and temporal wideband channel impulse responses from 1 to 100 GHz carrier frequencies, and for channel bandwidths ranging from CW to 800 MHz bandwidth.

The updated version, 1.6.1, provides two major improvements to NYUSIM, based on user feedback. The first improvement provides a complete MIMO channel representation. The second improvement fixes a crash when the RF bandwidth is set to be smaller than 800 MHz.

More details can be found on the web site at http://nyuwireless.com/nyusim, and in the user manual. Please feel free to download and use NYUSIM Version 1.6.1. We welcome your feedback at nyusim@nyuwireless.com.

Rappaport Elected as National Academy of Inventors Fellow

Professor Rappaport's pioneering work in radio wave propagation for cellular and personal communications, wireless communication system design, and broadband wireless communications circuits and systems has earned him recognition as a National Academy of Inventors (NAI) Fellow. NAI honored Ted for his spirit of innovation in creating or facilitating outstanding inventions that have made a tangible impact on quality of life, economic development, and the welfare of society.

Ted and the other 2018 NAI Fellows will be inducted on April 11, 2019, at Space Center Houston in Texas, with U.S. Commissioner for Patents for the United States Patent and Trademark Office Andrew H. Hirshfeld keynoting the event. In addition to his other accomplishments, Ted has more than 100 U.S. or international patents issued or pending.

NYU WIRELESS Professor Shivendra Panwar presents a mini-lecture to NYU WIRELESS faculty and Industrial Affiliates

Faculty Mini-lecture Series

One of the many benefits to each NYU WIRELESS Industrial Affiliate company is the NYU WIRELESS faculty Mini-lecture Series. At each faculty meeting, one NYU WIRELESS faculty member presents a 15-minute overview of his or her current research, along with the most important and latest results. These ongoing lectures provide a vast array of expertise, and give early insights into the state-of-the-art findings in many technical areas within the six NYU WIRELESS thrust areas: (1) Terahertz (THz) Communications and Sensing, (2) Mobile Edge and Low Latency Networking, (3) Quantum Devices & Circuits, (4) 5G & 6G Applications, (5) Communications & Machine Learning Foundations, and (6) Testbeds & Prototyping.

All employees of each Industrial Affiliate member may live stream the lectures during the faculty meetings, as well as view them later on the Industrial Affiliate portal maintained by NYU WIRELESS. Spring 2019 lectures are listed to the right, and demonstrate the wide range of research topics being pursued at the center. Lectures from previous semesters are also available at the Industrial Affiliate portal.

January 23, 2019
Anirudh Sivaraman
Fast and Programmable Network Infrastructure for Future Wireless Communications

February 6, 2019
Shaloo Rakheja
Engineering Predictive Behavior in III-Nitride HEMTs

February 27, 2019
Yong Liu
Dynamic Predictive Streaming of 360 Degree Video for Wireless Applications

March 6, 2019
Siddharth Garg
Energy-efficient and fault-tolerant hardware accelerators for deep learning

March 27, 2019
Ludovic Righetti
Optimal control for robust robotic behaviors over wireless

April 17, 2019
Giuseppe Loianno
Vision-based Agile Human Friendly Drones using 5G

May 1, 2019
Tom Marzetta
Will Super-Directive Antenna Arrays Play a Role in 6G?

Deloitte, a professional services organization, has chronicled the evolving technology landscape in its Tech Trends report for a decade. Its latest edition, published in January 2019, covers the types and increasing speed of technological change, and the effects of these changes on business competition. Tech Trends is led by Deloitte Consulting global CTO, Bill Briggs, and Emerging Technologies Research Director and Government & Public Services CTO, Scott Buchholz. As quoted in in the introduction, "To stay ahead of the game, companies must work methodically to sense new innovations and possibilities, define their ambitions for tomorrow, and journey beyond the digital frontier...The good news is that much of the tech-driven disruption each of us experiences today—and will likely experience going forward—is understandable and knowable."

Deloitte tapped the expertise of NYU WIRELESS Professor Ted Rappaport for their report. In a wide ranging interview, Rappaport discussed his perspective on the benefits of future connectivity, which is reproduced by permission here. You may also read the entire report at www.deloitte.com/insights/tech-trends.

MY TAKE

PROFESSOR THEODORE RAPPAPORT, NEW YORK UNIVERSITY, TANDON SCHOOL OF ENGINEERING

The amount of data consumed globally increases by 50 percent each year, and I predict that four years from now our current 50 percent annual ramp will reach 70 to 80 percent. Why the jump? Because the rollout of 5G will accelerate data consumption exponentially. Organizations continually need wider pipes to accommodate ever-growing data volumes. Base stations and other 5G infrastructure will be rolling out in 2019 and 2020, and as they come online, 5G's impact will be felt around the world: in urban and rural areas, in burgeoning IoT ecosystems, on factory floors, and in corporate boardrooms.

Think about 5G's potential. For the first time, cell phones will perform as if they were connected to wireless fiber optic cables. In the arena of networking, this is a historic event, one that many doubted could ever come to pass. This bears out my longstanding argument that millimeter waves—unused bands at the top of the radio spectrum—could work better than any generation of cellular thus far.

My colleagues and I demonstrated the usage of millimeter waves in Texas and New York in 2011 and 2012. Our demonstrations showed that if you use directional antennas that point the beam in specific directions, you get better coverage for the same bandwidth and the same radiated power. Moreover, you get better coverage and a better signal-to-noise ratio as you go higher in frequency. This is completely counterintuitive, but it proved to be true (neglecting the impact of heavy rain or snow, which can be compensated for with more antennas or power).

In terms of performance, 5G—which uses those high-frequency bands and the existing lower bands—exceeds 4G by several orders of magnitude. With 5G, applications traditionally dependent on cable connectivity will be able to seamlessly function on mobile devices. Think about everything right now that depends on a fiber optic or copper cable connection. Whether it be data-center functions or entire office buildings, 5G allows pretty much everything to be done wirelessly, untethering applications and networks themselves in new ways. 4G launched a wireless renaissance in which everyone (at least in urban markets) uses a cell phone for everyday activities such as banking, communication, and transportation.

5G looks to magnify this renaissance globally, with wireless pervading every part of our lives and new applications we cannot even yet envision.

There is another aspect of the global wireless renaissance that is historic. I believe that 5G can benefit rural and suburban areas that have not enjoyed the same access to wireless as cities. Throughout rural America and the world, there is a lot of aging copper wire that was installed decades ago to support voice transmission. While carriers could replace it with fiber optic cable, from a technical perspective, there is nothing preventing them from replacing it with in-band backhaul. Fixed point-to-point links can be easily accommodated by 5G spectrum allocations to daisy-chain base stations and small cells, and to carry traffic back to the internet and public switch networks for rural areas.

For carriers, 5G presents a ripe opportunity to become more valuable to their Fortune 500 clients by getting deeper into enterprise operations. Consider network slicing, a relatively new concept in which carriers spin up virtual networks using portions of 5G spectrum for particular users or use cases. Let's say that a factory within a certain geographic area needs a low-latency, high-bandwidth capability to control its mobile robots. A carrier could provide this customer with a dedicated virtual network over the 5G spectrum, but with huge bandwidth pipes and the specific millimeter waves that the government is auctioning off, carriers will also be able to parse out spectrum to enterprises on demand. Moreover, large enterprises—particularly those with campus networks—may soon find millimeter wave products in the marketplace that will enable them to provision connectivity between buildings. Expect these products to quickly become so reliable and easy to install that IT personnel will have control and flexibility as they manage on-site networks. Unlicensed band products will also allow enterprises to install "instant fiber" using on-campus wireless infrastructure.

Opportunity awaits.
The time to start thinking about your organization's networking strategy is now.

To Stand Alone or Not—That is the Question for 5G mmWave

By James Kimery, Director of Marketing, Wireless Research/SDR, National Instruments

2019 will be the year of 5G. 5G will become real in 2019 as service operators around the world have already begun deploying 5G services. To date, mmWave deployments have been targeted to fixed wireless access, or in other words fiber to the home (FTTP) replacements. The early 5G sub 6 GHz rollouts are a milestone but mmWave is the pathway to the transformational impact needed for the 5G ecosystem.

mmWave spectrum has been a major focus for wireless researchers and 5G ecosystem suppliers because of the copious amount of spectrum available for mobile access in both the licensed and unlicensed bands. In fact, mmWave spectrum for 5G dwarfs the spectrum available for prior generation cellular, WiFi and Bluetooth combined! More spectrum equates to higher data rates and the ability to accommodate more users assuming similar spectral efficiencies.

Today, most 5G deployments target sub 6 GHz spectrum and the Non-StandAlone (NSA) architecture. NSA uses LTE as the anchor for the control plane, and the user plane flows directly to the EPC (4G) or NGC (5G) depending on the specific NSA architecture. 5G mmWave will likely follow mainly because the technology is still in its infancy. Sub 6 GHz 5G does increase bandwidth but not at the scale of 5G mmWave. The 5G mmWave deployments will rely on the NSA architecture and in thinking about this issue, a question arises, "Does 5G standalone (SA) make sense?"

Although there is quite a bit of spectrum earmarked for 5G mobile access in the mmWave bands, the propagation of waveforms at these frequencies is much shorter than the sub 6 GHz implementations. In addition, mmWave waveforms are highly directional and can be blocked causing disruptions to the link. The 3GPP has devoted a good portion of the specification to the concepts of beam management and beam recovery to address these scenarios that should work in theory, but the question is whether they will work in practice and at what efficiency?

Now, consider the configuration—NSA or SA for 5G mmWave. The advantages of SA for any 5G deployment include lower latency and lower cost as the network does not need to rely on 4G/LTE for the control information. However, NSA also makes a lot of sense for 5G mmWave because LTE deployments are available and robust. In the SA 5G mmWave scenario, the control channels utilize the same 5G mmWave spectrum as the data. For NSA 5G mmWave, LTE provides the anchor and the control information is transmitted over that link.

For example, when a 5G mmWave UE is connected to a gNodeB where both the control and user planes utilize a mmWave band, the control information is subjected to the same interference and blocking challenges as the data plane and thus the beam management and recovery will be engaged to maintain the link but these procedures take time and the likelihood of link disruption is quite high. NSA provides a more stable link for the control plane and may prove critical in terms of gNodeB handoff and cell selection for the mobility case. Handoff is very important because the rate of handover will be much higher in a mmWave network due to the greater density of base station deployments.

As the industry moves closer to a 5G reality, mmWave continues to be an important technology for mobile access to realize the goals and objectives of 5G. Architectural choices such as the tradeoffs between NSA and SA become more poignant and perhaps difficult. It will be interesting to see if service operators do, in fact, deploy 5G SA mmWave technologies, but I suspect we will see mmWave deployments dominated by NSA for the short-term.

5G NR for wireless communications, with new bands, wider bandwidth, and new beamforming technology, presents significant design and test challenges that require powerful tools to accelerate innovation. For more information, please visit ni.com/5g.

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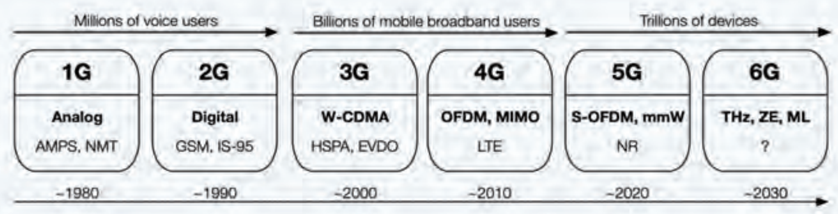
The Market's at 5G—Time to Look to 6G!

Commentary by Industrial Affiliate Member Interdigital

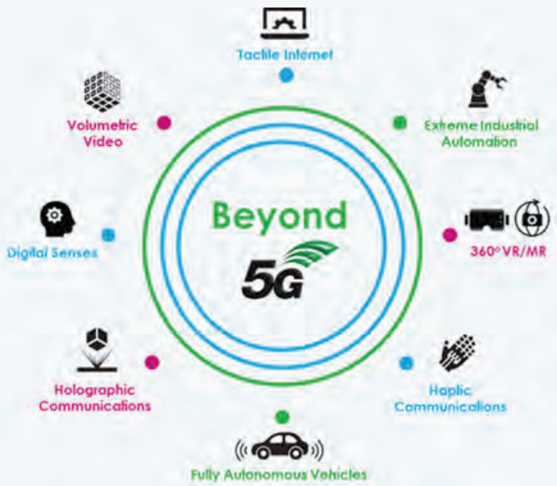
Mobile communication has become an essential element in the fabric of human life, influencing the way we live, work and play. This massive adoption of cellular technology has dramatically increased the amount of data we consume as a society. And you could argue that we're only getting started, since the evolution to date has primarily driven a single use case—the smartphone.



In order to keep up with these and future demands, cellular technology has evolved over several generations since its inception in 1980, with a new "G" roughly every ten years.

The fifth generation, 5G, is being rolled out now, which brings multi-gigabit data rates, ultra low-latency and mMTC functionality as dramatic improvements over the prior generation. Yet these highly publicized capabilities would still not be able to meet the insatiable demand in the coming decade. Quoting CTO of Vodafone UK, Scott Petty, "5G will not be able to handle the number of 'things' which are connected to the network in a couple of years' time. We need to start thinking about 6G now."

Societal demand for pervasive and truly immersive applications in the coming decade will drive stringent requirements. These include captivating virtual-meets-physical experiences, including holographic communications requiring multi-terabit/sec data rates; guaranteed high-precision services, such as motion control with fast response requiring precise latencies as low as 10's of Qsec; and rearchitecting the digital world for full human-sense perception—not to mention trillions of connected 'things' with sensing and intelligence embedded.



In order to enable the next 'G', several enhancements to air-interface technology are required. First, to support Tbps applications like 3D telepresence and holographic communications in 6G, data rates from several hundred Gbps up to Tbps will be needed. The necessary channel bandwidth can only be found in the THz band. New types of video codecs may also be needed. Second, cellular devices draw power to operate even when idle. For many MTC devices located in hard to reach places or where battery swapping is impractical, a 'zero-energy' (ZE) radio technology that supports relatively low data rates while only using power drawn from the radio waves is highly desirable. Third, intelligent and self-learning algorithms, in conjunction with RF sensing available on cellular devices will be needed to fully exploit and maximize the use of available transmission channels in the future.

Several times over the past decades of wireless, we've reached a point where we felt that the achieved technology level was enough… and yet, that has proven to never be the case, with new generations opening new, unforeseen possibilities. 5G is here and it's been a huge achievement for all companies who, like us, work to drive fundamental research. And yet, for those of us in core research, we're always looking ahead. The world is rolling out 5G, but we're already focused on 6G, and the challenge ahead!

Wireless Class wins trip to IEEE International Conference

What started out as a challenging homework problem turned into an important technical contribution that has been accepted for presentation and publication at the 2019 IEEE International Conference on Communications (2019 ICC), in Shanghai, China.

"When I gave the homework on scattering for frequencies above 100 GHz, I knew there was little known on the topic as it pertains to wireless communications, yet it is sure to become important for future 6G communications, sensing, and imaging," said Prof. Ted Rappaport, the instructor for EL-6023, the M.S./Ph.D. level course entitled "Wireless Communications" at NYU.

Syed Hashim Ali Shah, Muhammad Affan Javed, Yunchou Xing, Girish Palteru, Prof. Rappaport, Shihao Ju, Jyotish Robin, Ojas Kanhere, and Jun Li.

"We had a small class, only five students, in addition to a handful of auditing students that included my own graduate students. I gave a very challenging homework problem about the Direct Scattering theory and the Radar Cross Section (RCS) model, as we sought to understand and corroborate these models over the entire spectrum from 1 GHz to 1 THz. The homework was extremely difficult, and took more than the allotted two weeks to solve. Instead of giving up, I challenged the course to keep at it, and for incentive, I suggested we solve the problem and submit the results as a conference paper for one of the flagship IEEE international conferences—ICC. I promised the students that if the paper was accepted, I would pay for all of them to attend and present the paper. That seemed to really inspire the students, and their result exceeded my expectations—they came up with a very comprehensive and valuable contribution on scattering that will help engineers for the next decade."

For three of the co-authors, the classwork paper is their first peer-reviewed contribution as a graduate student. "This is my first published paper so I was thrilled when I got the news," said Syed Hashim Ali Shah. "The splendid supervision of respected Prof. Rappaport and his passion for wireless communications have made it possible. Who would have thought that a homework problem from the Wireless Communications class will turn out to be such an amazing piece of research?" Student Shihao Ju added, "This paper makes our class unique! We were immersed and tried our best to demystify the scattering mechanism at Terahertz frequencies. Prof. Rappaport shows us that good research can stem from basic knowledge that we learned in the class."

The paper is titled, "Scattering Mechanisms and Modeling for Terahertz Wireless Communications," by Shihao Ju (Prof. Ted Rappaport), Syed Hashim Ali Shah (Prof. Sundeep Rangan), Muhammad Affan Javed (Prof. Shivendra Panwar), Jun Li (Prof. I-Tai Lu), Girish Palteru, Jyotish Robin (Prof. Elza Erkip), Yunchou Xing (Prof. Ted Rappaport), Ojas Kanhere (Prof. Ted Rappaport). The students shall present their contribution at the IEEE International Conference on Communications (ICC), May 20-24, 2019, Shanghai. https://arxiv.org/pdf/1903.02657.pdf.

NYU WIRELESS Welcomes New Faculty Members

Assistant Professor Siddharth Garg's research is part of the *Communciation Foundations and Machine Learning* thrust area of NYU WIRELESS. His research is focused on cyber-security and computer hardware design, with a particular interest in hardware security, low power design, and computing architectures for machine learning. He has received numerous awards, including the NSF CAREER Award in 2015 and the Angel G. Jordan Award from the ECE Department of Carnegie Mellon University for outstanding thesis contributions and service to the community.

Siddharth received his Ph.D. degree in Electrical and Computer Engineering from Carnegie Mellon University, and a B.Tech. degree in Electrical Engineering from the Indian Institute of Technology Madras. He was previously an Assistant Professor at the University of Waterloo from 2010-2014 prior to joining NYU Tandon School of Engineering.

Associate Professor Ludovic Righetti's work is part of the *5G & 6G Applications* thrust area of NYU WIRELESS. Ludovic leads the Machines in Motion Laboratory. His research focuses on the planning and control of movement for autonomous robots, with a special emphasis on legged locomotion and manipulation. He is more broadly interested in questions at the intersection of decision making, automatic control, optimization, applied dynamic systems and machine learning and their application to physical systems.

Ludovic received his engineering diploma in Computer Science and a Doctorate in Science from the Ecole Polytechnique Fédérale de Lausanne (Switzerland). He started the Movement Generation and Control Group at the Max-Planck Institute for Intelligent Systems in Tübingen, Germany, where he became a W2 Independent Research Group Leader in September 2015. He moved to NYU in September 2017. Ludovic's awards include the 2016 IEEE Robotics and Automation Society Early Career Award and the 2016 Heinz Maier-Leibnitz Prize from the German Research Foundation.

Assistant Professor Giuseppe Loianno is working in the *5G and 6G Applications* thrust area of NYU WIRELESS. Giuseppe spearheads the Agile Robotics and Perception Lab, which performs fundamental and applied research in the area of robotics autonomy, including the use of Drones. The main mission of the lab is to create agile autonomous machines that can navigate by themselves using only onboard sensors in unstructured and dynamically changing environments, without relying on external infrastructure, such as GPS or motion capture systems.

Giuseppe received B.Sc. and M.Sc. degrees in Automation Engineering with honors from the University of Naples Federico II. He was a Ph.D. student and research scientist at the GRASP Lab at the University of Pennsylvania, working with Professor Vijay Kumar.


Siddharth Garg


Ludovic Righetti


Giuseppe Loianno

Michael Knox Receives Best Paper Award for Interference Cancellation


Michael Knox

NYU WIRELESS faculty member Michael Knox won the "Best Paper/Poster" at the IEEE International Workshop on Antenna Technology (iWAT 2019) for his work "Passive Interference Cancellation in a 2x2 STAR MIMO Antenna Network." The iWAT conference is organized into two parts having all oral presentations delivered by invited researchers, and all accepted papers are presented during interactive poster sessions. There were 77 papers selected to the conference covering 40% Asia/Pacific, 37% United States, 16% Europe, Middle East, Africa, 7% Canada and Latin America.

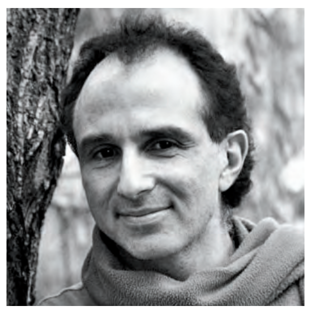
NYU WIRELESS Faculty, Post-Docs, and Research Engineers


Theodore Rappaport
Founding Director,
ECE, CS, Med.


Thomas L Marzetta
Associate Director, ECE


Sundeep Rangan
Associate Director, ECE


John-Ross Rizzo
Associate Director,
NYU Langone Health


Dennis Shasha
Associate Director, CS

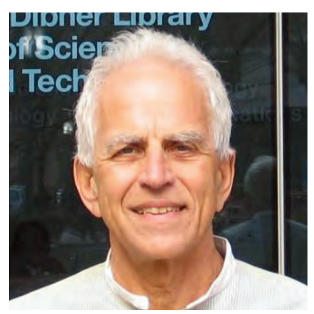

Henry Bertoni
Professor Emeritus, ECE


Aditya Dhananjay
Postdoctoral Associate, ECE

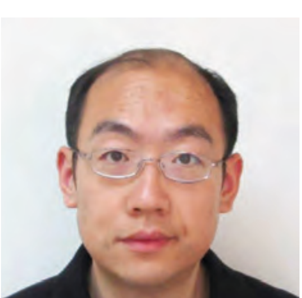

Elza Erkip
Institute Professor, ECE


Fraida Fund
Postdoctoral Associate


Siddharth Garg
Assistant Professor, ECE


David Goodman
Professor Emeritus, ECE


Michael Knox
Industry Professor, ECE


Pei Liu
Research Scientist, ECE

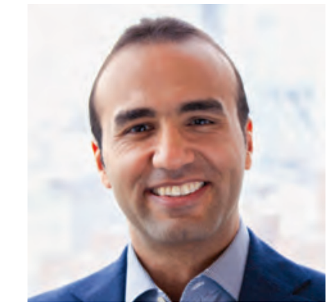

Yong Liu
Associate Professor, ECE


Giuseppe Loianno
Assistant Professor


Marco Mezzavilla
Research Scientist, ECE


Shivendra Panwar
Professor, ECE


Ludovic Righetti
Associate Professor, ECE & MAE


Davood Shahrjerdi
Assistant Professor, ECE


Farhad Shirani
Research Assistant Professor,
ECE


Lakshminarayan Subramanian
Associate Professor, CS


Yao Wang
Professor, ECE & BioMed

Industrial Affiliate partners, we invite you to hold the dates for the following events:

NYU WIRELESS Board Meeting,
April 23, 2019

The Brooklyn 5G Summit,
April 24–26, 2019

NYU WIRELESS Recent Publications

October 2017–December 2018

Terahertz Communications & Sensing

S. Ju, Y. Xing, O. Kanhere, T. S. Rappaport, S. Shah, M. Javed, J. Li, G. Palteru, J. Robin, "Scattering Mechanisms and Modeling for Terahertz Wireless Communications," IEEE International Communications Conference (ICC), Shanghai, China, pp. 1-7, May 2019.

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