NYU WIRELESS

Pulse

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Featured Articles

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About the cover
Associate Professor J.R. Rizzo shown with a wearable technology platform designed to help people with blindness and low vision better understand and navigate their local environments. Photo courtesy of NYU Langone Health.

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

Centered at 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 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, followed in October by the prestigious invitation-only Brooklyn 6G Summit (B6GS.com), in cooperation with Nokia, for the Center's Industrial Affiliates and thought leaders throughout the global telecommunications industry. The NYU WIRELESS Workshop is scheduled for June 13 & 14, 2024, on the NYU Tandon School of Engineering campus.

NYU WIRELESS, info@nyuwireless.com

Leadership Founding Director Ted Rappaport, Director Thomas L. Marzetta, and Associate Directors Sundeep Rangan, John-Ross Rizzo, and Dennis Shasha manage NYU WIRELESS across Brooklyn and Manhattan campuses of NYU. Rappaport has powered the 5G millimeter wave era and is a leading educator in the wireless arena, having authored many books and started two companies and three major academic wireless research centers. 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. Marzetta originated the concept of Massive MIMO and seeks ten-fold improvements over Massive MIMO through a closer union of wave propagation physics and communication theory. Rizzo is an Associate 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. Shasha of Courant's Computer Science Department is widely known for his expertise in data-intensive algorithms and streaming data and is a highly acclaimed inventor of mathematical puzzles.

The Industrial Affiliates Program NYU WIRELESS invites global companies to join our Industrial Affiliates program, which offers instant access to cutting-edge research results and talented students in a mutually beneficial relationship among NYU WIRELESS researchers, students, facilities, and leading industry partners. NYU WIRELESS would like to thank our Industrial Affiliate Partners as well as NSF, NIH, and DOD for their continued support. Learn more about our Industrial Affiliates program by visiting nyuwireless.com/industrial-affiliates.

NYU WIRELESS Newsletter

Download and read copies of our previous newsletters online by visiting **nyuwireless.com/nyu-wireless-newsletter**

The Impact of Undirected Research: Part II

In a previous *From the Director* essay, I made a case for undirected fundamental research, using Massive MIMO as an example. It is now my great pleasure to highlight two recent examples from NYU WIRELESS of this type of research.

Thomas L. Marzetta
Director, NYU WIRELESS

Professor Ted Rappaport and his students Mingjun Ying, Dipankar Shakya, and Hitesh Poddar (now with Sharp Labs) received the Globecom 2023 Best Paper Award in the Green Communications Systems and Network Symposium for their paper, "Waste Factor: A New Metric for Evaluating Power Efficiency in Any Cascade" (see page 15). Waste Factor enables the systematic and convenient evaluation of total power consumption in a chain of devices in a manner that parallels the classic 1944 treatment by H. T. Friis ("Noise Figures of Radio Receivers") of the cumulative effects of additive noise in a chain of devices. Waste Factor provides a standard metric for quantifying and comparing power consumption just as Noise Factor is the standard metric for quantifying and comparing noise performance. Future impact should be huge given the ever-growing emphasis on energy-efficient wireless solutions.

A paper by my student Amritpal Singh and myself, "Shannon Theory for Wireless Communication in a Resonant Chamber," was accepted by the journal IEEE JSAC Special Issue on Electromagnetic Signal and Information Theory. We postulate that the ideal structure for either a robot-manned factory or a data center is a copper box, offering near-lossless propagation and complete shielding of the interior from the exterior. Communication cables can be dispensed with, and there is the additional possibility of efficient wireless power transfer. The wireless channel within the box is unprecedented in communication theory, having poles on or near the real frequency axis. We found—contrary to all expectations—that the capacity-attaining allocation of transmit power versus frequency avoids placing power close to the resonant frequencies. Currently, we are searching for an alternative to OFDM given the long reverberation time of the channel.

Both of these research projects were made possible by donations from NYU WIRELESS Industrial Affiliate Members. We are very grateful for their support! Please email info@nyuwireless.com to learn more about becoming an Industrial Affiliate Member.

NSF Grant Awarded to Assist People with Blindness and Low Vision

With the help of a three-year $5 million grant from the National Science Foundation (NSF), a team at NYU Tandon School of Engineering has kicked off its second phase of an ambitious research project that aims to transform navigation and accessibility for many of the 285 million people worldwide with blindness and low vision (pBLV).

Led by John-Ross Rizzo—Associate Director of NYU WIRELESS, Associate Professor in NYU Tandon's Biomedical Engineering Department, affiliated faculty at the NYU Tandon Center for Urban Science and Progress (CUSP), and Associate Professor in the Department of Rehabilitation Medicine at NYU Grossman School of Medicine—the team will continue developing VIS^{4}ION (Visually Impaired Smart Service System for Spatial Intelligence and Onboard Navigation), a wearable technology platform designed to help pBLV better understand and navigate their environments.

"Engineering can even the playing field, and it is research like this, led by J.R., that ensures that everyone can navigate both urban and rural communities."

NYU TANDON DEAN JELENA KOVAČEVIĆ

VIS^{4}ION works by using miniaturized sensors—including cameras, microphones, GPS, and motion sensors on wearable devices—to collect data about the user's environment. Artificial Intelligence (AI) services running locally within the platform and remotely in the cloud process the sensor data to interpret the environment and tell the user where to walk, what to avoid, and how to maneuver through hazards.

"People with blindness and low vision have unacceptably high unemployment rates, with some studies showing levels at about eighty percent," said J.R., who is the project's Principal Investigator (PI). "A critical obstacle to employment is commuting difficulties and navigation within the workplace itself. This project takes a fundamental step in solving this problem. If successful, we believe it will significantly improve pBLV's quality of life and unlock their potential to contribute fully to the communities in which they live."

In 2022, the NSF awarded the team a Phase One Convergence Accelerator Grant to support its early VIS^{4}ION work. These highly competitive grants fund research to address societal challenges. The team's promising preliminary results prompted the NSF to advance the VIS^{4}ION project to its Phase Two funding round.

During Phase One, the researchers successfully built a lightweight wearable VIS^{4}ION backpack prototype with cameras, on-board processing, and audio and haptic feedback. They subsequently demonstrated that the backpack could be used for safe navigation through a variety of environments.

The team also developed VIS^{4}ION mobile, a stand-alone platform for use entirely on a smartphone. The signature microservice—offered on both the wearable and mobile platforms—is UNav, a software that creates camera-based, infrastructure-free "digital twins" or 3D maps of complex indoor and outdoor environments, supporting wayfinding to close- or far-range destinations through audio and haptic user prompts.

In collaboration with New York City's Metropolitan Transit Authority, the VIS⁴ION researchers also unveiled an early version of Commute Booster, a smartphone app that guides users to their destinations in subway stations by "reading" the directional signage it encounters.

Moving forward, the team will continue to improve VIS⁴ION services while reducing the wearable's size and weight. The goal is a commercially available wearable product, a breakthrough that user advocates have sought for years.

"NYU has the rare ability to bring faculty from across schools and departments to collaborate on the creation of technologies that help create greater accessibility," said NYU Tandon Dean Jelena Kovačević. "Engineering can even the playing field, and it is research like this, led by J. R. Rizzo, that ensures that everyone is able to navigate both urban and rural communities."

Vital to the work is the team's collaborations with industry leaders, including NYU WIRELESS Industrial Affiliate Qualcomm, whose ongoing research and development efforts contribute broadly to the wearable technology ecosystem.

"Snapdragon platforms enable compelling new applications that require high performance compute, wireless, and AI capabilities," said Junyi Li, Vice President, Engineering at Qualcomm Technologies, Inc. "Qualcomm is looking forward to the collaboration with NYU in this NSF-awarded project to enable powerful wearable devices with advanced assistive technologies for people with blindness and low vision."

Dell Technologies, another NYU WIRELESS Industrial Affiliate, will provide critical Dell Precision rack workstations to enable the cloud-based AI microservices for the wearable.

"Collaborating with NYU on this project is an incredible opportunity to use our technology to advance and transform accessibility," said Charlie Walker, Senior Director and GM, Precision Workstations, Dell Technologies. "Using Dell Precision rack workstations equipped with powerful GPUs, NYU can run computing-intensive tasks, such as real-time object detection and vision-language models, to expand and improve the AI services on the wearable."

In addition to J. R., senior personnel involved in the project reflect an integrated effort that crosses disciplines and engages multiple departments and centers: NYU WIRELESS members Sundeep Rangan (Associate Director of the Center), Yao Wang, and Marco Mezzavilla, as well as Tommy Azzino, graduate research assistant; and NYU Tandon professors Chen Feng, Maurizio Profiri, and Yi Feng. Additionally, others from NYU Tandon involved in the project include Anbang Yang, Junchi Feng, Fabiana Ricci, and Jacky Yuan. Clinical Associate Professor Ashish Bhatia at NYU Stern School of Business will also contribute. From NYU Grossman School of Medicine, team members include Mahya Beheshti, Giles Hamilton-Fletcher, Todd Hudson, and Joseph Rath.

Associate Professor J.R. Rizzo with former Prime Minister of Finland Sanna Marin.

Tactile Navigation Tools (TNT), the team's start-up partner, will drive the project's commercialization efforts, beginning with increasing the technology applications to improve accessibility and quality in NYC real estate for customers with and without navigational challenges. TNT is led by its CEO Van Krishnamoorthy, a physician entrepreneur.

The project's nonprofit collaborators include the Lighthouse Guild—whose Chief Research Officer William H. Seiple will help direct and develop protocols for all workplace studies—and VISIONS. Key government agencies including the MTA and NYC Department of Transportation are also involved.

In addition to Qualcomm and Dell, collaborators include Google, AT&T, and TaggedWeb.

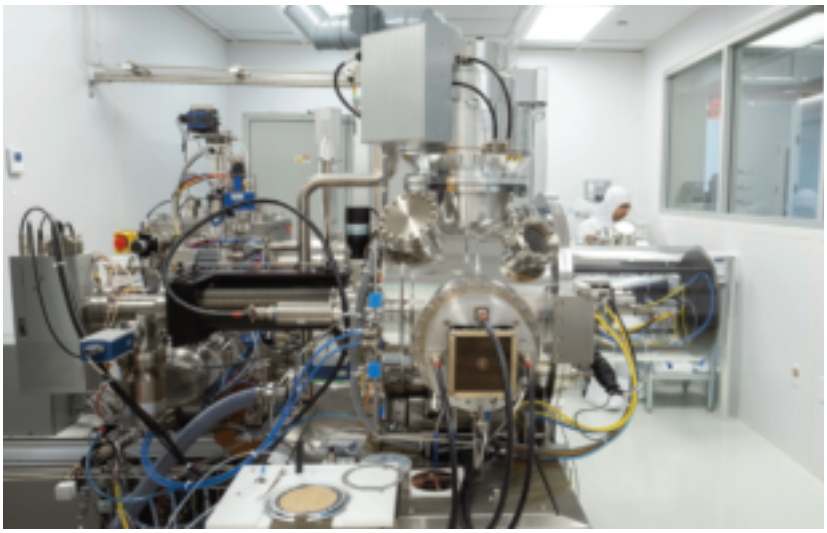
The VIS⁴ION project reflects NYU Tandon's commitment to solving problems related to health, one of the seven interdisciplinary "Areas of Excellence" that define the school's research and educational priorities.

NanoNews

NanoFab Update

NanoFab provides NYU and NYC technology communities with cutting-edge capabilities to fabricate next-generation semiconductor chips.

In October of 2023, the NYU Nanofabrication (NanoFab) Cleanroom officially opened on the Tandon campus. The facility provides a specialized research environment where scientists and engineers can fabricate cutting-edge semiconductor chips to advance research in quantum science and engineering, precision medicine, neurotechnologies, next-generation communications technology, and secure computing.

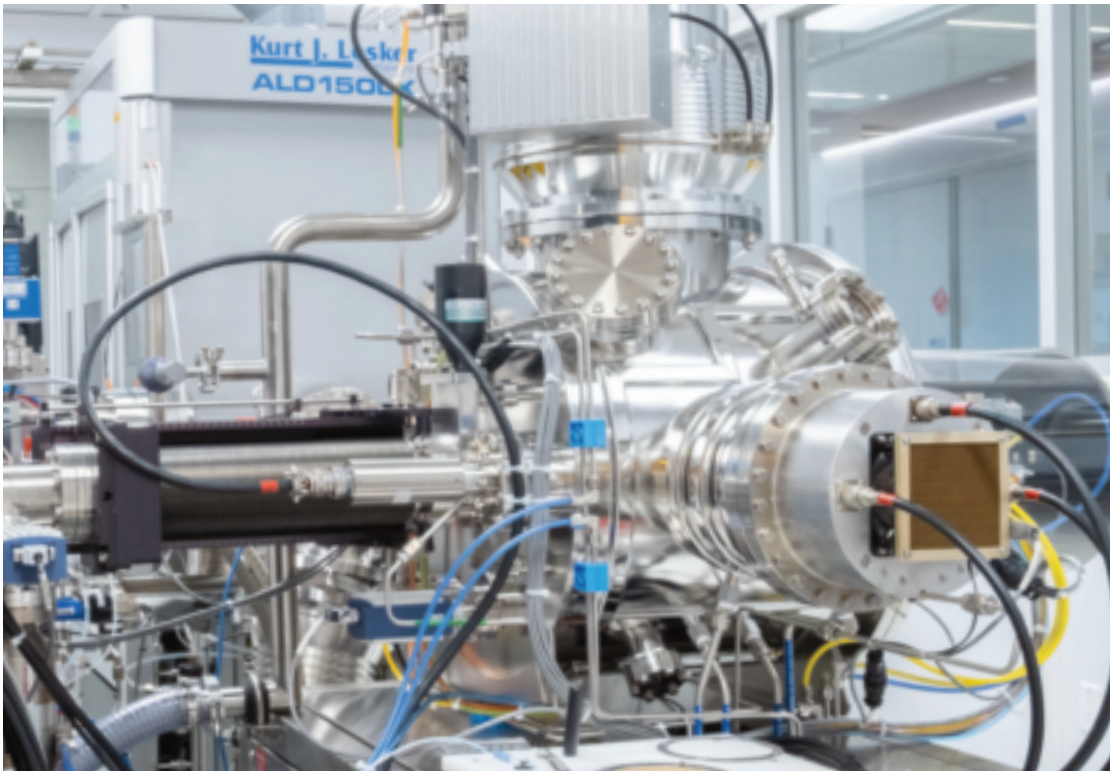


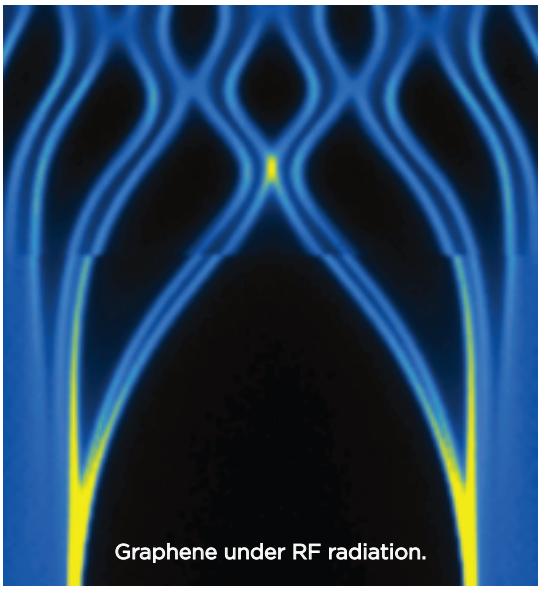
Under the leadership of Davood Shahrjerdi, NYU Associate Professor of Electrical and Computer Engineering, NYU NanoFab helps fulfill the promise of the bipartisan CHIPS Act, signed into law by President Biden in 2022. The CHIPS Act aims to bolster U.S. chip manufacturing to meet growing global demand and to support related research and development and workforce cultivation.

NYU NanoFab, the only such academic facility in Brooklyn, is available to all NYU faculty and students and to the academic and tech communities in Brooklyn and beyond. The state-of-the-art facility enables researchers to make semiconductors that accelerate artificial intelligence advances, power quantum computing, produce new medical devices, and develop other innovations that improve people's lives. NYU and NanoFab are part of the NORDTECH Microelectronics Commons consortium, a group that contributes facilities and infrastructure in targeted R&D projects as well as education and workforce development. NORDTECH received $40 million from the U.S. Department of Defense's Microelectronic Commons Program, which the CHIPS and Science Act also funds.

At NYU Tandon, the NanoFab aligns with the ongoing research of NYU WIRELESS and the Center for Cybersecurity, as well as areas of excellence at the school, which range from health to urban tech and sustainability. It will continue to drive university leadership in quantum computing, artificial intelligence, and robotics, providing research capabilities rarely found in academia.

"NYU Tandon's new Nanofab cleanroom in Brooklyn is a state-of-the-art laboratory where our world-class scientists, scholars, and students—as well as our partners and collaborators





Graphene under RF radiation.

NYU NanoFab offers notable capabilities for processing emergent semiconductors and quantum materials, including:

- Plasma-enhanced atomic layer deposition of high-quality metal oxide and metal nitride dielectrics
- A state-of-the-art ion beam etch system to thin down exotic materials, such as magnetic materials, with nanoscale precision enabled by secondary ion mass spectroscopy endpoint detection
- An atomic layer etch system for thinning quantum materials with atomic precision
- A sputtering system for deposition of superconducting metals
- Capability to support 200 mm substrates to facilitate collaboration with other cleanrooms, fostering innovation and advancement in materials research

from around the city—can harness their ingenuity and innovative prowess to advance scientific discoveries while boosting both New York's economy and its burgeoning tech sector," said Linda G. Mills, President of NYU.

NanoFab Director Davood Shahrjerdi commented, "I am grateful for the opportunity and support to lead the effort in shaping the vision and infrastructure of NanoFab. After two demanding years of enhancing infrastructure and experimental research capabilities, I am excited that this project came to fruition, and this core research laboratory is now available to support cutting-edge research on functional materials and nanoscale devices. Nanofab's mission is to equip our community with cutting-edge experimental capabilities to advance the frontiers of semiconductors and quantum materials, while empowering us to educate the next generation of scientists and engineers equipped with critical knowledge for tackling the grand challenges of our time. Our mission aligns perfectly with the goals of the CHIPS and Science Act."

Wearable Health Microchips

Davood Shahrjerdi
Associate Professor,
NYU WIRELESS

Elisa Riedo
NYU Professor
of Chemical and
Biomolecular
Engineering

Dr. Giuseppe Maria de Peppo
Director of Internal
Research, Mirimus, Inc.

Imagine that you wake up one morning sometime in the future with a tickle in your throat and a stuffy nose. Your first thought might be a twinge of fear—Maybe it's something more serious than a cold, or a contagious disease! But before you call in sick or cancel your evening plans, you decide to check. So you cough into the band of your smartwatch. Moments later, you get your results: negative for COVID-19, negative for flu, negative for anything nastier than seasonal allergies.

Thanks to a partnership between NYU Tandon's researchers and the Brooklyn biotech company Mirimus, what may now seem like science fiction is closer than you might think.

This groundbreaking research is led by Davood Shahjerdi of NYU WIRELESS; Elisa Riedo, NYU Professor of Chemical and Biomolecular Engineering; and Dr. Giuseppe Maria de Peppo, Director of Internal Research at Mirimus, Inc., a biotech company making waves in the medical testing field.

Elisa and Davood partnered with Mirimus early in 2024. Established in 2010 by co-founder and CEO Dr. Prem Premsrirut, Mirimus developed an affordable and non-invasive testing methodology in 2020 to respond to the COVID-19 pandemic. The test, SalivaClear, was one of the winners of the XPRIZE Rapid COVID Testing competition.

Elisa is particularly well known for her pioneering work on thermal scanning probe lithography (tSPL), an innovative method to nanofabricate devices and materials with molecular resolution using a heated "nano-chisel." Work in collaboration with Davood and Giuseppe showed that tSPL can be used for fabricating state-of-the-art electronic circuits with atomically thin materials, as well as sculpting, in a biocompatible material, the exact structure of bone tissue, with features smaller than the size of a single protein—a billion times smaller than a meter.

Davood's research focuses on the study of electronic materials and devices for making nano-engineered integrated systems. Previously, his research led to a new way of enhancing the performance of electrochemical microsensors used in biochemistry for the detection of biomolecules, such as dopamine, at lower concentrations than was previously possible.

Giuseppe has been working for more than a decade in the field of stem cells and tissue engineering and was the first to engineer functional bone grafts from skin cells via a process referred to as cell reprogramming. Additional work includes the development of orthopedic implants and biomaterials, the design and validation of bioreactor systems for lab-on-a-chip applications, and stem cell-based therapy.

The team's unique combination of expertise in nanoelectronics, nanofabrication, and biomedical research makes them the ideal trio to meet this incredible and exciting challenge.

This partnership not only could result in a small, affordable device that can test for COVID-19, but could also produce a prototype for an electronic microchip that can be embedded in your watch or smart band, which is capable of monitoring a variety of human health threats. Such an important breakthrough would result in healthier workplaces and communities, putting you at ease on those days when you wake up feeling a bit under the weather.

What's in the Air?

In more NanoNews: Davood and Elisa are currently working on developing sensors to detect pathogens in the air. Thanks to their groundbreaking research, people could soon be alerted to potentially deadly airborne threats—including pollutants, bacteria, and viruses—in schools, buses, and other indoor spaces.

The project is supported by a nearly $1 million grant by Lendlease, an international property and infrastructure company that develops residential communities and mixed-use urban districts around the world. The funding will provide Davood and Elisa with the resources to build the underlying technology and prototypes of the sensors.

The NYU engineering researchers aim to create a novel technological platform that electronically detects the presence of airborne viruses and other hazards through the use

of a special microchip that generates a digital signal when it interacts with an airborne threat. Currently, the most reliable and widely used methods for detecting viruses rely on chemical analysis of physical samples, such as the polymerase chain reaction (PCR) test for COVID-19.

Davood and Elisa's research, along with other advancements in electronic virus detection, promises to revolutionize the field by offering more efficient and accessible methods of virus detection. This has far-reaching implications for both public health and biodefense. It could, for instance, facilitate the instant lockdown of buildings upon detection of a dangerous virus, or prompt a rapid emergency response to airborne biological hazards.

Their work with Lendlease intersects with a project the two started with Mirimus, as previously reported in this article. "As with Mirimus, Lendlease has afforded us an amazing opportunity to test the limits of our vision on how we can use electronic technology to create spaces that are safe and healthy for everyone, something particularly pressing given what we've all endured in recent years," said Davood.

"The Lendlease project is uniquely ambitious because of its technical complexity," added Elisa. "The first hurdle is developing electronic technology that has the capacity to reliably and consistently sense airborne threats. The second challenge is making that technology function not just when a threat comes into direct contact with a device, but when it's in the air at a distance from the device."

"Collaborating with Elisa and Davood represents the boundless possibilities when private industry and academia join together towards goals that can deliver enormous benefits to people's lives," said Tommaso Boralevi, Innovation & Technology Director, Lendlease Italy. "The COVID-19 pandemic revealed the critical need for modernizing buildings with advanced technologies that can detect and counter novel public health threats in real time. This deficiency in present-day buildings is largely the reason for reliance on basic risk-mitigation strategies in public spaces such as mask-wearing and entry passes. A sensing technology that allows sensitive, selective, and rapid detection of various public health threats is needed for realizing this vision for the buildings of the future."

Developments in electronic virus detection serve as a prime example of NYU Tandon's focus on healthcare advancement, one of its foundational areas of excellence.

NanoBioX

NanoBioX, or NBX, is an initiative at NYU designed to provide an R&D home for disruptive innovations powered by collaborations in nanofabrication, nanoelectronics, data science, and biotechnology designed to solve pressing societal challenges in precision medicine and neurotechnologies, as evidenced by the previous articles. You can keep current by checking the website https://nanobiox.nyu.edu.

Importance of Upper Mid-Band Frequencies

Sundeep Rangan
Associate Director,
NYU WIRELESS

Hamed Rahmani
Assistant Professor,
NYU WIRELESS

Marco Mezzavilla
Associate Professor,
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Arjuna Madanayake
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NYU WIRELESS Associate Director Sundeep Rangan received one of the first grants awarded by the new Public Wireless Supply Chain Innovation Fund, a federal CHIPs Act program that supports the development of open and interoperable 5G and future-generation cellular technologies.

Sundeep's project was one of only three selected by the Biden Administration from among the 127 proposals received. The $2 million five-year award will be overseen by the U.S. Department of Commerce's National Telecommunications and Information Administration (NTIA).

The grant will support NYU WIRELESS's work on optimizing cellular services within the upper mid-band 7 to 24 GHz frequency range, known as FR3. This range offers more data capacity than lower frequencies used in traditional cellular communications and has better coverage than higher frequencies capable of transferring large amounts of data.

"FR3 is attracting significant attention from wireless carriers as a promising option for advanced wireless networks like 5G and 6G," said Sundeep, who leads the project team. "Our research will focus on ways to test and evaluate how well cellular services can use FR3 while adaptively sharing that spectrum with existing satellite and radio astronomy systems. We will investigate how to make these services robust against intentional disruptions caused by jammers."

Along with Sundeep, the project team includes Assistant Professor Hamed Rahmani, who recently joined NYU WIRELESS as an assistant professor (see page 17); Marco Mezzavilla, Associate Professor, Polytechnic of Milan; and Arjuna Madanayake, Associate Professor of Electrical and Computer Engineering at Florida International University.

The academic partners are joined by Aditya Dhananjay, Co-Fouder and President of Pi-Radio, an NYU Tandon spin-off company that develops advanced software-defined radios for research and testing labs. Pi-Radio will develop the radio frequency (RF) transceiver board for the project.

Analog Devices (ADI), a global semiconductor leader and an NYU WIRELESS Industrial Affiliate member, will supply the researchers its O-RU reference board, an advanced Radio Unit hardware platform that enables testing and experimenting with various aspects of 5G & 6G radio technology.

"The NYU WIRELESS team is at the leading edge of next-generation wireless research, and ADI is pleased to provide important radio technology and support for this 6G research program, said Joe Barry, Vice President, Cloud and

pi-radio

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Communications at Analog Devices. "The grant funds important work necessary for the industry to understand the challenges of expanding into these new FR3 Bands."

Launched in 2023, the $1.5 billion Wireless Innovation Fund supports the Biden Administration's push for open and interoperable wireless equipment that it says will help drive competition, strengthen global supply chain resiliency, and lower costs for consumers and network operators. According to the Department of Commerce, the development of new, open-architecture approaches to wireless networks will help to ensure that future wireless equipment is built by the U.S. and its global allies and partners, not vendors from nations that may threaten U.S. national security.

This important work builds on NYU WIRELESS's extensive expertise in cellular systems, with its pioneering track record in the high-frequency millimeter wave bands (mmWave) used in 5G cellular networks. NYU WIRELESS has played an active role in standards including influencing 3rd Generation Partnership Project (3GPP) channel models for mmWave. Several FCC documents regarding the mmWave spectrum cite NYU WIRELESS's work. The Center is currently engaged in the NextG Alliance, an initiative to advance North American wireless technology leadership over the next decade through private-sector-led efforts.

In a separate related project, funded by the NYU WIRELESS Industrial Affiliates, Professor Ted Rappaport's group is conducting pioneering measurements of the spatial and temporal channel at 6.75 GHz and 16.75 GHz for new channel models and penetration loss data for emerging 6G FR1C and FR3 spectrum bands. The team has worked with Mini-Circuits to create a dual-band wideband channel sounder, with 1 GHz RF bandwidth. Measurements are on-going with early results presented at Ted's keynote address for the WCNC conference in Dubai in late April 2024. As with all propagation measurements, NYU WIRELESS Industrial Affiliates will benefit from early access to the raw channel data and resulting models.

Theodore Rappaport
Founding Director,
NYU WIRELESS

Research Aims to Make 3D Video More Accessible

R. Luke DuBois
Associate Professor,
NYU Tandon

Yong Liu
Professor, NYU WIRELESS

Yao Wang
Professor, NYU WIRELESS

A groundbreaking research project spearheaded by NYU WIRELESS researchers will bring cutting-edge immersive three-dimensional (3D) video to dance education, making learning the art form available to a greater number of students. More broadly, the research will make 3D media readily accessible to mobile users in NextG wireless systems.

The project, supported by a $1.2 million four-year grant from the National Science Foundation (NSF), aims to make Point-Cloud Video (PCV) technology suitable for streaming onto standard Internet-connected devices.

Developed over the past decade, PCV is a type of highly detailed 3D video that allows viewers to "move" within an immersive video environment, observing objects and scenes from any angle or distance as if they were physically present. Unlike traditional video that relies on two-dimensional pixels, PCV captures scenes as point clouds, collections of data points in 3D space.

Currently, streaming PCVs requires bandwidth and computational power that exceeds what is generally available, limiting its real-world applications. The NYU WIRELESS team's project addresses those obstacles, reducing bandwidth consumption and delivery latency and increasing power consumption efficiency so that PCVs can be streamed far more easily.

"With recent advances in the key enabling technologies, we are now on the verge of completing the puzzle of teleporting holograms of real-world humans, creatures, and objects through the global Internet," said Professor Yong Liu of NYU WIRELESS, who leads the research team that includes NYU WIRELESS Professor Yao Wang and R. Luke DuBois, an Associate Professor in the Technology, Culture, and Society Department.

"The success of the proposed research will contribute toward wide deployment of high quality and robust PCV streaming systems that facilitate immersive augmented, virtual, and mixed reality experience and create new opportunities in many domains, including education, business, healthcare, and entertainment," said Yong.

From a technical perspective, beyond developing the PCV testbed used specifically for dance experimentation, the NYU Tandon researchers want the project to make fundamental strides in three areas that will advance PCV more broadly.

First, they will develop efficient PCV compression using object-based coding schemes, hierarchical slicing structures, and advanced prediction techniques that enable bitstream adaptation based on the predicted viewer's field of view and the network throughput. Second, they will create a progressive streaming framework that refines spatial resolution based on viewer needs, considering computation-communication trade-offs and low-latency live streaming. Finally, they will design edge-based caching algorithms, multi-user delivery strategies, and cross-user Field-of-View (FoV) predictions to enhance PCV streaming efficiency and robustness.

To test PCV streaming with human motion, Luke's team has partnered with the Department of Dance at NYU Tisch School of the Arts and the

Mark Morris Dance Group's Dance Center, a cultural hub in Brooklyn that serves 1,500 students.

"Point-Cloud Video holds tremendous potential to transform a range of industries, and I'm excited that the research team at NYU Tandon prioritized dance education to reap those benefits," said Jelena Kovačević, Dean of NYU Tandon. "NYU encourages cross-disciplinary research, and that means bridging engineering with new fields. Collaborating with dancers from NYU Tisch and Mark Morris makes the innovative power of engineering imminently real."

Dancers from both organizations will perform on a volumetric capture stage—a specialized production environment for shooting 3D video—at NYU Tandon @ The Yard, the school's production and research facility for emerging media at the Brooklyn Navy Yard. Their movements will be streamed live and on-demand, using the new PCV testbed the researchers developed. The goals of NYU Tandon @ The Yard include advancing integrative research in AR/VR/XR, virtual production, and other areas relevant to experiential computing.

"By facilitating the use of emerging technologies, we are laying the groundwork for greater accessibility in the dance and education spaces while broadening the creative possibilities for artists," said Allyson Green, Dean of NYU Tisch School of the Arts. "As a longtime choreographer, performer, and dance educator, I am thrilled that our Department of Dance has joined NYU Tandon and Mark Morris Dance Group at the forefront of this research, and I'm eager to see how these advancements modernize the field."

Students watching the 3D streams will be able to observe the dancers from varying angles and distances, necessary for learning dance techniques and choreography properly.

"Integrating dance education into our PCV research brings to life the real-world benefits of this technology, demonstrating how it can open doors for people everywhere to learn things that previously would have been possible only in person," said Luke.

Mark Morris Dance Group and the Department of Dance at NYU Tisch have recruited students and instructors to take part in the project.

This project builds on NYU Tandon's advanced work to expand the next generation of foundational wireless communications and media processing technologies. It will also beneficially impact industry collaborations with leaders in immersive video and virtual production, including Evercoast, Final Pixel, Argus, Epic Games, and Walt Disney, bringing research-grade emerging technology within reach of media, entertainment, and cultural institutions while developing technologists to further the field of emerging media.

A dancer on the volumetric capture stage at NYU Tandon @ The Yard.

2023 Summit Sets the Foundation for Next Generation Wireless and Beyond

The tenth annual Brooklyn 6G Summit (B6GS) at the NYU Tandon School of Engineering offered a sweeping perspective of present challenges and future opportunities in wireless. Despite a sharp focus on America's lagging status in 5G, participants were optimistic about current projects and strategies that will lay the groundwork for returning the U.S. to a leadership role in the next generation of telecommunications.

In addition to providing an overview of the state of 5G, the three-day Summit, which kicked off on October 31, included panels and keynotes that addressed pressing issues such as:

- **Artificial intelligence in wireless, including 6G as a de facto AI-native ecosystem**
- **Ways of achieving higher energy efficiency and sustainability goals**
- **The state of standardization**
- **The talent pipeline in both academic and industry contexts for electrical engineers focused on wireless careers**
- **How wireless is shaping—and being shaped by—IoT in every realm, from agriculture to medical diagnostics**
- **The disruptive potential for wireless networks of 6G applications like robotics and the metaverse**

The world's flagship event for 6G innovation, the B6GS is hosted each year by NYU WIRELESS and Industrial Affiliate Nokia. The 2023 B6GS, which focused on "Creating a Foundation for 6G," drew industry leaders from around the globe, including the Center's Founding Director Ted Rappaport; Peter Vetter, President of Nokia Bell Labs Core Research; and more than fifty speakers and panelists across industry, government, and academia.

During a panel held on the Summit's second day, NYU Tandon's Dean Jelena Kovačević touched on how the U.S. can exploit strong synergies between academia and industry to leapfrog to pole position in 6G.

Said Dean Kovačević, "One of the reasons we are all here is because we all believe in strong cooperation … integration between academia and industry is key to going anywhere in the future generations of wireless. … [Having] bold ideas and pushing them to the market and figuring out what the current political climate and economic climate allow us to do is really up to all of us."

The Summit included more than twenty demonstrations of cutting-edge tech from industry partners and researchers, with nearly 300 attendees from around the globe representing vendors, academia, operators, regulators, and experts from multiple industries—"all helping to build the future of the mobile ecosystem," as emcee and IDC analyst Patrick Filkins put it during his introductory remarks.

In his keynote, Nokia's Peter Vetter discussed important trends that will shape technology over the next decade and presented an overview of Nokia's recently launched technology strategy, "Vision 2030" for 6G around AI. He also discussed cloud and connectivity and offered an exhortation: The wireless community needs to work toward a sea change in network architecture to realize higher efficiency and much lower latency and address future demands from such disruptive technologies as wireless VR.

Chris Sambar, EVP of Technology at AT&T, spoke about the company's Standalone 5G core as well as edge computing, AI, and non-terrestrial network (e.g., satellite) integration and how end-to-end alignment across architectures will be vital to making 6G a success. Margaret Martonosi, Assistant Director for Computer and Information Science and Engineering at the National Science Foundation, detailed the foundation's rubric for advanced research funding.

Ozge Koymen, Senior Director of Technology at Qualcomm, an NYU WIRELESS Industrial

Pictured (l. to r.): Andrea Goldsmith, Dean of Engineering at Princeton University; Jelena Kovačević, Dean of NYU Tandon School of Engineering; and Gregory Abowd, Dean of the College of Engineering at Northeastern University.

Affiliate, spoke about the company's research on making 5G Advanced and 6G possible, in part through efficiency and new spectrum. Mingxi Fan, General Manager of System Design at Mediatek, Inc., another Industrial Affiliate, discussed device-level engineering for 6G. He reviewed the mobile device architecture evolution, WAN, and proximity connectivity across different types of spectrums as well as the convergence of computation and communication, including AI native design. Other speakers included Victor Bahl, CTO at Microsoft Azure, and Shyam Prabhakar Mardikar, who leads Reliance Jio's mobile network.

The Summit presented more than half a dozen panel discussions exploring vertical applications and IoT for 6G, as well as examining the challenges and opportunities for universities to work with industry to advance 6G.

A panel during the second day of the Summit featured engineering school deans who examined opportunities for academia to step up to enterprise-scale innovation ecosystems with industry partners. The panel took a hard look at the Klondike-like gold rush of students and prospective students lured away from electrical engineering by what many students perceive as more lucrative Silicon Valley opportunities.

During the Dean's Panel—with NYU Tandon's Jelena Kovačević; Gregory D. Abowd of Northeastern University College of Engineering; Andrea Goldsmith, Dean of Engineering at Princeton University; and moderator Albert P. Pisano of the UC San Diego Jacobs School of Engineering—Dean Kovačević discussed the most effective ways to ensure the best and brightest pursue electrical engineering and wireless research.

"Big tech has done a lot to make [computer science] interesting and lucrative," she said. "With the understanding that we are behind, and with the government making a big investment, you will see more people coming into wireless—into the physical layer. I would add that there has to be a concentrated effort on all fronts, and government has to lead, including by providing funds—the CHIPS Act came as the rarest of birds: bipartisan support for a major investment."

John-Ross Rizzo, M.D., an Associate Director at NYU WIRELESS with an appointment at NYU Health, participated in a panel focused on end uses for next generation wireless and 6G applications. He was joined on the panel by Ben Craker of AgGateway; Onur Altintas, Fellow at Toyota's InfoTech Labs; Meryem Simsek, Head of Network Architecture at Nokia Bell Labs; and Matti Latva-Aho of the University of Oulu. The discussion—led by Doug

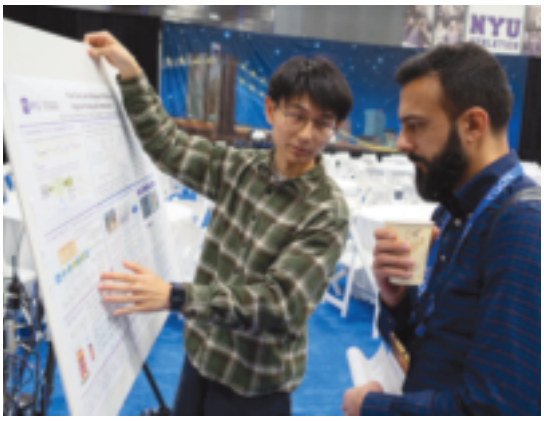
"It is heartening to see industry and academic centers sharing a mutual interest in building new opportunities together, brick by brick."

THEODORE RAPPAPORT, NYU WIRELESS FOUNDING DIRECTOR

Castor, Head of Wireless Research at InterDigital, another Industrial Affiliate—looked at the demand for IoT smart devices and industrial applications. J. R., who discussed the medical device vertical, cited numerous opportunities for 6G-capable wireless.

"We are hitting an inflection point, moving beyond simple interventions to more complex ones where we can put the clinician and the patient in the loop," he said, noting new possibilities for wirelessly connected devices in the realm of diagnostics. "I'm excited about the possibilities of multiple vantage points in an environment—getting sensor feeds from IoT and capitalizing on the diagnostic opportunities. Not just for quality of service but for quality of experience: Can I take this input and project it into the ER; can I make it available to clinicians and can it be valuable enough to support remote healthcare?"

Other panels delved into next-generation wireless and the implications and risks of globalization; 6G and the regulatory landscape, with an eye to the FCC's opening of additional licensed and unlicensed spectrum for flexible use; how 6G will intersect with the advance of the metaverse, which included speakers from NVIDIA; how to collaborate toward protocol standardization within the complex framework of multiple organizations; and cloud native architecture and 6G with a focus on the 6G-life project from TU Dresden and TU Munich.



Ted Rappaport commented, "Though 6G may be a decade down the road—and 5G even today is hitting a few speed bumps—it is heartening to see industry and academic centers sharing a mutual interest in building new opportunities together, brick by brick. After all," he added, "it's because of NYU WIRELESS's partnerships with companies like Nokia that we are able to perform the seminal work we do, be it opening the doors to hitherto unexplored regions of the spectrum such as the sub-THz realms; unveiling new ways of leveraging AI to make radio vastly more efficient, sustainable, and seamless for the user; or developing new consumer and enterprise technologies that presage 6G wireless. All of which would be inconceivable had we not worked to lower silos between areas of expertise within our own institution, while encouraging partnerships with industry, the government, and others."

This year's Brooklyn 6G Summit will be held October 23–25, 2024. To learn more, visit B6GS.com.

Pictured (l. to r.): NYU WIRELESS Founding Director Ted Rappaport and industry visionaries Neera and Raj Singh, who received the Wireless Pioneer Award.

New Metric for Evaluating Power Efficiency

Those who are concerned about power-efficient design in circuits, systems, data centers, power electronics, communications, and green engineering—basically, in any type of cascade—will find Waste Figure to be a powerful and convenient analysis tool.

A recent paper by NYU WIRELESS Founding Director Ted Rappaport and Ph.D. students Mingjun Ying, Dipankar Shakya, and Hitesh Poddar (now with Sharp Labs) discussed this timely topic.

Wireless communications systems currently account for 2% of the world's energy consumption. Forecasts project this number will increase 20% by the end of 2030, with 6G networks being a significant contributor. This anticipated leap, characterized by ultra-wide bandwidths and elevated data rates, compounds the dilemma of energy oversight. This energy imperative becomes even more accentuated for Internet of Things (IoT) devices, which are known for their operation within stringent resource parameters. The global initiative to curb greenhouse gas emissions and mitigate climate change further accentuates the urgency to innovate energy-efficient solutions, particularly within wireless networks.

Waste Factor (W) or Waste Figure (W in dB) is a practical tool used for understanding the energy efficiency in communication networks. It was inspired by H. T. Friis's Noise Factor, first described in 1944. W provides a tangible means to measure power efficiency in cascaded communication systems. The recent NYU study used the established Power Usage Effectiveness (PUE) metric, commonly used in data centers, to expand the practical applications of W to better evaluate the power efficiency of data centers. Simulations focused on the impact of cell radius, carrier frequency, system bandwidth, and component efficiency in communication systems, providing concrete insights into real-world energy efficiency scenarios.

In the past, advancements in massive MIMO, network slicing, renewable energy-powered base stations, and energy harvesting technologies have significantly contributed to reducing energy consumption in 5G networks. Furthermore, artificial intelligence (AI) and machine learning (ML) techniques, including reinforcement learning, may be instrumental in maintaining a balance between quality of service and energy consumption. Despite these strides, there remains a lack of a comprehensive theoretical framework to measure and compare power efficiency across diverse wireless system architectures. W and Consumption Efficiency Factor (CEF) aim to fill this gap. By providing a standardized metric for comparing power consumption and energy efficiency across various system designs, W and CEF can guide engineers and product designers toward more sustainable and energy-efficient solutions and towards minimal power consumption in future wireless network design, particularly those operating at sub-THz frequencies.

You can learn more about this important metric at https://arxiv.org/abs/2309.01018.

Theodore Rappaport
Founding Director,
NYU WIRELESS

Mingjun Ying
Ph.D. Student,
NYU WIRELESS

Dipankar Shakya
Ph.D. Student,
NYU WIRELESS

Hitesh Poddar
Sharp Labs

Launching Summer Internships

Ozan Aygun
Apple,
San Diego, CA

Ufuk Usubutun
Marvell Semiconductor
Santa Clara, CA

Yueyu Hu
Apple,
Cupertino, CA

Sai Meghana Kuchana
Interdigital,
New York City

Chen Li
Amazon,
San Diego, CA

NYU WIRELESS Ph.D. students have stellar opportunities each summer to work with our Industrial Affiliate Members on a variety of projects that can help boost them into career orbit. During our Open House every January, our students connect with Affiliates to see which positions would be a good fit. Pictured here is a sampling of students who have internships that will surely help them reach new heights.

Ozlem Yildiz
Meta,
Burlingame, CA

Jyotish Robin
Interdigital,
New York City

Ruth Gebremedhin
Nokia Bell Labs,
Hybrid

Fatih Berkay Sarpkaya
Interdigital,
New York City

Mingjun Ying
MediaTek,
Warren, NJ

Welcome Hamed!

We're pleased to welcome Hamed Rahmani to NYU WIRELESS as the newest Assistant Professor in the Electrical and Computing Engineering Department at NYU Tandon School of Engineering.

Hamed is leading the Research in Advanced Integrated Systems and Electronics Laboratory (RAISE Lab). His research interests include integrated circuits and systems for intelligent sensing and communication in emerging applications, with specific focus on RF/mmWave and THz circuits, applied electromagnetics, and low-power integrated sensors and systems for biomedical and Internet of Things (IoT) applications.

Before joining NYU Tandon, he held multiple positions in industry and research. As a research scientist, he contributed to high-speed electrical/optical interconnects at IBM T. J. Watson Research Center in Yorktown Heights. He has served as an Adjunct Professor at Columbia University in New York, NY, and as a visiting lecturer at Princeton University, where he taught graduate-level courses in analog and RF circuit design. Additionally, he was a senior RFIC design engineer at Qualcomm Inc., focusing on advanced 5G transmitters for cellular applications and RF front-end designs. He earned his Ph.D. from the University of California, Los Angeles, his M.Sc. from Rice University, and his B.Sc. in Electrical Engineering from the Sharif University of Technology in Tehran.

Hamed has been honored with several prestigious awards and fellowships, including the IEEE MTT-S Graduate Fellowship for medical applications and the Texas Instruments Distinguished Fellowship. He played a pivotal role on the technical committee for the International Microwave Symposium in 2022. He is a member of the "MTT-26: RFID, Wireless Sensors and IoT" and an affiliate member of the "MTT-25: Wireless Power Transfer and Energy Conversion" technical committees within the IEEE Microwave Theory and Techniques Society.

SAVE THE DATES

NYU WIRELESS Board Meeting

The NYU WIRELESS Board Meeting will be held on October 23, 2024.

NYU WIRELESS Workshop

The NYU WIRELESS Workshop will be held June 13 & 14, 2024, on the NYU Tandon School of Engineering campus. An invitation-only event, the Workshop brings together the foremost wireless researchers for a free exchange of ideas.

Brooklyn 6G Summit

The annual Brooklyn 6G Summit will take place on the NYU Tandon School of Engineering campus on October 23-25, 2024. We are excited to announce that this year's Summit will feature an NYU WIRELESS Summit Open House and lab tours for all attendees. Please visit b6gs.com for more information.

January 2024 Open House

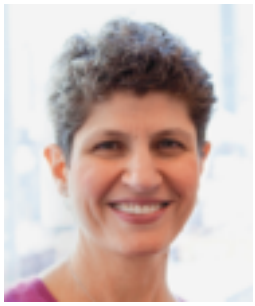
NYU WIRELESS hosted an impressive group of Industrial Affiliate Members at the Open House, held January 26.

In addition to updates from NYU WIRELESS Associate Director Sundeep Rangan on his recent grant awards (see page 8), Assistant Professor Hamed Rahmani (see page 17) presented an overview of his upcoming research activities. Attendees had the opportunity to view posters created by students to highlight their latest research. Year after year, the Open House has proven an ideal way for Industrial Affiliate Members to get to know our amazing students and their work in anticipation of summer internship openings and full-time positions.

Women in 6G

NYU WIRELESS is proud to be "home" for women who excel in wireless research.

Institute Professor Elza Erkip and Associate Professor Marwa Chafii were both recently named to the 2024 list of "100 Brilliant and Inspiring Women in 6G." The list was originally compiled and announced by the "Women in 6G" community founded by Pavithra Nagaraj, an independent researcher from India working on 6G and AI. The group's mission is to eliminate the gender gap and increase diversity in telecommunications. The extraordinary minds included on this list are leading the way for other women by serving as mentors, offering educational and networking opportunities, and actively working to ensure that their female colleagues benefit from the path they have forged. We are honored that Elza and Marwa are part of the Center. To learn more about Women in 6G or to see a full list of 2024 honorees, visit womenin6g.org/spotlight.



Elza Erkip
Institute Professor,
NYU WIRELESS

Marwa Chafii
Associate Professor,
NYU WIRELESS

NYU WIRELESS Recent Publications

January 2023–April 2024

5G and 6G Applications

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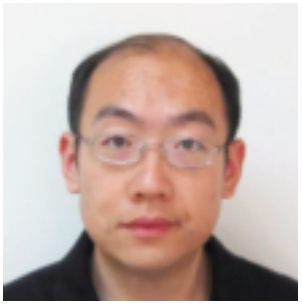

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