Spring 2023

The Brief

ENGINEERING FOR GLOBAL IMPACT
AT **NORTHEASTERN UNIVERSITY**

Next-Gen Wireless Communications

From The Dean

How can billions of wireless devices all share finite bandwidth for fast, reliable, and ever-growing high-capacity communications? How can intelligent implantable medical devices improve patient health and quality of life? And how can smart sensors be used to extend battery life to fuel Internet of Things applications?

With first-of-its-kind testbeds, pioneering technology, and collaborations with government, industry, and academia, our researchers at Northeastern University's College of Engineering are increasing speed, reliability, power, affordability, interoperability, security, and more to enable next-generation wireless communications that will transform society in unimaginable ways.

Read on to learn more and I invite you to reach out with ideas for collaboration and more information.

Kind regards,

Gregory D. Abowd, D.Phil.
Dean of the College of Engineering
Northeastern University
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WHAT'S INSIDE

Editorial credits and contributions: Nat Panek, Bill Ibelle, Northeastern Global News

Q+A

Driving innovation in systems, networks, and artificial intelligence to transform the way society is connected

In 2019, Northeastern created a universitywide research institute–the Institute for the Wireless Internet of Things (WIOT)–to bring together interdisciplinary expertise from across the university and with government, industry, and academic partners to shape the wireless internet of the future. **Tommaso Melodia**, William Lincoln Smith Professor of electrical and computer engineering, is director of the institute. In this Q&A, he describes the institute's mission, work, and unmatched experimental capabilities.

Institute for th Internet of Thi at Northeaste

What is the Internet of Things vision?

The vision of the Internet of Things is a globally connected continuum of wireless, untethered, AI-powered devices and objects that interact with the physical environment, people, and each other. The IoT of the future connects our physical world–where people live and operate–with the digital world, where the data resides. This data is used to make intelligent decisions that affect the physical world. The IoT also includes autonomous, wireless networks of systems of tomorrow, operating in uncertain, challenging, and extreme environments such as a network on the ocean floor, in the human body, on the battlefield, or in space.

What is WIOT's role in making the IoT vision a reality?

Through innovative research, WIOT is at the forefront of creating an internet that will be very different than it is today–faster, more efficient, and more secure. We have ten government agencies and an industry consortium made up of 19 companies sponsoring research of WIOT faculty and researchers. Some industry sponsors, for example, are InterDigital, Raytheon, Nvidia, Mavenir, Dell, and Qualcomm. In 2021, WIOT received over $20 million in new grants.

The institute's work is multifaceted. We design and research wired and wireless networked systems, train the next generation of wireless and IoT professionals, serve as a technical incubator, and operate as a think tank by sharing our technical expertise and opinions to influence and develop industry standards and policies.

How are you influencing industry policies?

We're one of only ten academic institutions with membership in the United Nations' International Telecommunications Union, and we serve on the board of the OpenAirInterface Software Alliance, one of the most well-known open software stack providers. We're also active members of the Alliance for Telecommunications Industry Solutions, the largest 6G-focused industry consortium in the U.S. And for the past three years, we've been an organizer of a major symposium on 6G, bringing together experts and innovators from industry, government, and academia.

Tommaso Melodia speaks during the Inauguration of the Institute for the Wireless Internet of Things in Northeastern's Interdisciplinary Science and Engineering Complex on October 18, 2019.

Photo by Ruby Wallau/Northeastern University

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What research are you doing?

We have core research areas in sensors and energy harvesting, wireless and networking, data analytics and machine learning, and security and blockchain. We apply research in these areas to key industry verticals, including the networked warfighter, smart oceans, connected vehicles and drones, internet of medical things, and the space internet.

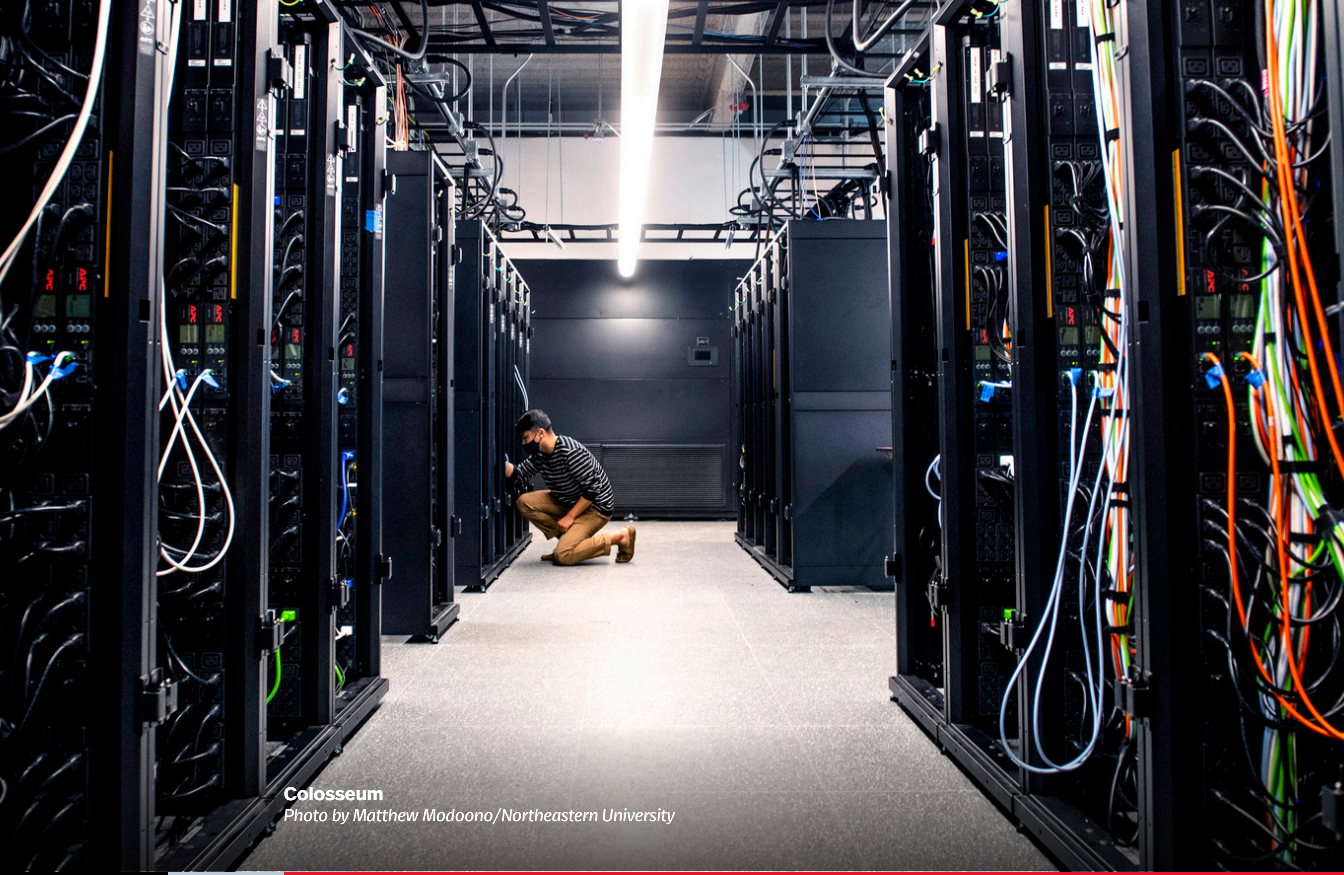
Several projects are underway, including furthering 5G systems and enabling 6G; using AI and machine learning to create smart and autonomous wireless systems; developing wireless networks for national security that can continue to operate under interference; and pioneering smart IoT systems for industry applications such as digital health, smart agriculture, blockchain, industrial units, and maritime.

Who will be affected by the work that WIOT is doing?

Whatever comes beyond 5G will affect 100 percent of the economy–and society at large; I would argue that the question should be who will ***not*** be affected by research in this area. Advances in 6G and IoT are important for U.S. industry leadership and economic competitiveness globally. And to sustain that leadership we need a new generation of trained professionals.

What is unique about WIOT?

Our testbed capabilities are unmatched in North America. Our faculty and researchers can collect data from multiple testbeds to train AI agents using different data, in different environments, and with different characteristics–from an emulated scenario to over-the-air transmissions and city-scale platforms. An AI agent can be trained in one environment and deployed in another to test.



Colosseum
Photo by Matthew Modoono/Northeastern University

Would you describe WIOT's experimental capabilities?

Here are some highlights.

Colosseum is the world's largest emulator of wireless systems. It looks like a supercomputer with 25 racks of equipment and 256 radios that can be programmed to emulate complex wireless systems such as a network in an area of a city, or in a battlefield environment. A unique AI and wireless experimentation rack was added in 2021. Colosseum can mimic in real time tens of thousands of RF channel interactions among hundreds of wireless devices within a square kilometer. The massive data center can process more information in a single second than is estimated to be held in the entire print collection of the Library of Congress.

Allowing researchers to test their ideas virtually before moving to real-world platforms, Colosseum is an enabler for research at scale at the intersection of future wireless systems, software virtualization of systems, applications of AI and wireless, and spectrum sharing. We currently have $7.5 million in grants related to Colosseum. It is used by 60 different research teams and 40 universities. Colosseum was developed by the Defense Advanced Research Projects Agency. DARPA and the National Science Foundation selected Northeastern to be Colosseum's home.

Arena is an open-access wireless testing platform, uniquely enabling sub-6 GHz and 5G spectrum research of transmissions happening over the air. It has 64 indoor antennas on the ceiling that are connected to programmable software-defined radios. The radios are connected to high-performance computing servers. For any of the antennas, researchers can instantiate a 5G, 4G, WiFi, or custom network. It can also be used along with Colosseum for experimentation.

TeraNova is the largest millimeter-wave testbed available in the U.S., and the world's only multi-band THz communication system able to cover 120 GHz, 240 GHz, and 1.1 THz. It is the first to enable data transmissions above 1 THz; the terahertz communications capability was developed by WIOT faculty.

X-Mili is an open, fully programmable research platform funded by the NSF and Northeastern, which serves as a testbed for millimeter-wave transmitters and receivers. It is the first to enable modeling and testing of both the hardware and software components of future wireless networks. The open and programmable architecture also supports software enhancements, such as AI-driven designs, that are important for 5G and 6G development.

Photo by Bella Martinez/Northeastern University

EDUCATING THE NEXT GENERATION

Elena Bernal-Mor, assistant teaching professor of electrical and computer engineering, and faculty member at the Institute for the Wireless Internet of Things, has created next-generation curriculum modules in wireless networking to address workforce development needs in wireless IoT. Additionally, two new master's degrees were offered starting in 2022, including an MS in Internet of Things, and an MS in Wireless and Network Engineering. Students in these master's programs can conduct research and experiential projects at WIOT, benefitting from its unmatched research capabilities and industry partnerships.

PAWR (Platforms for Advanced Wireless Research) is a key program for U.S. leadership in wireless innovation. It is building city-scale testbeds for advanced wireless technologies and digital ecosystems. PAWR is a $100 million public-private partnership of the NSF and an industry consortium of 30 companies. The NSF selected Northeastern's WIOT and nonprofit organization US Ignite as co-directors of the PAWR Project Office. WIOT also provides PAWR technical leadership.

Expeditionary Cyber and Unmanned Aerial Systems Lab is a 150'x200'x60' netted outdoor test area with a flight path to a 50'x50'x22' indoor anechoic chamber for testing unmanned aerial and ground technologies, antennas, and navigation and communications equipment. It is funded by the U.S. Navy Office of Naval Research and is the first of its kind in the U.S.

FCC Spectrum Innovation Zone at Northeastern is the fourth such hub in the U.S. and the first to enable experimentation for wireless communications and sensing technologies above 100 GHz, including a frequency band that is crucial for the development of 6G technologies. It is split between two geographic locations–Northeastern's Boston campus and its Innovation Campus in Burlington, Massachusetts. This rare FCC designation allows experimental testing that is normally not possible. An approval to test on a number of frequency bands can be obtained in days versus months.

Northeastern is one of just four FCC Spectrum Innovation Zones and the only one handling terahertz frequencies. It is split between two geographic locations; Northeastern's Boston and Burlington campuses.

Open6G is a new Department of Defense-supported industry-university cooperative research and development center that looks at the future of open, programmable, and disaggregated 6G systems. An open environment is important to the growth of IoT by enabling different parts of systems from different manufacturers to work together. Open systems also enable software to operate on general-purpose hardware while being programmed to define the functionality in virtual software containers in the cloud or at the network edge.

Learn more about the Institute for the Wireless Internet of Things at **wiot.northeastern.edu**.

Using Sound to Understand the Undersea World

Innovative hydrophone array has potential to revolutionize ocean research

Photos courtesy of Professor Purnima Ratilal-Makris

Purnima Ratilal-Makris, professor
Photo by Matthew Modoono
Northeastern University

How do you track and study leviathans that roam 3,000 miles of open ocean, then dive to 700 feet and swim off in the vast sea?

The answer is with sound. That's why the National Science Foundation recently awarded **Purnima Ratilal-Makris**, professor of electrical and computer engineering, $1.28 million to improve her large-aperture 160-element coherent hydrophone array. Her what?

Simply, the hydrophone array is an insulated electrical cable that stretches the length of two football fields and includes 160 underwater microphones. The device is rolled onto a large spool on the back of a ship, much like a garden hose, so that it can be deployed in oceans anywhere in the world. Because of its power, range, and mobility, her invention has the potential to revolutionize ocean research.

"Our technology is advanced because we developed the entire system in-house, from the sensing array hardware design and fabrication to the array data processing and analysis methods and software," says Ratilal-Makris. "We can continuously optimize and enhance the system."

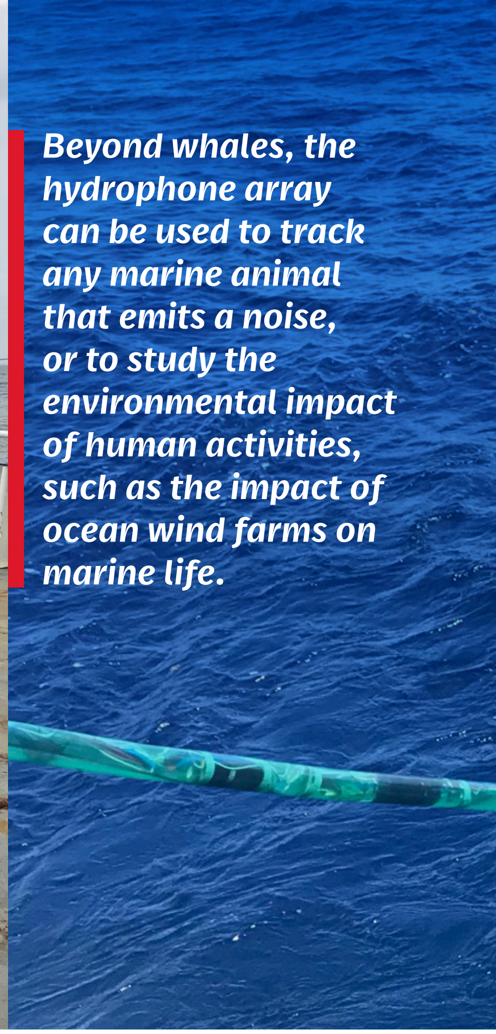
Ratilal-Makris emphasizes that her device is not limited to the study of whales. It can be used to track any marine animal that emits a noise, or to study the environmental impact of human activities, such as the impact of ocean wind farms on marine life. It also has defense applications, such as the tracking of ships and submarines, which is why the project has received significant funding from the Office of Naval Research.

In 2019, Ratilal-Makris won a patent for the device and demonstrated its excellent acoustic performance during an extended sea trial in 2021.

"But while at sea, we also experienced mechanical glitches that required repairs and caused much down-time," she says. "This grant is to improve the mechanics and also refine the software so that scientists will have real-time analysis of enormous amounts of data while at sea."

Those improvements will be made by Ratilal-Makris' team in Northeastern's Laboratory for Ocean Acoustics and Ecosystem Sensing.

The hydrophone array is an insulated electrical cable that stretches the length of two football fields and includes 160 underwater microphones. The device is rolled onto a large spool on the back of a ship, much like a fishing net, so that it can be deployed in oceans anywhere in the world.



Beyond whales, the hydrophone array can be used to track any marine animal that emits a noise, or to study the environmental impact of human activities, such as the impact of ocean wind farms on marine life.

What makes this invention so revolutionary?

Power. It can pick up sounds from whales 100 kilometers away and engine-powered ships 200 kilometers away. During a recent study of eight species of marine mammals, it covered an astonishing 100,000 square kilometers–an area larger than the state of Connecticut.

Range. Unlike other hydrophone arrays, it can detect a wide range of sounds from 20 Hertz to 50 kiloHertz, which means it can detect marine animals from the largest whales to the smallest fish.

Precision. Because it has 160 sensors, it can determine the direction of underwater sounds and pinpoint the exact location of the animals being studied.

Clarity. The numerous sensors create a strong signal and screen out noise from other underwater sources.

Mobility. Most other ocean monitoring hydrophones are single sensors deployed from either floats on the surface of the ocean or are fixed to the sea floor. Because this device is stored on the deck of a ship, it can be deployed anywhere in the ocean and towed to a new location if needed.

Several years ago, an eight-element prototype of the device was used to study cod fisheries in the fjords of Norway. During a two-week voyage in 2006, Ratilal-Makris and her collaborators used an earlier incarnation of the 160-element array hardware, an Office of Naval Research asset and an inspiration for the current system, to study the feeding patterns of eight species of whales and dolphins in the Gulf of Maine. Her findings, published in the prestigious scientific journal ***Nature*** in 2016, were hailed as groundbreaking research. They found that the species hunt in groups and even though all eight feed on the same herring shoals, they establish separate territories and honor the territories of the other species.

In the fall of 2023, the updated version of the device is slated to be used in another large study off the U.S. Northeast coast.

“This is a huge project that has been in development for 13 years,” says Ratilal-Makris. “It is in demand nationally and internationally. It can be used for ecosystem and oceanographic study as well as surveillance and security studies.”

View Research in *Nature*

Wang, D., Garcia, H., Huang, W. et al. Vast assembly of vocal marine mammals from diverse species on fish spawning ground. Nature 531, 366–370 (2016). doi.org/10.1038/nature16960

City-Scale Testbeds to Advance Wireless Research

The next generation of wireless technology has the potential to connect the physical and digital worlds in unimaginable ways. Enabling smart cities and infrastructure, autonomous air and ground vehicles, and reliable, high-speed broadband connectivity in rural and remote areas are just some of the possibilities.

Testing new wireless technologies is critical to advancing their development and sustaining U.S. leadership in the industry and for economic competitiveness. As such, in 2017 the National Science Foundation and an industry consortium of 30 of the nation's leading companies and associations in wireless-related industries launched the Platforms for Advanced Wireless Research as part of a $100 million public-private partnership. PAWR's goal is to find new ways to enable the Internet of Things by building city-scale testbeds for advanced wireless technologies–wireless devices, communication techniques, networks, systems, and services–and digital ecosystems.

The NSF selected Northeastern University and US Ignite, a nonprofit organization, to lead the PAWR Project Office. The PPO is responsible for the vetting, selection, deployment, and management of up to four city-scale testbeds, including disbursing over seven years the nearly $100 million in investments to winning testbed project teams.

"We want to be sure the platforms cover a broad range of wireless technologies," says **Tommaso Melodia**, William Lincoln Smith Professor of electrical and computer engineering, principal investigator, and director of research for the PPO, "that each one is unique, that they are designed to enable groundbreaking research, and that they can operate in conjunction with one another."

Northeastern is also the academic lead of PAWR, and the PPO functions within the university's Institute for the Wireless Internet of Things, led by Melodia and including several electrical and computer engineering faculty. Since its inception, PAWR has enabled the development of four city-scale testbed platforms, three fully operational as of 2022.

Kaushik Chowdhury, professor of electrical and computer engineering, who serves as academic outreach director for the PPO, explains, "There's waste in replication at different, smaller test sites. Here is something at scale, spanning an entire community of deployed base stations, or drones that fly over large fields, or communication over kilometers with new kinds of technologies. These are the sorts of experiments that PAWR enables. And it's really become a national resource for advancing the future of wireless."

Melodia adds, "PAWR is enabling innovations to be tested in diverse real-world applications, within different types of communities and by a variety of users, from businesses of all sizes and across industries, to schools and the public–accelerating not only development of next-gen technologies but also industry standards."

"We want to be sure the platforms cover a broad range of wireless technologies, that each one is unique, that they are designed to enable groundbreaking research, and that they can operate in conjunction with one another."

Tommaso Melodia
William Lincoln Smith Professor
of Electrical and Computer Engineering
Director, Institute for the Wireless Internet of Things
Co-director, PAWR Project Office

Photo by Matthew modoono/Northeastern University

Platforms for Advanced Wireless Research (PAWR) Testing Platforms

FOR MORE INFORMATION

POWDER-RENEW: Platform for Open Wireless Data-driven Experimental Research with Massive Multi-Input Multi-Output (MIMO) Capabilities

Salt Lake City, Utah

Automatic spectrum sharing and massive multi-input multi-output

POWDER-RENEW is being used to develop an automatic spectrum sharing management system to share the electromagnetic spectrum between experimental systems and existing users, and between multiple experimental systems. It is also developing a highly programmable and flexible massive multi-input multi-output (MIMO) platform.

COSMOS: Cloud Enhanced Open Software Defined Mobile Wireless Testbed for City-Scale Deployment

West Harlem, New York

Millimeter wave radio communications and dynamic optical switching

COSMOS enables experimentation in the sub-6 GHz bands and in the millimeter wave frequency bands in a densely populated, urban setting. It focuses on ultra-high-bandwidth and low-latency wireless communications, with tightly coupled edge computing.

AERPAW: Aerial Experimentation and Research Platform for Advanced Wireless

Raleigh, North Carolina

Unmanned aerial vehicles and mobility

AERPAW is a first-of-its-kind aerial wireless experimentation platform built to accelerate the integration of unmanned aerial vehicles into the national airspace, and to enable new advanced wireless features for unmanned aerial system platforms.

ARA: Wireless Living Lab for Smart and Connected Rural Communities

Ames, Iowa

Rural broadband and agriculture technology

ARA will feature a wide range of wireless technologies as well as a deeply programmable infrastructure including services that directly benefit precision agriculture in both crop and livestock farms. ARA's combination of wireless access networks, long-distance, high-throughput links and low-earth-orbit satellite networks will allow field-testing and research of new wireless technologies, while also providing experimental broadband access to homes, schools, and offices.

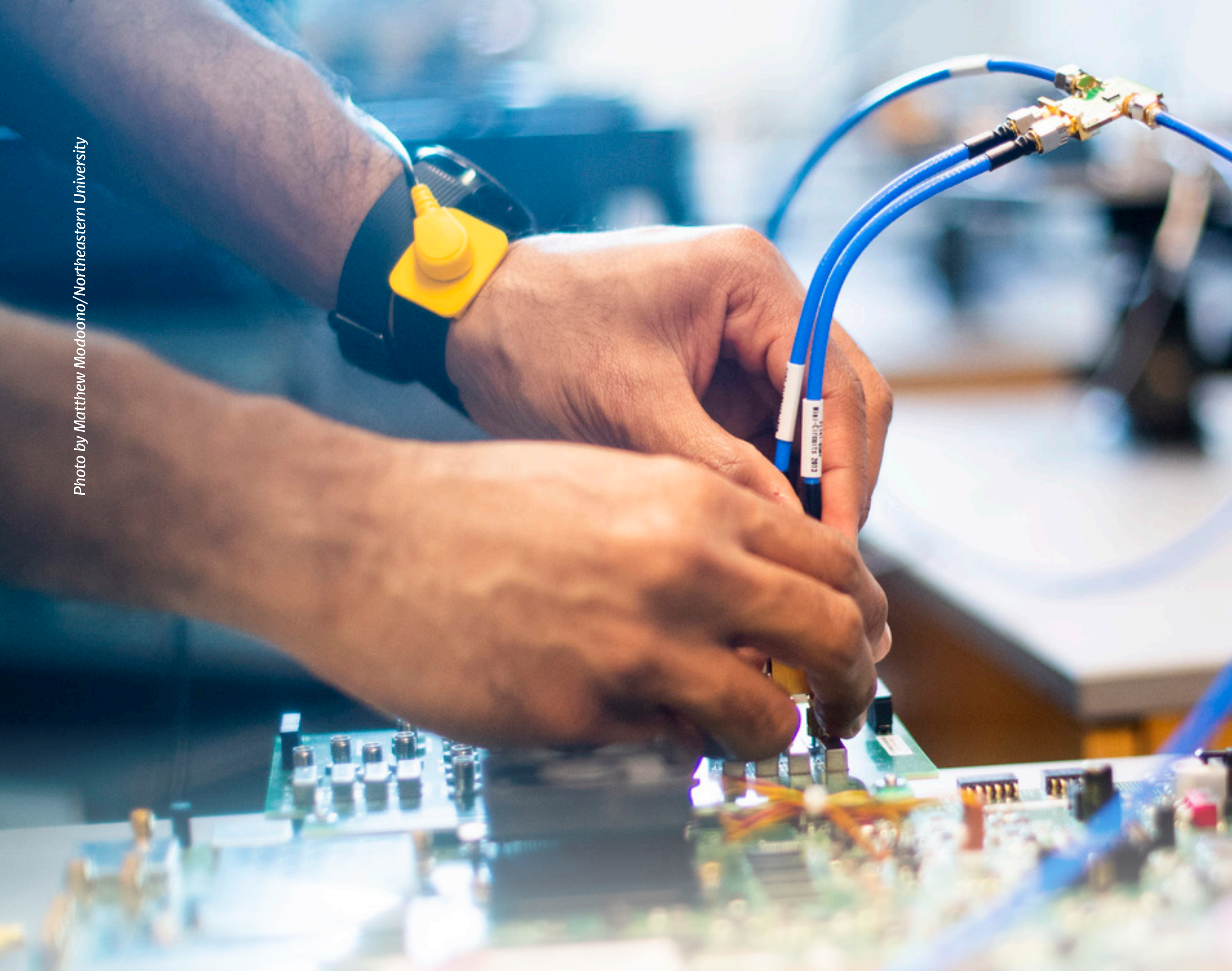


Photo by Matthew Modoono/Northeastern University

Spectrum Sharing Demonstrated for the First Time in Terahertz Band

Wireless devices such as the common smartphone rely on a natural resource to function: the electromagnetic spectrum. And the EM spectrum, like many natural resources, is finite. The growing number of devices demanding bandwidth to connect at high speeds will eventually require more spectrum resources. Where will those resources be found?

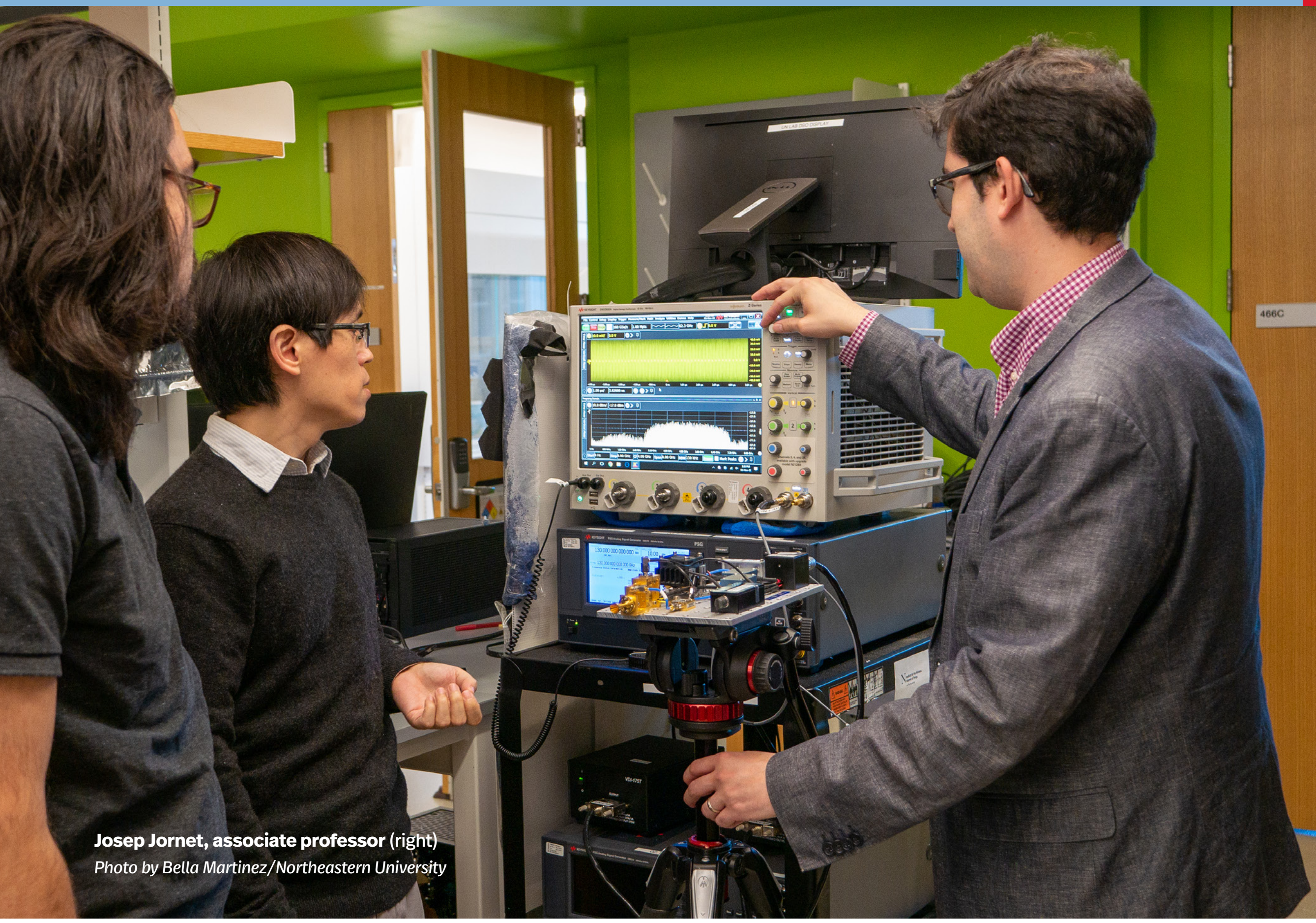
“In the terahertz band,” answers **Josep Jornet**, associate professor of electrical and computer engineering (ECE) and a member of Northeastern’s Institute for the Wireless Internet of Things (WIOT).

The terahertz band resides between the millimeter-wave and infrared regions of the EM spectrum, roughly from 100 gigahertz to 10 terahertz. This largely vacant swath of frequencies, along with next-generation hardware and network protocols, will form a vital component of 6G wireless technology according to Jornet.

A challenge, however, is that the terahertz spectrum is not entirely unpopulated. For over 20 years, stakeholders like NASA have carved out slices of it for use in high-precision sensing scenarios like radio astronomy and atmospheric study by satellites. They see the potential for conflict with their sensitive systems if terahertz communication becomes commercially widespread.

In 2020, Northeastern became a member of the International Telecommunications Union, the U.N. agency that ensures global cooperation in the use of radio technology. With a seat at this table, Northeastern ECE/WIOT faculty have helped craft proposals that open the door to robust terahertz research.

The spectrum sharing system can seamlessly shift between two different frequencies in real-time to avoid interfering with scientific users who need to use the terahertz band for their research.



Josep Jornet, associate professor (right)
Photo by Bella Martinez/Northeastern University

Jornet joined with other ECE/WIOT researchers, including Principal Research Scientist **Michele Polese**, William Lincoln Smith Professor **Tommaso Melodia**, Assistant Professor **Francesco Restuccia**, and Associate Research Scientist **Viduneth Ariyarathna**, to explore a strategy for the coexistence of active and passive users of the terahertz spectrum through time sharing. They were aided by researchers from NASA's Jet Propulsion Laboratory in collaboration with the National Science Foundation Spectrum Innovation Initiative, the Air Force Research Lab, and the Office of Naval Research. They developed and tested a radio solution that operates in two frequency bands. When the radio detects a satellite orbiting over the area of the deployed wireless link, it automatically switches to a different frequency, and then switches back to the original when the satellite is safely out of range.

The results, published in ***Nature Communications Engineering***, report the first spectrum-sharing system in the spectrum above 100 GHz with experimental results. The experiment was conducted at Northeastern University, which is an FCC Spectrum Innovation Zone—one of only four in the U.S. and the only one to enable experimentation for wireless communications and sensing technologies above 100 gigahertz. While developing the prototype, the researchers addressed challenges from the design of the radio transmitter and receivers for the dual-band setup, to the dynamic control and integration of multiple systems that were not designed to work together.

View Research in *Nature Communications Engineering*

Polese, M., Ariyarathna, V., Sen, P., Siles, J., Restuccia, F., Melodia, T., and Jornet, J. Dynamic spectrum sharing between active and passive users above 100 GHz. Nature Commun Eng 1, 6 (2022).

Paving the Way for Consumer Bandwidth-Intensive Applications

X-Mili is the first testbed connecting the mmWave band with an open, programmable ecosystem

Advances in wireless communications have the potential to improve billions of people's lives with applications ranging from autonomous vehicles to virtual reality, telepresence, and more. So, what is needed to further development of these applications? Robust communication over next-gen networks.

"5G and 6G networks hold incredible promise for enabling faster data transfers, up to 20 times faster than the previous generation of 4G/LTE," explains **Dimitrios Koutsonikolas**, associate professor of electrical and computer engineering. "However, that requires robust communication in the 28 and 39 gigahertz spectrum bands, as well as at even higher frequencies. Current-generation transmitters and receivers lack the capability to support uninterrupted, reliable communication at these frequencies, which are short-range and easily blocked by human bodies and other obstacles; this represents a significant challenge to the broad adoption of 5G and 6G."

To help meet this challenge, the National Science Foundation and Northeastern University awarded Koutsonikolas $3 million in 2021 to support research aimed at increasing communication speed and improving communication robustness in millimeter-wave frequency bands—those between 30 and 300 GHz. Koutsonikolas and his colleagues are developing an open, programmable research platform called X-Mili that serves as a testbed for millimeter-wave transmitters and receivers.

X-Mili is the first to enable modeling and testing of both the hardware and software components of future wireless networks, which will drive system-level innovation. Not only can hardware such as router and antenna technologies be tested, but the open and programmable architecture also supports software enhancements, such as novel AI-driven designs, that will result in leapfrog performance improvements for next-generation wireless networks.

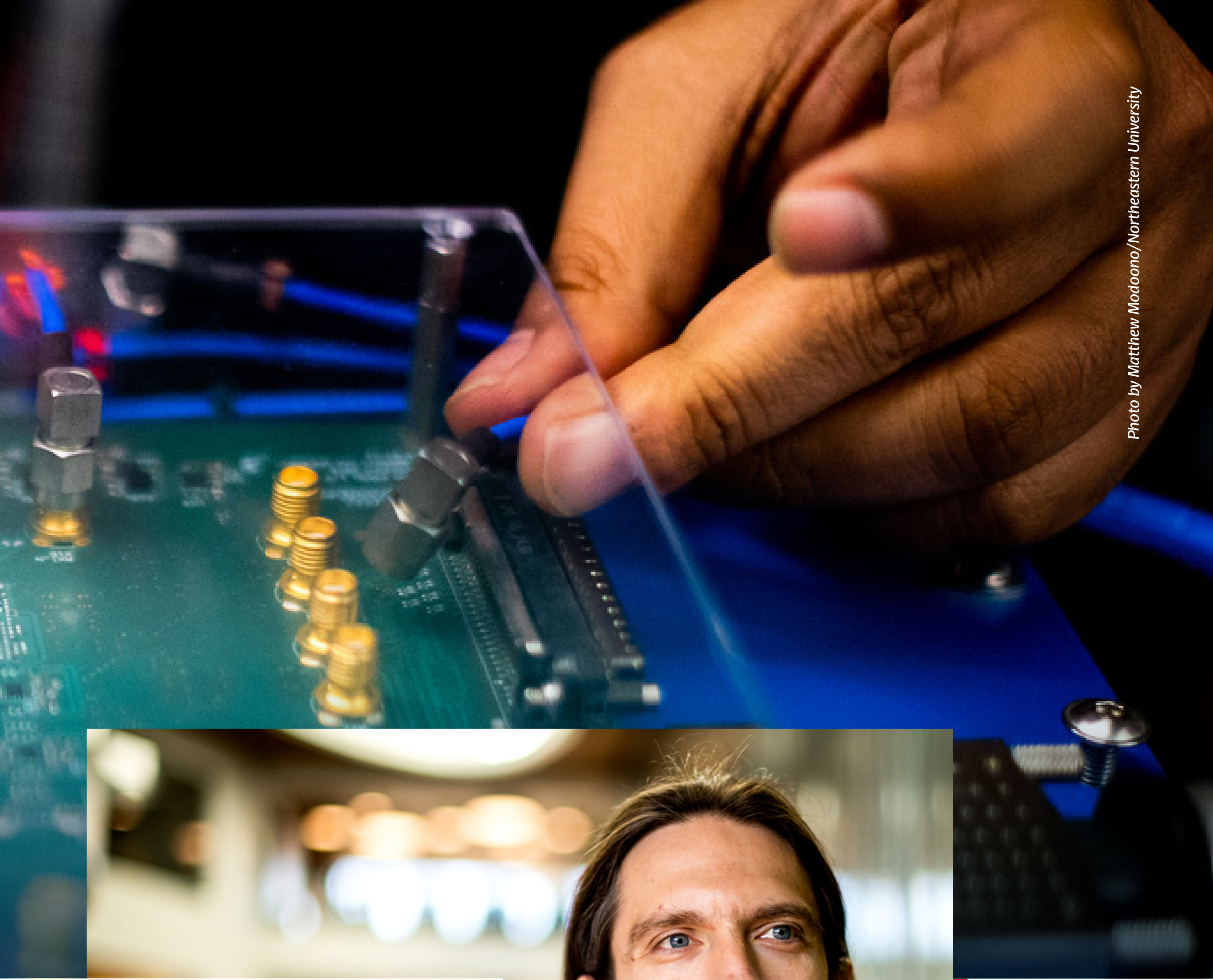


Photo by Matthew Modoono/Northeastern University

Photo by Matthew Modoono/Northeastern University

“5G and 6G networks hold incredible promise for enabling faster data transfers, up to 20 times faster than the previous generation of 4G/LTE.”

Dimitrios Koutsonikolas
Associate Professor
of Electrical and Computer Engineering

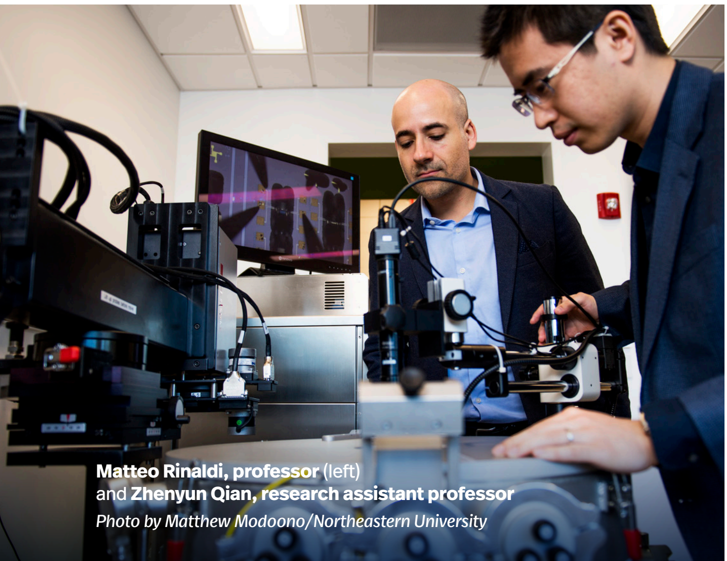
The testbed consists of eight separate nodes around Northeastern’s Boston campus, serving as cellular base stations, or Wi-Fi access points. Uniquely, it relies primarily on software to test Wi-Fi and cellular capabilities, a departure from the hardware-dependent platforms used by today’s carriers. “One big part of the movement from 5G to 6G is the movement from hardware to software infrastructure,” says Koutsonikolas.

In addition, X-Mili will enable other wireless research teams to test their ideas for improving millimeter-wave communications, networking, and sensing. All measurement data generated during the Northeastern team’s development phase, as well as data contributed by research groups using the platform, is made publicly available, leading to the rapid commercialization of 5G- and 6G-compatible solutions.

Co-investigators on the project include Professor **Stefano Basagni**, Associate Professor **Josep Jornet**, and William Lincoln Smith Professor **Tommaso Melodia**, as well as Principal Research Scientist **Michele Polese** as senior personnel, all from Northeastern’s Department of Electrical and Computer Engineering and the Institute for the Wireless Internet of Things.

Dormant but Always-Alert Sensors to Power the 'IoT Grid'

When stationed in dangerous, rural areas, the last thing soldiers should worry about is replacing a dead battery. That's one reason why in 2017 the Defense Advanced Research Projects Agency awarded **Matteo Rinaldi**, professor of electrical and computer engineering, a grant to develop devices that use virtually no power at all.



Matteo Rinaldi, professor (left) and **Zhenyun Qian, research assistant professor**
Photo by Matthew Modoono/Northeastern University

Rinaldi, who is also director of the Northeastern SMART research center, and his research team, designed a new type of sensor that consumes no power in standby mode. When the sensor recognizes a specific infrared wavelength signature, it uses the tiny amount of power contained in the infrared radiation to wake itself, significantly extending battery life for years.

The discovery, which addresses a key challenge posed by the Internet of Things revolution on how to power and maintain the rapidly increasing connected devices worldwide, was published in ***Nature Nanotechnology***. Since then, this zero-power sensor technology has been patented and applied to many other applications. With funding from the Bill & Melinda Gates Foundation, Rinaldi and his team developed a sensor for monitoring agricultural crop health. When plants are infected by a disease, struggling to find water, or attacked by pests, they produce volatile organic chemicals. Those chemicals are used to trigger a chemical reaction in the sensor, which acts like a switch, turning on a circuit to connect the system to an otherwise unused battery. The device can then use battery power to wirelessly broadcast a signal to alert the farmer that there is a problem.

"When the chemical is not present, the sensor will consume absolutely zero power," says **Zhenyun Qian**, research assistant professor of electrical and computer engineering. "Only when the chemical is released by the plant it is near will the device be activated. Since the device doesn't require power until it is activated, it can remain on standby until the end of the battery's natural lifetime, which could be as long as a decade."

In the same agriculture sector, the technology was transformed into a low-power crop water stress sensor that exploits the sunlight transmitted through a plant leaf in the short-wave infrared spectral band for long-term monitoring of water stress and sensor-automated irrigation. This research was supported by the ARPA-E OPEN 2018 program.

In addition, with a grant from the National Science Foundation, the same concept was used to develop a flame sensor for fire monitoring. This time, the sensor was designed to selectively harvest energy from specific infrared signatures that hydrocarbon flames release, and use it to activate a wireless transmitter to communicate the time and the location of the detected fire accident. Numerous other applications are also possible. Most recently, the technology is being applied to people presence detection for smart home, building automation, and security applications with research and development funding supported by the Department of Homeland Security and Northeastern University.

“We can now make passive wireless devices that are smart enough to turn on only when there is a need… This enables the deployment of persistent and ubiquitous wireless monitoring systems in any environment and at a low cost.”

Matteo Rinaldi
Professor of Electrical and Computer Engineering

Photo by Matthew Modoono/Northeastern University

Additionally, a Northeastern University spin-out, Zepsor Technologies, Inc., is currently licensing the technology to develop and market zero-power infrared sensor products for touchless interface.

“We can now make passive wireless devices that are smart enough to turn on only when there is a need,” Rinaldi says. “This approach completely eliminates the standby power consumption by the sensor, extending the battery lifetime from days to years, which ultimately eliminates the need for battery replacement and enables the deployment of persistent and ubiquitous wireless monitoring systems in any environment and at a low cost.”

View Journal Paper in *Nature Nanotechnology*

Qian, Z., Kang, S., Rajaram, V. *et al.* Zero-power infrared digitizers based on plasmonically enhanced micromechanical photoswitches. *Nature Nanotech* 12, 969–973 (2017).

Sound Waves: The Next Frontier of Wireless, Implantable Medical Devices

Since the first cardiac pacemaker in the 1950s, implantable medical devices have grown steadily more sophisticated and powerful, yet technical challenges remain. The devices rely on electromagnetic radio waves to operate. These radio waves are largely absorbed by water, and the human body is between 60 and 70 percent water. As a result, when two portions of a pacemaker need to communicate with each other, signals must be transmitted via wire leads, which can become infected or break. They are also energy inefficient, so patients must periodically undergo additional surgeries for battery replacements.

While more modern implantable devices often use microwave-based wireless technologies like Bluetooth or WiFi, these too are not without drawbacks. Continuous real-time monitoring functions, for example, rapidly deplete the power of implanted batteries.

For years, **Tommaso Melodia**, William Lincoln Smith Professor of electrical and computer engineering, wondered if sound waves–which easily propagate through water and human tissues–were the solution to these problems. A research grant from the National Science Foundation gave him the opportunity to test the idea.

“We’re using ultrasonic waves–frequencies that cannot be heard–to carry information between different implantable medical devices,” says Melodia. The pacemaker being developed by his research group is comprised of multiple implants, each smaller than a dime, that nestle within the different chambers of the heart and maintain its rhythm through synchronized, invisibly pulsing ribbons of sound. No wire leads are required, and a tiny battery, rechargeable by sound waves from the outside world, sits under the skin. Ultrasonic-pacemaker patients would also be less vulnerable to hackers attempting to interfere with radio signals, Melodia points out. With ultrasonic implantable devices, he says, “[hackers] have to at least touch the person–and chances are you’d notice if someone was touching you–so it’s an additional layer of security.”

Expanding ultrasonic applications

Melodia, together with partners Emrecan Demirors and Jorge Jimenez, founded a spinoff company, Bionet Sonar, to develop the technology that he believes could one day treat a broad range of ailments, including diabetes, epilepsy, and Parkinson’s disease, as well as heart conditions.

Diabetics could someday benefit from a wirelessly controlled “artificial pancreas” entirely within the body. An implanted glucose-measuring sensor would continuously send signals to an internal pump that would, in turn, deliver the exact dose of insulin required by the patient.

People with certain neurological conditions could use this technology as well. For instance, Melodia is working to develop a tiny chip embedded within brain tissue that could predict incoming seizures and send signals to a second device that could counteract the seizure with carefully calibrated neurostimulation. And he partnered with a neurosurgeon to investigate the possibility of creating lead-less, battery-less deep-brain stimulation to treat tremors in people with Parkinson’s disease.

Melodia and his colleagues have received several patents for systems that use ultrasound to transmit signals through biological tissue, both for power and data transfer, and even to form networks of devices worn on or implanted in the body.

Jennifer Rodowicz, MS in electrical and computer engineering, studies the effect of the Internet of Things on smart medical implants focused on optimizing the path of communication signals through human tissue.

Photo (top) by College of Engineering/Northeastern University

Photos (bottom) by Ruby Wallau/Northeastern University

The technology uses ultrasonic waves—frequencies that cannot be heard—to carry information between different implantable medical devices. No wire leads are required, and a tiny battery, rechargeable by sound waves from the outside world, sits under the skin.

First-of-Its-Kind Expeditionary Cyber and Unmanned Aerial Systems Lab

Researchers at Northeastern University continue to push the frontiers of unmanned aerial systems and cybersecurity research with a unique asset at their disposal: the Expeditionary Cyber and Unmanned Aerial Systems Research and Development Facility (UAS Lab) at the university's Innovation Campus in Burlington, Massachusetts.

A 150'x200'x60' outdoor test cage with a flight path to a 50'x50'x22' indoor anechoic chamber, the UAS Lab, funded by the U.S. Navy Office of Naval Research, is the first of its kind in the United States. It is designed for military and business leaders to partner with the university in cybersecurity testing on drones. In 2019, the Air Force Life Cycle Management Center provided a $2.8 million grant to fund research through its unit at nearby Hanscom Air Force Base.

The walls, floor, and ceiling of the radio-silent drone testing facility are lined with hundreds of blue protruding arrowheads, made of foam, which are designed to absorb radio frequency waves. They transform the square room into an anechoic chamber for researching defenses against potential drone attacks. The facility is also encased with a Faraday cage of conducting material that creates an electromagnetic shield.

The indoor facility is connected to a netted enclosure outdoors that is large enough for GPS testing. Drones can be navigated in and out between the two areas for seamless exercises in all conditions. Additionally, sophisticated equipment enables researchers to understand expeditionary cyber, including handling electromagnetics and cyber over a very large frequency range; effects on navigation; and effects on global positioning signals, and how those can be corrupted at the expeditionary edge.

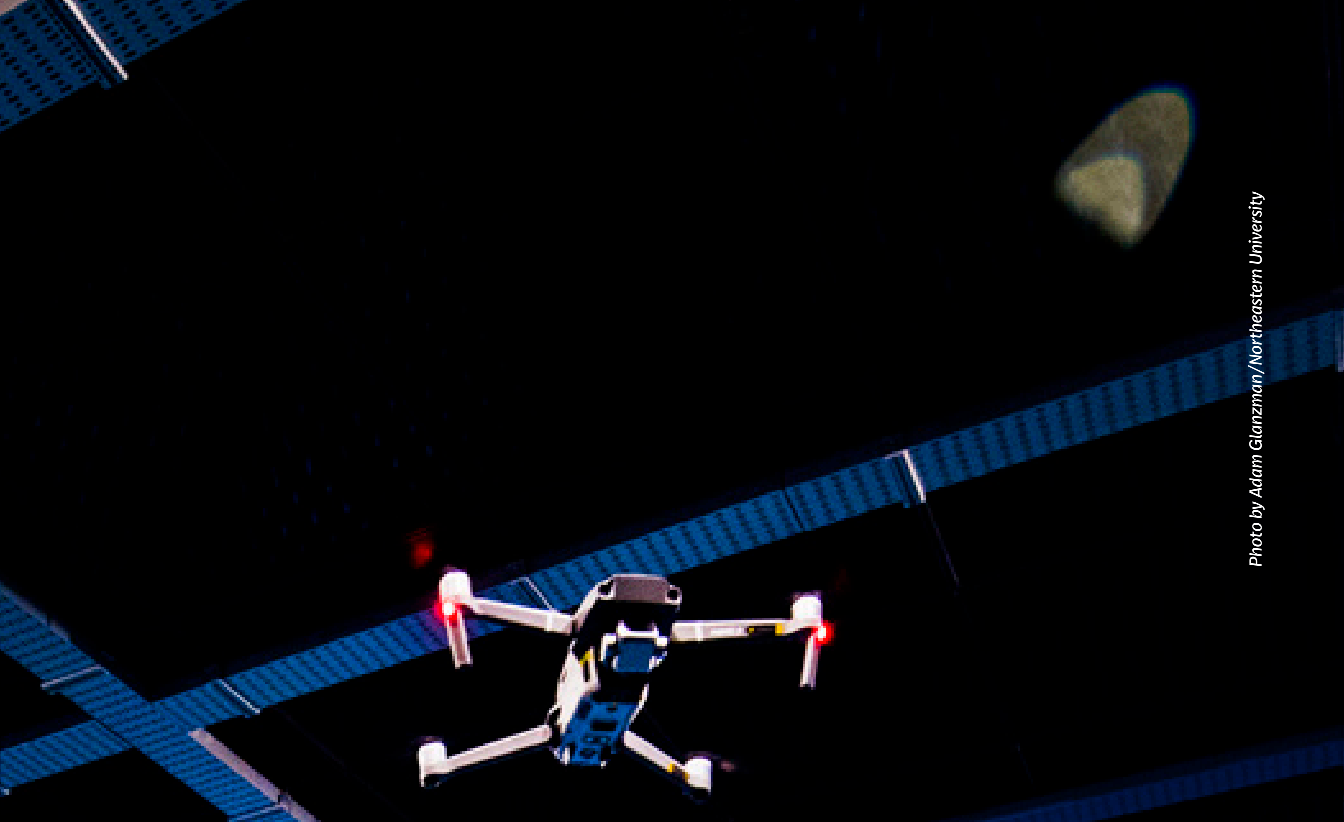


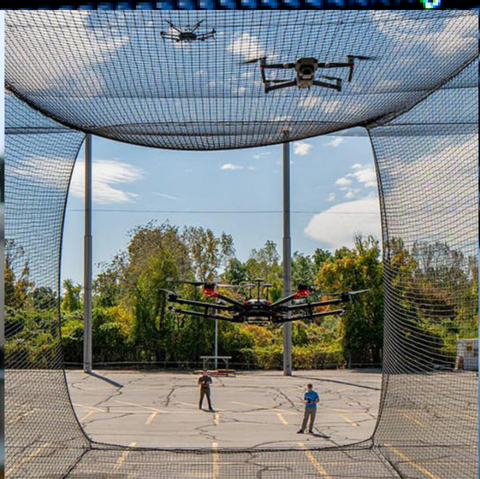
Photo by Adam Glanzman/Northeastern University

Tommaso Melodia, William Lincoln Smith Professor of electrical and computer engineering, and director of the Institute for the Wireless Internet of Things, says, “As a user of the UAS Lab, my work is at the intersection of autonomous robotic drones and connectivity; how these drones are connected with each other so they can exchange information.”

“We’re working on new technologies to connect drones that operate at a high-frequency rate–specifically 60 GHz–that’s known as millimeter-wave communications, one of the foundational technologies for 5G and beyond,” Melodia continues. “What this facility enables us to do is fly drones of different sizes that carry payloads, like millimeter-wave radios, and test their performance.”

Kaushik Chowdhury, professor of electrical and computer engineering, also uses the facility for his research. “We have done plenty of experiments with drones inside that anechoic chamber,” he says. “Signals that are transmitted don’t leak out of that space, and it’s not interfered with by external signals. I can transmit at any frequency I like without being worried about the Federal Communications Commission knocking on my door.”

Among the applications that Melodia and his team are working on are creating an on-demand mobile network of drones to provide additional wireless connectivity in specific locations when needed. They are also looking at using drones to provide connectivity in disaster scenarios. For example, in catastrophic hurricanes where entire wireless networks are wiped out, a network of drones could provide temporary connectivity to help locate survivors or provide disaster relief.



LEFT: **Sara Garcia-Sanchez**, PhD student, electrical and computer engineering, won the Best Paper Award at the International Workshop on Drone Assisted Wireless Communications for 5G and Beyond, co-located with ACM MobiCom, for her paper “Camera-enabled Joint Robotic-Communication Paradigm for UAVs Mounted with mmWave Radios.” RIGHT: The UAS Lab at Northeastern has a 150’x200’x60’ outdoor test cage with a flight path to a 50’x50’x22’ indoor anechoic chamber with a Faraday cage to create defenses against potential drone attacks. Sophisticated equipment also enables researchers to understand expeditionary cyber.

Jumpstarting Beyond-5G Systems with New Open6G DoD Research Center

The number of Internet of Things (IoT) devices worldwide is forecast to almost triple from 9.7 billion in 2020 to more than 29 billion in 2030, according to Statista. Creating an open architecture, whereby parts of systems from different manufacturers work together, and software can be programmed to operate on general purpose hardware, is important to create a ubiquitous IoT of tomorrow.

Open6G–a new federal-industry-university cooperative research center focused on future open, programmable, and disaggregated 6G systems–has been established by the Department of Defense to address this challenge. The technical effort of Open6G is based at Northeastern University's Institute for the Wireless Internet of Things (WIOT).

"The 6G-oriented research, development, test, and evaluation infrastructure developed by Open6G with federal and industry partner support will constitute a key element of North American leadership in future 'Next G' technologies."

Sumit Roy
Former Program Director for Innovate Beyond 5G at the Office of the Undersecretary of Defense, Research and Engineering

A research, development, testing, and commercialization hub, Open6G will develop a common reference architecture and open-source software for 6G based on the 3rd Generation Partnership Project (3GPP) standards and open radio access network (O-RAN) specifications, via public releases of the OpenAirInterface Software Alliance (OSA) stack. The center will explore themes such as future spectrum access and exploitation, performance of O-RAN architectures, artificial intelligence/machine learning for inference and control, millimeter-wave and terahertz systems, digital twins, augmented and virtual reality, and Web 3.0, among others.

Open6G will also provide testbed-as-a-service capabilities to its partners through state-of-the-art infrastructure and unique test facilities. The new 4,600-square-foot Open6G facility at Northeastern's Innovation Campus in Burlington, Massachusetts, is co-located with Colosseum, the world's largest radio frequency channel emulator; a massive AI computing capability; and one of the world's largest anechoic chambers. Additionally, Open6G will be supported by WIOT's unique capabilities such as Arena, X-Mili, and TeraNova. Examples of industry partners and collaborators of WIOT who are active in the wireless, defense, computing, and manufacturing industries include A5G Networks, AiRANACULUS, AMD, ANDRO Computational Solutions, AT&T, Bionet Sonar, Dell Technologies, InterDigital, Keysight Technologies, MathWorks, Mavenir, MITRE, Nexcepta, NI (formerly National Instruments), NVIDIA, Qualcomm Inc., Raytheon Technologies, Red Hat, US Ignite, and VIAVI.

"Open6G will offer the expertise of Northeastern faculty, researchers, and students to create partnerships that will shape the future of our connected world," says **Tommaso Melodia**, WIOT's director and William Lincoln Smith Professor of electrical and computer engineering. "We will work with our partners in academia, industry, and government to consolidate the role of Open6G as a leading national resource for next-generation wireless systems, their applications, and their societal impact."

Sumit Roy, former program director for Innovate Beyond 5G at the Office of the Undersecretary of Defense, Research and Engineering, notes, "The 6G-oriented research, development, test, and evaluation infrastructure developed by Open6G with federal and industry partner support will constitute a key element of North American leadership in future 'Next G' technologies."

For more information, visit: **open6g.wiot.northeastern.edu**

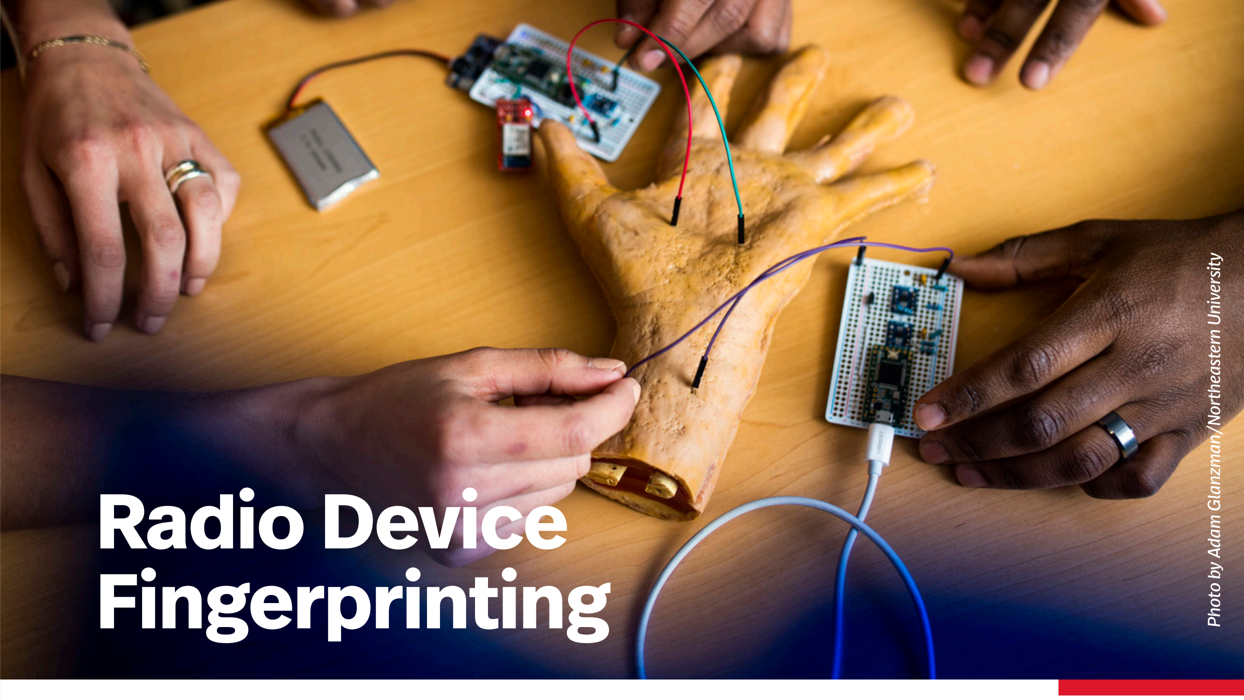


Photo by Adam Glanzman/Northeastern University

Radio Device Fingerprinting

Machine learning algorithms make signal identification practical on a massive scale

Every wirelessly connected device in the global wireless Internet of Things communicates via radio transmitters and receivers. Even when multiple devices are transmitting the same information, each device imprints its own unique signal pattern on the transmission that makes it possible to identify individual smartphones or laptops.

"Due to manufacturing variances, each electronic device has minor hardware differences in its processing chain, which makes it slightly different from every other device," explains **Kaushik Chowdhury**, professor of electrical and computer engineering. "You can think of these distinct characteristics as a fingerprint. By studying the unique distortions within a received radio signal, you can identify which device is sending it."

Identifying the source of a signal has important implications for both cybersecurity and emergency preparedness. By impersonating the signal of an authorized device, cyber terrorists could disrupt the safe operation of an airplane or access critical national security data. In the realm of emergency preparedness, rapidly identifying nearby devices could aid in alerting emergency responders, saving crucial seconds and, potentially, human lives.

Based on these and other important implications of device fingerprinting, the U.S. Defense Advanced Research Projects Agency (DARPA) awarded Chowdhury $1.5 million to optimize the capability. He and an interdisciplinary team are applying machine-learning algorithms to make signal identification practical on a massive scale.

Chowdhury is joined by electrical and computer engineering faculty members Associate Professor **Stratis Ioannidis**, William Lincoln Smith Professor **Tommaso Melodia**, and Professor **Jennifer Dy**. While Chowdhury and Melodia focus research on wireless networks and communications, Ioannidis and Dy have expertise in signal processing. Their shared goal is to adapt machine-learning techniques such as deep convolutional neural networks—which are already proven for image recognition—into the domain of wireless signal pattern recognition.

The team is leveraging the DARPA funding to develop new methodologies and machine-learning architectures that can correctly classify 10,000 devices with an accuracy rate of 99%. The researchers are using a 14-terabyte database of radio transmitters and radio frequency signals collected by DARPA across different wireless channels to demonstrate the robust operation of their innovative new methods.

Identifying the source of a radio signal has important implications for both cybersecurity and emergency preparedness. Researchers are applying machine-learning algorithms to make signal identification practical on a massive scale.

"Northeastern has worked hard to develop leading expertise in the Internet of Things, recognizing the huge importance of the IoT to society, industry, and the military," says Chowdhury. "It's gratifying to see all this expertise coming together to solve a practical problem and achieve a common goal."

News Bytes Selected Highlights

Young Investigator Awards for Advancing Future Data-driven Wireless Systems and 6G Spectrum Dominance

Francesco Restuccia, assistant professor of electrical and computer engineering, was awarded an Air Force Office of Scientific Research Young Investigator Program Award to establish the theoretical foundations of next-generation dynamic data-driven wireless systems. The research focuses on optimizing wireless networks for edge-based and edge-assisted artificial intelligence tasks like object recognition. Restuccia also received an Office of Naval Research Young Investigator Program Award for exploring the concept of dynamic neural networks to enable real-time, autonomous modification of communication networks based on user and device needs. This convergence of computation and communication in 6G networks is critical for next-generation applications such as real-time telepresence and the metaverse.

ONR Young Investigator Award to Develop THz System-on-a-Chip

Xufeng Zhang, assistant professor of electrical and computer engineering, received an Office of Naval Research Young Investigator Program Award for “Cryogenically Enabled Ultrabroadband THz System-on-a-Chip.” He is applying advancements in silicon photonics, superconducting devices, and terahertz (THz) instrumentation to develop a novel THz system-on-a-chip (SOC). With comprehensive on-chip signal processing capabilities, including THz generation, routing, manipulation, and detection, Zhang’s SOC will be suitable for a broad range of applications, including quantum networks and wireless communication for 6G and 7G networks.

NSF CAREER Award to Use Ultra-low Power Analog Computing Circuits to Develop Machine Learning Hardware for Biomedical Devices

Aatmesh Shrivastava, assistant professor of electrical and computer engineering, received a $500,000 National Science Foundation CAREER Award for “An Ultra-low Power Analog Computing Hardware Design Framework for Machine Learning Inference in Edge Biomedical Devices.” He is developing ultra-low power machine learning system-on-chip hardware with inference capability for wearable and implantable biomedical applications. Using analog rather than digital computing, the chip will be 5 to 10 times smaller (millimeters vs. centimeters in size) and use 5 to 50 times less power.

$2.1M DOE Award for Greenhouse Gas Sensor Technology on Drones

Matteo Rinaldi, professor of electrical and computer engineering, who is also director of the Northeastern SMART Center, received a $2.1 million award from the Department of Energy Advanced Research Projects Agency-Energy for "High-Performance and Miniaturized Greenhouse Gas Sensor for Drone-based Remote Sensing." He will develop a palm-sized sensor that can be affixed to drones to scan acres of land faster, cheaper, more accurately, and with less power using pioneering zero-power smart sensor technology, allowing farmers to detect harmful nitrous oxide emissions on their land.

$1.8M for Research on AI in Next-Generation Edge Networks

Northeastern is part of a team led by the Ohio State University that was awarded $20 million for the National Science Foundation AI Institute for Future Edge Networks and Distributed Intelligence (AI-EDGE). Northeastern is responsible for $1.8 million led by electrical and computer engineering faculty, including Professor **Kaushik Chowdhury** (PI), and co-PIs William Lincoln Smith Professor **Tommaso Melodia** and Associate Professor **Stratis Ioannidis**. AI-EDGE will leverage the synergies between networking and AI to design future generations of wireless edge networks that are highly efficient, reliable, robust, and secure, and facilitate solving longstanding distributed AI challenges.

$1M NSF Award to Create Resilient, Energy Efficient, and Secure IoT Networks

Associate Professor **Marvin Onabajo**, Professor **Yunsi Fei**, Assistant Professor **Aatmesh Shrivastava**, and Assistant Professor **Francesco Restuccia** of the Department of Electrical and Computer Engineering, were awarded $1 million from the National Science Foundation for "RINGS: Internet of Things Resilience through Spectrum-Agile Circuits, Learning-Based Communications and Thermal Hardware Security." They will create spectrum agile IoT networks with low-power adaptive radio frequency (RF) circuits at the sensor nodes, and with coordinated optimization and enhanced security at the edge device.

Self-Powered Sensorial 'Skin' the Future of Motion and Gesture Recognition

Groundbreaking research on flexible photodetectors with computational powers by **Canek Fuentes-Hernandez**, associate professor of electrical and computer engineering, and Dean of the College of Engineering **Gregory D. Abowd**, has been published in the Nature journal ***npj Flexible Electronics***. The paper, titled "Flexible Computational Photodetectors for Self-Powered Activity Sensing," describes a new approach to achieve motion and gesture recognition using arrays of thin and flexible organic photodetectors distributed in space.

Photo by damian israel shiner/Northeastern University

ISEC

Northeastern's Interdisciplinary Science and Engineering Complex is a six-story, 230,000 sq. ft. hub for collaborative research. With state-of-the-art facilities, it brings together industry leaders, federal agencies, and scholars from around the world.

Northeastern University
College of Engineering

With over 215 tenured/tenure-track faculty and 18 multidisciplinary research centers and institutes with funding by eight federal agencies, the College of Engineering is a leader in experiential education and interdisciplinary research focused on discovering solutions to global challenges to benefit society.

About Northeastern University

Founded in 1898, Northeastern is a global research university and the recognized leader in experiential lifelong learning. Our approach of integrating real-world experience with education, research, and innovation empowers our students, faculty, alumni, and partners to create worldwide impact.

Northeastern’s personalized, experiential undergraduate and graduate programs lead to degrees through the doctorate in 10 colleges and schools across our 14 campuses worldwide. Learning emphasizes the intersection of data, technology, and human literacies, uniquely preparing graduates for careers of the future and lives of fulfillment and accomplishment.

Our research enterprise, with an R1 Carnegie classification, is solutions oriented and spans the world. Our faculty scholars and students work in teams that cross not just disciplines, but also sectors–aligned around solving today’s highly interconnected global challenges and focused on transformative impact for humankind.

Northeastern University
College of Engineering

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About the Cover

Kaushik Chowdhury, professor of electrical and computer engineering, equips an unmanned aerial vehicle with a millimeter-wave radio device (the white box beneath the UAV) operating in the 60 GHz spectrum. Millimeter wave technology offers high data rates, wide bandwidths, and low latency. Chowdhury's research pushes the envelope further for flexible, UAV-mounted base stations that could provide temporary connectivity in areas affected by disasters that knock out communications infrastructure. *See pages 18-19 for more information.*

Photo by Ruby Wallau/Northeastern University

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