Data REINFORCEMENTS

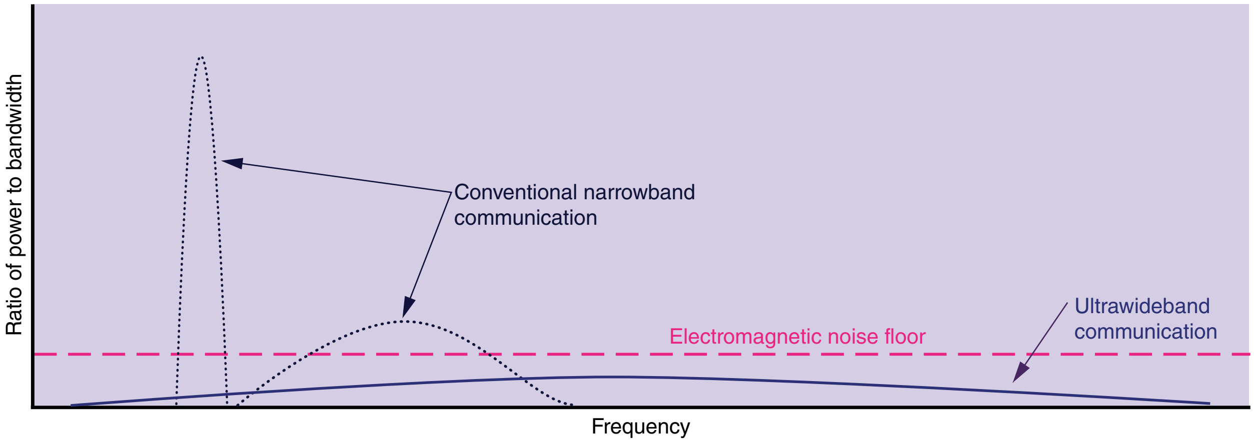
International Atomic Energy Agency (IAEA) inspectors must retrieve nuclear reactor data from hundreds of sites, often climbing a tall ladder and reaching past protective barriers to access data cards. (Photo by IAEA.)

THE International Atomic Energy Agency (IAEA), often referred to as the world's "Atoms for Peace and Development" organization, operates with partners internationally to ensure that nuclear materials and technology are applied solely to the safe use of nuclear energy. In-field inspections and reactor monitoring are key elements to oversee nuclear facilities or operational and treaty compliance. Surveillance cameras, for example, monitor storage and transit locations where nuclear materials pass so inspectors can compare recorded images to reported operations at the facility.

While some facilities are remotely monitored, IAEA inspectors must retrieve stored camera images at hundreds of nuclear facilities worldwide. The thick concrete containment walls that encase nuclear reactors and are designed to contain ionizing radiation complicate data collection efforts, however. The IAEA inspector must don protective clothing and a dosimeter, enter the reactor area, and climb a ladder to retrieve data cards from security cameras mounted inside the space. Even then, the data cards only provide information about past conditions and events that triggered sensors or security locks. Access to real-time sensor data would enable more timely response to nuclear security issues. In addition, gathering data without having to enter the nuclear reactor would reduce radiation exposure and safety risks to inspectors.

The easy-sounding solution—remote data gathering—is, in fact, complicated. Conventional narrowband wireless communications cannot penetrate reactor walls. Using a wired system would require drilling through 1.5-meter-thick walls fortified with steel-reinforcing bars to install communication lines, ethernet, and other components—a costly option that risks damaging the inherent safety feature of the walls. When pursued, requests to bore through nuclear reactor containment walls come with long approval times and detailed review from regional regulatory committees and organizations charged with certifying reactors to ensure facility walls retain their integrity.

Lawrence Livermore National Laboratory and Dirac Solutions, Inc. (DSI), working collaboratively to address the need to gather



Conventional wireless data communications (black dotted lines) use continuous, nonpulsed-based radio frequency (RF) waveforms to transmit large data sets, but they occupy too little of the frequency for data to penetrate thick walls. Short-duration ultrawideband (UWB) pulses (solid line) spread across a wider frequency band to penetrate thick, nuclear reactor walls. UWB communications also fall below the electromagnetic noise floor (pink dashed line), making transmitted pulses difficult to detect by unauthorized readers and robust despite harsh electromagnetic environments.

real-time reactor data and minimize safety risks to IAEA inspectors, developed the Pulse-Based Ultra High Frequency (PB-UHF) Communications System. This portable system builds on an earlier Livermore invention in the field of wideband radio frequency (RF) signaling to achieve wireless data transmission across reinforced barriers. The PB-UHF system collects data from cameras inside the reactor facility in secure, unhackable, real-time videos and images that can be continuously transmitted through nuclear reactor containment walls.

"The PB-UHF Communications System offers data access and security monitoring not possible before to solve what has been a critical issue for nuclear facility compliance worldwide," says Livermore researcher Don Mendonsa, who leads the project for the Laboratory. In recognition of this achievement, the PB-UHF Communications System was selected as a finalist for the 2023 R&D 100 awards, an international competition sponsored by *R&D World* to identify the year's top 100 most innovative new technologies.

Pulse-based Signaling

Aligning all the features required for remote data collection through nuclear facility walls proved challenging for the inventors. In particular, meeting one frequency requirement negated another. Higher frequencies are required to transmit large data sets, such as videos and high-resolution images, but only lower frequencies can penetrate concrete walls with narrowband signals.

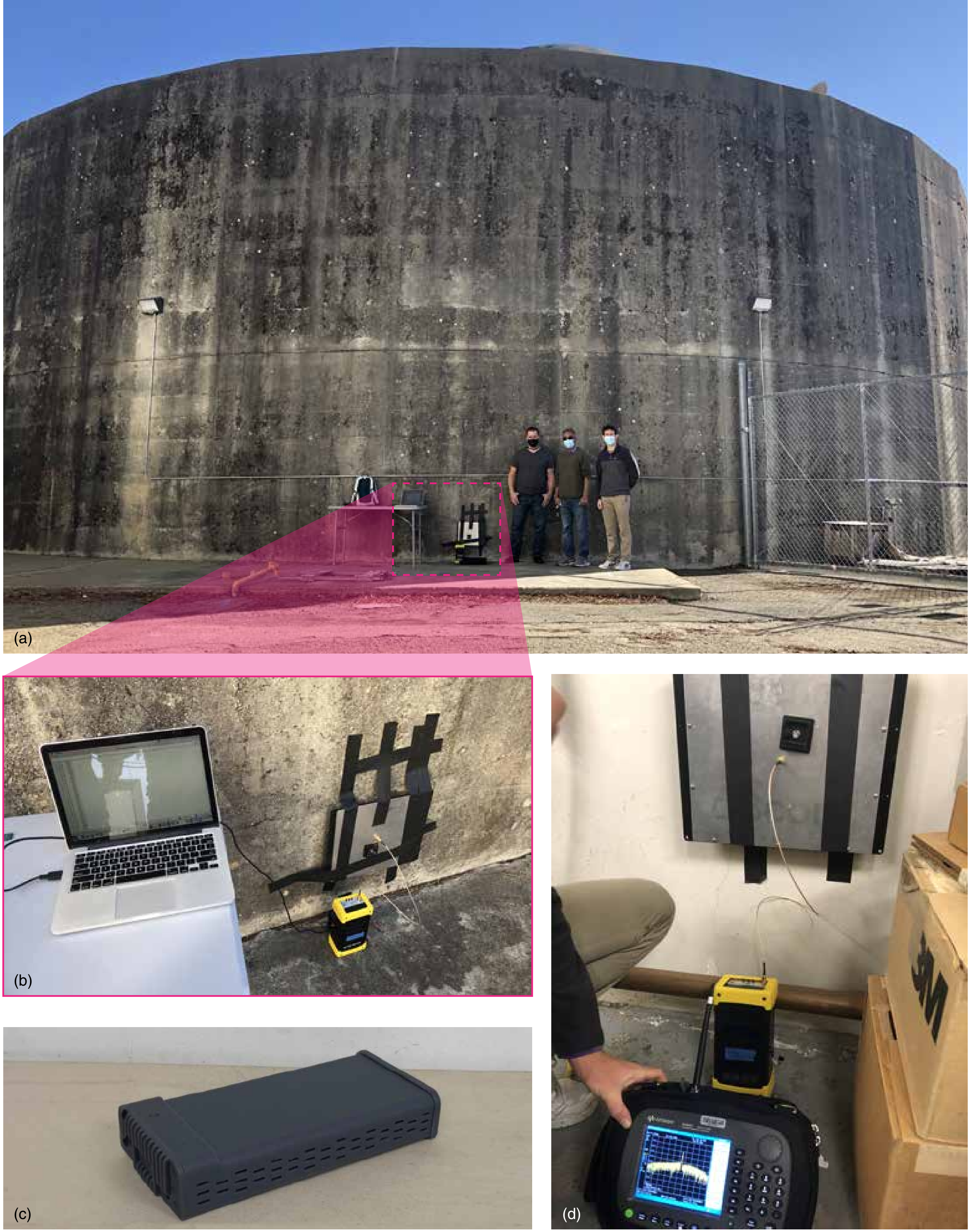
Bluetooth, which uses radio waves on a specific frequency to transmit data from device to device, can only operate successfully over short distances. Therefore, the researchers ruled out Bluetooth and similar wireless data communications that use continuous (nonpulsed), sinusoidal radio frequency waveforms, such as LoRA, a proprietary radio communication system, and Zigbee, a low-power machine-to-machine networking system. Bluetooth, LoRA, and Zigbee waveforms occupy too small a portion of the narrowband frequency spectrum for data transmission.

The team looked to ultrawideband (UWB) as a possible solution. UWB is a pulse-modulated form of RF signaling that applies extremely short pulses to devices. When fired in rapid succession, nanosecond-range RF pulses achieve a high-enough frequency for effective data transfer—nearly 1 gigahertz (GHz) of bandwidth. At the same time, the power of the short-duration pulses is spread over a wide frequency band. For this reason, UWB is used in x-ray imaging and precision radar, enabling emergency personnel to see inside buildings for search-and-rescue operations. UWB ensures signals penetrate thick walls. Further, UWB's ability to achieve both high and low frequencies necessary to transmit large data sets and penetrate concrete walls pointed to the pulse-based RF signaling strategy as the solution the team sought for real-time remote data collection.

Perfect Partnership

The Laboratory and DSI had worked together on several projects to develop technologies, particularly in wideband electronics and RF identification systems. Livermore's Innovation and Partnerships Office provided oversight and approval of their collaborative research efforts, which resulted in multiple patents and publications over many years.

When considering IAEA's nuclear reactor monitoring challenges, Livermore researchers looked to DSI to help transform UWB technology into a system that addressed IAEA's issues. The expertise


(a)
(b)
(c)
(d)

in pulse-based communications among DSI's research staff, including founder Dr. Rick Twogood and Chief Technology Officer Dr. Faranak Nekoogar, as well as the company's focus on wireless monitoring technology for key government and industrial assets, pointed to an ideal collaboration for the project.

With funding from the International Nuclear Safeguards Engagement Program under the Department of Energy's (DOE's) National Nuclear Security Administration, the partners set out to develop through-the-wall wireless video communications technology to support IAEA inspection efforts. In their initial project, Livermore and DSI worked together to modify the Laboratory's foundational technology to improve communication and detection through reinforced concrete containment walls.

The team met its goal of developing a low-bit rate, pulse-based RF signaling communication system, testing technology prototypes in settings representative of nuclear reactor infrastructure and ensuring video data could be accessed even in harsh electromagnetic environments created by other electronic devices and nuclear facility concrete itself. By placing antennas on each side of a containment wall, the pulse-based system offered added security by confining signals to the small space between the antennas. Scattering was minimal behind the antennas as well.

In its first successful test, researchers received clear text communications from inside the McClellan Nuclear Center at the University of California at Davis. A follow-on test at Lawrence Livermore proved the system could transmit video and images over the UWB link with a commercial TCP/IP camera at 5-GHz frequency through interior facility walls. Based on those results, the team modified its design for a low-frequency transmission to receive video and images through a wall as thick as those used at nuclear reactor facilities. In 2022, the technology's UWB transmitter and receiver communicated video and text data at a 1-meter standoff range through the 1.5-meter reinforced concrete nuclear reactor containment wall at Lawrence Livermore's radiation containment facility. "In the future, the system could connect to a more comprehensive monitoring system within the reactor space," says Mendonsa.

A follow-on Livermore–DSI collaboration has focused on developments enabling U.S. manufacture of secure, wireless communication systems. Central to the team's goal were steps to optimize the technology and incorporate commercial-off-the-shelf (COTS) components to achieve a smaller, low-power, low-cost device. The team advanced software to improve the security of COTS monitoring systems by securely networking multiple readers and making further refinements so communications would become more reliable in environments with a higher incidence of electromagnetic interference, such as power lines, other electrical devices, and data center equipment.

Following the successful tests, the team delivered the PB-UHF Communications System to IAEA. The IAEA Safeguards Team has since tested the technology in their facilities and requested additional units for testing and deployment at new reactor facilities globally. "This collaboration has been a rewarding experience for all parties involved including Lawrence Livermore, DOE, DSI, and the government customers," says DSI's Nekoogar. Mendonsa adds, "Providing a portable, quick-to-deploy solution as a resource to IAEA inspectors demonstrates the strength of national laboratory innovation, industry partnerships, and the Laboratory's technology transfer initiative."

—*Suzanne Storar*

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(a) The PB-UHF system enables inspectors to obtain real-time data safely, from outside nuclear reactor containment walls. (b and d) Data was successfully transmitted from inside the facility through the facility's 1.5-meter-thick concrete wall to an outside monitor. (c) The PB-UHF Communications System device has been optimized for portability by encasing components—made secure by software developed by the Livermore–DSI team—in a 3D-printed shell.

The Lawrence Livermore and Dirac Solutions, Inc., PB-UHF Communications Systems team: (standing from left) Greg Nelson, Genaro Mempin, Torsten Eckert, Farid Dowla, David Kooi, and Maxime Dowla. (Seated from left): Faranak Nekoogar, Don Mendonsa.