5G-ENABLED ENERGY INNOVATION

ADVANCED WIRELESS NETWORKS WORKSHOP FOR SCIENCE

Workshop Report

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Workshop Report
5G Enabled Energy Innovation

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5G Enabled Energy Innovation Workshop Report

Executive Summary

Rapidly expanding, new telecommunications infrastructure based on 5G technologies will disrupt and transform how we design, build, operate, and optimize scientific infrastructure and the experiments and services enabled by that infrastructure, from continental-scale sensor networks to centralized scientific user facilities, from intelligent Internet of Things devices to supercomputers. Concurrently, 5G will introduce, or exacerbate, challenges related to protecting infrastructure and associated scientific data as well as to fully leveraging opportunities related to expanded infrastructure scale and complexity.

The U.S. Department of Energy (DOE) Office of Science operates scientific infrastructure, supporting some of the nation's most advanced intellectual discoveries, spanning the country and including 30 world-class user facilities from supercomputers to accelerators. Along with field experiments and remote observatories, every aspect of DOE's scientific enterprise will be affected by 5G, which amounts to a complete renovation of the underpinnings of the nation's information infrastructure. In this report we explore the scientific opportunities and new research challenges associated with 5G, ranging from scalability to heterogeneity to cybersecurity.

The rapid commercial deployment of 5G opens the opportunity to rethink and reinvent DOE's scientific infrastructure and experimentation, from intelligent sensor networks at unprecedented scales to a *digital continuum* (§3) of cyberinfrastructure spanning low-power sensors, high-performance computing embedded within and at the *edge* of the network (§4), and DOE's large-scale user instrument and computing facilities. New programming paradigms, workflow and data frameworks, and AI-based system design, operation, and autonomous adaptation and optimization will be necessary in order to exploit these new opportunities. Field deployments and centralized *scientific instruments* (§5) can also be revolutionized, moving (without traditional performance penalties) from wired to wireless connectivity for data and control systems, improving flexibility, and opening new sensing modalities, including the use of the 5G electromagnetic spectrum itself as an environmental probe. For DOE science, in contrast to commercial 5G applications and settings, devices will be deployed in *extreme* environments (§6) such as cryogenically cooled instrument control systems and in remote settings with harsh conditions, requiring the design of new materials for RF communication and edge processing to operate in these regimes.

Concurrently, 5G infrastructure comprises both hardware and sophisticated software systems—currently closed and proprietary. The cybersecurity challenges to 5G-empowered reinvention mirror the complexity and variety of new 5G features, from virtualization to private network slices to ubiquitous access. Research is also needed in order to accelerate the development of secure and open 5G software infrastructure, reducing reliance on hardware and software produced outside the United States and providing the transparency and rigorous evaluation and testing afforded through open software.

Twelve broad *research thrusts* are laid out in four chapters, with a companion fifth chapter (and three additional research thrusts) underscoring the needs and opportunities for an aggressive testbed program co-designed by networking experts and scientists involved in the 15 research thrusts. The urgency of undertaking this research is fueled by a global, accelerating deployment of new telecommunications infrastructure that is designed for entertainment and commercial applications—barely scratching the surface of what 5G can do to extend U.S. leadership in scientific discovery.

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1 Preface

Digital wireless communication has become a foundational technology for the nation. The U.S. Department of Energy's Office of Science (DOE-SC) is the nation's largest supporter of basic research in the physical sciences, discovering new materials, designing advanced microelectronics, and understanding the physics of radio frequency signaling.

The expanding national rollout of a new fifth-generation (5G) mobile network, coupled with the torrent of scientific data generated by next-generation devices such as battery-powered Internet of Things (IoT) sensors, has created an urgent need to enhance cutting-edge wireless technology. Breakthroughs in the deployment, integration, security, and operational range of wireless networking can provide new scientific capabilities for the next decade—from autonomous mobile instruments for scientific user facilities to intelligent sensors networks distributed over thousands of kilometers for studying environmental processes. To realize this promise, however, we must continue to drive innovations in computing, artificial intelligence (AI), advanced materials, high-speed networking, and microelectronics.

In March 2020, the DOE-SC convened a workshop to identify the potential opportunities and explore the scientific challenges of advanced wireless technologies. The workshop was arranged in ten technical focus areas:

- Advancing science missions
- Cybersecurity
- Critical infrastructure
- Extreme environments
- Scientific user facilities
- Edge computing
- Distributed instruments
- New science exploration paradigms
- Software architectures
- Data management

Workshop participants also submitted white papers that were discussed in breakout sessions organized around the focus areas. Plenary sessions were used for keynote presentations to frame scientific opportunities and present roadmaps for future technologies. On the second day, focus area leaders facilitated discussion groups that identified five priority research directions, detailed in the following pages. This report is available from https://www.osti.gov/ at DOI: 10.2172/1606538.

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2 Introduction

New and rapidly expanding telecommunications infrastructure based on 5G technologies will disrupt and transform how we design, build, operate, and optimize scientific infrastructure and the experiments and services enabled by that infrastructure, from continental-scale sensor networks to centralized scientific user facilities, from intelligent IoT devices to supercomputers. Concurrently, 5G will introduce, or exacerbate, challenges related to protecting infrastructure and associated scientific data as well as to fully leveraging opportunities related to expanded infrastructure scale and complexity.

The U.S. Department of Energy Office of Science operates scientific infrastructure, supporting some of the nation's most advanced intellectual discovery, spanning the country and including 30 world-class user facilities, from supercomputers to accelerators. Along with field experiments and remote observatories, every aspect of DOE's scientific enterprise will be affected by 5G, which amounts to a complete renovation of the underpinnings of the nation's information infrastructure. In this report we explore the scientific opportunities and new research challenges associated with 5G, ranging from scalability to heterogeneity to cybersecurity.

We discuss 5G from the point of view of designing, operating, optimizing, and maintaining scientific experiments across and within a computational *digital continuum* from remotely deployed sensors at the "edge" of the network (that is, edge devices, including programmable *edge computing* systems) to centralized user facilities comprising high-performance computing (HPC) and large-scale scientific instruments.

Edge devices range from battery-powered environmental sensors measuring phenomena unfolding over days to months, to carefully synchronized real-time sensors and actuators on scientific instruments operating on timescales of nanoseconds. Edge device capabilities also span a wide range of computing power, from rudimentary devices with little programmability to powerful HPC systems such as are already being deployed on 5G towers by telecommunications providers, within urban infrastructure, or embedded in vehicles, sensor networks, and other instruments to provide ultra-low-latency service, in situ data analytics, and autonomous response to conditions and events. With rapidly evolving low-power hardware designed specifically for AI and machine learning (ML) workloads, edge devices will implement AI capabilities—*AI@edge*.

Edge devices will interact over 5G networks with one another as well as with intermediate (edge devices on 5G towers) and centralized systems and services, from exascale machines to exabyte data repositories to billion-dollar light sources. This interaction will create new opportunities and challenges for *scientific instrumentation*. For example, the concept of "digital twins"—computational models running in real time representing the state of infrastructure (e.g., buildings) or instruments—will drive tighter integration between sensor and control networks operating the physical infrastructure and HPC systems running the real-time models.

Beyond fixed infrastructure, scientific facilities such as remote environmental sensor networks will leverage 5G features such as low-power communications to increase the capabilities, scale, and reach made possible with low-cost battery-powered sensors. These advances will open the potential for fundamentally new architectures along the digital continuum, with edge systems preprocessing data in the field and providing near-real-time data to computational models running digital twins providing forecasts of the movement of a wildfire, hurricane, or toxic plume based on current conditions and updated in near-real time.

For many of these and other experiment and measurement needs, edge devices, including sensors, edge computers, and radios, will have to operate in *extreme environments* such as inordinate, rapid changes in temperature, high pressure, or exposure to water or corrosive materials. Consequently, an examination of 5G for science must extend into the device and materials design realms, with scientific requirements significantly exceeding those of commercial telecommunications applications.

The rapid deployment of 5G worldwide will necessitate a fundamental rethinking of experimental scientific infrastructure and workflows in order to leverage new features such as network hardware-layer security and privacy functions, network slicing, and ultra-reliable communication. The scales afforded by 5G with respect to sensors and density of deployment also bring complexity with respect to design, operation, optimization, and protection of scientific infrastructure, requiring new AI-based methods for the entire life cycles of infrastructure and experiments.

The powerful software-defined 5G features such as network isolation provide a pathway to introduce wireless architectures to instrument and environmental controls, raising fundamental challenges to cybersecurity and trust. The risks associated with the benefits of wireless controls in terms of flexibility, cost, and maintainability require that the design, prototyping, and testing of such systems at scale be performed by using dedicated *testbeds*.

Unlike previous generations of cellular technologies, 5G is more than merely a set of radio and bandwidth upgrades. The power and promise of 5G rely on sophisticated software infrastructure. Thus, the challenge of assessing risk and vulnerabilities and the promise of new embedded cyber-defense capabilities require transparency that is lacking in proprietary commercial systems. Progress harnessing 5G for science as described in this report will require accelerating the development and adoption of virtualization features and the movement to open source in the 5G software stack.

From the standpoint of national security and competitiveness, the United States stands at a disadvantage today in that the hardware and software systems constituting this next generation of communications infrastructure not only are proprietary, closed systems but also are designed and built outside of the United States. The vast majority of capital invested in that infrastructure will be private, with the predominant applications being entertainment and civilian communications. Here DOE's mission requirements, along with those of other federal agencies such as Defense, Homeland Security, and State, require a level of information protection and operational security above and beyond commercial market requirements. Consequently, we lay out a 5G-for-Science research agenda that will also contribute to the mission integrity and protection of intellectual advantage of the country.

Organization and Structure of This Report

In this report we have organized the discussions and associated presentations and notes at the workshop into five areas, recognizing their interdependence and overlaps.

- *The Digital Continuum.* We begin with a high-level, architectural view of scientific cyberinfrastructure, focusing on how 5G capabilities change the nature, opportunities, and challenges of its design and operation as well as how those changes impact cybersecurity and trust. Three research thrusts here address the software ecosystem necessary to harness increased scale and heterogeneity in cyberinfrastructure, new paradigms for cybersecurity and trust, and new methods and approaches to workflows and optimization.
- *Edge Computing.* Within the continuum, new 5G technologies enable (indeed rely upon) embedding high-performance computing within the telecommunications infrastructure. Low-energy 5G communications and dramatic reductions in the energy cost for computing (fueled by DOE's Exascale Computing Project) will catalyze new low-power device architectures that must support new computing models, chief among them embedding AI (or *AI@edge*) within edge devices. Three research thrusts here are developing low-power scientific edge computing hardware and software architectures, programming models for AI@edge capabilities, and devising new AI/ML algorithms for low-power heterogeneous edge systems.
- *Scientific Instrumentation.* Combined with rapid evolution of edge hardware, from sensors to radios to computing and actuation, new 5G communications, low-power operations, and low-latency features transform the underlying assumptions of traditional, typically centralized command-and-control instruments and observatories. Harnessing these opportunities will require research thrusts in the optimal design of the underlying network fabrics of large experiments and observatories as well as understanding the impact of electromagnetic emissions on the environment, the experiments themselves, and the interaction between the electromagnetic emissions and environmental phenomena, providing *new forms of data and observations*. Given that 5G extends high-bandwidth, low-latency communications to increasingly sophisticated personal devices, a third research thrust is necessary: developing the methodologies, scalable and open hardware and data systems, and strategies to catalyze community engagement, including citizen science.
- *Extreme Environments.* Designing and operating instruments with the sophisticated capabilities offered by 5G radios and edge computing systems, with the ability to operate effectively under extreme conditions (including intermittent network connectivity), will require increased reliance on autonomy, new sensing modalities, and new control structures. These and other 5G opportunities and challenges will require research thrusts in the design of novel materials with targeted electronic and magnetic properties, development of new materials and architectures for sensing in extreme environments, and improvement in our fundamental understanding of materials operating in such environments with frequencies above 50 GHz.

- *Testbeds.* A unifying theme for all the opportunities and challenges identified in this document is a common need for real-world testbed opportunities. Scientific applications of advanced wireless technologies, the creation of a secure open source 5G/mmWireless software and hardware stack, and integration with industry and private-sector resources cannot be successful without a DOE science-focused environment for testing, evaluation, and building the future of scientific data management. This testbed activity will ensure the creation of a new, secure future for scientific management and control of sensors, facilities, and critical infrastructures and will help ensure U.S. leadership in the new kinds of science that will be created by advanced wireless.

Taken together, these five areas lay out an aggressive, broadly scoped, integrated research, development, prototyping, and testing program. The rapid deployment of 5G infrastructure across the country underscores the urgency of this program in order to drive, rather than react to, a comprehensive overhaul of the foundations of the nation's information infrastructure.

3 Digital Continuum

3.1 Introduction and Opportunities

The emergence of a wireless communication alternative that provides wired-like performance on some metrics will enable tight coupling of computation across the various hierarchies stretching from the edge to the cloud, including what has emerged as fog computing. This tapestry of computing, which we call a "digital continuum," is a cyberinfrastructure that spans every scale. Components vary from small edge devices to modest-priced servers with mid-range resources to expensive high-performance computers with extensive compute, storage, and network capabilities.

Priority Research Direction: Digital Continuum

Reinvent the digital continuum linking the wireless edge to advanced scientific user facilities, data analysis, and high-performance computing

Key Questions: What novel programming frameworks will enable fast, secure data movement and in situ analysis to span the continuum from wireless to cloud computing, scientific user facilities, and supercomputers? What AI techniques can learn from and then automatically optimize and operate end-to-end infrastructure?

To effectively integrate the torrents of data from advanced wireless sensors, new computational toolsets must provide end-to-end services such as data movement and caching, data analysis and integrity, and automated performance optimization. New methods, algorithms, and microelectronic devices must address the challenges of mobile endpoints and unreliable links, in order to build a programmable digital continuum for science.

The continuum, enabled by 5G and equally fueled by increasingly powerful edge devices, is fundamentally different from traditional sensor and control networks with fixed edge functions and command-and-control architecture (all computing done centrally) in that (as we discuss in §4) the components are all programmable. Consequently, the continuum will require a software architecture that exploits 5G features such as communication speed, low latency, low power, and high bandwidth to revolutionize the way scientists build distributed systems. These new communications features will enable a rethinking of the design of systems, for example for analyzing data at federated instruments, coupling computational models with real-time measurements in extreme environments, or introducing autonomy and adaptive computing capabilities to edge devices in remote locations.

Developing experiments, services, and persistent cyberinfrastructure on the continuum is much deeper than a natural evolution to Internet-based scientific workflows and distributed computing environments, and it is more fundamental than previous improvements in network capacity and speeds. New 5G network technologies such as private network slices, clock synchronization, rapid adaptability, and field-deployed HPC within the network (e.g., on 5G network towers) change the cost and performance coefficients for various functions such as security, timing, reconfiguration, or data compression and analysis. Consequently, 5G demands a re-examination of the assumptions and common architectural approaches to the organization of scientific components and functions, and even the feasibility of integrating across the entire continuum. These new 5G features enable the science community to rethink the placement of functions, the balance of cost and performance for different functions and components, and the agility with which systems can be reconfigured or indeed can reconfigure themselves. Some of these new capabilities are already contemplated and outlined in the DOE AI for Science report [71]; and 5G network infrastructure adds specific capabilities, with complexities that reinforce the need for alternative approaches to system and experiment design, configuration, optimization, adaptation, and management. Indeed we anticipate that each of these facets of providing and using scientific infrastructure will migrate over different timescales to using AI-based tools and methodologies.

New programming and runtime environments will be required, architected for the continuum and new 5G features, constraints, and capabilities. The complexity of the continuum, with both larger numbers of components and more heterogeneity, and the opportunity to much more tightly integrate network features with application and system software will require new AI-based tools for system design, testing, verification, and optimized operation.

3.2 New 5G Capabilities

Below we discuss several specific 5G capabilities that are particularly salient to new approaches to the continuum and that will also come into play in subsequent chapters.

Private Network Slices. A network slice is a mobile network service tailored for a specific customer application. The mobile network allocates spectrum and other resources to meet each application's unique requirements (e.g., latency, bandwidth, availability, privacy). Today's internetworks are built to support a wide range of applications but are not optimized for any one of them. Network applications must constantly adapt to changing bandwidth availability and latency and must protect their own privacy and communications integrity. In contrast, an application using a network slice is assured that its unique requirements will be met by the service provider network.

Given assurances of consistent service and privacy by the underlying network, application developers can focus on addressing the scientific problem at hand. No longer must application developers incorporate resilience against wildly varying network performance and malicious interference—reducing complexity, risk, and cost. And applications with hard requirements for low latency and high availability (e.g., real-time scientific instrument control)—that simply cannot be implemented on today's internetworks—become feasible when the underlying network slice consistently meets those hard application requirements.

New Data Transmission Modes. 5G New Radio (NR) provides a novel flexible substrate for enabling new services and applications. On the one hand, it increases raw over-the-air data rates via more sophisticated waveforms, increased spectrum availability and multiple-in multiple-out (MIMO) techniques. Resource Unit (RU)-based multiplexing supports time-frequency resource allocation tailored to uses such as Internet-of-Things (power constrained, low bandwidth transmissions). The 5G NR flexible slot-based multiplexing framework is the key enabler of new services and capabilities. The smaller frequency/time slots allow low-power, low-bandwidth devices to turn off significant portions of their radios most of the time, resulting in dramatic energy savings. At the other extreme, a device requiring high bandwidth or low latency is scheduled more frequency/time slots, providing the application guaranteed latency and bandwidth.

This flexibility expands both ends of the range of potential wireless scientific applications. Low-bandwidth 5G devices could work within highly constrained power budgets typically associated with harvested energy sources such as solar, thermal, radio frequency, or piezoelectric. At the other extreme, guaranteed bandwidth could support higher-resolution sensors. And with bounded latency guarantees, instrument control and other time-sensitive scientific applications could feasibly move from traditional wired to 5G wireless networks.

Time Synchronization. The smaller time slots used by 5G NR require significantly improved time synchronization among 5G network elements. Differences in propagation delay between MIMO channels become significant and must be managed for 5G NR to operate properly. The smallest schedulable slot timing in 4G LTE is 1 millisecond, driving a requirement for base stations to be synchronized with a time arrival error (TAE) limit of +/-1.5 microseconds. In 5G NR, ultra-low latency and massive IoT time slots can be as short as 125 microseconds, driving the TAE down to +/- 390 nanoseconds. In order to achieve the new 5G 3-meter mobile device positioning accuracy requirement, however, the relative time offset of 5G base stations should be less than 10 nanoseconds.

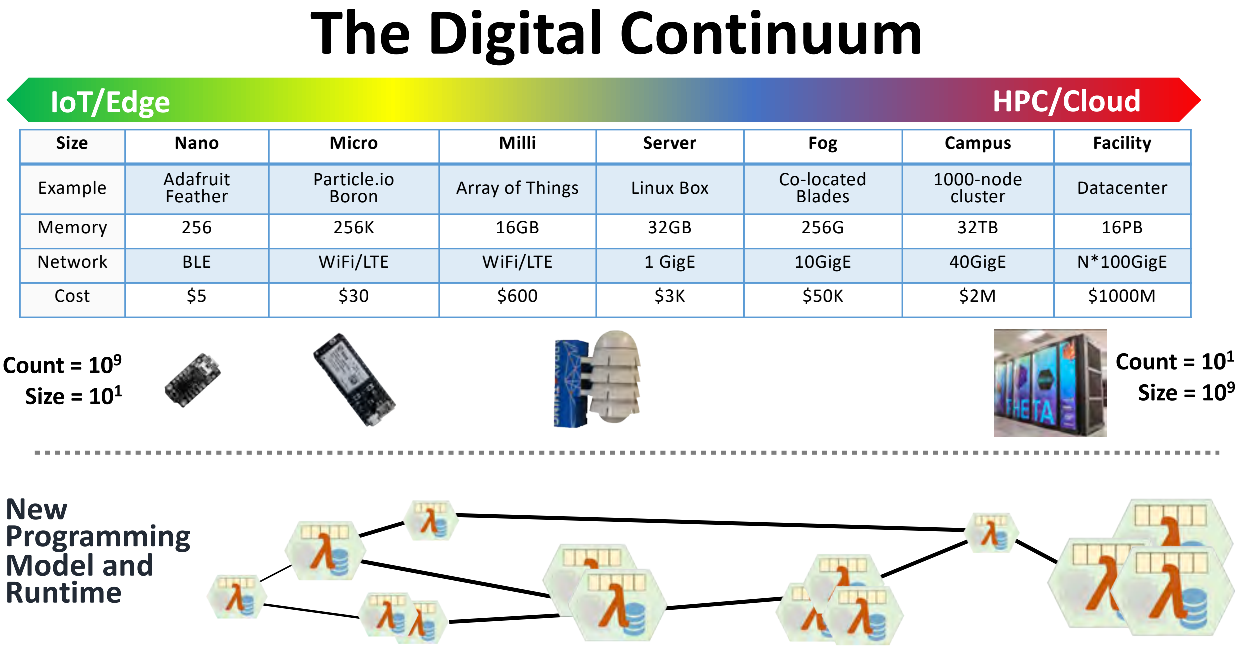
The criticality of time synchronization is well illustrated by the 2012 OPERA neutrino time-of-flight anomalous result. The results were ultimately traced to a pair of unknown instrumental effects [13]. One was that a fiber optic cable was not plugged in properly, reducing the optical power to a photodiode in the timing chain. This reduction in optical power increased the time to charge the photodiode capacitance by 70 nanoseconds.

As with many applications requiring precise timing, the OPERA experiment depended on the Global Positioning Service. Scientific experiments operating indoors or underground must build infrastructure to transfer GPS time to the individual sensor. 5G can offer time resolution and accuracy competitive with GPS, using radio frequencies that can penetrate structures (or be built out underground by using commodity off-the-shelf 5G components). These features should dramatically reduce the cost, complexity, and risk associated with traditional time distribution systems for scientific applications.

Rapid Reconfiguration and Adaptation. The 5G Core network is designed from the ground up to quickly provision network slices on demand. This design includes just-in-time end-to-end provisioning of mobile devices, radio spectrum, and transport networks to meet emergent customer requirements. Traditional telecommunication resource provisioning time is generally measured in weeks or months. Scientific applications must therefore provision (and pay for) circuits and services sized for their peak requirements, even when actual peak utilization is rarely achieved. The ESnet must plan years in advance for infrastructure upgrades to meet exponentially increasing bulk wide-area data transfer requirements.

Cloud computing offers just-in-time API-driven provisioning of compute and storage resources, reducing the forecasting risk and associated capital and operational expense of building dedicated compute and storage resources. Analogously, the new 5G core rapid reconfiguration and adaptation capability could free scientific collaborations from building massively overprovisioned networks to support relatively rare bursts of communication requirements.

For example, electromagnetic observations (optical, X-ray, and radio telescopes) have been cued within 30 minutes of gravitational wave detection [13]. This is well within the time window anticipated for provisioning 5G network slices, allowing electromagnetic observational data to be quickly gathered and analyzed via quickly provisioned dedicated bandwidth.



Size	Nano	Micro	Milli	Server	Fog	Campus	Facility
Example	Adafruit Feather	Particle.io Boron	Array of Things	Linux Box	Co-located Blades	1000-node cluster	Datacenter
Memory	256	256K	16GB	32GB	256G	32TB	16PB
Network	BLE	WiFi/LTE	WiFi/LTE	1 GigE	10GigE	40GigE	N*100GigE
Cost	$5	$30	$600	$3K	$50K	$2M	$1000M

Figure 1: The 5G-enabled digital continuum needs new paradigms to scalably link distributed resources across the scientific computing infrastructure.

3.3 5G-Enabled Scientific Opportunities and Research Challenges

The 5G network features and services outlined above combine to provide new opportunities for supporting science on the continuum. but they also raise associated research challenges and gaps in current R&D programs. We discuss these challenges in three categories, each driving a digital continuum priority research thrust.

Scale and Heterogeneity Driving a Holistic Software Ecosystem. The combination of embedding HPC systems within the 5G infrastructure itself and of deploying tens of thousands of endpoints (e.g., low-power sensors or real-time instrument sensors) unleashes the potential to build much larger-scale networks of devices than ever before. Over time, the introduction of new features and the accelerating pace at which electronics and computing hardware are advancing will mean these large-scale infrastructures will also be heterogeneous. These infrastructures will often span both high-connected geographies (e.g., urban areas) and sparsely or intermittently connected remote locations, adding to the challenge of system optimization.

New Paradigms and Challenges for Cybersecurity and Trust. 5G features such as virtualization and network slices are implemented with sophisticated software infrastructure, opening new types of vulnerabilities such as side-channel attacks between virtual slices. The proprietary nature of commercial 5G hardware and software will confound risk assessment as well as limit the extent to which new, more effective cybersecurity features such as anomaly detection or intrusion response (leveraging 5G features) can be implemented deep in the systems. Consequently, accelerating the development of secure, open 5G software infrastructure is a prerequisite to introducing 5G into mission-critical infrastructure.

Data Management and Movement: New Methodologies and Approaches to Workflow and Optimization The scale and heterogeneity of emerging network infrastructures will present challenges to the design and optimization of workflows and distributed software systems given the diverse latency and bandwidth constraints associated with data (and software function) movement among scientific instruments (fixed and field-deployed), instrument-associated edge computation, and HPC and data systems in data centers. New communication protocols, APIs, and data management methodologies and tools will be needed to enable research empowered by 5G-enabled instruments and devices. Indeed in some cases performance can be improved through simplified protocols if privacy and data integrity can be guaranteed by underlying 5G constructs—modulo the cybersecurity challenges just noted. Achieving these new levels of scale, performance, and optimization will require leveraging machine learning, deep learning, and AI over 5G networks. Also needed will be autonomous functions such as providing rapid reconfiguration, quality of service, and load-balancing services.

3.4 Research Thrusts

3.4.1 DC-1: Holistic Software Ecosystem Addressing Scale and Heterogeneity

5G technology will enable intermittent, untethered, and emerging devices (e.g., that leverage novel computing paradigms such as neuromorphic computing and quantum computing) that span scale and heterogeneity in terms of capacity, latency, and functionality—for example, smart and non-smart devices and high-power and low-power devices [68]. 5G capabilities will also be foundational to support a plethora of use cases, for instance, scientific experimentation in extreme environments [64], consumer applications (e.g., autonomous vehicles [52], cellular networks [32]), AI and ML applications [21, 27], simulation and data analytics [63, 72], and software-defined or cognitive radio. A holistic software ecosystem will be required to support such a wide array of devices and use cases.

Deploying applications connecting edge devices using 5G and advanced wireless to other resources such as HPC systems, data centers, and the cloud can be done in one of two scenarios [81]. In the first scenario, the application might be deployed as loosely coupled agents and services that would interact using 5G and advanced wireless networks. In this scenario, the application would run on top of the 5G and advanced wireless network and computing resources that are virtualized in a platform such as the service cloud. In such a setting, all resources (not only the computing resources) would need to provide compliant resource virtualization or allocation. In the second scenario, the application would reserve an end-to-end enclave gathering resources all the way from edge devices to HPC systems, data centers, or clouds. In this scenario, resources would need to provide an Infrastructure as a Service type of virtualization. This scenario suits applications needing a high level of resource control (dependable applications, intensive streaming applications, etc.).

To support such a wide array of devices and use cases within these two scenarios will require a *programming and runtime environment* that can deliver high performance and resiliency and is adaptable to the needs of a diverse set of users [37]. This will entail connecting applications running on edge devices to the software architecture embedded within the 5G and advanced wireless fabric [44]. Such an environment will also benefit from redesign of compilers, workflows, or even programming languages. A resilient programming and runtime environment will not only require that the diagnostics be built into the infrastructure of 5G and advanced wireless but will also require low-level programmability and control for troubleshooting purposes. In order to be adaptable, the programming and runtime environment must account for intermittent and untethered devices, as well as supporting the incredible diversity in terms of the hardware on which programs will run [39]. The connectivity of software to the hardware must be clearly demarcated by using virtual machines, containers, or logical processes. Developing such a high-performing, robust, resilient, and adaptable programming and runtime environment could leverage AI and ML techniques for resource utilization, failure prediction, and scheduling of algorithms [34]. These could also be running on emerging devices using nonconventional computing paradigms such as neuromorphic computing [25] and quantum computing [29] that have been embedded in the 5G and advanced wireless fabric.

An important aspect of the hardware-software stack will be the *runtime system* (RTS), which acts as an interface between the underlying hardware and the software stack. The RTS will be customized through parameterization to support various hardware and software scenarios [11]. Contrary to traditional runtime systems, RTS systems in a 5G and advanced wireless network will have to contend with variable quality of service in terms of bandwidth, latency, power, and security. This will widely exceed requirements found in benign, wired environments. To address this combinatorial resource problem, these runtime systems will have to apply dataflow-style scheduling policies to route data over the network [57]. Latency-hiding techniques in addition to latency reduction techniques will also be critical. Hence, the RTS will need to trade parallelism for latency in massively multithreaded environments. In addition, the RTS will have to handle different computation motifs. For instance, passive edge devices will not actively participate in any distributed computing, whereas active edge devices will actively contribute to the evolution of a program; opening up questions of trust and integrity as well as questions of resiliency in light of the brittleness of the network. For the RTS to assess the capabilities of the network will require a cost model that relates the different performance parameters such as bandwidth, latency, power, and security. These cost models will also be used at compile time; but, in the case of the RTS, dynamic data will continuously update the models.

A holistic software ecosystem for 5G and advanced wireless will need to have an *adversarial network design* [49]. 5G and advanced wireless will require connecting software-defined networks to the compute fabric. The processor on which computation actually takes place will not necessarily be bound by the physical location. Therefore, standardized protocols and abstractions will need to be developed that let users take advantage of the highly distributed network of compute infrastructure. One can imagine that such an adversarial network design might be brittle and would need to be made robust. AI and ML models in conjunction with nonconventional compute platforms such as neuromorphic computing [26] and quantum computing [28] could once again be leveraged to enable a robust software ecosystem.

Applications using 5G and advanced wireless to connect edge devices and HPC systems will have a different set of requirements, will run on a mix of environments with different properties and constraints, and will have to be *fault tolerant* [58]. Because application requirements for such applications will be diverse (permanent streaming connection on the one hand and temporary connections transferring massive data volumes on the other hand) and because part of these environments will be highly volatile and shared, new research questions in fault tolerance and resilience will need to be addressed in order to run these applications with certain quality of service [31]. First, 5G will mix two types of environments that are classically considered separately for fault tolerance: distributed systems and HPC. Fault tolerance for distributed systems and streaming applications is oriented toward executions and resources replication because of the high volatility and relative low cost of resources, whereas HPC heavily relies on checkpointing because of the low volatility and high resource cost. Second, applications will be deployed on a mix of private and public environments. The private environment might be controllable by the applications, whereas the public part of the environment would typically be controlled by a service provider. Checkpointing the full application from edge to HPC system will probably be impossible and even undesirable for an application involving streaming. Using replication will probably be too expensive on the HPC side and may simply not be offered (or only to a certain level) by the service provider. New flexible fault tolerance paradigms (probably involving application and system levels) will be needed to ensure that applications deploy from edge to HPC and deliver their scientific results [67].

5G and advanced wireless will have to account for devices that leverage *nonconventional computing paradigms* such as neuromorphic computing and quantum computing [25, 28]. Neuromorphic computing devices offer low-power solutions for running ML tasks, control tasks, and data analytics [26]. Quantum devices (for example, quantum sensors) equipped with 5G and advanced wireless will provide experimental data in extreme environments and might also support ML and AI applications [29]. Quantum-encrypted communication using quantum key distribution (QKD) could make messages transmitted over 5G networks more secure [55]. These devices could be active (i.e., devices that are part of the holistic software ecosystem executing some or all parts of a program) or passive (devices that do not participate in the execution of a program but feed data to be transmitted over the 5G network). While the active devices will require their own runtime environments, passive devices will not require any runtime environments. Both active and passive devices could be intermittent, and the software ecosystem must account for this possibility. While such devices leveraging nonconventional computing platforms would use 5G and advanced wireless for communication and data transmission, they would also be used to build and improve the holistic software ecosystem. The 5G and advanced wireless software ecosystem must not only account for all these devices during execution of a program but also leverage them for making the 5G technology more efficient and secure.

Another important consideration in designing a holistic software ecosystem for 5G and advanced wireless networks is *cost models and resource management* [30]. Cost and performance models must be defined for any piece of software leveraging 5G and advanced wireless networks. For instance, when we go beyond the exascale computing timeframe and post Moore's law era, energy efficiency will become one of the most important performance metrics for any computation on 5G and advanced wireless networks. Resource management with a 5G advanced wireless fabric, including bandwidth and energy use as well as traditional hardware resources, will require more dynamic and configurable approaches for provisioning of resources. This in turn will rely upon not only more detailed capture of system data (e.g., tracing, logging, journaling, auditing) but also predictive capabilities. Two elements are of prime importance for 5G and advanced wireless environments: (i) dynamic and configurable resources with intermittent availability ("detached" mode); and (ii) managing of trust at all layers. The resource management for the distributed environment spanning edge computing to HPC requires balancing different resource constraints for very different platforms. These heterogeneous environments require isolation mechanisms to ensure that users are properly separated and also to ensure platform security and performance requirements. The end-to-end orchestration will require published interfaces that enable different stakeholders and resource providers to coordinate the use of available resources. The 5G-enabled environments have the added complexity that resources may be more dynamic or intermittent and therefore the resource management must take quality-of-service requirements into play when performing orchestration. The distributed runtime environment for the edge-to-HPC continuum can provide a critical basis for establishing trust, backed by existing hardware mechanisms for creating a trusted computing base that can be established across the distributed environment. This can span the 5G links using dedicated "virtual lanes" for isolation. We discuss these in more detail next.

3.4.2 DC-2: New Paradigms for Cybersecurity and Trust

How do we reinvent the fundamental tenets of cybersecurity (e.g., situational awareness, trust, confidentiality, and data integrity) for securing real-time point-to-point connections and multipoint connections? What are the vulnerabilities of 5G network slices? How does network virtualization increase or mitigate these vulnerabilities? How can we provide efficient, scalable algorithms for real-time and critical use cases ranging from autonomous systems, environment monitoring, and smart buildings, districts, and cities to electrical generation, transmission, and distribution systems and remote instrument control? How do new capabilities such as network slices alter the approach to end-to-end privacy and security? Can these and other 5G security features enable reduced complexity (and thus reduced associated risk and increased performance) in security and privacy functions?

New architectures, applications, and use cases discussed in the following chapters will exploit 5G features such as higher-bandwidth data movement, lower-latency communications, and increased capacity with respect to the density of devices within a geographic area or scientific instrument. As these systems grow in scale and complexity, the opportunities for nonlinear impact of even small cyber-physical attacks will also grow, as will the number of attack surfaces available for disruption or information exfiltration.

The promise of architectural, software-implemented, and even hardware-implemented secure communications features such as network slices or virtualization has the potential to improve system performance by moving security functions to the system level, analogous to the performance gains afforded by hardware virtualization in microprocessors. Ultimately, however, a 5G network infrastructure is a complex, software-controlled infrastructure, and these new functions must also be examined for new vulnerabilities and attack vectors.

New, secure open 5G software infrastructure must be developed based on open standards and protocols that can be rapidly updated and deployed (keeping in mind that telecommunications software infrastructure is traditionally slow to evolve) and verified. Doing so will require significant research both in open, secure software and virtualization software capabilities; in development of new cybersecurity test, verification, detection and real-time response tools and functions. As will be seen throughout this report, the scale and complexity of new generations of scientific infrastructure will necessitate the use of AI techniques such as deep learning to discover vulnerabilities or anomalies that might not be anticipated by human experts. Also required will be autonomous response systems that can detect and counter cybersecurity threats and incursions within milliseconds.

Efficient encryption mechanisms that can be readily integrated with scientific workflows and applications will be required irrespective of the cybersecurity improvements that may evolve with 5G. Classical cryptography methods for data encryption exist, but they will be increasingly under threat as quantum computers come into play. Such classical cryptography systems also fare poorly compared with quantum encryption methods such as QKD [85]. Incorporating QKD along with other quantum encryption methods in 5G and advanced wireless technology would go a long way in ensuring the security of data and information exchanged over 5G and advanced wireless networks.

Current frameworks for security, resiliency, and trust are built on high-level programming languages and assumptions related to system architecture, for instance contemplating the movement of data but not necessarily of software modules. Vulnerabilities associated with the insertion of AI@edge code (e.g., a man-in-the-middle attack that alters or substitutes an instrument control edge software update) must be contemplated in new frameworks for the digital continuum.

3.4.3 DC-3: New Methodologies and Approaches to Workflows and Optimization

In contrast to traditional workflows that interconnect fixed resources within data centers, the 5G continuum will extend such workflows to include data from thousands and eventually tens of thousands of individual and diverse sensors, integrated with hundreds of diverse edge systems performing data analytics and reduction. Indeed, with large-scale user facilities we may see hundreds of thousands of low-cost, narrowly targeted sensors monitoring as many exascale CPUs or light source control systems. A single sensor measurement will thus carry provenance, including sensor type, location and environment data, sampling algorithm, and data reduction (e.g., averaging) algorithms, as well as traditional data/time and other metadata. In cases such as instrument control, the time precision of real-time instrument sensor readings may also include location to compensate for propagation latencies. In such larger, more complex continuum systems, research is required in order to understand how data provenance and its integrity can be preserved, along with measurement meaning and uncertainty, and retained across the data life cycle.

Using advanced wireless technologies necessitates the development of a scalable, geographically distributed, and federated network fabric that accommodates N scientific instruments (sensors, actuators, etc.) communicating data with M repositories. Such a network should do the following:

- Be intelligent enough to be resilient against failure of components, including nodes, repositories, edge systems, and partial failures of the fabric itself.
- Provide a baseline QoS (performance) for data life-cycle steps, including time synchronization for determining order of events (including measurements and process execution). Experiments being interpretable in experiment timescale is a critical factor for success.
- Be capable of resiliently guaranteeing data transmission in light of potential component, partial fabric, or widespread failures.

Concurrently, new 5G-enabled workflow systems will require research related to data acquisition, including the development of storage mechanisms that can work with such distributed and multimodal data across the DOE landscape. These must scalably accommodate data that varies in modality (different kinds of information or instrument types), time (nodes can come up or go down; some transmit more frequently than others), space (location of a node transmitting data can move), and volume.

Furthermore, the workflow and data management infrastructure must enable scientists—ultimately via autonomous agents—to monitor, aggregate, and use such geographically and modally disparate data.

3.5 Scientific Impact and Outcomes

New 5G systems will enable the science community to design a new generation of digital infrastructure—a continuum from low-cost edge to \$B user facilities—with an increase in scale for sensor, control, and distributed processing systems that is on par with the transition from 128-node parallel architectures to million-core exascale machines. The digital continuum, however, also introduces challenges of geographic scale and continually evolving heterogeneity as devices are introduced and retired over time, in many cases by cooperating but distinct infrastructure operators and owners. Utilizing these diverse resources requires placement decisions and tradeoffs that cannot easily be adjudicated by individual users and administrators. Instead, new approaches are required for mapping workloads onto continuum resources in ways that satisfy high-level policies concerning, for example, response time, metadata, and data preservation. While serverless models and containerization techniques can enable portability, extensive research is required to express and implement, concisely, portably, and reliably, distributed placement and optimization policies.

A new generation of cybersecurity methodologies, tools, and techniques will be foundational, and indeed 5G introduces a number of promising new features that could revolutionize the security and integrity of distributed systems. To realize this revolution, however, DOE and other US agencies must coordinate and accelerate the development of secure, open 5G software infrastructure that will neutralize the threat of foreign-controlled, proprietary, closed hardware and software technologies.

Atop a secure digital continuum, new scientific workflows and experiments can be enabled, as we describe in more detail in subsequent chapters, empowering multidisciplinary science teams to address some of the most vexing challenges such as those in the natural sciences related to energy and associated infrastructure and the interplay between energy, water, and the environment. For example, independent investments in sensor networks, user facilities such as light sources and accelerators, HPC systems, and 5G networks can be integrated into virtual instruments that at one point combine to forecast the path of a wildfire or hurricane or at another point are reassembled to optimize an experiment based on faster-than-real-time computational simulations (or the reverse). All of these capabilities are potentially achievable only with new 5G networks and also require new software, cybersecurity, design, optimization, and autonomy, leveraging and indeed driving breakthroughs from projects such as the DOE exascale and AI initiatives [71].

4 Edge Computing

4.1 Introduction and Opportunities

5G cellular and WiFi-6 [33] can enable wirelessly deployed compute resources at the edge of the communication infrastructure. This far edge has historically presented three challenges: communication, power, and space. With the advent of 5G, the communication challenges are alleviated, providing communication capabilities over wireless that are comparable to wired networks with respect to the metrics of latency, bandwidth, and availability. These enable us to position more advanced computing at the edge than has been possible before 5G.

Indeed, edge computing is viewed as essential to enable many of the new use cases targeted by 5G. These include mission-critical IoT applications in healthcare, industrial control, and power systems, which require high-reliability and tight-latency guarantees. Another use case is augmented and virtual reality, which again requires tight-latency guarantees. Supporting such applications can be done only by both improving the latency and reliability of the air interface (one of the key targets of 5G) and by moving compute to the edge of the network. All major cellular providers have plans to deploy edge computing in their networks to enable such use cases. The 3rd Generation Partnership Project, which develops the 5G standards, has also developed functionality to better support edge computing, such as frameworks that expose edge services to end users. Edge computing is also viewed as a key enabler of 5G deployments themselves by allowing for dedicated hardware to be replaced by virtual network functions running on general-purpose edge compute. In summary, 5G is the first generation of wireless systems designed from the start to enable and exploit efficient edge computing.

Priority Research Direction: Edge Computing

Revolutionize AI-enabled edge computing for advanced wireless

Key Questions: Using a co-design approach, how can we optimize computer architecture for power, precision, and programmability to support scientific AI at the edge for 5G? What novel software architectures can leverage network slicing and provide energy-efficient computation and scalability across heterogeneous edge resources?

The research community and computer industry are rapidly developing new hardware and software architectures for machine learning at the edge. Current limitations on electrical power and computing efficiency for scientific workloads can be overcome with a co-design methodology that links advanced wireless providers, scientific applications developers, and computer scientists, creating novel hardware and software architectures.

An example of the current state of the art in programmable edge computing for science is the Waggle platform [17]. The system uses an ML-optimized processor and wireless modem to process data directly at the edge. Waggle is the core platform used by the Array of Things (AoT) [19, 20]. The NSF-funded AoT project began in 2015, and over the next few years deployed more than 100 nodes in Chicago to study urban activity and measure air quality (see Figure 2). The AoT system pioneered the availability of programmable edge cyberinfrastructure tightly coupled to wireless modems.

Figure 2: Left: Two Northwestern University students put up a Waggle node in a prairie to perform environmental monitoring; Right: The Chicago Department of Transportation installs an Array of Things node on a pole in the city.

While the Waggle platform has provided a system for developing and deploying optimized edge systems linked to wireless networks, the architecture does not yet leverage or extend the capabilities of 5G. However, since Waggle is built on open source Linux devices, the system could readily incorporate 5G into its suite of communication protocols as part of a testbed (see §7)

4.2 Scientific Challenges and Gaps

Operation and control of distributed systems—creating *intelligent user facilities*—are natural challenges for 5G technology. There are many varied examples of large and complex user facilities at DOE laboratories, some with up to hundreds of thousands of sensors. The data is being created at extreme rates, from kilohertz to megahertz frequencies, and often requires intelligent processing and compression in the data pipeline at the sensors to the edge before being aggregated in a central location. These sensors and their modality are often diverse in the data type, volume, and rate they produce; and the systems should be flexible to both add and move the sensors based on changing facility conditions. Furthermore, these systems often require a feedback mechanism such that decisions made at every stage in the data pipeline may result in control loop input upstream and downstream, requiring bidirectional information flow. In addition to being complex and data-intensive, some systems have challenging latency requirements. For example, in systems that control relativistic particle beams traveling at nearly the speed of light, timescales for physical processes are extraordinarily short. Current non-wireless control systems operate all the way down to the millisecond scale, and thus transmission latencies should be at that level. A control system over a vast network of distributed, multimodal sensors producing data at high rates and requiring fast communication latencies will greatly benefit from intelligent processing; and 5G communication to improve user facility operations would accelerate experimental design and enable scientific discovery.

Programming at the AI@edge should not be viewed in isolation but in relation to the programming model for the entire digital continuum (§3). We must begin by describing the computing/inference goal and should integrate two primary activities with multiple subsidiary goals: (1) developing a goal-oriented annotation and high-level programming model that specifies desired outcomes for the aggregate, rather than a collection, of component behaviors and (2) building mapping tools, a runtime system, and an execution model for managing continuum resources, including the AI@edge, as an abstract machine that also monitors behavior and triggers remappings when necessary.

4.3 Research Thrusts

4.3.1 EC-1: Development of Advanced Low-Power Scientific Edge Computing Architectures

Availability of 5G networking will make it easier to deploy large numbers of high-bandwidth sensors, greatly increasing the observational data volume and computing requirements. Deploying specialized sensing and computing devices throughout the experimental pipeline is crucial in order to increase scientific throughput, automate control of experiments (no human in the loop), and reduce the burden on networks and HPC data centers. These devices can range from tiny distributed low-latency sensors with minimal computing capabilities, to powerful high-bandwidth advanced sensors such as hyperspectral imagers and cameras, and to FPGA and ASIC accelerators and processors. In these settings with a diverse set of sensors and actuators, efficient use of edge computing has the potential to enable fast and timely data processing in support of a much wider science area portfolio with increased value to DOE.

With Moore's law flattening, the physical limits of CMOS technology make it almost impossible to achieve high energy efficiency through the dominant traditional "deterministic and precise" computing model. Further, the upcoming data explosion will comprise statistics and inferences gleaned from uncertain and imperfect real-world environments. Thus, traditional computing approaches will likely be ineffective for harvesting the full benefits of 5G. Emerging computing architectures beyond von Neumann, such as neuromorphic computing and probabilistic computing, will be necessary in order to overcome the challenges [12]. We predict that computing will evolve to encompass increasingly heterogeneous architectures both at the chip level and at the system level, posing new integration and orchestration challenges.

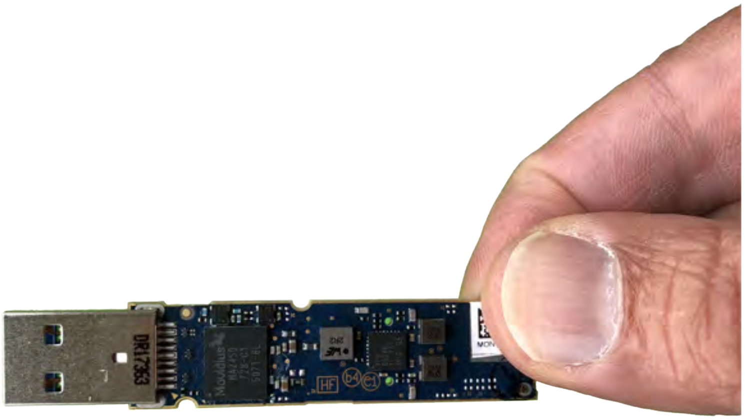


Figure 3: The Intel Movidius Neural Compute Stick, an example of a low-power edge computing device.

Fundamental and applied computer science research is needed to devise novel computing architectures for scientific experiments that can deliver the breakthrough 5G capabilities and benefits to a broad range of DOE's focus areas. In particular, we consider the following key capabilities:

- Latency: compute closely coupled to real-time streaming data
- Bandwidth: compute to analyze and distill data at sensor rates
- Privacy: stateless compute, protected compute
- Resilience/agility: redundant compute, fault tolerance, flexible/configurable architecture
- Energy: scalable compute from tiny power through to server-level power

Each of these capabilities must be seamlessly integrated, in different combinations and with differing constraints depending on the specific scientific workflow or application, in a 5G environment to support new science requirements including mobility, multitenancy, synchronization, broadcast, and aggregation. The integration should be end-to-end (via wired edge compute and in-network compute to cloud/HPC servers) without being difficult to configure, program, and use. Such integration requires a hardware-algorithm co-design approach that leads to a system best suited for the specific applications. For example, the capability of directly processing analog signals acquired from sensors without analog/digital conversion can substantially reduce power consumption; performing computation in the sensor network itself utilizing physical laws may dramatically reduce the data movement and hardware overhead. On the other hand, event-driven computing algorithms allow for much lower static power since the system will perform work only in response to meaningful or significant signals.

5G edge computing necessitates the fusion of sensing, computing, and actuating into a unified framework, one that could not be imagined before. 5G edge computing demands novel computer science approaches where architectures and algorithms are not separate software and hardware entities but instead are various aspects of a continuously evolving, large-scale, spatially distributed network.

4.3.2 EC-2: Design of a New AI@edge Programming Model

In edge computing, the data is available at the edge; however, the computing often needs to be performed by a resource higher up and deeper in the connected network space. Modern computing involving AI/ML includes traditional codes and their binaries and also large data files that describe the AI/ML models. AI/ML computing also requires the support of a large number of underlying mathematics and statistics software libraries. These models are continuously improved with new data and need to be updated at the edge. Exploiting the full capability of edge computing when interlinked with 5G requires a software architecture that can take advantage of the flows and the latencies, to enable the best use of both traditional and AI/ML-model-based computing.

Three factors are fundamental to the next-generation edge architecture. First is an incentive to provide an *edge hardware-agnostic approach to both developing and deploying applications, codes, or compute kernels*. Currently, tools such as containers and virtual machines provide some of the needed abstraction. In addition to the abstractions, they can

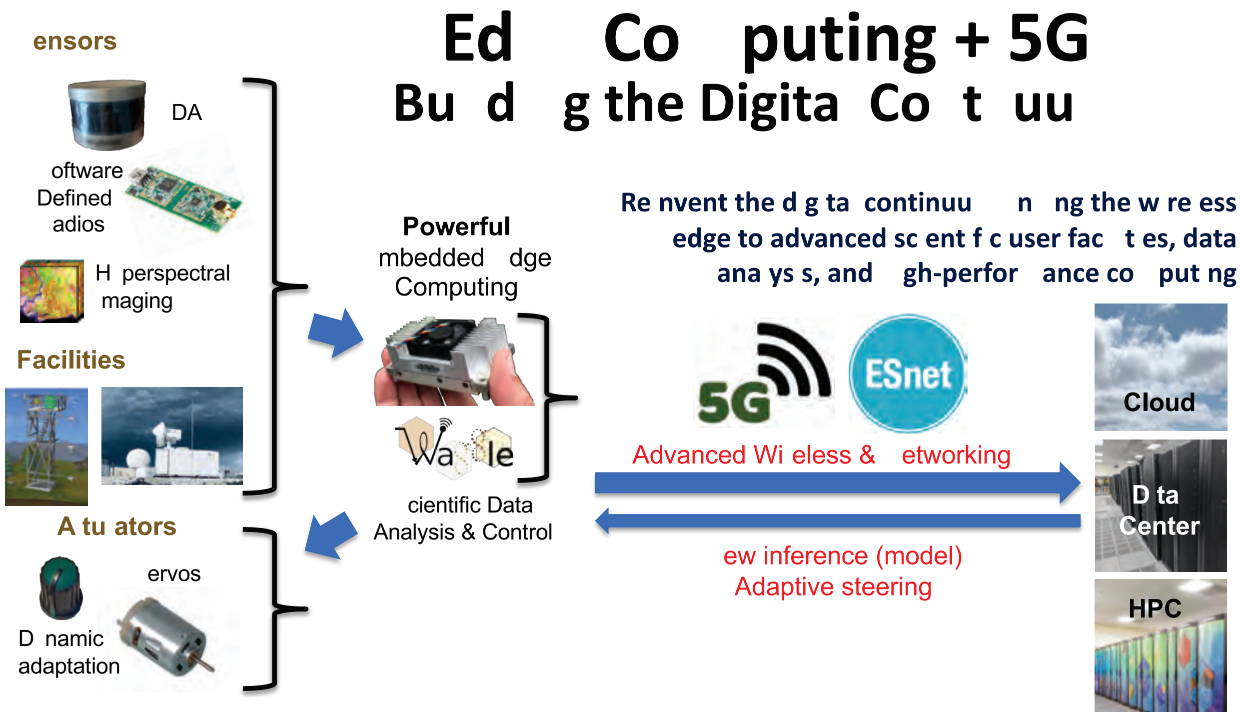


Figure 4: New techniques for processing data at the edge can improve autonomy and collection of high-value data.

enable packaging and extending the base set of libraries and subroutines in a simple and eloquent fashion. The concept of containers may also be extended for edge computing on more centralized compute resources such as cloud and HPC server farms or even stand-alone desktop systems.

Second, *different programming languages and models* need to be supported in order to enable the development and execution of edge applications. Two use cases are likely: execution that is self-contained on the edge and execution that is linked with computation that is more centrally located. In the linked computation model, there may be many-to-one, one-to-many, or many-to-many links, each either triggering computation or in real-time providing feedback leading to a tight closed loop. An example is the notion of edge-triggered HPC and HPC-steered edge sensing and computing.

Third, the edge may need to support *execution of several distinct or collaborative applications that might be able to share hardware (sensors, actuators, etc.) and software (intermediate results from AI/ML models, results from some kernels, etc.) resources, and outputs or may need exclusive access to or control of resources*. The third pillar of the software architecture, then, is resource management and orchestration. A variety of resources need to be managed at the edge, with traditional resources such as CPU, GPU, FPGA, RAM, and disk-space resources; specialized devices such as sensors and actuators; and communication to and from the edge. For example, inference results could use low-latency, low-bandwidth paths, and models could be delayed in transmission but use high-bandwidth channels on 5G. With 5G, the multifaceted nature of the communication becomes important in edge scheduling and data aggregation. An edge device may request various 5G profiles to optimize data transfer in order to meet its latency and bandwidth requirements.

4.3.3 EC-3: Exploration of New Algorithms and Approaches for Edge Computing

Many scientific research applications rely on the analysis of large-scale heterogeneous data sources, from imagery and text to time series and videos, produced by using advanced instruments.

The NSF-funded SAGE [4, 16] project provides an excellent use case for these new edge algorithms. SAGE, which started in 2019, builds on the tools and capabilities of the Waggle [17] and AoT [19, 20] projects but extends the intelligent edge computing nodes to the mountaintops of California where towers provide wireless connectivity to

Figure 5: Images of fires as captured by wireless towers in southern California.

science experiments as part of the High Performance Wireless Research and Education Network (HPWREN). SAGE will bring edge computing resources to the towers so that real-time imagery from pan-tilt-zoom cameras, infrared cameras, and seismometers can be fused and integrated. By writing a "software-defined sensor" for wildfires, images from the towers (see Figure 5) can be processed and sent in real time over the wireless networks to supercomputers forecasting the path of the blaze. This realistic and timely example highlights several key computational challenges associated with utilizing AI/ML approaches for analyzing scientific data at the edge. First, the appropriate network design (i.e., the deep learning network topology and hyperparameters) is not known a priori for a given dataset. A typical attempt to use AI for a novel scientific application starts by training an "off-the-shelf" neural network model, typically optimized for a specific scientific dataset. When results are suboptimal, domain expertise is used to guess at small tweaks to the network to improve the accuracy. This hand-tuning process is time intensive and tedious and requires some intuition about the hyperparameters to change in order to improve inference performance. Second, because finding an appropriate neural network for novel scientific applications is already difficult, it is hard to also optimize on the secondary characteristics of the networks, such as prediction time or power consumption, characteristics that are key to successful deployment of AI on edge computing devices. For many scientific data applications, real-time prediction is vital. Many existing AI/ML tools are developed for *static* data such as images and texts, whereas high-frequency sensing data from the edge is highly *dynamic*. Innovations in AI/ML methods are needed in order to capture complex dynamics, make real-time forecasting, and be robust in highly nonstationary environments [48, 82]. In particular, advanced AI/ML techniques are needed that will leverage 5G capabilities for reduced latency and increased bandwidth in order to process the data and make predictions in real time.

Machine learning is extremely data intensive, and the proliferation of data produced at the edge will exponentially increase beyond data and bandwidth availability. ML at the edge has the potential to greatly mitigate these challenges in multiple ways: (i) dramatically reducing the required communication bandwidth by performing significant computing and processing at the edge; (ii) allowing the agent to continuously adapt to the environment and perform intelligent, distributed decision-making that is optimized for each edge instance; and (iii) improving the resiliency of the system (and reducing its vulnerability to random or targeted attacks) through the distributed nature of the 5G computing at the edge. These requirements will lead to new challenges in the field of edge ML such as the following:

- Time series and dynamics learning: We need to develop new AI/ML frameworks that can capture complex dynamics in the data produced at the edge. Furthermore, they need to be robust to missing data, sensor heterogeneity, and various anomalies introduced by noisy environments and instruments malfunction.
- Transfer learning and domain adaptation: We need to determine the extent to which a given algorithm adapts to changing conditions on the fly with robust and reliable behavior.
- Online learning: We need to train AI/ML models on the fly when data is generated through a stream of sequential events.
- Streaming real-time system modeling: In complex systems, we require real-time simulations in order to develop virtual twins for intelligent control.
- Reconfigurability and controls: We need to determine how to provide a feedback loop into the system that can react at scale and varying latencies.
- Energy-efficient algorithms, for example, neuromorphic and probabilistic computing: Edge ML will naturally require

efficient implementations of algorithms to meet energy, latency, and bandwidth constraints.

State-of-the-art AI/ML models are computationally intensive and require multi-megabytes to gigabytes of coefficients. The compute and data transfer requirements imposed by them on the networking infrastructure and processing resources significantly impact their scalability, latency, and deployability. Furthermore, the conventional precise computing paradigm of AI/ML models will be intractable in many real-world applications, which demand extremely high-inference/watt/dollar AI/ML performance. Therefore, energy efficiency and high performance (low latency) remain key bottlenecks for effectively developing and applying AI/ML in the era of edge computing.

4.4 Scientific Impact and Outcomes

5G-enabled edge computing will pioneer a new era of computational fluidity across low-latency computing and storage resources. Tightly integrating edge computing into the scientific process will enable a new generation of near-real-time optimization for control systems, AI@edge, and distributed data collection and analysis. To realize the potential of 5G edge computing, new methods are urgently needed in order to facilitate the high-level specification of computations and to encode and compile workloads for execution on arbitrary devices, from heterogeneous edge devices to leadership resources and the cloud. Such a programming model will empower scientists, researchers, and students to rapidly develop scientific codes and seamlessly apply them without regard for the underlying hardware. This capability would simplify code development and deployment, for example, by enabling the application of a code at an instrument while simultaneously deploying a digital twin of the code elsewhere for evaluation. New methods are also required in order to capture scientific functions in high-performance, retargetable workloads that can be used to perform end-to-end science.

The proliferation of diverse edge devices will necessitate research related to resource allocation, scheduling, adaptation (e.g., to delay or reduce fidelity of analyses and data), abstractions, and the programming models required to realize their use. As sensor networks trend toward extreme-scale data generation, new data reduction, fusion, and processing techniques will drive innovation through unprecedented insight into on-going experiments and will facilitate acting on data that would otherwise be archived for future analysis or be lost.

The 5G network can be a potential game changer for the train-on-cloud and deploy-on-edge system model. Compared with previous generations, the 5G network enables a higher degree of programmability, which provides the flexibility to deliver differentiated levels of services for a wide range of new use cases [62], including (1) enhanced Mobile Broadband (eMBB), to support high-bandwidth data-driven use cases such as virtual, augmented, and mixed-reality-based applications; (2) ultra-reliable low-latency communications (), to support mission-critical communications such as remote control of autonomous land and aerial vehicles; and (3) massive machine type communications, to support dense deployments of Internet of Things devices to enable smart homes, industrial facilities, and cities. These new services can be enabled over 5G thanks to the revolutionary design of its software-defined core and transports networks on the one hand and the radio access network on the other hand, which supports advanced wireless communication technologies such as millimeter waves, massive multiple-input multiple-output, beamforming, and heterogeneous network densification [9, 84].

UAVs, especially those in the form of quadcopter drones, can operate as flying mobile terminals within a 5G network to perform a plethora of tasks involving sensing, communications, and data analysis [53, 83]. Applications range from search and rescue missions and inspection of unreachable areas in order to advance understanding of the environment, climate, and geosciences, to civilian applications such as real-time video streaming and drone-based item delivery [42]. Thanks to 5G's stringent specifications for eMBB and URLLC, these applications can be performed efficiently with both edge and cloud intelligence working in tandem.

We envision a system of 5G networked intelligent UAV swarms in support of the U.S. Department of Energy's environmental management program in remote areas. Such systems will leverage recent advances in AI/ML and 5G technology to enable a life-long learn-and-control framework in which autonomous intelligent UAVs make decisions on a fast timescale based on their local AI/ML models, while fine-tuning of models to response to environmental changes will be constantly performed on DOE leadership-class systems and the results will be disseminated to UAVs over a 5G mission-critical network slice at a slower timescale.

5 Scientific Instrumentation

5.1 Introduction and Opportunities

From tokamaks to telescopes, environmental field sites to the urban jungle, instrumentation is required in order to gain insight into phenomena across scales and to answer key science questions. Complex configurations of sensors are used to document processes, to build new theories, and to advise scientific development. These sensor networks are often constrained, however, by the need for physical data connections, thus limiting possible configurations. Advanced high-speed wireless technologies such as 5G can untether sensor networks and radically transform scientific instrumentation.

In order to achieve this goal, key investments are needed in three strategic research thrust areas.

First, the deployment of sophisticated new wireless infrastructure for instruments depends on improved optimized designs of the network fabric for large experiments and observatories. A related research area is to understand electromagnetic emission from 5G and the environment given that scientific instrumentation may be sensitive to the frequencies used by advanced wireless. Likewise, naturally occurring modulations in the spectrum can be used as a probe to understand the environment. Furthermore, scientific instruments are often developed with the most recent sensors and advanced computational techniques. For many science domains, ordering a commodity part and then simply attaching it to a 5G radio is not possible. The computation at the edge, the sensor, and the integration of the radio must be done as part of a complex optimization process that takes into account power, price, accuracy, and computational complexity. Therefore, in the same way that scientific computing communities use Linux, Python, and cloud services to build scientific workflows from open source tools, the scientific instrumentation community needs 5G-based radio toolkits and software libraries to aid in the construction of new instrumentation. These will enable custom applications—from the large distributed facility to the community college.

Priority Research Direction: Scientific Instrumentation

Reinvent scientific instrumentation and critical national infrastructure with wireless technology to provide rapid AI-driven adaptation

Key Questions: How can we create scientific sensing networks that provide near-real-time feedback across a wide range of deployment conditions? What new AI-driven algorithms and methods are needed to assimilate heterogeneous data streams and autonomously control critical infrastructure and scientific instruments?

Leveraging advanced wireless, such as 5G, can enable new architectures that support a dynamic, near-real-time end-to-end fabric that predicts and responds to measurement conditions, thus dramatically improving the value of collected data. Likewise, critical infrastructure must respond to a continuously evolving environment. Breakthroughs in wireless instrumentation architectures are required in order to provide dynamic, robust, reliable, and repeatable operations.

Once advances in these areas are made, instruments in the lab, at critical infrastructure sites, and in the field will become more configurable and agile, reducing the time to redeploy sensors as the need for expensive and cumbersome fiber optic cables is reduced. In the first research thrust, the computational fabric will enable the creation of new scientific instruments, provide new ways of integrating knowledge, and lower the time needed for exploration, learning, and innovation.

The second research thrust has two components: using the electromagnetic radiation produced by 5G networks as an instrument and understanding the impact of 5G radiation on sensitive scientific instruments. Success in this area is vital to achieving the vision of the first thrust. Electromagnetic waves emitted by 5G equipment propagate along many paths, through the atmosphere between cells. From interactions with the environment a gamut of physical information can be encoded into the 5G and advanced wireless signals through attenuation and phase shift. For example, power levels can drop because of liquid water path attenuation; and 5G signals, specifically those around 30 GHz, sit near a water vapor absorption frequency that could open up the possibility of using 5G hardware or even 5G networks themselves (in collaboration with service providers) to improve our understanding of the environment around cities. Since the spectrum of 5G is broad and a dense network of transmission sites is likely, understanding the impact of the signal on

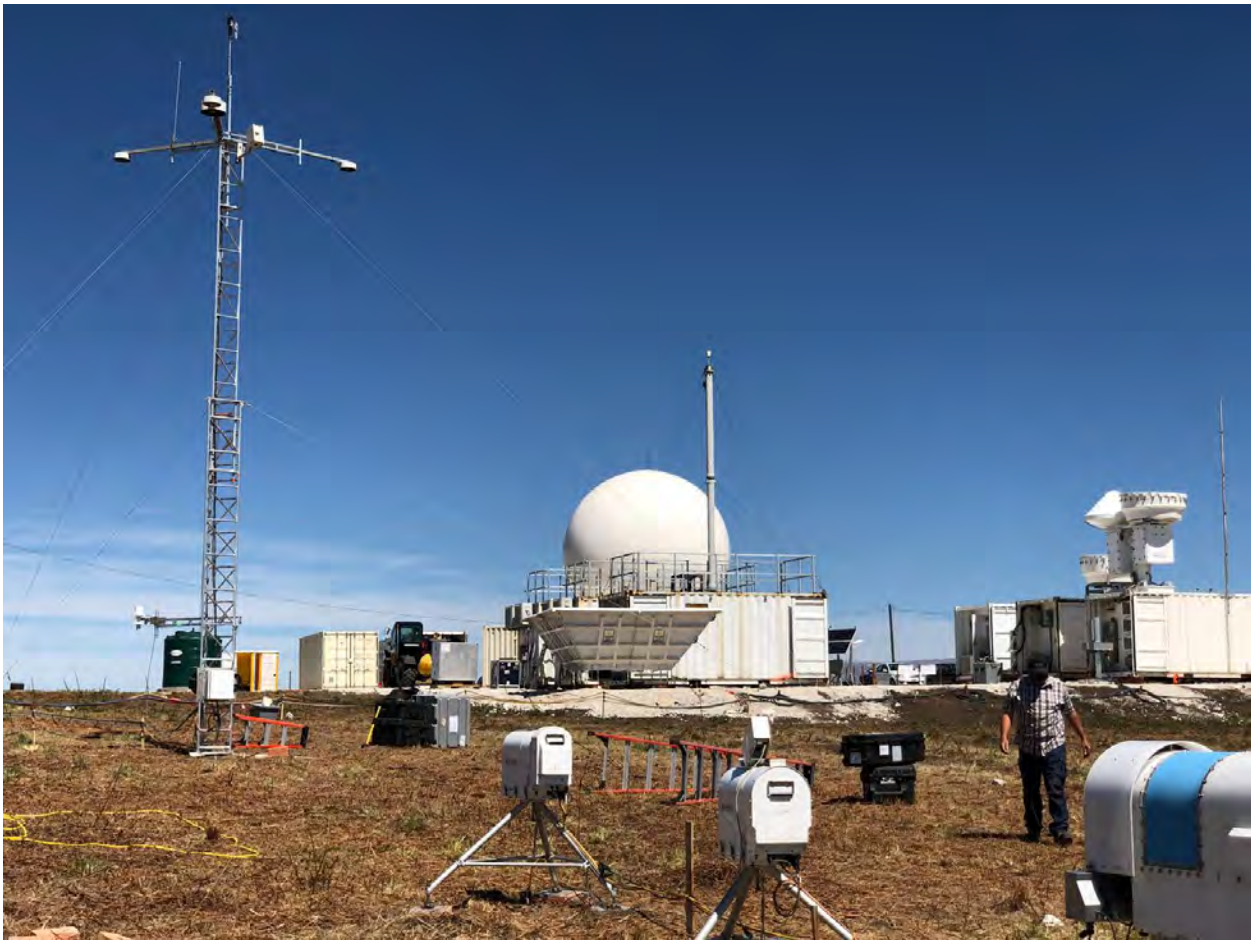


Figure 6: The Atmospheric Radiation Measurement User Facility deployed to Argentina.

sensitive laboratory equipment and grounding configurations is vital, especially if 5G is to be used for science.

The third research thrust seeks to piggyback on the successes of open hardware platforms such as Arduino, Adafruit, and Raspberry Pi and provide the scientific instrumentation community "hackable hardware" to integrate wireless components. The adoption of low-cost software-defined radio by industry has led to a number of low-cost devices that can operate on many frequencies simultaneously. This technology lowers the barriers for entry into 5G development and testing. A history of embracing this approach can be seen where vendors have supported this capability in several consumer products. One example is Linksys WRT54g (see Figure 7). It is sold as a ready and capable wireless router but also supports the open source development environment that can modify, customize, or completely replace the firmware.

Figure 7: The WRT54g, an open, customizable wireless device.

By developing prototypes, standards, and demonstration networks for 5G and other advanced wireless technologies, this research thrust will allow a broader ecosystem of scientists to extend, enhance, and improve scientific facilities and create custom network fabrics interlinking complex instrumentation using advanced wireless technologies.

5.2 Scientific Challenges and Gaps

Several challenges regarding instruments and the monitoring of critical infrastructure confront the widespread use of advanced wireless and 5G technologies by the science enterprise. Currently 5G is a set of standards and frequency allocations; a large amount of technology development still needs to occur. The DOE Office of Science should consider 5G as a substrate of opportunity on which to map advanced (distributed instrumentation-centric) scientific innovations for the 21st century.

The creation of networks of instruments for monitoring large experiments, field sites, and critical infrastructure requires a mix of technologies to construct the network fabric. Advanced wireless protocols such as 5G add a new mix of bandwidths and latencies into the mix. 5G itself is a complex mix of communications standards covering many frequencies. At times these standards can seem opaque, especially to scientists and decision-makers whose expertise is in a different area. A key scientific challenge is to develop a network fabric of sensors, computing, and storage from an à la carte menu of network (wired and wireless) technologies. Both real and virtual tools are needed for the optimal design of network fabrics for large experiments and observatories. Such tools, which can be part of an "ESnet-like" facility, will be essential in designing data flow and control and can help identify major cost savings and efficiencies, such as replacing conduits full of optical fibers with high-speed point-to-point links.

Many of the wireless technologies taking advantage of the higher frequencies covered by the 5G standards are still being developed. Currently, such development is taking place with purely commercial communications imperatives. The key challenge is developing technologies to meet the communications needs of science. Commercial vendors will use configurations of hardware that offer the best solutions for their communications enterprises but will also be pragmatic in adopting the best solutions. To this end significant investment (private, public partnerships) is needed in developing open radio-sensor-computing instrumentation building blocks. By getting out in front of the 5G (and other advanced wireless) technology rollouts, the science community can help develop key hardware standards.

For the true potential of 5G and other advanced wireless to be realized, the science community needs to understand how a heavily utilized spectrum can be a benefit (from passive sensing of the environment) and how potential RFI issues can be mitigated. A key challenge to widespread use of 5G to connect instruments will be understanding how 5G frequencies interact with the environment, both in the field and in the experimental hall.

5.3 Research Thrusts

5.3.1 SI-1: Optimal Design of Network Fabric for Large Experiments and Observatories

Advanced wireless, including 5G, has the potential to be a disruptive technology to the traditional user facility paradigm by enabling mobile, distributed end stations and distributed manufacturing. Currently most of the user facilities are located in one central location, and users are required to send their people and samples to the user facility to accomplish their science. Indeed, this model is required for very large, sensitive instruments. In a manner similar to ARM and ESnet, however, mobile user facilities are agile and go to the user. These mobile facilities can involve multiple national laboratories, industry, and academic institutions.

One such mobile facility is enabling distributed manufacturing using local and diversified feedstocks to produce fuels

Figure 8: From the experimental hall to the field site, advanced wireless, including 5G, will revolutionize the configuration of sensor networks. The left panel shows the next National Spherical Torus Experiment Upgrade experiment with high-speed data collection needs. The figure on the right, courtesy of Rusen Oktem (LBNL), shows one of a pair of stereo cameras [66] deployed to the ARM [8] Southern Great Plains site in Oklahoma.

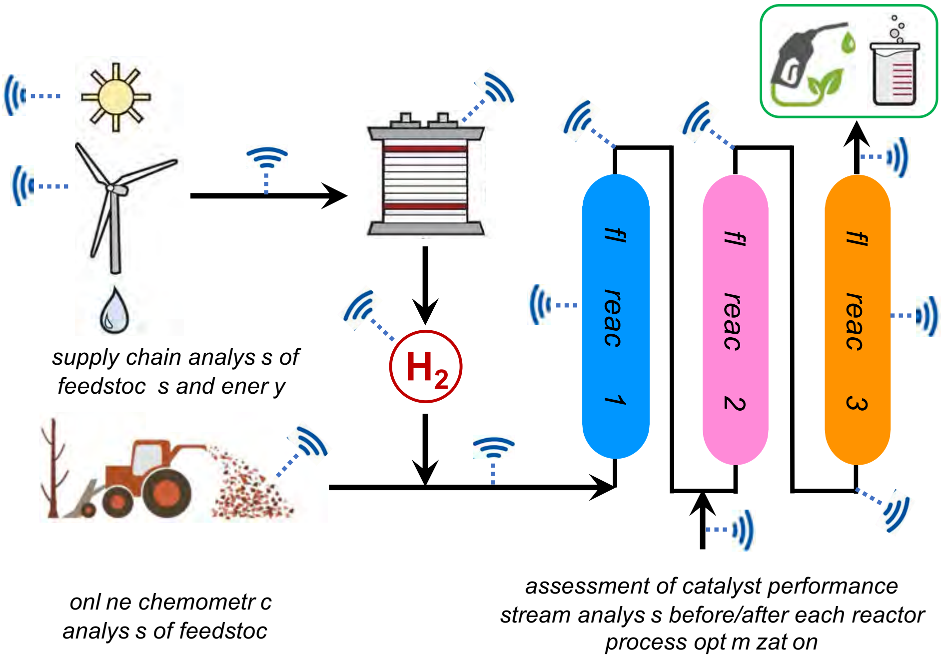


Figure 9: Proposed working scenarios using a smart 5G-enabled integrated system to manufacture fuels and chemicals in the field. Image by Long Qi, Ames Laboratory.

and chemicals needed in a local area (Figure 9). Currently, manufacturing of fuels and chemicals is based primarily on pure feedstocks in centralized processes that are maintained at a steady state over the catalyst lifetime for maximum efficiency. However, the emerging and divergent feedstocks (e.g., shale gas, carbon dioxide) are transforming the chemical industry. Distributed manufacturing can take advantage of these local and diversified feedstocks and avoid the need for expensive transportation to centralized processing plants. Other feedstocks, based on biomass or polymer upcycling, are mixtures of similar molecules, requiring chemo-selective conversion to minimize energy-intensive separation. Upgrading diverse feedstocks by distributed manufacturing requires regulated process control and data-driven decision-making over the whole course of the multistep synthesis and separation to achieve the most desired physicochemical properties.

In order to maximize the utility of 5G in development of large experiments or observatories, a holistic approach must be used in the optimal design of the network fabric interlinking instruments and computing. The design should move beyond using 5G technologies solely with regard to data transfer, from collection and control, to edge computing and/or data centers. To this end, technology development is needed: from experimental halls to field sites, built-in edge compute capabilities, 5G cells for mesh networking, fiber and Power over Ethernet connections, instruments, and backhaul. Testbeds to point to the benefits and shortfalls of this technology would be beneficial to user facilities and others looking to adopt this technology or otherwise address needs.

The ability to implement heterogeneous edge computing and machine learning are two of the biggest net gains to having such an increase in available and reliable bandwidth and adaptive agile sensing. Such bandwidth allows for increased monitoring and quick (real-time or near-real-time) decision-making. Additionally, 5G will permit an increase in potential sensor density as a result of not having to run cables and could allow for greater collaboration at DOE scientific user facilities with visiting instrumentation without the host facility having to account for providing bandwidth.

However, 5G will not be a comprehensive solution to all experimental design considerations. For example, the design should consider where it is beneficial to utilize wireless over fiber, if fiber is available (which it will be if 5G infrastructure is present), as well as any security concerns. Ultimately the optimal experiment design will be a “hybrid model” with some components using wired networking and others using 5G/WiFi 6 (802.11ax) based on need and function.

5.3.2 SI-2: Electromagnetic Emission from 5G and the Environment

The physical layer of advanced wireless networks differs significantly from previous-generation communication systems. Massive multiple-input, multiple-output (MIMO) technology relies on large antenna arrays, measuring the RF channel response with unprecedented accuracy to improve the quality and reliability of the communication link. The RF channel matrix also provides a valuable source of information on the physics of the surroundings. Furthermore, previously untapped frequencies in the RF spectrum are used for 5G, both sub-6 GHz and in the millimeter-wave domain. The specific physical properties of these RF signals will affect the future of scientific measurements and instrumentation, as advanced wireless networks are rolled out for commercial and scientific purposes in field sites and laboratories. On the one hand, the electromagnetic signal itself can be used as a carrier for instrumentation, leading to increased precision of existing instruments and disruptive new measurement techniques in many scientific domains. On the other hand, 5G emissions can become a source of electromagnetic interference for experiments or instrumentation.

Spectrum as an instrument: The radio technology for advanced wireless communications is a powerful tool for electromagnetic sensing. The vast spectrum of radio frequencies and the directional signal properties of antenna arrays enable sensing applications in a plethora of scientific domains. The physical propagation properties of millimeter waves can be used for measuring, understanding, and monitoring material properties and processes in lab environments. Taking this knowledge out of the lab, channel information of commercial or scientific 5G hardware can be used for large-scale sensing applications in the field. For example, the dense distribution of mmWireless equipment and user devices in urban areas can provide opportunities for monitoring environmental parameters (moisture, pollutants, temperature, precipitation, etc.). Sub-6 GHz massive MIMO technology will be used to cover rural areas, enabling remote RF sensing applications for agricultural and geophysical research. When the spectrum becomes a sensor, the channel matrix can provide on-the-fly data with an unprecedented spatiotemporal resolution, allowing a deeper understanding of physicomechanical and hydro-biogeochemical dynamics without the need to deploy discrete sensors. Using the spectrum as a sensor requires access to advanced radio hardware and test equipment (e.g., anechoic chambers), as well as collaborations with industry to get access to commercial 5G networks. With these resources, the research can be performed to determine the opportunities and boundaries of using advanced radio technology as a sensor.

Spectrum as interference to instruments: The effect of 5G network electromagnetic emission on instrumentation is an important thrust area of research. The reason is that throughout the scientific community, the instrumentation used can be commercial off-the-shelf (COTS); an integration of multiple COTS components from different vendors; or specifically developed equipment that is designed, maintained, and upgraded by national laboratory or university personnel. This range of instrumentation equipment utilization does not allow for traditional practices of meeting standards for electromagnetic compatibility. Another basic fundamental research question is how the 5G electromagnetic emission affects standard engineering practices. Given the physical differences between millimeter waves and microwaves, different parts of a test system can be affected. This situation requires advanced research in shielding, grounding, system instrumentation, and custom instrumentation in mmWireless environments. In order to study the effects of 5G interference, electromagnetic compatibility tests should be performed. Anechoic chambers are an important tool for these evaluations since they provide full control of the electromagnetic field exposure.

Because the deployment of 5G networks will increase the localized exposure resulting from all wireless technologies, studies on compliance with national limits should be performed to address public concerns.

5.3.3 SI-3: Democratization of Advanced Wireless with Open Radio Hardware.

Widespread incorporation of 5G and advanced wireless connectivity into science requires the establishment of a new research paradigm in which sensing devices and scientific instrumentation, infrastructure, network architectures, and algorithms are developed in parallel and in an integrative framework. Research will be needed into customized network designs that enable usage across scales of research. Nested, interconnected network architectures will be desired for multipurpose scientific research. The combination of AI-driven approaches with advanced wireless networking will also play an important role in using these capabilities for scientific research, especially in the design of network fabrics that enable real-time communication with instrumentation.

A key missing component in existing 5G and other advanced wireless hardware is devices readily adoptable for

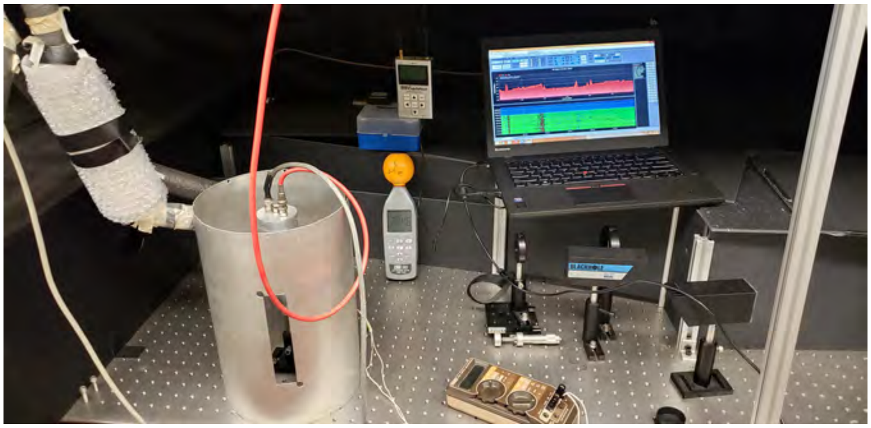


Figure 10: Measuring the efficiency of RF shielding at the laser lab.

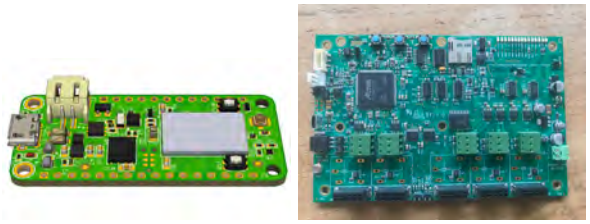


Figure 11: The nRF9160 FeatherWing, an LTE-M-based cellular module (left) and Argonne's Wagman [17] control board (right) as examples of open hardware.

scientific use. While 5G network rollout continues, there exists a golden opportunity for developing open hardware and standards. A parallel example is the explosion in small computing devices such as the Raspberry Pi, NVIDIA's Jetson, and Google's Tensor Processing Unit. Standards such as the General Purpose InputOutput (GPIO) [36] allow scientists, hardware engineers, and the general public to hack together various IoT appliances such as weather stations, garden watering systems, and even device counters using Bluetooth low-energy devices that are being used in COVID-19 related activities.

If standards were designed for 5G and other advanced hardware, which could allow the easy addition of communications and spectrum monitoring to IoT edge devices, roadblocks in thrusts one and two would be ameliorated. Investment, particularly in partnership with telecommunications and semiconductor companies, in producing programmable modular hardware with open and well-documented APIs will give scientists a toolbox of appliances they can use to construct a network fabric. Furthermore, such hardware can be used in education, outreach, and workforce development. By having kits in primary and secondary schools as well as universities, some of the unwarranted negative attention 5G is receiving can be countered.

With strategic investment opening hardware development to labs, schools, and institutes of higher learning, the private sector will benefit from the added innovation and workforce development feeding back into their sector.

5.4 Scientific Impact and Outcomes

Distributed instrumentation and the monitoring of critical infrastructure need information flow. The problem is multiscale, and an à la carte menu of solutions is required in order to build network fabrics to enable science and monitoring. Instrumentation is used in two distinctly different settings: in the field, monitoring the environment (natural and anthropogenic) around us, and in laboratory conditions where we control the environment to probe the nature of matter and energy.

In the Field 5G and other advanced wireless technologies, combined with the technology advances discussed in this chapter, will untether instruments so that their placements will not depend on physical networks. In addition to advances in solar and battery technologies, experimental fields such as those operated by the Atmospheric Radiation

Measurement User Facility [51] could deploy “drop pod” sensing units to measure phenomena at their natural scales, not those dictated by physical infrastructure. As well as “drop-in sensors,” advanced wireless will enable truly Lagrangian observations (sensors that move with the phenomena and measure or react in the object’s frame of reference). Imagine a LIDAR system on rails or wheels (e.g., [75]) that moves with the motions of cloud systems and gives a true measure of the life cycle of a cloud and how it interacts and modifies its environment. Or imagine a field-operative chemical reactor that responds to humidity and feedstock changes or the needs of the community in moving from site to site. Advanced wireless combined with UAV technologies will create the ultimate instrument or network fabric for in situ and remote sensing of the environment. Drone payloads can be minimized by having computation located on the ground with high-speed, low-latency links thanks to new hardware developed inspired by this report. As mentioned in Subsection 5.3.2, the 5G signals themselves can be used to understand our environment. Work using 4G signal attenuation [47] can be expanded for urban settings; and since there is some overlap with water vapor attenuation frequencies, the 5G spectrum can be used to understand the spatial distribution of water vapor around cities, vital for understanding urban heat islands and other impacts of cities on their environment.

In the Lab Laboratory experimental halls use miles of expensive fiber optics to get data from instruments for computation, storage, and dissemination. Advanced wireless technologies, including 5G, will unlock new experimental configurations by reducing or eliminating the need for physical network infrastructure. Research outlined in this thrust will enable “experimental network hubs,” allowing many instruments at, say, the D3D National User Facility to be multiplexed into a unit containing edge computing and a 5G (or other) point-to-point link back to a master hub in the experimental control room. These hubs will allow new agility in the deployment of novel high-bandwidth instrumentation. Other user facilities, such as the Advanced Photon Source, which is used extensively by private industry (e.g., in understanding the structure of COVID-19) will use advanced wireless to enable “connect and play” (as against plug and play) modules at beamline stations. By using hackable hardware, recognizing the impact of RFI on sensitive instruments and how to construct network fabric, users can design their network and instrument fabric offsite and then simply connect it on installation to a network access point.

By understanding how 5G and advanced wireless will disrupt traditional sensor networks and fabrics, recognizing its effect on the environment, and fostering innovation in hackable advanced wireless hardware, scientific endeavors will see a revolution in the use of sensors to gain new insights into phenomena across scales.

6 Extreme Environments

6.1 Introduction and Opportunities

The Frequency Range 2 (FR2) of 5G and the Spectrum Horizons range provide unique opportunities to revolutionize the way we can sense and control experiments under extreme environment conditions, such as radiation, extreme hot and cold temperatures, high pressure, or corrosive chemical environments. The combination of high bandwidths and low latencies makes it ideal for edge applications. At the same time, 5G provides an opportunity to extend the range of our sensing capabilities, for instance leveraging the environment or the 5G signal itself to develop self-powered devices or the beam-forming capabilities available at higher frequencies to achieve spatial selectivity in the way the information is propagated.

The range of extreme conditions encompasses high particle and photon fluxes, chemically reactive or corrosive environments, and thermal and pressure extremes. In all these cases we can have both static and dynamic situations characterized by large, sudden fluctuations in environmental conditions. Extreme environments often involve hard-to-access locations, because they are physically remote, because the process of safely entering the environment requires a complex or time-consuming procedure, or because immediate retrieval of equipment or materials may not be possible due to inherent biological, chemical, or radiological hazards. These environments are critical for DOE and the nation, from fundamental research to manufacturing, energy generation, national security, and space applications.

5G and higher-frequency ranges have the potential to transform the way we operate and interact in extreme environments. In some cases, the opportunities afforded by innovation in this area are similar to those in conventional settings mentioned in other parts of this report. What is different is how transformational these opportunities are, compared with what is currently possible. Conceptually, we can divide these opportunities into four areas.

Priority Research Direction: Extreme Environments

Revolutionize wireless communication in extreme environments through advances in materials science and physics

Key Questions: How can we combine physics, advanced materials, and novel architectures to overcome the current limitations of 5G wireless technology in extreme environments? What innovations can increase the coverage, density, and reliability of sensors by orders of magnitude beyond today's solutions?

Wireless in the terahertz regime can revolutionize experimental science under severe conditions, such as radiation, corrosive agents, or extreme temperature. To realize this potential, we need coordinated research in physics, materials science, and device architectures to provide novel materials with targeted electronic and magnetic properties. Advanced models are needed to predict performance and support integration into advanced wireless platforms.

Enabling new sensing capabilities 5G allows us to have dense, information-rich sensing networks in environments beyond our current capabilities. The ability to deploy such networks under extreme temperatures and corrosive environments would have an impact in areas such as Earth sciences and ecology, where it could both enhance our scientific understanding and improve our monitoring, for instance allowing the development of more comprehensive early warning systems. It would also affect a wide range of industrial domains, from the energy sector to the chemical industry and manufacturing. A network of sensors could also play a key role in environmental monitoring: for example, such a network capable of withstanding forest fires could help provide real-time information to first responders. Furthermore, dense networks of sensors in high-radiation environments would greatly benefit our ability to understand, model, and predict the behavior of systems throughout the nuclear fuel cycle, from energy generation to long-term storage.

Enabling new control capabilities 5G's low latency could greatly expand our ability to remotely control systems in remote and hard-to-reach locations. Access to extreme temperatures and corrosive environments would allow us to extensively monitor industrial facilities across a wide range of sectors, from energy to manufacturing and chemical plants. Having wireless networks of sensors and actuators in high-radiation areas would have a tremendous impact on the operations of nuclear reactors. In both cases, the low latency afforded by 5G and higher frequencies would allow us to detect and correct potential runaway conditions before they cause irreversible damage or to establish fast feedback loops for remote, real-time control. Higher atmospheric attenuation of the wireless signal at frequencies such as 60

GHz could provide an additional layer of security by keeping the communication within controlled facilities while still enabling the design of distributed sensor-to-sensor networks. Other areas such as unmanned autonomous systems, sensing in engines and electric vehicles, off-shore wind farms, and mining could greatly benefit from extending the temperature range in which these sensors can operate.

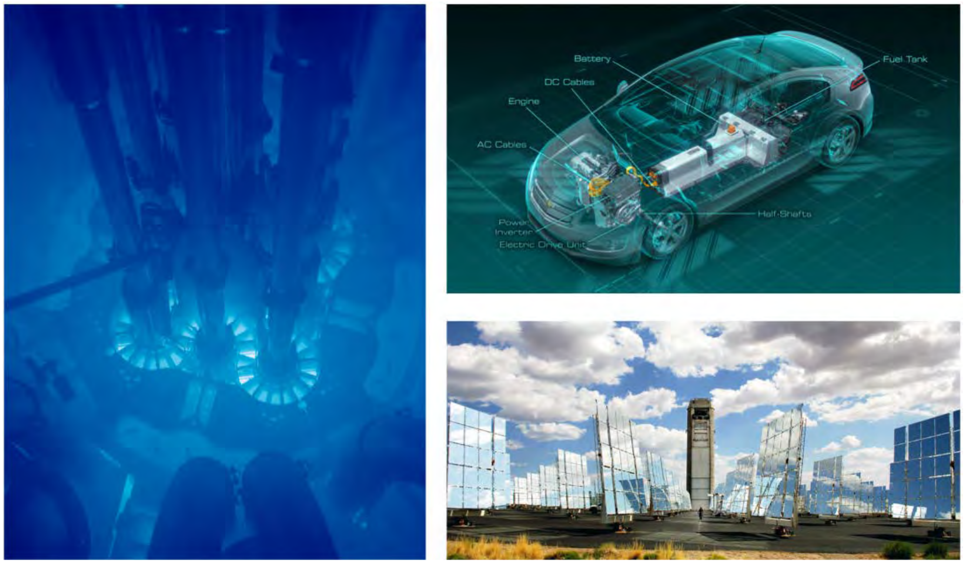


Figure 12: 5G can revolutionize our ability to probe extreme environments, including radiation, thermal, and chemical extremes.

Extending the reach of autonomous sensors The higher energy density of the FR2 and the Spectrum Horizons can lead to new opportunities in the development of autonomous sensors that can be self-powered by using energy harvesting or remotely powered through precisely directed beams. This would greatly enhance the lifetime of remote sensors, which would no longer be limited by battery lifetime or require built-in energy generation capabilities for long-term off-grid independent operation. This capability is particularly valuable in areas where sensor retrieval is not feasible because of the harshness or remoteness of their location or because the sensors are located in hazardous environments.

New sensing modalities The introduction of millimeter-wave RF capabilities into extreme environments can lead to new sensing modalities that leverage the RF signal itself: for example, beam-forming capabilities can be leveraged to monitor the position of mobile sensing platforms. The sensitivity of attenuation to the environment could also be leveraged to monitor and detect changes in an area without requiring the use of more complex imaging technologies that would not be capable of operating reliably without shielding or insulation. This would allow us to augment a few complex, highly engineered sensors with a large network of simpler, smaller, and more robust sensors capable of operating in harsher environments.

6.2 Scientific Challenges and Gaps

We can conceptually divide 5G-enabled devices into three components (Figure 13).

- The *RF component* of the device comprises all the RF operations, including the transceiver and potentially other functionalities such as energy harvesting.
- The *processing component*: is the computing component of the device, typically a host microcontroller or microprocessor.
- The *sensing component* represents the part of the edge device that interacts with its surroundings, either by gathering information (sensing) or by interacting with other components.

These three components have to operate under extreme environmental conditions. They should also be capable of RF communication, both sensor-to-sensor inside the environment and with the outside. In the case of a sealed environment,

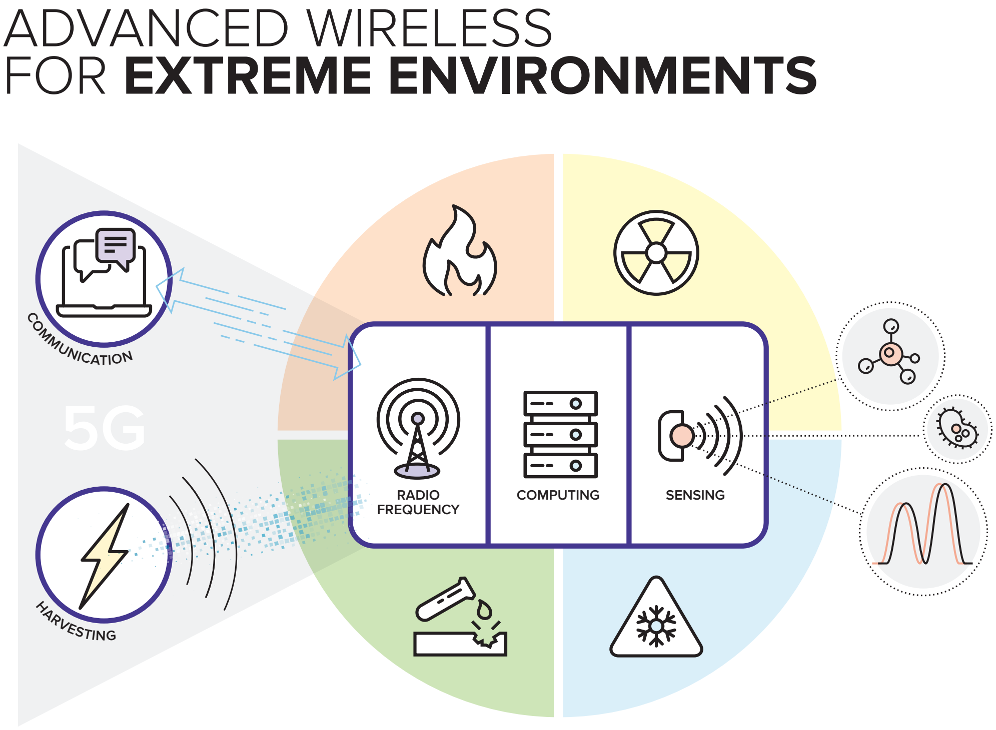


Figure 13: Fully taking advantage of 5G applications under extreme environments will require overcoming fundamental challenges in RF, computing, and sensing. This will have a transformational impact on our ability to do science in harsh and remote environments and across a range of application domains, from Earth sensing and environmental monitoring, to energy generation, advanced manufacturing, nuclear safety, and space applications

this requires either an RF-transparent window or radome or a transmitter/receiver device integrated into the seal to get information through.

Realizing the full potential of advanced wireless devices under these conditions will therefore require overcoming a number of scientific challenges, as described below.

6.2.1 Extending the environmental range of RF processing and computing

One fundamental challenge is how to extend RF processing and computing to extreme environments. While the technology innovation underpinning Moore's law has led to an improvement in our computational capabilities by many orders of magnitude, the more advanced technology nodes have a limited operational range: for instance, silicon RF CMOS is a commercially well-established RF technology, with existing products breaking into the FR1 region of 5G. However, the temperature range of existing devices is limited, with current sub-6 GHz devices having a temperature range of up to 85°C.

Two fundamental challenges prevent the application of advanced semiconductor materials to extreme environmental conditions.

Achieving reliable performance at the high frequencies that are required for advanced wireless applications at extreme temperatures Silicon's limitations are imposed both by manufacturing and packaging technology and by the fundamental properties of silicon as a semiconductor material. Bulk CMOS designs based on 1-micron SOI technology can push the temperature up to 250°C, but with a factor of 4 reduction in performance and clock frequencies below 5 MHz[40]. GaAs sensors, while exhibiting higher radiation hardness, have similar temperature limits.

Wide bandgap semiconductor materials such as SiC, AlN, and GaN offer the opportunity of higher thermal stability. Figure 14 shows examples of target temperatures by applications, together with the temperature limits for some of the promising technologies. SiC transistors have been demonstrated to work up to an ambient temperature around 200°C, albeit retaining only 30% of their room temperature gain [15]. Recent examples have shown SiC JFET's ability to withstand the extreme conditions of Venus's environment, recording the stable operation of a ring resonator at 500°C over more than a week [56]. However, these extreme examples operate at significantly lower frequencies than those required for 5G applications.

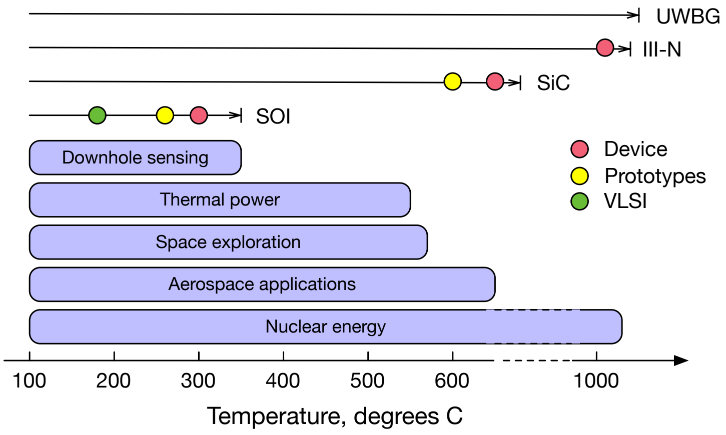


Figure 14: Temperature range for different semiconductors and application domains.

III-nitrides also provide the foundational capability to meet the power and frequency demands of the next-generation wireless communication and sensing systems. GaN has long been considered an alternative platform to Si RF CMOS for RF integrated circuits. GaN-on-Si and GaN-on-SiC are two dominating technologies used for high-frequency switching applications. GaN-on-Si high electron mobility transistors (HEMTs) have shown advantages because of the low cost of the silicon substrate. The technology of GaN-based HEMTs has improved significantly over the past decade: the cut-off frequency, defined as the theoretical frequency for which a device gain falls to a value of one, exceeds several hundreds of gigahertz, while delivering output powers greater than 1 W/mm. The highest current gain cut-off frequencies for GaN-on-Si and GaN-on-SiC HEMTs are respectively 310 GHz and 454 GHz [74, 78]. There are some remarkable examples of high-temperature operations of III-N devices. For instance, InAlN/GaN HEMTs have been shown to operate at 1000°C for 25 hours, albeit at megahertz frequencies. These studies showed that contact degradation was one of the limiting factors [50]. Likewise, in order to achieve low-leakage currents and therefore increase their power efficiency, some heterostructures require the use of gate dielectrics [23]. Typical materials such as aluminum oxide or hafnium oxide do not meet the temperature requirements either, thus constraining the temperature limits of these types of devices.

Novel wide bandgap (WBG) materials and ultra-wide bandgap (UWBG) materials, such as diamond, AlN, and Ga_2O_3, show strong promise in terms of output power, operating temperature range, and breakdown strength compared with GaN. WBG and UWBG materials are well positioned to be used in sensors (strain, pressure, and temperature sensors, accelerometers, and photodetectors) to collect data from extremely harsh environments, where legacy materials are unable to operate or provide the intended level of robustness. However, the level of maturity of device fabrication technologies for these emergent materials is still low.

These challenges extend to all components and building blocks required to build 5G-enabled sensors. Some of the fundamental questions that need to be addressed are how to achieve memory devices that are stable yet allow efficient read/write operations over a high temperature range; how to manage power efficiently, from storage, distribution, and dissipation standpoints; and how to design communication protocols that would help mitigate some of the computing limitations at extreme conditions.

How to implement dense and power-efficient architectures for computing How to achieve CMOS-like levels of performance in terms of power efficiency, density, and speed is a fundamental challenge that needs to be overcome in order to take full advantage of advanced wireless at high temperatures. Si CMOS is limited to temperatures below 300°C. For SiC, a variety of approaches have been explored. Bipolar integrated OR/NOR gates have been fabricated capable of operating at 500°C [46]. However, device sizes on the order of 100 μm and reliable high-temperature ohmic contacts, metallization, and interdielectrics are mentioned as specific challenges. Demonstrations at temperatures exceeding 800°C have been shown for the ring resonator architectures based on JFETs. MOSFET-based designs; however, they suffer from the problem of gate dielectric degradation at such temperatures. Implementation of CMOS in III-N is not possible because of the low mobility of p channels. NMOS GaN-based logic gates, including NOT, NAND, and NOR, have been demonstrated by integrating E/D-modes GaN MOSHEMTs on Si, and they have been shown to operate at temperatures up to 300°C [86]. The level of development of all these approaches, however, is at most at medium-scale integration.

Nontraditional architectures and emergent materials could provide an alternative approach to overcoming this challenge. For instance, machine learning accelerators could help streamline the implementation of complex operations at extreme environments. Recently some algorithms have shown the ability to operate with up to 40% errors in write operations and device variability in architectures based on crossbar arrays, which could help operate at the limit of device reliability [80]. The bulk of research on memristors and selectors, however, has focused on room-temperature operations, and the switching behavior of some existing materials is sensitive even to thermal crosstalk. The interest in high-temperature devices thus far has come primarily from the desire to increase their retention properties, with chalcogenide-based devices reporting stable operations at 150°C [18, 38].

6.2.2 Improving our ability to manipulate electromagnetic fields

Signal-processing technologies play an essential role in RF applications. Examples include high-performance power amplifiers that deliver high-power RF signals with good efficiency, on-reciprocal devices that guide and redirect RF waves to avoid signal jamming at transceivers, high-Q filters and frequency selective limiters that discriminate and filter RF signals to reduce interference, and signal-to-noise enhancers that preferentially absorb small signals. All these devices function through materials that can interact with the electric or magnetic field component of electromagnetic waves, such as ferromagnetic, antiferromagnetic, and ferroelectric materials.

The manipulation of RF signals becomes more challenging in the high-frequency regime because of reduced source power density, larger signal attenuation, larger insertion losses, and requirements for larger dynamic range and bandwidth. Millimeter wavelength requires compact devices that are comparable in size to half of the wavelength. Therefore, miniaturized components must be densely placed within a compact device. Heat dissipation issues can then become more pronounced, leading to temperature instability. Materials and devices that can work within a higher temperature range are needed.

Another challenge associated with reduced device size is increased power density, which causes material dielectric breakdown. In order to avoid this, devices are designed to accommodate reduced power density, which again calls for an increased number of elements, leading to design complexity and signal interference. In addition, impedance typically scales with frequency. Any mismatch will be amplified and can result in additional losses. Hence, achieving low insertion loss at high frequencies can be challenging. At high frequencies, the electromagnetic spectrum is absorbed and scattered more significantly by atmospheric conditions and path obstacles, causing signal attenuation. To maximize the possibilities of 5G and high-frequency wireless, we need to develop materials that enhance our ability to manipulate electromagnetic fields with high efficiency. We also need dynamic materials that are more capable of design flexibility and adaptation to maximize electromagnetic coupling, for instance, to increase the efficiency of energy harvesting or to manipulate the emission (smart antennas).

6.2.3 Understanding the impact of ionizing radiation on advanced semiconductors

Radiation hardness analyses are available for commercial Si-based devices. However, these devices are limited to frequencies below 10 GHz. GaN transistors became available commercially in 2010, but they have not yet found their way into space instruments, despite their potential to reduce an instrument's size, weight, and power consumption. Although GaN is predicted to be resistant to many types of radiation, neither NASA nor the U.S. military has established standards for characterizing the performance of these transistor-enabled devices under extreme radiation exposure. When struck by galactic cosmic rays or other ionizing particles, electronic equipment can experience catastrophic or transient single-event upsets. Although the standard of silicon transistors failure is well assessed, the radiation hardness of GaN transistors remains underexplored, particularly at high frequencies.

At the device level, the effect of proton, electron, gamma ray, and neutron irradiation has been studied on various GaN-based HEMTs. While some fundamental studies have looked at the impact of radiation from a materials science perspective in model systems [41], the majority of research has focused on evaluating the impact of irradiation on the electrical performance [60]. Common effects include the decrease of the saturation current and transconductance, which have been attributed to a degradation of the 2D electron gas. These effects have been observed under proton, electron, neutron, and gamma ray irradiation [61, 79] in AlGaN/GaN, AlN/GaN, and InGaN/GaN HEMTs. In some cases, negative threshold voltage shifts and an increase in 2D electron gas sheet concentration, attributed to radiation-induced nitrogen vacancies acting as donors, have been observed for irradiation with gamma rays.

Proton irradiation results also indicate that the effect of radiation can be higher for devices operating at RF frequencies when compared with DC operation [22]. The devices showed a reduction in the cutoff frequency with increasing exposures, but they were limited to frequencies below 10 GHz. This work also observed that NH_3-rich devices showed more degradation in RF gain than did Ga-rich devices, suggesting that radiation effects could be mitigated through synthesis control of the semiconductor.

Our lack of understanding of how radiation affects device performance above 50 GHz and our lack of knowledge about the fundamental causes leading to that degradation are fundamental challenges that need to be overcome. They both negatively impact our ability to build III-N devices that can reliably operate in the Frequency Range 2 of 5G and the Spectrum Horizons range, which extends beyond 100 GHz. Few studies have focused on the RF performance of devices. Also, the behavior under neutron irradiation has been comparatively less studied, and microdose experiments that could provide detailed mechanistic information on the temporal dynamics of the damage on different layers and junctions are scarce [10]. Even fewer studies combine the effect of both radiation and extreme temperatures. For novel WBG and UWBG materials, the effect of radiation and their impact on active channels at high frequencies remains largely unexplored.

6.2.4 Understanding the fundamentals driving device reliability at high frequencies

Reliability and time-dependent degradation of the underlying transistor technology are major concerns for operation under extreme environments, since they reduce the operational lifetime of any communication and sensing infrastructure. Reliability studies are also done after often costly design and fabrication processes, and results from reliability measurements are usually fitted to empirical models that do not provide a link between materials science, physics, and time-dependent circuit failure. In some cases, such as high-radiation environments, replicating the desired environment is difficult and beyond the reach of device manufacturers.

Computational approaches, such as Monte Carlo techniques, can model the interaction of radiation with matter, providing key insights into degradation processes pertinent to harsh environments. Examples of Monte Carlo simulators used for radiation transport and energy deposition include COSMIC, MCNPX, CUPID, SEMM/SEMM-2, and FASTRAD [43, 65, 73, 77]. Monte Carlo-based assessment of radiation effects go beyond analytical computations that are suited mainly for legacy technologies. However, the speed and cost of implementation of Monte Carlo methods become prohibitive in complex scenarios.

Gaps also remain in our understanding of and ability to predict the reliability and failure mechanisms of advanced semiconductors at high frequencies. The effect of large gradients of electric field and temperature and strong radiation in WBG and UWBG materials is not well understood. First, the physics of matter when driven far from equilibrium cannot be captured by using statistical methods, and first-order transport equations typically fail to capture key carrier dynamics. In equilibrium, the distribution functions of electrons and phonons are described by the Fermi-Dirac and Bose-Einstein statistics, respectively. However, under nonequilibrium conditions that are to be expected in extreme environments, such as cyclic wide-temperature-range environments, the distribution functions assume a significantly different shape, something that is not fully captured with existing simulation tools.

Existing models treat thermal resistance empirically, thus lacking the connection between device performance, degradation, and key material and layout parameters. Apart from the creation of hotspots and thermal runaway challenges, large temperature excursions also fundamentally change the dynamics of traps. Therefore, new insight into the interaction between thermal and electric field gradients and trap characteristics will be needed to enable reliability-aware computational frameworks.

6.2.5 Developing accurate models to predict performance in extreme, dynamic environments in real time

To design and deploy 5G-enabled networks of sensors capable of operating in extreme environments, we need to develop advanced models that can predict performance and model their integration into advanced wireless platforms in real time.

Existing approaches to model signal propagation at high frequencies focus on standard environmental conditions, combining atmospheric attenuation with propagation models that can account for the impact of multiple paths on signal intensity at a given location. Demonstrating the enabling capabilities of advanced wireless in extreme environments will require the extension of existing models to incorporate a range of behaviors and conditions that are not usually found in standard applications.

These include distinct chemical environments, for instance incorporating molecules that could impact propagation at specific frequencies, sometimes with strong concentration gradients, strong turbulence, or the presence of large thermal gradients that may lead to changes in RF coupling. Likewise, these models should be capable of simulating novel sensing modalities, for instance leveraging beam forming to locate specific sensors or using attenuation as a sensing tool itself. Furthermore, they should be able to simulate dynamic environments where atmosphere, temperature, and surrounding objects are all changing with time. A fundamental challenge is how to achieve these goals in real time. This is a key requirement for developing digital twins that can be used to validate and predict experimental observations and the performance of wireless-enabled sensors in physically remote or hard-to-access environments.

6.3 Research Thrusts

6.3.1 EE-1: Design of novel materials with targeted electronic and magnetic properties that will help us transmit, control, and manipulate electromagnetic fields with high selectivity

The development of novel materials that enhance our ability to manipulate high-frequency electromagnetic fields should be a research priority. These include novel materials and composites whose enhanced electronic and magnetic properties are enabled by new chemistries, crystal structures, electronic structures, magnetic substructures, and microstructures (Figure 15). Materials and composites that take advantage of the interplay between two or more magnetic subsystems such as multiferroics will also play a fundamental role [70]. This research thrust should also include the development of novel synthesis routes that will enable better integration.

We also need to deepen our understanding of how to fully leverage microstructure manipulations to enhance material properties. Examples include the utilization of interface effects and short-range coupling in thin films and composite materials, such as exchange-spring and exchange-bias interactions in magnetic multilayers, and the use of metamaterials and metasurfaces to redirect the electromagnetic wave propagation.

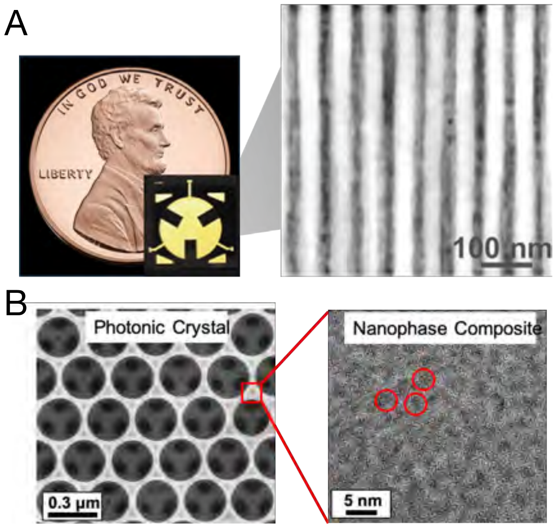


Figure 15: Novel materials, such as aligned magnetic nanofibers or hierarchical materials, combining microstructure at multiple length scales, such as refractory nanocermets infiltrated in periodic scaffolds, offer the possibility of manipulating high-frequency fields in unique ways [14, 24].

Extreme environments also impose additional requirements on materials in terms of reliability and durability. Therefore, we should focus on developing materials that are stable in extreme environments, such as magnetic materials with high Curie temperatures and a small temperature coefficient of magnetization, required for high-temperature applications, and materials that

are radiation resistant and stable at extremely low temperatures,
key for space communication applications.

Moreover, we need to develop novel approaches to synthesize these novel materials and magnetic nanostructures in ways that will allow the integration on semiconductor substrates. These include not only films but also novel approaches that allow a full 3D control of the material microstructure and that enable some of the unique magnetic properties afforded by the microstructure control. Magnetic nanowire metamaterials integrated with SiC/AlN MMICs and magnetoelectric antennas made from suspended ferromagnetic/piezoelectric thin film heterostructures are two such examples [24, 54].

Designing materials for 5G applications in extreme environments must account for potential changes in temperature and pressure that can trigger phase transformations, with negative impact on material properties. Since such changes are difficult to predict, modern design methodologies incorporate uncertainty quantification to add confidence levels to material performance during operation. Recent developments in *design within uncertainty* provide a framework for creating new multicomponent 5G materials that respond well to changes in extreme environments [59].

6.3.2 EE-2: Development of novel materials and architectures to enable computing, sensing, and control platforms under extreme environments

Fully realizing the potential of high-frequency wireless technologies under extreme environments will require foundational research on materials and architectures to enable computing and RF signal processing under extreme conditions.

We need to deepen our understanding of novel WBG and UWBG materials such as aluminum nitride and other III-N materials, gallium oxide, or aluminum gallium oxide. We also need to study the stability of the different interfaces required for high-temperature devices in order to better understand the absolute limits of device operation. Moreover, we need to determine how to design heterostructures that can replicate the advantages in terms of power efficiency of Si CMOS in novel WBG and UWBG semiconductors and are thermally stable up to the physical limit of the semiconductor material. The integrity and robustness of these newer platforms will also be determined by other key components such as passivation layers, contacts, interconnects, and gate dielectrics. These will require developing materials that can maintain a well-defined electrical behavior over a wide range of static and dynamic conditions, including large thermal fluctuations.

A second priority should be the exploration of materials that can preserve state under harsh conditions, yet at the same time are volatile enough to enable read and write operations, for instance leveraging either chemistry or external fields to control the energy barrier between different states. These materials can provide the foundation for high-temperature volatile memory technologies or enable high-temperature neuromorphic architectures.

In parallel with the exploration of novel materials and heterostructures, we need radically different approaches to computing and sensing under extreme environments. Photonic and optoelectronic devices, stochastic devices, or neuromorphic computing could provide a more robust bridge between the RF and sensing components that would alleviate the need for having a complex CMOS-based computing layer at the edge. The bulk of research on emergent materials and devices for microelectronics has focused on room temperature conditions, and therefore a priority should be to understand how to extend these promising approaches to high-temperature, high-radiation, and corrosive environments.

We also should prioritize the development of co-design approaches to accelerate the transition of novel materials into relevant technology for advanced wireless applications. These approaches need to integrate materials discovery with novel architectures, algorithms, and their physical implementations. Co-design approaches that can optimize the performance of relevant tasks in the RF and edge processing and simultaneously optimize the hardware layer at the device or circuit level could help drive the design of emergent materials in advanced wireless platforms and accelerate the integration of fundamental discoveries. Coordination with other priority research directions, such as edge computing, could lead to the identification of novel sensing modalities that leverage the presence of a dense sensor of networks and that could be implemented with simpler architectures.

6.3.3 EE-3: Improvement of our fundamental understanding of the behavior under extreme environments of physical media and materials at frequencies above 50 GHz, in order to enable computing, sensing, and control

Fundamental studies are necessary to establish solid foundations at the materials and physics levels that will help us understand the behavior of materials in harsh environments as well as the fundamental limitations of different device designs.

The first priority is to develop novel in situ and in operando techniques to probe novel materials and model heterostructures under high-frequency fields at relevant experimental conditions, such as high temperature and high neutron and charged particle fluencies. These new techniques should augment more traditional device-level characterization and provide direct information about the behavior and properties and the materials and interfaces to inform the development of better physics-based theoretical models and simulation tools. DOE's X-ray and neutron facilities are well suited for this task (Figure 16). For instance, submicron spatial resolution through the use of focused beam and coherent X-ray sources can be used to map strain and temperature fields in active areas of devices. Improved time resolution would allow the visualization of transient effects under ionizing radiation conditions.

Figure 16: DOE user facilities, such as the Advanced Photon Source (top) and the Los Alamos Neutron Source Center (bottom), can enable the development of novel characterization tools to probe electronic materials under nonequilibrium conditions, such as high frequencies and fields, at extreme temperature and radiation environments.

We also need to develop advanced computational tools that bridge the material, device, and architecture scales and that incorporate the stochastic nature of reliability and failure. Achieving this goal will require developing better models that are suited for novel advanced semiconductor materials, as well as leveraging existing high-performance computing capabilities to create detailed physics-based models that can realize circuits of the level of complexity and during timescales that are relevant for advanced wireless applications.

For instance, new models are needed that can capture effects derived from the ultra-scaled dimensions of WBG and UWBG devices designed to achieve cut-off frequencies exceeding several hundreds of gigahertz. Development of such models would necessitate the integration of tools such as full-band Monte Carlo simulations and the hydrodynamic formalism to treat the subsystems corresponding to free carriers, traps, and the lattice separately as the device is driven out of equilibrium. These formalisms should then be integrated into the RF circuit or architecture scales. The ability to scale these simulations into DOE's leadership computing capabilities would allow the simulation of realistic architectures with a level of fidelity that is well beyond current capabilities.

6.4 Scientific Impact and Outcomes

The proposed research thrusts will impact the following areas.

Discovery of new ways of controlling and manipulating electromagnetic fields. Millimeter waves sit at the crossroads of various disciplines, including composites and traditional magnetics, semiconductor processing, additive manufacturing, and metamaterials. A focused research thrust on the synthesis of novel fundamental and engineered materials and nanomaterials will help advance our ability to manipulate electromagnetic fields in the millimeter-wave range. It will also bring together researchers from diverse fields, creating a critical mass that will accelerate novel discoveries and foster cross-pollination and will enhance our understanding of the fundamental aspects of these materials. Fundamental breakthroughs carried out in this area provide opportunities to generate new functionality and applications, such as voltage-tunable filters, inductors, bandpass filters, phase shifters, and energy-harvesting devices.

Development of the critical building blocks that will enable computing and communication under harsh environments Moore's law has led to the development of devices and architectures that are not well suited for extreme environmental conditions. The research thrusts in this priority research direction will provide the foundations—in terms of novel materials, devices, and architectures—that will enable sensing, computing, and communications well beyond where such activities are currently possible.

Attainment of an atomistic view and mechanistic understanding of the interaction of radiation with novel electronic materials This priority research direction will lead to a better understanding of the impact of radiation at the microstructure level and its impact on the electron transport and on the properties of heterostructures. The combination of spatially resolved in situ and in operando techniques coupled with more advanced simulation techniques adapted to run on DOE's leadership computing facilities will lead to detailed atomistic understanding of radiation-induced defects and the capabilities of modeling the dynamic response of the material during single events.

Development of a fundamental understanding of the electronic properties of materials at high frequencies and extreme temperatures The proposed research will further our understanding of the electronic properties of semiconductor materials under nonequilibrium conditions, including high frequency and high fields. These fundamental aspects will seed novel predictive computational frameworks that account for reliability physics specific to WBG and UWBG materials. These will guide the experimental fabrication of highly reliable devices and streamline the transition from lab to market. The computational tools framework will also lead to the development of new reliability-aware compact device models that are specifically targeted to studying the long-term dynamic response of ultra-high-frequency transceivers and sensors. The unification of physics of reliability with device scalability and compact models will ultimately create an ecosystem of WBG and UWBG materials ready for their deployment in 5G and millimeter-wave infrastructure.

7 Testbeds

7.1 Introduction and Opportunities

Our ability to measure events in the world and dynamically coordinate sensors and analytics will soon be revolutionized by advancements in mobile communications. Diverse application communities are now grappling with the challenges and opportunities that 5G, mmWireless, and other emerging advanced wireless technologies will bring to logistics, smart cities, transportation, manufacturing, food production, education, and many other facets of national activity. Fundamental unknowns exist in our understanding of how such wireless capabilities will be deployed and which R&D investments will best serve national needs for critical infrastructures use of 3GPP 5G NR and other advanced wireless options. Among these critical infrastructures is the national scientific and industrial base, supported by DOE's national laboratories.

An integrated set of 5G community testbed activities is necessary in order to support exploration of the unresolved research questions, and opportunities outlined throughout this report:

- How will we adapt current science workflows to take advantage of advanced wireless network features and the promise of the emerging **digital continuum**, as described in §3?
- How can we successfully deploy **edge computing** resources as an integral part of advanced wireless science systems, as described in §4?
- How can we lower the cost and difficulty of integrating **scientific instruments** into advanced wireless hardware and software stacks, as described in §5?
- How can we extend the range in which advanced wireless technologies may be deployed to include the **extreme environments** often encountered in the field, in space, or inside laboratory settings, as described in §6?

Priority Research Direction: Testbeds

Accelerate innovation by using community testbeds to explore advanced wireless for science

Key Questions: How does advanced wireless interact with scientific instrumentation? How can we develop scalable deployments for 5G-enabled science, test integration with new or existing scientific infrastructure, and benchmark the real-world performance of wireless sensors for scientific instruments and facilities?

Building an open wireless testbed with a capable wired backhaul to DOE scientific user facilities is foundational for developing next-generation applications and new hardware and software architectures and for testing new scientific instruments. Such a testbed can ensure that innovative research can successfully transition from concept to practice and also provide insight into resilience, performance, and security.

To resolve these unknowns, testbed capabilities will play a vital part as we identify technology needs and use cases, craft successful technology solutions, and create the tacit workforce skills necessary to integrate technology with applications. Multiple advanced wireless testbeds have been established by other nations seeking competitive advantages in this technology, to shape ITU frequency allocations and technical standards. There are several ongoing trials of 5G in Europe [1]. Domestically, such advanced wireless testbeds have also been deployed to support application areas such as smart city planning, disaster management, and product development [6]. The DOE national laboratory science complex is a critical component of American prosperity, security, and efforts to ensure global R&D leadership and technological advancement. Maintaining the excellence of 27 Office of Science user facilities, as well as ensuring U.S. technology leadership by developing "a robust, dynamic, and flexible spectrum environment," depends on the ability to study, deploy, and shape compute, data management, and communications resources [45].

In the absence of a science-complex-wide capability to test, operate, and integrate advanced wireless with DOE mission activities, the United States will face difficulty addressing many of the key challenges specific to our national science and technology infrastructure posed by this technology revolution.

- How will we ensure that this new vital national wireless infrastructure will successfully leverage U.S. strengths in virtualization and open source development and will prevent scientific supply-chain dependencies on any individual

or foreign technology provider? For example, in order to fulfill the intent of the 2020 **National Strategy to Secure 5G of the United States**, the ability to prototype, test, and integrate improved virtual radio access network and other standards will be essential to ensure performance and supply-chain security. Such testbed facilities may be a key enabler also for DOE and DoD joint interagency programs and agreements and for related network and supply-chain security research, such as support for DARPA's Open, Programmable, Secure 5G [69].
- How will networks manage different application needs for latency, security, and reliability, and how will these applications connect to national scientific high-speed wired networks (such as ESnet) or supercomputing facility resources (such as at ORNL, ANL, and LBNL)?
- How will we more efficiently partner with private-sector infrastructure 5G communications and sensor networks, to better support DOE's science mission and the benefits provided to our country?
- Most vitally, as 5G catalyzes new technologies, new skills, new fields of scientific inquiry and new methods, how will we ensure that the United States remains the world's leading technological and scientific innovator?

DOE has a long history of supporting national objectives for previous generations of wireless communications [5]. However, the potentially much wider applicability of 5G and advanced wireless capabilities to support national science objectives far exceeds what was offered by 4G and previous wireless data capabilities. The following are some salient examples of "new science" that 5G/advanced wireless may enable:

1. Tying field bioagricultural experimentation directly to high-fidelity simulation and laboratory-controlled plant growth environments, supporting identification of metabolic, environmental, and genetic plant/soil organism linkages
2. Monitoring the Earth dynamically and in near-real time with robotic, unattended, and mobile platforms and scientific models informed by private-sector sensor systems such as SailDrone and Digital Earth
3. Preventing pandemic and disease outbreaks, such as through the collection of rich, dynamic data on public health, population patterns of movement, IoT tracking of health resource use, and patient self-reporting via social media

To manage the scientific risks and rewards from the advanced wireless, the DOE national laboratories should take on the challenge of **developing an advanced wireless testbed capability** comprising targeted science applications, both fixed and redeployable, and where experiments can be conducted to support the broad range of research questions articulated throughout this report. The goal of this testbed effort should be to boost access and resources available for innovative advanced wireless research into **both the fundamentals of the technology and in the applications made of it by science users**. Such a testbed capability is essential for supporting applications, experiments, new architectures, and new cyberinfrastructure approaches across the DOE mission space, from fixed-site user facilities, to mobile Earth and energy science, and to dense IoT sensor networks, and would provide access to national—lab-deployable and commercial wireless—assets. Via high-speed connectivity with ESnet, DOE's current high-speed science network user facility, **all existing DOE sites and user facilities would be enabled by this testbed resource**.

7.2 Scientific Challenges and Gaps

Whether a single physical entity or more of a virtual and distributed resource, this advanced wireless science testbed capability should be focused on three key areas (based on our present understanding of the use of this technology for Office of Science applications).

1. A 5G-enabled computational continuum focus area that can support exploration of new, open source wireless software stacks and associated cybersecurity evaluation and testing of edge computation in distributed environments for DOE science
2. A 5G-enabled future scientific research facilities focus area that can support integrated scientific measurement campaigns and the design of new instruments ranging from fixed user facilities to distributed or mobile deployments, including extreme environments
3. A national-scale integration focus area for the development and optimization of protocols, methodologies, and policies for both technical and administrative scientific capability and user facility interoperation

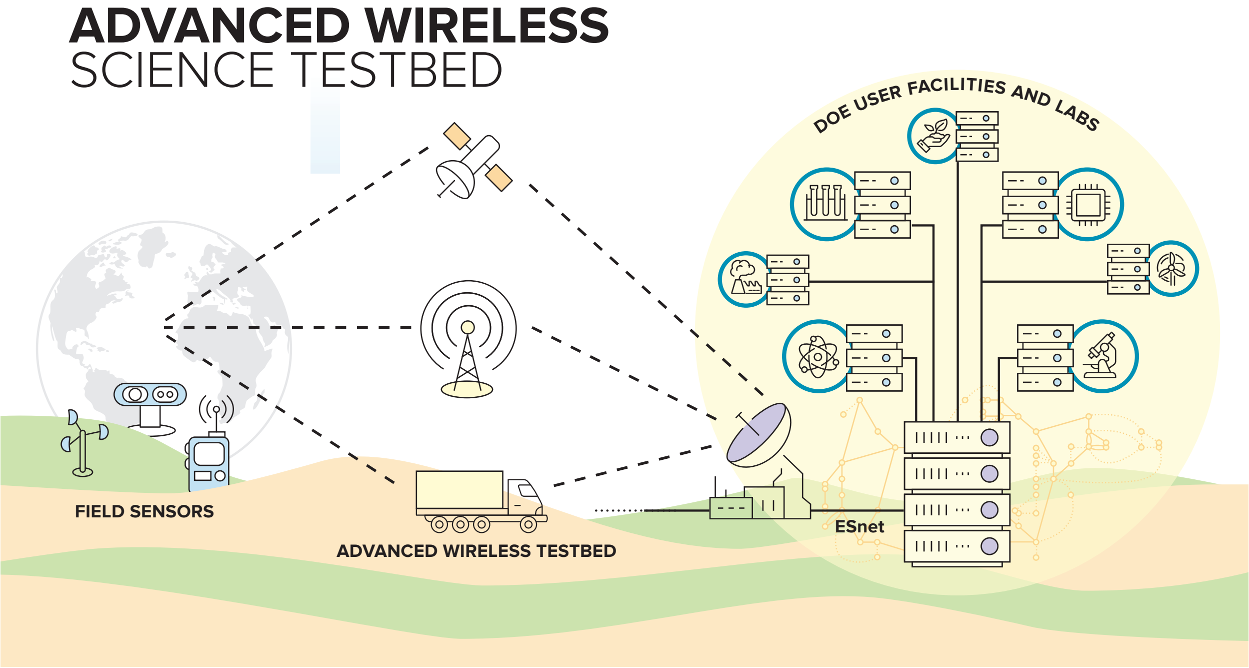
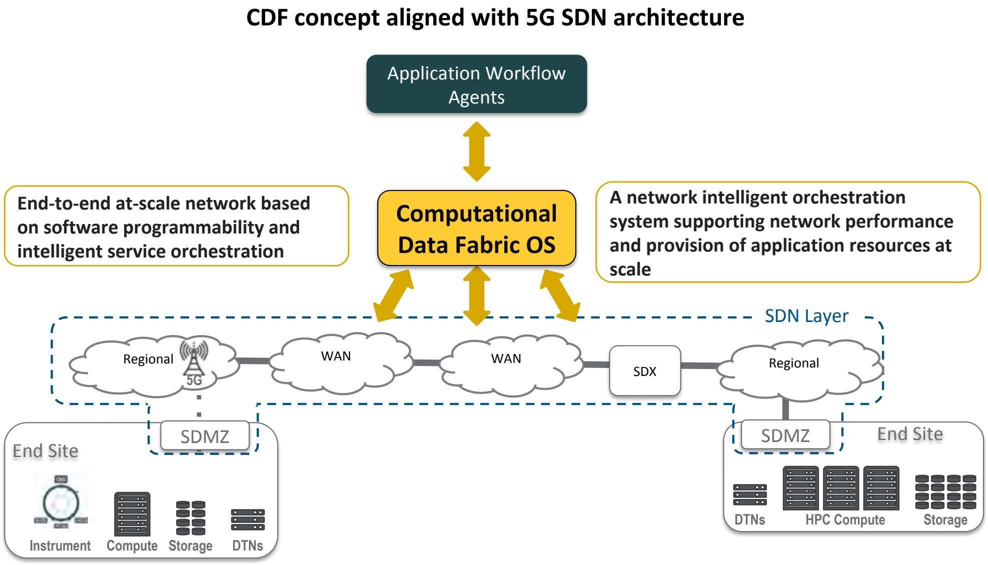


Figure 17: Advanced wireless science testbed, ensuring the global sensor reach of DOE labs and user facilities.

7.2.1 Creation of a 5G-Enabled Computational Continuum Focus Area

Our understanding of the world relies on our ability to measure and to provide those measurements to a wide set of analytic workflows. Future instruments supporting global science measurement must be deployed widely and will generate increasingly large datasets in a multitude of formats. The creation of a computational continuum, comprising a computational data fabric (CDF) spanning from edge to network to HPC, is essential to enable seamless translation between data and knowledge and to effectively guide scientific discovery, decision-making, and data management.



End-to-end at-scale network based on software programmability and intelligent service orchestration

A network intelligent orchestration system supporting network performance and provision of application resources at scale

Figure 18: Enabling the computational continuum through a wireless-enabled computational data fabric.

In order to create a wireless-enabled computational continuum, application workflows must be automated, supporting computing both on the edge and throughout the network architecture, able to automatically move data across mixed wired, terrestrial wireless, and orbiting satellite non-terrestrial networks (NTNs) as needed. Furthermore, the computational continuum vision implies seamless movement of large data volumes between different administrative domains, including to and from compute, storage, and analysis resources. Accordingly, the network-based control logic for such movements will dynamically manage fundamental and situational infrastructure limits (latencies, network topology changes) as part of intelligently meeting science objectives.

The computational continuum focus area research could start with the construction of one or more "scientific wireless blanketed" national laboratory sites. By creating a dedicated, secure, and at least partially DOE-owned advanced wireless (5G, mmWireless, NTN) infrastructure, researchers could experiment with applications support from all DOE science user facilities leveraging backhaul from ESnet's existing optical high-speed links. This approach would jump-start research in science-focused wireless software-defined networking (SDN) methods, AI, and automated large data movement, as well as other next-generation applications, ensuring that technologies are "wireless-compatible from birth." Such an approach maximizes the chances that CDF and other computational continuum components can successfully transition from theory to practice. In addition, research enabled by this approach ensures that Office of Science requirements for networking hardware (such as edge computing via FPGA-based SmartNICS) are identified early and impact industry plans for sensor data management and hardware integration standards, sustaining DOE leadership in the development of advanced wireless standards and industry partnerships.

7.2.2 Creation of a 5G-Enabled Future Scientific Research Facilities Focus Area

The advanced wireless science testbed should be capable of supporting deployment of resources both at national laboratory sites and out in the world where science must increasingly be conducted. By leveraging both laboratory sites and external "field" testbed environments as part of an integrated program, DOE would ensure integration of 5G and mmWireless capabilities across the range of potential science applications. One such approach might be to create a total of 20–30 scientific research test zones, each 1 km^2, interconnected via ESnet, designed to support tens of thousands of devices, from sensors to valves to drones, robots, or traditional computing platforms. Wireless testbed "research test zones" could include DOE laboratories, key universities, remote instruments, and industry zones to support research partnerships with U.S. industry (e.g., manufacturing, chemicals/materials, robotic self-driving laboratories, environmental and urban sensing). These testbed scientific research test zones would be fully separated from the Internet with only several strategic entry/exit points through ESnet, enabling research in new approaches to cybersecurity, infrastructure controls and protection, and the design and operation of scientific facilities from exascale computers to advanced light sources. Within each area, different activities would be studied depending on the research focus of each lab or field site.

At National Laboratory Sites: As scientific advanced wireless attains its potential, existing facility control and data-management capabilities currently supported by expensive wired connection "cable salads" may be replaced by small, low-power wireless communication devices throughout the scientific facility or instrument. This change in fixed-site wireless capabilities will create integration challenges for existing systems and applications not designed with these communications in mind. For example, unintended RF emissions from wireless telemetry devices may have an effect on scientific instruments, which must be studied prior to full-scale deployment. Sensors often will be deployed inside difficult connectivity environments such as fermentation tanks or while subject to extreme conditions proximate to hazardous chemicals or magnetic or radiation fields. National advanced wireless science testbed capabilities should be solution agnostic so that they can support use of both DOE-owned dedicated or commercially provided 5G and mmWave-band network resources, allowing exploration of the full range of emerging wireless options supporting facility design and retrofit. Near-term testbed studies leveraging existing user facilities will prove crucial in identifying benefits of increased sensor deployment for future research facilities, and many benefits will accrue from identifying and mitigating these risks in a testbed versus waiting for deployment of a wireless system as part of a new facility program.

Figure 19: Examples of current “cable salads” impacting facility spaces and operational flexibility.

Out in the World: While in the past, many “high data-generating” science applications were physics related, data collection rates have now made connectivity an increasing challenge for environmental, energy science, national security, and other field science projects as well. This challenge is not always a simple function of distance from infrastructure; domestic and international scientific field sites (such as a meteorological sensor in South America or an agricultural field station in California’s Central Valley) may equally lack adequate connectivity to national laboratory image-processing or simulation resources. Field science practitioners are increasingly capable of deploying sensor arrays that can generate large amounts of data, but they face compromises on how science can be performed because of a lack of network options with sufficient performance, reliability, or traffic management capabilities.

In addition to enabling advanced network connectivity at national laboratory sites, therefore, advanced wireless science testbed capabilities should be relocatable to meet the needs of field science applications. Such resources will be especially valuable for improving the ability to task and manage dense networks of sensors in the world. Understanding and enabling prediction of field operational factors such as wireless attenuation, spectrum interference, power use, and integration of scientific sensors with in situ private-sector infrastructure will be vital activities for relocatable advanced wireless testbeds. These mobile testbeds will allow for more effective and efficient deployment of sensor systems and networks in remote locations and will increase our understanding of the effects of advanced communication technologies on scientific research and discovery. Nimble relocatable testbed resources will also be vital to assay science sensor system vulnerabilities to cyber vulnerabilities and hostile attempts to disrupt RF spectrum use, since essential commercial infrastructure cannot be severed as part of network threat experiments.

As a secondary benefit, investment in robust relocatable advanced wireless capabilities for field science use could create an additional stockpile of 5G and mmWireless equipment supporting national resilience and communications restoration, since many capabilities of interest for science users (such as mobile 5G/mmWireless COWs (Cell sites-on-Wheels), COLTs (Cell-on-Light Trucks), and high-altitude aerostats) could be repurposed in an emergency to reconstitute civilian communications.

7.2.3 Creation of a National-Scale Integration Focus Area

Leveraging industry partnerships and integrating advanced wireless capabilities into existing national infrastructure will be an essential focus of testbed activities to support science. Not only is this integration necessary in order to widen the reach of science, ensuring that a sustainable model is built out that can be scaled appropriately; it is also necessary to leverage affiliated private-sector technology research and investments already underway. Existing ASCR leadership-class computing resources at ANL, LBNL, and ORNL, as well as multiple large-scale scientific user facilities and the ESnet high-performance optical network, must be connected at one or many sites supporting a national testbed capability. For example, **dedicated 5G test zones at DOE laboratories, interconnected with ESnet**, would support research, development, and prototyping of 5G capabilities to instrument data centers (ANL, LBNL, ORNL) or user facilities such as large-scale light sources (LBNL, ANL, BNL). 5G test zones at partner university campuses would

Figure 20: Tying testbed activity to other scientific network advances, such as FABRIC.

support workforce development and tapping academic expertise in key areas of basic research. Similarly, 5G test zones could be used to support uses by strategic industries (transportation, manufacturing), energy, and water utilities and to leverage DOE investments in basic and applied research field programs ranging from the Atmospheric Radiation Measurement user facility to deployments to instrument the urban-rural gradient, urban energy innovation districts, or major transportation hubs. Accordingly, design and operation of such a testbed should be carefully coordinated with existing community projects, such as the NSF-funded FABRIC [3] research infrastructure, as well as component assets within FABRIC such as US-Ignite, TAMU, and COSMOS.

A testbed area supporting wireless integration of national scientific data movement capabilities will facilitate the creation of standards, the development of new communication and data management protocols, and the evaluation of technology opportunities by private-sector investments in wireless technology. This integration testbed, or "proofing" area, would allow DOE science assets to reduce risk to long-duration science user facilities and associated wireless components essential to the success of these facilities. As part of the advanced wireless testbed for science, the integration area would also maintain ties to the standards, practices, and methods used by non-scientific wireless communities and infrastructures, in order to identify points of mutual interest or to assess impacts from spectrum allocation changes, ITU decisions, supply-chain changes, or other external matters impacting science wireless use. Commercial cloud and wireless network providers would therefore play a key role in this part of the DOE wireless testbed effort, and the success of engagement with non-DOE wireless technology partners in the nation's advanced wireless will be a key constituent of successfully enabling science through 5G and mmWireless communications.

7.3 Testbed Development and Research Support Thrusts

The deployment of an advanced wireless science testbed capability can be achieved by undertaking the following research thrusts.

7.3.1 TB-1: Technology Assessment and Evaluation

5G and advanced wireless capability development is being driven predominantly by private-sector investment. Network operators are expected to invest up to $1.1T between 2020 and 2025 on equipment and service upgrades [35]. This investment dwarfs resources available to the science community for wireless investment. Any U.S. advanced wireless science testbed will need a robust capacity to evaluate and assess the impact of proposed changes in private-sector-led technology standards, frequency allocations, networking and encryption protocols, and hardware stack developments.

The following research activities will contribute to this capability:

(a) **Virtual and real advanced wireless testing capabilities.** While physical testing and deployment of advanced wireless equipment will be essential, just as necessary will be a high-fidelity **simulation-based "virtual testbed" capacity**. Future and emerging advanced wireless technologies (for example, massive MIMO technology, high-linearity devices, and phased array radios) will have implications for all parts of the advanced wireless "system," from device/handsets, to use cases, to backhaul and even associated wired optical data transmission protocols. Many of these interactions cannot be forecast well in advance by using physical testing, yet influencing technology requirements and international standards-setting bodies may require U.S. participation five or more years ahead of time. Unless either analytic or simulation testbed capabilities are available, accurate, and part of any national advanced wireless science testbed program, the value of the concept to national science planning and investment will not be realized.

(b) **Full technology stack experimentation:** Advanced wireless, 5G, and emerging mmWireless technologies range across a wide space of capabilities. 5G consists of many still-evolving subsystems, deployment spans a wide spectrum range (from 600 MHz to 72 GHz), and various design-basis use cases are supported (enhanced mobile broadband, ultra-reliable low-latency communications, and massive machine-type communications). Other advanced wireless technologies such as satellite-based NTNs and mmWireless radio employ separate signal and control protocols as well as different antenna, hardware, backhaul, and interconnection methods with application components. In order to capitalize on these to support scientific uses, a testbed capability should promote a "full stack" approach to investigation of advanced sensors, sensor management algorithms, and machine learning supporting wireless applications and analytics from distributed sensors. **The integration of capabilities into science measurement campaigns is not simply a matter of eliminating a tethered connection**. In order to ensure that new science uses for advanced wireless are deployed successfully, testbed activities will need to explore the suitability of upstream and downstream components, including implications of these components on system power management, energy efficiency, cost, reliability, and vendor hardware or service lock-in.

7.3.2 TB-2: 5G Testbed Co-Design—Integrating Networking & Domain Science Expertise

An advanced wireless science testbed should **include an engagement, training, and technical consulting capability** to ensure the validity of application testing. Understanding how best to provide this capability will require planning and research into application needs and how those needs are likely to develop as the activity is integrated with 5G or other wireless capabilities. For example, testing the best way to connect a field-agriculture mesocosm with simulation modeling/microcosm grown chambers (per the example of the EcoPODS [2] project) will require the ability to help scientists identify the right solutions, assist with either physical or simulated analysis of alternatives, help with testbed equipment procurement and deployment, and provide support during application testing to evaluate the results and interpret lessons learned. Additionally, advanced wireless science testbed activities should be captured and shared around the DOE science complex. This could be done in a variety of ways—from the deployment of wireless application deployment guides provided online or via community portals, to in-person tours and training, to the creation of a Wireless Champions program on the model of the NSF Xsede Campus Champion program [7].

7.3.3 TB-3: Technology Spin-Off and IP/Open Source collaboration

Testbed activities should be limited in scope; the purpose of a testbed program is to transition applications and integration efforts back to the program responsible for the science mission. Advanced wireless science testbed activities will need to develop clear standards, processes, and metrics for which applications should be studied, as well as how architectures, capabilities, and methods used (or created) to support application integration will be transitioned back to activity communities around the DOE complex. In addition, some application integration testing activities may require the involvement of private-sector wireless hardware snd service providers. **Tailoring the right kind of information sharing or intellectual property arrangements may require the creation of a policy research resource supporting**

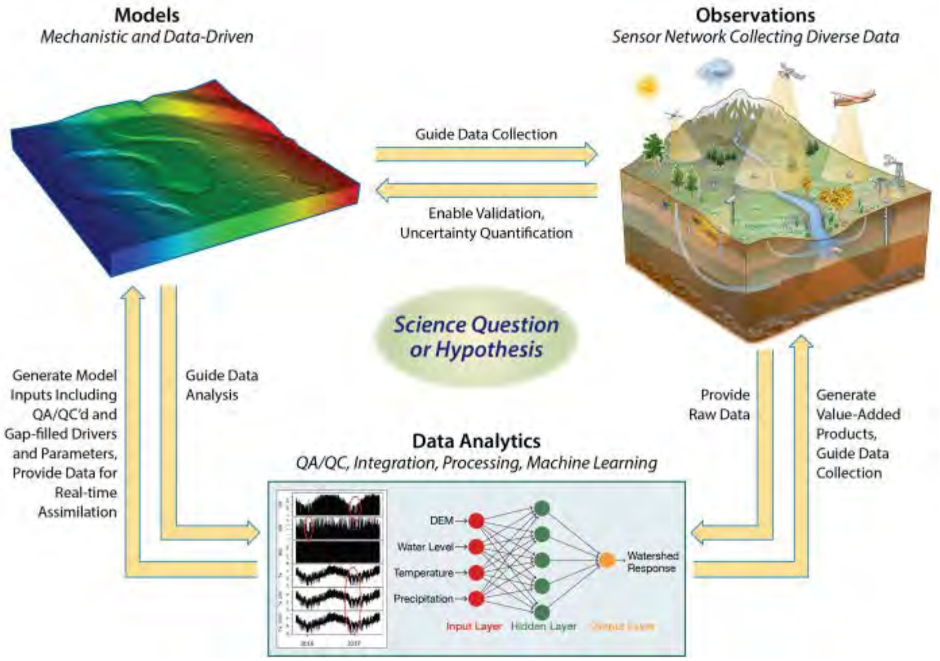


Figure 21: Integrating sensors, models, and machine learning through advanced wireless for science testbed capabilities [76] .

testbed operations, and related application requirements and regulatory limits shaping application use of wireless science-enabled capabilities.

7.4 Scientific Impact and Outcomes

A diverse set of highly connected wireless communication testbeds, spanning the national laboratories system and with interconnections to industry and academia, will provide the tools and coordination needed to ensure cybersecurity requirements are "baked in" to scientific applications for advanced wireless technologies, while also ensuring that the development of the advanced wireless technology stack benefits from the intellectual rigor and scientific methods that the DOE national laboratories have long provided.

We cannot now anticipate all of the impacts 5G and advanced wireless capabilities will have upon science. Through investment in a national advanced wireless testbed capability, however, we can foresee (at a minimum) that national science objectives will be advanced in the following three ways:

1. Augmenting simulation with real-time data will enable new ways to perform measurements and bring sensor data back to the lab. For example, the ability to accurately predict the weather is essential to our country's ability to predict drought, supply food, prepare and respond to natural disasters, and restore vital infrastructure. Advanced wireless testbed deployment will provide many opportunities to explore new and potentially more effective ways to predict the weather and improve microclimate prediction, leveraging future CDF and a highly connected set of sensor devices to dynamically task both simulation modeling and measurement assets.
2. Creating targeted advanced mobile communication capabilities for science will fuel scientific research and allow DOE scientists to leverage and shape wireless infrastructure investments made by commercial and industry entities, while enabling more rapid transfer of scientific data standards, networking protocols, and application contributions to industry. For example, advanced wireless applications by the pharmaceutical and automotive industries may be "co-enabled" by DOE standards for automated laboratories, providing researchers with high-precision, repeatable

experimental capabilities, reducing the risk to experimenters by removing them from hazards and allowing researchers more time to focus on experimental design and execution. Advanced wireless capabilities in the laboratory can also help with laboratory space by reducing the cost and time to reconfigure a space so that new experiments can be set up efficiently without “rewiring,” allowing a wider range of experimental designs to be tested.

3. Deployable advanced mobile communication capabilities can be used to enable research in the field, allowing researchers to explore previously inaccessible areas and measure phenomena with greater responsiveness and precision. The ability to task sensors dynamically, based on results obtained from simulation, or to manage suites of sensor modalities will especially improve our understanding of biological, geophysical, energy, and anthropomorphic interactions and possibilities. Edge computing will further enable immediate computation of data, instead of postprocessing data sometimes months later. This will have a tremendous impact on the ability to practically apply improved physical simulation in the service of improving laboratory operational efficiency and the operation of closed-loop control systems of all kinds.

New capabilities offered by advanced wireless communications and the computational data fabric will unshackle science to experiment in new places, at new resolutions, and with more flexibility. Connecting the physical and digital worlds by integrating a vast network of machines and sensors will enable science users to dynamically task sensors, employ automated laboratories, and use AI-enabled data-processing workflows to analyze streaming data in near-real time. **The creation of an advanced wireless testbed capability ensures that DOE’s national laboratories remain at the forefront of the coming wireless-enabled revolution in scientific measurement and real-time control of sensor systems.**

Appendix 1 Agenda and Attendees

1.1 Workshop Agenda

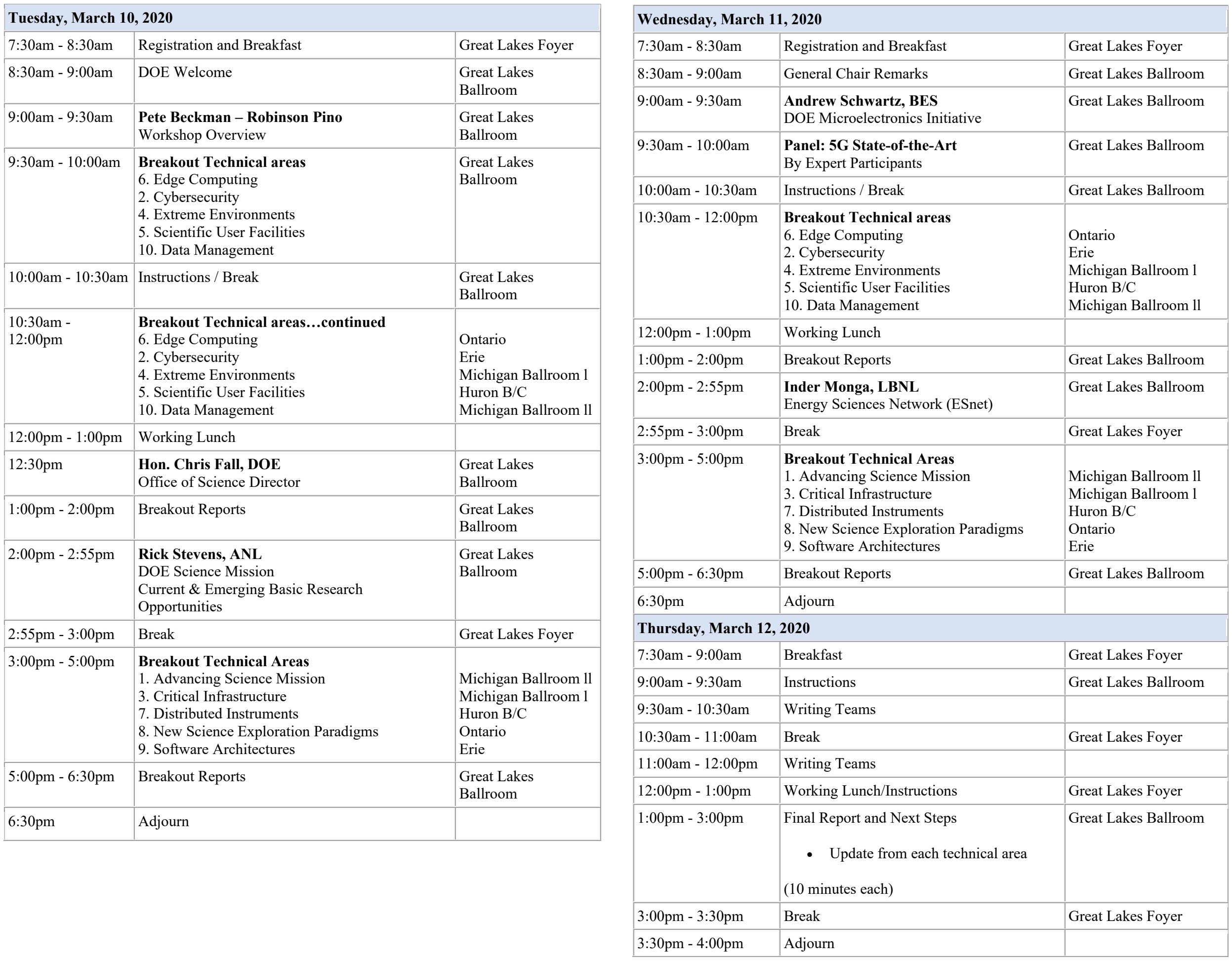
The 5G Enabled Energy Innovation Workshop (5GEEIW) was held in Chicago, Illinois, March 10–12, 2020. Participants were selected based on an open call for position papers, with breakout groups organized around two sets of five themes (see Figure 22).

The workshop included keynotes from Dr. Chris Fall (Undersecretary for Science), Rick Stevens (Associate Laboratory Director, Argonne National Laboratory), and Inder Monga (Director, ESnet) and an overview of context and objectives by Dr. Robinson Pino (Office of Science, ASCR) and Dr. Pete Beckman (workshop chair, Argonne National Laboratory).

1.2 Attendees

In-person participants numbered 120, with an additional 50 remote participants (not listed).

Moinuddin **Ahmed**, ANL— Mohammed **Alawad**, ORNL— Mihai **Anitescu**, ANL— Praveen **Ashokkumar**, US Ignite— Arturo **Azcorra**, Carlos III Univ. Madrid. Spain— Pavan **Balaji**, ANL— Sarankumar **Balakrishnan**, UBuffalo— Prasanna **Balaprakash**, ANL— Pete **Beckman**, ANL— Randall **Berry**, Northwestern— Andrew **Bigoney**, Battelle Ecology Inc.— Gordon **Brebner**, Xilinx Labs— Mark **Bryden**, Ames Laboratory— Anastasiia **Butko** ,



Tuesday, March 10, 2020		
7:30am - 8:30am	Registration and Breakfast	Great Lakes Foyer
8:30am - 9:00am	DOE Welcome	Great Lakes Ballroom
9:00am - 9:30am	**Pete Beckman – Robinson Pino** Workshop Overview	Great Lakes Ballroom
9:30am - 10:00am	**Breakout Technical areas** 6. Edge Computing 2. Cybersecurity 4. Extreme Environments 5. Scientific User Facilities 10. Data Management	Great Lakes Ballroom
10:00am - 10:30am	Instructions / Break	Great Lakes Ballroom
10:30am - 12:00pm	**Breakout Technical areas…continued** 6. Edge Computing 2. Cybersecurity 4. Extreme Environments 5. Scientific User Facilities 10. Data Management	Ontario Erie Michigan Ballroom l Huron B/C Michigan Ballroom ll
12:00pm - 1:00pm	Working Lunch	
12:30pm	**Hon. Chris Fall, DOE** Office of Science Director	Great Lakes Ballroom
1:00pm - 2:00pm	Breakout Reports	Great Lakes Ballroom
2:00pm - 2:55pm	**Rick Stevens, ANL** DOE Science Mission Current & Emerging Basic Research Opportunities	Great Lakes Ballroom
2:55pm - 3:00pm	Break	Great Lakes Foyer
3:00pm - 5:00pm	**Breakout Technical Areas** 1. Advancing Science Mission 3. Critical Infrastructure 7. Distributed Instruments 8. New Science Exploration Paradigms 9. Software Architectures	Michigan Ballroom ll Michigan Ballroom l Huron B/C Ontario Erie
5:00pm - 6:30pm	Breakout Reports	Great Lakes Ballroom
6:30pm	Adjourn	

Wednesday, March 11, 2020		
7:30am - 8:30am	Registration and Breakfast	Great Lakes Foyer
8:30am - 9:00am	General Chair Remarks	Great Lakes Ballroom
9:00am - 9:30am	**Andrew Schwartz, BES** DOE Microelectronics Initiative	Great Lakes Ballroom
9:30am - 10:00am	**Panel: 5G State-of-the-Art** By Expert Participants	Great Lakes Ballroom
10:00am - 10:30am	Instructions / Break	Great Lakes Ballroom
10:30am - 12:00pm	**Breakout Technical areas** 6. Edge Computing 2. Cybersecurity 4. Extreme Environments 5. Scientific User Facilities 10. Data Management	Ontario Erie Michigan Ballroom l Huron B/C Michigan Ballroom ll
12:00pm - 1:00pm	Working Lunch	
1:00pm - 2:00pm	Breakout Reports	Great Lakes Ballroom
2:00pm - 2:55pm	**Inder Monga, LBNL** Energy Sciences Network (ESnet)	Great Lakes Ballroom
2:55pm - 3:00pm	Break	Great Lakes Foyer
3:00pm - 5:00pm	**Breakout Technical Areas** 1. Advancing Science Mission 3. Critical Infrastructure 7. Distributed Instruments 8. New Science Exploration Paradigms 9. Software Architectures	Michigan Ballroom ll Michigan Ballroom l Huron B/C Ontario Erie
5:00pm - 6:30pm	Breakout Reports	Great Lakes Ballroom
6:30pm	Adjourn	
Thursday, March 12, 2020		
7:30am - 9:00am	Breakfast	Great Lakes Foyer
9:00am - 9:30am	Instructions	Great Lakes Ballroom
9:30am - 10:30am	Writing Teams	
10:30am - 11:00am	Break	Great Lakes Foyer
11:00am - 12:00pm	Writing Teams	
12:00pm - 1:00pm	Working Lunch/Instructions	Great Lakes Foyer
1:00pm - 3:00pm	Final Report and Next Steps • Update from each technical area (10 minutes each)	Great Lakes Ballroom
3:00pm - 3:30pm	Break	Great Lakes Foyer
3:30pm - 4:00pm	Adjourn	

Figure 22: Agenda: 5G Enabled Energy Innovation Workshop (5GEEIW), March 9–12, 2020

LBNL— Franck **Cappello**, ANL— Charlie **Catlett**, Discovery Partners Institute (UIllinois) / ANL— Ryan **Chard**, ANL— Austin **Clyde**, ANL— Susan **Coglan**, ANL— Scott **Collis**, ANL— Michael **Cooke**, U.S. DOE— Johnathan **Cree**, PNNL— Jody **Crisp**, ORISE— Matthew **Curry**, SNL— Dipankar **Dasgupta**, UMemphis — Prasanna **Date**, ORNL— Sheng **Di** , ANL— Ahmed **Diallo**, PPPL— Jakob **Elias**, ANL— Anatoly **Evdokimov**, UIllinois Chicago— Manouchehr **Farkhondeh**, DOE Office of Nuclear Physics— Hal **Finkel**, ANL— Ian **Foster**, ANL— Anna **Giannakou**, LBNL— Jie **Gu**, Northwestern— Colby **Harper**, Pathfinder Wireless— Michael **Honig**, Northwestern— John **Hryn**, ANL— Shantenu **Jha**, BNL— Yier **Jin**, UFlorida— Ai **Kagawa**, BNL— Dimitrios **Katramatos**, BNL— Kibaek **Kim**, ANL— Mariam **Kiran**, LBNL— Robert **Kozma**, UMass Amherst— Misha **Krassovski**, ORNL— Ushma **Kripani**, ANL— Harinarayan **Krishnan**, LBNL— Yatish **Kumar**, LBNL— Linqing **Lou**, UC Berkeley— Yu **Luo**, Miss State Univ.— Heng **Ma**, ANL— Barney **Maccabe**, ORNL— Matt **Macduff**, PNNL— Andres **Marquez**, PNNL— Lena **Mashayekhy**, UDelaware— Rick **McGeer**, UC Berkeley— John **Mitchell**, ORNL— Inder **Monga**, LBNL— Mackenize **Morris**, SRNL— Thomas **Naughton**, ORNL— William **Nickless**, PNNL— Bogdan **Nicolae**, ANL— Andrew **Nonaka**, LBNL— Dennis **Ogbe**, Purdue— Thrasyvoulos **Pappas**, Northwestern— Robert **Patton**, ORNL— Elena **Peterson**, PNNL— Trever **Pfeffer**, ANL— Robinson **Pino**, DOE— Thomas **Potok**, ORNL— Lina **Pu**, USouthern Miss— Shaloo **Rakheja**, UIllinois at Urbana-Champaign— Arvinda **Ramanathan**, ANL— Yihui **Ren**, BNL— Verónica **Rodríguez Tribaldos**, LBNL— Sumit **Roy**, UWashington— Alec **Sandy**, ANL— Rajesh **Sankaran**, ANL— Michel **Schanen**, ANL— Bryan **Schromsky**, Verizon— Andrew **Schwartz**, DOE Basic Energy Sciences— Nicholas **Schwarz**, ANL— Devanand **Shenoy**, — Julie **Slaughter**, Ames Laboratory— Dan **Small**, SNL— Suhas **Somnath**, ORNL— Carlos **Soto**, BNL— Marius **Stan**, ANL— Rick **Stevens**, ANL / UChicago— Cory **Stuart**, ORNL— Ryan **Sullivan**, ANL— Valerie **Taylor**, ANL— Dingwen **Tao**, University of Alabama— Gregory **Tchilinguirian**, PPPL— Douglas **Thompson**, SNL— Keith **Tracey**, SNL— Nhan **Tran**, Fermilab— Hubertus **van Dam**, BNL— Jeffrey **Vetter**, ORNL— Leroy **Walston**, ANL— Xin **Wang**, Stony Brook Univ.— Bruce **Warford**, ORISE— Ermin **Wei**, Northwestern— Yang **Weng**, Arizona State Univ.— Andrew **Wiedlea**, LBNL— Stijn **Wielandt**, LBNL— Theresa **Windus**, Ames Laboratory— John **Wu**, LBNL— Wei **Wu**, LANL— Yuxin **Wu**, LBNL— Xi **Yang**, LBNL— Yongchao **Yang**, Michigan Technological Univ.— Angel **Yanguas-Gill**, ANL— Zhi **Yao**, LBNL— Kazutomo **Yoshii**, ANL— Yuping **Zeng**, Univ. of Delaware— Yuepeng **Zhang**, ANL— Rommel **Zulueta**, National Ecological Observatory Network (NEON)

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