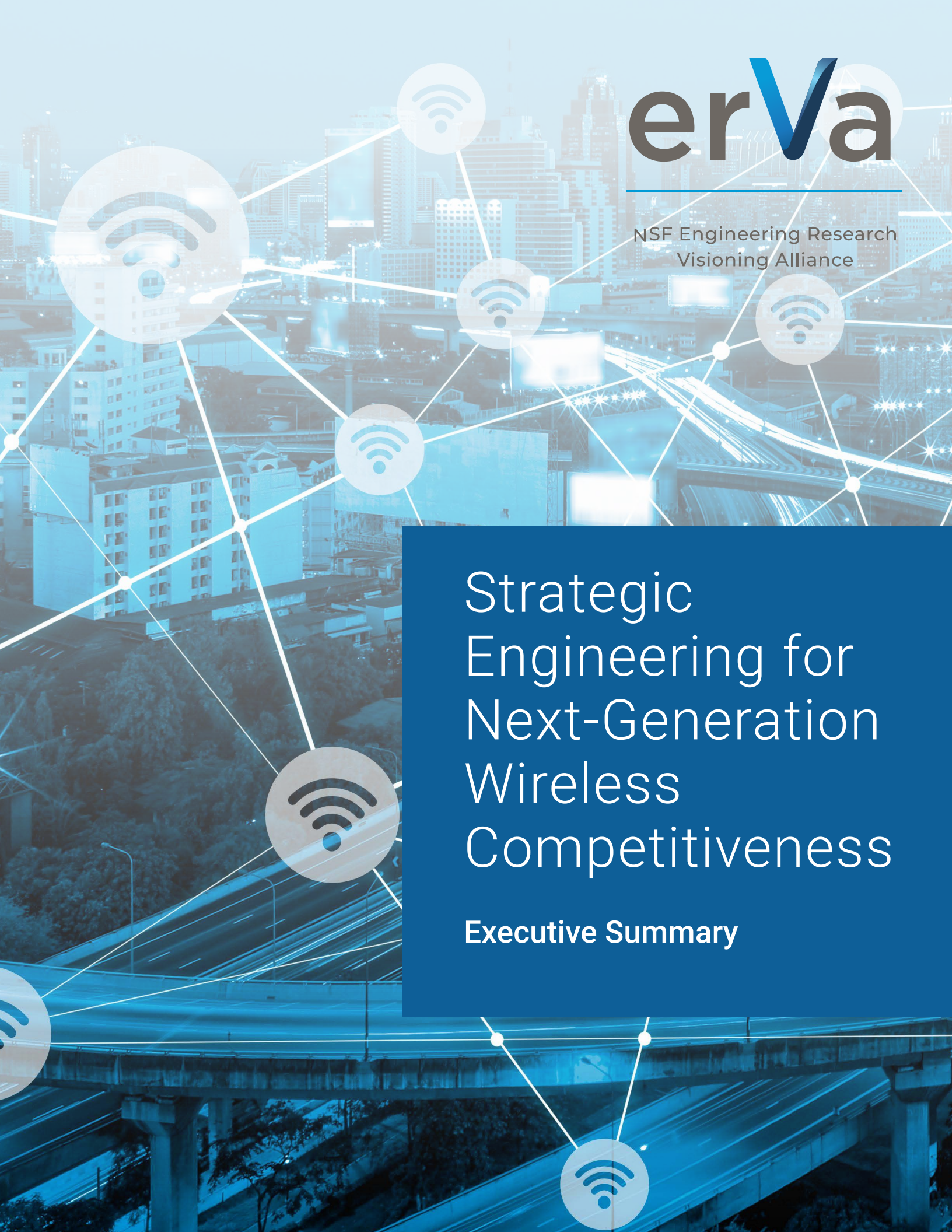


erVa

NSF Engineering Research Visioning Alliance

Strategic Engineering for Next-Generation Wireless Competitiveness

Executive Summary

Executive Summary

Strengthening research efforts in next-generation wireless networks is crucial for the United States to maintain its competitive edge in the global technology landscape. As the world becomes increasingly connected, the demand for faster, smarter, more reliable, more secure, and higher-capacity networks continues to grow. Investing in advanced wireless technologies beyond 5G will ensure that the United States can meet these demands, supporting initiatives from smart cities and autonomous vehicles to advanced health care applications. By leading in wireless innovation, the United States can drive economic growth, create high-tech jobs, and enhance the quality of life for its citizens.

By leading in wireless innovation, the United States can drive economic growth, create high-tech jobs, and enhance the quality of life for its citizens.

The United States is facing significant challenges in maintaining its competitiveness in next-generation wireless technologies, particularly in the race to 5G and beyond. One of the primary reasons is the substantial investment gap compared to other countries, notably China, over the last decade. Research in many aspects of "beyond 5G" systems has accelerated significantly in China, most EU nations, Japan, South Korea, and elsewhere, while U.S. efforts in these frontier areas have lagged by comparison. For example, the nation of Finland initiated the "6G Flagship," a multi-institutional holistic research and development (R&D) program, in 2018, seeded by approximately $300 million in both public and private investment. In Germany, the "6G Platform" unifies several regional research hubs to advance research and standardization efforts, with an initial allocation of €250 million in 2021. The France 2030 Initiative, announced in 2023, includes €750 million for research on future networks. In contrast, the United States has no existing or planned efforts on a comparable scale. Illustrative of the lack of U.S. thought leadership in next-generation wireless research, when the first textbook covering the topic of terahertz (THz) communications, envisioned as a foundational aspect of 6G, was published in 2022, it included approximately 100 co-authors, but only a handful of these had a U.S. affiliation.

In addition, the United States has so far participated only peripherally in the development of global standards for wireless systems beyond 5G. Even with existing (5G) network systems, the ripple effect of this funding deficit manifests in important ways, such as U.S. spectrum policy. This is also true for emerging 6G standards. For example, the first wireless standard for the frequency range above 100 gigahertz (GHz) was assembled over a 10-year period by a global team of researchers with almost no U.S. participation.

In addition to engaging for global standards development, the United States must also work within our borders to enhance collaboration between the public and private sectors. Effective partnerships can drive innovation and ensure that the nation remains at the forefront of technological advancements. This includes fostering relationships between government agencies, private companies, and research institutions to accelerate the development and deployment of new technologies. Such partnerships have been highly successful elsewhere, including in the EU and Japan.

The geopolitical landscape plays a role in the nation's standing in the global wireless technology race. Several recent reports, including the *NextG Communications Research and Development Gaps* report from the National Institute of Standards and Technology (NIST) and the *Edge Networks, Core Policy* report from the Center for a New American Security, have addressed the topic of future wireless communication systems, the ambitious goals and visions that they inspire, and the research tasks required to realize them. What these reports generally have failed to acknowledge is that the United States is already well behind in research in some of these topics, a reality that changes the strategic landscape.

To identify U.S. engineering research opportunities in next-generation wireless competitiveness, 51 researchers, industry leaders, policymakers, and other stakeholders met on June 13-14, 2024, at a visioning event convened by the Engineering Research Visioning Alliance (ERVA). During the two-day event, participants generated and refined 10 essential engineering research priorities for U.S. wireless competitiveness for the next decade.

This report offers a strategic research roadmap that acknowledges the current global landscape and important research investments already in place. Because other nations are already making significant progress and heavily funding some research areas, this report describes 10 important areas of research needed and prioritizes five areas that are underfunded or where U.S. researchers can establish leadership and have a greater impact on the global effort to develop future network technologies. Each of these 10 global engineering research priorities is critical to achieving next-generation wireless technology goals; all are briefly described here and discussed in more detail in the full report.

Strategic Engineering Research Priorities with Potential for Highest U.S. Impact

01

Near-Field Channel Modeling
Numerous researchers have recognized the importance of accounting for near-field physics in wireless links operating above 100 GHz, but few outside the United States have considered the unique opportunities that such considerations present. As a result, this is a ripe area for establishing U.S. leadership, particularly through exploiting the synergy with ideas drawn from the optics community.

02

New Waveform and Coding Paradigms
As the number and type of wireless devices connected to networks increases, there is a need to increase efficiency in both spectrum use and energy consumption through design of new modulation formats, coding strategies to leverage all information in a channel, and waveforms solely for communication. There is also an opportunity for engineering research to integrate other applications, such as sensing and over-the-air computation, into communications waveforms. These joint solutions could reduce spectrum sharing burden and digital processing hardware component load. The ideas contained in this topic have enormous potential and are largely underappreciated in the research community to date. As a result, this focus area has significant potential for U.S. researchers to develop high-impact results.

03

Control Plane for Resilient and High-Performance Next-Generation Networks
Many of the exciting advances in hardware and physical-layer systems will rely on concurrent advances in the protocols and systems that must be developed to control them. While a great deal of effort has been directed toward the hardware, much less consideration has been paid to these control systems. Networks cannot work without a control plane, and it is clear that future networks' control planes will be very different from what we use today. This is a critical missing element in many nations' existing research portfolios and is thus a priority research topic for the United States.

04

Security in Future Networks
Wireless security plays a significant role everywhere these systems are employed. The special considerations surrounding wireless security are under-researched in networks employing broadband highly directional signals. Some of the earliest studies were performed in the United States, but interest is growing rapidly in China and elsewhere. Due to the strategic importance and the opportunities for establishing global leadership, this is a key topic for immediate U.S. research attention.

05

Non-Terrestrial Networks
The United States enjoys a leadership position in many space-based systems given its long history of space exploration and the recent successful private efforts such as SpaceX and Blue Origin. Given the strategic importance of this research area and its potential as a solution for future network coverage concerns, it is a priority topic for U.S. research.

06

New Device and Computing Paradigms

The core of this technology area is integrated circuit technology and systems. The United States has some of the leading researchers in this area, but other nations also compete here (with leading researchers in Germany, Japan, and China, for example). The critical need for home-grown expertise in this area has already been recognized and codified in the CHIPS and Science Act, which provides considerable research funding to seed the lab-to-fab development of new technologies for 5G/6G and other areas of strategic importance.

07

Integrated Sensing and Communication

This diverse and active research area is essential for realizing the 6G vision. Indeed, this foundational idea is recognized worldwide and has already attracted considerable research attention in many countries. A recent textbook, *Integrated Sensing and Communications*, contains 22 chapters on different aspects of the technical research progress and includes approximately 90 co-authors, but most do not list a U.S. affiliation. This is likely an area where the lead held by other nations (notably China) is already insurmountable, such that significant U.S. funding in this area may not have as big an impact as equivalent funding in other areas.

08

High-Fidelity Real-Time Channel Emulation Models for Digital Twins

The development of effective digital twins for channel modeling could have a significant impact as it would address one of the key roadblocks to rapid progress in the field: lack of access to experimental measurement capabilities. However, this is a research area with significant activity already underway in other nations, especially in connection with the recent surge in interest in artificial intelligence (AI).

09

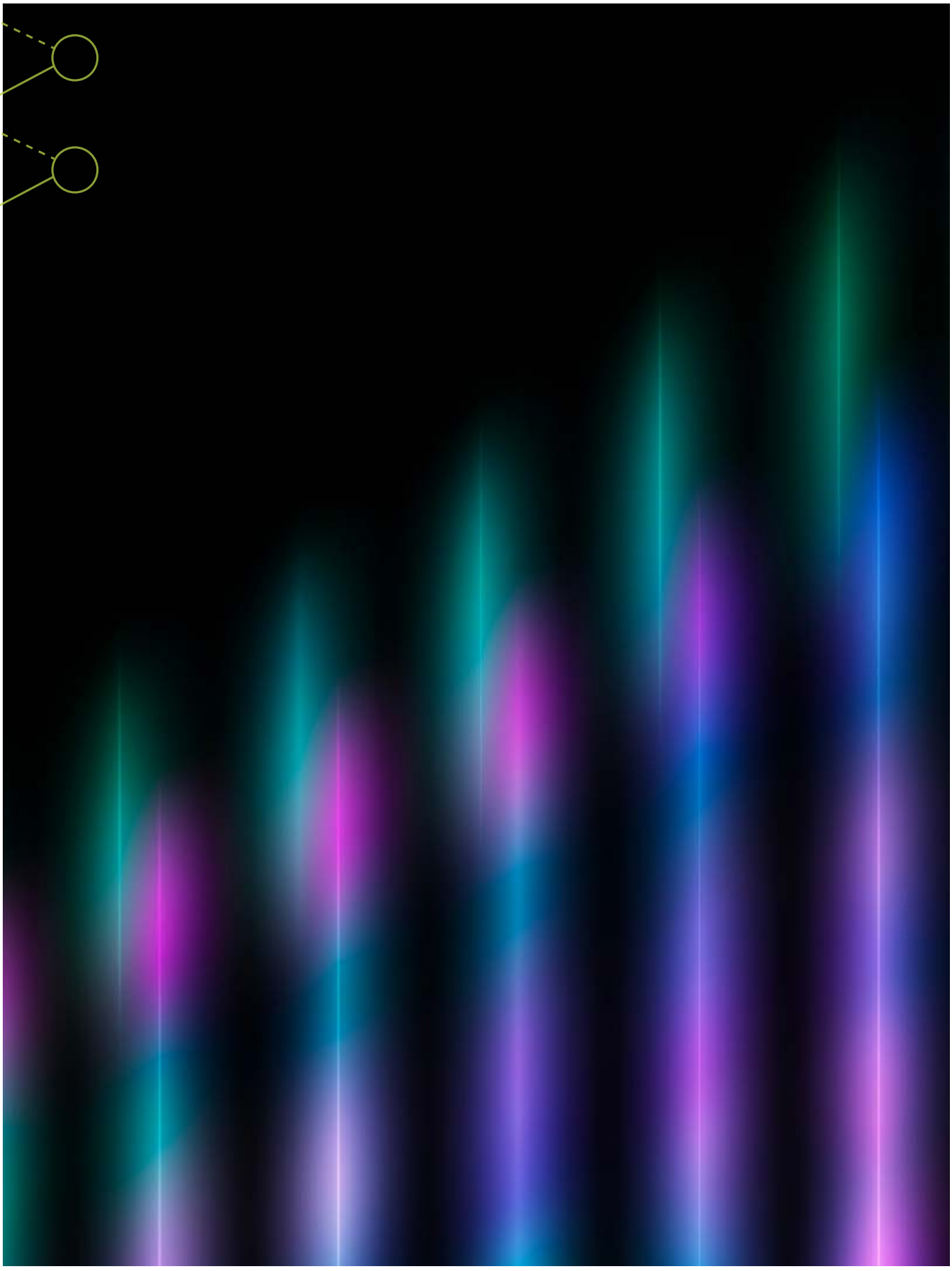
AI in Wireless Networks

The importance of AI in future technologies is well recognized, with significant recent attention paid to this topic. Although the impact of intelligent systems on wireless networks will undoubtedly be large, it is clear that such systems already enjoy significant support and cannot be considered to be an underserved research topic.

10

Spectrum Sharing above 100 GHz

The exploitation of frequencies above 100 GHz will be extremely difficult without the development of an effective means of spectrum sharing that protects the needs of passive users, such as radio astronomy or earth-observing satellites. However, the U.S. Federal Communications Commission (FCC) is still using outdated channel models to estimate interference, inhibiting U.S. research in this area. While these problems must urgently be addressed, the United States cannot attain engineering leadership in this area (currently led by EU nations) without significant changes in the current regulatory landscape, which is outside the engineering research focus of this report.



Taking Action

The United States is at a critical juncture in wireless network technology strategy. As the complexity of wireless technology accelerates and entire new systems are developed, the U.S. must take bold steps to maintain its leadership in critical research areas. The essential engineering research described in this report requires action from research funders, regulators, and engineering researchers to enable this critical work.

This report distinguishes the essential engineering research directions where the United States can take a leadership position and advance next-generation wireless competitiveness. It provides a contextual understanding of the relative return on investment, as well as highlighting regulatory and other challenges that could be overcome with increased federal agency awareness of the impact of policies that impede research progress. Expanding interdisciplinary teams to include experts in data science, cybersecurity, and policy could accelerate progress and contribute to comprehensive solutions.

For impactful research to occur, substantial strategic funding increases will be required. While the CHIPS and Science Act has provided funding for some new 5G/6G technologies, other areas remain under-resourced. Investing in the five priority areas outlined in this report (Near-Field Channel Modeling, New Waveform and Coding Paradigms, Control Planes, Network Security, and Non-Terrestrial Networks) should enable the United States to rise as a dominant force in these areas. Given that this research not only explores fundamental science but also has significant implications for U.S. science and technology development, there are opportunities for both private and public funders.

To advance engineering research in next-generation networks, decisive action by regulatory bodies, including the FCC and National Telecommunications and Information Administration (NTIA), is also critical. The regulatory environment in the United States has impeded research into some key priorities, including spectrum sharing over 100GHz, which has relegated U.S. researchers to playing a minor role in innovation. While the FCC has initiated or explored reforms of some processes and regulations, accelerated action is needed to create a more conducive environment for research.

Other regulatory agencies can support and accelerate next-generation wireless research by altering the emphasis on traditional standards and slow development processes (NIST), updating spectrum allocation practices (Federal Aviation Administration), and recalibrating risk aversion practices (NASA).

Importantly, efforts to encourage public-private partnerships can take advantage of synergies between academic research and industry applications, thus increasing access to resources and expertise for innovative projects that align with national interests. Such partnerships have stimulated considerable progress in other nations such as Finland, Germany, and Japan, and could also play an important role in future U.S. research activities with the appropriate changes to current funding and regulatory incentives.

NSF Engineering Research
Visioning Alliance

Our mission is to identify and develop bold and transformative new engineering research directions and to catalyze the engineering community's pursuit of innovative, high-impact research that benefits society.

ERVA IS FUNDED BY THE NATIONAL SCIENCE FOUNDATION THROUGH AWARD NUMBER 2048419

This material is based upon work supported by the National Science Foundation under Grant # 2048419. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Ervacommunity.org