Future Directions Workshop on Wireless Communications: XG and Beyond

June 8-9,2022

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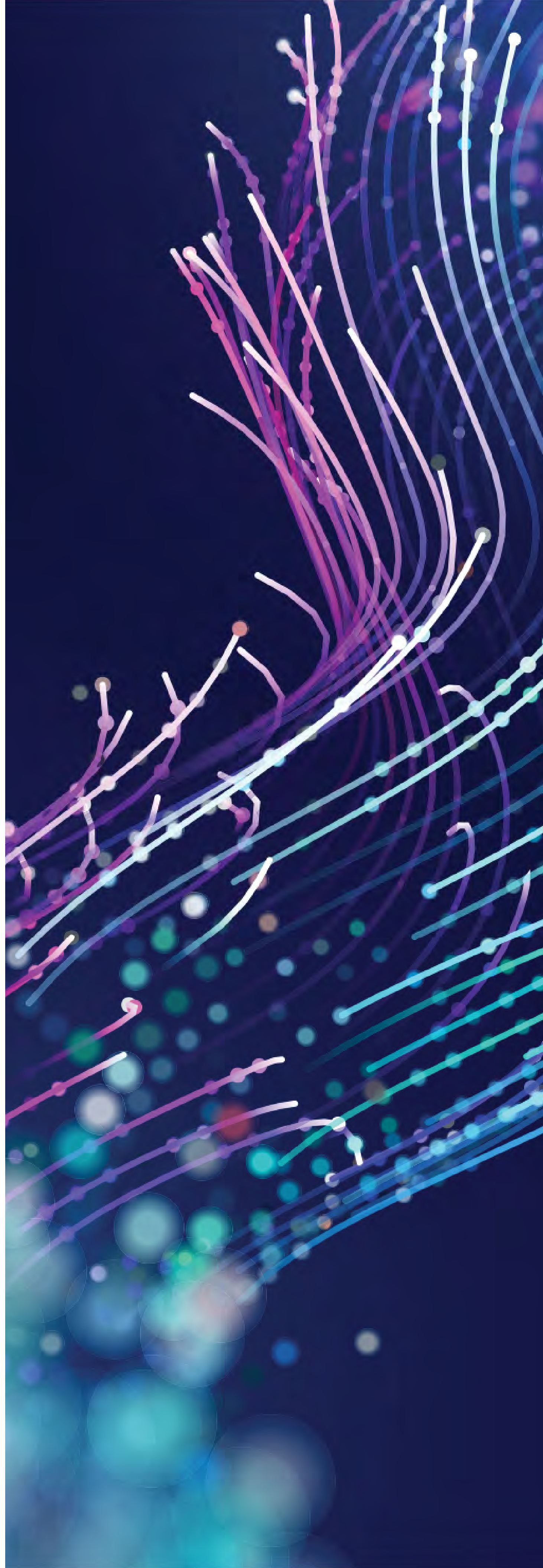

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Innovation is the key to the future, but basic research is the key to future innovation.
–Jerome Isaac Friedman,
Nobel Prize Recipient (1990)

Preface

Over the past century, science and technology has brought remarkable new capabilities to all sectors of the economy; from telecommunications, energy, and electronics to medicine, transportation and defense. Technologies that were fantasy decades ago, such as the internet and mobile devices, now inform the way we live, work, and interact with our environment. Key to this technological progress is the capacity of the global basic research community to create new knowledge and to develop new insights in science, technology, and engineering. Understanding the trajectories of this fundamental research, within the context of global challenges, empowers stakeholders to identify and seize potential opportunities.

The Future Directions Workshop series, sponsored by the Basic Research Directorate of the Office of the Under Secretary of Defense for Research and Engineering, seeks to examine emerging research and engineering areas that are most likely to transform future technology capabilities. These workshops gather distinguished academic researchers from around the globe to engage in an interactive dialogue about the promises and challenges of each emerging basic research area and how they could impact future capabilities. Chaired by leaders in the field, these workshops encourage unfettered considerations of the prospects of fundamental science areas from the most talented minds in the research community.

Reports from the Future Direction Workshop series capture these discussions and therefore play a vital role in the discussion of basic research priorities. In each report, participants are challenged to address the following important questions:

- How will the research impact science and technology capabilities of the future?
- What is the trajectory of scientific achievement over the next few decades?
- What are the most fundamental challenges to progress?

This report is the product of a workshop held June 8-9, 2022, at the Basic Research Innovation and Collaboration Center in Arlington, VA on the future of research in Wireless Communications: XG and Beyond. It is intended as a resource for the S&T community including the broader federal funding community, federal laboratories, domestic industrial base, and academia.

Executive Summary

Wireless communication is ubiquitous in our daily lives. It is hard for many to imagine how we lived before the advent of this technology. We are all connected via a wireless paradigm—a fact that became evident and essential during the COVID-19 pandemic. The fifth generation (5G) of the wireless cellular networks, with frequency ranges < 6 GHz (FR1) and 24–54 GHz (FR2), began to be implemented around 2019, and it is anticipated that by the mid-2020s, over 1.7 billion users in the world will be using 5G networks. This system offers higher bandwidth and consequently higher download speed, allowing better parallel connectivity among various devices, particularly for applications for the Internet of Things (IoT) and machine-to-machine connections. The advent of 5G has moved us into a Mobile Virtual Reality revolution, with wireless technologies providing us with new ways to interact with the real and virtual worlds. While virtual-reality (VR), augmented-reality (AR), and gesture recognition are well-anticipated applications, one can speculate that there are many others of possibly even greater impact.

To explore the promise and challenges of wireless communications, particularly for technologies associated with terrestrial networks, a future directions workshop was held on June 8–9, 2022, in Arlington, VA. This workshop gathered 19 distinguished researchers from academia, industry, and government from the photonics, electronics, networks and artificial intelligence (AI) communities for unfettered discussion and debate on the current research challenges, opportunities, and trajectory for research over the next twenty years.

The two-day workshop was organized to encourage lively discussion and debate about the future of wireless communications. The first day was spent in small group discussions about the fundamental challenges and opportunities for the three subdomains of networks, photonics, and electronics. The second day of the workshop was spent as a whole group to examine cross-cutting themes and topics not covered in the first day. This report summarizes the findings of the workshop as research challenges and opportunities and the trajectory for wireless communications research over the next twenty years.

Research Challenges

The workshop participants examined and explored the possible future of wireless science and technology. They identified the following research challenges in advancing wireless communications technologies:

- Developing a New Layering Architecture to Enable the Growth of Communication and Computation
- Combating Lack of Coverage, Blockage, and Disconnectivity at Higher Frequencies
- Integration of Heterogeneous Domains of Electronic and Photonic Platforms (driven by applications)
- Energy Efficiency and Cost
- Conversion Loss in Interconnects and Frequency Conversion
- Developing Low-Latency Scheduling Protocols
- New Spectrum vs. Spectrum Efficiency
- Seamlessly Integrating Edge Computing and Storage with the Network Architecture
- Challenges in Photonic Computation and Storage
- Challenges in Enhancing Nonlinearity in Photonics
- Securing Future XG Systems
- Trustworthy Dynamic Sensing
- Ensuring End User Privacy
- Automating Network Functionalities
- Using Data to Develop a Unified Framework for Real-time Network Control

Research Opportunities

After identifying the research challenges for advancing the wireless technology in the next 20 years, the workshop participants identified several potential opportunities, and associated science and technology advances, to overcome the aforementioned challenges.

- Developing New Foundational AI for Network Design and Control
- Developing a Scalable Experimental Toolbox
- Establishing New Security Principles for Future XG Networks
- Designing XG Networks to Enable Distributed Learning and User Privacy
- Wave-based Signal Processing, Computation, and Data Storage
- Reconfigurable Intelligent Surfaces
- Sub-millimeter-wave Spectrum Utilization
- Massive, Distributed Multi-band Multi-Input and Multi-Output (MIMO) at Millimeter-waves
- Ultra-low Latency Wireless Links
- Convergence of Sensing and Communications
- Heterogeneous Integration of Silicon with III-V/III-N/Wide Bandgap Technologies
- Photonics-Assisted Electronics
- Wireless Power Transfer
- Adaptive Shape-Changing Electronics

Anticipated Trajectory for Wireless Communications Research

The workshop participants anticipated a trajectory for the research opportunities identified above with a vision for the five-, ten-, and twenty-year horizons.

Five-year vision

- 5–10 millisecond communication latencies using a combination of theoretical models based on network optimization, AI/Machine Learning (ML), and protocol development
- Hybrid frequency usage to ensure sustained connectivity at high data rates
- Real-time spectrum sharing using databases. While some of this is already in progress, the key will be to ensure that such databases become increasingly ubiquitous and dynamic.

- A new layering principle to enable the growth of communication and computation, with possible loose coupling among layers
- Development of automated and scalable mechanisms for the verification of the security of 5G cellular and XG network protocols
- Metrics to establish privacy/utility tradeoffs for networks
- Frameworks for the systematic analysis of "network programs" to identify defects exploitable by adversaries
- Advancement in material innovation to achieve low loss and giant nonlinear optical responses for signal detection and generation capabilities at high frequencies (e.g., sub-mm-wave, THz, mid-IR, optical regimes)
- AI-driven material engineering to obtain optimal functionalities for electromagnetic manipulation in optoelectronic platforms
- Reconfigurable, scalable, and programmable materials, devices, and systems for optimizing network performance, e.g., simultaneous multi-band, multi-beam, and multi-function performance
- Co-design of algorithms and architectures with the optoelectronic devices and systems
- Advancement in wave structuring to minimize EM-matter interaction and beam divergence
- Advancement in III-V and wide bandgap semiconductor technology to enable 5W/mm power density and 50% PAE at 140GHz operation frequency.
- Advancement in front-end circuit technology to enable 200mW of output power at 30% PAE and Noise Figure of 4dB at 140GHz.

Ten-year vision

- Enabling AI/ML-based network control algorithms at all layers of the protocol stack
- Enabling new interactive applications using distributed ML which resulting in ultra-low latency performance
- New architectures (such as increased cell density, multi-hop backhauls) to exploit available bandwidths in the higher frequency bands
- Trustworthy dynamic spectrum sharing
- Real-time, automatic prediction of network failures using AI/ML techniques
- A mathematical framework for architectures for communications and computation
- Security verification of hardware; scalable formal methods; real-time network monitoring/diagnostics, attack containment
- Automatic network configuration to meet privacy/utility requirements per user/application
- Reduction of noise (e.g., thermal noise, shot noise, phase noise) and enhancement of dynamic range through new device physics and system design.
- Wave-based distributed analog computation, storage, and programmability at high data rates e.g., holographic, and photonic meshes.
- Direct electromagnetic wave processing as a part of computation pipeline, e.g., through neural networks.
- Reconfigurable metasurfaces, smart skin and/or architectural building blocks with embedded distributed multi-functional surfaces for beam amplification, re-routing, beamforming, etc. to enable high-frequency signals to be rerouted and transported to longer ranges.
- Advancement in III-V and wide bandgap semiconductor technology to enable 5W/mm power density and 40% PAE at 200GHz operation frequency.
- Advancement in front-end circuit technology to enable 200mW of output power at 30% PAE and Noise Figure of 4dB at 200GHz.

Twenty-year vision

- A unified AI/ML and model-based network algorithm cross-layer design that bridges across the domains of networks, physics, and electronics
- Reliable and low-latency networks incorporating ultra-high frequency links
- AI/ML for automated operation of networks with exponential growth in the number of components compared to the number of users
- A new established network architecture to enable growth, innovation and competition while delivering high performance
- A mathematical framework for architectures for communications, sensing, storage, and computation
- Providing assured security in a post-quantum computing and communication world
- Quantum optical materials enabling generation, amplification, modulation, and detection of photons to enable various functionalities and capabilities including entanglement, bandgap engineering, etc.
- Large-scale and/or bio-inspired material synthesis, growth, nanofabrication, and integration
- Advancement in III-V and wide bandgap semiconductor technology to enable 5W/mm power density and 30% PAE at 300GHz operation frequency.
- Advancement in front-end circuit technology to enable 200mW of output power at 30% PAE and Noise Figure of 4dB at 300GHz.

Accelerating Research

The workshop participants determined the following resources and supports that can enhance and accelerate the future research opportunities described above:

- Testbeds that allow experimentation at scale: While government funding agencies have made significant investments in some aspects (e.g., the NSF PAWR program), more needs to be done to increase the scalability of these testbeds, make them accessible to the general community, and to provide support in using testbeds.
- Data sets for training AI/ML and for use within the XG systems ecosystem. These data sets would include data obtained from experimental platforms, typical data used for training and classification, and data merged with experimental platforms to do real-time control.

- Training for programs for AI-driven material engineering and co-design
- Infrastructures for bio-inspired device/system development
- Incentives for creating new infrastructures for developing monolithically integrated optoelectronic heterogenous platforms
- Infrastructure for developing scalable and embedded reconfigurable intelligent materials and surfaces (e.g., reconfigurable intelligence surfaces (RIS))
- Training for students to be industry ready. The XG marketplace is very large, and employees are having difficulty finding qualified students to hire. Greater investments in research that is directed towards graduate and undergraduate students is needed to keep up with the demand and will have a significant payoff to the US economy in the long-run.
- To address societal issues and wireless standards globally, and to address the need for collaboration across nations, spectrum usage and regulations, negotiations, and relevant technical standards and policies.

In conclusion, while the working groups were formed around the three main themes of network, photonics, and electronics, it has been clear that essentially all relevant topics for future technological capabilities of wireless paradigms are interrelated, and thus these areas are going to merge together. This is particularly important as we go to 6G, 7G, XG and beyond into higher frequency domains. The workshop participants are confident that this will serve as a launching pad for future discussions among various research groups with interest in wireless science and technology, and are excited to work on the future together.

Introduction

Wireless communication is ubiquitous in our daily lives. It is hard for many to imagine how we lived before the advent of this technology. We are all connected via a wireless paradigm—a fact that became evident and essential during the COVID-19 pandemic. The fifth generation (5G) of the wireless cellular networks, with frequency ranges < 6 GHz (FR1) and 24-54 GHz (FR2), began to be implemented around 2019, and it is anticipated that by the mid-2020s, over 1.7 billion users in the world will be using 5G networks. This system offers higher bandwidth and consequently higher download speed, allowing better parallel connectivity among various devices, particularly for applications for the Internet of Things (IoT) and machine-to-machine connections. The advent of 5G has moved us into a Mobile Virtual Reality revolution, with wireless technologies providing us with new ways to interact with the real and virtual worlds. While virtual-reality (VR), augmented-reality (AR), and gesture recognition are well-anticipated applications, one can speculate that there are many others of possibly even greater impact. For example, networks of cars and aircraft will, after observing each other and their surroundings through radar, LIDAR, and HD CMOS cameras, share this information and then cooperate to regulate traffic. A drone or UAV carrying an array of CMOS imagers will communicate a real-time HDTV 4π panorama to remote observers and to a remote image processor that recognizes the environment and then tells the drone how to respond. Wireless technology coupled with VR/AR and AI technologies could help medical practitioners perform remote surgeries, alleviating the need for specialists in rural settings. More immediately, a next-G wireless network would provide easy, reliable, and cheap access to content (TV shows, videos, Zoom video meetings, and the like) in remote rural locations, or in an airplane. Many of these potential applications demand very low latency or high reliability and availability, and all demand orders of magnitude increases in data capacity, guaranteed security, higher flexibility, and low cost of access. To meet the future needs, experts in the field are now beginning to consider the next generations of wireless communications (6G, 7G, and beyond, or XG), providing possibilities for multiscale, global connectivity, and distributions. New generations will bring ample new opportunities, but also new challenges. Transformative and multidisciplinary research approaches are needed to identify and address such challenges to enable the anticipated opportunities.

With our current mindset, and from the technological and scientific points of view, a wireless system can be divided into three subsystems: photonics, electronics, and networks (Figure 1). The boundaries between these subsystems are not sharp and, in fact, contain important synergistic and cross-cutting factors that are important for all three subsystems. These include artificial intelligence (AI), robustness, security, quantum phenomena, and societal effects, just to name a few.

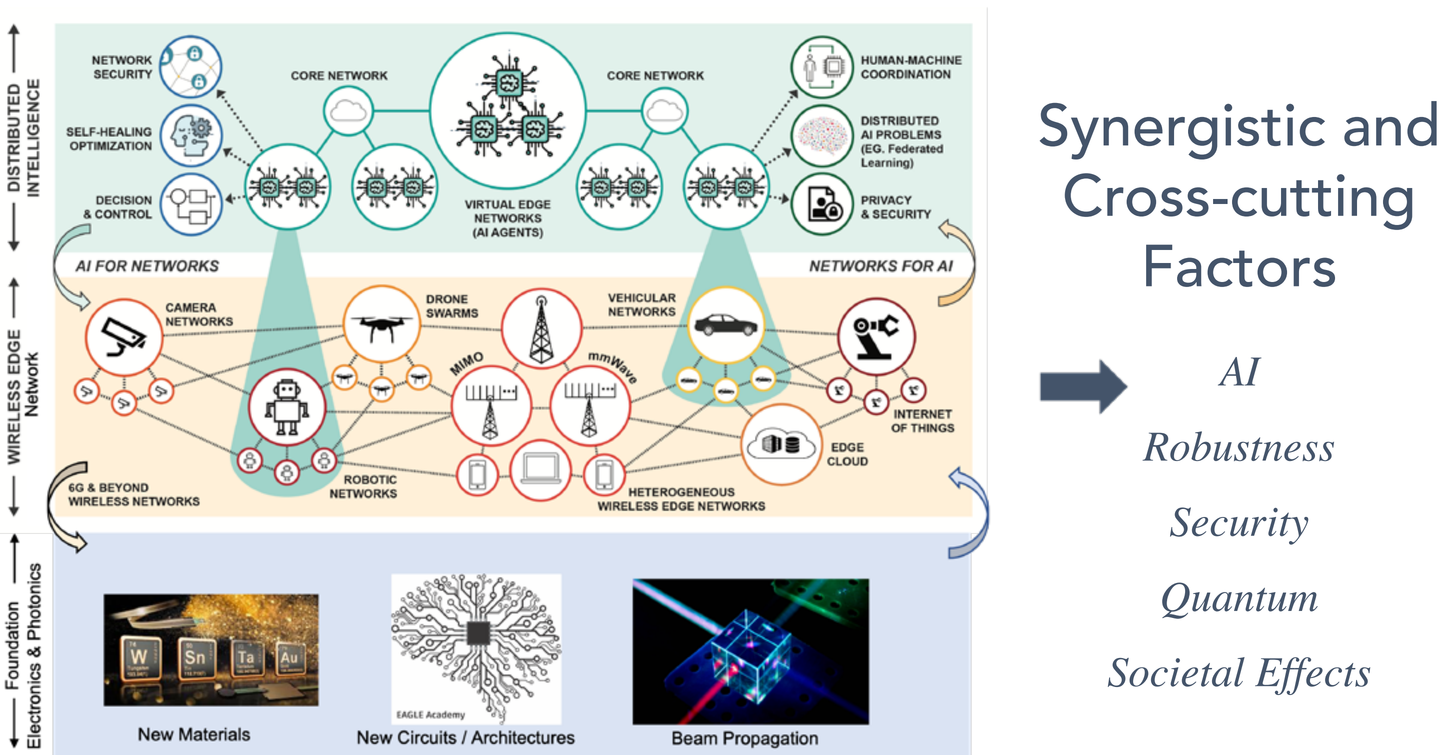


Figure 1: Future wireless networks will integrate intelligent systems (AI) and exploit advances in electronic and photonic materials, circuits/ architectures, and devices. In addition to the camera networks illustrated here, future wireless networks may include other sensor networks, as well as satellite networks to provides space infrastructures functionality. [Source: Adapted from ai-edge.osu.edu]

From an operational point of view, a wireless system must handle communications, networking, signal processing and computation, data storage, energy budget, security, privacy, etc. The networking portion has traditionally employed a form of distributed hierarchical modularity or layering for simplicity and scalability. This concept of distributed layering has been key to the success of the Internet. For example, in the Internet, functionalities are separated by layers across large geographic areas, where only certain aspects of the architecture are standardized. Thus, the Internet does not care about the underlying technology used by individual distributed entities (or networks) as long as they speak the "language of IP (Internet Protocol)" across the networks. This separation of functionalities has allowed innovation to flourish, resulting in a decentralized architecture that has largely been responsible for the tremendous growth of the Internet (James F. Kurose & Keith W. Ross, 2002). Further, the routing architecture allows for resilience from failures, and error-control mechanisms are in place to combat packet-drops, data corruption, etc., which are critical to its success. However, such architectures have prevented the Internet from providing any performance guarantees to the end users. Future XG networks may have to intelligently cross these layers in order to provide performance guarantees while maintaining the decentralized structure that is so essential for scalability and growth. The communication portion of each link in the network has been achieved via propagation of electromagnetic (EM) waves. To increase channel capacity, higher bandwidth, and therefore higher frequency EM signals (sub-millimeter waves, THz, mid-infrared (mid-IR), IR, and visible) are needed. However, higher frequency signals exhibit shorter propagation range, requiring smaller network cell distances and line-of-sight propagation. New materials and waveform shaping, and propagation may allow for highly tailored signals that improve information transfer (e.g., achieve near line-of-sight for high-frequency transmissions that are currently being blocked by obstacles). Electronic subsystems have traditionally handled the computation and signal processing part of wireless systems. However, recent scientific and technological advances in photonics, electronics, and networks open new possibilities and generates intriguing basic research questions:

- Can we achieve significant advancement in the fundamental sciences that underlie revolutionary concepts of future wireless technology, such as network science, EM wave shaping and propagation, mathematics and compressed sensing, cryptography, etc.?
- How might advances in photonic computation be hybridized with electronic computation to revolutionize wireless systems?
- Can we innovate in data interface/conversion between the photonic and electronic platforms to create "electro-photonic-network" platforms?
- Can we develop cross-layer architectures that incorporate advanced electronics and photonics as part of the design? Is this even desirable and how will it impact modularity?
- Can we develop a new fundamental theory of network optimization and control that takes into account the new needs of XG systems (latency, dynamic connectivity, etc.), and leverage opportunities from photonics and electronics advances?
- Can we leverage advances in AI to design distributed and intelligent XG wireless systems that are self-optimized, self-healing, and robust?
- What role will computing and data storage play in the overall XG network design?
- What system and component designs drive down capital and operating costs in XG systems?
- Similarly, data storage has been mostly achieved by electronic systems, so can we envision future photonic storage that may offer transformative opportunities for XG systems?
- For energy handling, how will the next generation of wireless power transfer impact wireless communications?
- How will quantum technology affect the future of wireless systems? Will it result in improved performance or also expose vulnerabilities in the security over these networks.
- What are the possible research trajectories of physical sciences in terms of new materials and architectures for wave-matter interaction, new circuits, nanoscale fabrication etc., over the next 10-20 years?

Workshop on Wireless Communications

To explore these questions and the promise and challenges of wireless communications, particularly for technologies associated with terrestrial networks, a future directions workshop was held on June 8-9, 2022, in Arlington, VA. This workshop gathered 19 distinguished researchers from academia, industry and government from the photonics, electronics, networks and AI communities for unfettered discussion and debate on the current research challenges, opportunities, and trajectory for research over the next twenty years.

The two-day workshop was organized to encourage lively discussion and debate and to maximize the interaction of participants. The first day began with short, introductory presentation from the co-chairs to frame the workshop goals. The remainder of the day was spent in small group discussions on the fundamental challenges to progress and technical capabilities. These breakout sessions covered specific subdomains: photonics, electronics, and networks. Each session was led by two experts in the field and was followed by an outbriefing to the whole group. The second day of the workshop began by reviewing the discussions of Day 1 followed by whole group discussion of any topics not covered in the first day and to discuss cross-cutting themes.

With this framework in mind, the following sections describe the research challenges and opportunities outlined at the workshop and maps a research trajectory for wireless communications research over the next twenty years.

Wireless Communications Research Challenges

To explore the research challenges for future wireless communication systems and projected science and technology advances to overcome these challenges, the workshop utilized three working groups on the topics of photonics, electronics, and networks. Below is the summary of the findings of these sessions on the most pressing challenges for wireless networking followed by how these challenges will need to be coupled across the broad research areas involving networks, photonics, and electronics. Since there are synergistic, cross-cutting, and multidisciplinary factors among these three subsystems, although the working groups were centered around these three general themes, in what follows we present the synthesized and collective summaries of our findings.

A New Layering Architecture to Enable the Growth of Communication and Computation

The success of the Internet has largely been driven by its open architecture where individual organizations were allowed to develop their own networking technologies as long as the networks spoke the language of IP when communicating beyond their domains. This distributed growth model allowed innovation and growth to take place. However, the success of this open model only resulted in "best effort" deliveries but did not translate to being able to provide any end-to-end guarantees on the performance of applications. Hence, a major challenge is how to design an architecture for XG networks that leverages the success of the Internet's open architecture, but also provides the hooks required to provide performance guarantees. Challenges include developing cross-layer, cross-functionality architectures (Xiaojun Lin et al., 2006) where photonics and electronics and even quantum become part of the cross-layer optimization. In this case, what would happen to modularity and separation of layers, a cornerstone of good network design? What will be the key pieces of information that will need to be exchanged between photonics, electronics, and networks to allow for an overall optimal solution and yet keeping some degree of modularity. Can such systems be fully distributed? What level of cooperation is needed between different autonomous systems and what data sharing mechanisms are needed? How will this lead to standards and who will define them? Will these systems be consistent with a competitive market structure to enable light handed regulation? How will these systems promote flexible spectrum sharing?

Combating Lack of Coverage, Blockage, and Disconnectivity at Higher Frequencies

It is critical for communication links to offer ubiquitous coverage and be reliable. As links move to higher frequencies, as mentioned above they get easily blocked by obstacles (Xiong Wang et al., 2018), particularly those that contain moisture, such as foliage and the human body. This is true today at 5G millimeter-wave frequencies and will be even more true as next-G technologies push to frequencies above 100GHz. This challenge is further exacerbated in mobile systems because transmitter-receiver pairs move in and out of line-of-sight, and blockage could occur more often. Therefore, a key challenge is to find ways to transmit higher frequency signals over larger distances and in varying or difficult environments. To overcome these challenges of coverage, blockage, and disconnectivity, advances are needed in all three subsystems (networks, photonics, and electronics). Potential solutions include 1) new electronic device and circuit technologies that allow for higher signal power generation, thus allowing signal propagation across longer distances, 2) architectures for larger arrays of antennas to leverage beamforming gain to overcome signal propagation losses, 3) the implementation of relays and repeaters that replenish signal energy as it decays, either based on circuit implementations, smart materials or reconfigurable intelligent metasurfaces, and 4) methods that use a combination of prediction/learning and leverage the ability to transmit at multiple frequencies and from multiple spatially diverse transmitters to sustain reliability at higher throughputs. Research in terahertz-frequency communications is an active field, exploring advantages and limitations of such frequency regimes (see the callout box below). A key challenge is whether these approaches can preserve the privacy preferences or requirements of the users (especially fine-grained location privacy).

Terahertz Wireless Communication Technology[1]

The speed of today's wireless communication systems is limited by the relatively narrow bandwidth of existing transceivers and the heavy use of the electromagnetic spectrum up to 60 GHz. These constraints have been forcing researchers to push the carrier frequencies to higher frequency bands, which have not yet been allocated to any specific active services. Therefore, it is not surprising that the terahertz band has been of special interest for 6G communication and beyond. Terahertz wireless datalinks require terahertz transceivers, driving circuits, data encoding and decoding modules operating at high speeds (Thomas Kürner et al., 2022). While operation frequency of integrated circuits is limited by the cutoff frequency of transistors, device parasitics, and interconnect losses, optics can offer many benefits for handling electrical signals, including simplified distribution and multiplexing; low propagation losses; as well as broad modulation and amplification bandwidths. To take advantage of these great potentials, a hybrid optoelectronic design methodology is required to realize key building blocks of terahertz communication systems, which cannot be realized through conventional integrated circuits (Sengupta et al., 2018).

1 Written by Professor Mona Jarrahi, University of California, Los Angeles

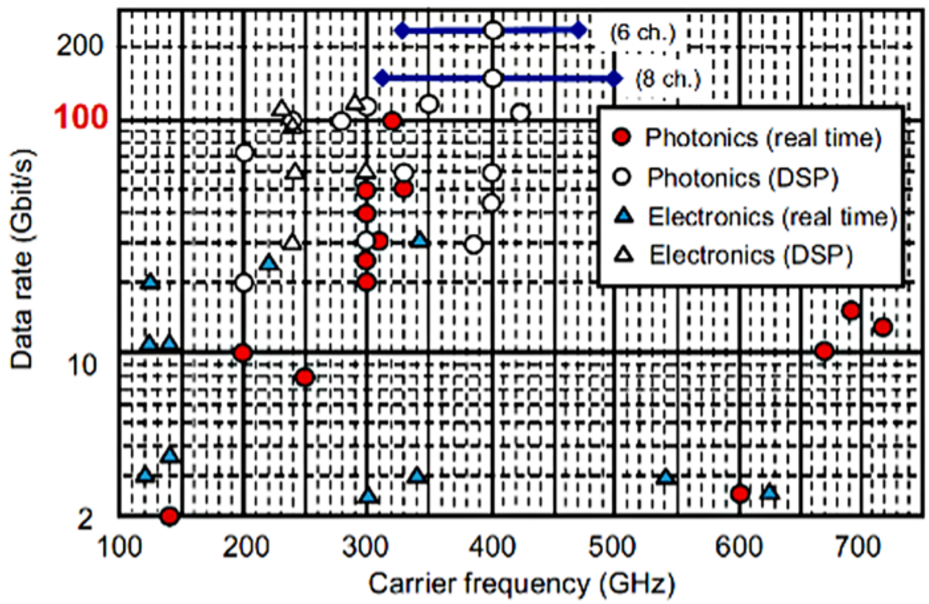


Figure 2: Carrier frequency vs. data rate obtained for single-channel terahertz wireless communication systems with real-time transmission (solid circle/triangle) and with off-line digital signal processing (open circle/triangle) (Thomas Kürner et al., 2022).

Because of their high power in the transparent atmospheric bands and their compatibility with telecommunication optical wavelengths, optoelectronic transceivers have been extensively used in terahertz communication systems. Starting with the pioneering demonstration of a 10 Gbit/s wireless datalink at a 120 GHz carrier frequency based on a uni-traveling-carrier photodiode (UTC-PD) transmitter and a HEMT MMIC receiver (Hirata et al., 2012), the reported data rates have been increasing year after year. By using carrier signals at higher frequencies and/or higher-order modulation methods combined with multichannel communication systems, data rate of communication systems went up as high as 260 Gbit/s, as shown in Figure 2 (Ducournau et al., 2014; Koenig et al., 2013; Li et al., 2019; Nagatsuma et al., 2016; X. Yu et al., 2016). This is more than 20 times faster than the 5G data rates, which could revolutionize future wireless links, autonomous vehicle systems and heavily loaded data centers. However, the game of chasing better wireless datalinks still goes on, and many important challenges—low energy efficiency, high cost and bulky size of terahertz communication system- need to be overcome. Further revolutionary advances in terahertz communication systems requires a monolithically-integrated, terahertz optoelectronics platform for scalable, compact, and low-cost system implementation. In the absence of monolithically-integrated, ultrafast optoelectronic systems, implementation of most communication, navigation, and remote sensing systems, which rely on a large array of radiation sources and detectors with independent amplitude, phase, and frequency control is not feasible (e.g., phased arrays). In addition, new types of natural and engineered materials could address some of the technological gaps in the terahertz regime. For example, new ferroelectric materials (Chen et al., 2022) could be utilized to provide terahertz modulation speeds through electrical/optical stimuli and new metamaterials could enable manipulation of the spectral and spatial properties of terahertz radiation in unprecedented ways. Therefore, innovative ideas and paradigm-shifting research directions are needed to remove such hurdles.

Integration of Heterogeneous Domains of Electronic and Photonic Platforms (driven by applications)

At higher frequencies, design of electronic and photonic functionalities becomes more complex due to the fact that various phenomena such as radiation leakage in electronic structures should be accounted for, and material loss in photonic systems need to be considered. Therefore the two domains should be designed as a whole single system, i.e. one needs to co-design electronic-photonic platforms. This will introduce new challenges in heterogeneous modeling, design, and integration of electronic and photonic platforms. However, such additional complexity may offer opportunities in devising structures with intricate functionalities, but also may reduce the modularity of each section, since the entire structures need to be designed to those functionalities. Potential future research directions may include AI-driven co-design of hybrid electronic-photonic platforms and relevant development of ultrafast simulators for such co-design strategies.

Energy Efficiency and Cost

Both higher frequencies of operation and paradigms with higher spectral efficiency result in increased energy consumption. The energy consumption associated with communication, both on the infrastructure side (base stations, small cells, repeaters etc.), as well as on the user side (handset devices, CPE devices etc.), is becoming an increasing bottleneck, even in today's 5G technology. The energy consumption poses both a technological challenge, in that the heat that is dissipated must be removed from the device in a low-cost fashion before it causes damage to the electronics, and a societal challenge, as we struggle to manage our energy needs while transitioning to sustainable and renewable sources of energy. When considering energy efficiency, it is important to consider energy consumed per bit communicated, as well as total energy consumed. Typically, new generations of communication technology improve energy consumed per bit, since the data rate improves while energy consumed does not scale proportionately. However, the total energy consumed also typically increases as the total data communicated and consumed increases, posing the technological and societal challenges described earlier. Techniques to improve energy efficiency span novel device technologies (for instance, III-V and wide bandgap semiconductor devices with higher speed, and therefore efficiency), circuit architectures (for instance, power amplifier architectures with higher average efficiency, large-scale array architectures), and system concepts (for instance, wireless power transfer), and network control architectures (e.g., energy efficient routing, duty-cycling of devices, infrastructure and applications, etc.).

Both higher frequencies of operation and paradigms with higher spectral efficiency result in increased cost, both in terms of capital expense in deploying the communications infrastructure, as well as the user devices, and the operating expense of running the networks. Consequently, it is critical for new communication technologies to pioneer new applications that justify (either economically or otherwise) their deployment. It is equally important that the cost structure supports competitive service provision, as this is a cornerstone of communication system regulation.

Conversion Loss in Interconnects and Frequency Conversion

When a signal from one frequency range is converted to another range (such as in modulation), the signal experiences conversion loss. Similarly, interconnects also present some signal loss. Moreover, as we move to higher frequencies, we must address latency in signal conversion (from analog to digital and from digital to analog). A challenge is to explore methods and technologies to mitigate and reduce such loss. In particular, the future wireless communications must rely on multiple bands (e.g., from RF to THz and optical domains), because different environmental conditions may require different bands. For example, the out-of-atmosphere line-of-sight communications can operate in the optical domains which have high bandwidth, whereas within the atmosphere clouds can be an obstacle for such optical line-of-sight communication. In such cases, RF may be more suitable, but the bandwidth is low. THz signals are also absorbed by water vapor. So, one will need to have very fast, agile frequency conversion with on-the-spot reconfigurability. Realizing low energy, low loss, scalable interconnects, and frequency converters will have positive impact on the future of wireless communications.

Developing Low-Latency Scheduling Protocols

As applications become increasingly sophisticated, providing ultra-low latency over networks becomes paramount. For example, in applications such as AR/VR even a few msec of delay (or jitter) could result in a detrimental end-user experience (e.g., Cybersickness (Chang et al., 2020), such as nausea, lightheadedness, etc.). In automated transportation applications, the "age of updates" (or freshness of information) is critically important in making precise control decisions to ensure the safe flow of traffic. Age (Kaul et al., 2012) is different from traditional delay in that it is not a monotonic function of the traffic load. Thus, a key challenge for future wireless networks will be how to schedule resources (power, users, interference, etc.) to minimize different forms of latency (mean delay, delay jitter, age of information, etc.).

New Spectrum vs. Spectrum Efficiency

Each new generation of wireless technologies looks to significantly enhance the data capacity over the previous generation. Data capacity can either be enhanced by utilizing new spectrum, typically at higher and higher frequencies, or by exploring communication paradigms that enhance spectrum efficiency and coexistence with heterogeneous spectrum users (especially passive users such as atmospheric sensing and radio astronomy). For instance, the two most critical technologies pioneered by 5G (Andrews et al., 2014) are the use of millimeter-wave spectrum ranging from 24GHz-100GHz, and the use of massive MIMO technologies, where large arrays of antennas at the base station enable simultaneous links to multiple users to enhance aggregate capacity. Each of these approaches is faced with fundamental challenges in coverage and reliability, energy efficiency and cost, as described below.

Seamlessly Integrating Edge Computing and Storage with the Network Architecture

Future XG networks are expected to grow in large part due to the high demand at the edge (e.g., IoT) driven by sophisticated and smart applications that will use content in increasingly intelligent ways. A major hurdle will be in the unification of networking, computation, storage (caching), to derive efficiencies, reduce delays, and increase reliability. Key challenges include finding the right trade-offs between computing and communication, leveraging geographical knowledge in making decisions, determining what to cache and when, etc. Furthermore, reconfiguring will require storage of signals and transmitting them through different channels and different modes. Another challenge will be how to leverage the storage and computation capabilities of cloud computing systems to decrease the computation and memory requirements of the end users.

Challenges in Photonic Computation and Storage

Currently, most signal processing and computation in wireless systems is handled by electronic systems. Exploring wave-based photonic processing and computation can bring new capabilities for ultrafast low-power processing. Spintronics may also be another platform to consider. Moreover, traditionally data storage has been achieved through electronic parts of wireless systems. An interesting challenge would be to explore how data can be stored photonically. Addressing this challenge can open exciting possibilities in reducing conversion loss and the possibility increasing processing speed. This may also lead to wireless system with distributed communication, processing, and storage systems.

Challenges in Enhancing Nonlinearity in Photonics

While electronic and radio frequency (RF) systems have benefited from high nonlinearity, optical systems experience relatively weak nonlinearity. Exploring ways to enhance nonlinearity, and with high speed, in optical regimes can bring a new set of tools in signal manipulations for the future wireless systems. There are challenges, such as requirement for high intensity level to initiate nonlinearity. Material innovation can be a path towards this goal and addressing some of the challenges. Potential research directions may include exploring materials with engineered phase transition, materials with desired quantum features, low-dimensional material platforms, topological structures, bio-inspired photonic structures, etc.

Securing Future XG Systems

It is critical that future XG systems be designed to take into account security features in the design itself and not as an afterthought. Resourceful adversaries (e.g., nation-states, terrorists, cyber criminals) can create havoc in network ecosystems and carry out malicious activities by exploiting network vulnerabilities. New wireless networks, like 5G and Wi-Fi 6, offer certain security advantages. For example, in mmWave communications, directionality can help mitigate spoofing and eavesdropping attacks. While the area of wireless security has seen significant growth, most of the efforts are based on a case-by-case basis with very specific attacks followed by specific defenses. However, securing future XG networks is a formidable challenge that will require the development of a comprehensive framework spanning hardware verification, protocol verification (both specification and implementation), scalable formal methods, real-time network monitoring/diagnostics, attack containment, etc. The increased "softwarization" of networks, on one hand increases flexibility, but on the other hand, it increases the numbers and types of vectors that can be used to attack networks. Further in XG systems, security will have to begin at the hardware level itself and further discussions on this aspect will be detailed in the electronics section.

Trustworthy Dynamic Sensing

The demand for mobile broadband access has led to significant commercial demand for bands below 6 GHz. Unfortunately, allowing new commercial access in a band usually generates some level of interference to legacy users operating in that band or in neighboring bands. Despite decades of research, spectrum sensing is in its infancy, both technically and institutionally. Ideally, mobile networks should be able to optimize network spectral efficiencies over any geographic area by utilizing all available white space in time, frequency, and space.

Dynamic sensing is a well-known effective mechanism to improve the utilization of wireless systems. In a nutshell, dynamic sensing is a mechanism to sense whether channels are currently being occupied. If they are not being used by the primary user of the channel (e.g., the owner), they may be used to for other activities. For example, frequencies used for emergency vehicles could be used for other transmissions when idle. However, dynamic sensing brings with it inherent risks for the user of the spectrum/system being sensed, as well as increasing the ability of an adversary to corrupt the sensing process itself. The key challenge here is to be able to develop mechanisms that ensure trustworthy dynamic sensing. Promising demonstrations (e.g., DARPA Spectrum Collaboration Challenge) have shown that if networks can collaborate and trust each other in real-time, substantial network spectral efficiency increases may be possible. There is an urgent need to support theory and experimental research to solve the technical, economic and sociological challenges and to convince legacy users and regulators of the viability of new spectrum access paradigms.

Ensuring End User Privacy

Future XG systems are expected to support a variety of applications that will involve personalization based on the end user environment, in an effort to improve the quality of the services provided. While the current state of the art focuses on privacy of end-user applications, preventing privacy-leakage, etc., in this new paradigm, needs exchange of information to be able to provide the services that the user demands. For example, a number of applications that will use XG systems will involve distributed learning. In these applications, information about the models being learned flows across the network. For example, in a federated learning algorithm, network users receive intermediate versions of a model and perform local updates to the model based on their own, possibly sensitive, data, before the result is forwarded to some parameter server. This opens the door to a host of attacks that aim at inferring users' private and sensitive data from the observed (intermediate) model. The key challenge will be to develop a systematic theoretical and algorithmic approach that can find suitable trade-offs between privacy, security, and end-user performance.

Automating Network Functionalities

In current wireless systems, cellular operators are constantly monitoring and tuning various cellular parameters to meet the needs of the users. For example, at any base station the carrier frequency bands have hundreds of parameters that need to be configured for various operations. The state of the art today is to manually set the parameters each time a change or update occurs, which is costly in time and resources, and can lead to inefficient solutions. This problem will only be exacerbated in future XG networks, where the scale and complexity of the systems will grow exponentially. A major challenge here will be to develop fully automated methods that can reconfigure these networks over a wide range of timescales (milli-seconds to weeks) depending on the individual parameter needs.

Such automation will also help improve the resilience of these systems, making the networks increasingly robust and self-healing. A further challenge is ensuring that the network state after the automated actions fall within the space of allowed configurations implicitly defined by operator-specified intents.

Using Data to Develop a Unified Framework for Real-time Network Control

There was a general consensus among workshop participants that new methodologies will be needed for managing the hyper-scalable complex networks. These networks are expected to be even more complex than today's distributed systems, consisting of an array of dispersed network elements, comprising heterogeneous software and hardware components and modules. Traditional approaches to managing these networks have fallen into two broad categories. The first category has been the development of control algorithms based on heuristic designs derived from domain knowledge, e.g., transmission control protocol (TCP), variants of 802.11, etc. The other category has been the development of optimization-based approaches for scheduling and resource allocation in networks. However, there was some degree of consensus in the working group that these methods in isolation will not suffice to control future XG networks, as neither practical algorithms developed from domain knowledge nor mathematical modeling based on simplified models can by themselves sufficiently grasp the vast scale, complexity, and uncertainty in these hyper-scale and heterogeneous networks. Given that future networks will generate a large amount of data, and also given the success that artificial intelligence/machine learning (AI/ML) tools have had in various domains, it is natural that AI/ML based algorithms be designed for real-time network control of these future XG networks. However, a major challenge identified was how to exploit the complementary strengths of AI/ML based algorithms and model-based algorithms in order to create a unified framework for real-time control of these hyper-scalable networks.

Wireless Communications Research Opportunities

The general consensus of workshop participants was that we need to move to higher frequencies in order to have higher bandwidth and higher data rate. In most cases, this will be accompanied with the higher propagation loss and blockage in air. While space communications and indoor communications will not be affected as much with this move, urban communications will be. In order to overcome this hurdle, we can explore multi-hop, multiple repeaters/base stations and multipath propagation (instead of traditional direct propagation) achieved by intelligent surfaces and reconfigurable surfaces embedded in buildings and structures (windows, walls, smart skin, smart garments). Just like solar panels on buildings, intelligent optical surfaces can be embedded on buildings, walls, garments, etc., in order provide multi-hop propagation systems, and allow longer range of signal reach.

The workshop participants in all three working groups discussed the potential opportunities, and associated science and technology advances, to overcome the aforementioned challenges to enable future generation of wireless communications, with the trajectory for the next 5-year, 10-year, and 20-year time frames.

Developing New Foundational AI for Network Design and Control

The astonishing successes of AI across a number of different engineering and scientific domains has provided a unique opportunity to design next generation XG wireless networks that are "intelligent" in many different ways. However, simply applying known AI techniques will not be good enough and may result in solutions that are far from optimal. The reason for this is that XG wireless networks are highly dynamic entities that have unique constraints that are not typically encountered in traditional uses of AI. For example, wireless networks are mobile entities where the environment changes could be non-stationary. These are systems in which both hard and probabilistic constraints need to be satisfied at the global level, as well as the user level. There is also several decades of domain knowledge that has resulted in the development of theoretical foundations, algorithms, protocols, and implementations that could substantially improve performance over a purely black box AI driven approach to network design. For these reasons, there is a tremendous opportunity to develop new AI tools and techniques that can exploit network dynamics and satisfy network constraints in order to design future networks. These developments will not only result in advances in network design and control, but also in the field of AI and ML itself. For example, we will need advances in (i) Reinforcement Learning (RL) and Online Learning (OL) for decision-making, or decision- making with imperfect or unknown information for network control. Here, the challenge that we will have to overcome is that constrained RL problems have few provable guarantees, and often have high complexity (both computational and the amount of data needed to make decisions); (ii) Decentralized learning in future XG networks where the edge nodes may have limited or heterogeneous memory, computation and straggler problems, communication links that could be unreliable and data collected are unbalanced, highly heterogeneous, and require privacy constraints. Here, the challenge will be to design scalable and network-aware decentralized/federated learning (FL) approaches that address the needs of end-users and are adaptive to practical computation, communication, and data constraints of network edge devices. (iii) Representation learning for learning features in the network data such as sensor fusion considering camera, GPS and LiDAR sensors, latent embeddings of beam-selection, etc. iv) Explainability of AI/ML models and actions to facilitate network operator adoption. v) Combining traditional algorithms and AI/ML methods to provide good performance when AI/ML based decisions are accurate and bound worst-case performance (unintended consequences) when AI/ML based decisions are inaccurate.

Developing a Scalable Experimental Toolbox

There is currently a major deficiency of large-scale experimental facilities to test out the designs and algorithms developed for next generation wireless networks. A major challenge is how to develop experimental facilities with automatic pipelines to collect large datasets, and to prototype data-driven solutions at scale. While there are some data-sets available at the physical layer, there is a pressing need for obtaining even data at the higher layers of the protocol stack. This is especially needed for higher layers of the protocol stack. This provides a significant opportunity for both the development of government-sponsored experimental testbeds (such as the PAWR platforms: https://advancedwireless.org/), as well as the development of new government-industry partnerships in order to develop scalable living labs where new technologies can be tested, validated, and further used to refine the theories and algorithms developed.

Establishing New Security Principles for Future XG Networks

As XG networks become increasingly intertwined with our daily lives (across diverse areas such as transportation, banking, education, and entertainment), they also provide opportunities for resourceful adversaries (e.g., nation-states, terrorists, cyber criminals) to create havoc in network ecosystems and carry out malicious activities by exploiting network vulnerabilities. The advantage of developing future XG wireless networks is that important security primitives can be built into the system at the design stage itself so that the system is not playing catch up later. Further, new wireless technologies such as mmWave communications can take advantage of directionality to help mitigate impacts of spoofing and eavesdropping. However, securing future XG wireless networks, such as 6G and beyond systems, is a formidable challenge because of the increased complexity of these networks, the huge numbers of connected devices, the low latency requirements, etc. Security must cover network design, operation, and evolution across both anticipated uses (common cases) and unanticipated-yet-possible uses (corner cases). While requiring 100% security often contradicts usability, the opportunity is present to develop a comprehensive network security framework based on three important pillars: (1) pre-runtime security: secure foundations for the networks via (potentially AI-enhanced) adversarial analysis methods for network protocols; (2) runtime-security: network protection through a security life-cycle, with AI-enhanced tools for each life-cycle phase; (3) post-runtime security: enhanced security mechanisms based on forensic analyses. Such a systematic analysis will lead to the development of tools for data reasoning driven forensics, automatically analyzing network protocol specifications and network protocol implementations, learning, and adapting network security policies, and being able to automatically detect network anomalies. Further, run-time security may go beyond software and into the development of the signals themselves. For example, one could shape the signal or provide a different way to embed information and also involve hardware into the approach.

Designing XG Networks to Enable Distributed Learning and User Privacy

As XG systems become increasingly sophisticated, we can expect that they will be used to interconnect devices that will provide different services to their users, often based on some AI application. Unlike the AI of today, the future of AI will be distributed and carried over these XG systems. The data needed for these learning applications is private and may not be co-located with learners, the computation will be distributed, the applications will be real-time, and interactions will need to occur between human and AI agents. The mechanisms that will enable these distributed learning will have the important societal benefit of democratizing AI, where no longer will users be solely reliant upon paying large sums of money to massive server farms in order to run their AI applications. The opportunity here is to be able to develop the foundation for new AI algorithms that are robust to immutable network and computing constraints, are adaptive to heterogeneity, and robust to failures, and provide privacy and fairness. These algorithms could be used in interconnected sensors and actuators for a whole host of applications from intelligent transportation, distributed robotics, automated manufacturing, tactical communications, etc.

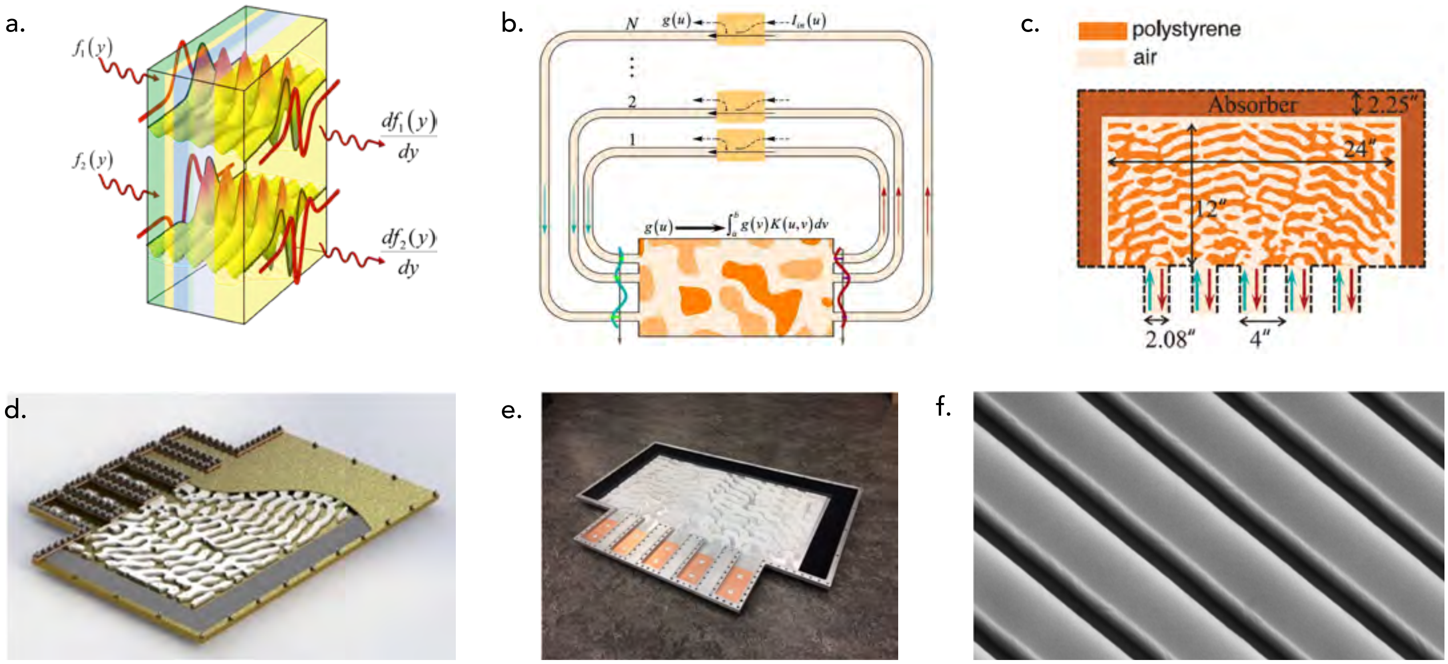
This will involve the development of

- communication-efficient and network-aware distributed optimization and learning systems where the end user AI will tailor itself to the constraints of the network
- AI-aware network operations, where the network will automatically reconfigure its resources based on the needs and objectives of the end user applications
- new collaborative methods across the humans-AI-networks-machines to make systems more efficient than either human or machines by themselves

Further, in these distributed AI systems, the information about the models being learned flows across the network. This opens the door to a host of attacks that aim at inferring users' private and sensitive data from the observed (intermediate) model. Fortunately, the last decade has seen the emergence of a rich theory called Differential Privacy (DP) to deal with privacy threats which has also been implemented in real systems, e.g., in the Chrome browser, in iOS-10 and by the U.S. Census Bureau for the 2020 census. While this theory has been rigorously defined, intuitively a differentially private computation is one where no individual's data has significant influence on the outcome. The opportunity will be to develop the theory and implementation of Differentially Privacy specifically for distributed learning over XG networks.

Wave-based Signal Processing, Computation, and Data Storage

In recent years, there has been growing interest in exploring how material structures and photonic platforms can provide suitable domains for signal processing and analog computation using electromagnetic waves. As one of the currently active research directions, metamaterials and metasurfaces have been investigated for performing mathematical operations, signal processing and mathematical equation solving with waves(Bogaerts et al., 2020; Camacho et al., 2021; Cordaro et al., 2019; Mohammadi Estakhri et al., 2019; Silva et al., 2014; Zangeneh-Nejad et al., 2021; Zangeneh-Nejad & Fleury, 2018). As electromagnetic signals propagate through such structures, which are judiciously designed to represent required some specific mathematical operations, the output waves contain the information about the processed signals and the solutions to given equations. Figure 3 shows the schematics of such ideas and some of the prototypes in two different wavelength regimes.



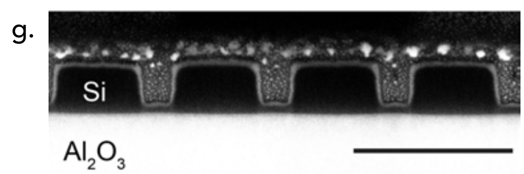


Figure 3: Material-based, wave-based analog computing structures: (a) Sketch of the idea of photonic metamaterials performing mathematical operations (such as differentiation, integration, convolutions, etc.) From (Silva et al., 2014)], (b) sketch of properly designed photonic metastructures with proper waveguide feedback, enabling solving linear equations with waves, From (Mohammadi Estakhri et al., 2019). (c) sketch of the microwave-based prototype for the proof-of-concept experiment for metamaterials that can solve equations with waves, from (Mohammadi Estakhri et al., 2019), (d) its rendition and (e) its photograph From (Mohammadi Estakhri et al., 2019). (f) Tilted SEM image of the Si metasurface capable of the second-derivative operation. From (Cordaro et al., 2019). (g) SEM image of a focused-ion-beam cross section of the same metasurface, i.e., the Si nanobeams on an Al^2O^3 substrate. The scale bar is 400 nm for both panels. From (Cordaro et al., 2019).

Since photons do not interact with each other in linear media, such wave-based, material-based photonic analog computing offers exciting possibilities in handling and processing data with near-speed of light, low power, and ability to perform parallel processing. In particular, the parallel nature of such analog processing offers promising platforms for high-speed image processing, in which the raster scanning may not be needed, and thus the entire image can be processed at the same time, providing ultrafast low power processing capabilities. However, there are also challenges with such systems. These include, for example: (1) noise accumulation, particularly in cascading such systems, (2) limited reconfigurability, and (3) lack of direct photon storage. Currently, there are several research directions to explore addressing some of these limitations, such as use of reconfigurable Mach-Zehnder interferometer (MZI) meshes (Miller, 2013, 2015; Tzarouchis et al., 2022) and phase-change materials (Moitra et al., 2022; Q. Wang et al., 2016). However, more research is needed to explore various ways to overcome such challenges, e.g., potential research directions on materials that retain wave history, structures that efficiently store photonic energy, materials with higher degrees of freedom in design, etc.

Reconfigurable Intelligent Surfaces (RIS)[2]

Properly engineered surfaces, known as metasurfaces (Achouri & Caloz, 2017; Estakhri & Alù, 2016; Holloway et al., 2012; Kildishev et al., 2013; Ra'di et al., 2017; Ra'di & Alù, 2020; Ramaccia et al., 2017; Tretyakov, 2015; N. Yu et al., 2011) have been introducing a compactification paradigm for electromagnetic systems, enabling a broad range of functionalities over an ultrathin platform, and unveiling a new degree of control and transformation of the electromagnetic wavefronts. Several wave phenomena have been demonstrated using electromagnetic metasurfaces, many of which are of direct relevance to wireless communications, but with a form of disconnect between the opportunities in controlling and engineering waves and the actual needs of wireless systems and the scope of this report. However, to date there has been a clear form of disconnect between the opportunities available to control and engineer waves and the actual needs of wireless communication systems. It is of high relevance to connect these two research areas, and foster investigations on how the progress in metasurfaces can actually be used to

2 Written by Professor Andrea Alu, City University of New York

revolutionize wireless technologies and gain widespread use.A concerted effort between hardware and system wireless engineers can leverage these advances in a two-way exchange, in which wireless systems take advantage of the new features of metasurfaces, and metasurfaces are adapted to address the needs of wireless communications. Reconfigurable Intelligent Surfaces (RIS) (Basar et al., 2019; Bjornson et al., 2022; di Renzo et al., 2021; Renzo et al., 2019; Strinati et al., 2021; Wu et al., 2020) have started to address this ambitious goal, and a close connection between metasurface advances and new wireless communication modes s may be revolutionary to address the needs of future wireless communication systems. Future reconfigurable intelligent metasurfaces may be able to control at will the communication spectrum, operate at THz frequencies, process in real-time and with low energy needs the incoming signals, engineer the channel properties and scattering features with large flexibility, self-adapting their response to changes in the environment and users, amplifying signals in the presence of channel loss, and maximizing all relevant metrics of interest. Programmable multifunctional metasurfaces and underlying communication protocols hold the promise for unprecedented opportunities in the future of wireless systems, changing the way we think about the propagation space and the frequency spectrum.

Figure 4 sketches some possibilities opened by such a reprogrammable intelligent metasurface platform: tailored nonlinearities (Figure 4b), active elements locally amplifying the incoming waves and compensating for propagation loss (Figure 4c), and temporal modulations enabling parametric phenomena, frequency conversion, and reprogrammability (Figure 4d) may be leveraged at the unit cell and few cell levels to rewrite the way we engineer wireless communications. Such surfaces may control the reflection wavefront pattern in its spatial distribution, polarization, frequency content, and dispersion to maximize the interference among multiple paths for all users. The real-time programmability of its elements may enable the implementation of a dynamic environment in which changes in the user positions and in the background are dynamically monitored, and the information may be used to program the metasurface response in real-time.

This vision, with its opportunities and challenges, requires a concerted effort of various communities. Operating at high frequencies, the challenges of implementing reliable gain, and fast modulation schemes requires the development of new hardware technologies and materials. In order to exploit optimally these new opportunities, new wireless architectures and deployment are needed to ensure service provision and interference management among wireless links and networks. New frequency regulations and policies should be developed to exploit intelligent metasurfaces that are capable of modifying at will the frequency spectrum and the bandwidth of wireless signals. At the same time, progress in power handling, fast and strong modulation techniques need to be developed on the hardware side to enhance the metasurface response.

The use of complex control networks with engineered feedback will enhance the number of degrees of freedom. New material discovery, moving beyond CMOS-based circuits, will be fundamental in this quest. For instance, the use of GaN and other high-power electronic materials may enable stronger tailored nonlinearities and better power handling. Interfaces between electronics and photonics will require the development of ad-hoc materials and tailored heterostructures, which may benefit also the merging of this flexible platforms with novel forms of information processing and transport, as in the context of spintronics, valleytronics and other forms of alternative logic. Quantum optical materials may be engaged in the loading of the metasurface unit cells to enable efficient generation, amplification, modulation and detection of photons.

One of the biggest roadblocks to enable a seamless connection between metasurface advances and their implementation in wireless platforms is the inherently complex problem of modeling efficiently the complex interactions among their many unit cells. It will be important to develop compact and efficient numerical models to tackle the electromagnetic response of these nonperiodic and time-varying surfaces, in order to efficiently analyze and optimize these structures and integrate them into communication models that can drive optimal strategies for connectivity. Modeling will involve co-simulations that combine electromagnetic and circuit analysis, to be able to optimize the entire metasurface and its loading for optimal performance. In parallel, this optimization will also involve network analysis and design, and optimal strategies for reconfiguration, information modalities and security to address optimal networking needs and algorithms developed around the metasurface platform.

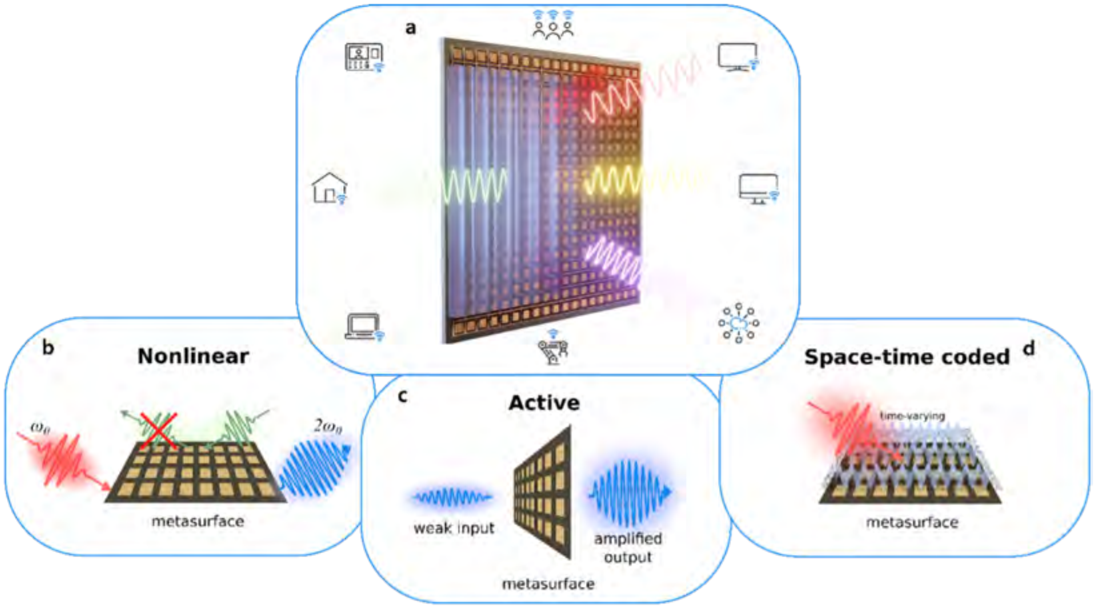


Figure 4: Reconfigurable intelligent metasurfaces for wireless communications. (a) Sketch of a reconfigurable metasurface for wireless communication systems, and (b-d) its basic features (Y. Ra'di et al., 2022).

Cross-channel interference will be an important photonic challenge to address. Orthogonal beams may mitigate this issue, for instance in the context of orbital angular momentum. Scalable manufacturing processes will need to be developed for THz systems. As for the future development for detectors, materials with proper carrier lifetime and conductivity to be embedded with photonic components can be considered. Advancement in materials science and engineering with low loss and strong optical nonlinearity is important for future wireless communications. As mentioned earlier, lack of integration of heterogeneous domains in optoelectronic platforms for higher carrier frequencies is a hurdle, which will need to be overcome to make next generation of wireless systems a reality. Advance optimization tools, mathematical approaches, and AI-assisted techniques for discovering new materials and quantum engineering of materials will need to be explored.

Sub-millimeter-wave Spectrum Utilization

As mentioned earlier, 5G technologies have pioneered the use of millimeter-wave frequencies, ranging from 24GHz to 100GHz. There is early-stage research that indicates that XG technologies will exploit frequencies beyond 100GHz (Rappaport et al., 2019), such as the 140GHz and 220GHz bands. This will require the development of front-end electronic devices, circuits and systems that can operate at these frequencies with sufficient performance to enable communication links across reasonable distances. Also critical is the development of back-end analog and digital signal-processing techniques that will enable the exploitation of proportionately wider bandwidths and data rates with reasonable energy efficiency. Emerging technologies, such as terahertz photonics and spintronics, may also unlock new pathways to the utilization of higher reaches of the spectrum.

Massive, Distributed Multi-band MIMO at Millimeter-waves

Today's 5G technology is deploying massive MIMO at <6 GHz operating frequencies to significantly enhance the aggregate data capacity beyond prior generations. In the future, we will see massive MIMO scaled to millimeter-wave frequencies (24-100GHz), concurrently operating across multiple bands. In addition, we will also see the advent of collaborative distributed MIMO, where distributed nodes that are not co-located with each other collaborate to establish massive MIMO links with enhanced data capacity and reliability. This will require techniques for coordination and control, which could either be accomplished using lower-frequency side channels or in-band control channels, as well as synchronization, potentially at carrier-grade levels, if coherent distributed MIMO is being pursued.

Ultra-low Latency Wireless Links

End-to-end latency in today's wireless networks is on the order of milliseconds. Latency is governed by both the time associated with physical-layer transport, namely propagation of the signal through the air or medium and through the electronics, as well as the time delays incurred in the higher layers of the network stack. Today, the latter dominates, while the former has the potential to operate in the micro-second range. New architectures that can substantially lower latencies in all layers of the stack can enable real-time applications that operate with closed-loop feedback over the communications infrastructure, such as remote robotic surgery, real time traffic control etc. Key techniques that would enable such latencies include in-sensor/near-sensor computing and decision-making, thus avoiding traversing the entire network for latency-critical applications.

Convergence of Sensing and Communications

Communication systems and sensing systems (radar, passive and active imagers, localization sensors etc.) have similar front-end architectures, but are built, deployed, and operated separately today. It is interesting to consider a common infrastructure base that can simultaneously perform communications and sensing, across wide bandwidths. Key research topics include: 1) cross-layer and system-level architectures supporting joint communication and sensing, 2) techniques through which sensing and communication systems can work together to enhance performance (for instance, information from radar and localization sensors can provide user location and mobility information to aid beamforming and channel estimation for communication), and 3) techniques to mitigate interference and promote co-existence between communication and sensing systems.

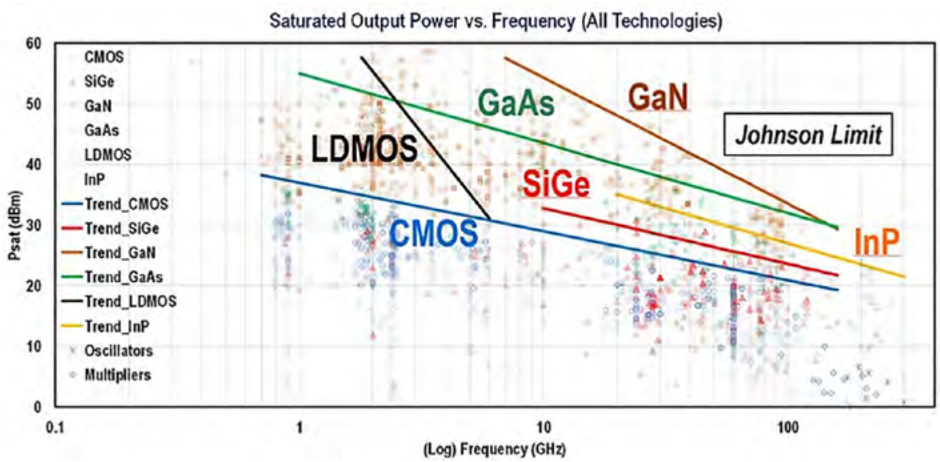


Figure 5: Saturated output power of amplifiers versus frequency of operation in different semiconductor technologies.(H. Wang et al., 2020)

Heterogeneous Integration of Silicon with III-V/III-N/Wide Bandgap Technologies

Scaling to higher frequencies (e.g. >100GHz) or to architectures with superior spectral efficiency (e.g. millimeter-wave multi-band massive, distributed MIMO) places more stringent performance requirements on the front-end and back-end electronics. All electronic devices are subject to the Johnson Limit, which dictates a trade-off between speed (bandwidth and/or frequency of operation) and breakdown voltage (output power, dynamic range and ultimately link range and reliability). Figure 5 depicts the saturated output power of amplifiers across a very large survey of state-of-the-art power amplifiers versus frequency in different semiconductor technologies (H. Wang et al., 2020). Silicon-based device technologies, such as CMOS and SiGe, are reaching their fundamental limits at millimeter-wave frequencies, and therefore, operation beyond 100GHz will require the use of materials and device technologies with superior Johnson Limit. These include III-V and III-N devices, such as GaAs, GaN, InP, as well as other emerging wide bandgap semiconductor devices. Since these device technologies offer superior performance but do not offer the integration capabilities of CMOS that are critical for the implementation of sophisticated analog and digital signal processing, the heterogeneous integration of these emerging devices with CMOS in a compact, high-performance, thermally and mechanically robust platform is critical for future electronic systems.

Photonics-Assisted Electronics

Photonics has the potential to overcome several fundamental bottlenecks associated with electronics. The first is associated with data transport—light can travel on optical fiber over extremely long distances with minimal loss, unlike the propagation of electrical signals over wires. This enables photonics-based links that allow for remote signal processing from the antennas and radio-frequency front ends. There is also increasing efforts towards photonics-based signal processing, with the promise of much lower energy expended per bit.

Wireless Power Transfer

There has been increasing research in the recent past on wireless power delivery. Traditional wireless power delivery has been focused on near-field capacitive or inductive power delivery over extremely short distances. More recently, there have been investigations into far-field power delivery, particularly exploiting higher frequencies where lensing and beamforming can be exploited to focus the beam and enhance the efficiency of power delivery. Fundamental challenges that need to be addressed include 1) the trade-off between frequency of operation, which governs the fraction of the radiated power that can be captured in the far field by a finite-sized aperture, and the efficiency of the power conversion electronics, and 2) localizing the wireless beam and rapidly adapting the beam to avoid health concerns arising from illuminating living beings and producing harmful tissue heating. Opportunities also exist in the utility of lasers for wireless power transfer, where lasers enable far narrower beams, thus eliminating the loss associated with free-space propagation, while trading off optical-to-energy conversion efficiency.

Adaptive Shape-Changing Electronics

The ability to configure the shape and size of an electronic/electromagnetic structure has great potential, particularly in the realm of reconfigurable antennas and antenna arrays. Antennas typically have a size that is related to the wavelength of operation, and antenna arrays are typically spaced half-wavelength apart to avoid grating lobes. This has traditionally imposed a hard barrier on large antenna arrays that can be reconfigured to operate across a wide range of frequencies.

Vision for Wireless Communication as a Continuum[3]

The range of features enabled by wireless communications has grown from audio and text, to surfing the internet, to real-time video streaming, to the internet-of-things. As this trend continues, new features will continue to grow, expand, and overlap to the point where the internet-of-things becomes the internet-of-everything, wherein anything and everything that interacts with the environment becomes a node within the network. In this way, the network becomes a sea of nodes that require a continuum of connectivity, which goes well beyond that of today's point-to-point (P2P) links. While this vision requires a new network topology that supports massive connectivity, it stands to reason that we cannot endlessly add bulky antennas throughout the environment. Therefore, a new antenna system must be realized that is seamlessly integrated within the social infrastructure, such as walls, buildings, etc. Such a network infrastructure will rely on distributed systems of antennas (DAS) where they provide both temporal and spatial signals from multiple spatial locations and when used in a collective and coherent manner can be used to render a 2D holographic communication continuum. This approach offers inherent spatial redundancy that is needed to ensure that every node in the network environment has adequate connectivity.

The realization of such a wireless medium needs a distribution of "holographic" antennas, where each hologram (in each DAS section) represents a collective superposition of the spatial frequency content within its regional environment such that its contribution to the medium extends far beyond a single user and rather contributes to the distribution of information within the continuum. In this case, each antenna is coordinated through an AI/ML engine that is also a coordinated and distributed platform where optimization is formed based on a global perspective rather than a base-transceiver-station (BTS) to user equipment (UE) approach. Notably, the small form factor offered by active metasurface antennas meets the required small form-factor antennas and only require DC power supply and a differential-based radio frequency (RF)-over-fiber signal distribution system. The control of this type of system uses a mathematical and closed-loop learning-based approach to configure the coherent DAS to ensure optimal communications is achieved and maintained.

This vision comes with the added necessity of a dynamic, adaptable, and flexible network that handles a wide range information content that will consist of different data formats, different information bandwidths, and different load requirements. As current wireless communication systems are based on networks that optimize connectivity on, mostly, a P2P basis, i.e., base-station to user equipment, they typically consist of a fixed number of nodes with each having an antenna whose patterns are also fixed. Thus, the primary degree of freedom for optimization is mainly based on power considerations, whether it be based on free-space-path-loss or simply the power level of the transmitter, i.e., BTS or UE. As XG networks continue to evolve, a new paradigm is evolving to become more than just connectivity and channels, but more like an immersive medium that is woven into the natural environment.

As a basis for this approach, imagine a surround-sound system where speakers are located around the perimeter of an auditorium. In this case, sound waves are transmitted in concert to ensure an immersive audio experience. From a wireless communications standpoint we can consider such an immersive continuum in the context of the RF environment where one is never "plugged" into the network, but rather is an integral part of the fabric that constitutes the network itself. As such, the challenge becomes one of optimizing "connectivity" within a dynamic medium that senses perturbations to the environment and adapts in such a way as to optimize the "continuum" itself, which extends well beyond a P2P optimization.

From this perspective, the communications medium becomes a continuum wherein a coherent DAS and AI/ML engines realize a collective platform where coordination and collaboration form a balanced embodiment of a wireless network that is self-governing. In this case, both sensing and learning are used to realize attentive and adaptable networks that are always searching to achieve optimal and resilient communications.

This approach sees a transition from the cellular based topology of today's networks to one where an embedded coherent DAS both transmits and receives holographically encoded RF wavefronts (spatial) and waveforms (temporal) throughout the collective network environment. Accordingly, every point within the continuum plays a role in determining the generation, relaying, and consumption of information, where locations that generate or consume more data attract more channel capacity through the elasticity of the continuum.

To implement this vision, new active metasurface antennas need to be developed where every meta-atom within the metasurface can both transmit and receive RF signals. This is possible using an RF-photonic approach where each meta-atom contains a photonic-integrated-circuit that uses a phased-locked pair of off-set lasers to encode the RF signal and waveform for transmit and, on receive, one of the lasers is used to modulate the received RF signal onto a sideband of the optical beam which is later down converted at a photodetector on the back-end. The motivation for using an RF-photonic approach is to overcome the synchronization challenges, power consumption, and inherent losses present in RF distribution networks, particularly as the RF frequency scales to higher regions of the electromagnetic spectrum.

3 Written by Professor Dennis Prather, University of Delaware

In summary, wireless networks are rapidly evolving to become the IoE, which will ultimately encompass all aspects of human endeavor and the environment therein. To the extent that the emerging connectivity requirements for the IoE significantly expand, they become a continuum that requires a new network topology that goes far beyond that of P2P links and becomes an immersive network. Such a network topology can be realized using a coherent-DASs that renders holographic spatial wavefronts based on advanced waveforms that are continually governed by AI/ML engines, which are seeking to optimize network performance in perpetuity.

Anticipated Trajectory for Wireless Communications Research

The workshop participants anticipated a trajectory for the research opportunities identified above with a vision for the five-, ten-, and twenty-year horizons.

Five-year vision

The following research opportunities have a 5-year horizon:

- 5–10 millisecond communication latencies using a combination of theoretical models based on network optimization, AI/ML, and protocol development
- Hybrid frequency usage to ensure sustained connectivity at high data rates
- Real-time spectrum sharing using databases. While some of this is already in progress, the key will be to ensure that such databases become increasingly ubiquitous and dynamic.
- A new layering principle to enable the growth of communication and computation, with possible loose coupling among layers
- Development of automated and scalable mechanisms for the verification of the security of 5G cellular and XG network protocols
- Metrics to establish privacy/utility tradeoffs for networks
- Frameworks for the systematic analysis of "network programs" to identify defects exploitable by adversaries
- Advancement in material innovation to achieve low loss and giant nonlinear optical responses for signal detection and generation capabilities at high frequencies (e.g., sub-mm-wave, THz, mid-IR, optical regimes)
- Artificial intelligence (AI)-driven material engineering to obtain optimal functionalities for electromagnetic manipulation in optoelectronic platforms
- Reconfigurable, scalable, and programmable materials, devices, and systems for optimizing network performance, e.g., simultaneous multi-band, multi-beam, and multi-function performance
- Co-design of algorithms and architectures with the optoelectronic devices and systems
- Advancement in wave structuring to minimize EM-matter interaction and beam divergence
- Advancement in III-V and wide bandgap semiconductor technology to enable 5W/mm power density and 50% PAE at 140GHz operation frequency.
- Advancement in front-end circuit technology to enable 200mW of output power at 30% PAE and Noise Figure of 4dB at 140GHz.

These advances are expected to enable wireless networks that support for 1Gbps/user at low-cost across 10 users resulting 10Gbps aggregate capacity, while supporting 30mph mobility and millisecond latency.

Ten-year vision

The following research opportunities have a 10-year horizon:

- Enabling AI/ML-based network control algorithms at all layers of the protocol stack
- Enabling new interactive applications using distributed ML which resulting in ultra-low latency performance
- New architectures (such as increased cell density, multi-hop backhauls) to exploit available bandwidths in the higher frequency bands
- Trustworthy dynamic spectrum sharing
- Real-time, automatic prediction of network failures using AI/ML techniques
- A mathematical framework for architectures for communications and computation
- Security verification of hardware; scalable formal methods; real-time network monitoring/diagnostics, attack containment
- Automatic network configuration to meet privacy/utility requirements per user/application
- Reduction of noise (e.g., thermal noise, shot noise, phase noise) and enhancement of dynamic range through new device physics and system design.
- Wave-based distributed analog computation, storage, and programmability at high data rates e.g., holographic, and photonic meshes.
- Direct electromagnetic wave processing as a part of computation pipeline, e.g., through neural networks.
- Reconfigurable metasurfaces, smart skin and/or architectural building blocks with embedded distributed multi-functional surfaces for beam amplification, re-routing, beamforming, etc. to enable high-frequency signals to be rerouted and transported to longer ranges.
- Advancement in III-V and wide bandgap semiconductor technology to enable 5W/mm power density and 40% PAE at 200GHz operation frequency.
- Advancement in front-end circuit technology to enable 200mW of output power at 30% PAE and Noise Figure of 4dB at 200GHz.

These advances are expected to enable wireless networks that support for 3Gbps/user at low-cost across 100 users resulting 300Gbps aggregate capacity, while supporting 100mph mobility and 100s of microseconds latency.

Twenty-year vision

The following research opportunities have a 20-year horizon:

- A unified AI/ML and model-based network algorithm cross-layer design that bridges across the domains of networks, physics, and electronics
- Reliable and low-latency networks incorporating ultra-high frequency links
- AI/ML for automated operation of networks with exponential growth in the number of components compared to the number of users
- A new established network architecture to enable growth, innovation and competition while delivering high performance
- A mathematical framework for architectures for communications, sensing, storage, and computation
- Providing assured security in a post-quantum computing and communication world
- Quantum optical materials enabling generation, amplification, modulation, and detection of photons to enable various functionalities and capabilities including entanglement, bandgap engineering, etc.
- Large-scale and/or bio-inspired material synthesis, growth, nanofabrication, and integration
- Advancement in III-V and wide bandgap semiconductor technology to enable 5W/mm power density and 30% PAE at 300GHz operation frequency.
- Advancement in front-end circuit technology to enable 200mW of output power at 30% PAE and Noise Figure of 4dB at 300GHz.

These advances are expected to enable wireless networks that support for 10Gbps/user at low-cost across 1000 users resulting 10Tbps aggregate capacity, while supporting 500mph mobility and microseconds latency.

Accelerating Research

The workshop participants determined the following resources and supports that can enhance and accelerate the future research opportunities described above:

- Testbeds that allow experimentation at scale: While government funding agencies have made significant investments in some aspects (e.g., the NSF PAWR program), more needs to be done to increase the scalability of these testbeds, make them accessible to the general community, and to provide support in using testbeds.
- Data sets for training AI/ML and for use within the XG systems ecosystem. These data sets would include data obtained from experimental platforms, typical data used for training and classification, and data merged with experimental platforms to do real-time control.
- Training for programs for AI-driven material engineering and co-design
- Infrastructures for bio-inspired device/system development
- Incentives for creating new infrastructures for developing monolithically integrated optoelectronic heterogenous platforms
- Infrastructure for developing scalable and embedded reconfigurable intelligent materials and surfaces (e.g., reconfigurable intelligence surfaces (RIS))
- Training for students to be industry ready. The XG marketplace is very large, and employees are having difficulty finding qualified students to hire. Greater investments in research that is directed towards graduate and undergraduate students is needed to keep up with the demand and will have a significant payoff to the US economy in the long-run.
- To address societal issues and wireless standards globally, and to address the need for collaboration across nations, spectrum usage and regulations, negotiations, and relevant technical standards and policies.

Conclusion

The participants of this 1.5-day Future Directions Workshop on Wireless Communications: XG and Beyond identified, discussed, and examined a diverse set of potential topics for the science and technology of future wireless communications for the 5-year, 10-year and even 20-year horizons. While the working groups were formed around the three main themes of network, photonics, and electronics, it has been clear that essentially all relevant topics for future technological capabilities of wireless paradigms are all interrelated and synergistic, and thus these areas are all going to merge together. This is particularly important as we go to 6G, 7G, XG and beyond into higher frequency domains. A variety of research challenges have been addressed and discussed, and some of their specific points have been listed in this report. These challenges point to various research opportunities and the need for new research directions that will enable the development of the future of wireless technologies. Proposed visions for the next 20 years have also been given. A set of potential resources and supports that can accelerate such future research opportunities have also been identified and listed. It is our hope that this report serves as a launching pad for future discussions among various research groups with interest in wireless science and technology.

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Appendix I—Workshop Attendees

Workshop Co-chairs

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Harish Krishnaswamy, *Columbia University*
Ness Shroff, *Ohio State University*

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Don Towsley, *University of Massachussetts, Amherst*
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Government Observers

Bindu Nair, *OUSD(R&E) Basic Research Office*
Lola Fatunmbi, *OUSD(R&E) Basic Research Office*
Ben Wolfson, *OUSD(R&E) Basic Research Office*
Tom Kazior, *DARPA*
Paul Maki, *Office of Naval Research*
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Kate Klemic, *Virginia Tech Applied Research Corporation*
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Firooz Aflatouni received the Ph.D. degree in Electrical Engineering from the University of Southern California, Los Angeles, in 2011. He was a postdoctoral scholar in the Department of Electrical Engineering at the California Institute of Technology before joining the University of Pennsylvania in 2014 where he is an Associate Professor in the Department of Electrical and Systems Engineering. His research interests include electronic-photonic co-design and low power RF and mm-wave integrated circuits. In 1999, he co-founded Pardis Bargh Company where he served as the CTO for five years working on design and manufacturing of inclined-orbit satellite tracking systems. From 2004 to 2006, he was a Design Engineer with MediaWorks Integrated Circuits Inc., Irvine, CA. Firooz received the Bell Labs Prize in 2020, the Young Investigator Program (YIP) Award from the Office of Naval Research in 2019, the NASA Early Stage Innovation Award in 2019, the 2015 IEEE Benjamin Franklin Key Award, 2011 USC Department of Electrical Engineering best Ph.D. thesis award, and 2010 NASA Tech Award for his work on development of a Ka-Band SiGe receiver MMIC for space transponder applications.

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Andrea Alu is the Founding Director and Einstein Professor at the Photonics Initiative, CUNY Advanced Science Research Center. He received his Laurea (2001) and PhD (2007) from the University of Roma Tre, Italy, and, after a postdoc at the University of Pennsylvania, he joined the faculty of the University of Texas at Austin in 2009, where he was the Temple Foundation Endowed Professor until January 2018. Dr. Alu is a Fellow of NAI, AAAS, IEEE, AAAS, OSA, SPIE and APS, and has received several scientific awards, including the Blavatnik National Award in Physical Sciences and Engineering, the AAAFM Heeger Award, the Dan Maydan Prize in Nanoscience, the IEEE Kiyo Tomiyasu Award, the Vannevar Bush Faculty Fellowship, the ICO Prize in Optics, the NSF Alan T. Waterman award, the OSA Adolph Lomb Medal, and the URSI Issac Koga Gold Medal.

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Elisa Bertino is the Samuel D. Conte Professor of Computer Science at Purdue University. Before joining Purdue, she was a professor and head of the Computer and Communication Department at the University of Milano. She has worked on data security and privacy for more than 35 years and is passionate about cybersecurity. More recently she has been working on security and privacy on 4G LTE and 5G cellular networks, security of mobile applications and IoT systems, zero-trust architectures, and machine learning techniques for cybersecurity. She is a Fellow member of IEEE, ACM, and AAAS. She received the 2002 IEEE Computer Society Technical Achievement Award for outstanding contributions to database systems and database security and advanced data management systems, the 2005 IEEE Computer Society Tsutomu Kanai Award for Pioneering and innovative research contributions to secure distributed systems, and the 2019-2020 ACM Athena Lecturer Award.

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Danijela Cabric is a Professor in the Electrical and Computer Engineering Department at the University of California, Los Angeles. She received M.S. from the University of California, Los Angeles in 2001 and Ph.D. from University of California, Berkeley in 2007, both in Electrical Engineering. In 2008, she joined UCLA as an Assistant Professor, where she heads Cognitive Reconfigurable Embedded Systems lab. Her current research projects include novel radio architectures, A signal processing, communications, machine learning and networking techniques for spectrum sharing, 5G millimeter-wave, massive MIMO and IoT systems. A She is a principal investigator in the three large cross-disciplinary multi-university centers including SRC/JUMP ComSenTer and CONIX, and NSF SpectrumX.

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Mona Jarrahi is a Professor of Electrical and Computer Engineering at UCLA and the Director of the Terahertz Electronics Laboratory. She has made significant contributions to the development of ultrafast electronic and optoelectronic devices and integrated systems for terahertz, infrared, and millimeter-wave sensing, imaging, computing, and communication systems by utilizing novel materials, nanostructures, and quantum structures, as well as innovative plasmonic and optical concepts.

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Harish Krishnaswamy (Senior Member, IEEE) received the B.Tech. degree in electrical engineering from IIT Madras, Chennai, India, in 2001, and the M.S. and Ph.D. degrees in electrical engineering from the University of Southern California (USC), Los Angeles, CA, USA, in 2003 and 2009, respectively. In 2009, he joined the Electrical Engineering Department, Columbia University, New York, NY, USA, where he is currently an Associate Professor and the Director of the Columbia High-Speed and Millimeter-Wave IC Laboratory (CoSMIC). In 2017, he co-founded MixComm Inc., Chatham, NJ, USA, a venture-backed start-up, to commercialize CoSMIC Laboratory's advanced wireless research. MixComm Inc. signed a definitive agreement to be acquired by Sivers Semiconductors for $155M in October 2021. His research interests include integrated devices, circuits, and systems for a variety of RF, millimeter-wave (mmWave), and sub-mmWave applications. Dr. Krishnaswamy was a recipient of the IEEE International Solid-State Circuits Conference Lewis Winner Award for Outstanding Paper in 2007, the Best Thesis in Experimental Research Award from the USC Viterbi School of Engineering in 2009, the Defense Advanced Research Projects Agency Young Faculty Award in 2011, the 2014 IBM Faculty Award, the Best Demo Award at the 2017 IEEE ISSCC, the best student paper awards at the 2015, 2018, and 2020 IEEE Radio Frequency Integrated Circuits Symposium and the 2020 IEEE International Microwave Symposium, the 2021 IEEE MTT-S Microwave Magazine Best Paper Award, and the 2019 IEEE MTT-S Outstanding Young Engineer Award. He has been a member of the technical program committee of several conferences, including the IEEE International Solid-State Circuits Conference since 2015 and the IEEE Radio Frequency Integrated Circuits Symposium since 2013. He has also served as a Distinguished Lecturer for the IEEE Solid-State Circuits Society and is a member for the DARPA Microelectronics Exploratory Council.

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Professor Dennis Prather began his professional career by joining the US Navy in 1982, as an E-1, where he served for more than 38 years and recently retired as a CAPT (O-6) Engineering Duty Officer. After his initial tour of active duty, he attended the University of Maryland and received the BSEE, MSEE, and PhD degrees in 1989, 1993, and 1997, respectively. During his graduate study, he worked as a senior research engineer for the Army Research Laboratory, where he performed research on both optical devices and architectures for information processing. In 1997 he joined the Department of Electrical and Computer Engineering at the University of Delaware, where he is currently the College of Engineering Alumni Distinguished Professor. His research focuses on both the theoretical and experimental aspects of RF-photonic devices and their integration into operational systems for imaging, communications, and Radar. To achieve this, his lab designs and develops fabrication/integration processes necessary for the demonstration of state-of-the-art RF-photonic devices such as: ultra-high bandwidth modulators, silicon photonic RF sources, photonic crystal chip-scale routers, meta-material antennas, and integrated RF-Photonic phased array antennas. Professor Prather is currently an Endowed Professor of Electrical Engineering, he is a Fellow of the IEEE, Fellow of the Society of Photo-Instrumentation Engineers (SPIE), Fellow of the Optical Society of America (OSA) and Fellow of the National Academy of Inventors. He has authored or co-authored over 650 scientific papers, holds over 40 patents, and has written 16 books/book-chapters.

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He is currently a Ken Byers Professor in the area of flexible electronics with the School of ECE, Georgia Tech and he has published more than 850 papers in refereed Journals and Conference Proceedings, 5 books and 25 book chapters. He has served as the Head of the Electromagnetics Technical Interest Group of the School of ECE, Georgia Tech. Also, he has served as the Georgia Electronic Design Center Associate Director for RFID/Sensors research from 2006-2010 and as the GT-Packaging Research Center (NSF-ERC) Associate Director for RF research and the leader of the RF/Wireless Packaging Alliance from 2003-2006. Also, Dr. Tentzeris is the Head of the A.T.H.E.N.A. Research Group (20 students and researchers) and has established academic programs in 3D Printed RF electronics and modules, flexible electronics, origami and morphing electromagnetics, Highly Integrated/Multilayer Packaging for RF and Wireless Applications using ceramic and organic flexible materials, paper-based RFIDs and sensors, 3D/inkjet-printed electronics, nanostructures for RF, wireless sensors, energy harvesting and wireless power transfer, Microwave MEM's, SOP-integrated (UWB, multiband, conformal) antennas and Adaptive Numerical Electromagnetics (FDTD, Multiresolution Algorithms). He was the TPC Chair for the IMS 2008 Conference and the Co-Chair of the ACES 2009 Symposium. He was the General Co-Chair of the 2019 IEEE APS Symposium in Atlanta, and he will be the General Co-Chair for Wireless Power Week 2023. He is one of the IEEE C-RFID Distinguished Lecturers and he has served as one IEEE MTT-Distinguished Microwave Lecturers (DML).

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Don Towsley is currently a Distinguished Professor at the University of Massachusetts in the College of Information & Computer Sciences. His research interests include quantum networks, quantum network science, and statistical inference. He was a founding Co-Editor-in-Chief of the new ACM Transactions on Modeling and Performance Evaluation of Computing Systems (ToMPECS) and has served as Editor-in-Chief of the IEEE/ACM Transactions on Networking, and on numerous editorial boards. He is a Fellow of ACM and IEEE and has received numerous IEEE and ACM awards including the 2007 IEEE Koji Kobayashi Award, and the ACM SIGCOMM and ACM SIGMETRICS Achievement Awards.

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Martin B.H. Weiss is a Professor in the Department of Informatics and Networked Systems in the School of Computing and Information and is Associate Director of the Center for Governance and Markets at the University of Pittsburgh. He also on the leadership team of SpectrumX, an NSF Spectrum Innovation Center. He earned his PhD. in Engineering and Public Policy from Carnegie Mellon University. He earned an MSE in Computer, Control, and Information Engineering from the University of Michigan and a BSE in Electrical Engineering from Northeastern University. His overall research theme is the analysis of situations where competing firms must cooperate technically; this has expressed itself in studying the standardization process, internet interconnection, and, most recently, radio spectrum sharing. His current research focus is on the governance of technological systems and infrastructures. He has been studying dynamic spectrum access, blockchains and emerging smart city applications. Recent aspects of this have involved studying enforcement in cooperative spectrum sharing approaches, governance of spectrum and applications of and governance of blockchain systems. Past projects include technical and cost studies new technologies, bandwidth markets, interconnection of packet networks that support quality of service (QoS), and technical standards.

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Alan Willner is a Distinguished Professor and the Steven & Kathryn Sample Chaired Professor of Engineering at the Univ. of Southern California. Prof. Willner's honors include: Member of U.S. National Academy of Engineering; International Fellow of U.K. Royal Academy of Engineering; Presidential Faculty Fellows Award from the White House; Ellis Island Medal of Honor; IEEE Eric Sumner Technical Field Award; Fulbright, Guggenheim, Packard, and DoD Vannevar Bush Fellowships; Fellow of National Academy of Inventors; IET Thomson Medal; Egleston Medal for Distinguished Engineering Achievement from Columbia Eng. Alumni Assoc.; Optica (formerly OSA) Forman Engineering Excellence Award; IEEE Photonics Society Engineering Achievement Award; Optica Hopkins Leadership Award; Honorary

Doctorate from Yeshiva Univ.; SPIE Presidents Award; Eddy Paper Award from PennWell Publications for Best Contributed Technical Article; and IEEE Globecom Best Paper Award. Prof. Willner's activities include: Co-Chair of U.S. National Academies Study on Optics & Photonics; President of Optica; President of IEEE Photonics Society; Editor-in-Chief of Optics Letters, IEEE/Optica Journal of Lightwave Technology, and IEEE Journal of Selected Topics in Quantum Electronics; Technical Chair of Unclassified Program for MILCOM; and General Co-Chair of CLEO. He is a Fellow of AAAS, APS, IEEE, IET, OSA, and SPIE.

Appendix II—Workshop Agenda and Prospectus

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DAY 1—WEDNESDAY, June 8, 2022

Time	Title	Speaker
8:00—8:15	Check-in and Continental Breakfast	
8:15 - 8:20	Welcome and Introductions and Expectations	Nader Engheta, UPenn
8:20 -8:45	Workshop Framing Talk	Co-chairs
8:45—9:00	Breakout Instructions and Morning Break	
9:00—10:45	Working Group I: Define the Problem *Small group discussions to frame a vision for future of wireless communications and identify the greatest hurdles to achieving it.* Group A –Photonics Group B—Electronics Group C—Networks	
10:45—11:00	BREAK - *Transition to main conference room and leads prepare outbriefing*	
11:00 –12:00	Working Group 1: Outbriefing	
12:00—1:00	LUNCH (provided for participants)	
1:00—3:45	Working Group II: Technical Capabilities and Opportunities *What are the promising research directions for wireless communications? What are the potential capabilities in the 10- to 20-year horizon?* Group A –Photonics Group B—Electronics Group C—Networks	
3:45—4:00	BREAK - *Transition to main room and leads prepare outbriefing*	
4:00—4:45	Working Group II: Outbriefing	
4:45—5:00	Summary of Day	Co-chairs
5:00	MEETING ADJOURNED FOR THE DAY	

DAY 2—THURSDAY, June 9, 2022

Time	Title	Speaker
8:00—8:15	Check-in and Continental Breakfast	
8:15—8:30	Welcome and Day 1 Recap	Co-chairs
8:30 -9:30	**'White Space' Discussion I** Discussion of topics which did not fit into the framework of day 1 but need to be discussed.	
9:30—10:30	**'White Space' Discussion II** Discussion of particularly far-out (or long-term), high-risk, high-impact ideas.	
10:30—10:45	BREAK	
10:45—11:45	Discussion of Key Ideas/Components for Report	
11:45—12:00	Closing Remarks Co-chairs	
12:00	DEPARTURE	

Co-Chairs: Nader Engheta (University Pennsylvania), Harish Krishnaswamy (Columbia University), Ness Shroff (Ohio State University)

5G has not been fully deployed in most parts of the world, but many experts and researchers have already begun to conceptualize the future generations of wireless communications, 6G and beyond, or "XG". These next generation wireless systems are envisioned to enable ubiquitous wireless connectivity across multiple scales, globally distributed. To make this vision a reality, comprehensive and multidisciplinary approaches will need to be applied to meet the anticipated technical challenges. A fundamental question is whether these advanced XG capabilities will develop as a natural progression of current wireless communication technologies or rather require a paradigm shift. More focused questions include: what are the enabling technologies (e.g., materials, sensors, computation, communications, networking, etc.) and what are the technical limitations for various operational scenarios and environmental conditions? Transformative basic research can drive the development of a rapidly growing number of advanced wireless technologies and intelligent devices and services. Advances in Artificial Intelligence (AI), mathematics and computer science will be paramount in designing and optimizing architectures, networks, protocols, and operations.

This Future Directions Workshop on Wireless Communications: XG and Beyond, sponsored by the Basic Research Office in the Office of the Under Secretary of Defense for Research and Engineering (OUSD(R&E)), aims to identify the key drivers, requirements, challenges, and essential basic research questions related to the future generation of wireless communications. The goal of the workshop is to address:

- How might basic research impact science and technology of the future for this field?
- What are the possible trajectories of scientific achievement over the next 10–15 years?
- What are the most fundamental challenges to progress?
- This Future Directions workshop will gather thought leaders from across the relevant communities in academia, industry, and government to discuss a range of basic research challenges and opportunities, in the areas of:
- Physical sciences—e.g., new materials, new circuits, beam propagation, nanoscale integration, etc.
- Mathematics and computer science - e.g., advances in AI to control and manage mix / match of frequencies; optimization; modeling and simulation of new architecture design; wave propagation/attenuation in realistic environments, etc.

The discussions will be informed by an appreciation of the potential health, environmental, and cybersecurity impacts of developing such technologies. The ensuing report will provide valuable long-term guidance to the DoD community, as well as the broader federal funding community, federal laboratories, and other stakeholders. Workshop attendees will emerge with a better ability to identify and seize potential opportunities in this rapidly evolving research area. This workshop is sponsored by the Basic Research Office within OUSD(R&E), along with input and interest from the Services and other DoD components.

Agenda

Rather than a standard conference format, this 1.5-day workshop emphasizes interactive dialogue with primarily small-group breakout sessions followed by the whole-group synthesis of ideas.

Day One: The majority of the first day will be spent in the small-group breakout sessions on fundamental challenges to progress and technical capabilities. The format of the workshop will include three breakout themes: Photonics, Electronics, and Networks. These themes will be interconnected by cross-cutting thrusts that span AI, Quantum, Security, Privacy, and Robustness.

1. **Photonics**
   Since electromagnetic propagation is one of the key ingredients in all XG systems, innovation in material platforms that can manipulate and control EM signals will play an important role in such systems. As the need for the enhanced channel capacity increases, one needs to go to the higher ranges of electromagnetic spectrum (e.g., THz, IR, and visible), which bring new opportunities and challenges. Therefore, out-of-the-box thinking and innovation in THz and photonic materials and metamaterials will be desired. Since the communication is primarily achieved by the propagation systems (and to some extent by the electronic system), while the computation is mainly performed by the electronic platforms, the interface and data conversion between these two platforms have played, and continue to play, important roles. Key questions include: How will innovation in photonic computation affect this paradigm? How will photonic computation and electronic computation be synergistically linked together

to form hybrid systems of computation that can be augmented by, and linked to, the hybrid photonic-electronic communications. While the data storage has traditionally been achieved by the electronic platforms, can new innovations in future photonic storage provide game changing paradigms for future XG systems and beyond? In addition, innovation for new XG systems will require re-thinking the energy budget for such systems. Key questions around energy budgets include: How can required energy be provided for the electronic and photonic (and their hybrid) platforms in the future? Can innovation in wireless energy harvesting be a route to address this challenge?

2. **Electronics**
   As described above, as we look towards the next generation of wireless networks, there is a growing consensus that increases in network capacity will be obtained by pushing further into higher reaches of the frequency spectrum. The so-called "terahertz" frequency range, defined here as 100 GHz-1 THz, has historically been less explored because this frequency range has been too high for electronics and too low for photonics-based approaches. Recently, there has been interest in advanced compound-semiconductor electronics (GaN, InP) and their heterogeneous co-integration with silicon-based technologies to enable highly integrated circuits and systems that access this frequency range. In addition, at extremely high frequencies, conventional communication architectures need to be revisited. It is expected that xG architectures will blur the boundaries between the traditional architectural domains of electromagnetics, analog electronics, and digital electronics. To move beyond the conventional discrete transmitter-receiver paradigm, there has been increasing interest in distributed communications through reconfigurable intelligent surfaces (RIS), where the environment is equipped with a multitude of active/passive elements that can shape and engineer the wireless channel to one's advantage. The concept of RIS is but one example of the convergence of electronics and photonics/electromagnetics to re-imagine how communications might be accomplished with greater capacity and reliability and lower latency. In addition, it is envisioned xG architectures will feature new ways in which emerging higher-layer algorithms related to AI, ML and security will seamlessly permeate to the lower layers of hardware implementations.

3. **Networks**
   Future generation networks will be even more complex distributed systems, consisting of an array of dispersed network elements, heterogeneous software and hardware components and modules, and will need to react and adapt to the needs of future applications. These networks will need to carry an unprecedented amount of data and bring it to the end-users within near instantaneous time. Hence, the networks will not only need very high-speed communication links but also control mechanisms to ensure timely delivery of information. Further, these networks will need to be designed such that they are secure against a variety of attacks ranging from individuals, organizations, and adversarial states. They will need to be robust to failures and be able to readily self-organize under extreme conditions. As the scale and complexity of these networks grow, they will also need to automatically react to different scenarios with little or no human intervention. That is, they will need to be embodied with an intelligence plan that is flexible, adaptive, and robust. Further, end-user data carried on these networks will increasingly need to have strong privacy protections built from the bottom up.

   Traditional approaches to managing these networks have been based on heuristic designs derived from domain knowledge or simplified theoretical models. These methods will not suffice to control these emergent networks: neither domain knowledge nor mathematical modeling can by themselves sufficiently grasp the vast scale, complexity, and uncertainty in these hyper-scale and heterogeneous networks. A promising area of investigation will involve the development of new theoretical tools from AI, algorithms, protocols, and control mechanisms that can leverage the decades of domain knowledge in networking, satisfy stringent network requirements (latency, throughput, power, energy, data freshness, etc.), and can account for and possibly exploit the various types of network dynamics (fading, mobility, location, etc.). New advances in quantum computing and quantum networks will be needed to substantially enhance the capacity and compute limits of these networks. Network security and privacy mechanisms will need to become part of the design and control mechanisms of these systems rather than as an afterthought.

Cross-Cutting themes to discuss

- Artificial Intelligence: How can advances in AI be used to further advance XG development from photonics, electronics, and networks to applications?
- Security: How should security be incorporated into the design of these systems to ensure protection from adversarial agents and disruption of services?
- Resiliency and Robustness: How should these systems be designed to ensure robustness and resiliency against failures, imperfect information, and multi-system, multi-technology interactions?
- Quantum: What role will quantum computing and networking play in the development of these XG systems?

Day Two: The second day of the workshop is a half-day consisting of white-space, whole group discussions on topics that did not fall into the Day 1 framework or were especially ambitious and/or high-risk. Participants will also discuss cross-cutting themes and the trajectory of the field over the next 10-20 years. At the end of the day, the whole group will discuss the overarching themes of the workshop that should be included in the final workshop report.